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Elements of a Decision Support System for Real-Time Management of Dissolved Oxygen in the San Joaquin River Deep Water Ship Channel

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ABSTRACT

A decision support system (DSS) has been designed and will be implemented over the next three years to assist in the control and management of episodes of low dissolved oxygen (DO) in a Deep Water Ship Channel (DWSC), located near Stockton, California. The DSS integrates three information technology functions. The first part is the collection and management of data on flow, pollution loads and water quality. The second part is the simulation model which can forecast the dissolved oxygen sag in the DWSC and determine management actions necessary to improve dissolved oxygen concentrations. The third part is the graphical user interface, which facilitates the computer simulations and posting of the forecasted dissolved oxygen and remedial measures to a stakeholder group for implementations.

1. BACKGROUND

The San Joaquin River (SJR) basin, located in the Central Valley of California, is an important agricultural region with an annual production of more than US$6 billion covering approximately 1 million hectares. In addition, the basin contains approximately 40,000 hectares of managed seasonal wetlands, both public and private – a small faction of an area that once dominated the Basin at the beginning of the century.. Agriculture and seasonal wetland habitat in this region both are dependent on irrigation and on drainage to eliminate imported salts. The soils on the west-side of the SJR basin are derived from marine shales that are high in natural salts such as sodium sulphate and boron. In the past decade, high concentrations of salts, such as selenium, also found in irrigation drainage, have created toxic conditions to waterfowl and other sensitive wildlife species. Recent studies have also implicated algae and nutrients in both irrigation and wetland drainage as an important factor contributing to the DO sag in the DWSC (Foe et al. 2002). Environmental regulation of water quality in the San Joaquin River and San Francisco Bay and the provision of more than seven million dollars of research funding has created an opportunity for management of the basin using an integrative ecosystem approach. This paper describes one of the more significant components of this integrative ecosystem approach directed at improving the DO levels in the DWSC near the City of Stockton (Figure 1).

1.1. Dissolved Oxygen Problems In The San Joaquin River

The low DO conditions are found where the SJR meets the estuary portion of the DWSC. Periods of low DO are mostly between June and October, but low DO conditions have been observed to occur year-round. Dissolved oxygen levels as low as 0.4 mg/L have been measured, but summer low DO concentrations are more typically between 2.0-2.5 mg/L (Foe et al 2002). Low oxygen conditions can block fish migration and may even result in occasional fish kills (Horne, 2001).The State of California placed the San Joaquin River on the EPA 303(d) list (a list of contaminated waters of the State requiring cleanup) in 1994 because the dissolved oxygen levels were below the water quality objectives of 6 mg/l between September 1st and November 30th and 5 mg/l at all other times. A 6-mg/l objective was adopted to protect the upstream migration of fall-run Chinook salmon (Foe et al 2002).

1.2. Factors Affecting Dissolved Oxygen Sag

Dissolved oxygen concentration is controlled by a large number of factors including tidal oscillation and mixing, stream flow, channel depth, winds, temperature, and the presence of oxygen demanding substances, including algal biomass, dissolved organic matter, ammonia, volatile suspended solids, and sediment oxygen demand (Chen and Tsai, 2001). Oxygen demanding substances contributed by upstream agricultural, wetland and municipal sources combined with algal biomass, produced within the San Joaquin River, all contribute to creating a DO sag within the DWSC (Figure 2). During the summer, mass loading of phytoplankton can be high from upper watershed sources, where water is often stagnant for periods of time and nutrient levels are in excess, creating ideal conditions for the growth of algae and aquatic plants. Municipal sources appear to be more important in the late summer and fall when a significant portion of the DO sag can be attributed to nitrogen loading, especially ammonia (Lehman, 2001).

The low dissolved oxygen problem is compounded by a transition from a shallow well-oxygenated conveyance (approximately 30 meters wide and 3 meters deep) to the deep, wide ship channel (approximately 150 meters wide and 10 meters deep). This transition increases hydraulic residence time, promotes settling of suspended material including algae, and encourages occasional water column stratification. Occasional mixing of the surface and near bottom water is provided by the passage of large ships which berth in the ship channel and which traverse the ship channel to the Port of Stockton Turning Basin. Residence time in the DWSC has been calculated to vary between 5 and 25 days (Chen, 2002). Oxygen production by algal photosynthesis and oxygen consumption by microbial respiration are major processes controlling DO concentration in the SJR and DWSC. In surface waters, algae produce much more oxygen by photosynthesis than they consume via respiration. The DO concentrations often exceed 150% of saturation, which is lost to the atmosphere in day. At night, photosynthesis ceases but respiration continues. Often, there is a net deficit of DO.

Other DO sinks include wastewater discharged by the City of Stockton, urban runoff and agricultural sources including dairy farms and private and public wetlands. Sediment oxygen demand is derived from organic matter that has accumulated in the river bed over time. The controlling factors for the DO can change with time by hour, day, and season. The dynamic nature of the estuary system make it impossible to isolate a single factor can be used to explain the observed DO change, because all factors work in concert to affect the DO in the Lower San Joaquin River.

Temporal discrimination of load contributions has significant implications for the development of an equitable dissolved oxygen Total Maximum Daily Load (TMDL). The TMDL allocation process is a USEPA sanctioned procedure, applied to impaired waterbodies, for ensuring that the pollutant assimilative capacity is not exceeded, and for distributing responsibility for cleanup (Foe et al. 2002).

1.3. Management Of Dissolved Oxygen Sag

Management solutions to address the Stockton DWSC problem involves (1) determining the relative contribution to the problem by agricultural, wetland and municipal sources; (2) coordinated continuous monitoring of the factors contributing to low DO in the DWSC; and (3) development of a decision support and management tool that allows forecasting of DO conditions in the DWSC and that guides action to prevent the low DO conditions.

Real-time DO forecasting can be used to improve coordination of activities among those entities that directly benefit from the resources of the San Joaquin River. Use of a decision support tool as a device for watershed coordination and to provide direction to a comprehensive monitoring plan has not been attempted before in the Basin but makes sense in this instance because of the complexity of the science and the large number of stakeholders potentially affected.

2. ELEMENTS OF THE DECISION SUPPORT SYSTEM (DSS)

Two primary considerations drove the design of the DSS – cost and robustness. Costs were minimized by building upon an existing data acquisition and information management frameworks. This monitoring network was developed for salinity forecasting by a public agency to serve the scientific community in the Sacramento-San Joaquin Bay-Delta.

2.1 Monitoring data acquisition

A large multi-disciplinary and multi-agency team of scientists, engineers, biologists and ecologists have been involved in Bay-Delta studies and in routine monitoring of the Deep Water Ship Channel (DWSC) and upstream tributary inflows for the past four years. The complexity of data ranges from short term synoptic studies of parts of the river and ship channel to long term continuous monitoring of water quality and flow using state-of-the-art solid-state sensors. The frequency of data collection varies from 15 minute to bi-weekly.

Real-time (continuous) flow and water quality monitoring has been promoted for the current project for the following reasons :

1. Continuous monitoring allows measurement of diurnal fluctuations in concentrations of certain analytes such as chlorophyll and dissolved oxygen that would be missed with discrete monitoring.
2. Continuous monitoring, if tied into existing SCADA or similar data collection systems, can be deployed at low cost. Maintenance can be simplified by having local water district personnel, trained in correct water and water quality sampling techniques, involved in site and instrument upkeep.

3. Continuous monitoring is essential for modeling of algae growth and transport in the San Joaquin River. Continuous telemetered flow and water quality data is essential for dissolved oxygen forecasting in the Deep Water Ship Channel.

The data collected will be entered into California Data Exchange (CDEC) by land-line phone modem, cellular phone, radio or satellite (GOES). The disadvantage of cell phone technology is that protocols have been changed a number of times during the past five years, limiting cell phone coverage during the change-over from one system to the next. Marketing forces have made it increasingly expensive to continue to operate cell phone modems using old technology. An advantage of GOES satellite technology, besides its minimal maintenance cost after installation, is that it lends itself to data retrieval automation. Computer programs and UNIX scripts have been written to data automatically retrieved from GOES platforms, land-line phone modem and cell phone modems. This software then error-checks the data and parses it into formats that can be read directly by the hydrodynamic and water quality models.

Continuous monitoring stations for flow and water quality monitoring that are located within a local water district can sometimes be operated and maintained by these entities for a considerable savings in annual costs. However these arrangements may have costs associated with more complicated data retrieval. Many more progressive water districts employ some form of SCADA (Supervisory Control and Data Acquisition) hardware to monitor diversions and drainage and operate pumps and control valves. Limited access to the computer running the SCADA network is a disadvantage of this form of data acquisition since most progressive water districts employ firewalls to keep their SCADA systems secure. Data retrieval through the firewall is more difficult to automate and access to water district operated monitoring systems will often involve some manual tasks.

2.2 Data Management

Monitoring data needs to be stored using best practices. The data management system serves both data providers as a permanent repository of monitoring data and the modelers who rely on access to continuously updated data in order to make water quality forecasts. Coordinated relational database management system(s) (RDBMS) have greatly assisted with Bay/Delta and tributary monitoring data management because of their ability to store and relate the diverse types of physical/chemical (e.g. water quality, hydrodynamics, meteorological), biological, terrestrial, wetland, fisheries, GIS and modeling information collected in the region. Data submitted to a RDBMS is stored along with those from other providers in tables related to each other according to key fields (location, date/time, data type, etc.) and made accessible online via any computer with Internet access. Modelers and other data users can perform simple and refined queries obtaining the data they need from numerous sources quickly and efficiently from a central comprehensive database or database node. In the simple form, the RDBMS is implemented using relatively simple table structure (e.g., with MS Access software or attribute tables of a GIS) for the data providers. In the comprehensive implementation, the RDBMS is implemented as a full object relational model using a specific database vendor.

2.3 Data retrieval

The RDBMS interface allows for extraction of tabular and the spatial data specific to making model runs. The ability to develop information systems that can convert data into information, based on access to a comprehensive set of Bay/Delta and Tributaries data also enhances many other operational, adaptive management and research efforts already underway in the region. Using distribution technologies, therefore, provides the opportunity for many groups to develop customized data retrieval systems that meet their specific needs or to develop processes that convert data into information that they can share with other interested parties via the Internet or other types of media. Data retrieval follows protocols established for the Real-Time Water Quality Management Program (Quinn et al, 1997; Quinn and Karkoski, 1997; Quinn and Karkoski, 1998; Quinn, 1999) which established the monitoring, communications, and modeling systems needed to provide water managers with information necessary to manage salt loads in agricultural and wetland return flows on a real-time basis.

3. DISSOLVED OXYGEN MODELING

Management decision will require the forecasting of DO conditions in the DWSC based on the current hydrology, water quality, and anticipated pollution loads. Our approach is to use and improve on several existing simulation models.

Models for DO concentrations in rivers and estuaries have existed for over a century. The mathematical and biochemical basis for DO analysis was formulated by O'Connor (1960) and Thomann (1963) who recognized that the process of stabilization of oxidizable material led to a reduction of DO in streams. Perhaps the most commonly used model for DO sag is the Streeter-Phelps equation which represents the DO response to a single point discharge of a pollutant (Thomann and Mueller, 1987).

3.1 Deep Water Ship Channel DO Model

Chen and Tsai (2000) developed a DO model which utilizes a link-node formulation of the San Joaquin River and South Delta. The model divides the water body into a series of nodes connected by links. The downstream end node accepts a tide and the upstream end node receive a river inflow, all of which can vary hourly. The model performs a hydrodynamic simulation to determine the flows occurring in links and head changes occurring in nodes. Mass balance calculations are performed to calculate the time-concentrations of various chemical constituents by accounting for advection, diffusion, and sinks and sources. For DO, it accounts for the solubility of DO as a function of temperature and considers sinks due to microbial decay of organic matters, ammonia oxidation, sediment biochemical oxygen demand, algal photosynthesis and respiration. The model was calibrated with 1991 data including real-time meteorological data, tide and waste load discharge data.

Results from the DWSC model simulations showed reasonable match to water quality observed during the months of August and September (Figure 3 for example). The model generally simulated the time series of the mid-depth DO for all locations and the concentration profile of DO for specific dates. Compared to the observed data of year 2000, the mean relative error of DO prediction for mid- depth values was approximately 0.25 mg/l and the mean absolute error was 0.59 mg/l. For the downstream section of the DWSC, where stratification develops during hot summer days when river stage and flow is low, Systech Engineering Inc. developed algorithms that incorporate a series of vertical layers into the existing model (Chen, 2002). This layered model accounts for the vertical variation of temperature, light, particulate settling and algae growth, which can cause a vertical variation of DO in the DWSC.

3.2 Upstream San Joaquin River DO model

The Delta Simulation Model (DSM-2) is the standard tool used by the Department of Water Resources for Estuary hydrodynamic studies. The water quality processes, sources, and sinks used in DSM-2 are similar to those used in the DWSC model of Chen and Tsai. Whereas the Chen and Tsai model is based on the Euler grid that tracks the mass moving in and out of stationary nodes, the DSM-2 water quality module uses a Lagrangian technique to track the mass in moving parcels of water.

The DSM-2 model has been extended by the Department of Water Resources along the SJR including the lower river and its major tributaries to create the Lower San Joaquin River DO model (Rajbhandari, 2001). The Lower San Joaquin River DO model accounts for tide, channel depth, river flow, headwater quality, sediment oxygen demand, point source and nonpoint source loads and can calculate various mass fluxes to support integrated data analysis and hypothesis testing. The calibrated model can be used to predict the response of DO in the river under various management scenarios of waste load reductions and river flow manipulations. The model comprises two submodels, HYDRO determines flow hydrodynamics and QUAL simulates both conservative and non-conservative constituents in the water body.

Different constituents will have different sinks and source terms. For conservative substances, the sink term is limited to water diversions and the source term is limited to waste discharges. For non-conservative substances, there is an additional sink term for decay. For DO, sinks include microbial decay, ammonia nitrification, sediment oxygen demand, algal respiration, and decay of volatile suspended solid. The model does not simulate organic nitrogen as a separate water quality parameter. Organic nitrogen is included in three pools (algae, pheophytin, and volatile suspended solid). When the parent pools decay, they release ammonia, which is a sink of DO. While Algal respiration is a DO sink, algal photosynthesis contributes DO to the water.

The model tracks five settleable groups of particles: chlorophyll-a, pheophytin, detritus, inorganic solids, and sand. Chlorophyll-a is live algae; pheophytin is dead algae; detritus is land derived organic matter; and inorganic solid is fine silt or clay. Each group settles to the bottom according to their settling velocities. The model assumes that settled algae become pheophytin. For that reason, the model accumulates only four groups of sediment: pheophytin, detritus, inorganic solid, and sand.

In the Lower San Joaquin River DO model, the original model algorithm was changed to use real tides for continuous simulation throughout the year. The input data for the tidal boundary was also changed to a background concentration (Co) and an exchange coefficient, which can be measured by a tracer study (Rajbhandari, 2001). During 2001 the Department of Water Resources calibrated the model with 1991, 1993, and 1996 data and the model parameters were expanded to include volatile suspended solids (VSS), total suspended solids (TSS), and pheophytin (dead or decaying algae) (Rajbhandari, 2001). Algorithms were added to simulate the settling of suspended particles, the scouring of sediment from bottom, and their effects on SOD. The model was also enhanced to simulate the growth of flagellate algae that stays in the upper layer of Turning Basin. The model is driven by the boundary conditions and a set of model coefficients. For each simulation, specific data of river flow, meteorology, tide, Stockton discharge and upstream water quality concentrations are supplied. The model simulates the dynamic variations of flow and water quality at various nodes of the San Joaquin River. The model predictions are compared to the observed values in time series and concentration profiles.

3.3 Model results for DWSC model

In the calibration performed the DO deficit was most sensitive to river load, river flow, and Stockton load, in that order. A 5% increase in river load was shown to increases the DO deficit by 50%. A 10% increase in river load increased the DO deficit by 185%. A 5% decrease in river load decreases the DO deficit by 34%. A 10% decrease in river load decreases the DO deficit by 76% (Rajbhandari, 2001). River flow, river load, and Stockton load are key control measures to solve the DO problems of the DWSC. At the low flow of 7 cubic meters/second, the Department of Water Resources modelers found that no reasonable reduction of Stockton load and/or upstream loads could help raise the DO above 5 mg/l (Rajbhandari, 2001). At a high flow of 50 cubic meters/second, reasonable reductions of Stockton load and river load could meet the DO objective. The analysis showed that the DO deficit would disappear if the DWSC were eliminated and the San Joaquin River were returned to its historic water depth of 2.5 meters. Model simulation also showed that deepening the channel was, in part, responsible for a deterioration of DO due to increase of residence time.

4. GRAPHICAL USER INTERFACES AND STAKEHOLDER COMMUNICATION

A graphical user interface has been developed that will serve to communicate current water quality conditions in the SJR and DWSC. The purpose of the GUI is to assist stakeholders who make operational decisions on drainage return flows and east-side reservoir releases that might affect the algal load of the SJR that lead to a DO sag in the DWSC. The GUI, facilitates the inspection of real time and forecast data, and features Internet communication capabilities that expedite the collection of certain model input and dissemination of water quality forecasts. The GUI consolidates modeling activities to one responsible party to eliminate confusion resulting from water managers viewing model results created from different input data. An Internet FTP site on a local area network stores files exclusively pertaining to GUI operation. The "visual" desktop image generated by GUI software allows the user to operate a computer by using a mouse or other pointing device to manipulate icons or menu options that represent application software, files containing data, and/or operating system commands.

The easy-to-use features of the GUI include the point-and-click system of Windows™, on screen data entry, map-based outputs, and Internet-based communication. The GUI main screen is depicted in Figure 4. The horizontal menu bar that appears on top of the map includes items File, Input, Results, Communication, Criteria, Model, and Help. Pointing then clicking at a menu item will lead to a pull down menu for additional choices. Key input and output sites (e.g. Vernalis) are located on a graphic of the SJR system. Pointing then clicking at such sites leads to a graphic that compares model results versus preliminary real time data.

Upon executing the GUI a map of the San Joaquin River system is displayed on the computer screen. Nodes depicting major tributaries, diversions and compliance points are represented as red dots on the display. According to the Windows convention, a horizontal menu bar is provided for the pull-down menus. The user can direct the arrow cursor to any part of the map on the computer screen, and, using the point and click system, recall the data for review or for changes of input conditions. Pointing and clicking on the any of the red dots allows the user to view either observed or simulated flow information at that site or obtain concentrations or mass load information for selenium, boron or total dissolved solids.

Within the communication menu are routines to upload operational schedules or to download model results. Reservoir operators can enter daily schedules of diversions and discharges and upload these schedules every two weeks to the person making the flow and water quality forecasts. Likewise, this person can also use the GUI to download operational schedules from agencies where timely data is routinely posted to a public ftp site.

The criteria menu may be selected to specify the color code used to display the spatial variations of water quality. These criteria selected are used in the calculation of the assimilative capacity. Results from model runs can be viewed as a time series or by spatial location. When time series is chosen, a dialog box appears for the selection of flow and pertinent water quality parameters. By clicking consecutively on the water quality parameter and, flow and a location on the map, the flow and water quality concentrations are graphed for a three week period. If spatial is chosen, a dialog box prompts the user to choose between flow, and the water quality parameter for display. The color representation of water quality is usually set according to a water quality objective. In the example shown of salinity, the concentration objective for the non-irrigation season is 618 mg/l (1000 uS/cm EC). When the EC in the river is above the threshold value of 618 mg/l, the river segment will be colored red. Below the threshold concentration, the river is colored green.

Another feature of the GUI is the ability to view the river's assimilative capacity at various selected locations. The Assimilative Capacity is selected on the Time Series menu instead of Concentration. The values for assimilative capacity are calculated on the basis of what the user entered for threshold criteria (e.g., 420 mg/l for TDS). In the case of DO, assimilative capacity will be assed using the more complex SJR and DWSC models. The user can scroll through a display of dates, viewing the temporal variations of water quality parameters at any map location on the screen and can display spatial color coded changes in water quality at any given time. By clicking at a time advance button, the user can create a near-animation of how a slug of poor quality water moves through San Joaquin River.

The GUI allows water managers to coordinate their operational decisions on a weekly basis by providing a spreadsheet-type entry of operational schedules consisting of the past week's operation and two weeks projected operation. Water managers can then upload their operational schedule to the FTP site for use by modelers, who then incorporate the information into model run input data. Water managers can download model run results from the FTP site, display the results and review the run-specific comments. Water managers who decide to change his/her operational schedule as a result of the model run output can contact SJRMP-WQS members by telephone or email. The model run input data are revised accordingly, then SJRMP-WQS staff runs the model again and posts the revised run results of the FTP site.

5. SUMMARY

This paper has described the elements of an ambitious DSS that is being developed for management of dissolved oxygen levels in the DWSC. Low dissolved oxygen levels in the

DWSC during the fall and spring threaten the successful migration of California's endangered salmon runs. The adaptive monitoring and modeling elements of the DSS are being coordinated through the San Joaquin River DO Technical Working Group, organized by the Water Quality Control Board, which will continually evaluate the success of the monitoring, modeling and stakeholder communication process. Arrangements have been made to freely exchange data between the participating agencies, providing the modelers making simulation runs and forecasts of DO on the San Joaquin River with accurate and timely information. An important element of real time water quality management is to communicate rapidly with stakeholders about the model forecast of impending DO violations and to allow simulation of the effects of potential remedial measures that may be undertaken to avoid these events. Examples of these measures include the operation of hydraulic barriers upstream of the DWSC, turning on and off aerators, drainage reuse and recycling in agricultural water districts and adjusting the timing of wetland water return flows to the SJR. Web sites have been created for the stakeholder process, through which these individuals can login, see a calendar of events, request model runs, and view model results in graphs, superimposed on GIS maps. The use of shared databases for enhancing communication between current monitoring and environmental restoration projects will result in improved technology transfer and will improve the likelihood that these initiatives will be continued after the current project term has expired. The goal of all watershed projects should be self-sufficiency - whereby government funding provides resources to overcome initial inertia and obtain evidence of real community benefit after which the local community finds ways to support at a minimum those aspects of the project that are likely to provide a positive benefit stream.

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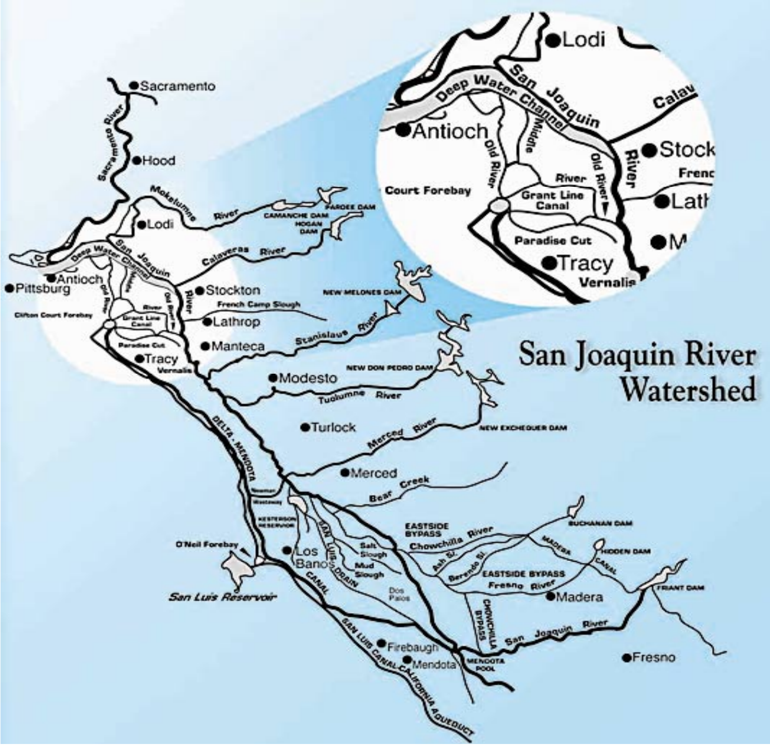


Figure 1. Map of the San Joaquin River Basin showing the location of the Deep Water Ship Channel (DWSC) near Stockton, California.

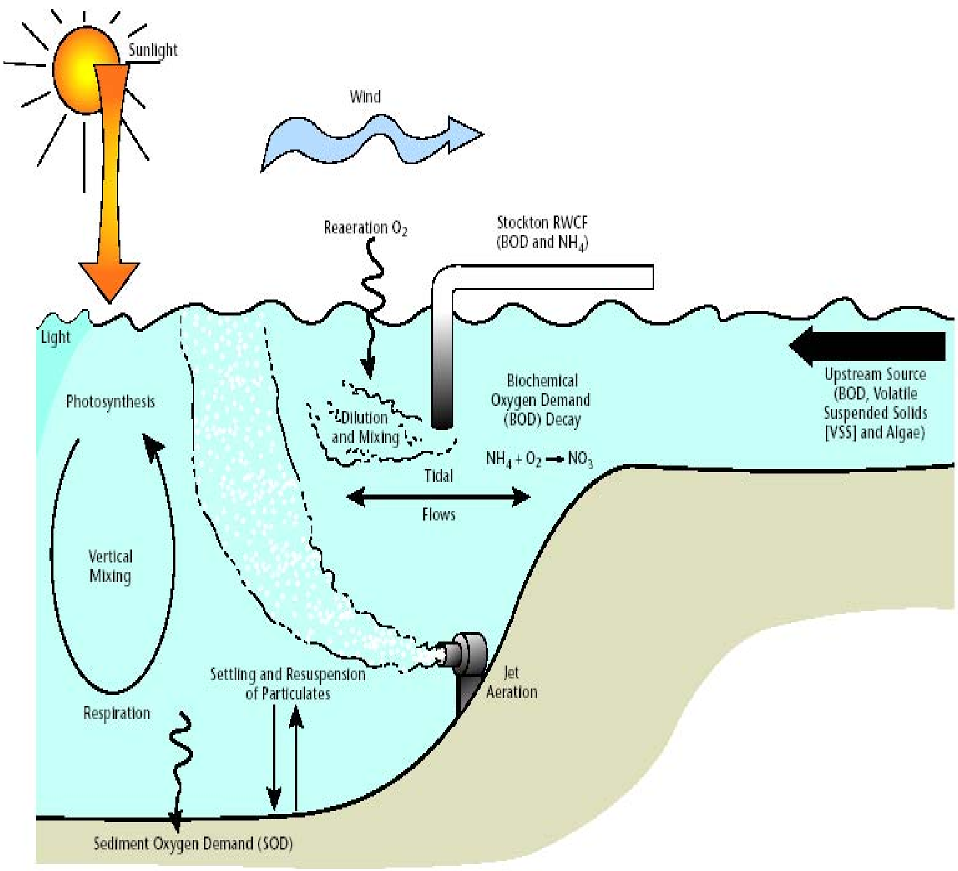


Figure 2. Conceptual model of factors affecting dissolved oxygen sag in the DWSC (Lee, 2002).

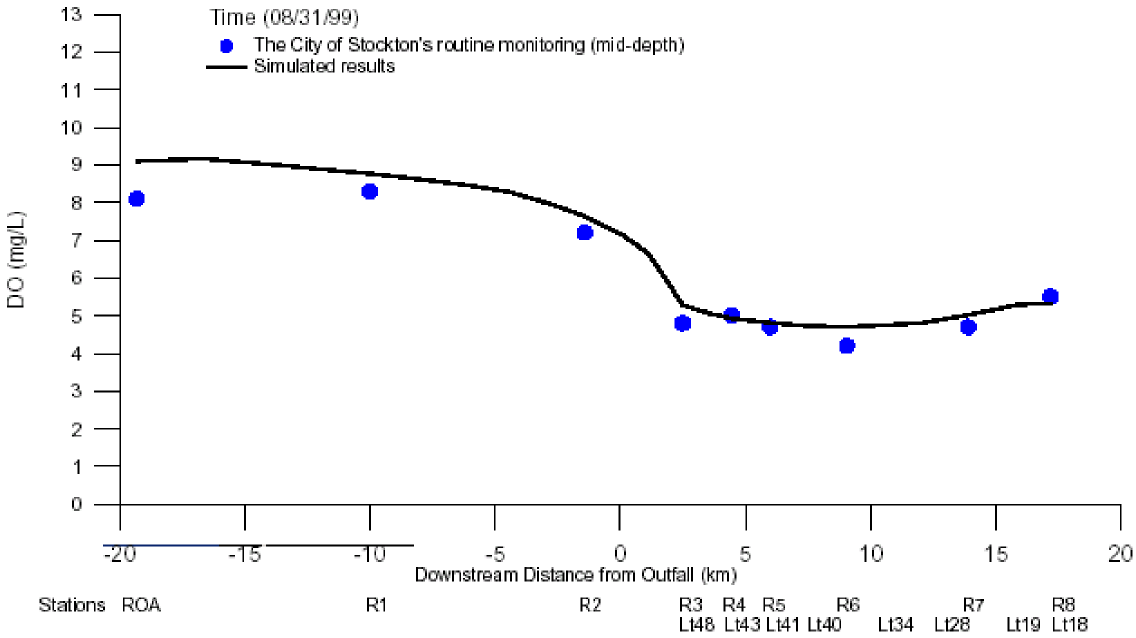
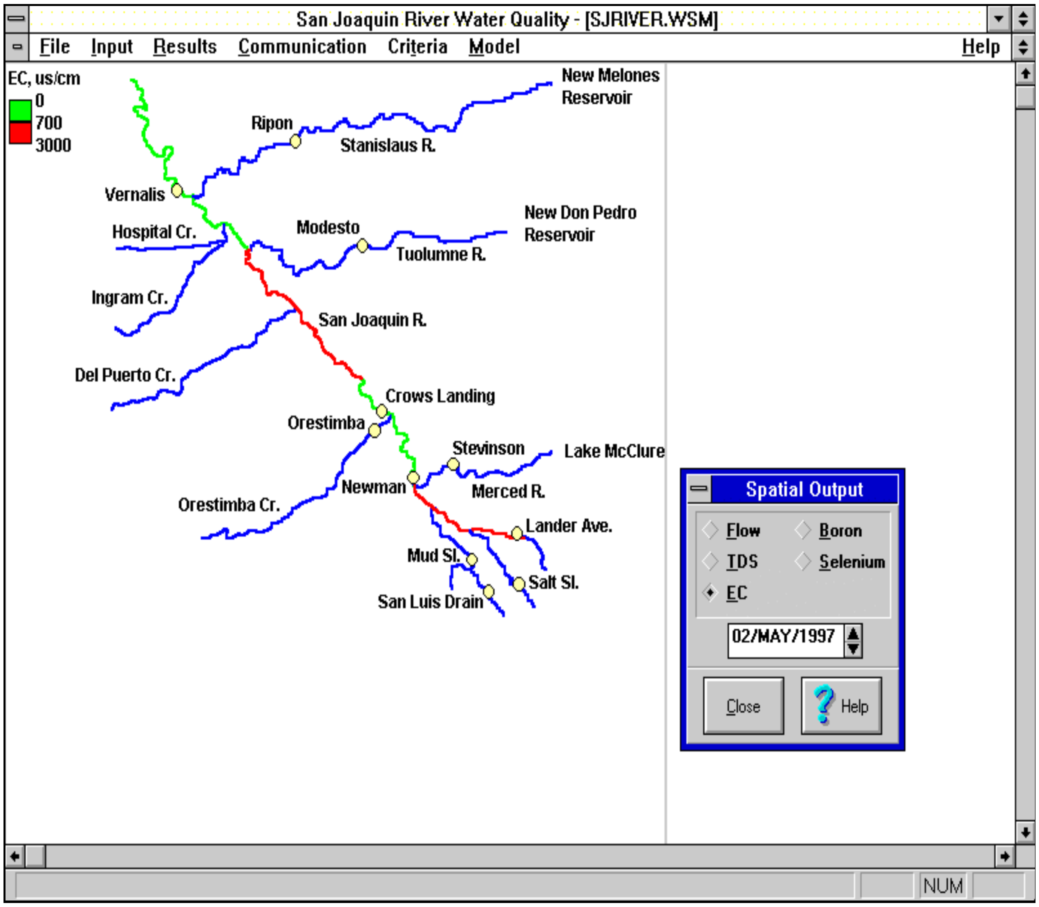


Figure 3. Calibration results from the Chen and Tsai dissolved oxygen model for the DWSC (Chen and Tsai, 2000).



○ Flow ○ Boron
○ TDS ○ Selenium
● EC

02/MAY/1997

Figure 4. User interface from the SJRIODAY salinity forecasting project adapted for use with the SJR DO forecasting model.

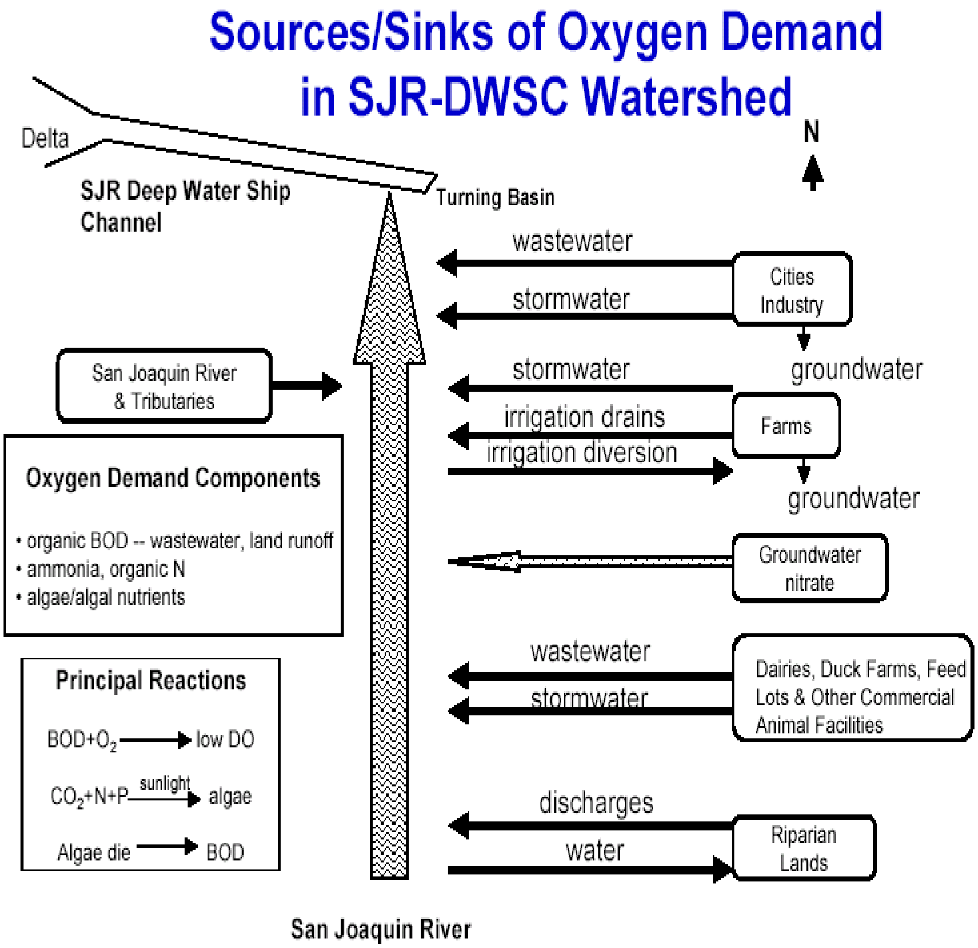


Figure 5. Sources and sinks of oxygen demand in the San Joaquin River Basin (Lee, 2002).