Managing Excessive Algal Caused Oxygen Demand in the San Joaquin River Deep Water Ship Channel[1]

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Abstract
Low dissolved oxygen concentrations in the San Joaquin River (SJR) Deep Water Ship Channel (DWSC) are caused by city of Stockton domestic wastewater ammonia discharges and algae that develop in the DWSC watershed tributaries. The algae that initially develop about 100 miles upstream in SJR tributaries, based on nutrients discharged from summer and fall agricultural tailwater and subsurface drain water discharges, multiply in the SJR until they reach the DWSC where they die due to limited light penetration, and become biochemical oxygen demand (BOD). A Total Maximum Daily Load (TMDL) control program has been established to control the low-DO problem in the DWSC. A combination of aeration of the DWSC, city of Stockton wastewater ammonia discharge control, selective nutrient/algae control, and increased flow of the SJR through the DWSC is being investigated to control the low-DO problem. The focus of the algae control program is to be directed to control the development of the "seed" algae in the upper parts of the SJR tributaries that lead to the high algal caused oxygen demand that is discharged to the upper SJR. Agricultural interests need to determine if cost-effective nutrient/algae BOD control can be established.

Keywords: Dissolved oxygen, nutrients, algae, aeration, TMDL, agricultural discharges

Introduction

During the summer and fall, the first approximately seven miles of the San Joaquin River (SJR) Deep Water Ship Channel (DWSC) near the Port of Stockton, Stockton, CA (navigation lights 22 to 48 in Figure 1) frequently experiences dissolved oxygen (DO) concentrations below the water quality standard. This low-DO problem also occurs during some winters. This has led to development of a total maximum daily load (TMDL) to control the substances/conditions that cause the violations of the DO water quality standard/objective (WQO). Beginning in the summer of 1999, through the fall of 2001, about $3 million of studies on the causes and sources of constituents responsible for violations of the DO water quality objective in the DWSC were conducted. Lee and Jones-Lee (2003a,b) have recently completed a "Synthesis Report" and "Summary" which present a synopsis of the results of these studies. This paper provides an overview discussion of the current understanding of the constituents responsible for low DO in the DWSC, their sources, and the factors influencing how oxygen-demanding constituents added to the DWSC lead to violations of the DO water quality objective. Also, information is provided on potential approaches to control the low-DO problem in the DWSC.

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Figure 1
Map of the Lower SJR and DWSC Study Area

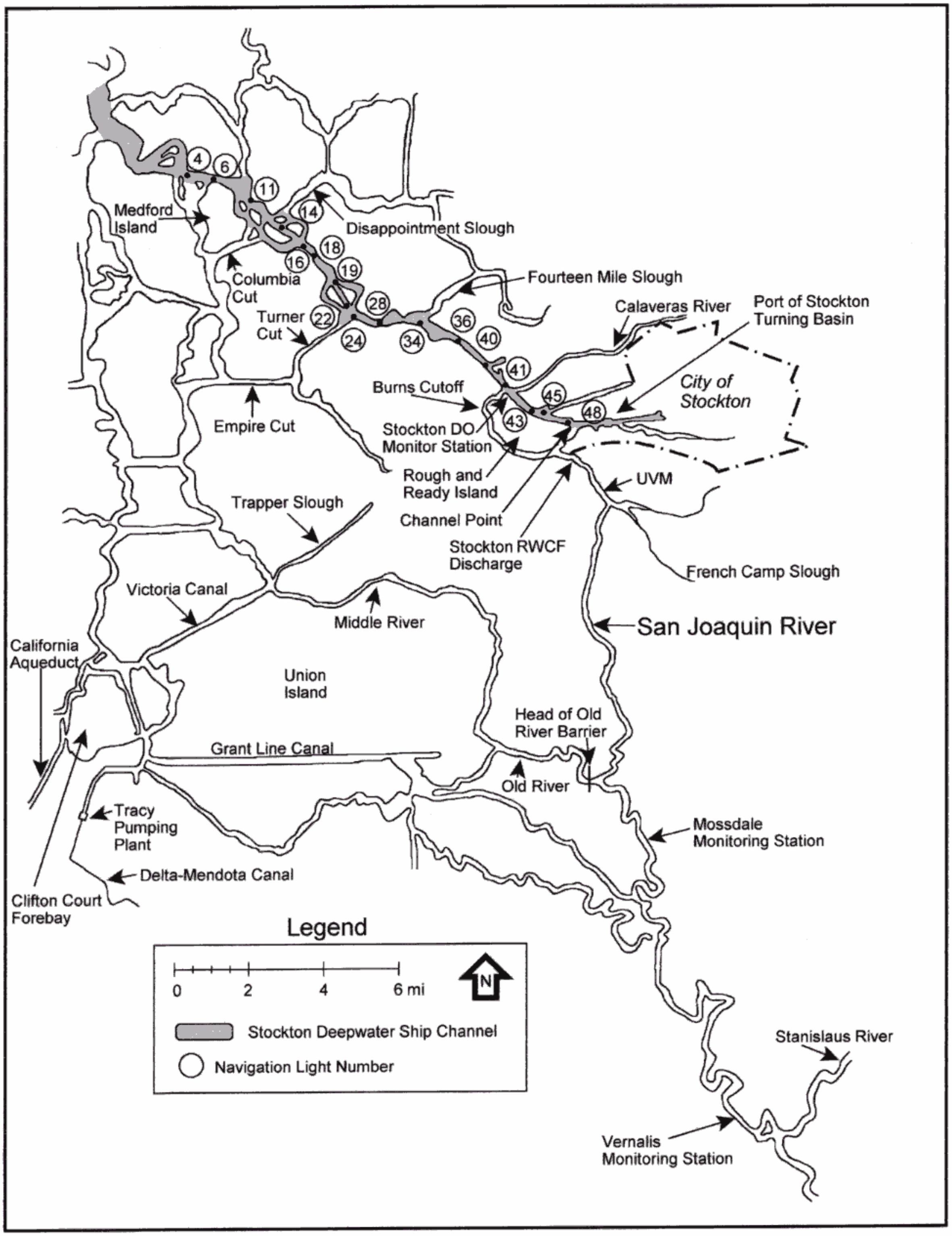
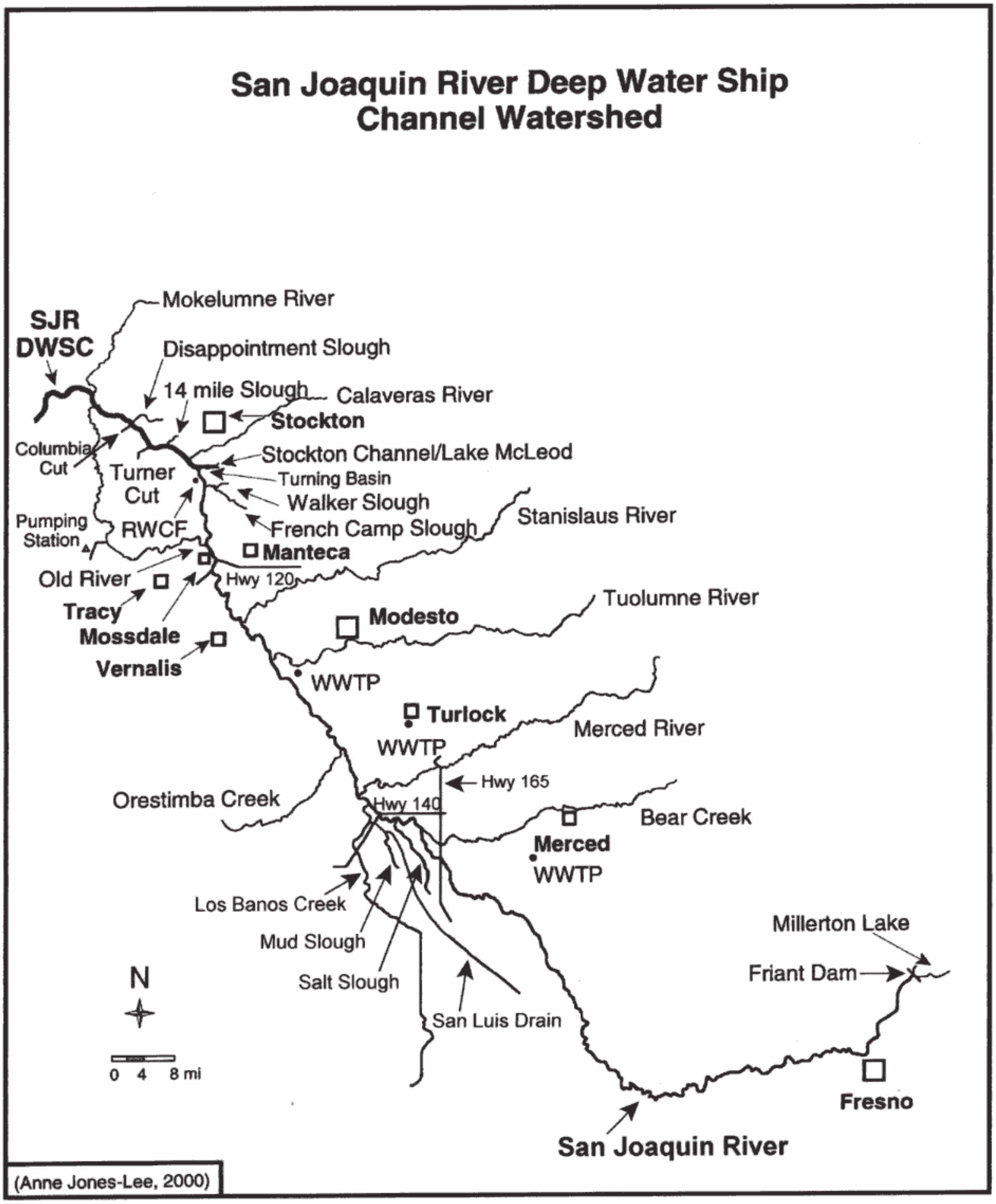


Figure 2
San Joaquin River Deep Water Ship Channel Watershed



feet wide and eight to 10 feet deep, and is freshwater tidal, with about a three-foot tide at the Port of Stockton. At the Port, the River is about 250 feet wide and is dredged to a depth of 35 feet to San Francisco Bay.

The flow of the SJR during the summer and fall is highly regulated by upstream reservoir releases and agricultural and other water diversions. These diversions increase the hydraulic residence time of the critical reach (first seven miles) of the DWSC, and thereby contribute to the low-DO problem within the DWSC. During the summer months, the flow in the SJR through the DWSC can range from a negative flow (i.e., upstream to Old River), to typically 500 to 1,200 cfs net downstream flow, to, at times, several thousand cfs downstream flow. The net downstream flows in the DWSC occur with a background of 2,000 to 4,000 cfs freshwater tidal flow.

The city of Stockton discharges its domestic wastewaters to the SJR approximately two miles upstream of where the SJR enters the DWSC at Channel Point. The critical reach of the SJR DWSC for low-DO problems is approximately the seven miles just downstream of the Port to Turner Cut. This reach has experienced DO depletion below the water quality objective over the past 40 years or so. The hydraulic residence time of the critical reach can vary from about four days, with SJR DWSC flows of 2,000 cfs, to approximately 30 days at 250 cfs. These travel times are important in determining the amount of time available for oxygen demand exertion within the DWSC before the oxygen demand is diluted by the cross-SJR DWSC flow of the Sacramento River at Disappointment Slough/Columbia Cut arising from the export pumping of South Delta water to Central and Southern California by the State and Federal Projects. This cross-SJR DWSC flow limits the downstream extent of DO depletion in the DWSC.

Constituents Responsible for Oxygen Depletion and Their Sources

The depletion of DO below the water quality standard of 5 or 6 mg/L (depending on the season) is caused by carbonaceous biochemical oxygen demand (CBOD) and nitrogenous BOD (NBOD). High planktonic algal chlorophyll *a*, which is correlated to high BOD SJR water at Mossdale, as well as upstream in the SJR, tends to be associated with the greatest DO depletion in the DWSC. The NBOD is composed of ammonia and organic nitrogen that is mineralized to ammonia, which is biochemically oxidized to nitrite and nitrate (nitrification). At times, especially during high ammonia concentrations in the wastewater effluent and low SJR DWSC flows, the City's wastewater effluent can contribute over 80 percent of the total oxygen demand load to the DWSC. At other times, the City's contribution to the oxygen demand load can be on the order of 10 to 20 percent of the total oxygen demand load to the DWSC. The relative proportion of the city of Stockton and upstream oxygen demand loads is variable, depending on the City's wastewater effluent ammonia concentrations, the planktonic algal concentrations in the SJR that discharges to the DWSC, and the flow of the SJR through the DWSC.

Factors Influencing DO Depletion in the DWSC

There are a number of factors that have been found to influence the DO depletion in the DWSC for a given oxygen demand load. These include the following:

- ***Port of Stockton.*** The development of the DWSC to the Port of Stockton greatly reduced the oxygen demand assimilative capacity of the SJR below the Port due to increased hydraulic residence time for BOD exertion in the critical reach of the DWSC. It has been found that, if the Deep Water Ship Channel did not exist, there would be few, if any, low-DO problems in the channel. The ship channel becomes a long thin tidal lake with limited light penetration and a longer hydraulic residence time due to its greater volume than was present in the SJR prior to dredging. The algae that develop upstream of the DWSC enter the DWSC, die due to limited light penetration, and become BOD.

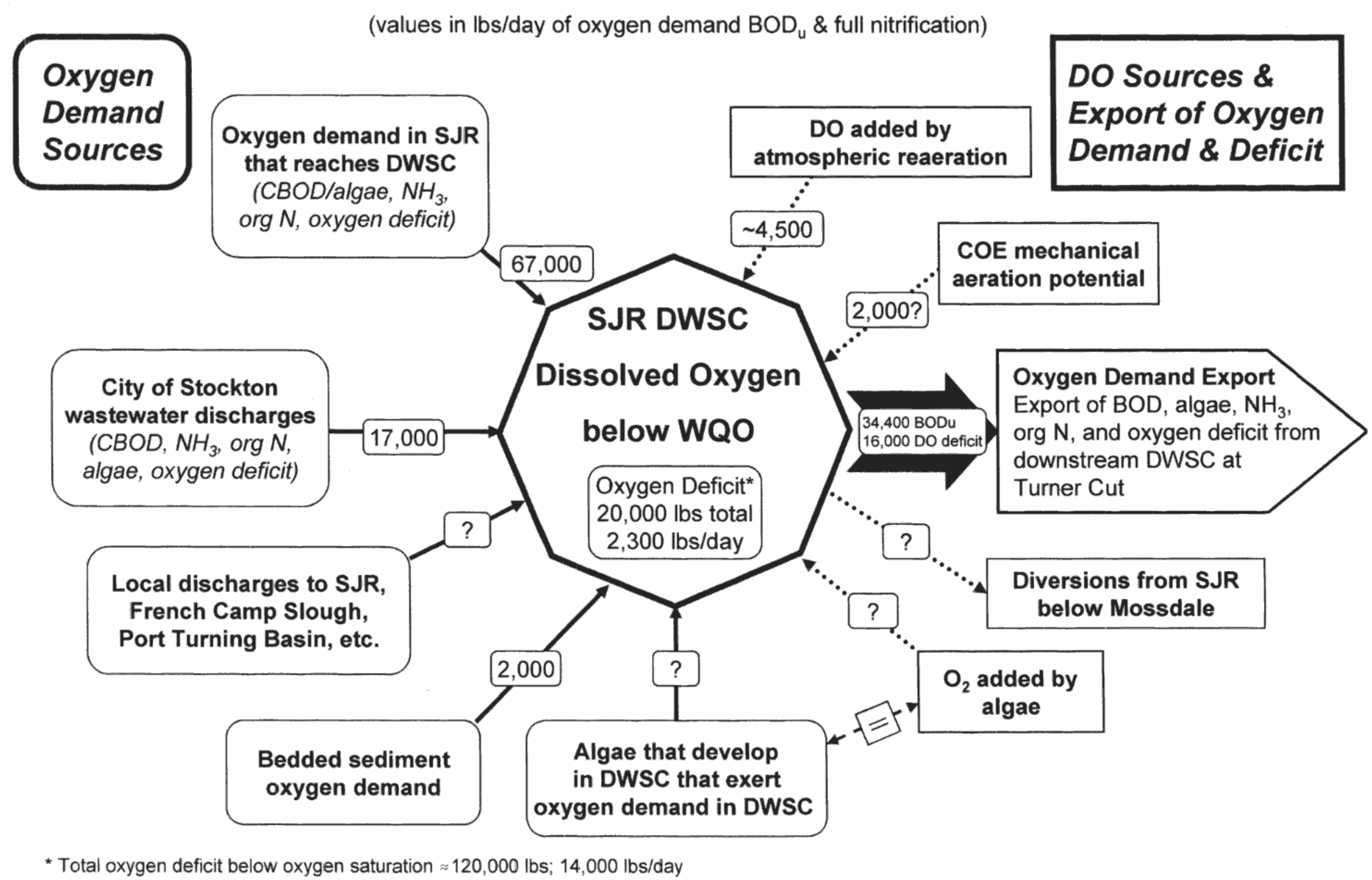
- ***SJR Flow through the DWSC.*** The flow of the SJR through the DWSC influences DO depletion by affecting the hydraulic residence time (travel time) of oxygen demand loads through the critical reach. Under high flow conditions (> about 2,000 cfs), DO depletions below the water quality objective do not occur in the DWSC. SJR flows through the DWSC of a few hundred cfs lead to the greatest DO depletion below the water quality objective.
- ***Sediment Oxygen Demand (SOD).*** Measurements of the bedded sediment oxygen demand within the DWSC are somewhat lower than normal SOD for "polluted" waterbodies. However, the tidal velocities that occur within the DWSC have been found to be sufficient to suspend bedded sediments and to hinder the settling of particulate oxygen demand. This leads to an increased oxygen demand associated with particulates in the near-bottom waters of the DWSC.
- ***Light Penetration.*** Secchi depths typically on the order of 1 to 2 ft are found in the SJR and in the DWSC during the summer and fall. The inorganic turbidity derived from watershed erosion significantly reduces the depth of the photic zone, where algal photosynthesis can occur, compared to photic zone depths that are found in most waterbodies where light penetration is controlled by light scattering and absorption by algae.
- ***Algal Nutrients.*** The concentrations of algal available nutrients (nitrate and soluble orthophosphate) within the SJR upstream of the DWSC and within the DWSC are at least 10 to 100 times surplus of those that are algal growth-rate-limiting. These nutrients are primarily derived from agricultural discharges of irrigation tailwater and subsurface drain water. Algal growth within the SJR and DWSC appears to be controlled by light limitation.

Oxygen Demand Loads

The results of box model load calculations made for the 43 DWSC and SJR monitoring runs conducted during the summer/fall 1999, 2000 and 2001 are shown in Figure 3. This figure presents a diagram of the three-year summer/fall average loads of oxygen demand in the SJR at Mossdale plus the City's oxygen demand wastewater loads, export of oxygen demand from the DWSC at Turner Cut, and the magnitude of oxygen deficit below the water quality objective within the DWSC between Channel Point and Turner Cut. On the average, during the summer and fall the ultimate oxygen demand (BOD_u) load in the SJR at Mossdale added to the DWSC is on the order of 67,000 lb/day. The city of Stockton on average adds about 17,000 lb/day of BOD_u. The upper end of the measurements of sediment oxygen demand was about 2,000 lb/day, for a total average oxygen demand load of about 86,000 lb/day BOD_u. Atmospheric reaeration adds about 4,500 lb/day of oxygen to the DWSC. The algae that develop in the DWSC represent potential oxygen demand that is compensated for by the oxygen they produce in photosynthesis.

Assuming that surface reaeration adds 4,500 lb/day of DO to the DWSC and assuming that the Corps of Engineers (COE) aerator is not operating, it is estimated that the total oxygen demand sinks are about 70,900 lb/day. This value is compared to the oxygen demand load of 86,000 lb/day. There is about a 15,100 lb/day difference. This difference is well within the reliability of oxygen demand measurements in the SJR at Mossdale, in the City wastewater discharges and in the DWSC near Turner Cut. On the average about 50,400 lb/day of BOD_u and oxygen deficit below saturation are exported downstream from the DWSC at Turner Cut. The total average oxygen deficit from the applicable WQO is about 20,000 lb which, when divided by the average travel time between Channel Point and Turner Cut of 8.6 days based on an average SJR DWSC flow of 930 cfs, translates to an average 2,300 lb/day oxygen deficit below the WQO.

Figure 3. Box Model of Estimated DO Sources/Sinks in SJR DWSC (SJR DWSC Flow: 930 cfs; Travel Time: 8.6 days)



Sources of Oxygen Demand

Based on SJR and its tributary monitoring and measured flows, it was found that the primary sources of oxygen demand are discharges of algae from Mud and Salt Sloughs to the SJR and in the SJR at Lander Avenue (Highway 165). This area, located about 100 miles upstream of the DWSC, consists of substantial irrigated agriculture and managed wetlands that are used for wildlife refuges and duck clubs. Based on monitoring of planktonic algal chlorophyll *a* and BOD along the SJR from where Mud and Salt Sloughs discharge to the SJR down to Vernalis, it has been found that the algae/oxygen demand that are discharged by Mud and Salt Sloughs to the SJR continue to develop in the SJR, ultimately leading to greatly elevated planktonic algal chlorophyll *a* and BOD concentrations and loads in the SJR at Mossdale. At times, 50 to 80 percent of the SJR at Mossdale loads of BOD originate from the Mud and Salt Slough discharges to the SJR and the SJR watershed upstream of Lander Avenue. It has been found that, on the average during the summers of 2000 and 2001, 1lb of algal oxygen demand discharged by Mud and Salt Sloughs to the SJR, as well as in the SJR at Lander Avenue, develops into about 8 lb of oxygen demand in the SJR at Mossdale.

Solving the Low-DO Problem

A management plan to control the low-DO problem in the DWSC includes supplemental aeration of the DWSC and the control of city of Stockton ammonia and upstream nutrients that lead to algae that contribute to the low-DO problem in the DWSC. Also, this plan includes attempts to at least stabilize, and preferably increase, the flow of the SJR through the DWSC, in order to reduce the hydraulic residence time of the water and oxygen demand constituents in the critical reach of the DWSC. The State of California has appropriated $40 million to solve the low-DO problem in the DWSC. A Phase I TMDL is being developed to allocate these funds.

Supplemental Aeration. Preliminary studies have shown that it appears to be technically and economically feasible to provide supplemental aeration of the DWSC to control DO depletions below the WQO. On the average about 2,300 lb/day of oxygen needs to be added to the DWSC to eliminate violations of the DO WQO. Considering the worst-case conditions for DO depletion below the WQO, on the order of about 6,000 lb/day of DO would be needed to keep the DWSC from violating a WQO. It has been estimated that the amount of needed aeration can be obtained for a construction cost of less than $2.5 million dollars, with annual operating expenses of less than $500,000. An engineering evaluation leading to pilot studies of DWSC aeration is being conducted to develop an aeration system that can maintain DO concentrations in the DWSC above the WQO.

Algal BOD Load Control. There is need to evaluate the potential for control of algae that develop in the Mud and Salt Slough watersheds and the SJR watershed upstream of Lander Avenue. Of particular concern are irrigation tailwater and subsurface drain water discharges in the head waters of Mud and Salt Sloughs and upstream of Lander Avenue. The relationship between decreased algae/BOD from the Mud and Salt Slough and SJR at Lander Avenue watersheds and decreased algae/BOD concentration/load in the SJR at Mossdale needs to be evaluated to determine the impact of controlling upstream algal growth on reducing the algal BOD discharged to the DWSC.

City of Stockton Ammonia Control. The state of California has recently adopted a revised wastewater discharge permit for the city of Stockton that limits the monthly average ammonia concentration in the effluent to 2 mg/L for aquatic life toxicity reasons. Achieving this discharge limit would result in a reduced ammonia oxygen demand load by about 20,000 lb/day BOD_u during the time when the City's effluent ammonia is above about 25 mg/L N.

Development of a TMDL and its Technical Allocation

The TMDL will be conducted in a phased approach, where the first phase will be largely devoted to pilot studies of aeration of the DWSC to control the low-DO problem. In addition, an engineering evaluation of the potential to achieve at least control of flow to avoid large changes, if not enhanced flow, of the SJR through the DWSC will be conducted during the initial phase of the TMDL implementation. Further, studies will be conducted to obtain additional information on the specific sources of oxygen demand in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds, and their potential control.

The initial phase of the TMDL implementation will likely require about five years. At that time, with continued substantial support of ongoing studies specifically directed toward evaluating the effects of the implementation of control programs, it should be possible to formulate a low-DO management program for the DWSC which would represent the final phase of the TMDL.

Background Information and References

The background approximately 40 reports that serve as a basis for this summary paper are listed in Lee and Jones-Lee (2003a,b), and are available from www.sjrtmdl.org.

Lee, G. F. and Jones-Lee, A., "Issues in Developing the San Joaquin River Deep Water Ship Channel DO TMDL," Report to Central Valley Regional Water Quality Board, Sacramento, CA, August (2000).

Lee, G. F. and Jones-Lee, A., "Synthesis and Discussion of Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA: Including 2002 Data," Report Submitted to SJR DO TMDL Steering Committee and CALFED Bay-Delta Program, G. Fred Lee & Associates, El Macero, CA, March (2003a). Available from gfredlee@aol.com upon request.

Lee, G. F., Jones, G. F**.**, **"**Summary of Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA" Report G. Fred Lee & Associates, El Macero, CA (2003b) Available from gfredlee@aol.com.

Unit Conversions

1 ft	= 0.3048 m	1 mi	= 1.609 km	1 cfs	= 28.32 liter/sec
1 sq mi	= 2.59 sq km	1lb	= 0.4536 kg	1 lb/day	= 0.4536 kg/day