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Mary K. Camarillo
University of the Pacific, mcamarillo@pacific.edu

William T. Stringfellow
University of the Pacific, wstringfellow@pacific.edu

Joel Herr
Systech Water Resources, joel@systechwater.com

Scott Sheeder
Systech Water Resources, scott@systechwater.com

Gregory Weissmann
University of the Pacific, g_weismmann@u.pacific.edu

See next page for additional authors

Authors

Mary K. Camarillo, William T. Stringfellow, Joel Herr, Scott Sheeder, Gregory Weissmann, Shelly Gulati, and Ashley Stubblefield

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Use of a One-Dimensional Link-Node Model to Develop Total Maximum Daily Load Strategies for the San Joaquin River Estuary

Mary Kay Camarillo[1], William Stringfellow[1,2], Joel Herr[3], Scott Sheeder[3], Gregory Weissmann[1], Shelly Gulati[1], Ashley Stubblefield[1]
[1]Ecological Engineering Research Program, School of Engineering and Computer Science, University of the Pacific, Stockton, CA, mcamarillo@pacific.edu
[2]Earth Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA
[3]Systech Water Resources, Inc., Walnut Creek, CA

Abstract: A one-dimensional link-node model was used to simulate water quality conditions in the tidally-influenced, deep water ship channel (DWSC) of the San Joaquin River located in Central California. The DWSC has been plagued with low dissolved oxygen (DO) conditions for decades and is currently a focus of restoration efforts. The model was calibrated using a six-year flow and water quality data set. Model simulations were run by removing the mass loads of each of the following major sources of oxygen depletion to determine the effects: elimination of the deepened ship channel (i.e., restore to its pre-existing depth), elimination of import of oxygen-demanding substances (ODS) from the San Joaquin River watershed, elimination of import of ODS from the urban tributaries, and elimination of discharge of ODS from the City of Stockton regional wastewater control facility. The model results suggest that elimination of the deepened ship channel resulted in the best projected improvement relative to the modelled baseline with a predicted 55% improvement, while reducing ODS from the watershed would likely cause a 44% improvement. These results demonstrate that there are multiple contributing factors causing low DO in the DWSC and that removal or elimination of any single variable will not result in a complete resolution of low DO events.

Keywords: Water quality; TMDL; dissolved oxygen; eutrophication; waste load allocation

1. INTRODUCTION

1.1 Project Description

Reoccurring low dissolved oxygen (DO) in the lower reaches of the San Joaquin River (SJR) of Central California has prompted a Total Maximum Daily Load (TMDL) regulatory effort for constituents contributing to these low DO conditions (CVRWQCB, 2005). As a result of anthropological inputs and modifications to the SJR system, native fisheries have drastically declined and water quality has been impaired beyond the river's assimilative capacity. The upstream portion of the SJR is highly regulated by dams and diversions that convey water away from the river for agricultural and domestic uses. The watershed is dominated by irrigated agriculture although there are also industries (mostly related to agriculture) and some population centers. The lower SJR is a tidally-influenced estuary that has been channelized and deepened along a section referred to as the Deep Water Ship Channel (DWSC) that permits navigation of large vessels into Stockton, CA. Although water quality problems persist throughout the SJR, the DWSC is the location where the occurrence of low DO is most severe. To restore ecosystem services in the SJR and in the downstream Sacramento-San Joaquin River Delta and San Francisco Bay, the State of California has initiated a major rehabilitation effort and adopted an adaptive management approach to carrying out this effort (CVRWQCB, 2005). Currently, the regulatory standard for DO (5 mg/L

except during September, October, and November when the standard is increased to 6 mg/L) is frequently exceeded during the warm summer months.

Low DO conditions in the DWSC are the result of physical, chemical, and biological processes that add and subtract DO in the water column. DO is added to the water column by photosynthesis, import from adjacent waters, and reaeration. DO is removed from the water column by degassing and reactions with reduced organic and inorganic compounds, collectively referred to as oxygen demanding substances (ODS). Types of ODS found in the SJR system include carbon associated with phytoplankton and inorganic ammonia-nitrogen associated with wastewater discharges and non-point sources. Phytoplankton grow abundantly in the SJR because it's a eutrophic river, rich in nutrients, and because it's warm, shallow, and exposed to abundant sunlight. In addition, channel geometry influences oxygen balance through mechanisms including the depth to which light penetrates (photic zone) and the surface to volume ratio, which is important for reaeration and degassing processes. Hydraulics also influence processes such as mixing and residence time, which affect biological processes and the balance between oxygen depletion, import, and reaeration. Temperature inversely affects DO saturation capacity and directly influences the rate of biological processes.

To promote rehabilitation efforts and resolve low DO conditions in the DWSC, the sources of nutrients and ODS in the SJR as well as other factors contributing to low DO must be determined. Due to the complexity of the dynamic mechanisms adding and removing DO from the water column, the use of computer modelling has become an essential component of management and regulatory efforts in the Sacramento-San Joaquin River Delta. Previously, a watershed model was developed and adapted to better understand sources of pollution and in-water processes in the upstream portion of the SJR. In the SJR estuary, one-dimensional models are considered most appropriate for predicting low DO conditions in the DWSC (Jones and Stokes, 2006). Stratification in the DWSC is unstable and the DWSC mixes vertically on a daily basis, even during the summer (Lehman et al., 2004). To better understand the factors contributing to low DO in the DWSC, a one-dimensional Link-Node model was adapted and applied to the SJR estuary (Chen and Tsai, 2002).

Previous studies have determined that DO impairment in the DWSC is caused by three main factors: low flow, modified channel geometry and ODS in the DWSC (CVRWQCB, 2005). To our knowledge, this TMDL is unique in the nation in that it assigns responsibility for control of DO below assimilative capacity jointly between those parties collectively responsible for the DWSC geometry, reduced flow, and contribution of ODS. Historically, the City of Stockton Regional Wastewater Control Facility (RWCF) has been identified as a major contributor of ODS that leads to low DO conditions. Other sources of ODS include non-point source urban runoff and discharges from irrigated agricultural land that is abundantly present in the SJR watershed. Diversions and system exports contribute to low flow rates that also exacerbate low DO conditions.

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). Downstream of Vernalis, the SJR is tidally influenced. The DWSC is the portion of the SJR between the City of Stockton and the confluence with the Sacramento River that has been dredged to allow for the navigation of ocean-going vessels to the Port of Stockton. Effluent from the City of Stockton RWCF is discharged into the SJR just upstream of the DWSC, while urban runoff from the city is conveyed directly into the channel.

1.3 Project Objectives

The objective here was to use the SJR-Link-Node model to determine the relative contributions of DO deficit in the DWSC for the following four sources and conditions: 1) dredging of the DWSC to deepen the channel beyond its natural, pre-existing depth, 2) ODS from the upstream SJR, 3) ODS from the City of Stockton RWCF, and 4) ODS from the urban tributaries from the City of Stockton directly discharging into

the DWSC. The work here is supportive of TMDL efforts and is intended to engage stakeholders by presenting practical modelling results that are beneficial for environmental decision-making.

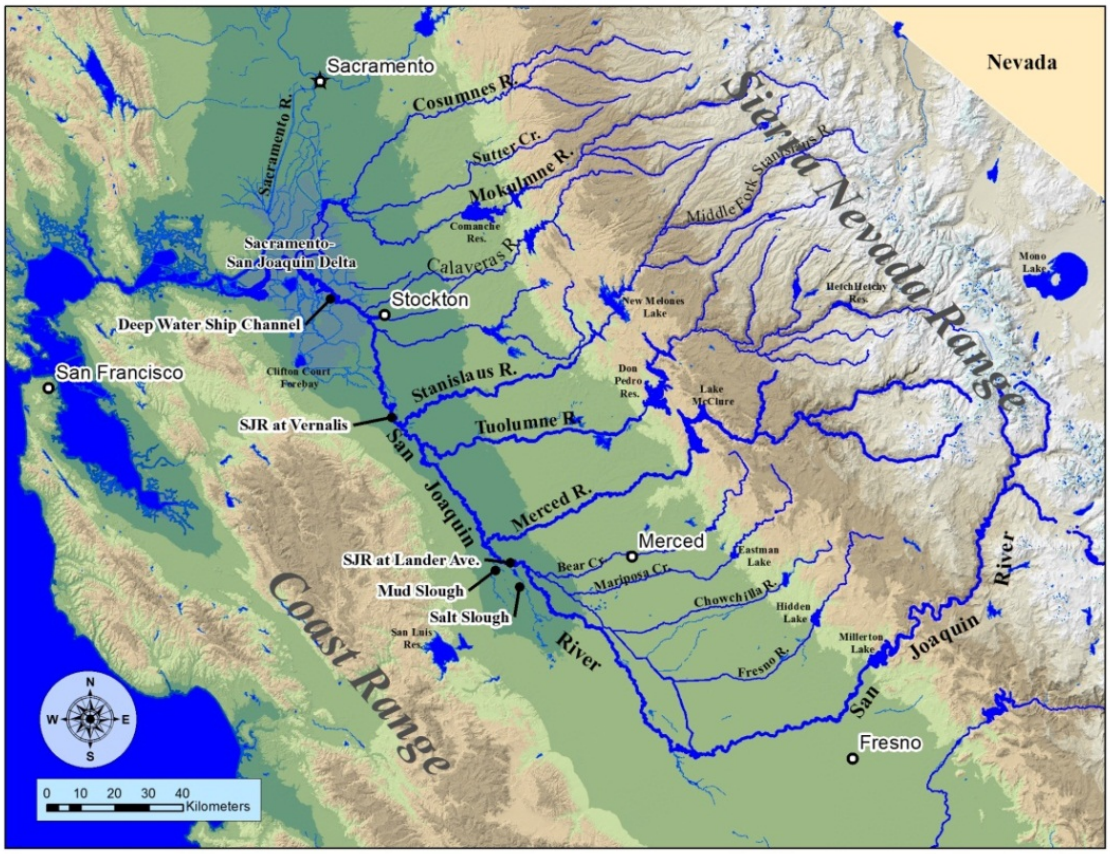

Figure 1. San Joaquin River watershed, located in Central California.

2 METHODS

2.1 Model Description

The SJR-Link-Node is a one-dimensional model that simulates flow and water quality in the tidally-influenced SJR estuary between Old River and Disappointment Slough (Figure 2). In the model, the river is divided into segments (nodes) that have bi-directional connections (links), simulating the tidally-influenced back and forth flow and mass transport. An Euler grid system is used. Numerical dispersion is calculated using the computational fluid dynamics approach of Roache (1972) with the UPWIND scheme. An anti-numerical dispersion term is used to prevent pollutants from advancing too fast from one node to another, which can be problematic in link-node models. The model now allows for the use of different reaction rates at different nodes (Systech Water Resources Inc., 2008).

The model was originally developed by Chen and Orlob (1975) and was integrated into the U.S. EPA model WASP5 DYNHYD5. The Link-Node model was subsequently adapted and applied to the SJR estuary (referred to here as SJR-Link-Node) for the City of Stockton (Schanz and Chen, 1993), and later used as part of the Interim South Delta Program (Chen and Tsai, 1997). The model was again used and calibrated as part of the CALFED program (Chen and Tsai, 2002). Next, SJR-Link-Node was used as part of the TMDL program (Systech Water Resources Inc., 2008), and was integrated with the SJR-WARMF-

2008 watershed model complete with a graphical user interface (Herr and Chen, 2006). As part of the TMDL project, WARMF model output and observed data were used to create flow and water quality input files to represent inflows to the Link-Node domain from tributaries entering the SJR in the vicinity of Stockton (Figure 2).

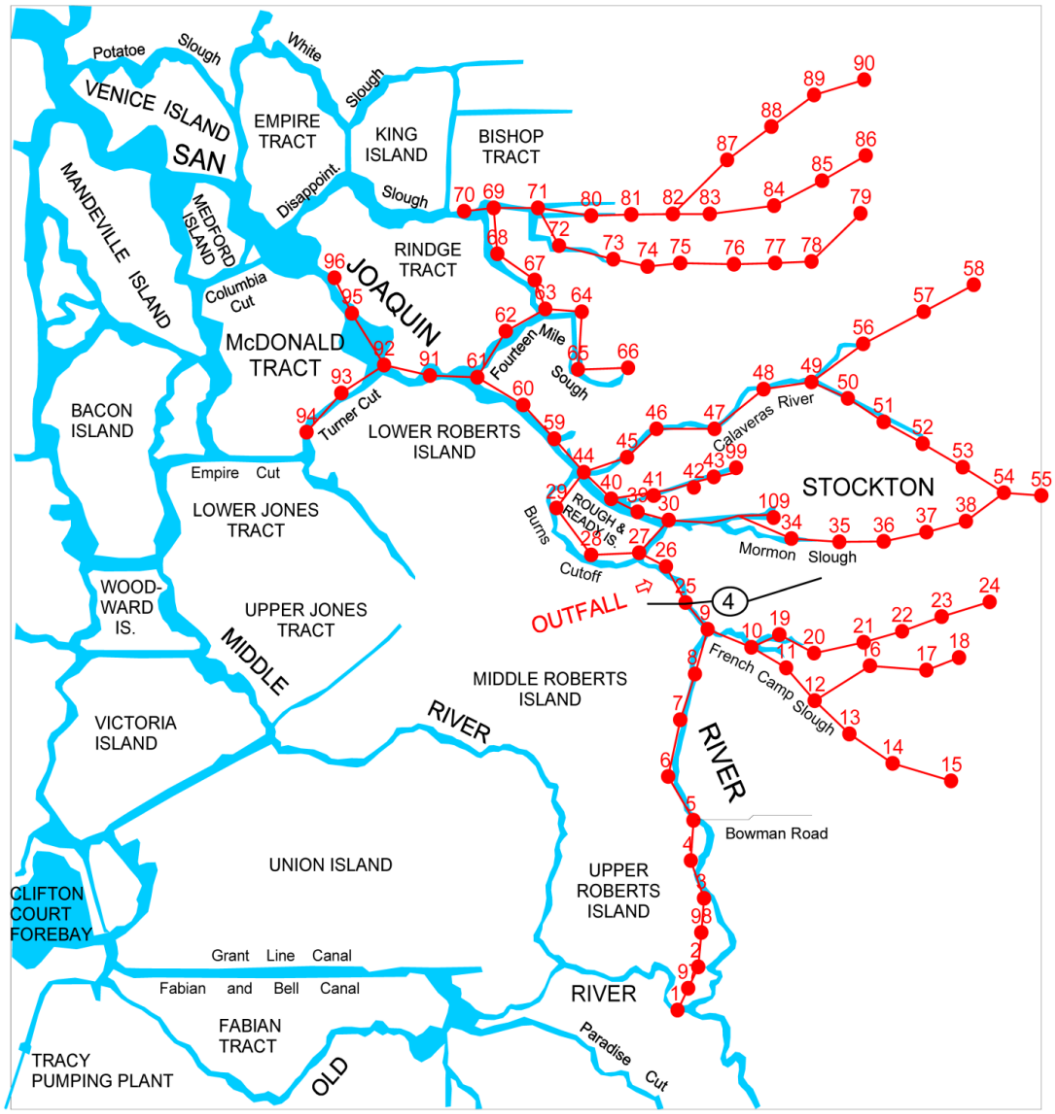

Figure 2. SJR-Link-Node model domain, located in the lower San Joaquin River. The monitoring station located near Rough & Ready Island (RRI) is located at Node 40. The Stockton RWCF outfall is located between Nodes 25 and 26.

The sources of DO in SJR-Link-Node are algal photosynthesis, point sources and tributary inflows, and reaeration, while sinks consist of BOD decay, nitrification, sediment oxygen demand, algal respiration, and decay of detritus (represented by volatile suspended solids, or VSS). The model is used to simulate the hydrologic parameters of flow, water depth, and velocity as well as the water quality parameters of DO, temperature, carbonaceous biochemical oxygen demand (CBOD), VSS, total suspended solids (TSS), ammonia, nitrate, phosphate, algae (as Chlorophyll-a), and pheophytin (dead algae). Light intensity is calculated using Beer's Law. Light limitation in the water column is calculated using Monod kinetics. Link-Node has been adapted to simulate real time tides that follow natural spring and neap tide

cycles. Zooplankton modelling capability has also been added, although further refinement (data) is needed to fully develop this capability. Reaeration is calculated using the empirical approach of O'Connor and Dobbins with an added term to account for the effects of wind. Five types of settlable particles are modelled in Link-Node: chlorophyll-a, pheophytin, detritus (VSS), inorganic solids (fine silt and clay), and sand. The sedimentation, resuspension, and sediment oxygen demand (SOD) associated with detritus is also modelled. As a result of the 1-D nature of the model, light intensity is averaged over the entire depth of the water column, which results in essentially no available light in deep areas such as the DWSC. To account for algae growth and photosynthesis, phytoplankton growth in the DWSC is simulated in the top two feet of the water column. Model output is hourly.

2.2 Model Inputs

A variety of inputs are needed to run SJR-Link-Node. Here, tidal boundary input files were created using data from the California Data Exchange Center (CDEC). Water surface elevation data was obtained for the stations of Turner Cut near Holt, Rough & Ready Island (RRI), and Venice Island. Tidal exchange was assumed to be 3% for every hour outside of the tidal boundary and approximately 10% over a tidal cycle. Flow data was also collected from CDEC, including flow data for the Garwood Bridge station (maintained by USGS) that was used for model calibration. Hourly meteorological data (temperature, dew point temperature, cloud cover, air pressure, wind speed) originated from a Stockton weather station, as reported by the California Irrigation Management Information System (CIMIS). In addition to flow data, continuous water quality monitoring data was obtained from CDEC for the Vernalis, Mossdale, and RRI monitoring stations. River channel dimensions were calculated using a combination of satellite imagery available in Google Earth and a GIS-based digital elevation model (DEM). The DEM was created by USGS, and has a horizontal resolution of 10 m and a vertical resolution of 0.1 feet. Flow and water quality data, consisting of compliance reports for the City of Stockton RWCF effluent, was collected from the facility managers. Grab sample data for water quality parameters originated from the TMDL projects. Model coefficients were used to simulate various processes affecting DO in the DWSC (Table 1).

Table 1. Link-Node model coefficients.

Model Coefficient	**Value**	**Units**
BOD5 decay coefficient	0.30	per day
Ultimate BOD/BOD5	2.54	mg/mg
Ammonia decay coefficient	0.05	per day
DO/ammonia ratio	4.57	mg/mg
Detritus decay coefficient	0.01	per day
DO/detritus ratio	1.6	mg/mg
N/detritus ratio	0.08	mg/mg
P/detritus ratio	0.012	mg/mg
Algae maximum growth rate	1.80	per day
Algae half-saturation constant of light	4.3	cal/m^2/sec
Algae half-saturation constant of P	0.003	mg/l
Algae half-saturation constant of N	0.1	mg/l
Algae respiration rate	0.25	per day
Algae settling rate	0.15	m/day
DO/algae ratio	1.6	mg/mg
Chlorophyll-a to pheophytin rate	0.13	per day
Pheophytin decay coefficient	0.1	per day
Aeration adjustment factor	1.8	unitless
Theta Values for Temperature Correction		
Nitrification	1.08	unitless
BOD decay	1.04	unitless
SOD decay	1.04	unitless

2.3 Model Calibration

Here, SJR-Link-Node was calibrated for the time period 1/1/2005 to 12/31/2010. Calibration was performed to minimize mean and absolute error, and to maximize the r-squared statistic for water surface elevation and DO, as measured at the RRI monitoring station. To improve the model fit for the observed data, a series of simulations were run to evaluate the sensitivity of the model to each of the parameters affecting DO concentration (temperature, ammonia, CBOD, and phytoplankton). The sensitivity analysis revealed that the reaeration and BOD decay rates had the greatest effects on simulated DO concentrations. Therefore, these parameters were used to fit the simulated DO concentrations with observed values at RRI. The mean error for DO is shown in Eqn. 1, where x_i is the DO concentration (mg/L) predicted by the model, c_i is the observed DO concentration (mg/L), and n is the number of paired data points.

$$\text{mean DO error (mg/L)} = \frac{1}{n}\sum_{i=1}^{n}(x_i - c_i) \quad (1)$$

3 RESULTS AND DISCUSSION

3.1 Model Calibration

The model calibration results indicate that the model errors (residuals) of the model, as calculated using Eqn. 1 without calculating the mean, follow a fairly normal distribution although there are some extreme values (Figure 3). The annual variability in model errors is not markedly different although model errors from the year 2007 demonstrated the most variability. The year 2007 had much less precipitation than the two previous years, which may have been influential in the outcome. The balanced model residuals indicate that the model is not significantly over-predicting or under-predicting DO except in the cases of 2007 where the model is over-predicting DO and in 2009 where the model is under-predicting DO. Over the six year observation period, the mean error was -0.110 mg/L. Although the model was very effective in predicting mean DO concentrations, the model was less effective in predicting DO violations. During the observation period, 13% of days had DO violations while the model only predicted violations on 5% of days.

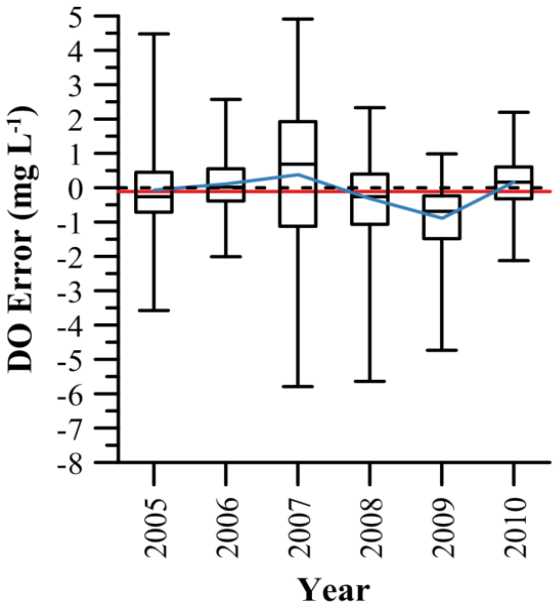

Figure 3. Error in SJR-Link-Node model predictions of dissolved oxygen (DO), as compared with observed data collected from a stationary continuous monitoring device (sonde) at Rough & Ready Island (RRI). The red line represents the overall mean error, while the blue line represents the annual mean error.

3.2 Model Simulations for Dissolved Oxygen

Following model calibration, simulations were run to predict the effect of altered management and control strategies. Although the results of the four simulations did not yield appreciably different average DO concentrations at RRI (no greater than 0.5 mg/L), the occurrence of predicted DO standard violations were reduced (Table 2). The model predictions suggest that the "No DWSC" scenario had the largest impact on DO, and that this scenario resulted in 55% fewer violations when compared with the model baseline. The improvements for the "No SJR", "No RWCF", and "No Tribs" scenarios were 44%, 20%, and 10% relative to the model baseline.

Table 2. Observations and model results for dissolved oxygen (DO) concentrations and days with violations at Rough & Ready Island (RRI). Mean ± standard deviation is reported for DO.

Basis of result	DO (mg/L)	Days with violations (%)
Observations at RRI	7.63 ± 1.37	13.0
Model baseline	7.53 ± 1.13	5.0
No DWSC scenario	8.03 ± 1.15	2.3
No SJR scenario	7.63 ± 1.24	2.8
No RWCF scenario	7.63 ± 1.12	4.0
No urban tributaries scenario	7.61 ± 1.13	4.5

The model results indicate that all scenarios resulted in some improvement in DO concentrations (Figure 4). While the "No DWSC" and "No SJR" scenarios resulted in the most improvement in DO concentration, the most significant improvements for the two scenarios did not always occur simultaneously. For example, the "No SJR" scenario was most beneficial early in 2008 while the "No DWSC" was more influential in DO concentrations in the latter part of 2008. Mass loads from the SJR are significant in the

winter when flows are higher and the transport of materials down the SJR is more significant. In the summer river flows are reduced, which suggests that a shallow estuary would be beneficial since residence times would be reduced and algal decay would be reduced by increased cycling of nutrients.

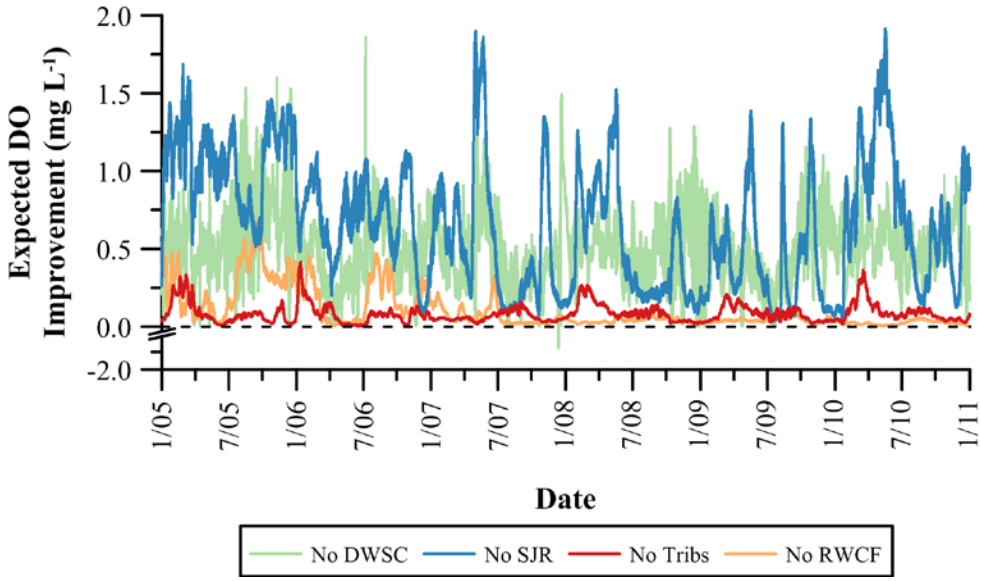

Figure 4. Predicted improvements in dissolved oxygen (DO) using the SJR-Link-Node model. Improvements are shown relative to a baseline (shown as the dashed line) that replicates observed conditions, while the four scenarios represent management alternatives.

4. CONCLUSIONS

The one-dimensional SJR-Link-Node model was successfully applied to the SJR Estuary to predict DO concentrations and examine the effects of altered management and control approaches. Characterizing such a complex river/estuary system as this is difficult due to the expansive nature of this system as well as the variability in flows and loadings that are more strongly connected to agricultural activities and reservoir releases than to natural hydrology. However, the results of the simulations suggest that the management alternatives considered would result in decreased DO violations and that alteration of the deepened ship channel had the largest impact, followed by the reduction of ODS from the upstream SJR. The urban tributaries and wastewater discharge had a less dramatic effect on DWSC DO concentrations. The results here demonstrate the effective use of modelling to assist in policy and management decisions to support TMDL and restoration efforts that engage stakeholders in decision-making processes.

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