Summary of Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA[1]

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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 (navigation lights 22 to 48 in Figure 1) frequently experiences dissolved oxygen (DO) concentrations below the water quality objective (standard). This low-DO problem also occurs during some winters. This has led to a Clean Water Act (CWA) section 303(d) designation of the SJR DWSC between the Port of Stockton and Turner Cut as an "impaired" waterbody, which requires the development of a total maximum daily load (TMDL) to control the violations of the DO water quality objective. Based on CALFED support, beginning in the summer of 1999 through the fall 2001, members of a Technical Advisory Committee (TAC) to the SJR DO TMDL Steering Committee of stakeholders conducted about $3 million of studies on the causes and sources of constituents responsible for violations of the DO water quality objective in the DWSC. In addition, the 2002 data on DO depletion in the DWSC at the Department of Water Resources (DWR) Rough and Ready Island (RRI) monitoring station and oxygen demand loads to the DWSC have been reviewed.

Lee and Jones-Lee (2003) have recently completed a "Synthesis Report" which presents a synopsis of the results of these studies, as well as information based on other studies and the authors' experience. Particular attention is given in this report to providing an overview discussion of the current understanding of the constituents responsible for the low DO, 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 low DO in the DWSC.

Physical and Hydrological Characteristics of the SJR and DWSC

The SJR watershed (Figure 2) consists of over 7,000 square miles in the Central San Joaquin Valley of California below the eastside reservoirs. The total watershed, which includes the western slope of the Sierra-Nevada mountains above the reservoirs is estimated to be 13,536 square miles. It is bounded on the east by the Sierra-Nevada mountains and on the west by the Coast Range mountains. It extends north from Fresno to the Sacramento-San Joaquin River Delta. The eastside rivers (Merced, Tuolumne and Stanislaus Rivers), including the upper San Joaquin River, which drain the western slopes of the Sierra-Nevada mountains, are the primary sources of water for the SJR. Upstream of the Port of Stockton, the SJR is about 150 feet wide and eight to 10 feet deep, and is freshwater tidal, with about a three-foot tide at the Port of

[1] Derived from 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 (2003).

Figure 1
Map of the Lower SJR and DWSC Study Area

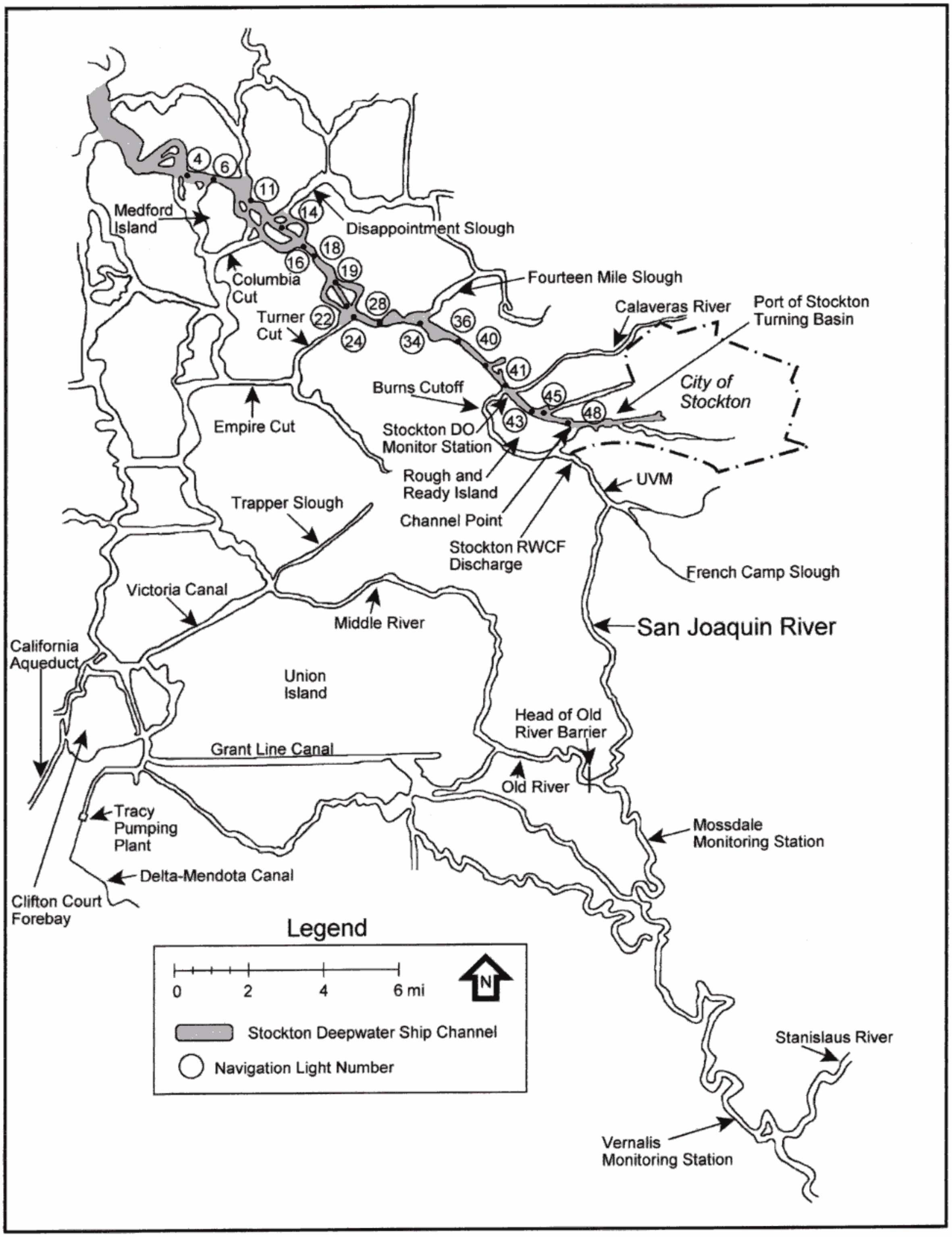
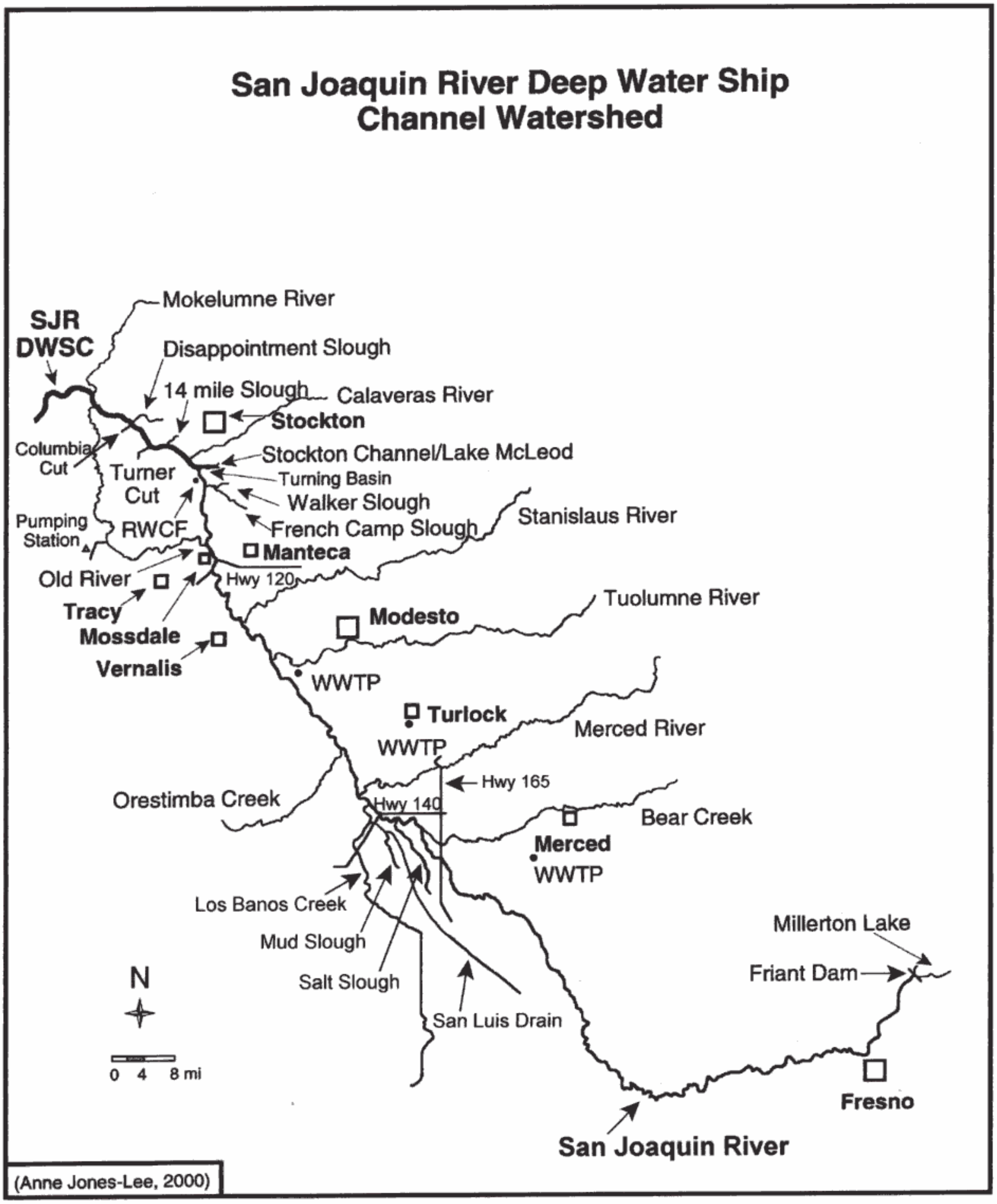


Figure 2
San Joaquin River Deep Water Ship Channel Watershed



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 through the DWSC 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, fall and winter 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 tidal flow.

The city of Stockton discharges its treated domestic wastewaters to the SJR approximately two miles upstream of where the SJR enters the DWSC at Channel Point. There are several other domestic and commercial wastewater discharges to the SJR and its tributaries in the SJR DWSC watershed. Further, there are numerous points where agricultural irrigation tailwater discharges to the SJR and its tributaries occur throughout the watershed.

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.

DO Depletion in the DWSC

Frequently during the summer and fall and during some winter months dissolved oxygen concentrations in the DWSC water column from just downstream of the Port to, at times, as far as Columbia Cut, are depleted, at times, one to several mg/L below the water quality objective of 5 mg/L during the summer through August, and 6 mg/L from September through November. Under low SJR DWSC flow conditions of a few hundred cfs, the DO concentrations in the DWSC waters at or near the bottom can be as low as about 1 to 2 mg/L. The DO concentrations near the bottom of the DWSC are sometimes one to two mg/L lower than those found in the surface waters. This difference is not due to thermal stratification within the DWSC, but is related to inadequate vertical mixing of the water column by tidal currents, algal photosynthesis in the near-surface waters and suspended particulate BOD in the near-bottom waters.

The point of maximum DO depletion in the critical reach of the DWSC is a function of the flow of the SJR through the DWSC, where higher flows cause the point of maximum DO depletion to shift downstream. During periods of significant algal photosynthesis, where planktonic algal chlorophyll *a* is greater than about 20 to 30 µg/L, there can be a several mg/L diel DO change in the surface waters of the DWSC.

Constituents Responsible for Oxygen Depletion and Their Sources

The depletion of DO below the water quality objective is caused by carbonaceous biochemical oxygen demand (CBOD) and nitrogenous BOD (NBOD). Figures 3 and 4 show the processes and reactions that lead to low DO in the DWSC. For a discussion of these figures, see Lee and Jones-Lee (2003).

The CBOD occurs primary in the form of algae, with city of Stockton residual CBOD present in their wastewater effluent, as well as CBOD derived from other sources. 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 primary source of carbonaceous and, to some extent nitrogenous, oxygen demand for the DWSC occurs in the form of algae that develop in the SJR upstream of the DWSC. At times the upstream oxygen demand loads represent on the order of 90 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, dependent on the City's wastewater effluent ammonia concentrations, the planktonic algal concentrations in the SJR that are discharged to the DWSC, and the flow of the SJR through the DWSC.

The limitation of the downstream extent of the DO depletion caused by the cross-SJR DWSC flow of the Sacramento River at Columbia Cut results in some situations where part of the oxygen demand load to the DWSC from the City and upstream sources is not exerted in the critical reach of the DWSC – i.e., it is transported into the Central Delta, where it is diluted by the cross-channel flow of the Sacramento River. As a result, an issue that must be better understood in order to appropriately manage the low-DO problem is a determination of the part of the oxygen demand load from the City and upstream sources that is exerted within the critical reach that leads to DO concentrations below the water quality objective. Additional information is needed on the amount of the oxygen demand load from the various sources and constituents that is exerted in the DWSC that leads to DO concentrations below the water quality objective (WQO).

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 downstream of the Port. It has been found that, if the Deep Water Ship Channel did not exist and the SJR was an undredged channel, there would be few, if any, low-DO problems in the channel.
- ***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

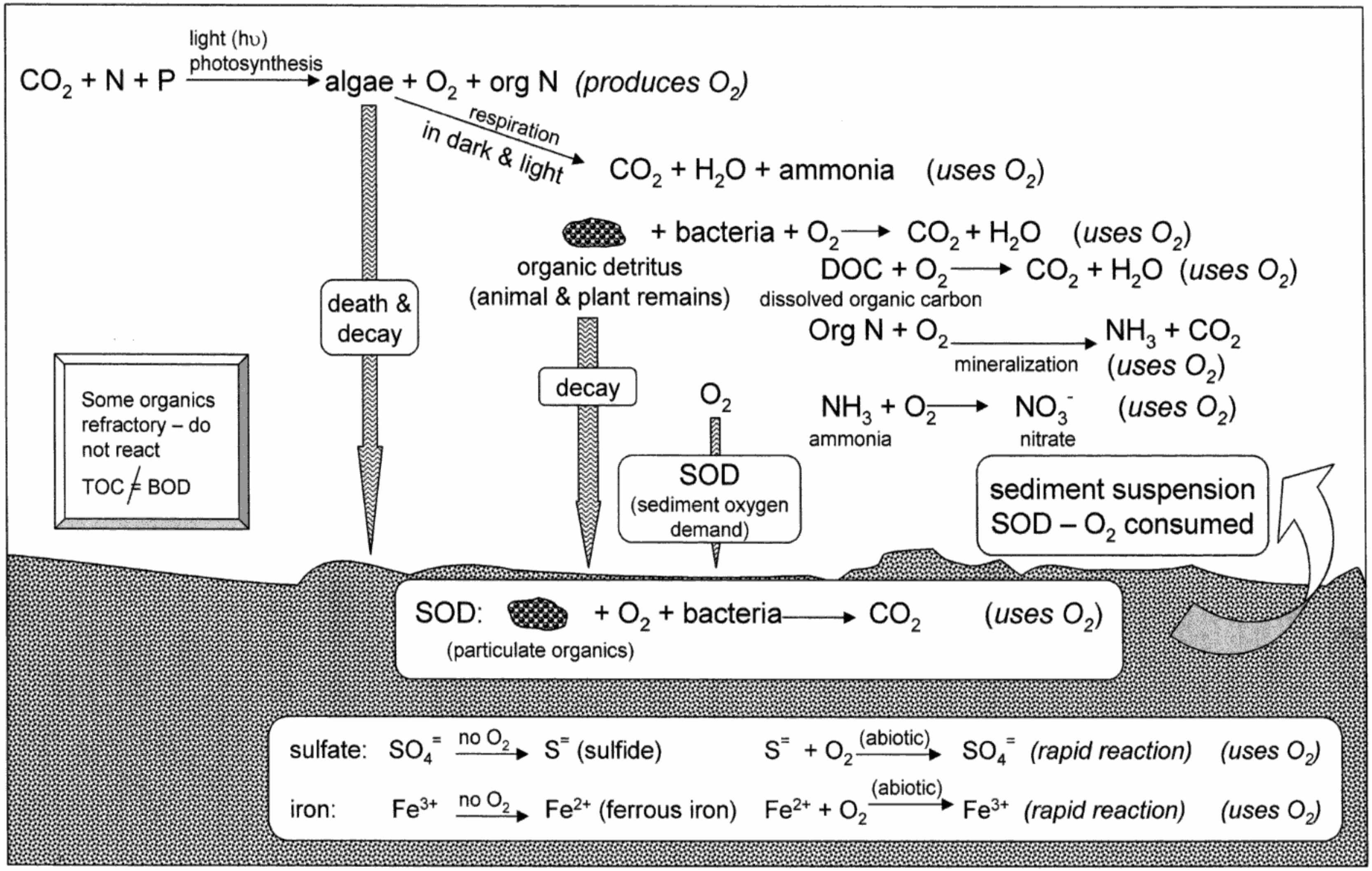


Figure 3. Algae & Organic Detritus as Sources of Oxygen Demand

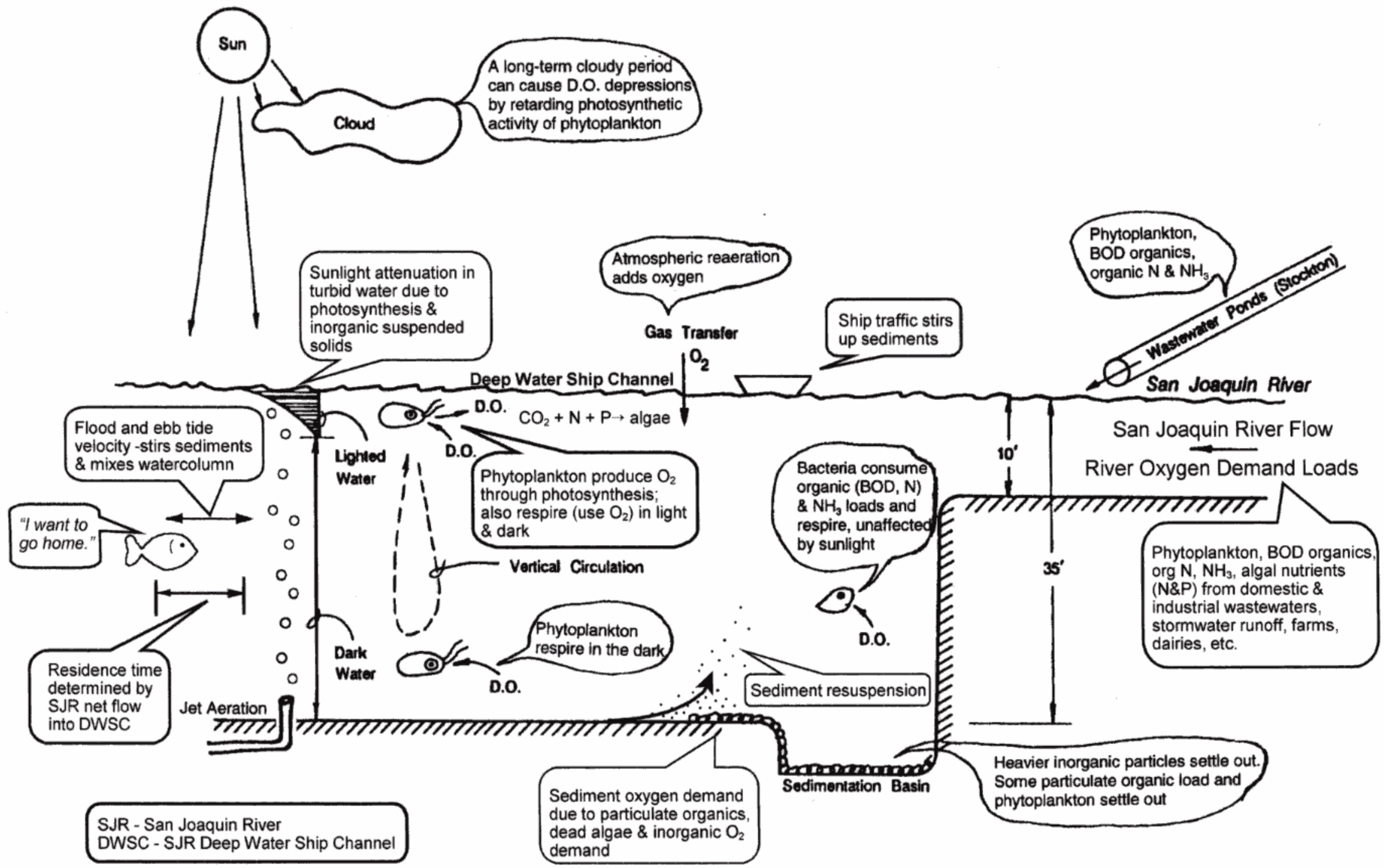


Figure 4. Factors Affecting Dissolved Oxygen in DWSC
(adapted from COE, 1988)

DWSC of a few hundred cfs lead to the greatest DO depletion below the water quality objective. The flow of the SJR through the DWSC influences the amount of upstream algal (oxygen demand) load that enters the DWSC, with greater oxygen demand loads occurring with higher flows. The magnitude of the oxygen deficit below the water quality objective is SJR DWSC flow-dependent.

- ***Sacramento River Cross Channel/Delta Flow.*** The export pumping of South Delta water by the State and Federal Projects to Central and Southern California creates a strong cross-Delta flow of Sacramento River water. This cross-Delta flow limits the downstream extent of DO depletion within the DWSC to upstream of Disappointment Slough/Columbia Cut.
- ***Growth of Algae within the DWSC.*** Appreciable algal growth occurs within the DWSC; however, this growth does not add to low-DO problems in the surface waters of the DWSC, since it is accompanied by photosynthetic oxygen production. The increased algal growth within the DWSC is likely causing increased DO depletion in the near-bottom waters of the DWSC, due to the settling and death of the DWSC-produced algae.
- ***Sediment Oxygen Demand (SOD).*** Measurements of the bedded sediment oxygen demand within the DWSC show that it tends to be 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. The bedded sediment oxygen demand of the DWSC between Channel Point and near Turner Cut is estimated to be about 2,000 lb/day, which is at the upper end of the measured SOD values.
- ***Atmospheric Aeration.*** Since the surface waters of the DWSC tend to be undersaturated with respect to dissolved oxygen, except possibly during late afternoon when intense photosynthesis is occurring in the surface waters, there is a net transfer of atmospheric oxygen to the DWSC through atmospheric surface aeration. It has been estimated that about 4,500 lb/day of oxygen is typically added to the critical reach of the DWSC through surface aeration.
- ***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. This limits the photic zone (where photosynthesis can occur) to the upper 3 ft or so of the DWSC. The inorganic turbidity derived from watershed erosion significantly reduces the depth of the photic zone, compared to photic zone depths that are found in most waterbodies where light penetration is controlled by light scattering and absorption by algae. Current efforts to control erosion within the SJR watershed could lead to increased water clarity and greater algal growth. It also appears that, at times, colored waters derived from the Mud and Salt Slough watershed wetlands areas can contribute sufficient color to the SJR and DWSC to reduce light penetration and thereby inhibit algal photosynthesis. This may lead to significantly greater DO depletion in the DWSC than would occur in the absence of the colored water.
- ***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. Algal growth within the SJR and DWSC appears to be controlled by light limitation.

- ***Temperature.*** Increases in temperature in the SJR and DWSC increase algal growth rates and rates of DO depletion reactions. Increased temperature also decreases the solubility of oxygen. Some of the year-to-year variations in DO depletion in the DWSC may be related to temperature differences, which influence algal growth in the SJR watershed and oxygen depletion within the DWSC.

A "Strawman" analysis of oxygen demand loads and impacts on DO depletions within the DWSC shows that the planktonic algal concentrations present in the SJR at Mossdale are related to the DO depletion at the DWR Rough and Ready Island continuous monitoring station. High planktonic algal chlorophyll *a*, which is correlated to high BOD in the SJR at Mossdale as well as upstream in the SJR, tended to be associated with the greatest DO depletion at the Rough and Ready Island station.

Using a deterministic model of oxygen demand loads and their impacts on DO in the DWSC, it is found that increasing the flow of the SJR through the DWSC decreased the dissolved oxygen deficit below the WQO within the DWSC. At SJR flows through the DWSC above about 2,000 cfs, there were few DO depletions below the water quality objective. These modeling results are in accord with the monitoring studies of the past three years and the past eight years of monitoring conducted by the California Department of Water Resources.

The magnitude of the oxygen deficit below the WQO has been found to be dependent on SJR flow through the DWSC. In the SJR DWSC flow range between 500 and 1,500 cfs, the interactions of flow, oxygen demand loads and oxygen depletion are not readily discernible based on mass balance calculations. There is need for a more comprehensive sampling program of oxygen demand loads and impacts to gain additional insight into the impact of SJR flow through the DWSC on DO depletion.

The Interagency Ecological Program (IEP) has been monitoring various water quality parameters in the Delta since 1971. Continuous monitoring of DO, temperature, electrical conductivity, etc., has been conducted at Rough and Ready Island monitoring station for the past 19 years. A statistical examination of these data shows that there is a strong correlation between DO depletion at the DWR Rough and Ready Island monitoring station and the planktonic algal concentrations measured at Vernalis. There were also correlations between the city of Stockton's ammonia discharges to the SJR and DO depletion at the Rough and Ready Island monitoring station.

Examination of the city of Stockton stormwater runoff oxygen demand concentrations shows that there is sufficient BOD in stormwater runoff from the city of Stockton to add a substantial oxygen demand load to the DWSC. It appears that a November 2002 DO depletion situation in the DWSC was caused, at least in part, by city of Stockton stormwater runoff-associated BOD.

Examination of the dissolved oxygen concentrations found in the DWSC at the DWR Rough and Ready Island monitoring station shows that DO depletions below the water quality objective occur in the winter in some years. During 2002 and 2003, DO depletions at the RRI station occurred below the WQO during January, February and/or March. In mid-February 2003, a surface water DO of 0 mg/L was found at this station for several days. Further, there was a period in late January through early March 2003 when the surface water DOs at the RRI station were below 3 mg/L. The low-DO conditions found in late January through early March 2003 occurred in the presence of a large winter algal bloom. The algal photosynthesis in the surface waters did not overcome the severe city oxygen demand load from the Stockton wastewater ammonia discharges at the low SJR DWSC flow of a few hundred cfs that occurred during this time. During the low-DO period when there were low SJR flows through the DWSC, the SJR at Vernalis flows were in excess of 1,800 cfs, which means that the low SJR DWSC flows were due to diversion of most of the SJR flow at Vernalis into the South Delta for export to Central and Southern California by the State and Federal Projects.

Oxygen Demand Loads

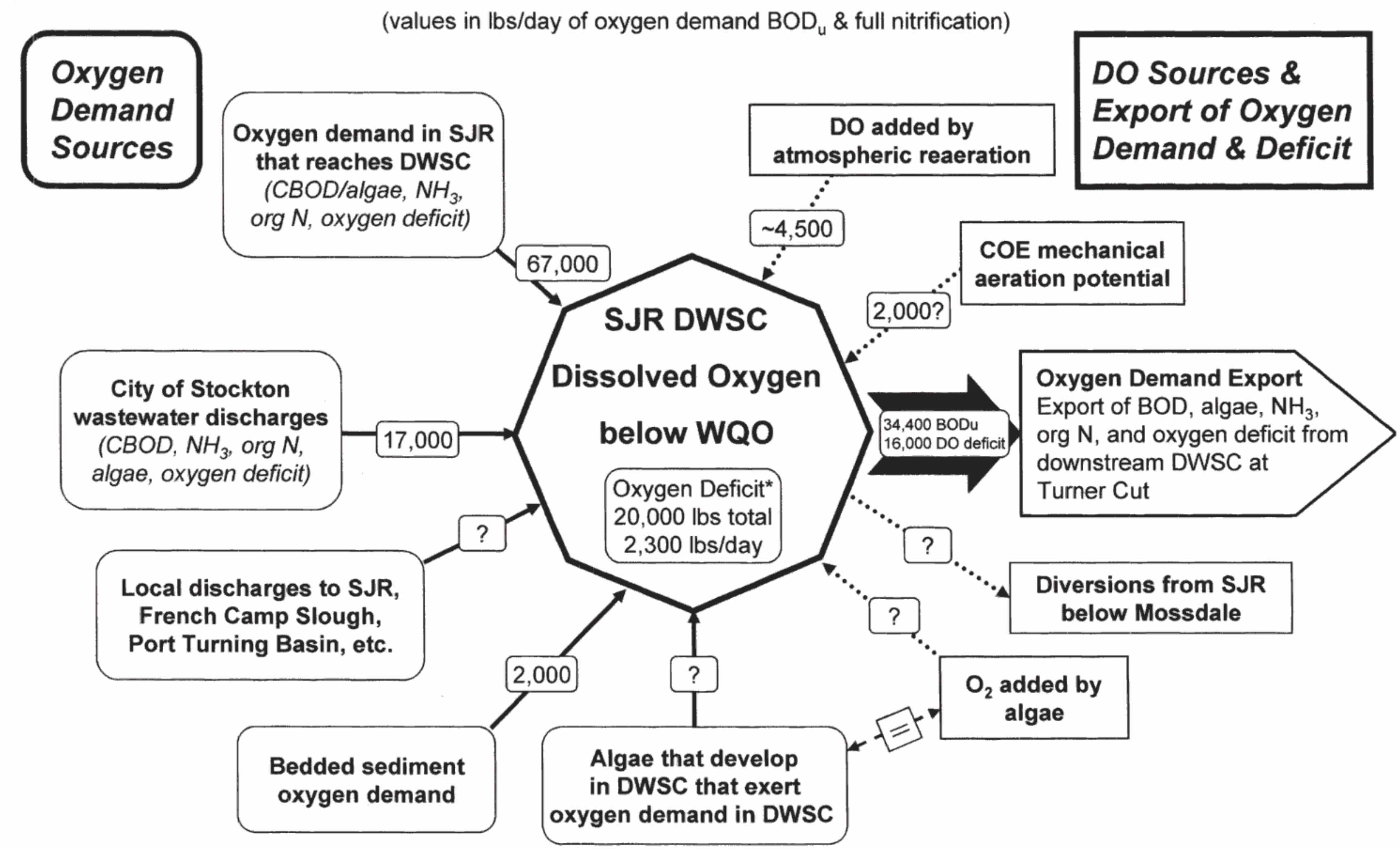
Box model oxygen demand load calculations were made for the 43 monitoring runs that the city of Stockton made during the summer/fall 1999, 2000 and 2001. The overall "average" results are shown in Figure 5 which presents the three-year summer/fall average loads of oxygen demand at Mossdale plus the City's 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. This diagram is based on the average of 43 city of Stockton sampling runs during August-October 1999 and June-October 2000 and 2001. This figure shows that on the average during the summer and fall the ultimate oxygen demand (BOD_u) load at Mossdale added to the DWSC is on the order of 67,000 lb/day with a range of about 7,500 to 129,000 lbs/day of BOD_u. The city of Stockton on average adds about 17,000 lb/day with a range of about 10,000 to 50,000 lb/day of BOD_u. The upper end of Litton's 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 and the Corps of Engineers' mechanical aerator at Channel Point has a potential of adding about 2,000 lb/day of dissolved oxygen to DWSC waters. This aerator is only operated some of the time when there is a DO deficit in the DWSC during the late summer and fall. It is not operated during the early to mid-summer. Further, Brown (2003) reported that the COE aerator operates at less than its design capability.

The algae that develop in the DWSC represent a potential oxygen demand that is compensated for by the oxygen they produce in photosynthesis. However there is likely a separation of the photosynthetically produced oxygen and the DWSC-produced algal oxygen demand as a result of the algae and detritus derived from the algae settling and adding to the near-bottom oxygen demand. The photosynthetically produced oxygen remains in the water column, reducing the magnitude of water column oxygen deficit.

Assuming that surface reaeration adds 4,500 lb/day of DO to the DWSC and assuming that the 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 at Mossdale, in the City wastewater discharges and the measurements made near Turner Cut. At the average flow of the SJR DWSC of 930 cfs, a 1 mg/L error in BOD_5 measurement translates to about 15,000 lb/day BOD_u. Considering all the approximations and assumptions used to make these estimates there is remarkable agreement (e.g., within about 25

Figure 5. Box Model of Estimated DO Sources/Sinks in SJR DWSC
(SJR DWSC Flow: 930 cfs; Travel Time: 8.6 days)



* Total oxygen deficit below oxygen saturation ≈ 120,000 lbs; 14,000 lbs/day

percent) between the three-year summer/fall average loads and sources/sinks of DO in the DWSC.

Figure 5 shows a potential loss of oxygen demand from the SJR between Mossdale and Channel Point, due to agricultural diversions of irrigation water. According to Quinn/Tulloch (2002) it is estimated that the maximum diversions during the May through August irrigation season would be about 500 cfs. Again, these diversions are likely to be the most significant during the times when the SJR DWSC flow is a few hundred cfs or less, which would occur during periods of drought and/or when essentially all of the SJR flow at Vernalis is diverted into Old River for export to Central and Southern California.

On the average about 50,400 lb/day of BOD_u and oxygen deficit below saturation are exported 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. This is an estimate of the average amount of aeration that is needed to eliminate the DO deficit below the current water quality objective. The total oxygen deficit during the summer and fall for all three years below saturation is about 120,000 lb or 14,000 lb/day.

Sources of Oxygen Demand

During 2000 and 2001, studies were conducted in the SJR watershed upstream of the SJR at Mossdale to define the sources of oxygen demand that cause the SJR at Mossdale to have elevated oxygen demand concentrations/loads. Figures 6 and 7 show the upstream oxygen demand sources. 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 the SJR watershed upstream of Lander Avenue (Highway 165). This area consists of substantial irrigated agriculture and managed wetlands, which 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 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 upstream of Lander Avenue. It has been found that, on the average during the summers of 2000 and 2001, 1 lb of algal oxygen demand discharged by Mud and Salt Sloughs to the SJR, as well as in the SJR at Lander Avenue, develops into 8 lb of oxygen demand at Mossdale.

The eastside rivers (Tuolumne, Stanislaus and Merced Rivers) have been found to discharge high-quality Sierra Nevada derived water to the SJR which has a low planktonic algal content and oxygen demand concentration, and therefore are not a major source of oxygen demand contributing to the low-DO problem in the DWSC.

Figure 6
Sources/Sinks of Oxygen Demand in SJR-DWSC Watershed

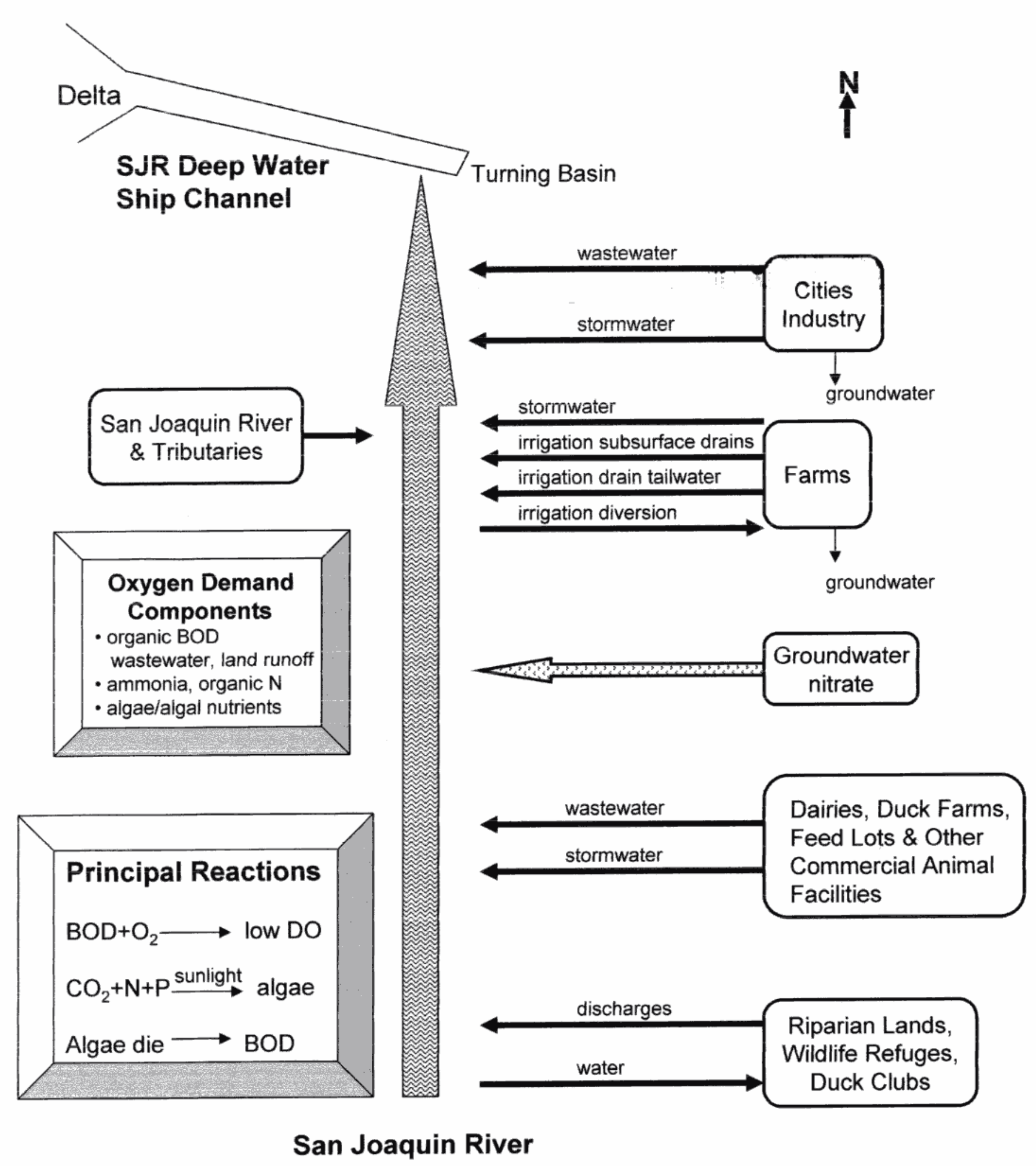
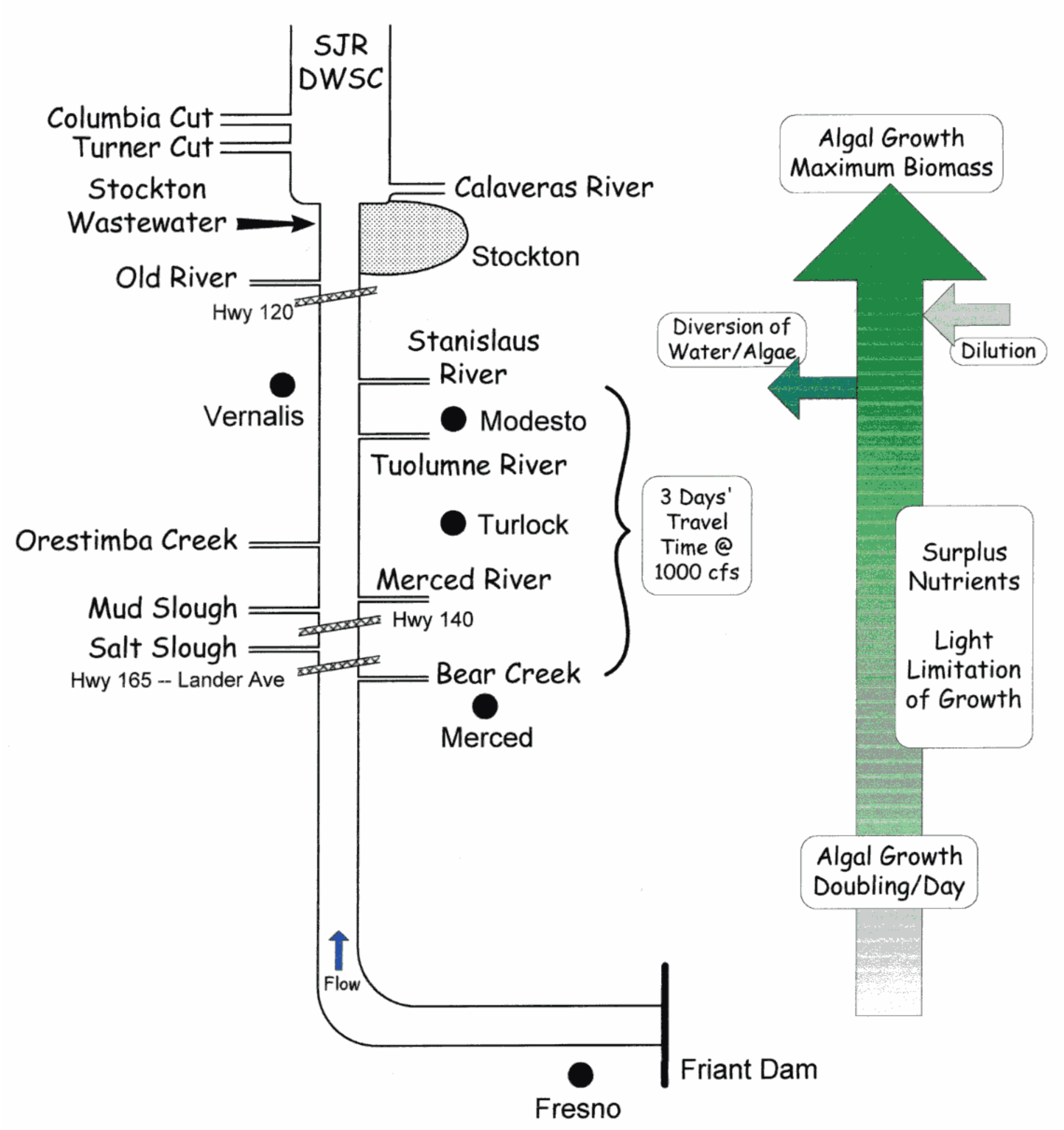


Figure 7
Schematic Representation of Algal Growth in San Joaquin River



The westside tributaries (except Mud and Salt Sloughs), such as Los Banos Creek, Orestimba Creek and Spanish Grant Drain, have been found to contribute a small part of the oxygen demand load and chlorophyll *a* to the SJR that ultimately are present in the SJR at Mossdale. The Harding Drain (TID 5), an eastside tributary, has been found to contribute oxygen demand to the SJR that is apparently not associated with algal chlorophyll *a*. This oxygen demand may be due to upstream domestic wastewater discharges from Turlock and from dairies.

There is a potential for municipal, commercial, industrial and agricultural stormwater runoff to be a source of oxygen demand associated with the rainfall runoff events that typically occur in October and November. Examination of the city of Stockton stormwater runoff-associated oxygen demand loads shows that a stormwater runoff event lasting one to two days can add as much BOD to the DWSC as is contributed from upstream of the DWSC sources during this same period.

SJR Water Diversions

There are substantial municipal and agricultural diversions of SJR water upstream of the DWSC. These diversions decrease the amount of SJR flow through the DWSC and therefore, increase the hydraulic residence time of oxygen-demanding substances in the DWSC. This leads to reduced oxygen demand assimilative capacity and greater DO depletion within the DWSC. All water diversions and managed shifts from summer flow to spring flow that decrease the flow of the SJR through the DWSC during the summer and fall below about 2,000 cfs contribute to the low-DO problem in the DWSC during the summer. This is especially true during the time when there is a rapid decrease in the SJR flow through the DWSC associated with the early June termination of the Vernalis Adaptive Management Plan (VAMP) flows, as well as in the fall, when the South Delta barriers are removed, which results in greater SJR flow down Old River.

There are several major upstream diversions, such as by the Central Valley Project (CVP) at Friant Dam, the city of San Francisco and various irrigation districts, that are potential contributors to the low-DO problem. While the impacts of low SJR flow through the DWSC leading to low DO are well documented, at this time there is an inadequate quantitative understanding of the impact of these upstream diversions on the flow of the SJR through the DWSC during the summer and fall months in the flow range of 500 cfs to 1,200 cfs and therefore the magnitude of the DO depletion below the WQO associated with these diversions.

It has been found during the summer months that approximately 500 cfs of SJR water is diverted for agricultural irrigation between where the Merced River discharges to the SJR and the SJR at Mossdale. These diversions reduce the SJR flow through the DWSC and, therefore, contribute to the DO depletion problems within the DWSC. At times from 25 to 50 percent of the SJR flow at Vernalis, in the 1,000 to 2,000 cfs range, is diverted from the SJR for agricultural use upstream of Vernalis. However, the SJR diversions below the confluence with the Merced River during the summer also divert algae/oxygen demand load. It is estimated that about 30,000 lb/day of BOD_u is diverted from the SJR between the Merced River and Mossdale, associated with water diversions for agricultural use.

The irrigation diversions are generally accompanied by some tailwater return to the SJR or its tributaries. This has been estimated to be about 15 percent of the diverted water and about 20 percent of the SJR flow at Vernalis. The irrigation return water (tailwater) appears to contribute about 2 percent of the chlorophyll *a* load in the SJR at Mossdale.

The federal Central Valley Project (CVP) and State Water Project (SWP) export through the Delta-Mendota Canal and California Aqueduct, respectively, up to about 11,000 cfs of South Delta water to Central and Southern California. The export pumping of South Delta water artificially changes the flows in the South Delta which results in more of the San Joaquin River going through Old River. These Old River diversions reduce the SJR flow through the DWSC, thereby directly contributing to the low-DO problem in the DWSC.

An analysis of the 2002 and thus far 2003 SJR DWSC flow data shows that there were several periods of low SJR flow through the DWSC, with flows less than 200 cfs. Examination of the SJR at Vernalis flows during 2002 and 2003 shows that the low flows of the SJR through the DWSC were not due to low SJR at Vernalis flows, but were due to diversion of most of the SJR flow at Vernalis down Old River for export through the CVP and SWP. The export of South Delta water, which led to very low SJR flow through the DWSC, was related to severe low-DO problems in the DWSC.

Water Quality Modeling

Several water quality modeling approaches have been used in this study. They include mass-balance box-model calculations of loads and responses, statistical evaluation of the 19-year IEP database and deterministic modeling. A one-dimensional deterministic water quality model has been developed for the DWSC which can be tuned to match somewhat the oxygen demand load DO deficit response found in the DWSC. There are, however, significant deviations between the tuned-modeling results for any particular year and the measured values at various times during the year. It is unclear at this time whether these differences are related to problems with the model structure and parameters and/or inadequate monitoring of the DWSC.

Long-term BOD measurements have shown that the BOD rate constants for waters taken from the SJR upstream of the DWSC and within the DWSC are somewhat lower than those normally used for oxygen demand modeling. The long-term BOD measurements show that BOD exertion did not show any lag due to a period of time associated with the death of algae and delayed BOD exertion in the BOD test that has been found in other studies involving algae as a dominant source of BOD.

There are significant questions about the reliability of using nitrification-inhibited BOD tests to estimate the carbonaceous and nitrogenous BOD rate constants. The approach that should be used to estimate these rate constants involves measurement of ammonia disappearance and nitrate appearance within the BOD test. Rate constants developed using this approach should be evaluated based on field studies involving Lagrangian monitoring of water masses as they pass through the critical reach of the DWSC.

There is some indication that the rates of nitrification that occur within the DWSC are somewhat elevated (enhanced) compared to a typical NBOD rate constant of 0.1 per day. If this is verified through further studies during the summer, fall and winter, nitrogenous BOD, such as the city of Stockton's wastewater ammonia discharges, would cause a greater oxygen deficit in the DWSC per unit BOD_u load to the DWSC than would be predicted based on typical nitrification rate constants. This is an area that needs further study in order to properly allocate the responsibility of the oxygen demand loads between the City's wastewater source and the upstream sources.

An issue that has not been addressed in these studies is the potential for zooplankton and clam grazing of algae that could, at times, cause changes in phytoplankton concentrations. While not quantified, there is some evidence for zooplankton grazing being potentially significant under certain conditions. Current measurements and modeling have not measured or incorporated the potential for zooplankton and clam grazing of phytoplankton as a factor that could influence phytoplankton populations in the SJR upstream of the DWSC and within the DWSC. Further, it is possible that pesticide-caused zooplankton toxicity pulses that are found in the SJR and DWSC influence zooplankton concentrations, which in turn influence phytoplankton populations.

South Delta Barriers

Temporary rock barriers are installed each year in three South Delta channels. These barriers trap incoming tides to mitigate for the lowered water levels caused by the operation of the SWP and CVP export pumps which draw Sacramento River water across the Delta. The barriers also are meant to re-establish unidirectional flow in these channels to improve water quality. CALFED is obligated to replace the temporary rock barriers with permanent operable barriers by 2007. Modeling has been conducted of whether it would be possible to operate the permanent barriers to raise the water level sufficiently in the South Delta so that a reverse flow of South Delta water could occur into the SJR via Old River. It has been found that, through low-head, reverse-flow pumping across the permanent barriers, there could be addition of South Delta water to the SJR at Old River, which would increase the flow of the SJR through the DWSC.

The reverse-flow, low-head pumping approach would introduce higher quality Sacramento River water into the South Delta and thereby, not only be a benefit to increasing the flow of the SJR through the DWSC, but also to reducing the magnitude of the water quality problems that have been found in the South Delta. This approach could potentially be used to help stabilize the flow of the SJR through the DWSC, and thereby minimize or eliminate the large changes in this flow that occur at times associated with the operation of the South Delta barriers. Further, stabilized flow would be an asset to managing aeration in the DWSC.

DO Water Quality Objectives

Currently, the Central Valley Regional Water Quality Control Board (CVRWQCB) Basin Plan DO water quality objective (DO standard) is 5 mg/L at any time and location in the DWSC between the Port of Stockton and Turner Cut during December 1 through August 31. During September 1 through November 30, the DO objective is 6 mg/L. The 5 mg/L WQO is similar to, but not the same as, the US EPA's national water quality criterion for DO. The current US EPA national water quality criterion for DO allows for averaging and for low-DO concentrations to occur near the sediment water interface. The 6 mg/L WQO was adopted to protect the fall run of Chinook salmon migration through the DWSC to their upstream home waters.

The CVRWQCB staff proposed a Phase I TMDL water quality goal of a seven-day average of the daily minimum DO concentration of 5 mg/L with no DO concentrations below 3 mg/L. This goal would apply everywhere between Channel Point and Turner Cut for the time period of June 1 through November 30. For the remainder of the year, the current water quality objective of 5 mg/L at any time and location would be applicable as the Phase I target concentration. The final water quality objective for the DWSC has not yet been determined. With respect to the proposed interim DO concentration target for Phase I of the TMDL, there is concern that the minimum 3 mg/L specified in the draft target may not be protective, where this value should be raised to at least 4 mg/L as the minimum that can occur at any time and location.

Implications of Technical Studies for Managing the Low-DO Problem

The studies of the past four years plus other data have provided information that can be used to formulate a management plan to control the DO problem in the DWSC. A summary of these results is presented herein.

Port of Stockton. Since the DO depletion problems that occur in the first seven miles of the DWSC below the Port of Stockton would not occur if the DWSC had not been dredged, it seems appropriate that the future budget for the maintenance dredging of the DWSC performed by the Corps of Engineers under its Congressional mandate, should be expanded for this reach of the DWSC to include funds to control the low-DO problem created by the continued existence/ maintenance of the DWSC. Justification for this approach stems from the fact that, without continued maintenance of the 35-foot deep DWSC, the DWSC would soon shoal and thereby become better able to assimilate the oxygen demand loads that are delivered to it from the SJR upstream of the Port. The SJR upstream of the Port is 8 to 10 feet deep. It has the same oxygen demand loads as the DWSC, but does not experience DO depletions below the water quality objective.

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. The box model calculations, Strawman analysis and the Brown evaluation of aeration for the DWSC show that, based on the three years' study data, 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 found in the box model calculations for data collected, on the order of about 6,000 lb/day of DO would be needed to keep the DWSC from violating a WQO. Other approaches for estimating the needed aeration have shown that, typically, a few thousand to ten thousand lb/day of oxygen is needed to eliminate WQO violations. It has been estimated that the amount of needed aeration can be obtained for a construction cost of less than \$2.5 million, with annual operating expenses of less than \$500,000. An engineering evaluation leading to pilot studies of DWSC aeration is needed to develop an aeration system that can maintain DO concentrations in the DWSC above the WQO.

It is likely that a combination of supplemental aeration, upstream oxygen demand load control and increased flow of the SJR through the DWSC will be used to control the low-DO problem in the DWSC. It should be noted, however, that increased flow through the DWSC would require increased amounts of aeration with the result that there is need to optimize increased flow versus aeration to control the DO depletion problem in the most cost-effective manner.

Nutrient/Algae Control in the Mud and Salt Slough and SJR Upstream of Lander Avenue Watersheds. It was found during the summer/fall 2000 and 2001 studies that the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds are the primary sources of algae/oxygen demand that lead to the DO problem in the DWSC. There is limited understanding of algal growth dynamics and nutrient sources that lead to high algal populations in discharges to the SJR from these areas. There is need to conduct studies within these watersheds to understand the specific sources of nutrients that lead to elevated concentrations of algae in the discharges (from Mud and Salt Sloughs and the SJR above Lander Avenue) to the SJR that ultimately lead to low-DO problems in the DWSC. Through such an understanding, it may be possible to effect some control of the high algal concentrations/loads that are discharged to the SJR from these watersheds during the summer/fall months that cause high oxygen demand in the DWSC.

It will be important to evaluate the relationship between decreased algae/BOD from the Mud and Salt Slough and SJR at Lander Avenue watersheds and decreased algae/BOD concentration/load at Mossdale. Guidance is provided in the Lee and Jones-Lee (2003) Synthesis Report on the studies that should be done in the Mud and Salt Slough watersheds to determine if it is economically feasible to control oxygen demand loads from these watersheds that impact DO depletion in the DWSC. The recommended approach involves the use of alum addition to bind the available phosphorus, thereby limiting algal growth in the headwaters of the Mud and Salt Slough watersheds.

City of Stockton Wastewaters. The city of Stockton wastewater discharges of elevated ammonia at times can be a significant contributor to the low-DO problem in the DWSC. The city of Stockton's wastewater oxygen demand load, which is principally in the form of ammonia, can represent up to about 90 percent of the total BOD load to the DWSC. The CVRWQCB has recently adopted a revised NPDES 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. The city of Stockton's appeal of this permit to the State Water Resources Control Board (SWRCB) was not supported by the Board. At this time, it appears that the city of Stockton may appeal the Board's decision to the courts. If the permit is upheld, then the oxygen demand load would be reduced by up to about 20,000 lb/day BOD_u during the time when the City's effluent ammonia is above about 25 mg/L N.

While there can be little doubt that, when the city of Stockton is discharging 25 to 30 mg/L ammonia nitrogen in its effluent to the SJR, and the SJR DWSC flows are a few hundred cfs or less, the City's wastewater ammonia oxygen demand loads are the principal source of oxygen demand for the DWSC, there are questions about the significance of the City's wastewater oxygen demand loads as a cause of DO depletion in the DWSC when the concentrations of ammonia in the effluent are a few milligrams per liter, especially when the SJR DWSC flows are above about 800 cfs. An issue that needs to be resolved is whether the City's ammonia discharges are subject to "enhanced" nitrification rates, which would lead to a greater proportion of the ammonia being oxidized in the critical reach of the DWSC before it is diverted/diluted into the Central Delta at Columbia Cut. This is an area that needs further study.

Additional Areas that Need Attention

In addition to those mentioned above, there are several areas that have evolved from the past four years' studies that need attention through further studies. These are briefly summarized below.

DO "Crashes" in the DWSC. At times there will be short-term DO depletions in the DWSC to relatively low levels -- i.e., 2 mg/L. These DO "crashes" are particularly significant since they may ultimately become the controlling DO depletions that must be managed. At this time, the causes of the DO crashes are not understood, but may be related to pulses of higher-than-normal algal concentrations in the SJR that enter the DWSC, or pulses of increased inorganic turbidity that decrease light penetration in the DWSC and thereby reduce the oxygen produced by algal photosynthesis in the surface waters of the DWSC. They may also be due to pulses of colored waters released from upstream wetlands areas that decrease algal photosynthesis in the DWSC. There is need for intensive field studies involving more frequent monitoring of sources and DO depletion than has been conducted in the past. Such studies should be designed to understand and thereby control the DO crash episodes that occur occasionally in the DWSC.

DO Depletions during the Winter. During the winters of 2001-2002 and 2002-2003 significant DO depletions below the WQO have been found in the DWSC off of Rough and Ready Island. There is need to understand the oxygen demand loads and other factors that lead to these low-DO conditions.

DO Depletions within the South and Central Delta. There are DO depletions below the water quality objective in some of the South Delta channels. The role of algal related oxygen demand added to these channels from the SJR via Old River has not been determined. It could be part of, or the primary cause of, the low-DO problems that are now occurring in the South Delta channels. This is an area that needs investigation.

At times, especially under high SJR DWSC flow, large amounts of oxygen demand and oxygen deficit are exported into the Central Delta at Turner Cut and especially Columbia Cut by the cross-DWSC flow of the Sacramento River on its way to the South Delta to be exported to Central and Southern California by the State and Federal Projects. At this time, no studies have been conducted to determine if low-DO problems are occurring in Turner Cut, Columbia Cut and/or Middle River due to the oxygen demand loads from the DWSC. These studies are needed as part of any implementation program that would alter flows through the DWSC. Particular attention should be given to the Turner Cut situation since the SJR flows that enter Turner Cut during ebb tide are not diluted to a significant extent by Sacramento River water.

Impact of Urban Stormwater Runoff Oxygen Demand Load on DO Depletion. City of Stockton stormwater runoff has been found to contain about 14 mg/L BOD_5. It is estimated that a 0.5-in storm in Stockton will result in a BOD load to the DWSC equal to the upstream BOD load from the SJR DWSC watershed including the City's wastewater treatment plant load. In November 2002 several inches of rainfall occurred in the Stockton area. Prior to the rainfall the DO in the DWSC was above the water quality objective. Within a few days the DO in the DWSC was below the WQO for several weeks. At the same time the DO concentrations decreased to low levels in the creeks and sloughs that drain Stockton rainfall runoff to the DWSC. There were major fish kills in these waterbodies apparently because of low DO. It appears that potentially significant DO depletion could occur in the DWSC associated with rainfall-runoff-associated BOD derived from urban areas. This is an area that needs further evaluation through examination of the DO concentrations as measured by the DWR Rough and Ready Island monitoring station and the occurrence of fall-winter rainfall runoff events.

Development of a TMDL and its Technical Allocation

There is sufficient information to develop a technical TMDL to control the low-DO problem in the DWSC. There is also sufficient information to allocate technical responsibility to tributary river mouths for the sources of oxygen demand loads that cause DO depletion problems in the DWSC. It is understood that the allocation may change somewhat during droughts. The approach that can be used is to assign an oxygen demand load allocation to the city of Stockton ammonia and the stakeholders in the Mud and Salt Slough and SJR at Lander Avenue watersheds. This allocation would need to assume that worst-case SJR flow and no aeration of the DWSC occurs. To the extent that assured funding can be developed for aeration of the DWSC from federal and/or state legislatures, the Port of Stockton and those who benefit from the existence of the Port and/or those who divert water from the SJR upstream of the DWSC (other responsible parties for the low-DO problem in the DWSC), the Mud and Salt Slough and SJR at Lander Avenue watershed stakeholders' oxygen demand load allocations can be reduced accordingly. Further, the funding from the other responsible parties could also be used to support the control of nutrients that lead to algae in the upstream watershed that are a significant source of oxygen demand in the DWSC.

TMDL Phased Approach. The TMDL will be conducted in a phased approach where the first phase will be largely devoted to obtaining 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. Further, the initial phase of the TMDL will need to be 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, if not enhanced flow, of the SJR through the DWSC will need to be conducted during the initial phase of the TMDL implementation.

An important issue that will need to be addressed during the Phase I TMDL effort is the potential secondary impacts of the programs that could be developed to control the low-DO problem in the DWSC. Any study that is conducted to develop information needed to evaluate a potential control program of the DO WQO violations in the DWSC should include studies to determine if the control program could lead to other adverse impacts to the beneficial uses of the waters in the SJR, DWSC and/or South and Central Delta. This information will be needed as part of developing the California Environmental Quality Act (CEQA) evaluation of potential control programs.

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 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.

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