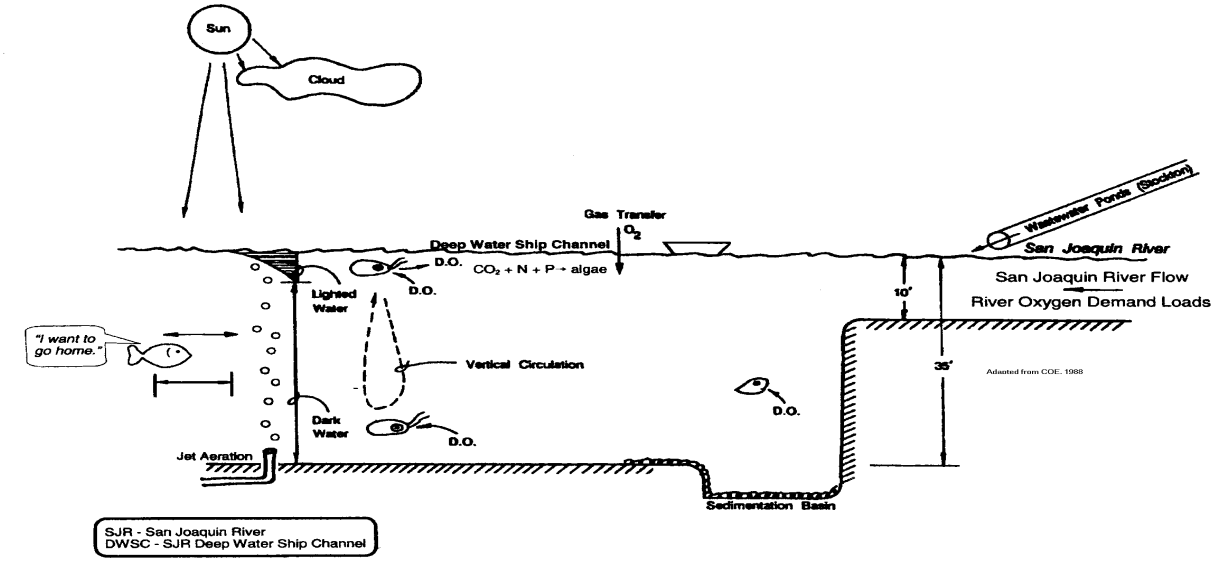

Issues in Developing the San Joaquin River Deep Water Ship Channel DO TMDL

Report to

**San Joaquin River Dissolved Oxygen Total Maximum Daily Load
Steering Committee and the**

**Central Valley Regional Water Quality Control Board
Sacramento, CA**

Submitted by

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Background to "Issues" of the SJR DO TMDL Development/Implementation Report

This report discusses issues that need to be considered as part of developing a dissolved oxygen depletion management program for the San Joaquin River (SJR) Deep Water Ship Channel (DWSC). It is designed to serve as a basis for the SJR DO TMDL Steering Committee/Technical Advisory Committee (TAC) development of a synthesis report covering the current state of knowledge of oxygen demand sources in the SJR DWSC watershed and their impacts on dissolved oxygen concentrations within the DWSC. It also discusses many of the issues that the Steering Committee/stakeholders will need to consider as part of TMDL development and implementation.

While the information on current oxygen demand loadings to the DWSC and the factors influencing the impact of these loadings on dissolved oxygen concentrations within the DWSC provided in this report is derived to some extent from TAC studies that were conducted during the summer and fall of 1999, the findings/views expressed in this report are those of the authors, and not necessarily those of all members of the TAC. This report may be used in total or in part by the TAC as a basis for developing a synthesis report to the SJR DO TMDL Steering Committee.

This report has been made available to TAC members and others for their review and comment. Comments received have been considered and appropriate changes have been made in the report. This "issues" report is an evolving discussion of SJR DO TMDL issues that will be periodically revised/updated as additional information becomes available.

The development of this report was funded in part by a contract with the Central Valley Regional Water Quality Control Board. Also, support was provided for the development of this report by funds made available through the DeltaKeeper and G. Fred Lee & Associates.

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August 17, 2000

Note

Some of the figures in this report are scanned from other sources. Further, several of the scanned figures are in color. Some of these figures can best be viewed from the computer screen in the zoom mode.

Synopsis of Issues in Developing the San Joaquin River Deep Water Ship Channel DO TMDL[1]

G Fred Lee, PhD, PE, DEE and Anne Jones-Lee, PhD

In 1994, the Central Valley Regional Water Quality Control Board (CVRWQCB) classified the San Joaquin River (SJR) Deep Water Ship Channel (DWSC) as "impaired" because dissolved oxygen (DO) concentrations routinely fell below the water quality objective (standard) (WQO) in the late fall. This listing requires that a total maximum daily load (TMDL) be developed to control the loads/conditions that cause violations of the DO WQO.

In 1998, the Regional Board classified the dissolved oxygen impairment as a high priority problem for correction, and staff committed to develop and submit to US EPA a TMDL report for controlling the problem by June 2003. Furthermore, the Regional Board, under the Bay Protection Plan agreed to allow a Steering Committee of local vested interests to help develop the control program if they committed to provide the Regional Board staff all the elements of the TMDL, including an implementation plan, by December 2002. If at any time the Steering Committee appeared unlikely to be able to do so then staff would take back development of the TMDL control plan.

This synopsis presents an overview of the DWSC DO depletion problem and the issues that need to be considered by the Steering Committee in developing a technically valid cost-effective TMDL that will enable compliance with the DO WQO. This is a summary of a more extensive 275-page discussion of the issues that will need to be addressed in oxygen demand TMDL development and allocation of the loads among the stakeholders presented by Lee and Jones-Lee (2000).

Background

As part of developing the Port of Stockton (Port), a navigation channel was dredged in the SJR through the Delta to Stockton. The SJR just upstream of Stockton is typically about 8 to 12 feet deep. It is a freshwater tidal river with about a 3 foot tidal range and a 2,000 to 4,000 cfs tidal flow. The non tidal flow is highly regulated with net flow at Stockton ranging from negative (upstream flow) associated with upstream diversions at Old River to net downstream flows between 100 to 2,000 cfs. Beginning at the Port, the SJR DWSC is dredged to 35 feet to allow ocean cargo ships to bring bulk materials to Stockton. This dredging greatly slows the net downstream transport rate of SJR water. The first 15 miles of the DWSC can have a hydraulic residence time that varies from about 5 days at a net flow of 2,000 cfs to about 30 days at 100 cfs.

The short hydraulic residence time of the DWSC has important implications for determining when the oxygen demand loads to the DWSC are potentially significant in leading to DO violations of the WQO. With hydraulic residence times of less than one month, the winter/spring SJR high flows and their associated oxygen demand/nutrient loads are not a significant contributor to DO depletion within the DWSC during summer and fall. All oxygen

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[1] Report to SJR DO TMDL Steering Committee and the CVRWQCB, G. Fred Lee & Associates, El Macero, CA, August (2000)

demand that is added during the winter/spring period is flushed through the DWSC during this time.

Dredging the DWSC altered the oxygen demand assimilative capacity of the SJR for about 10 to 15 miles downstream of the Port (critical reach) by increasing the hydraulic residence time of the water and decreasing the amount of reaeration/unit volume of the channel. Further, the greater volume of the DWSC increases water volume and dilutes the algal photosynthetically produced dissolved oxygen (DO). Also, the sediment oxygen demand (SOD) impact is diluted over a greater volume in the DWSC. These factors, coupled with upstream diversions by the State and Federal Water Projects (CVP and SWP) and other municipal and agricultural intakes, lead to DO concentrations in the DWSC below the CVRWQCB WQO. The objective during September through November is 6 mg/L and during December through August is 5 mg/L. While the primary time of concern for DO depletions below the WQO is summer and fall, there also can be DO WQO violations at other times such as during spring low flow.

Characteristics of the San Joaquin River Watershed

The SJR is one of California's primary rivers. It originates in the central Sierras, flows through the agricultural Central Valley and discharges into the Delta where it mixes with the Sacramento River before discharging into upper San Francisco Bay or being diverted by the CVP and SWP. The SJR drains the Central Valley between Fresno and Stockton. It has a 7,345 sq mi watershed that is composed of about one million acres of irrigated agriculture (Kratzer and Shelton 1998). The primary crops are fruits and nuts (almonds), corn, pasture and cotton. The SJR watershed contains the metropolitan areas of Stockton, Modesto, Merced and Fresno. There are also substantial dairies and other animal husbandry activities. The current estimated urban population in this watershed is approximately two million. The SJR watershed urban population is rapidly expanding with a rate of growth of 2 percent/yr and expected to double to about 4 million people by 2040.

Upon entering the San Joaquin Valley floor, the SJR quality deteriorates due to agricultural, municipal and industrial stormwater runoff, wastewater discharges; municipal, industrial, dairy and animal feed lot/husbandry activities and natural/riparian runoff/drainage. In addition to adding oxygen requiring substances (carbonaceous and nitrogenous BOD), the discharges contribute substantial amounts of nutrients (N and P compounds) which develop into algae. The death of these algae are a source of oxygen demand in the DWSC where SJR at Vernalis flows represent a significant part of the flow into the DWSC. Vernalis is located about 30 miles upstream of the DWSC. Between Vernalis and the DWSC is the Old River diversion which can at times divert substantial flow into the South Delta.

Also, it is possible that detritus (dead plant and animal remains and waste products-manure) derived from the SJR watershed may contribute to the oxygen demand that is present at Vernalis and, under certain SJR flow/diversion conditions, exerts oxygen demand in the DWSC. The processes that cause oxygen demand below the WQO are listed in Table S-1.

The SJR at Vernalis typically has several mg/L nitrate N and about 0.1 to 1 mg/L soluble orthophosphate P. These nutrients result in the SJR at Vernalis and the DWSC containing 20 to

100 µg/L planktonic algal chlorophyll during late summer. The death of these algae in the DWSC is one of the primary sources of DWSC oxygen demand.

Table S-1
Factors Influencing DWSC DO Depletion Below Water Quality Objectives

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DWSC: Flow (Channel Residence Time), Depth, Turbidity, Temperature, Nutrients (N and P), Algae, Light, Ship Traffic, Sediment Oxygen Demand

Local (below Vernalis) and Upstream of Vernalis: CBOD, Ammonia, Organic N, Phosphorus, Algae

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DWSC 1999 Characteristics

A study was conducted of the oxygen demand sources and DO depletion in the DWSC by the SJR Technical Advisory Committee (TAC) during the late summer and fall 1999. Part of the data from these studies are presented in Figure S-1. Station 41 is near the point where the SJR enters the DWSC at the Port of Stockton. Station 18 is about 10 miles downstream of this point.

It was found that the DO concentrations in the DWSC decreased below the WQO of 5 mg/L in August and 6 mg/L during September through early December 1999. During August and most of September the SJR flow into the DWSC was about 900 cfs. In late September through October the SJR flow into the DWSC ranged from about 100 to 900 cfs as a result of upstream SJR diversions into Old River. Under the low flow conditions, the DO in some areas of the DWSC decreased to about 2 mg/L. Further, during November and early December 1999 the concentrations of ammonia in the SJR just upstream of where it enters the DWSC was over 3 mg/L N. Ammonia at these concentrations and the SJR DWSC temperature and pH is toxic to many forms of aquatic life and also can be a significant source of oxygen demand. This ammonia was primarily derived from the city of Stockton's domestic wastewater discharge just upstream of the DWSC. Table S-2 presents a summary of the oxygen demand sources for the DWSC.

Table S-2
Sources of Oxygen Demand for DWSC

- Domestic and Industrial Wastewater Discharges and Stormwater Runoff
- Agricultural Stormwater Runoff and Irrigation Return Water
- Dairies, Commercial Animal Facilities
- Riparian Runoff
- Groundwater Discharges of Nitrate to SJR Tributaries and Main Stem
  The groundwater nitrate is due to agricultural activities, dairies, and domestic wastewaters that are applied to land

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Figure S-1
DWSC DO Data Summer/Fall 1999
Adapted from DWR Lehman (2000)

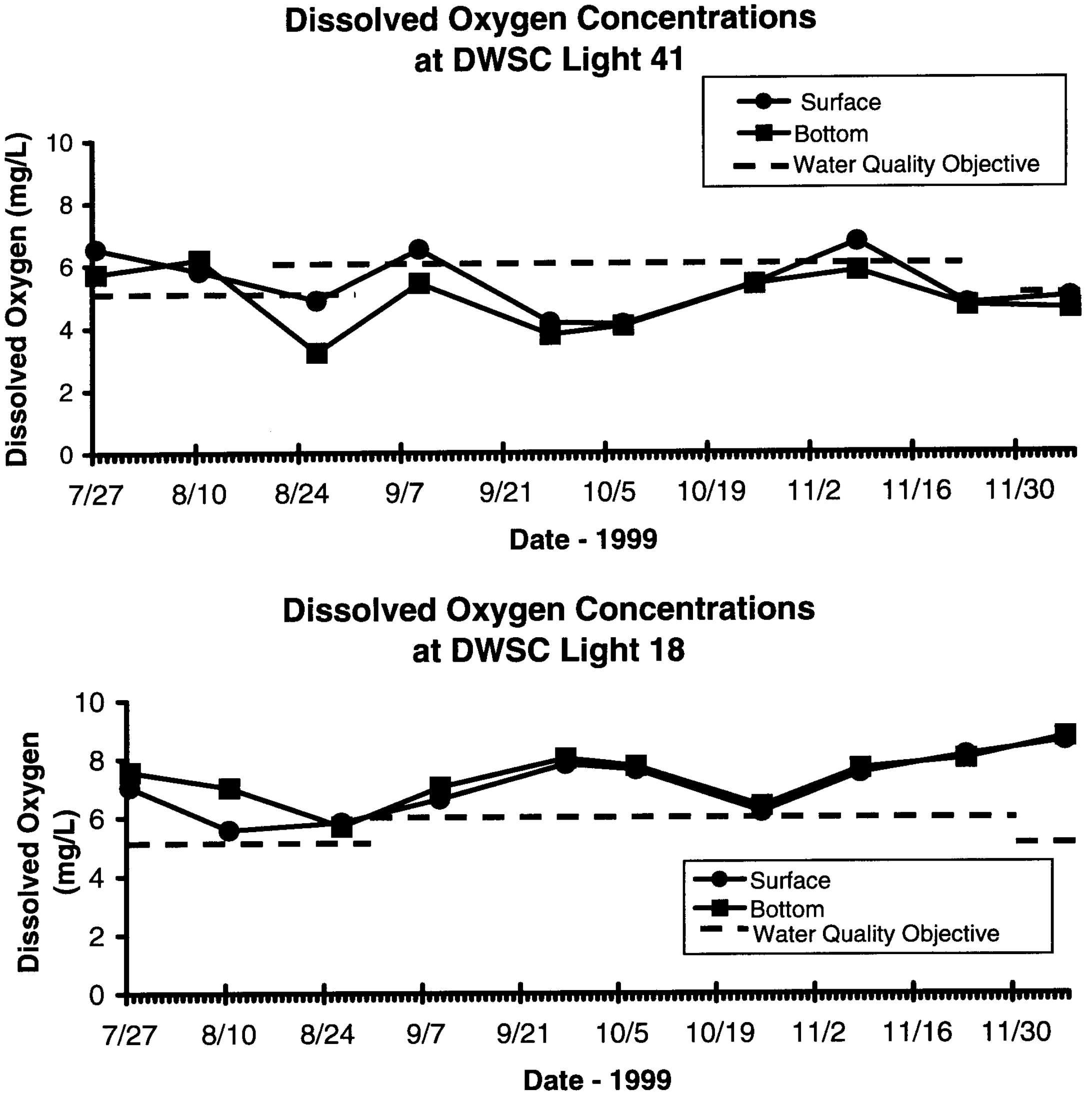

Table S-3 presents the results of box model calculations of the major sources of oxygen demand during the summer/fall 1999.

Table S-3
Summary of DWSC Oxygen Demand Sources Summer/Fall 1999

Source	BOD$_u$ (lbs/day)				
	August	September	**October**		
SJR Flow (cfs):	~900	~900	**150**	**400**	**1,000**
Upstream of Vernalis	61,000	70,000	6,300	14,130	35,325
City of Stockton	5,600	9,300	12,200	12,000	12,000
Local DWSC	?	?	1,750	1,750	1,750
SOD	6,000	6,000	6,000	6,000	6,000
Aeration (Natural)	5,500	5,500	?	?	?
Aeration (Mechanical)	2,000	2,000	?	?	?
DWSC Algae	?	?	?	?	?
Export from DWSC	27,000	27,000	?	?	?

The primary source of the oxygen demand to the DWSC during August and September 1999 was algae, detritus and other organics in the SJR from above Vernalis. During August and September, the City of Stockton wastewater discharges were a small part of the oxygen demand load to the DWSC. However, in late September-early October when the flow of the SJR into the DWSC was about 150 cfs, the upstream of Vernalis flow and its associated oxygen demand load was largely diverted down Old River. Under these conditions the City of Stockton wastewater flow of about 40 cfs and its associated about 20 mg/L N ammonia was an important source of oxygen demand to the DWSC.

These results demonstrate that the upstream diversions of SJR water are important in determining the source of the oxygen demand loads contributed to the DWSC. These results also show that it will be necessary to expand the TMDL load analysis to the SJR watershed upstream of Vernalis. Both carbonaceous and nitrogenous BOD and algal nutrients derived from irrigated agriculture are potentially important sources of oxygen demand that enter the DWSC.

The city of Stockton supported Chen and Tsai (1997) to develop a mathematical model of oxygen demand/DO impacts in the DWSC. This model, with appropriate modification, will be used to develop the oxygen demand TMDL as a function of SJR flow through the DWSC. Also a model is being developed to relate oxygen demand and nutrients discharged to the SJR and its tributaries in the SJR watershed upstream of Vernalis to oxygen demand in the DWSC.

TMDL Development and Allocation

The SJR DWSC oxygen demand TMDL is being developed by a Technical Advisory Committee (TAC) of the SJR DO TMDL Steering Committee. Excessive DO depletion in the DWSC has been a long-standing problem. Brown and Caldwell (1970) determined that the DWSC could assimilate 40,000 lbs/day BOD$_u$. Since that time, the SJR DWSC has been deepened by an additional five feet. Further, the Brown and Caldwell estimated allowable BOD$_u$ load did not include the safety factor required in TMDL development. It appears that the required load reduction to meet the TMDL will likely be on the order of 20,000 to 40,000 lbs/day BOD$_u$. This means that the oxygen demand load of BOD, including algae, will likely have to be reduced by at least 50 to 75 percent. This amount will be refined by additional studies and modeling.

Calculation of the 1999 oxygen deficit suggests that the maximum deficit in the DWSC during both August and September was about 75,000 pounds of oxygen. The DWSC average hydraulic residence time was about 10 days during both months. This suggests the loading rate would have to be reduced to about 7,000 to 8,000 pounds of oxygen requiring substances/day to meet the Basin Plan objective. Actually, the loading rate will need to be reduced even more than this since a substantial part of the oxygen demand added to the DWSC can, at flows greater than about 1,000 cfs, be exported into the central Delta.

Some relief from this oxygen demand load reduction may be achieved by increased flow of SJR water through the DWSC. In the summer and fall of 1998 the SJR flow through the DWSC was over 2,500 cfs. The DO in the DWSC did not fall below the WQO. However, there is no information on whether these high SJR flows lead to DO depletion elsewhere in the central Delta. Similarly, the diversion of SJR flow down Old River could be causing low DO in the South Delta. Both of these issues will need to be examined as part of evaluating how SJR flows into the DWSC impact DO depletion below a WQO.

Another important factor that will have to be considered in developing the TMDL is that the population in the SJR DWSC watershed is projected to double in the next 40 years. This increase in population will increase the demand for water and the potential for wastewater discharges to increase the oxygen demand load to the SJR DWSC.

CALFED has made available $866,000 during 2000 for the SJR DO TMDL TAC to conduct some of the additional studies needed to better define the relationship between oxygen demand load to the DWSC and DO depletion below the WQO. It is expected that at least this amount will be obtained from CALFED in 2001 to do further work on oxygen demand sources and their potential control.

Steering Committee Responsibilities

The SJR DO TMDL Steering Committee is composed of stakeholders in the SJR DWSC watershed. There are a variety of issues this Committee will need to resolve as part of providing guidance to the CVRWQCB in developing and implementing this TMDL. These include establishing an appropriate DO TMDL goal, with particular reference to whether the DO concentration goal of 6 mg/L for September through November and 5 mg/L for the rest of the year should be interpreted as a worst-case standard not to be violated at any time or location, including the early morning hours and near the sediment water interface. The US EPA (1986, 1987) has indicated that the primary impact of DO depletion below 5 mg/L but above about 4 mg/L is on the rate of fish growth. The importance of DO excursions below 5 mg/L but above about 4 mg/L on the fisheries resources of the DWSC, San Joaquin River and the Delta need to be better understood. A potentially large difference in allowable oxygen demand load could exist between achieving a worst case-based DO goal versus an “average” daily water column DO goal.

The allocation of the oxygen demand load/responsibility among the oxygen demand dischargers in the DWSC watershed to meet the TMDL will be a challenging task that the Steering Committee must complete by December 2002 in order to meet the CVRWQCB deadline. Failure to meet this deadline will mean that the CVRWQCB will establish the TMDL allocation.

Another important issue that will need to be addressed by the Steering Committee/stakeholders is how to balance the control of oxygen demand constituents, including aquatic plant nutrients that develop into algae that exert an oxygen demand in the DWSC, with the significantly reduced assimilative capacity of the DWSC associated with upstream of DWSC diversions of SJR water for the City of San Francisco, other communities and various irrigation districts, as well as the development and maintenance of the 35-foot navigation channel through the San Joaquin River to the Port of Stockton. The diversions of SJR water and the 35-foot navigation channel significantly adversely impact the ability of the SJR in the DWSC to accept oxygen-demanding materials without violations of the DO water quality objective.

An area of particular concern in this balancing is the potential for solving some of the DO depletion problems in the DWSC through aeration of the SJR DWSC. The Steering Committee/stakeholders will need to consider how the construction and especially the operation of the aerators would be funded and whether responsible entities, including oxygen demand and nutrient dischargers, water diverters and the Port of Stockton/those who benefit from the existence of the Port, will fund the aeration of the channel and other remedial approaches that will evolve out of the implementation of the TMDL.

Other issues that need to be addressed/defined/assessed include:

- Export/loss of BOD_u, CBOD, NBOD, algae, N and P between source - land runoff/discharges and DWSC
- Assess additional oxygen demand and nutrient loads to the SJR between Vernalis and Channel Point in the DWSC
- Impact of SJR flow at Vernalis and in the DWSC on DWSC DO depletion
- Understanding the factors controlling SJR flow through the DWSC on DO depletion below WQOs
- Understanding the significance of DWSC DO excursions below 5 mg/L that occur for a few hours to a few days on the growth rates of fish in the DWSC
- Assessing the significance of DO depletions below 6 mg/L in serving as a inhibitor of upstream Chinook salmon migration
- Cost of controlling N, P, NBOD and CBOD from wastewater, stormwater runoff and irrigation return (tail) water
- Can a reliable oxygen demand load - DO depletion below WQO model for a given SJR DWSC flow be developed that can be used to establish an oxygen demand TMDL?
- How best to manage the increasing urbanization (~ 2 percent/yr) of the SJR DWSC watershed with its potentially increased oxygen demand load.

Further information on the issues pertinent to the DO depletion problem in the DWSC is discussed by Lee and Jones-Lee (2000) and Jones and Stokes (1998).

Acknowledgment

The authors acknowledge the assistance provided by the SJR DO TMDL TAC in developing the SJR DO TMDL Issues report upon which this synopsis of issues is based. We also wish to acknowledge the reviewers of this report, especially Dr. Chris Foe, CVRWQCB; Dr. Gary Litton, University of the Pacific; Kevin Wolf of Kevin Wolf Associates and Dr. C. Kratzer of the USGS.

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Executive Summary

Background

The San Joaquin River (SJR) and its primary tributaries originate in the Sierra Nevada mountains with high-quality water. Upon entering the San Joaquin Valley floor its quality deteriorates due to agricultural, municipal and industrial stormwater runoff and drainage, municipal, industrial, dairy and animal feed lot/husbandry activities and natural/riparian runoff/drainage. In addition to adding carbonaceous (carbon) BOD and ammonia/organic nitrogen (orgN) (nitrogenous) BOD to the SJR which serve as a source of oxygen demand, substantial amounts of algal nutrients (N and P compounds) are added to the SJR, which develop into algae. These algae are a source of oxygen demand in the SJR Deep Water Ship Channel (DWSC) under conditions where the SJR flows at Vernalis (see Figure 2 for a map of the SJR, DWSC and the watershed) represent a significant part of the flow of the SJR into the DWSC. Vernalis is located about 30 miles upstream of the DWSC. Also, it is possible that detritus (dead plant and animal remains and waste products-manure) derived from the SJR watershed is a cause of oxygen demand that is present at Vernalis and, under certain SJR flow/diversion conditions, exerts oxygen demand in the DWSC.

As part of developing the Port of Stockton (Port), a navigation channel was dredged through the Delta to Stockton. This 35 ft deep channel (Deep Water Ship Channel, DWSC) altered the oxygen demand assimilative capacity of the SJR in the DWSC for about 10 to 15 miles downstream of the Port (critical reach) by increasing the hydraulic residence time of the water in this reach of the DWSC and decreasing the amount of reaeraton/unit volume of the DWSC. Further, the greater volume of the DWSC increases the volume of the DWSC that dilutes the algal photosynthetically produced dissolved oxygen (DO). Also, the sediment oxygen demand (SOD) impact is diluted over a greater volume in the DWSC. These factors, coupled with upstream of the DWSC State and Federal Water Projects (CVP and SWP) and other municipal and agricultural diversions of the SJR, lead to DO concentrations in the DWSC just downstream (within 10 to 15 mi) of the Port to fall below the Central Valley Regional Water Quality Control Board's (CVRWQCB's) water quality objective (WQO) (standard) for the SJR of 6 mg/L during September through November and 5 mg/L during December through August. While the primary time of concern for DO depletions below the WQO is summer and fall, there also can be DO WQO violations at other times such as during spring low flow.

The DO concentrations below the WQO caused the CVRWQCB to list the SJR DWSC critical reach where DO does not meet the WQO on the Clean Water Act (CWA) 303(d) list of "impaired" waterbodies in 1998. The CWA requires that any waterbody that is in violation of WQOs by any amount more than once every three years be designated as an impaired waterbody. The 303(d) listing requires that a total maximum daily load (TMDL) of substances that cause the WQO violation be established to control the WQO violation. In 1998, the CVRWQCB issued the requirement for the development of a TMDL to control the DO WQO violations in the critical reach of the SJR DWSC.

The CVRWQCB developed a TMDL management plan that involved the development of an SJR DWSC watershed stakeholder-based process to formulate the DWSC oxygen demand/condition control program to prevent the depletion of DO in the DWSC below the

WQO. The SJR DO TMDL Steering Committee organized a Technical Advisory Committee (TAC) to develop the technical information that is needed to formulate and implement the TMDL to control the DWSC DO depletion problem below the WQO. During the summer of 1999 the TAC initiated a limited-scope (funding limited) monitoring of the SJR and DWSC to obtain information on the 1999 DO depletion problem and to gain some information on oxygen demand sources for the DWSC during late summer and fall. The TAC decided to develop a series of reports that present and discuss the 1999 data. Further, a synthesis report was to be developed that would summarize the individual reports on the 1999 conditions and present recommendations for future studies. The report presented herein is an "Issues" report which presents a discussion of many of the issues that need to be considered in developing the SJR DO TMDL and its implementation. It provides information for the TAC to use in developing the synthesis report.

The summer/fall 1999 studies conducted by the TAC were designed to address several issues with reference to the sources of oxygen demand for the DWSC. Of particular concern is the relative significance of SJR upstream of Vernalis sources versus local DWSC sources as a cause of DO depletions below WQOs in the DWSC. Vernalis is the location of a stream gaging station on the SJR above the tidal part of the SJR. Until recently the focus of regulatory activities on the DWSC low DO problem was domestic wastewater discharges of the City of Stockton. The City of Stockton discharges treated wastewaters to the SJR just upstream of where the SJR enters the DWSC. Between Vernalis and the DWSC is Old River where the SJR can be diverted to the State and Federal Water Projects. These projects and other diversions divert for agricultural and domestic use several million ac ft/yr of SJR water that at one time used to pass through the DWSC.

The SJR watershed upstream of Vernalis is about a 7,300 mi^2 watershed that has substantial area devoted to irrigated agriculture. The SJR at Vernalis typically has several mg/L nitrate N and about 0.1 to 1 mg/L phosphate P. These nutrients result in the SJR at Vernalis containing 20 to 100 µg/L planktonic algal chlorophyll during late summer.

The flow of the SJR through the DWSC during late summer and fall can vary from a negative flow, with upstream flow through the DWSC due to upstream diversions, to a few hundred cfs to several thousand cfs flow through the DWSC. These SJR flows result in residence times ranging from a few days to over a month.

DWSC 1999 Characteristics

It was found that the DO concentrations in the DWSC decreased below the WQO of 5 mg/L in August and 6 mg/L during September through early December 1999. At that time the SJR flow into the DWSC was about 900 cfs. In late September through early October the SJR flow into the DWSC ranged from about 100 to 900 cfs as a result of upstream diversions. Under the low flow conditions the DO in some areas of the DWSC decreased to about 2 mg/L. Further, during November and early December the concentrations of ammonia in the lower SJR just upstream of where it enters the DWSC was over 3 mg/L N. Ammonia at these concentrations is toxic to many forms of aquatic life and also can be a significant source of oxygen demand.

A major source of the oxygen demand during August and September 1999 was found to be algae, detritus and other organics present in the SJR at Vernalis. During August and September, the City of Stockton wastewater discharges were a small part of the oxygen demand load to the DWSC. However, in late September-early October when the flow of the SJR into the DWSC was about 150 cfs, the upstream of Vernalis flow and its associated oxygen demand load was largely diverted down Old River. Under these conditions the City of Stockton wastewater flow of about 40 cfs and its associated about 20 mg/L N ammonia was an important source of oxygen demand for the DWSC.

These results demonstrate that the upstream diversions of SJR water are important in determining the source and amount of oxygen demand loads contributed to the DWSC by the SJR watershed and the City of Stockton wastewaters. These results also show that it will be necessary to expand the SJR DO TMDL oxygen demand source definitions and quantification to the SJR watershed upstream of Vernalis. Both carbonaceous and nitrogenous BOD and algal nutrients derived from irrigated agriculture are potentially important sources of oxygen demand that enters the DWSC.

Modeling of Oxygen Demand DO Depletion

In the early 1990s, the City of Stockton sponsored the development of the Stockton SJR DO Model for the purpose of assessing the impact of the City=s wastewater treatment plant discharge to the SJR just above where it enters the DWSC. This model is a deterministic model developed by Schanz and Chen, which relates oxygen demand loads to DO depletion as influenced by flow, climate, tide and other factors. This model was tuned to 1991 oxygen demand load, flow and other conditions. There was reasonable fit between the measured DO concentrations in the DWSC and the model simulations. When the model was applied to the 1999 data and conditions, without adjusting the modeling coefficients, it was found that it still tracked reasonably well the average DO concentrations found during August and September 1999. The modeling results were about 1 mg/L high throughout most of this period. There were also some spurious values of low DO that occurred in 1999 that were not simulated with the current model.

The model needs to be tuned to best represent the 1990s data on oxygen demand load and DO depletion. The updated, tuned model then should be used to develop an estimate of the Phase I TMDL of oxygen-demanding materials that can enter the DWSC under various SJR flow and other factors that influence how oxygen demand loads impact DO depletion in the DWSC.

Because of the complexity of the oxygen demand load SJR dissolved oxygen response relationships, it will be necessary to use a phased TMDL implementation approach, where Phase I will be based on the best available information on oxygen demand load/DO depletion below water quality objective response relationships. This TMDL will then be allocated through the Steering Committee/CVRWQCB to various stakeholders. Upon completion of the implementation of the oxygen demand load reductions, a several-year (likely, five-year) period of monitoring should be undertaken to determine how well the implementation of the Phase I TMDL of oxygen-demanding materials corrected the dissolved oxygen depletion problem below the WQO. It is likely that a Phase II TMDL will need to be developed which will estimate the residual TMDL load reductions that are needed to eliminate violations of the WQO. This phased implementation approach will evolve over the next 10 to 20 years.

Funding of TMDL Technical Information Development

One of the primary issues in developing the TMDL and its allocation is the need for substantial funding to develop the technical information base upon which a technically valid, cost-effective TMDL and its allocation can be implemented. A grant proposal was submitted by the TAC to CALFED for support of these studies. CALFED is an organization of federal and state agencies and stakeholders involved in Sacramento/San Joaquin River/Delta water resources management. It has as one of its primary missions the restoration of the fisheries resources of the Delta, Sacramento and San Joaquin Rivers and San Francisco Bay. It is, therefore, interested in situations that adversely impact anadromous fisheries of these waters and, in particular, any blockage of fish migration to their home waters for spawning.

The SJR Steering Committee TAC obtained an $866,000 one-year CALFED grant to develop background information that can serve as the basis for developing and implementing the SJR DO TMDL. There is an opportunity to renew this grant for two additional years. One of the objectives of the TAC=s development of a synthesis report was to help guide the development of studies that could be supported by this CALFED grant. This “Issues” report provides a discussion of areas that need investigation in order to formulate and then implement the TMDL.

One of the major areas of study that will need to be undertaken with the CALFED grant and other sources of support is an assessment of the dominant nutrient sources and their location and monthly magnitude that are discharged to the SJR and its tributaries in the SJR watershed above Vernalis. Further, there will be need to conduct studies to relate the discharge of nitrogen and phosphorus to the SJR and its tributaries from any particular location to the amount of algae that develop in the SJR that are present at Vernalis during July through November. This information is essential to be able to predict the amount of N and P reduction from various sources in the SJR DWSC watershed on the reduction in oxygen demand loads that enter the DWSC during late summer and fall.

Issues that Need to be Resolved

There are a variety of issues the SJR DO TMDL Steering Committee will need to address and resolve as part of providing guidance to the CVRWQCB in developing and implementing the TMDL. This report discusses a number of these issues, including the establishment of the appropriate DO TMDL goal, with particular reference to whether the DO concentration goal of 6 mg/L for September through November and 5 mg/L for the rest of the year should be interpreted as a worst-case standard not to be violated at any time or location, including the early morning hours and near the sediment water interface. An alternative goal could be an “average” DO concentration that considers algal diel photosynthetic oxygen production and microbial respiration, which cause lower DO in the surface waters during the early morning hours. Of further concern in achieving the TMDL goal is the averaging of the water column dissolved oxygen concentrations to reflect that near the sediment water interface, depletion of DO associated with the exertion of SOD occurs at some times.

Another important issue that will need to be addressed by the Steering Committee/stakeholders is how to balance the control of oxygen demand constituents, including aquatic plant nutrients that develop into algae that exert an oxygen demand in the DWSC, with the significantly reduced assimilative capacity of the DWSC associated with upstream of DWSC diversions of SJR water for the City of San Francisco, other communities and various irrigation districts, as well as the development and maintenance of the 35-foot navigation channel through the San Joaquin River to the Port of Stockton. As discussed in the report, the diversions of water and the 35-foot navigation channel significantly adversely impact the ability of the DWSC to accept oxygen-demanding materials without violations of the DO water quality objective.

An area of particular concern in this balancing is the potential for solving some of the DO depletion problems in the DWSC through aeration of the SJR DWSC. The Steering Committee/stakeholders will need to consider how the construction and especially the operation of the aerators would be funded and whether responsible entities, including oxygen demand dischargers, nutrient dischargers, water diverters and the Port of Stockton/those who benefit from the existence of the Port, will fund the aeration of the channel and other remedial approaches that will evolve out of the implementation of the TMDL.

Summary of SJR DO TMDL Development and Implementation Issues

Presented below is a synopsis of the key issues pertinent to managing, through the TMDL process, the dissolved oxygen (DO) concentration violations of the water quality objective (WQO) within the San Joaquin River (SJR) Deep Water Ship Channel (DWSC).

The Problem

- The dissolved oxygen concentrations in the SJR DWSC over the first approximately 15 miles downstream from the Port of Stockton at times violate the water quality objective (standard) for protection of aquatic life. In accord with the Clean Water Act (CWA) requirements, the Central Valley Regional Water Quality Control Board (CVRWQCB) listed the SJR DWSC as an impaired waterbody, which places it on the CWA 303(d) listing of impaired waterbodies. This listing requires that a total maximum daily load (TMDL) of constituents that cause the oxygen depletion within the DWSC be developed. Further, the CWA requires that the excess of oxygen-demanding materials compared to the TMDL be allocated among sources (dischargers) and a program be implemented to control the oxygen demand constituent loads to eliminate the violations of the WQO.

Cause of the Problem

- The oxygen demand constituents responsible for DO depletion within the DWSC are biochemical oxygen demand (BOD) discharged by municipal, industrial and commercial wastewaters and agricultural discharges/runoff to the SJR and its tributaries within the SJR DWSC watershed. Further, part of the oxygen demand is due to algae that die within the DWSC that develop from nitrogen and phosphorus discharged to the SJR and its tributaries.

- The oxygen demand loads to the DWSC are divided into “local” below SJR at Vernalis and upstream of Vernalis sources. Approximately 70,000 to 80,000 lbs/day of oxygen-demanding materials entered the DWSC during August and September 1999, with 80 to 90 percent of this load being derived from upstream of Vernalis. During this time, the SJR flow into the DWSC was about 800 to 1,000 cfs.

- While the allowable oxygen demand load to the DWSC has not been determined in the current studies, previous studies estimated that the allowable oxygen demand load was on the order of 40,000 lbs/day. One of the major tasks in TMDL development will be to determine the allowable oxygen demand load that will prevent dissolved oxygen from decreasing below the WQO in the DWSC.

Importance of Flow

- The relative significance of upstream of Vernalis versus local sources of oxygen demand is controlled to a considerable extent by the amount of the SJR flow that is present at Vernalis that actually enters the DWSC. The difference is the amount of SJR flow that is diverted down Old River.

- During the summer months, with SJR flows into the DWSC of about 500 cfs or greater, the principal sources of oxygen demand are derived from upstream of Vernalis in the form of BOD, including algae, where the City of Stockton's wastewater discharges are a small, but not insignificant, part of the oxygen demand load to the DWSC. During October, November and December, especially under low SJR flows into the DWSC, the City of Stockton's wastewater ammonia discharges are an important factor in influencing the dissolved oxygen depletion within the DWSC. Further, under low flow conditions of a hundred or so cfs of SJR flow into the DWSC (i.e., essentially complete diversion of SJR at Vernalis flows into Old River), the concentrations of ammonia in the SJR as it enters the DWSC and the upper part of the DWSC are sufficient to be toxic to aquatic life.

- At high SJR flow into the DWSC (greater than 2,000 cfs), the frequency and severity of DO depletions in the DWSC during the summer and fall are significantly decreased. However, the high SJR flows, coupled with the Sacramento River cross-SJR flows may carry the oxygen demand loads into the central Delta. No information is available at this time on DO depletion within the central Delta due to SJR DWSC oxygen demand loads.

- The amount of diversion of SJR flow at Vernalis down Old River is a major controlling factor in the magnitude, areal extent and duration of DO depletion below WQOs during both the summer and fall. This flow is controlled by the operation of the South Delta tidal barriers. The diversion of SJR flow into the South Delta may be causing low DO problems within this area. This is an area that needs investigation.

- While those who manage/divert the SJR flow at Old River and the flow through the Delta greatly influence the allowable oxygen demand loads to the DWSC, there is no assurance that it will be possible to gain sufficient control of SJR flow through the DWSC to minimize the amount of oxygen demand control costs that the SJR DWSC watershed stakeholders will have to bear.

Impact of the Deep Water Ship Channel

- The SJR upstream of Stockton is about ten feet deep and does not have DO depletion problems, even though it has about the same oxygen demand load as the DWSC. Originally, the SJR downstream of Stockton was also about ten feet deep. The construction of the Deep Water Ship Channel (now, 35 feet deep) as part of developing the Port of Stockton, which enables ocean-going vessels to transport materials to Stockton, has adversely impacted the ability of the San Joaquin River below the Port of Stockton but above Disappointment Slough to accept oxygen demand materials, i.e., has reduced the oxygen demand assimilative capacity (allowable load) of the DWSC. This is primarily the result of increasing the retention time of oxygen demand constituents in the DWSC due to its greater volume with the deeper channel.

  Algae and other suspended particulates slowly move downstream through the DWSC just downstream of the Port of Stockton. The greater depth and width of the DWSC greatly reduce tidal velocities and flow turbulence, thereby reducing the ability of the SJR to carry the suspended oxygen demand load downstream. Part of the suspended load settles to the bottom of the DWSC and becomes sediment oxygen demand.

Modeling of Oxygen Demand Impacts

- The relationship between oxygen demand load to the DWSC and the DO depletion below WQOs needs to be developed. This will be done through the use of the Stockton SJR DO mathematical model. This model provides an estimate of how oxygen demand and various factors such as flow, etc., impact the dissolved oxygen concentrations within the DWSC. This model, after appropriate modification, will be used to establish the TMDL for oxygen-demanding materials that can be discharged to the DWSC under various flow regimes and seasons (i.e., summer, fall).

- Because of the complexity of the processes controlling oxygen depletion within the DWSC, the TMDL will need to be implemented in a phased approach, where the initial (Phase I) allowed oxygen demand load to the DWSC will need to be estimated and allocated and the load reductions implemented. The DWSC DO will need to be monitored for several years to determine if the initial TMDL is adequate to prevent DO depletion below the WQO. If WQO violations still occur, then a revised Phase II TMDL and allocation will need to be made and implemented.

Controlling Upstream of Vernalis Oxygen Demand

- At this time, there is a significant surplus of nitrogen and phosphorus present in the DWSC and in the SJR at Vernalis compared to algal needs for further growth. This means that large amounts of N and P reductions at their various sources will have to occur to impact the growth of algae within the SJR at Vernalis and the DWSC to significantly change the oxygen depletion that will occur within the DWSC.

- It may not be possible under moderate flow conditions (500 to 2,000 cfs of SJR flow into the DWSC) for agricultural interests to control nitrogen and phosphorus loads in their runoff/discharge from their land to a sufficient extent to significantly impact the algae-related oxygen demand that occurs in the DWSC that is derived from upstream of Vernalis sources.

Aeration of the DWSC

- Part of the impact of oxygen demand loads to the DWSC on DO depletion within the DWSC can be controlled by aeration. The cost of construction and operation of the aeration system will need to be determined and a mechanism for funding these costs will need to be developed.

Allocation of Oxygen Demand/Nutrient Loads

- A key component of the TMDL allocation among the oxygen demand/nutrient sources is the development of information on the cost to each constituent stakeholder (municipalities, dairies, irrigated agriculture for dominant crop types, etc.) to achieve control of oxygen demand/nutrients to various degrees. This cost information will be important in determining how the allocation of oxygen demand/nutrients will be made among stakeholders.

Organization of TMDL Effort

- An SJR DO TMDL Executive Committee, Steering Committee and Technical Advisory Committee (TAC) have been established to provide guidance to the CVRWQCB on the implementation of the allocation of the oxygen demand loads from various stakeholder responsible entities (local - downstream of Vernalis and upstream of Vernalis domestic and industrial wastewaters and agricultural activities).

- Studies are needed to define the relative significance of oxygen demand load constituents that are present in the SJR at Vernalis that are contributed from various types of sources of oxygen demand (BOD, ammonia and algal nutrients that develop into algae that are present in the SJR at Vernalis and within the DWSC).

- There is need to define how the discharge of oxygen-demanding materials and algal nutrients (nitrogen and phosphorus) from any location and source within the SJR watershed upstream of Vernalis impacts the load of oxygen-demanding materials in the SJR at Vernalis that contributes to DO depletion in the DWSC below WQOs. It is known that discharges from various parts of the SJR at Vernalis watershed have an impact that is influenced by the distance from the SJR at Vernalis. There will likely be need to consider this situation in allocation of oxygen demand load, where the dischargers near the SJR DWSC will have to remove a greater proportion of their oxygen demand load than those in the upper portion of the SJR DWSC watershed.

Regulatory Hammer

- The oxygen demand load allocation and implementation plan must be completed by December 2002. This is a short period of time to develop the technical information and to achieve agreement on the TMDL for oxygen-demanding materials and their allocation among stakeholders.

- If the SJR DO TMDL Steering Committee stakeholder-based process does not result in a consensus-based oxygen demand/factor allocation of loads that could result in the elimination of dissolved oxygen depletion below the WQO in the DWSC, then the CVRWQCB will, in 2002, develop an oxygen demand load allocation that will be assigned to the various stakeholder dischargers of oxygen demand. Primary emphasis in this allocation will be on NPDES-permitted dischargers, such as municipalities, industry, commercial establishments, dairies, etc.

- The development and implementation of an oxygen demand wasteload allocation is extremely important to the municipal NPDES permit holders, since failure to develop a consensus TMDL allocation could mean that further development of urban areas will be severely constrained. The California Department of Finance has projected that the SJR DWSC watershed will likely double in population over the next 40 years. Municipalities could find that they cannot grow, since such growth would lead to increased oxygen demand loads to the SJR, its tributaries, and the DWSC.

Need for Financial Support

- There is need for funding to support certain stakeholder (environmental and agricultural interest) group participation in the TMDL development and allocation process, in order to help gain their support for this approach. Without it, a meaningful consensus may not be established, which would lead to the CVRWQCB having to develop the oxygen demand load allocation.

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Acronyms, Synonyms, and Definitions

Biochemical Oxygen Demand (BOD) The dissolved oxygen consumed by biochemical processes associated with the bacterial and other organism respiratory conversion of organic matter to carbon dioxide, water and/or other forms of organics. It also includes the bacterial conversion (nitrification) of ammonia to nitrite and nitrate.

Deep Water Ship Channel (DWSC) The San Joaquin River has been dredged through the Delta to the Port of Stockton to a depth of 35 feet. The dredged channel is called the Deep Water Ship Channel. The primary area of the DWSC of concern with respect to low dissolved oxygen is the reach of the channel between the Port of Stockton and Disappointment Slough. Normally, the greatest concern for low DO occurs between the Port of Stockton and Turner Cut.

Organic Detritus The remains of plants and animals and their particulate waste products. This detritus can be a source of particulate oxygen demand and SOD.

Oxygen Demand (OD) The oxygen demand of a water is the sum of all of the processes that consume dissolved oxygen. It is composed of the organic (carbonaceous) BOD, nitrogenous BOD due to nitrification of ammonia, the death and decay of algae, and the oxygen consumed by biotic and abiotic reactions associated with bedded and suspended sediment particles.

SJR DWSC Critical Reach The reach of the SJR DWSC where the DO falls below the CVRWQCB WQO. This reach is normally the first 10 to 15 miles below the Port of Stockton.

ac	acre
ac ft/yr	acre feet/year
BOD	biochemical oxygen demand
BOD_5	five-day BOD
BOD_{10}	ten-day BOD
BOD_u	BOD ultimate (30-Day)
CBOD	carbonaceous BOD
ChlBOD	algae associated BOD
CO_2	carbon dioxide
Corps/COE	US Army Corps of Engineers
CVP	Central Valley Project
CVRWQCB	California Regional Water Quality Control Board, Central Valley Region
cfs	cubic feet per second
DFG	California Department of Fish and Game
DO	dissolved oxygen
DOC	dissolved organic carbon
DWR	California Department of Water Resources
DWSC	Deep Water Ship Channel
ft	feet
ft/sec	feet per second
EC	electrical conductivity
g	grams

Acronyms (continued)

H_2O	water
lbs/day	pounds per day
m^2	square meters
mgd	million gallons per day
mg/L	milligrams per liter
mi	miles
µg/L	micrograms per liter
µmhos/cm	micromhos (reciprocal ohms) per centimeter
µS/cm	microsiemens per centimeter
N	nitrogen
NBOD	nitrogenous BOD
NH_3	un-ionized ammonia or ammonia, which is the sum of NH_3 plus NH_4^+
NO_2^-	nitrite
NO_3^-	nitrate
O_2	oxygen
OD	oxygen demand
orgN	organic nitrogen
P	phosphorus
SJR	San Joaquin River
SJR TAC	San Joaquin River DO TMDL Technical Advisory Committee
m/sec	meters per second
msl	mean sea level
nitrate-N	nitrate-nitrogen
NPDES	National Pollutant Discharge Elimination System
RWCF	Regional Wastewater Control Facility (City of Stockton)
SOD	sediment oxygen demand
SWP	State Water Project
SWRCB	State Water Resources Control Board
TSS	total suspended solids
TKN	total Kjeldahl nitrogen = NH_3 plus OrgN
TMDL	total maximum daily load
TOC	total organic carbon
USBR	US Bureau of Reclamation
USV	upstream of Vernalis
UVM	ultrasound velocity meter
USGS	US Geological Survey
VSS	volatile suspended solids
WQO	water quality objective

Issues in Developing the San Joaquin River Deep Water Ship Channel DO TMDL

Background

San Joaquin River Low DO Problem

The San Joaquin River (SJR) is one of the major tributaries of the Sacramento River/San Joaquin River Delta and San Francisco Bay. This river below Stockton is a dredged channel that enables large ocean ships to transport bulk goods to and from Stockton. Each year, the upper reaches of this dredged channel (Deep Water Ship Channel - DWSC) have experienced dissolved oxygen concentrations below the Central Valley Regional Water Quality Control Board's (CVRWQCB's) Basin Plan general objective for protection of aquatic life of 5 mg/L minimum DO.

In the 1970s, the California Department of Fish and Game (DFG) (Hallock, *et al.*, 1970) conducted studies on the migration of Chinook salmon up the San Joaquin River through the Delta into the San Joaquin River and its tributaries upstream of Stockton. These studies seem to show that the Chinook salmon were inhibited in their upstream migration through the DWSC. One of the factors that was indicated as being potentially responsible for this inhibition was dissolved oxygen concentrations below 5 mg/L within the DWSC. This situation caused the State Water Resources Control Board (SWRCB) in 1994 to adopt a water quality objective that established a minimum dissolved oxygen concentration in the San Joaquin River of 6 mg/L during September through November. As a result, dissolved oxygen concentrations below this amount during this period represent a violation of the water quality standard (objective) for the SJR DWSC. Further, dissolved oxygen concentrations below 5 mg/L within the DWSC for the rest of the year (December through August) represent a violation of the water quality objective (standard) (WQO).

In accord with Section 303(d) of the Clean Water Act, a violation of a water quality standard requires that the regulatory agency, in this case, the CVRWQCB, list the waterbody as an "impaired" waterbody for which corrective action must be taken to eliminate the water quality standard violation. The Clean Water Act requires that the water quality standard violation be controlled through the establishment of a total maximum daily load (TMDL) of constituents responsible for the WQO violation. In 1998, the CVRWQCB and the State Water Resources Control Board (SWRCB) adopted requirements to develop a TMDL to control the dissolved oxygen concentration violations of the WQO that occur in the SJR DWSC. Appendix C presents the CVRWQCB San Joaquin River dissolved oxygen depletion control plan.

Development of the TMDL Process

In the spring of 1999, the CVRWQCB initiated what has become a watershed-based effort to define the TMDL for oxygen-demanding substances within the DWSC that cause violations of the dissolved oxygen WQO. The CVRWQCB indicated that it would be more desirable for the stakeholders in the SJR DWSC low DO problem to work together using a watershed-based approach to develop a control program that would eliminate the violations of the dissolved oxygen WQO. An SJR DO TMDL Executive Committee and a Steering

Committee were organized to develop the TMDL and, most importantly, the allocation of the oxygen-demanding substance loads to the SJR DWSC that cause dissolved oxygen concentrations to decrease below the WQO. A review of the SJR DO TMDL structure and its operations is appended to this report in Appendix A. An overall master plan for development of the TMDL and its allocation has been developed by the SJR DO TMDL Steering Committee (2000).

Since the SJR DWSC is part of the Sacramento/San Joaquin River Delta and an important fish migration pathway between the Delta and upstream spawning areas, there is considerable interest by a number of governmental agencies and others in controlling conditions that could affect the fisheries of the Delta, San Francisco Bay, and their tributary waters. The CALFED Bay-Delta Program, initiated in 1995, is a collaboration among state and federal agencies and the state's leading urban, agricultural and environmental interests to address and resolve the environmental and water management problems associated with the Bay-Delta system. CALFED consists of the decision-makers of these agencies, as well as technical staff. Representatives of California stakeholder groups serve on this federally chartered advisory group. The mission of the CALFED Bay-Delta Program is to develop a long-term comprehensive plan that will restore ecological health and improve water management for beneficial uses of the Bay-Delta system. CALFED is therefore interested in the low dissolved oxygen problem that occurs in the SJR DWSC, because of its potential impact on the anadromous fisheries of the Delta, its tributaries, and San Francisco Bay, as well as its impact on Delta aquatic life resources.

A Technical Advisory Committee (TAC) of the SJR DO TMDL Steering Committee was organized to focus on reviewing the existing information on the causes and sources of oxygen-demanding materials within the SJR DWSC that lead to violations of the dissolved oxygen WQO. In the spring of 1999, this TAC submitted a proposal to CALFED for studies designed to provide information that could be used to control the dissolved oxygen WQO violations in the DWSC. This proposal was submitted through the California Department of Water Resources (DWR), with Dr. Peggy Lehman as its principal investigator. This proposal was approved by CALFED in the amount of $866,000 for one year. Except for a small amount of initial startup funding, the CALFED proposal is scheduled to begin in the spring/summer of 2000, an intensive data-gathering effort to provide the necessary information to formulate a technically valid TMDL for oxygen-demanding materials contributed to the DWSC. CALFED has indicated that it may be possible to obtain additional funding under this grant for two more years beyond the year of initial funding.

The SJR TAC determined that it would be desirable to collect data on some of the oxygen-demanding sources and their impacts on the SJR DWSC during the summer and fall of 1999. Most of the data that has been used to characterize this problem was based on 1991 or prior information that was compiled by the City of Stockton (Jones and Stokes, 1998) as part of providing background information to its revised NPDES permit for the city’s domestic wastewater discharges to the SJR. These discharges occur just upstream of where the SJR enters the DWSC.

In the early 1990s, the City of Stockton sponsored the development of the Stockton SJR DO Model that could be used to relate oxygen-demanding substance loads to the lower SJR and DWSC to oxygen depletion below WQO. This model was developed by Dr. Carl Chen of Systech Engineering (Schanz and Chen 1993, and Chen and Tsai 1996, 1997). This model is a deterministic-based model, in which the various processes that influence the dissolved oxygen in the DWSC are represented by mathematical equations (Chen and Orlob, 1975). Using the 1991 database for the characteristics of the SJR and DWSC, it was concluded that even if the City of Stockton found a way to eliminate the City's domestic wastewater discharges to the SJR, the DWSC would still have dissolved oxygen WQO violations.

On behalf of the City of Stockton, Jones and Stokes Associates conducted a comprehensive review of the SJR DWSC dissolved oxygen WQO violation problem. Jones and Stokes (1998) issued a report, "Potential Solutions for Achieving the San Joaquin River Dissolved Oxygen Objectives." This report presented a review of the SJR DWSC dissolved oxygen depletion issues. It made use of the Stockton SJR DO Model developed by Chen and Tsai in projecting how various DO depletion control programs could influence the frequency, occurrence and magnitude of WQO violations within the DWSC. The Jones and Stokes report relied on the early 1990s and prior years' database. 1991 was an unusually dry year, and, while dry years are one of the conditions of primary concern, it is desirable to have data for other years on oxygen-demanding loads and their impacts on the DWSC dissolved oxygen resources during the summer and fall months.

The SJR TAC determined that there was need to obtain data on the characteristics of the SJR DWSC during 1999, which was, at that time, thought to be a more representative flow year than 1991. As a result, the Department of Water Resources (DWR) under the leadership of Dr. P. Lehman; the CVRWQCB under the leadership of Tom King and Dr. Chris Foe; Dr. Gary Litton of the University of the Pacific; and the City of Stockton (Jones and Stokes – Dr. R. Brown , D. Brewer and B Jorgeson) conducted a monitoring program during the late summer and fall of 1999 for the purpose of obtaining current data on SJR oxygen-demanding loads and their impacts on the oxygen resources of the SJR DWSC during 1999. It was determined by the SJR TAC that the Stockton SJR DO Model should be run using the 1999 data that was being obtained in these studies.

The SJR TAC determined that a summary synthesis report covering the 1999 data and additional modeling runs and other information would be developed in order to establish the current state of information on the causes and sources of oxygen-demanding materials within the SJR DWSC. It was also determined that it would be desirable to explore, in a preliminary way, how modification of some of the factors that potentially influence the magnitude of dissolved oxygen depletion, such as SJR flow through the DWSC, for a given oxygen-demanding load from some of the dominant sources, contribute to the dissolved oxygen depletion in the SJR DWSC.

An area of particular concern to the SJR TAC was whether there was need to expand the understanding of oxygen demand sources within the San Joaquin River watershed above Vernalis, as part of developing a TMDL and, especially, formulation of oxygen demand loads from point and non-point sources in the upper San Joaquin River watershed. The basic issue being addressed is whether agricultural activities and wastewater discharges in the SJR watershed above Vernalis are significant contributors to the dissolved oxygen depletion that occurs in the SJR DWSC each summer/fall. If it was found that agricultural activities and wastewater discharges above Vernalis are potentially significant sources of constituents that contribute to the SJR DWSC DO WQO violations, then there would be need to expand the monitoring and modeling of the SJR watershed as part of the CALFED and other data collection efforts that are scheduled to begin in 2000 to upstream of Vernalis.

The overall plan for the development of the synthesis report, which would present the current understanding of oxygen demand causes, sources and their impacts, involved several members of the SJR TAC developing a comprehensive report of the 1999 studies and modeling results. These individual reports would then serve as the basis for the development of a summary synthesis report. The individual reports would be included as appendices to the synthesis report. The synthesis report is to be based on the information that has been made available in the draft individual reports that have been completed. The overall objectives of the synthesis report are:

- Determine the need to include future monitoring and modeling of oxygen-demanding materials and their sources that arise within the SJR watershed above Vernalis.
- Examine the ability of the Stockton SJR DO Model to match the dissolved oxygen depletions that occur in the SJR DWSC using 1999 data.
- Provide guidance on the studies that need to be done during 2000 and beyond to provide the information needed to formulate a technically valid TMDL for oxygen-demanding substances. Of particular concern is the formulation and prioritization of the various projects that were included in the original CALFED proposal, in light of the information that is available today.
- Provide guidance to the various stakeholders on the need to begin to develop information on the potential to control oxygen-demanding substances in their wastewater discharges, land runoff and/or stormwater runoff. This information is considered essential to begin to formulate wasteload and load allocations for oxygen-demanding substances/conditions that will lead to technically valid, cost-effective control of DO WQO violations in the SJR DWSC.

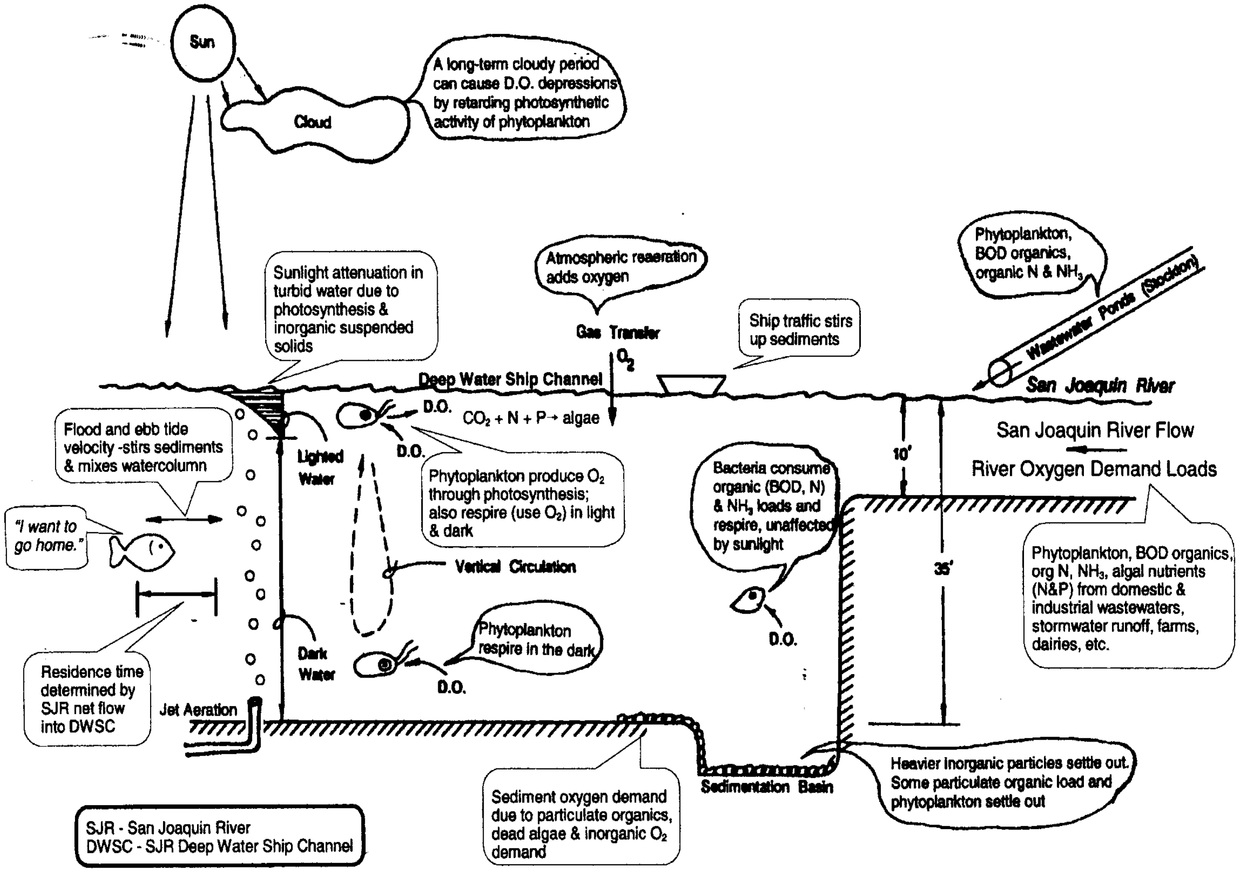
Characteristics of the SJR DWSC

The Corps of Engineers, as part of assessing the potential impacts of deepening the DWSC to 35 feet, developed a report (USA COE 1988) that summarized information on the characteristics of the San Joaquin River and the DWSC that is pertinent to understanding the dissolved oxygen depletion problem that occurs in the DWSC. The processes/factors governing DO depletion are presented in Figure 1. The following section is adapted and updated from the USA COE (1988) report.

The San Joaquin River originates as high quality water in the Sierra Nevada Mountains east of Fresno. Its head waters are stored behind Lake Millerton/Friant Dam, and releases are made for flood control, irrigation, fishery, and recreation purposes. After reaching the San

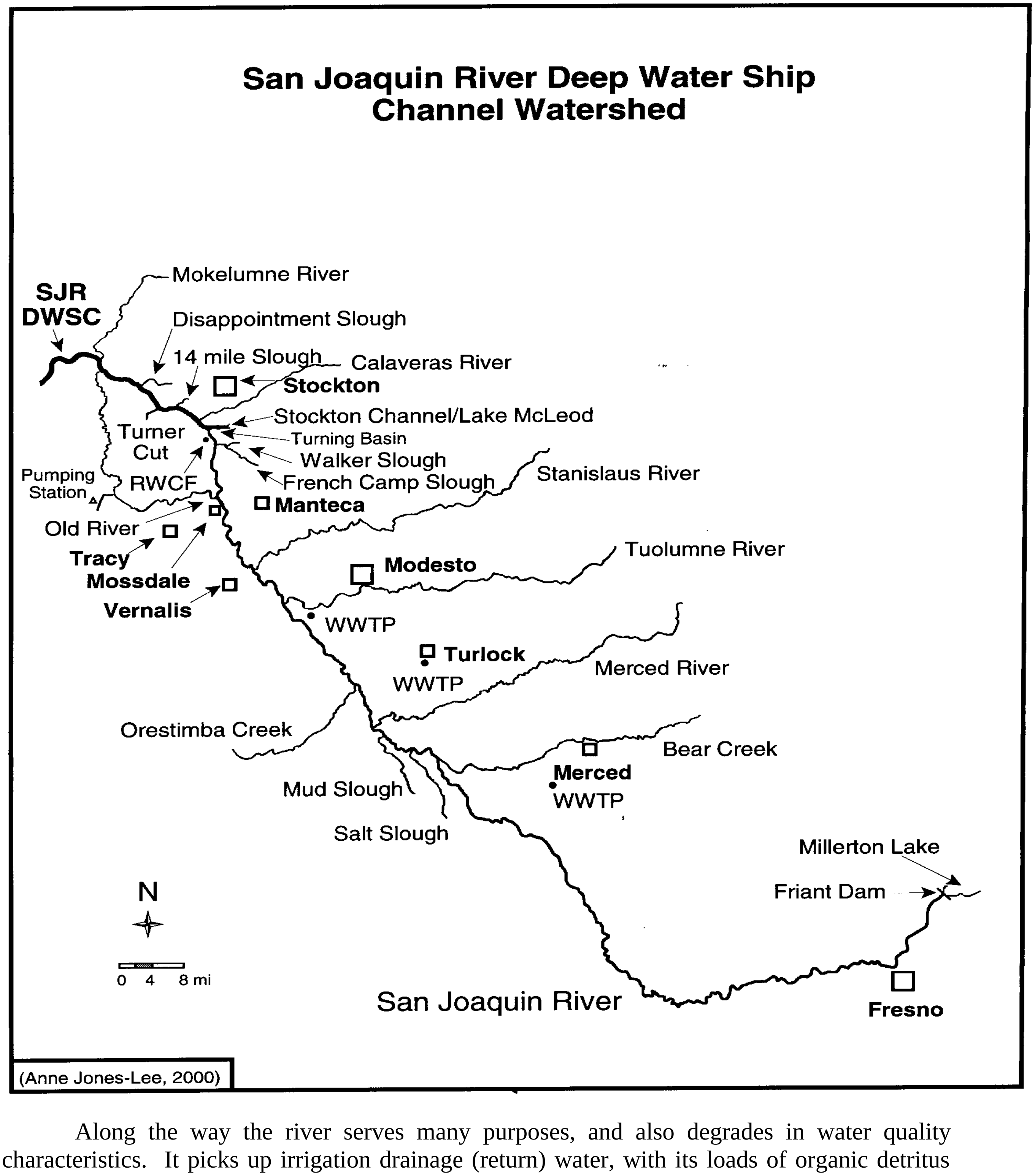
Joaquin Valley floor, the river flows north, where it enters the Delta area near Mossdale (Figure 2).

Figure 1



Factors Affecting Dissolved Oxygen in the Ship Channel
(adapted from COE, 1988)

Figure 2



Along the way the river serves many purposes, and also degrades in water quality characteristics. It picks up irrigation drainage (return) water, with its loads of organic detritus (plant and animal remains) and salts, which contain the phytoplankton (algal) nutrients nitrogen and phosphorus. It also picks up some domestic wastewater effluent and nonpoint runoff, which similarly contain nitrogen and phosphorus.

In the fall, a salmon run makes its way through the Delta and seeks to migrate up the river and into such tributaries as the Stanislaus, Tuolumne, and Merced Rivers. Some basic requirements of those salmon are a downstream-flowing current against which to swim that also provides the chemical signal of their home waters, and sufficient DO.

As the river flows, sunlight penetrates its surface and supplies the energy needed for phytoplankton to grow on the abundant nitrogen and phosphorus present. Large concentrations of phytoplankton have been noted along the river as it approaches the Delta, and an excess of DO produced from phytoplankton photosynthesis has occasionally caused supersaturated DO conditions.

After entering the tidally-influenced area of the Delta near Mossdale (see Figures 3 and 4), the river continues its flow toward Stockton. From Mossdale Bridge to Stockton, a distance of 16 miles, stream depth ranges from 5 to 15 feet at mean half-tide (Bain, *et al.*, 1968). Substantial man-induced changes in flow conditions occur in this reach. Historically, most of the river water continued on to Stockton, while some small portion of the flow split off and flowed westward in Old River. Now, a significant portion of the San Joaquin River flow, and sometimes all of its flow, along with some central Delta water, is pulled into Old River as a result of the hydrostatic head produced by the state and federal pumps at Tracy.

That portion of the San Joaquin River which does continue its flow to Stockton continues to do so in its natural channel. Once the river enters the Port of Stockton area, however, substantial man-induced changes to its depth have been made. The approximately 10-foot-deep river becomes a 35-foot-deep ship channel. The water velocity decreases because of the enlarged cross-sectional area of the ship channel. The water velocity in the area is also affected by the rise and fall of the tide (about 2 to 4 feet in the Stockton area). Sunlight penetrates the channel surface (Secchi depth about 1 ft), but most of the depth is without sunlight. Vertical mixing from wind action and channel turbulence is decreased by the increased depth. Sedimentation of particles increases because of the more quiescent conditions of the ship channel. Because of this, the Corps of Engineers has constructed a sedimentation basin at the confluence of the river and ship channel, consisting of a 5-foot deeper cut in the channel bottom extending for more than a mile (see Figure 1).

There is a dead-ended portion of the ship channel in the port area called the Turning Basin (see Figure 4). Except for stormwater inflow, the interchange of water here occurs through tidal action. Since some of the river phytoplankton load and city wastewater effluent is transported into this basin during flood tide, and because of the long detention time here, severe DO deficits have been measured in the Turning Basin. During each ebb tide, some of this low DO water is transported back into the ship channel.

Figure 5 presents a diagram showing the reactions that influence how algae and detritus (plant and animal remains) impact DO concentrations in a waterbody. The phytoplankton load

Figure 3

Delta Waterways

Sacramento–San Joaquin Delta Atlas *Department of Water Resources*

10

carried by the river into the ship channel area is affected by the conditions described above. The algae occupy a water column that is now 35 feet deep rather than 10 feet deep, as the river water becomes mixed with the ship channel water. Thus the phytoplankton in the deeper waters are in an area without adequate sunlight needed for photosynthesis, and the photosynthetic production of oxygen decreases or stops. However, these same phytoplankton continue to utilize oxygen in respiration. As some vertical circulation occurs in the channel, most of these deeper phytoplankton return to the surface waters where photosynthetic oxygen production again picks up. However, they are replaced by other phytoplankton which were at the surface but have now been mixed to the deeper waters. The net effect is that less photosynthetic production of oxygen per unit volume at a given location occurs in the ship channel than occurred in the river, and the deeper the ship channel, the lower the phytoplankton's exposure to sun-lighted surface waters as they undergo their vertical circulation. The effect is that the **net** photosynthetic production of oxygen **in the water column** is negative.

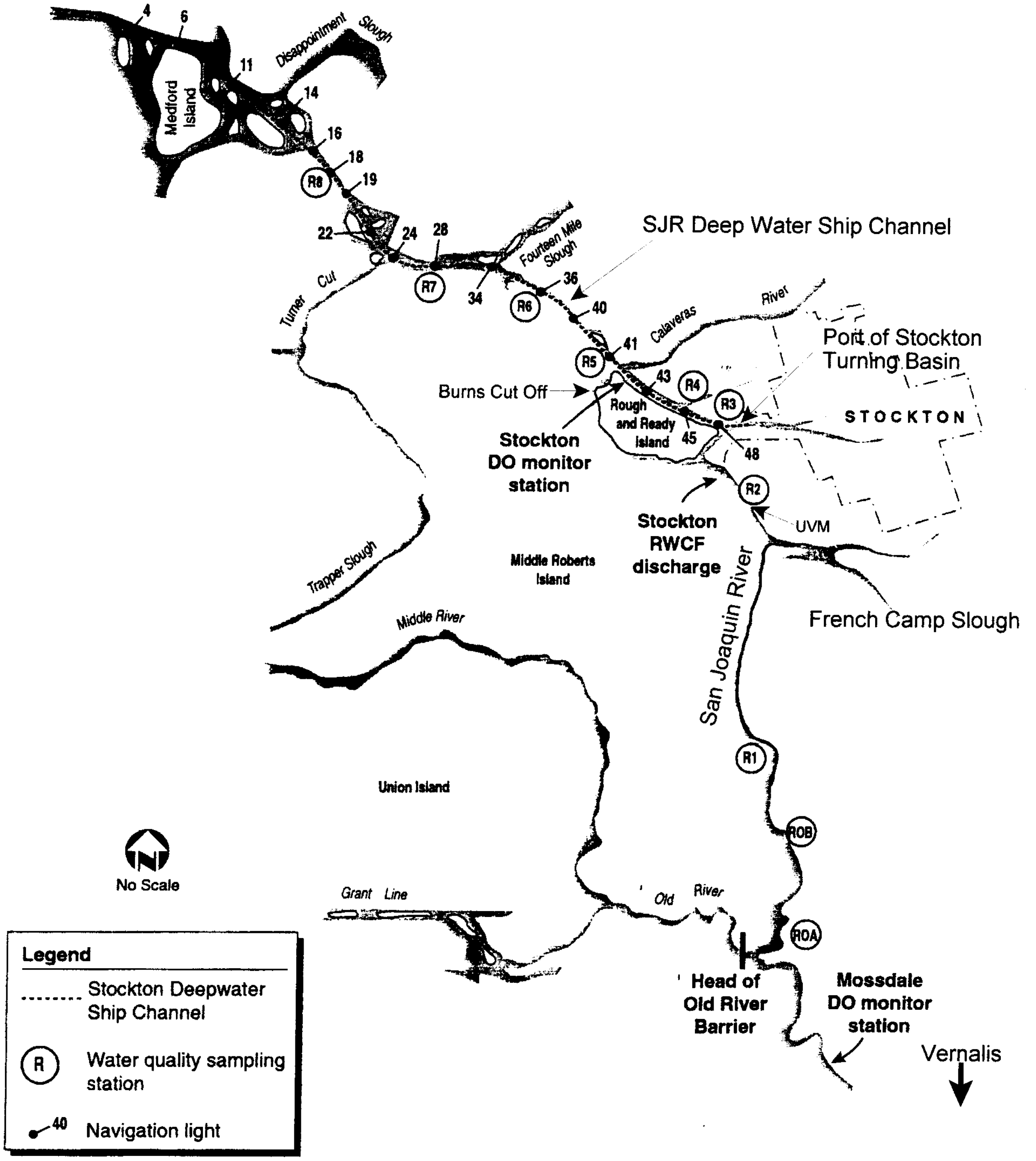
While the above vertical circulation of phytoplankton occurs, there is still a portion of the phytoplankton which are dying and settling to the channel bottom along with other organic detritus and sand, silt, and clay carried from upstream. Bottom-dwelling organisms consume this organic detritus along the channel bottom, also consuming oxygen. Some of the organic detritus undergoes microbial decay in the absence of oxygen (anaerobic processes).

Just upstream of the ship channel, the City of Stockton discharges its domestic wastewater effluent (see Figure 4 at Stockton RWCF) into the river. This effluent exerts an oxygen demand in the river as river bacteria use DO as they consume the organic and nitrogenous (ammonia and organic nitrogen) fractions of the waste load.

The water quality problem is that the DWSC near Stockton frequently experiences DO concentrations below the CVRWQCB water quality objective of 6 mg/L from September through November and 5 mg/L for the rest of the year. Figure 6 presents the relationship between water temperature and dissolved oxygen saturation. Saturation is the amount of DO that a water can hold in equilibrium with the atmosphere. If DO saturation conditions existed in the water in October, with its temperature range of 16-20°C, the saturation concentration would be 9-10 mg/L. However, the DO concentrations in the ship channel fronting Stockton are decreased because of the oxygen-demanding loads, and frequently drop below the 6 mg/L objective desired for the fall salmon run.

The State and Federal Water Projects' export pumps (see Figure 3) can draw San Joaquin River water into Old River. In fact, with low summer and fall flows in the San Joaquin River, and typical summer/fall export rates, the entire flow of the San Joaquin River can be drawn into Old River and, additionally, flow reversal can occur at Stockton to draw that water upstream into Old River and to the export pumps. Flow reversals occur in other Delta channels for the same reason, and by this process Sacramento River water is drawn southward through the Delta and to the export pumps. Some of this Sacramento River water is drawn to the vicinity downstream of Stockton (Disappointment Slough-Turner Cut), as shown in Figures 3 and 4, and can serve to improve water quality conditions by replacing some of the phytoplankton-laden water there.

Figure 4



Jones & Stokes (1999)

Location of Water Quality Stations and Navigation Lights on the San Joaquin River in the Vicinity of Stockton

Figure 5

Algae & Organic Detritus as Sources of Oxygen Demand

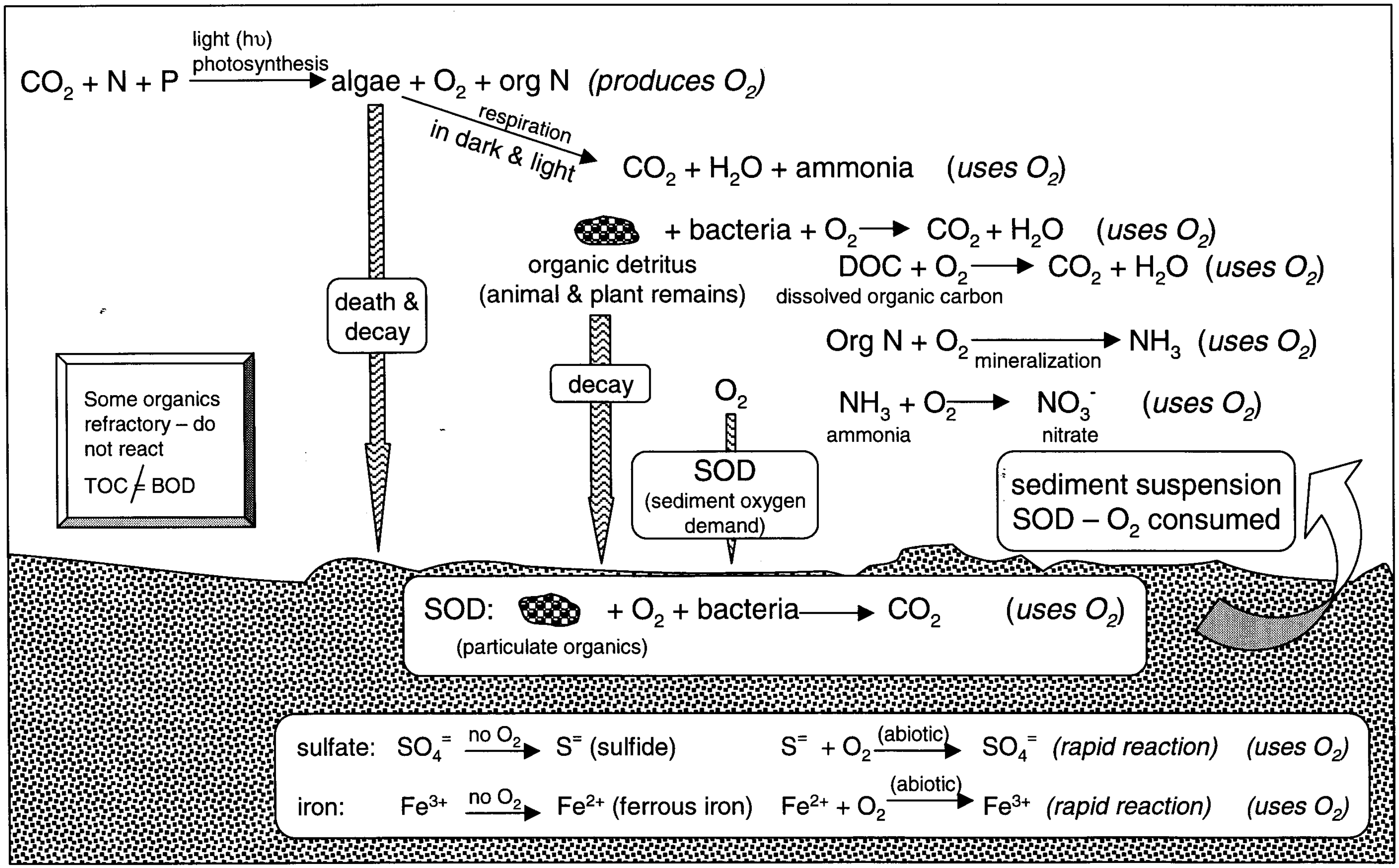
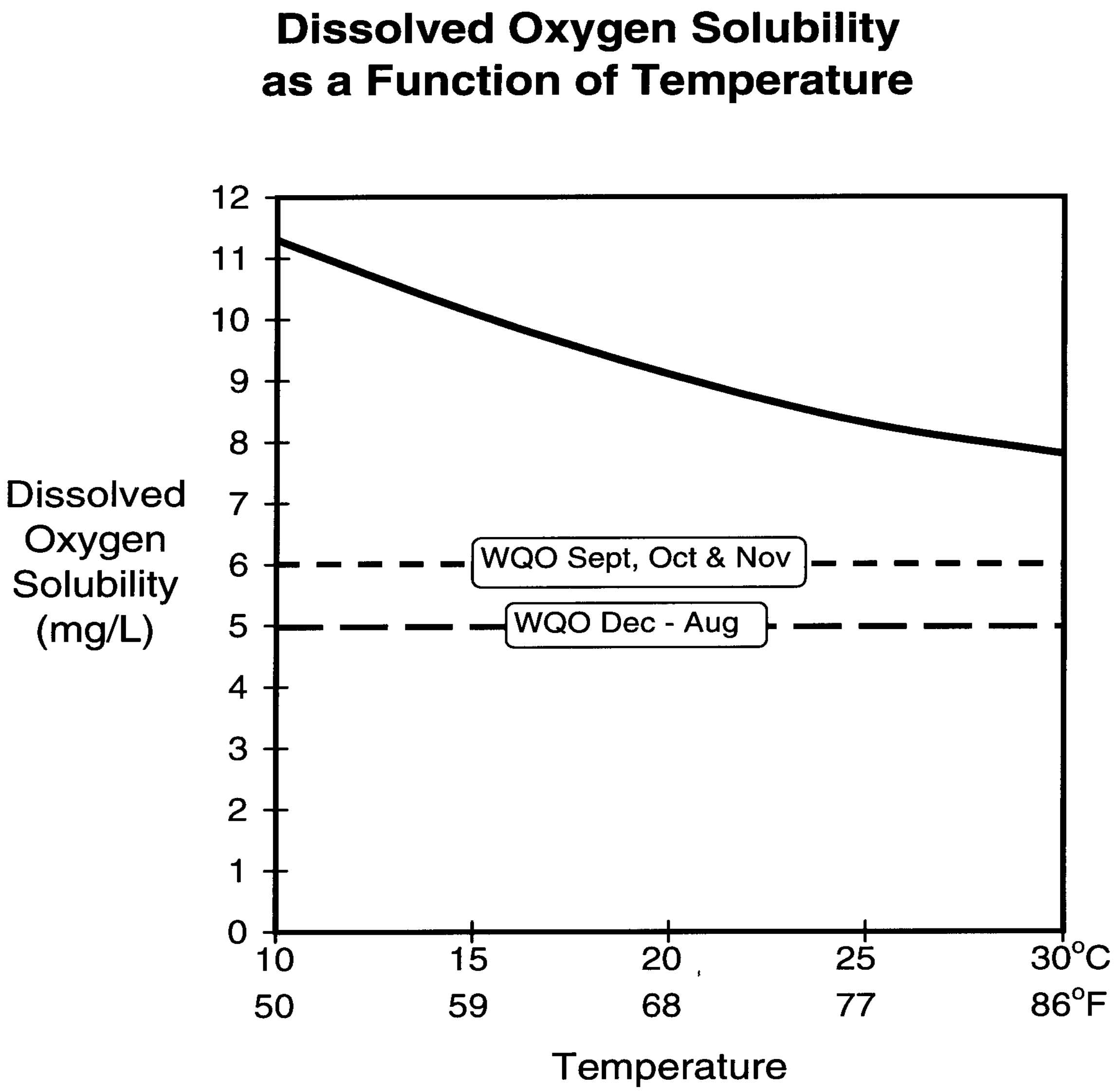


Figure 6



(after APHA *et al*., 1998)

Thus, the DO concentrations in the ship channel at Stockton are affected by a multitude of factors:

- A respiring phytoplankton population in the darker waters;
- An oxygen demand from non-viable organics and nitrification;
- A benthic oxygen demand from bottom-dwelling organisms and organic decay in the upper sediments;
- A decrease in atmospheric aeration impact as channel depths increase;

- Deepened channels and export rates which can slow the water velocity and allow greater time for oxygen demand exertion;
- Export rates which affect how much phytoplankton and other oxygen-demanding load enters the ship channel, or how much Sacramento River water is drawn into the area.

In order to try to improve water flow through the DWSC during the fall salmon run, a removable dam (rock closure) is constructed across the head of Old River at SJR in normal- and low-flow years to force SJR flow down through the DWSC.

The equations in Figure 5 represent the various processes that govern dissolved oxygen production and depletion in the DWSC. These equations are designed to show the dominant components of the reactions, and are not balanced. Beginning in the upper left of Figure 5 is the dominant photosynthesis reaction governing the rate at which algae can grow, as a function of the light available, and this, in turn, is a function of temperature. In light, photosynthesis leads to oxygen production and more algae. In the temperature and light conditions of the Stockton area summer, algae can double to quadruple in numbers in one day.

In the light and dark, algae respire, utilizing organics to produce CO_2 and water. This reaction also releases ammonia, either directly or through the production of organic nitrogen, which, in turn, is mineralized to ammonia by bacteria. This is an oxygen consumption process, which is the dominant process below the photic (lighted) zone. This zone, in the DWSC, is typically from one to about three feet in depth below the surface.

In addition, detritus, which is plant and animal remains, including algal remains and other dissolved or particulate materials derived from various sources, is used by bacteria as food through normal respiration, which involves the consumption of oxygen to produce CO_2 and water. This is the typical BOD reaction. Organic detritus can be derived from both terrestrial (land) sources and water. With respect to water sources, these include dead algae, aquatic plants and aquatic animals.

The algae and the organic detritus decay in the water column, to some extent. They also settle slowly, typically at the rate of a foot or so per day, to the bottom, and any residuals that reach the bottom become part of the biotic (organism) sediment oxygen demand. This biotic sediment oxygen demand will eventually consume all dissolved oxygen present in the sediments, except possibly just at the sediment water interface, provided that there is oxygen above the sediment water interface. This situation leads to the reduction (chemical oxidation reduction reaction) which converts ferric iron to ferrous iron and sulfate to sulfides and polysulfides. Both ferrous iron and sulfides (polysulfides) react with dissolved oxygen rapidly in an abiotic (nonbiological) reaction. In many sediments, most of the sediment oxygen demand is an abiotic reaction due to the accumulated ferrous iron and sulfides. The suspension of sediments into the water column can result in a rapid oxygen depletion, due to the reaction between ferrous iron, sulfides and dissolved oxygen.

Ferrous iron and sulfide frequently occur as ferrous sulfide or polysulfide particles. When suspended in the water column, these exert a high oxygen demand for a short period of time, and then, within usually a few hours, the rate of oxygen demand slows down considerably. This situation leads to a rapid oxygen consumption rate within the first few hours, and then a slower oxygen consumption rate that can resemble biotic oxygen consumption, but takes place in the absence of any bacteria or other organisms.

Frequently, attempts are made to measure the dissolved oxygen consumption by sediments (sediment oxygen demand - SOD) through dome chamber measurements. Such an approach does not yield reliable sediment oxygen demand measurements since the sediment oxygen demand is highly influenced by the amount of mixing of the sediments into the water column. The dome chamber SOD measurements do not properly simulate this mixing process and typically underestimate the sediment oxygen demand that actually occurs.

It is important to understand that the total organic carbon (TOC) or dissolved organic carbon (DOC) is not a reliable measure of oxygen demand, either in the water column or in sediments. In most waterbodies, there are large amounts of TOC and DOC, which are refractory, i.e., are not useable by bacteria as a source of food.

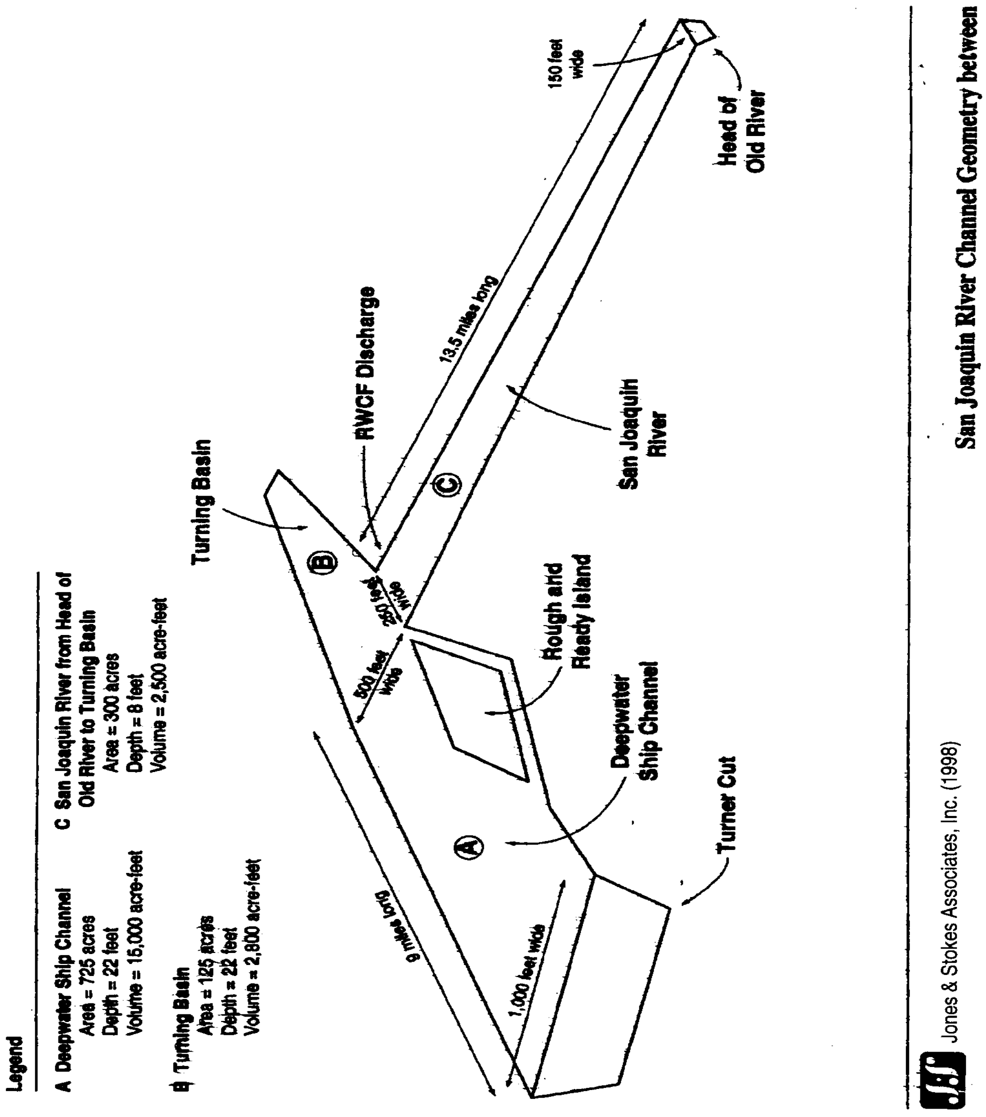
Another important reaction that governs oxygen consumption is nitrification, in which nitrifying bacteria utilize oxygen to convert ammonia to nitrite and nitrate. As discussed herein, this is an important reaction influencing the oxygen depletion within the DWSC.

Jones and Stokes (1998) provided a diagrammatic representation of the lower San Joaquin River between the head of Old River and Turner Cut associated with the DWSC. This diagram is presented as Figure 7. At the Head of Old River, the SJR is about 150 feet wide. At the point where the SJR enters the DWSC, it is about 250 feet wide. The average depth of the river through this reach is about 8 to 10 feet. The volume of the river in this reach is about 2,500 acre feet.

As presented by Jones and Stokes (1998), the reach of the DWSC of concern with respect to low dissolved oxygen starts at the point where the SJR enters the DWSC. It extends about 9 miles to Turner Cut. The volume of this river reach is about 15,000 acre-feet. During 1999 low DOs were encountered in the DWSC to Disappointment Slough. This situation has occurred in other years as well.

As shown in Figure 7, associated with the DWSC is the (ship) Turning Basin. While the Turning Basin is part of the DWSC, it has no significant tributary input, and, although tidal, it is treated as an appendage to the DWSC, since the main flow path for the SJR being mixed with Sacramento River water that mixes with the SJR DWSC in the vicinity of Disappointment Slough is down the former SJR channel. Low dissolved oxygen concentration occurs upstream of where the SJR joins the DWSC, including the Turning Basin. While there is limited tributary flow into the Turning Basin, there is significant tidal mixing of waters within the Turning Basin and upstream and downstream of the Turning Basin.

Figure 7

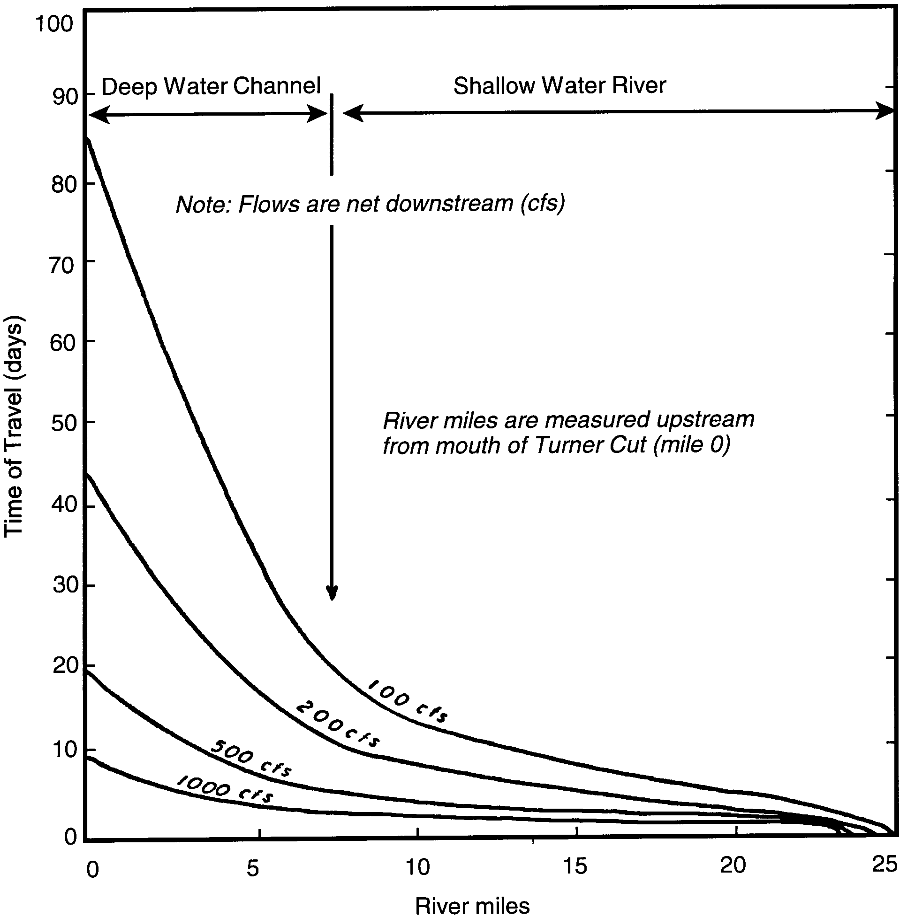


San Joaquin River Channel Geometry between Head of Old River and Turner Cut

Jones & Stokes Associates, Inc. (1998)

The US EPA (1971) developed Figure 8, which presents the travel time of water within the San Joaquin River near Stockton, as well as the Deep Water Ship Channel. Examination of Figure 8 shows that, at SJR flows in the DWSC on the order of 100 to 200 cfs, the travel time of water within the DWSC from where it enters near the Port of Stockton to Turner Cut was projected by the US EPA to be on the order of 40 to 80 days. At 1,000 cfs, the travel time for this reach of the DWSC approaches 10 days. The information presented in Figure 8 is based on the DWSC configuration prior to its deepening to 35 feet. This deepening would increase these travel times in the DWSC beyond those shown in Figure 8. The net result is that there is ample time for oxygen-demanding substances to exert their oxygen demand within the DWSC, especially during low-flow conditions.

Figure 8



Time of Travel, San Joaquin River near Stockton

Source: US EPA (1971)

Figure 9 is an updated version of the travel times information on the DWSC. This relationship was developed by C. Chen and R. Brown (personal communication, 2000). This diagram considers the DWSC current geometry and the influence of tidal mixing that occurs at low SJR flow. At SJR flows into the DWSC of a few hundred cfs, tidal mixing decreases the residence time of the water/substances added to the DWSC from those predicted by the US EPA (1971).

Figure 10 presents a summary of the sources of oxygen-demanding materials in the DWSC. Figure 11 provides additional information on oxygen demand sources and some of the factors that impact how an oxygen demand of a certain type from a particular source influences how the oxygen demand substances impact DO resources in the DWSC. On the right side of

Figure 10 are the principal sources of materials that, either directly or, in the case of algal nutrients, through conversion to algae and their subsequent death, lead to oxygen demand. Cities and industry contribute both wastewater and stormwater runoff, which have oxygen demand and nutrients. Further, some cities practice wastewater disposal on land, which can lead to groundwater contamination by nitrate. In addition, the use of fertilizers on lawns, golf courses and other green areas can lead to groundwater pollution by nitrate. The nitrate-polluted groundwaters can be a source of nitrate for algal growth if the groundwaters discharge to the SJR or one of its tributaries.

Figure 9

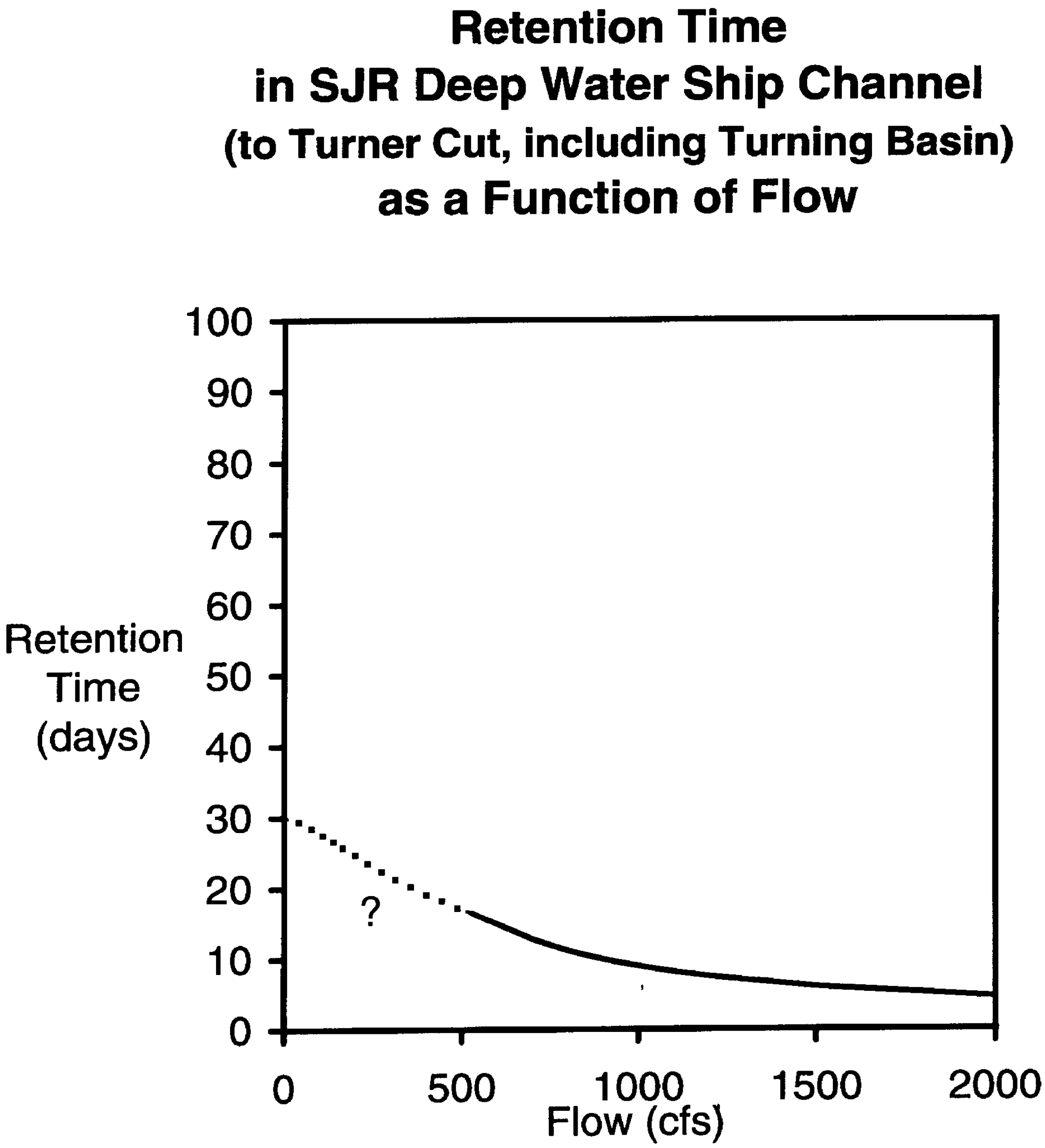
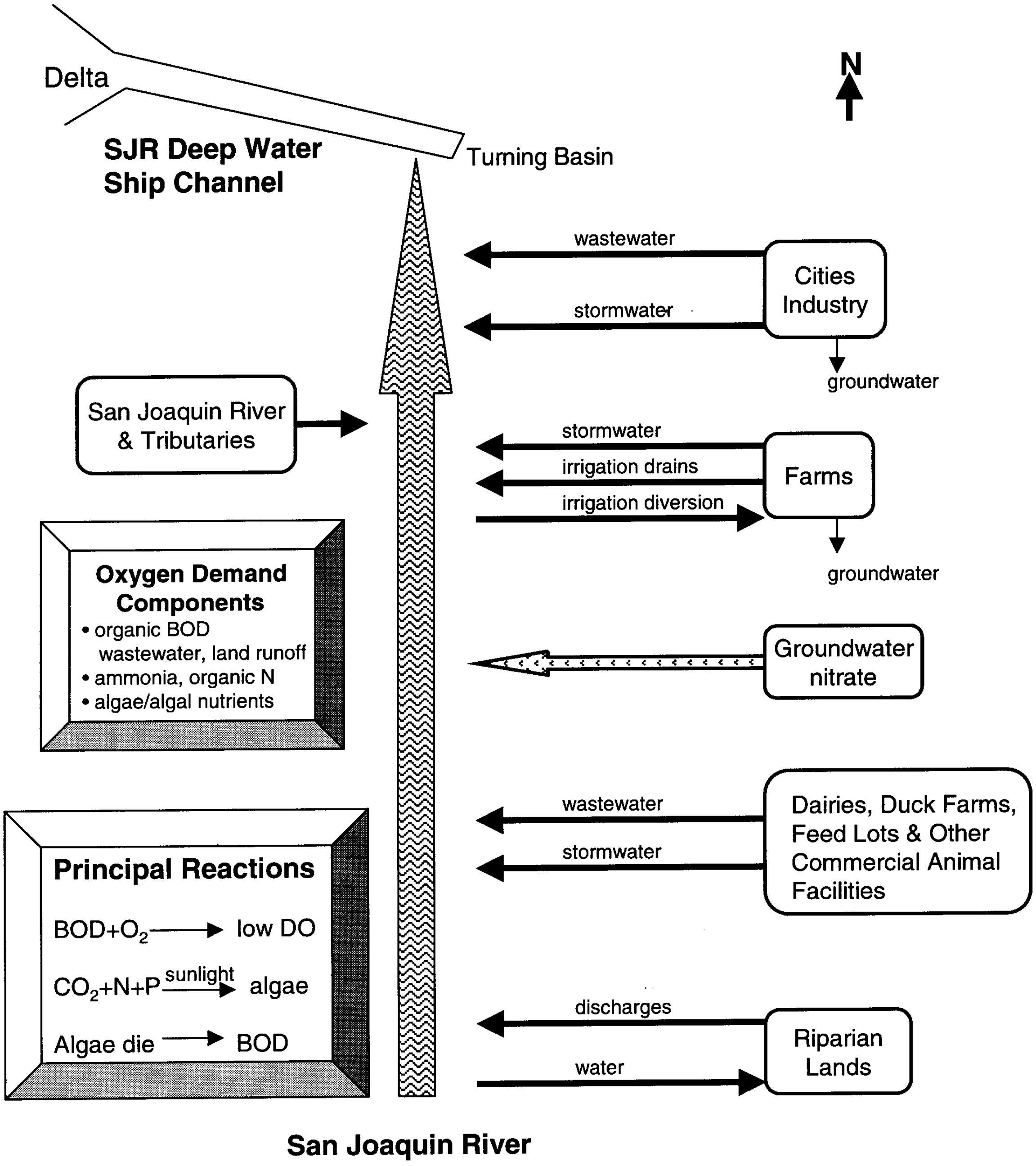


Figure 10

Sources/Sinks of Oxygen Demand in SJR-DWSC Watershed



Groundwater pollution by nitrogen compounds, such as organic nitrogen and ammonia, that lead to nitrate in the groundwaters is a problem with agricultural activities, dairies and other animal husbandry. Consideration has to be given not only to current discharges to surface waters that have high nitrate, but the potential for a nitrate front moving through the groundwater that will eventually reach surface waters. In order to understand whether this is an existing or future problem, it is necessary to have a good understanding of the groundwater hydrology and its characteristics between a potential source of constituents that can lead to elevated nitrate in groundwater (ammonia and organic nitrogen), such as a dairy=s wastewater pond or a municipal wastewater land disposal area, and the surface waters of the region.

With respect to agriculture, there is particular concern about the irrigation return flows (tailwater), which contain nutrients and organic substances which can exert an oxygen demand. These discharges occur during the summer when the DO depletion in the DWSC occurs. With respect to stormwater runoff from urban and rural areas, as discussed herein, much of the runoff-associated oxygen demand and nutrients occur at times of the year when oxygen depletion is typically not a problem in the DWSC. It is important to note, however, that, while dissolved oxygen depletions below the water quality objective of 5 mg/L for the winter-spring period are rare, they do occur. Ultimately, these oxygen depletions at those times will need to be managed as well.

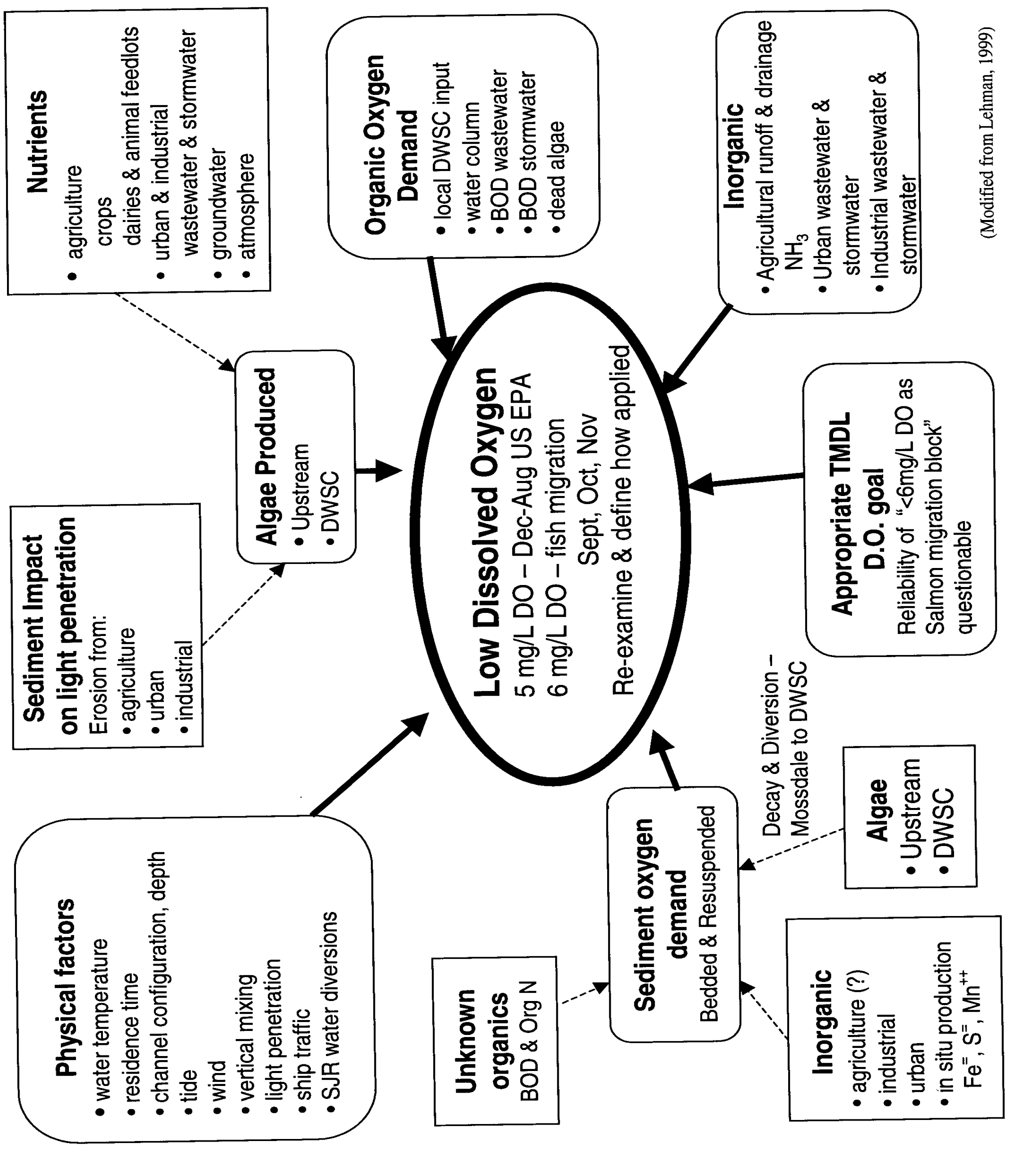
An area of particular concern is the highly concentrated wastes such as those associated with dairies and other animal husbandry activities, including feed lots, fowl and waterfowl farms, and other areas where large numbers of animals are present in a confined area, which results in an accumulation of animal manure. High concentrations of both nutrients and oxygen demand can occur from these activities. There is also concern about both NPDES-permitted and illegal discharges from such facilities.

There are considerable riparian lands within the SJR watershed, some of which, according to Kratzer and Shelton (1998) are discharging high concentrations of nitrate to the SJR tributaries. These areas will need to be critically evaluated for their potential significance as a source of constituents that impact DO depletion in the DWSC.

The use of SJR and its tributary water for agricultural irrigation removes nutrients from the SJR discharged from upstream sources. This situation can lead to reductions in the amount of upstream nitrate and phosphorus that is ultimately transported downstream to the mid- and lower SJR where it leads to the production of algae, either in the river, its tributaries or within the Deep Water Ship Channel. This is advantageous to the upstream dischargers and places a greater burden of responsibility on the agriculture and other dischargers who are discharging in lower parts of the SJR and DWSC watershed.

In summary, it is important in evaluating whether a particular type of source, such as an orchard, a dairy, a feed lot, urban stormwater drainage or a city=s wastewaters, discharged at a particular location within the SJR watershed contributes constituents that cause an oxygen demand problem in the DWSC. This requires an understanding of the amount of constituents discharged from a particular type of land use and the fate and transport of the constituents from the point of discharge to the DWSC. In the case of the nutrients, consideration has to be given to how much of the nutrients discharged from a particular location are converted into algae, which, in turn, reach the DWSC, where they die and become part of the oxygen demand at that location. These issues are discussed within this report.

Figure 11
Factors Influencing Dissolved Oxygen Depletion in the SJR DWSC



(Modified from Lehman, 1999)

Figure 11 presents a summary of the various factors that influence dissolved oxygen depletion within the Deep Water Ship Channel. The key issue of concern is avoiding violations of the water quality objective for dissolved oxygen, which is 5 mg/L during the period December through August, and 6 mg/L during September through November. There is controversy about the appropriateness of the 6 mg/L DO objective as a barrier to Chinook salmon migration. As discussed herein, the Department of Fish and Game studies (Hallock, *et al.*, 1970) which are stated to have served as a basis for developing that value were not sufficiently comprehensive to justify the conclusion that DO less than 6 mg/L is an effective barrier to Chinook salmon migration. The Hallock, *et al*., studies indicated that dissolved oxygen concentrations below 5 mg/L were a potential barrier to salmonid upstream migration. The SWRCB, however, adopted 6 mg/L as the DO water quality objective to protect against inhibition of salmonid upstream migration. Justification for the SWRCB increasing the DO concentration objective to protect against migration inhibition from 5 to 6 mg/L is not available at this time.

There are also significant questions about the significance of minor DO excursions below the WQO that can occur over the diel (night to day) algal photosynthetic microbial respiration cycle. However, as discussed herein, the present language of the CVRWQCB water quality objective apparently requires full compliance with this objective at all times and locations. This objective and condition establishes the TMDL goal for control of DO depletion in the DWSC.

Two areas of greatest concern are the organic oxygen demand and the nutrients which produce algae that, in turn, exert an oxygen demand upon their death and decay. The sources of organic oxygen demand include the BOD associated with domestic and industrial wastewaters, urban stormwater runoff and local runoff and discharges to the DWSC.

The aquatic plant nutrients (nitrogen and phosphorus) are derived from a variety of sources, including agricultural, crop land, dairies and animal feed lots, urban and industrial wastewater and stormwater runoff, groundwaters polluted by nitrate and the atmosphere. The algae of concern in DO depletion within the DWSC originate both upstream of the DWSC and from within the DWSC, including the Turning Basin. The category in Figure 11 of “Inorganics” is concerned with ammonia as an oxygen demand material through nitrification reactions, which can be derived from agricultural sources, domestic and industrial wastewaters, and urban and industrial stormwater runoff.

Another potential significant source of oxygen demand is the sediment oxygen demand associated with the constituents in sediments, both organic and inorganic, that react, either abiotically or biotically, with DO. The sediment oxygen demand is derived from organic particles that settle to the bottom. These can originate from agricultural releases, domestic and industrial wastewater sources and stormwater runoff. Sediment oxygen demand can also arise from the settling of algae to the sediments, where their death and decay leads to particles in the sediments that consume dissolved oxygen. As discussed herein, the biodegradable organics that are added to the sediments lead to a depletion of the oxygen within the sediments, which, in turn, leads to the production of iron and sulfur compounds that can react with dissolved oxygen abiotically. An area of particular concern is whether there is an appreciable particulate SOD that travels along the bottom as well as resuspended sediments in the water column in the SJR between Vernalis and the Deep Water Ship Channel that have not yet been adequately characterized. The resuspension of the bedded sediments in the DWSC can be due to tidal or river currents, organisms, stirring of the sediments, ship traffic, as well as biochemical reactions that occur in sediments that lead to gas formation, which stirs the sediments as the gas bubbles rise through the sediments.

The upper left box on Figure 11 lists many of the physical factors that influence how a particular load of oxygen-demanding materials to the DWSC or that develop within the DWSC influence the dissolved oxygen within the DWSC. Temperature influences the rates of various reactions, where, typically, a doubling of rate occurs with a 10 C increase. The SJR flow, which determines the residence time within the DWSC is an extremely important factor that determines how long the oxygen-demanding materials have to react with dissolved oxygen within the critical reach of the channel before they are diluted by the cross-channel flow of the Sacramento River near Disappointment Slough. The three to four foot tide that exists within the DWSC plays an important role in keeping the system well-mixed and in transporting materials within the DWSC. Mixing also occurs as a result of ship traffic.

One of the most significant factors in influencing DO within the DWSC is the diversions of SJR water above the DWSC. This, in turn, influences the residence time of the water and oxygen-demanding materials within the critical reach of the channel.

Channel configuration and, especially, depth, as influenced by the presence of the navigation channel, is of importance in influencing DO depletion. Light penetration, as influenced by the algae that develop, as well as erosional materials from the watershed, are also important in controlling the amount of algae that develop and their oxygen production.

One of the unquantified potentially significant sources of oxygen demand and algal nutrients is the agricultural drains from irrigated agriculture. Figure 12 is a presentation of the ag drains that at one time discharged to the SJR. Each of the boxes on this figure is an ag drain or was an ag drain that was and may still be active. There is need to update and quantify the oxygen demand and algal nutrients added to the SJR and its tributaries. The relative significance of each of the sources of oxygen demand in the SJR DWSC and their respective sources within the SJR watershed should be the primary focus of the water quality characteristic monitoring that should begin in summer 2000.

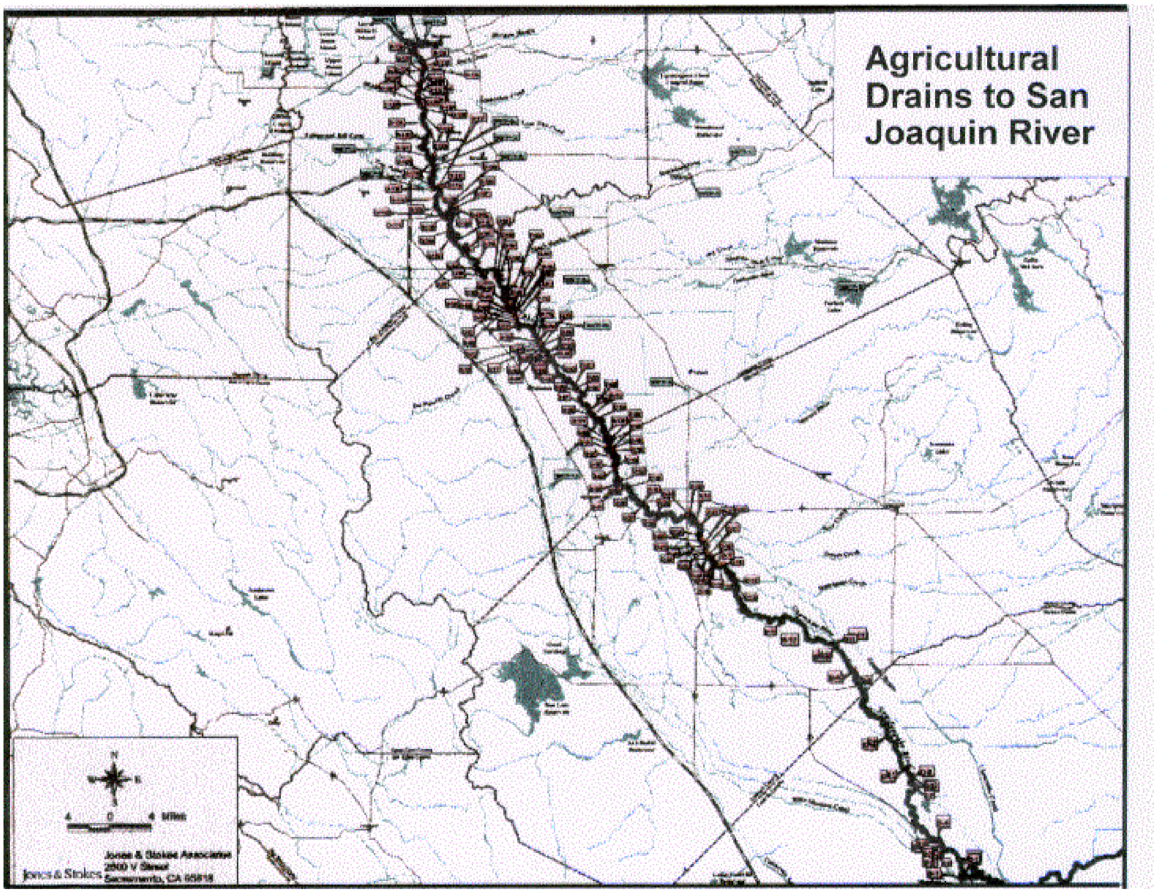
In summary, the substances that are contributing to oxygen depletion in the SJR DWSC below WQOs include:

- Domestic and industrial/commercial wastewaters' biochemical oxygen demand (BOD).
- Agricultural and urban stormwater runoff, irrigation return flows.
- Discharges of ammonia that, through nitrification reactions, lead to oxygen depletion.
- Nitrogen and phosphorus compounds that contribute to the growth of algae in the SJR and/or DWSC that lead to their death and decay in the SJR DWSC:

  High-nitrate groundwater discharges to the SJR.
- Sediment oxygen demand (SOD) that causes DO depletion in the water column overlying the sediments:

  The SOD can have organic, as well as inorganic, characteristics. It can also be associated with the bedded/deposited sediments, as well as the sediments stirred into the water column.

Figure 12



Factors Influencing Oxygen Depletion within the DWSC

There are a number of factors that influence how a given load of an oxygen-demanding material from a particular source impacts dissolved oxygen depletion within the DWSC. Some of the more important factors include:

- Flow of SJR through the DWSC:

  The flow of the SJR through the DWSC determines the amount of oxygen-demanding materials added to the DWSC and the residence time of the water within the DWSC.
- Depth of the DWSC:

  Since the SJR above the DWSC does not experience low DO problems, it appears that the construction of the Deep Water Ship Channel in the SJR below Stockton was a cause, if not one of the primary causes, of the dissolved oxygen depletion problems that are occurring in the SJR DWSC.
- Ship traffic, which stirs sediments into the water column, may also exert a greater oxygen demand than would occur without the ship traffic.
- Diversions of water upstream of the DWSC that divert not only flow, but also oxygen-demanding materials out of the SJR.
- Particulate materials that reduce light penetration within the SJR and DWSC:

> Particulate materials from the SJR watershed can slow the growth of algae. Also, particulate materials can reduce light penetration for an established algal population and lead to their more rapid death than would occur naturally.

As part of the SJR DO TMDL study program, consideration should be given to gaining additional insight into the role of these factors and their potential control influences on DO depletion within the SJR DWSC.

Summer/Fall 1999 DWSC Conditions

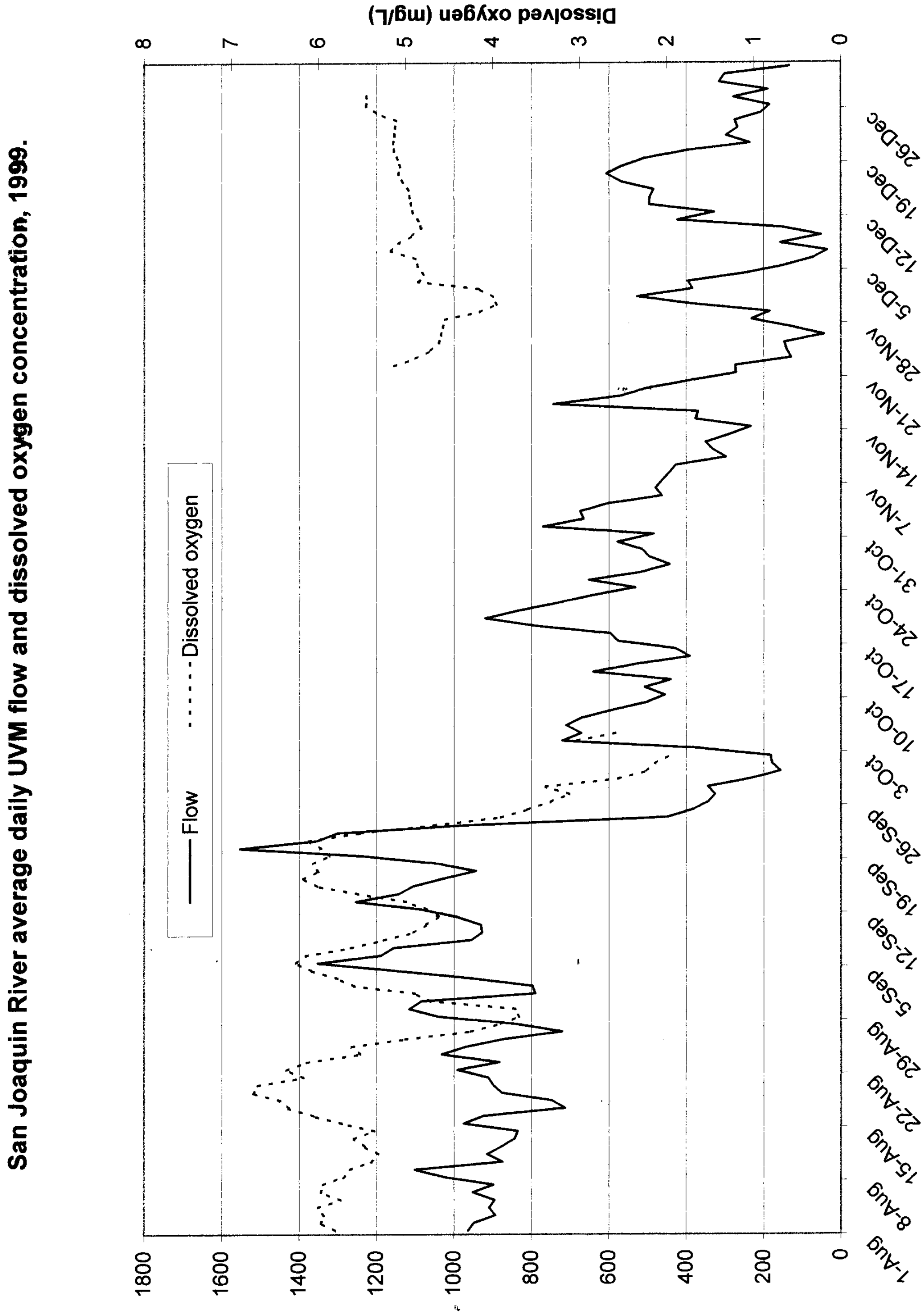
One of the objectives of the SJR TAC summer/fall 1999 SJR DWSC studies was to examine the oxygen demand loads and the associated dissolved oxygen concentrations that occurred in the SJR DWSC during the summer of 1999. August and September 1999 had a different SJR flow regime than occurred in 1991. The 1991 conditions served as the basis for the development and tuning of the Stockton SJR DO Model. According to Jones and Stokes (1998), during 1991, the flows of the San Joaquin River into the DWSC during the summer/early fall period were on the order of several hundred cfs. In addition, there were reverse flows during this time from the DWSC upstream to Old River. 1991 was a severe drought - low SJR flow year. Figure 13 presents the 1998 and 1999 flows of the San Joaquin River into the DWSC based on the USGS ultrasound velocity meter (UVM) flow monitoring just upstream of where the SJR enters the DWSC.

As shown, the flows during August through September were on the order of 800 to 1,000 cfs. These flows are higher than those that were encountered in the early 1990s. However, at the end of September 1999, the flows in the SJR just upstream of where it enters the DWSC decreased to about 150 cfs. The flow of the SJR at Vernalis was about 1,800 to 2,000 cfs and did not change during this time. While not confirmed, it is presumed that this decrease in SJR flow into the DWSC during late September was due to an export of SJR water through Old River to the export pumps. The net result of this situation is that summer/fall 1999 experienced two significantly different flow regimes for SJR water entering the DWSC. During the 1999 summer through September, there was appreciable SJR water and its associated oxygen demand load derived primarily from upstream of Vernalis in the form of phytoplankton, that entered the DWSC.

Beginning at the end of September through October, November, and part of December 1999, the SJR flow into the DWSC at times became low, apparently due to upstream diversions. These "diversions" reduced the oxygen demand load to the DWSC from the SJR watershed above Vernalis. Prior to the end of September, a substantial part of this load was entering the DWSC.

Other than diversion into Old River, the fate of the BOD found in the SJR between Vernalis and the DWSC is poorly understood. Vernalis is located about 30 miles upstream of the DWSC. Some studies seem to show decreases, others show an increase in BOD. The problem is apparently related to inadequate sampling of the SJR to reliably assess the BOD loads at any time and location. According to Jones and Stokes (1998) the travel time between Vernalis and the DWSC is about 3 days at an SJR flow into the DWSC of 500 cfs. At 1,000 cfs, the travel

Figure 13


San Joaquin River average daily UVM flow and dissolved oxygen concentration, 1999.

time is reduced to 1.5 days. Based on these travel times, major changes in SJR BOD load increases due to algal growth or decreases due to death would not likely greatly change the non-diverted SJR Vernalis BOD loads that enter the DWSC.

An issue that has not been addressed is the impact of the oxygen demand that is present in the SJR at Vernalis that is diverted into Old River on the oxygen demand resources of the South Delta. During times when substantial parts of the SJR flow at Vernalis is diverted into Old River, there are substantial loads of oxygen-demanding materials diverted into the South Delta. These loads could cause low DO problems in this area. This is a topic area that needs attention.

Reliability of UVM Flow Measurements (prepared by C. Foe)

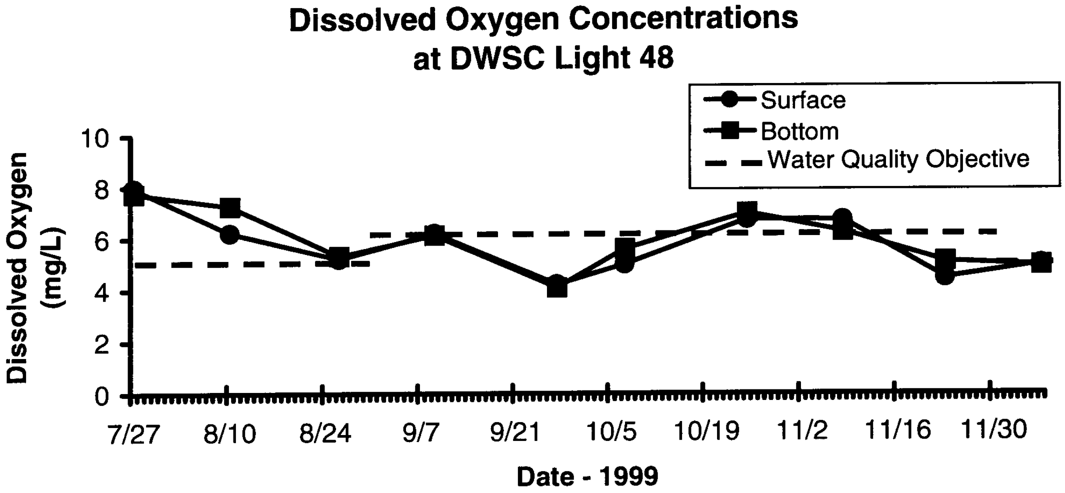
No estimate of the accuracy of the UVM flow device at Stockton has been made. However, the accuracy of a similar device at Three Mile Slough in the western Delta was determined (Simpson and Bland, 1999). The accuracy of the net daily discharge measurements at Three Mile Slough was estimated to be about 0.5 percent of peak tidal flow. R. Oltmann (personal communication) estimated the maximum tidal flow at Stockton to be about 4,000 cfs and suggested the accuracy of the Stockton UVM device to be about 0.5-1.0 percent of maximum tidal flow. Therefore, the best estimate of the accuracy of the net daily discharge measurements at Stockton is believed to be on the order of plus/minus 20 to 40 cfs.

Analysis of flow between July and September 1999 (Appendix D) demonstrates that over 90 percent of the net daily flows were greater than 400 cfs. This suggests a maximum error rate for flow at Stockton of plus/minus 5 to 10 percent. In contrast, 20 percent of the daily flows between October and December were less than 200 cfs, indicating a possible error rate of 10 to 20 percent. Finally, it is noted that the lowest flows coincided with the lowest oxygen concentrations in September and October (Appendix D), emphasizing the importance of flow in determining oxygen concentrations. It is recommended that a sensitivity analysis be performed with the Chen SJR DO model to determine the sensitivity of in-stream oxygen concentrations to variations in flow during negative and low flow conditions.

Dissolved Oxygen Depletion in the DWSC

Lehman (2000) provided a preliminary draft summary report covering the studies that DWR conducted under her supervision during August and September 1999 on selected water quality characteristics of the SJR DWSC. Detailed monitoring was conducted of selected parameters of the DWSC at 18 stations from the Turning Basin to Prisoners Point on August 10 and 26, and September 9 and 27, 1999. Further, a number of monitoring runs of the DWSC were conducted by DWR beginning on July 27, 1999, through December 7, 1999. The data from these studies are presented in Figure 14. A map showing the location of the sampling stations is presented in Figure 4.

Figure 14
DWSC DO Data Summer/Fall 1999
Adapted from DWR Lehman (2000)



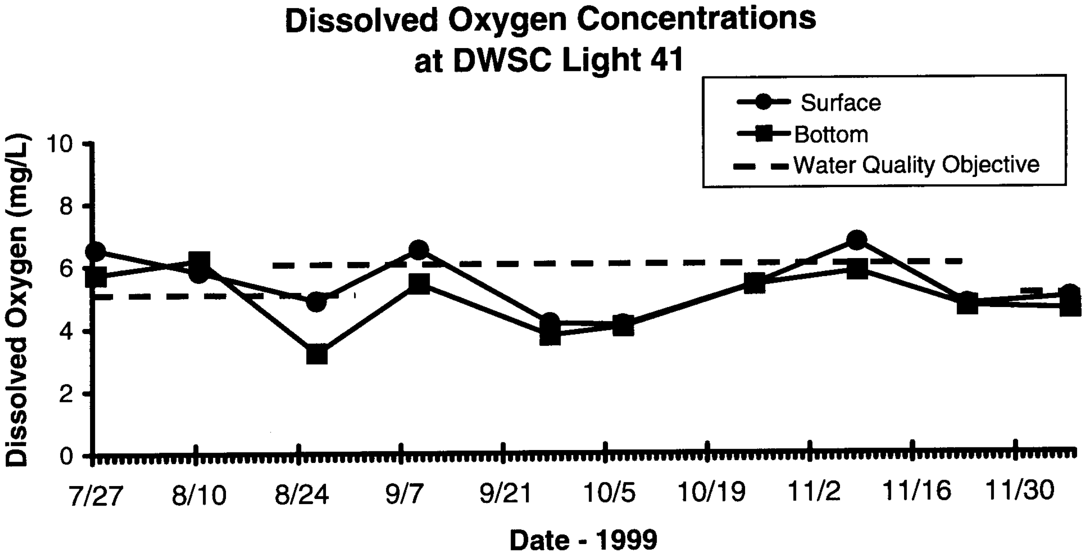
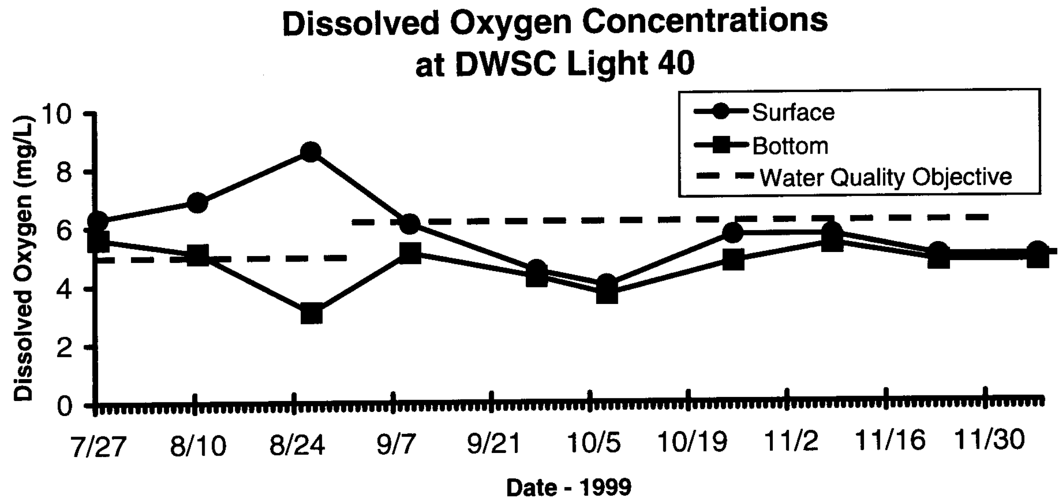


Figure 14 (continued)



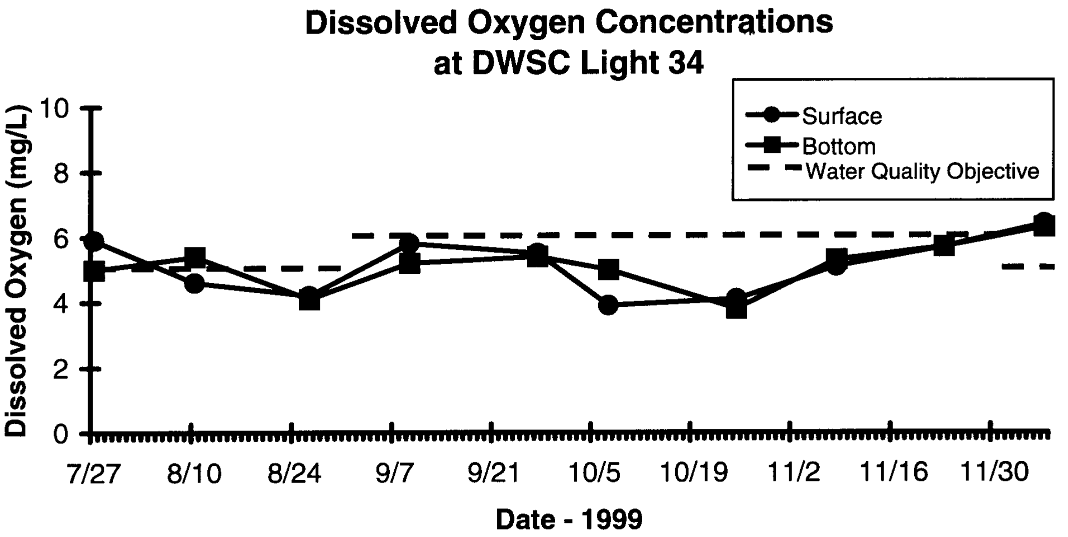
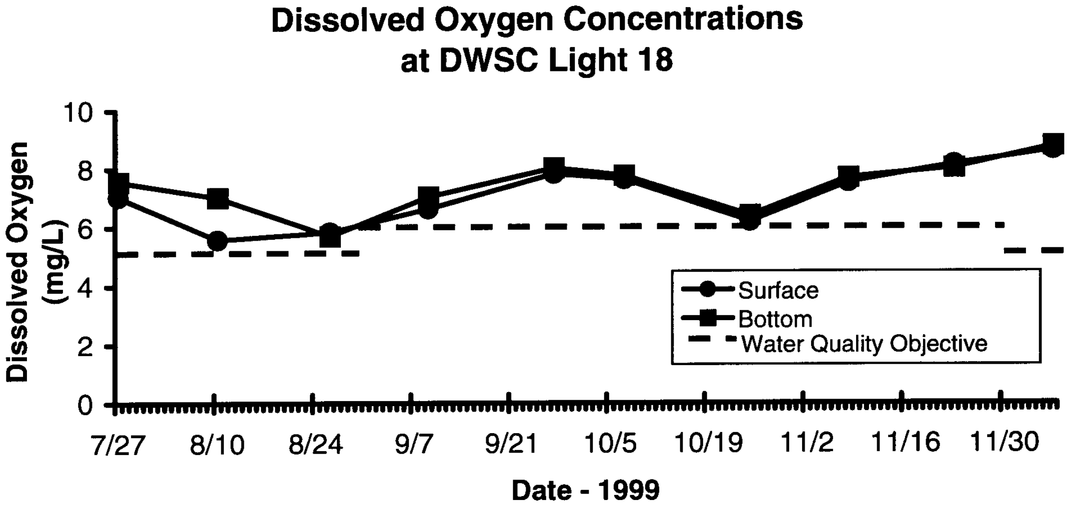


Figure 14 (continued)



The DWR Lehman DO monitoring data show that there were substantial periods of time when the dissolved oxygen in the DWSC was below the WQO of 6 mg/L during September-October-November and 5 mg/L during December and August in both surface and bottom waters at various locations in the Channel during the summer-fall 1999. The data for DO concentrations at Light 18, which is about halfway between Turner Cut and Disappointment Slough, showed no exceedances of a DO WQO. This means that the DO depletion below a WQO in the summer-fall 1999 was restricted to about upstream of Turner Cut.

Near Light 34, which is upstream of Turner Cut near Fourteen Mile Slough, exceedances of the WQOs in surface and bottom waters occurred in August through November. Near Light 40, which is about halfway between the downstream end of Rough and Ready Island-Calaveras River and Fourteen Mile Slough, DO depletions occurred in surface and bottom waters in September-October-November 1999. Exceedances occurred at this location (Light 40) only in bottom waters in August and December 1999. At Light 41, which is near the downstream end of Rough and Ready Island and near the location of the DWR continuous surface water monitoring station, exceedances of the WQO occurred in surface and bottom waters in August through November. They also occurred in the bottom waters in December at this location. At Light 48, which is at Channel Point where the SJR enters the DWSC, DO depletions below the WQO occurred in September-October-November in both surface and bottom waters, but only in bottom waters during December 1999.

Examination of the Lehman (2000) data presented in Figure 14 with respect to the occurrence of DO depletions that are more than 1 mg/L below the applicable WQO shows that at Light 34 during October there was DO depletion below the WQO in the surface waters only, while in November, DO depletions more than 1 mg/L below the WQO occurred in both the surface and bottom waters. At Light 40, DO depletions greater than 1 mg/L below the WQO occurred in surface and bottom waters in September and October, and only in bottom waters in

November. At Light 48, DO depletions more than 1 mg/L below the WQO occurred in surface and bottom waters in September. They only occurred in surface waters in November, and in bottom waters in December.

It is evident that the Channel near Light 40, i.e., the downstream end of Rough and Ready Island, is typically the area of the main Channel (excluding the Turning Basin) where DO depletions of greater than 1 mg/L below a WQO frequently occur. It is also clear from these data that surface water monitoring only at the DWR continuous monitoring station does not necessarily reflect the severity of DO depletion near the bottom at this location. For example, on August 26, 1999, the surface water DO near Light 40 was found to be 8.6 mg/L. The mean water column DO was reported as 7 mg/L. However, the near bottom water DO was 3.1 mg/L. That pattern was not found consistently at this location or at any other location.

It is of interest to find that, at times, the difference in the DO between the bottom waters and surface waters was on the order of 1 mg/L higher DO concentrations in the bottom waters. There were about 20 measurements (out of a total of 80) from the end of July through early December 1999, where the DO in the bottom waters was recorded to be higher than that in the surface waters at a particular location and date. This situation may be related to the diel changes in DO in the surface waters associated with the algal photosynthesis and microbial respiration that occur in these waters, which cause the DO at certain times in the day to be lower than the average for the water column. There were a number of situations reported, such as on November 8, 1999, where the surface water DO concentrations were less than the mean water column DO concentrations. Examination of the times of day when many of these measurements were taken shows that they were not taken in the early morning, when the greatest diel DO depletion would be expected to occur. The depletion of DO in the surface waters at midday that exceeds the DO depletion in the bottom waters is an area that needs further investigation.

The concentrations of chlorophyll *a* found in the DWSC generally decreased on any particular sampling date from about 20 µg/L near the Turning Basin to about 5 µg/L below Turner Cut, during August 1999. In September the upstream chlorophyll *a* concentrations just downstream of the Turning Basin were on the order of 5 to 10 µg/L. These concentrations of planktonic algal chlorophyll support the conclusion that there would be significant diel variations in the DO in the surface waters of the DWSC. This is what was found in the DWR continuous monitoring of the surface waters near Rough and Ready Island, where diel changes in DO were typically on the order of 2 mg/L with some values exceeding 3 mg/L (Jones and Stokes, 2000).

Lehman also presented data for the mean water column DO at Light 40. These data show that there can be significant differences between the average water column concentration of DO and the DO measured in either surface or bottom waters. This issue will become extremely important in establishing the TMDL goal; i.e., will this goal be, as currently required, the worst-case, lowest DO at any time and location within the DWSC, or can it be an average DO in the water column. A considerably lower TMDL will likely be required if the absolute minimum (worst-case) DO depletion is used, compared to an average DO depletion.

Upstream of DWSC Oxygen Demand Loads

King (2000) presented a comprehensive report on the amount of oxygen demand (BOD) that was present in the San Joaquin River at Vernalis during August and September 1999. He also estimated how much of the oxygen demand present at Vernalis entered the DWSC. Further, information is provided on the amount of oxygen demand contributed to the SJR by French Camp Slough. This slough discharges to the SJR about three miles upstream of the DWSC and is one of the "local" sources of oxygen demand for the DWSC.

King reported that the average monthly BOD_5 added to the DWSC that originated from sources upstream of Vernalis was about 15,000 lbs/day during August and most of September 1999. During this time, the flow of the SJR into the DWSC, based on UVM measurements, ranged from about 800 to about 1,000 cfs. On September 30, the UVM-measured flow into the DWSC decreased to about 150 cfs. As discussed herein, this decrease appears to be related to upstream diversions of SJR water at Old River.

King (2000) reported a correlation between chlorophyll *a* and BOD_5 in the SJR at Vernalis. At the beginning of August 1999, the chlorophyll *a* in the SJR at Vernalis was about 45 µg/L and the BOD_5 was about 4.8 mg/L. During August and September 1999, the chlorophyll *a* in the SJR at Vernalis was typically about 30 to 40 µg/L. Through October, the concentrations of chlorophyll *a* decreased to about 8 µg/L. In early November, the BOD_5 was about 2 mg/L.

Based on the data obtained using October 1999 data for BOD and flows, French Camp Slough contributed about 460 lbs/day of BOD_5. This BOD load was associated with an estimated flow of 30 to 60 cfs. Under the dominant flow conditions for August and September, French Camp Slough appears to be contributing a small BOD load to the DWSC. However, under the SJR low flow conditions that occurred in late September, it appears that French Camp Slough could be a more significant source of BOD for the DWSC.

King (2000) conducted a 30-day BOD test on a sample of SJR water taken at Vernalis on October 7, 1999. At 30 days, there was still appreciable oxygen consumption occurring within this sample. To the extent that this sample is representative, it appears that the oxygen demand of the BOD (algae, detritus, some of the DOC and the organic nitrogen plus ammonia) at Vernalis is exerted over a much longer period of time than typically occurs with domestic wastewater BOD. Normally, approximately 70 percent of domestic wastewater BOD is exerted within 5 days. For the October 7 SJR Vernalis sample, the 5-day BOD value was about 30 percent of the 30-day BOD. These issues are discussed further in a subsequent section of this report.

Sediment Oxygen Demand and BOD Rate Constants

Litton (2000) conducted a study of SJR Deep Water Ship Channel water and sediments to estimate the sediment oxygen demand and the BOD rate constants for oxygen-demanding materials in the Deep Water Ship Channel, City of Stockton wastewater effluent and the SJR at Mossdale. Studies on the DO profiles within the DWSC at various locations indicated that, under some conditions, there is a depletion of oxygen near the sediment water interface, apparently due to the oxygen demand of the sediments. An attempt to use this depletion as an assessment of the sediment oxygen demand showed that two SOD measurements performed on August 26, 1999, yielded an SOD of 3 $g/m^2/d$ for one and a negative value for the other. Basically, while this approach can be used under certain conditions in the Deep Water Ship Channel, because of the strong tidal influence and the variable composition of the water, it may not be a viable technique for estimating oxygen demand.

Chen and Tsai (2000) estimated that the sediment oxygen demand in the DWSC was about 6,000 lbs/day. This SOD value includes not only the true oxygen demand associated with sediments, but also any oxygen demand added from local sources. Chen and Tsai (2000) indicated that they used an SOD coefficient of 1.3 to 2.6 g O_2/m^2/day. As used in this model this value includes not only the true SOD but also local oxygen demand sources. US EPA (1971) conducted dome chamber measurements of SOD in the DWSC and reported that the SOD found was on the order of 1 $g/m^2/d$. Sediment oxygen demand of about 1 to 2 $g/m^2/d$ is typical of SOD values found at other locations (Hatcher, 1986).

Litton (2000) also made measurements of DWSC particles that were trapped in a suspended sediment trap to estimate the oxygen demand of these sediments. He found an initial rate of oxygen uptake over a period of an hour or so that was considered to be due to abiotic oxygen demand on the order of 0.3 mg of oxygen per gram dry weight of sediments. The 5-day oxygen demand for these same sediments was on the order of 2 mg DO per gram of sediment dry weight.

Litton found the BOD first order rate constants (base e) for the San Joaquin River samples and the City of Stockton wastewater treatment plant effluent samples to be on the order of 0.1 per day. BOD rate constants on the order of 0.1 per day are typical of what is normally found for river water and wastewater effluents.

Litton investigated the ratio of the ultimate BOD (BOD_u) to the 5-day BOD (BOD_5). This ratio was about 2.5, indicating that only about 40 percent of the oxygen demand had been exerted after five days. The remainder was exerted over a period of about 30 days. This is somewhat atypical for domestic wastewater effluents, where normally about 70 percent of the oxygen demand is exerted in five days, and the ultimate oxygen demand is assessed within about 20 days. It is important to note that the City of Stockton's domestic wastewater effluent is not typical wastewater effluent, since it has been through an oxidation pond, where there is appreciable algal growth. This wastewater effluent, therefore, may be more like river water, where large algal populations exist, compared to typical domestic wastewaters.

McCarty (1969) conducted a study devoted to evaluating algal decomposition in the San Joaquin River Deep Water Ship Channel. McCarty indicated in his studies that the oxygen depletion that occurs within the ship channel appeared to be the result primarily of decomposition of algae. At that time, the algae were derived from both SJR upstream of Vernalis sources and the City of Stockton oxidation pond. McCarty evaluated the 100-day decomposition of organics in selected SJR samples. He found that the ultimate BOD, as measured by oxygen consumption, at 100 days was about 4 to 5 times the 5-day BOD. He also found that the first order decay constants were about a factor of 10 less than normal domestic wastewaters. He also reported that an appreciable part of the oxygen demand measured in his long-term incubation studies was due to nitrification.

Ball, of the DWR (personal communication, 2000) indicated that he conducted long-term BOD studies on waters taken from various Delta channels in the 1970s. He also found that the rate of oxygen exertion in the BOD test for these waters typically took place over 40 days. It can be concluded, therefore, since King (2000), Litton (2000), McCarty (1969) and Ball all have independently found that the relationship between 5-day BOD and ultimate BOD is on the order of 2.5 to 4 for SJR DWSC and Delta waters, that a factor of at least 2.5 should be used to convert BOD_5 to BOD_u for these waters. The higher values (near 4) represent conditions where there is appreciable nitrification occurring within the BOD test. This would be expected to take a longer period of time and have a greater oxygen consumption than carbonaceous BOD.

City of Stockton Wastewater Flow and Oxygen Demand Loads

Jones and Stokes (2000) presented a data compilation on the average characteristics and loads of the City of Stockton domestic wastewater discharges to the SJR during August through October 1999. The total BOD_5 load to the SJR during August and September averaged about 1,800 lbs/day, with a maximum of 4,300 lbs/day and a minimum of 500 lbs/day. During October, similar values were obtained for the average total BOD; however, a greater percentage of this BOD was due to ammonia discharged by the City's wastewater ponds. Beginning in August through the end of October, there was an increase in the ammonia concentrations and ammonia load to the SJR. As discussed herein, in November and early December 1999, the ammonia concentrations within the DWSC near where the SJR enters the DWSC were on the order of 3 to 4 mg/L N. The apparent source for this ammonia was the City of Stockton wastewater pond discharges. Examination of the total BOD_5 data compared to the$CBOD_5$ values shows that about 40 percent of the total BOD_5 was due to nitrification in the BOD_5 test.

The City of Stockton also conducted an expanded SJR monitoring program during August, September and October 1999. The mean daily dissolved oxygen at the DWR Burns Cutoff Rough and Ready Island sampling location, which is just downstream of where the SJR enters the DWSC, decreased during late August to less than the 5 mg/L DO objective. A low value occurred on August 29 of about 3.8 mg/L at this location. During September 1999, most of the DO readings at the Burns Cutoff sampling station were less than the 6 mg/L DO objective, with some values below 5 mg/L. Beginning in late September, the dissolved oxygen in the DWSC at the Burns Cutoff monitoring station decreased to about 2.5 mg/L.

The daily diel changes in DO concentrations measured at the Burns Cutoff location were about ±1 mg/L through mid-August 1999. During the period August 15 through 26 a daily change in DO of about 4 mg/L was experienced. There is, therefore, appreciable diel DO change related to algal photosynthesis and microorganism (algae and bacteria) respiration in some parts of the surface waters of the DWSC.

The City of Stockton monitoring of the SJR DWSC on August 24, 1999, showed mean concentrations of dissolved oxygen throughout the reach from where SJR enters the DWSC to just above Turner Cut, of less than 5 mg/L, with some concentrations less than 3 mg/L. The extreme low value occurred opposite Rough and Ready Island. Similarly, on August 31, the DO values between the Turning Basin and Turner Cut were all less than 5 mg/L. On September 7, 1999, the mean DO values for this reach of the DWSC were less than the 6 mg/L water quality objective, with some values less than 5.

The September 28 monitoring of the DWSC showed a mean dissolved oxygen concentration off of Rough and Ready Island of about 3 mg/L. It is evident from this dataset that there was appreciable dissolved oxygen depletion below the water quality objective through August and September in the DWSC upstream of Turner Cut.

The City of Stockton’s monitoring of the DWSC (Jones and Stokes, 2000) included measuring dissolved oxygen as a function of depth at the various sampling locations. These data showed that at some sampling stations during August and September 1999, there was an appreciable change in dissolved oxygen concentrations with depth. Many of the DWSC sampling stations showed elevated DO near the surface and significantly depressed DO near the bottom.

From an overall perspective, the City of Stockton DWSC monitoring data show that during August, September, and October there was appreciable dissolved oxygen depletion below the water quality objective throughout the DWSC from the Turning Basin to Turner Cut. The magnitude of the DO depletion was, as expected, greater near the bottom of the DWSC.

Modeling Dissolved Oxygen Depletion in the DWSC during August and September 1999

Chen and Tsai (2000) conducted a number of runs with the Stockton SJR DO Model to examine how well this model, that was tuned to 1991 oxygen demand load and flow conditions, predicted dissolved oxygen concentrations in the DWSC based on 1999 oxygen demand load and SJR flow conditions. The model was run with its original coefficients except for minor adjustments and an adjustment in the model that enabled the upstream of Vernalis oxygen demand load to be considered as a separate load. A comparison was made between the calculated modeling results and those observed in the DWR (Lehman, 2000) and City of Stockton (Jones and Stokes, 2000) DWSC data. The model, without retuning for 1999 conditions, generally predicted the average dissolved oxygen concentrations found in the DWSC during August and September 1999. The data presented by Chen and Tsai (2000) for measured DO do not show the diel changes that occur each day in the surface waters of the DWSC. Also the DO modeling results do not show the DO depletion that occurs near the sediment water interface.

One of the areas of concern with respect to the lack of agreement between the model’s predicted results for dissolved oxygen at any particular time and location and the measured results, is the situation where the measured DO is considerably less than that predicted. There are a number of situations of this type, where there was an apparent “crash” in DO concentrations that is not accounted for by the model. An example of this situation occurred in August 1999, where the DO was low compared to predicted values. It was noted by Litton (personal communication) that, at that time, the DWSC was highly turbid due to inorganic turbidity. It appears plausible that this inorganic turbidity, possibly derived from erosional sources, reduced the amount of light available to algae, with the result that there was a greater die-off of algae in the darker water than normally occurs. This could be an important reason for the lack of agreement between the model and the field data.

One of the primary uses of the Stockton SJR DO Model is to estimate the relative significance of oxygen demand loads from various sources. Estimating oxygen demand loads for the SJR at Vernalis, as was done by King (2000), is relatively straightforward, since the stream gage flow values at Vernalis can be used to convert the measured BOD concentrations into BOD loads. At Mossdale, the San Joaquin River system is freshwater tidal, where the total tidal flow past a particular point can readily exceed the net downstream flow of the SJR. Under these conditions, it is necessary to have a reliable flow model that considers the influence of tide on the transport of oxygen demand into the DWSC and downstream within the DWSC.

Chen and Tsai (2000) have estimated, based on the 1999 City of Stockton wastewater pond discharge characteristics, that during August and September 1999, the City of Stockton was discharging about 1,245 lbs/day of CBOD and 1,882 lbs/day of NH_3-N. A review of the data presented by Jones and Stokes (2000) and the calculated information by Chen and Tsai (2000) for the CBOD loadings shows that the Chen and Tsai value is slightly less than the Jones and Stokes reported value. Jones and Stokes reported a mean loading of CBOD during August and September ranging from 1,310 to 1,417 lbs/day, respectively. The Chen and Tsai CBOD loading value was reported as 1,245 lbs/day.

While Jones and Stokes report an ammonia nitrogen loading during August and September to the SJR from the wastewater treatment plant ponds of 1,128 and 2,928 lbs/day, respectively, Chen and Tsai estimated an average value of 1,882 lbs/day.

Chen and Tsai (2000) also estimated the amount of BOD that would be transported into the DWSC from the DWSC downstream boundary as a function of SJR net flow through the DWSC and downstream oxygen demand concentration.. An SJR flow of 1,000 cfs into the DWSC and an estimated oxygen demand of the downstream water of about 10 mg/L, results in an estimated 7,300 lbs/day of oxygen demand import into the DWSC. At this time there is no information on the oxygen demand concentrations in the downstream waters that could be a source of oxygen demand for the DWSC and, therefore, it is not possible to estimate the amount of oxygen demand that is imported upstream into the DWSC from the Sacramento River system. It is believed, however, that this import represents an insignificant load to the DWSC compared to upstream of Vernalis SJR and City of Stockton loads.

As discussed herein, the Sacramento River has a major influence on the concentrations of oxygen-demanding and other constituents in the DWSC beginning between Turner Cut and Disappointment Slough. This situation is the result of the State and Federal Water Projects' export pumps drawing the Sacramento River water across the SJR DWSC. The low-BOD Sacramento River water mixes with and, therefore, dilutes the San Joaquin River water in the reach of the DWSC downstream of Turner Cut. This results in limiting the extent of oxygen depletion in the DWSC to about Disappointment Slough.

The influence of the DWSC (ship) Turning Basin on DWSC DO resources is of concern. Oxygen demand present in the DWSC could be transported into the Turning Basin by tidal action and be exerted there. Of particular concern is the transport of particulate oxygen demand in the form of detritus and algae that would settle to the sediments and exert SOD that would be transported out of the Turning Basin into the DWSC. Also, algal growth in the Turning Basin could add to the DWSC oxygen demand load. Chen and Tsai (2000) estimated that there was a net flux of algae from the SJR DWSC Turning Basin into the DWSC of about 4 lbs/day. They indicate this value is likely low.

Box Model Calculations of Oxygen Demand Sources/Sinks and DO Sources

In order to assess the relative significance of upstream-of-Vernalis oxygen demand loads in the SJR that ultimately reached the DWSC during August and September 1999, it is necessary to compare the 15,000 lbs/day BOD_5 estimate developed by King (2000) to the City of Stockton BOD loads from its wastewater treatment plant ponds and other local (DWSC watershed below Vernalis) oxygen demand sources/sinks.

Figures 15, 16, 18, 19 and 20 present a summary of the Box Model calculations of oxygen demand sources, sinks, and DO sources for the DWSC during the months of August, September, and October 1999, respectively. Table 3 presents the background calculations for the values presented in these figures.

August 1999. Based on the August 1999 SJR and DWSC monitoring, it is found that the total oxygen demand (BOD_u) present in the SJR at Vernalis that reaches the DWSC is about 61,000 lbs/day. This value is based on a UVM-measured average SJR flow into the DWSC of 880 cfs. 40,000 lbs/day of the 61,000 is derived from measured BOD at Vernalis. Another almost 20,000 lbs/day of oxygen demand enters the DWSC during August from ammonia and total Kjeldahl nitrogen present in SJR water at Vernalis during August. This value has been corrected for the amount of nitrification that was found in the BOD_5 test on SJR water at Vernalis. About 50 percent of the total BOD_5 was apparently derived from nitrification. Since the SJR water at Vernalis is not saturated with oxygen, it has an oxygen deficit of 2,850 lbs/day below saturation.

During August, the total estimated City of Stockton wastewater oxygen demand load was about 5,600 lbs/day. About 3,000 lbs/day of this amount was due to CBOD, with the remainder, about 2,400 lbs/day, due to NBOD. This value has been corrected for the nitrification in the BOD_5 test, which amounted to about 40 percent of the total BOD_5. The oxygen deficit on the City of Stockton wastewater ponds discharged during August was about 230 lbs/day.

During August and September, Chen and Tsai (2000) estimated that the dissolved oxygen added by reaeration was about 5,500 lbs/day. They also estimated that the sediment oxygen demand was about 6,000 lbs/day. These same values have been used to estimate the amounts of SOD and reaeration that occurred in September and October 1999. The oxygen added during August by the COE mechanical aeration was estimated to be its potential of 2,000 lbs/day. This approach may overestimate the amount of DO added by the COE aerator during August, since the aerator was not operating full-time during August.

Figure 15

Box Model of Estimated DO Sources/Sinks in SJR DWSC August 1999

(values in lbs/day of oxygen demand BOD_u & full nitrification)

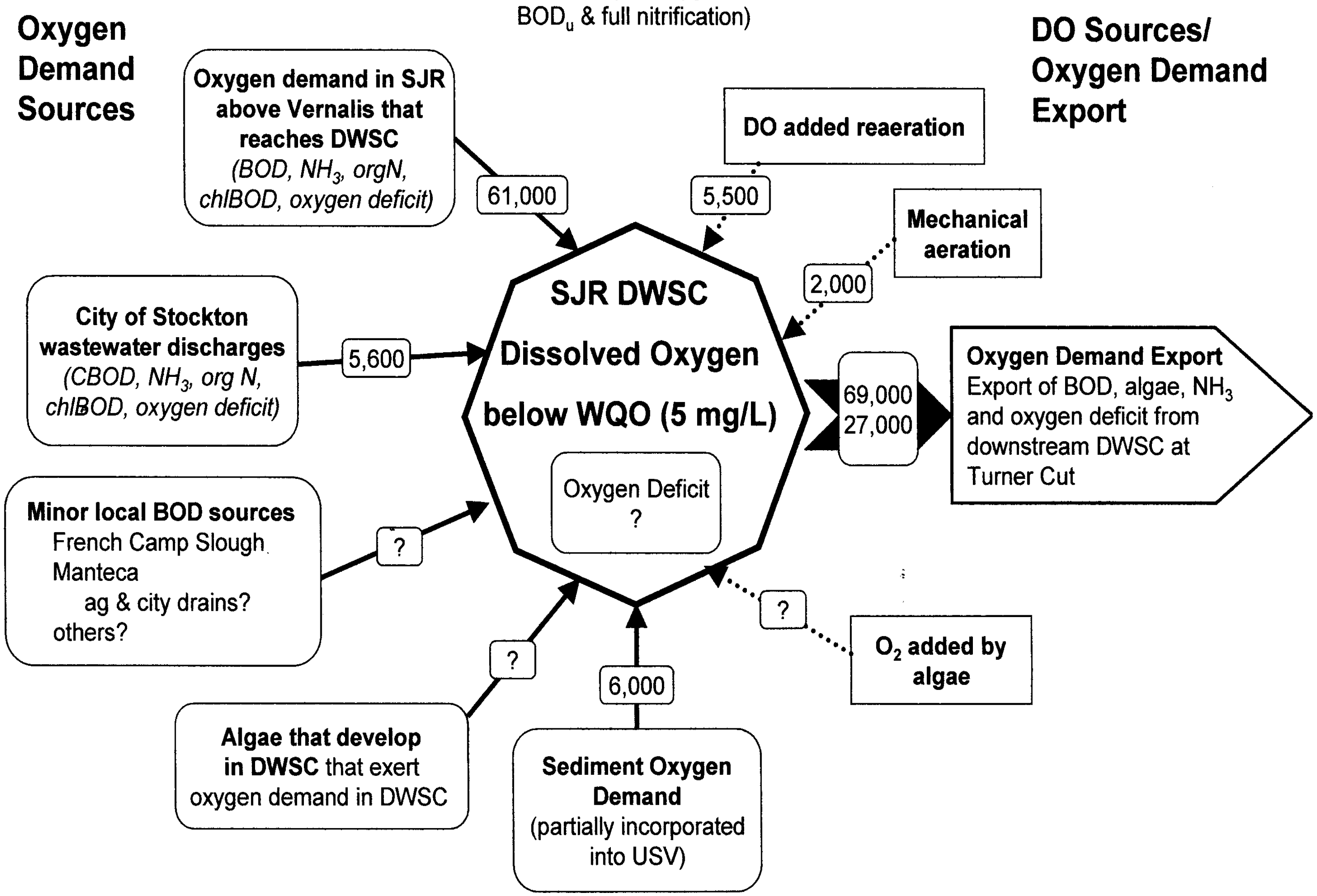
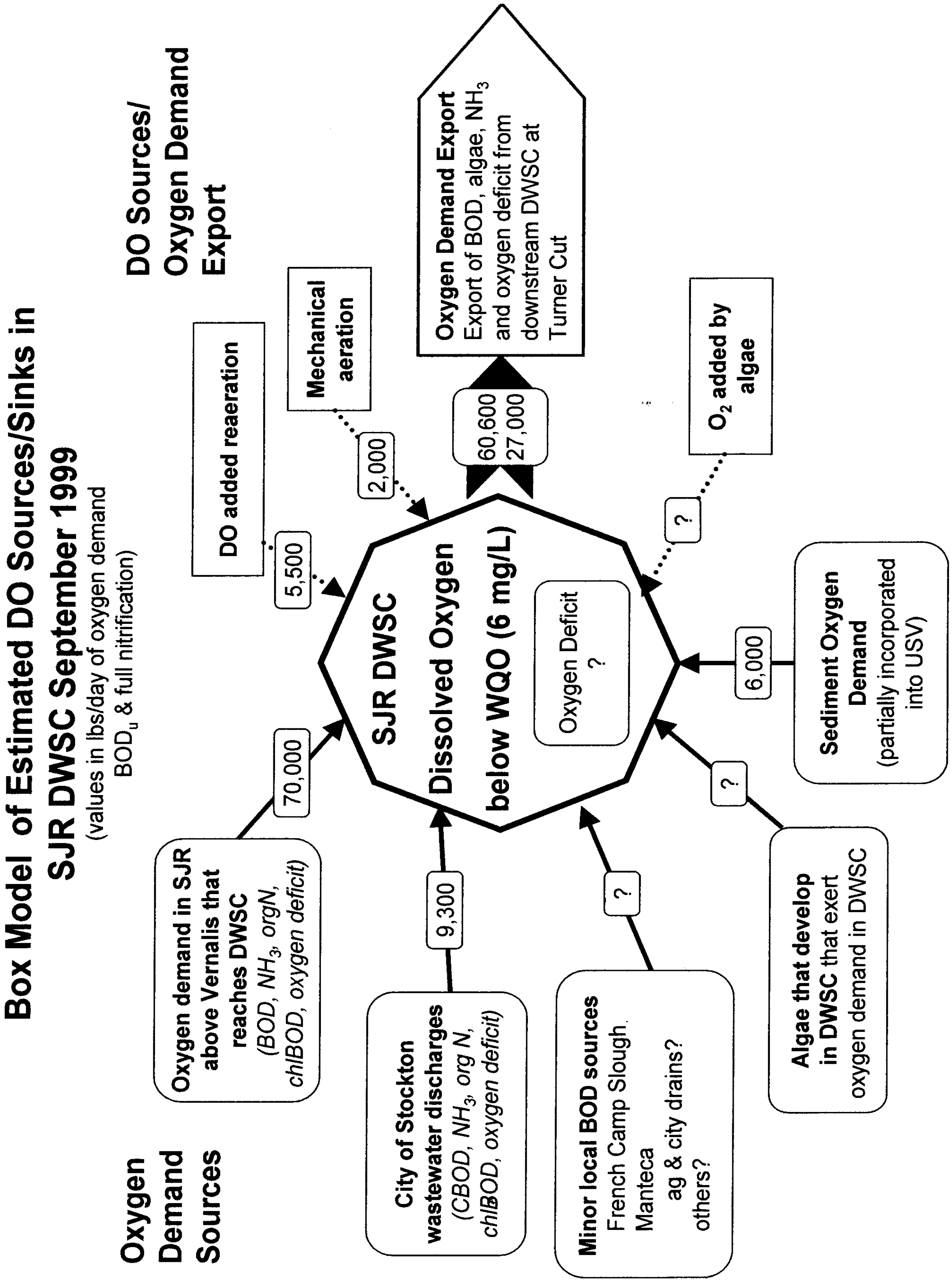


Figure 16


Box Model of Estimated DO Sources/Sinks in SJR DWSC September 1999
(values in lbs/day of oxygen demand BOD$_u$ & full nitrification)
Oxygen Demand Sources
DO Sources/ Oxygen Demand Export
Oxygen demand in SJR above Vernalis that reaches DWSC (BOD, NH$_3$, orgN, chlBOD, oxygen deficit)
70,000
City of Stockton wastewater discharges (CBOD, NH$_3$, org N, chlBOD, oxygen deficit)
9,300
Minor local BOD sources French Camp Slough. Manteca ag & city drains? others?
?
Algae that develop in DWSC that exert oxygen demand in DWSC
?
Sediment Oxygen Demand (partially incorporated into USV)
6,000
SJR DWSC Dissolved Oxygen below WQO (6 mg/L)
Oxygen Deficit ?
DO added reaeration
5,500
Mechanical aeration
2,000
Oxygen Demand Export Export of BOD, algae, NH$_3$ and oxygen deficit from downstream DWSC at Turner Cut
60,600
27,000
O$_2$ added by algae
?

There is insufficient information during August and September to estimate the amounts of local BOD sources (such as from French Camp Slough, agriculture and city drains, etc.) contributed to the DWSC. Also, it was not possible to estimate the amount of algae that developed within the DWSC that exerted an oxygen demand within the DWSC, as well as the oxygen added by algae through photosynthesis in the upper waters of the DWSC. For the purposes of the mass balance calculations presented below, it is assumed that these two balanced.

September 1999. Based on the September 1999 SJR and DWSC monitoring, it is found that the total oxygen demand (BOD_u) present in the SJR at Vernalis that reaches the DWSC is about 70,000 lbs/day. This value is based on a UVM-measured average flow of the SJR into the DWSC of 930 cfs. 37,500 lbs/day of the 70,000 is derived from measured BOD at Vernalis. Another almost 30,000 lbs/day of oxygen demand enters the DWSC during September from ammonia and total Kjeldahl nitrogen present in SJR water at Vernalis during September. Since the SJR water at Vernalis is not saturated with oxygen, it has an oxygen deficit of 3,500 lbs/day below saturation.

Estimated Oxygen Deficit in DWSC *(Developed by Dr. C. Foe)*

The oxygen deficit is defined as the pounds of oxygen addition required to bring a well-mixed deep-water ship channel back into compliance with the Basin Plan dissolved oxygen water quality objective. Oxygen deficits were calculated for 1999 in two ways. First, the Department of Water Resources conducted four cruises in August and September of 1999 and measured instantaneous oxygen concentrations as a function of depth at eleven sites between the northeast corner of Rough and Ready Island and Turner Cut (Lehman, personal communication). An instantaneous depth averaged oxygen depletion value was computed for each site from the difference between the measured oxygen concentration at each depth and the appropriate water quality objective. These values were averaged for each location to calculate a depth averaged oxygen depletion value. Oxygen deficits were determined for each segment by multiplying the volume of the segment by its depth averaged oxygen depletion value. The Department of Water Resources did not report depth averaged instantaneous oxygen depletion values for several segments. A depletion value was estimated for each of these by averaging the oxygen concentration of the two adjoining segments and multiplying this value by the volume of the missing segment. The oxygen deficit of the entire deepwater ship channel was calculated by summing the deficits of all segments. These instantaneous deficits are reported for each of the four Department of Water Resource cruises in column 6 and 7 of Table 1. The calculation reveals that there was a net surplus of 32,000 pounds of oxygen in the channel on 10 August. The deficit on 26 August and 9 September was estimated at 7,000-8,000 pounds while on 27 September it increased to 42,000 pounds.

Also estimated in Table 1 is the instantaneous unallocated loading rate (deficit) required to bring oxygen concentrations in the channel back into compliance with the Basin Plan objective. The unallocated loading rate is an estimate of ultimate BOD removal needed to bring the deep-water ship channel back into compliance with the Basin Plan objective dissolved oxygen WQO. The unallocated loading rate was estimated by dividing the total channel oxygen deficit by the hydraulic residence time of the channel. Flow rates for the San Joaquin River at the City of Stockton were obtained from the IEP server (http://iep.water.ca.gov) while residence time was estimated from Figure 9 of this report. The unallocated loading rate for 26 August and 9 September was 700 to 800 pounds/day but increased to 1,690 by the end of September.

Table 1 also lists both the instantaneous depth averaged dissolved oxygen concentrations measured by the Department of Water Resources off Rough and Ready Island and the 24-hour range of values recorded by the continuous dissolved oxygen sensor at the same location. The continuous oxygen sensor measured diel oxygen fluctuations of 0.8 to 2.7 mg/L on the four dates. The instantaneous oxygen concentrations reported by the Department of Water Resources were always within this range but were never the minimum sensor values observed. This discrepancy suggests that the unallocated loading (deficit) rates calculated in Table 1 using the Department of Water Resources' instantaneous oxygen deficit profiles are insufficiently large to maintain oxygen concentrations above the Basin Plan objective during the most critical parts of the diel oxygen cycle. The analysis suggests the need for a second, "worst-case type" estimate of the unallocated (deficit) load.

Table 1
Summary of Oxygen Deficits and Instantaneous Unallocated Loading Rates
Measured during the Summer of 1999 by the Department of Water Resources in the San Joaquin River Deep Water Ship Channel

Date	**Flow[1] (CFS)**	**Residence time[2] (days)**	**Dissolved Oxygen (mg/L)**		**Oxygen Deficits[5] (lbs oxygen)**		**Instantaneous unallocated loading rate[6] (lbs oxygen/day)**
			DWR[3]	**IEP range[4]**	**5 mg/L**	**6 mg/L**	
10 Aug	950	10	6.5	4.9-6.7	+32,082		
26 Aug	1,000	10	4.8	3.9-6.6	-7,825		782
9 Sept	950	10	6.0	4.4-5.9		-7,361	736
27 Sept	300	25	3.6	2.8-3.6		-42,274	1,690

[1/] Net daily flows for the San Joaquin River at Stockton as reported by the IEP server.
[2/] Estimated hydraulic residence of water in the deep-water ship channel (Figure 9 of this report)
[3/] Instantaneous depth averaged oxygen concentrations off Rough and Ready Island as measured by DWR (Lehman, personal communication).
[4/] 24-hour range in oxygen concentrations as measured by the continuous dissolved oxygen sensor off Rough and Ready Island and reported on the IEP server.
[5/] Calculated oxygen deficit for the 5 and 6 mg/l Basin Plan objective. 5 mg/l is enforceable from 1 December through 30 August while 6.0 mg/l is the applicable objective between 1 September and 30 November. Plus values indicate no oxygen deficit present.
[6/] The instantaneous unallocated loading rate is the amount of pure oxygen required to bring channel back into compliance with the Basin Plan objectives. Rate calculated by dividing the oxygen deficit by the residence time.

A worst case estimate of the unallocated loading rate was made to attempt to determine the amount of oxygen required to maintain dissolved oxygen levels above the Basin Plan objective at all times in August and September 1999. Table 2 lists the lowest 15-minute average dissolved oxygen concentrations measured by the continuous oxygen sensor off Rough and Ready Island in August and September. Table 2 also lists an estimate of the worst-case oxygen deficit and the unallocated loading rate required to correct it. The calculation assumes that the oxygen concentration in all channel segments under worst case situations in August and September were in similar proportions as that observed by the Department of Water Resources on 26 August and 27 September. This assumption is obviously not entirely correct but is probably the best approximation now possible without continuous oxygen sensors in all channel segments. The calculation suggests that the maximum deficit in both August and September was about 75,000 pounds of oxygen. The average hydraulic residence time of the ship channel was about 10 days during both months suggesting an unallocated loading rate of about 7,000 to 8,000 pounds of oxygen per day.

Table 2
Summary of the Lowest 15-Minute Dissolved Oxygen Concentration
Measured off Rough and Ready Island in the San Joaquin River
Deep Water Ship Channel in 1999
(Also included are the associated oxygen deficits & worst case monthly unallocated loading rate)

Month	**Average Monthly Flow**[1] **(CFS)**	**Average Monthly Residence Time**[2] **(days)**	**Lowest Monthly 15-Minute Dissolved Oxygen Concentration**[3] **(mg/L)**	**Oxygen Deficit**[4] **(Lbs oxygen)**		**Worst Case Monthly Unallocated Loading Rate**[5] **(Lbs oxygen/day)**
				5 mg/L	**6 mg/L**	
Aug	921	10	3.1	-74,366		7,436
Sept	913	10	1.7		-75,740	7,574

[1/] Average monthly flows for the San Joaquin River at Stockton as reported by the IEP server.
[2/] Average monthly estimated hydraulic residence of water in the deep-water ship channel (Figure 9 of this report)
[3/] Lowest 15-minute monthly oxygen concentration oxygen concentrations as measured by the continuous dissolved oxygen sensor off Rough and Ready Island and reported on the IEP server.
[4/] Calculated oxygen deficit for the 5 and 6 mg/l Basin Plan objective. 5 mg/l is enforceable from 1 December through 30 August while 6.0 mg/l is the applicable objective between 1 September and 30 November.
[5/] Unallocated loading rate is the oxygen deficit divided by the residence time.

October 1999. Figure 17 presents the flow for SJR at UVM for October. As shown in Figure 17, at the end of September the SJR flow at the UVM flow monitoring station decreased from about 900 cfs to 150 cfs. The 150 cfs that was present at the end of September persisted for a few days into October. After that time, the flows increased to almost 1,000 cfs and then dropped back down to about 800 cfs for the rest of the month. Figure 17 also shows the magnitude of the tidal flows relative to the net SJR flow. With SJR net flows of less than about 500 cfs, the tidal flows dominate the flows in the SJR. The average flow for October was about 600 cfs, which is a couple of hundred cfs less than what was found in August and September.

Figures 18, 19, and 20 present box model calculations for three assumed SJR flows into the DWSC that cover the range of the flows experienced during October. During October, King (2000) made measurements of the BOD and other characteristics of the SJR at Vernalis. The City of Stockton (Jones and Stokes, 2000) made measurements of the characteristics of the

City's wastewater discharges to the SJR from its wastewater oxidation ponds. The three assumed flows were used to calculate the oxygen demand loads from upstream of Vernalis and the City's wastewater discharges for the DWSC.

Based on the October 1999 SJR and DWSC monitoring, it is found that the total oxygen demand (BOD_u) present in the SJR at Vernalis that reaches the DWSC is about 6,300 lbs/day (see Figure 18). This value is based on an estimated average flow of the SJR into the DWSC of 150 cfs, which was the UVM measured flow during the last few days of September and first few days of October. 3,640 lbs/day of the 6,300 is derived from measured BOD_u at Vernalis. Another 1,800 lbs/day of oxygen demand enters the DWSC during October from ammonia and total Kjeldahl nitrogen present in SJR water at Vernalis during October. The SJR at Vernalis is not saturated with oxygen; it had an oxygen deficit of 890 lbs/day below saturation.

During October, the total estimated City of Stockton wastewater oxygen demand load was about 12,200 lbs/day. About 2,100 lbs/day of this amount was due to $CBOD_u$, with the remainder, about 9,900 lbs/day, due to $NBOD_u$. The oxygen deficit in the City of Stockton wastewater pond effluent during October was about 162 lbs/day.

During October 1999, King (2000) took several samples of French Camp Slough water and estimated the flows into the DWSC. Based on this estimate and the measurements, it is roughly estimated that about 1,750 lbs/day of BOD_u entered the DWSC from French Camp Slough.

The load boxes for the various assumed October SJR flows do not present values for DO added by reaeration and mechanical aeration. They also do not present information on the amount of oxygen demand exported across the downstream boundary of the critical reach of the DWSC. It was felt that there was insufficient information available to make these estimates.

Figure 19 presents the results of the box model calculations for October conditions, assuming an SJR flow into the DWSC of 400 cfs. Under these conditions, the oxygen demand in the SJR derived from above Vernalis that reaches the DWSC was about 17,000 lbs/day. The City of Stockton's wastewater discharges were 12,200 lbs/day. Therefore, with SJR UVM flows in the range of 300 to 400 cfs, the City of Stockton and the upstream of Vernalis loads are about equal.

Figure 20 shows similar calculations for an assumed SJR flow of 1,000 cfs. Under these flow conditions and the concentrations of the constituents present in each of the two major load sources, the upstream of Vernalis load now increases to about 42,450 lbs/day, while the City of Stockton's load is still 12,200 lbs/day. These results point to the significance of SJR flow into the DWSC controlling the total load and relative significance of the two major load sources (upstream of Vernalis and the City of Stockton's wastewater discharges) as a source of oxygen demand for the DWSC.

Figure 17

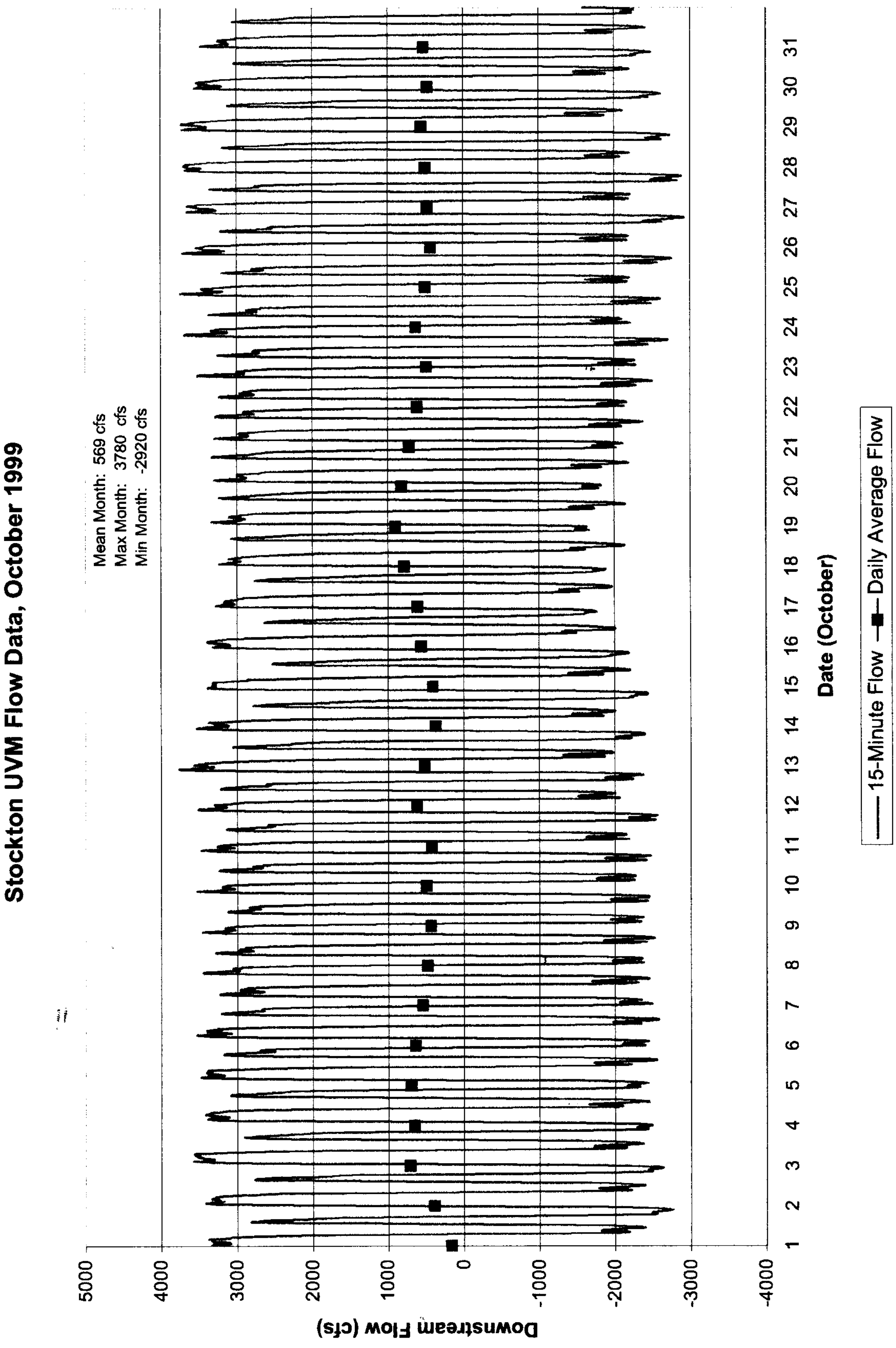
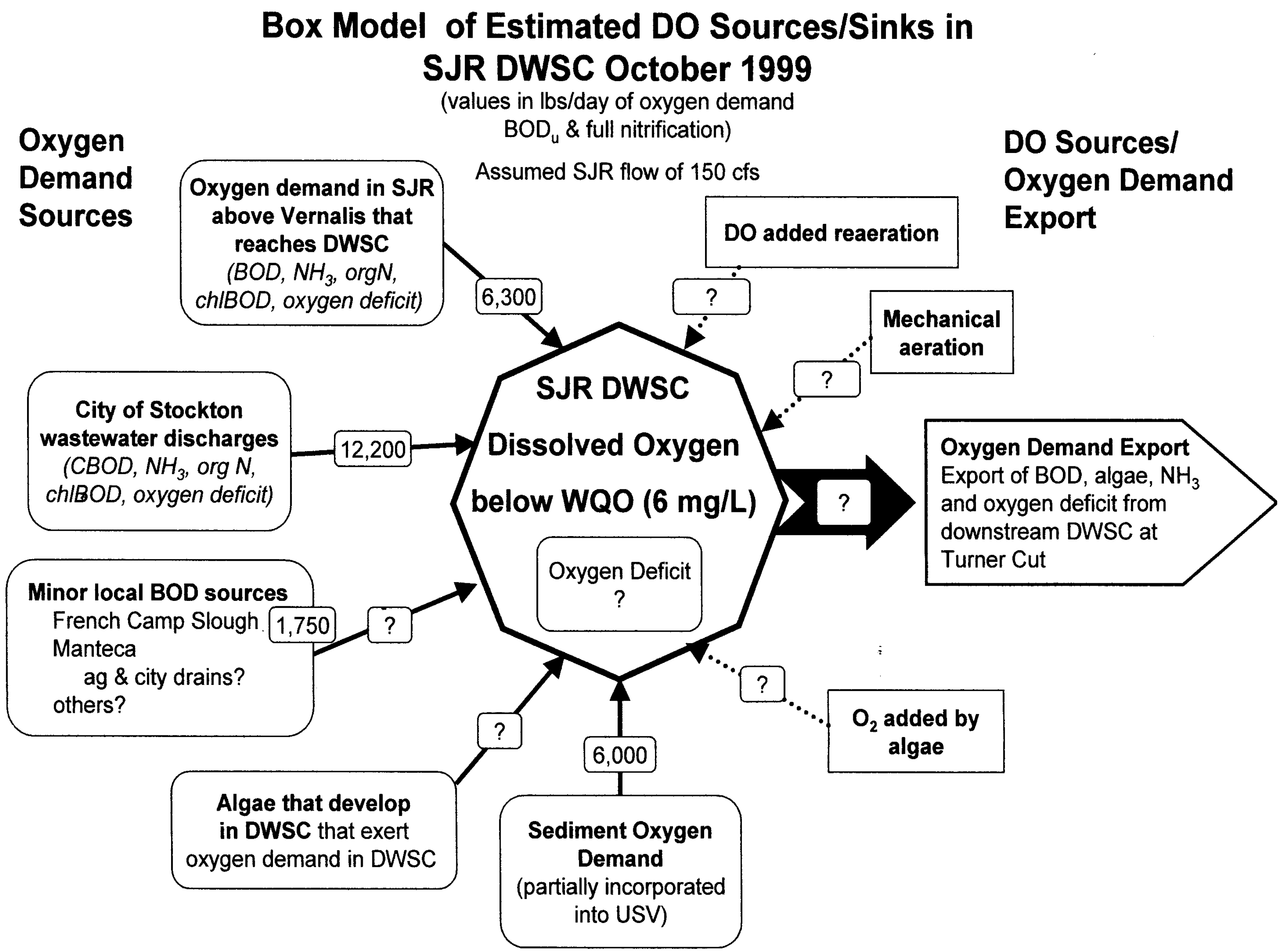

Stockton UVM Flow Data, October 1999

Figure 18

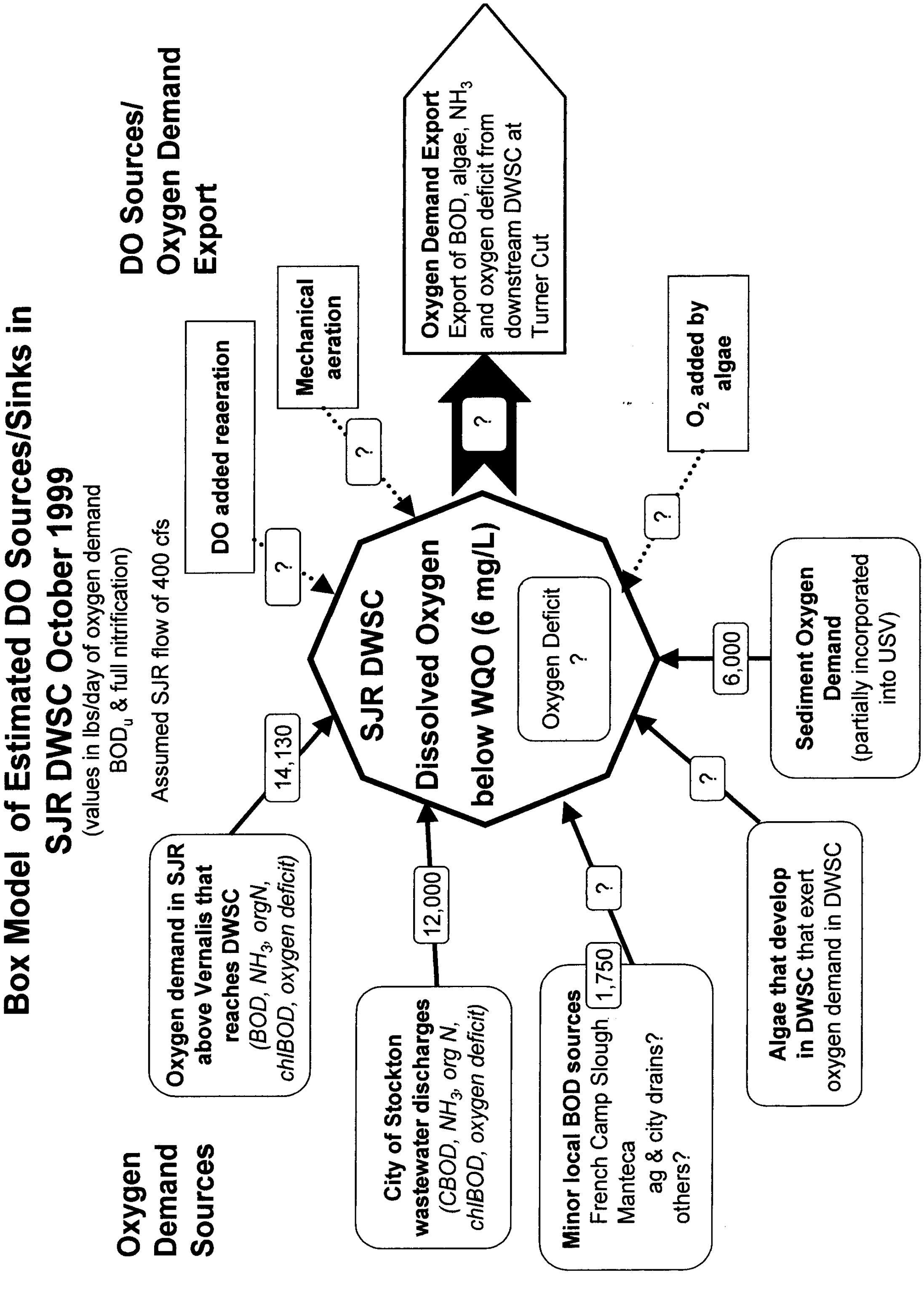


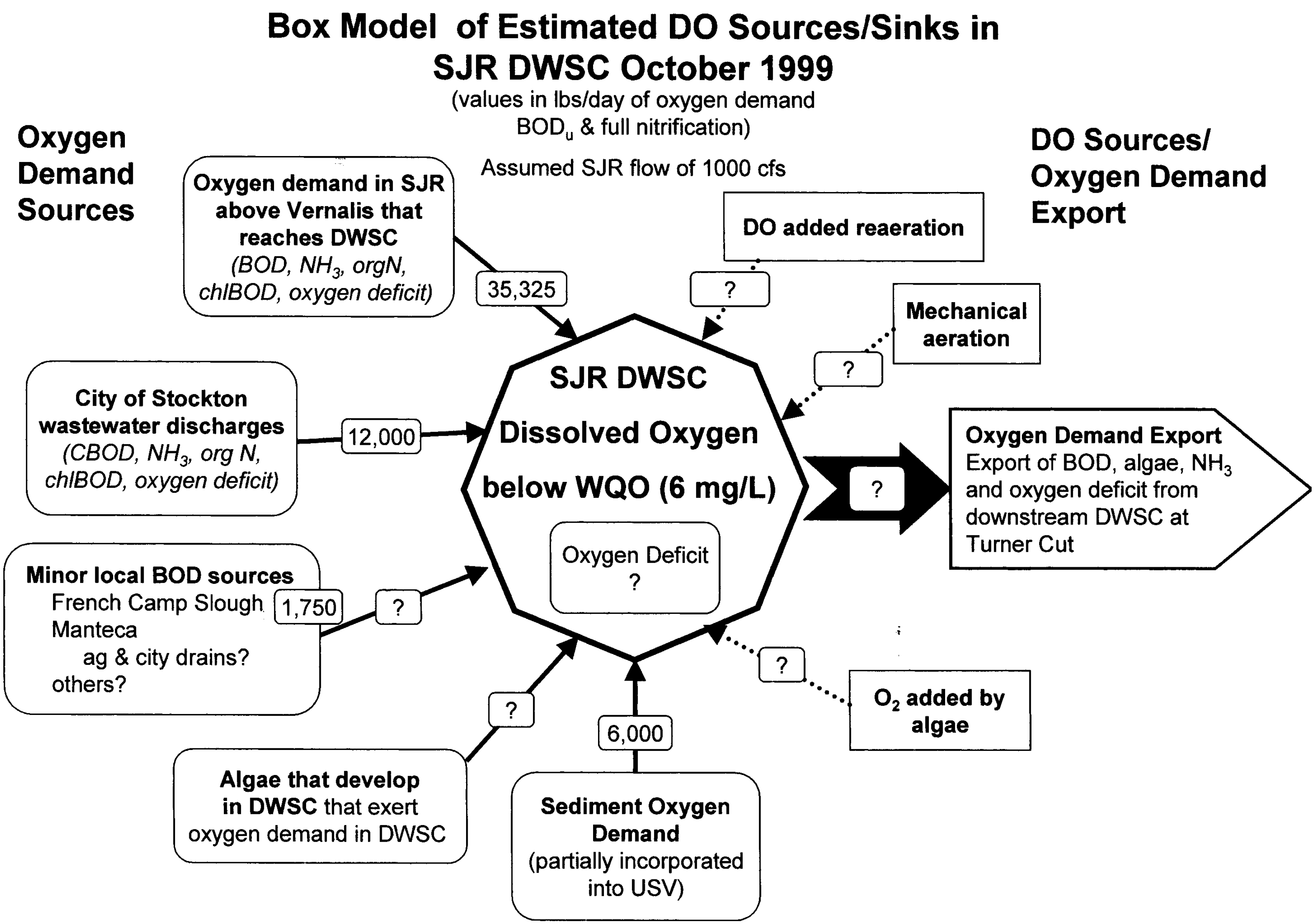
Box Model of Estimated DO Sources/Sinks in SJR DWSC October 1999

(values in lbs/day of oxygen demand BOD_u & full nitrification)

Assumed SJR flow of 150 cfs

Figure 19


Box Model of Estimated DO Sources/Sinks in SJR DWSC October 1999
(values in lbs/day of oxygen demand BOD_u & full nitrification)
Assumed SJR flow of 400 cfs
Oxygen Demand Sources
DO Sources/ Oxygen Demand Export
Oxygen demand in SJR above Vernalis that reaches DWSC (BOD, NH_3, orgN, chlBOD, oxygen deficit)
14,130
City of Stockton wastewater discharges (CBOD, NH_3, org N, chlBOD, oxygen deficit)
12,000
Minor local BOD sources French Camp Slough Manteca ag & city drains? others?
1,750
?
Algae that develop in DWSC that exert oxygen demand in DWSC
?
Sediment Oxygen Demand (partially incorporated into USV)
6,000
SJR DWSC Dissolved Oxygen below WQO (6 mg/L)
Oxygen Deficit ?
DO added reaeration
?
Mechanical aeration
?
Oxygen Demand Export Export of BOD, algae, NH_3 and oxygen deficit from downstream DWSC at Turner Cut
?
O_2 added by algae
?



Box Model of Estimated DO Sources/Sinks in SJR DWSC October 1999

(values in lbs/day of oxygen demand BOD_u & full nitrification)

Assumed SJR flow of 1000 cfs

Figure 20

Table 3
Estimated Oxygen Demand Loads to SJR DWSC

Relationships Used in These Calculations

Daily load (lbs/day) = 5.4 x Effluent Flow (cfs) x Concentration (mg/L)

$NBOD_u$ (lbs/day) = Ammonia (lbs/day) x 4.5

$CBOD_u$ (lbs/day) = BOD_5 (lbs/day) x 2.5
10 µg/L chlorophyll = 1 mg/L BOD_5

1 mg/L BOD_5 = 1 mg/L VSS

SOD 1 g O_2/m^2/day = 9,000 lbs/day of oxygen consumed for 1,000 acres of DWSC

1 mgd = 1.55 cfs

1 ac ft/year = cfs

DWSC Reach of Concern

Volume: 15,000 ac ft	Area: 1,000 ac
Average Depth: 22 ft	Length: 10 mi
Maximum Depth: 40 ft near Channel Point	
Navigation Channel Depth: 35 ft	

Chlorophyll Concentrations in SJR at Vernalis
Average Chlorophyll a during August at SJR Vernalis: 38 µg/L
Average Chlorophyll a during September at SJR Vernalis: 28 µg/L
Average Chlorophyll a during October at SJR Vernalis: 17 µg/L

Upstream of Vernalis Oxygen Demand Loads
Based on Information Provided by King (2000)

Average SJR Flow into DWSC based on UVM measured flow

August:	880 cfs
September:	930 cfs
October:	150, 400 or 1,000 cfs (assumed)

Average BOD Loading to the SJR DWSC from SJR at Vernalis
Average BOD_5 added to SJR DWSC, August 1999: 16,000 lbs/day
This translates to an ultimate BOD_u of 16,000 x 2.5 = **40,000 lbs/day**
Average BOD_5 during August at SJR Vernalis was 3.3 mg/L

Table 3 (continued)

Average BOD$_5$ added to SJR DWSC, September 1999: 15,000 lbs/day	
This translates to an ultimate BOD$_u$ of 15,000 x 2.5 =	**37,500 lbs/day**
Average BOD$_5$ during September at SJR Vernalis was 3.4 mg/L	
Average BOD$_5$ added to SJR DWSC, October 1999:	
Assumed flow of 150 cfs translates to an ultimate BOD$_u$	**3,640 lbs/day**
Assumed flow of 400 cfs translates to an ultimate BOD$_u$	**9,720 lbs/day**
Assumed flow of 1,000 cfs translates to an ultimate BOD$_u$	**24,300 lbs/day**
Average BOD$_5$ during October at SJR Vernalis was 1.8 mg/L	
Average monthly Ammonia N (TKN) added to SJR DWSC	
(Based on correcting for nitrification in BOD$_5$ test, which was 50% of the BOD$_5$)	
Average Ammonia during August at SJR Vernalis: <0.5 mg/L N	
Average TKN during August at SJR Vernalis: 1.8 mg/L N ⇒ 8,500 lbs/day	
Average Nitrogen-caused oxygen demand (NBOD$_u$)/2:	**19,250 lbs/day**
Average Ammonia during September at SJR Vernalis: <0.1 mg/L N	
Average TKN during September at SJR Vernalis: 2.6 mg/L N ⇒ 13,000 lbs/day	
Average Nitrogen-caused oxygen demand (NBOD$_u$)/2:	**29,400 lbs/day**
Average Ammonia during October at SJR Vernalis: 0.26 mg/L N	
Average TKN during October at SJR Vernalis: 1 mg/L N ⇒	
Assumed flow of 150 cfs translates to an (NBOD$_u$)/2	**1,800 lbs/day**
Assumed flow of 400 cfs translates to an (NBOD$_u$)/2	**4,900 lbs/day**
Assumed flow of 1,000 cfs translates to an (NBOD$_u$)/2	**12,150 lbs/day**
Average Dissolved Oxygen Deficit Added to SJR DWSC	
Average temperature during August at SJR Vernalis: 24.7 C	
Average DO during August at SJR Vernalis: 7.7 mg/L	
DO Saturation at 25 C: 8.3 mg/L	
DO Deficit: 0.6 mg/L	
Average DO Deficit added to SJR DWSC:	**2,850 lbs/day**
Average temperature during September at SJR Vernalis: 22.6 C	
Average DO during September at SJR Vernalis: 7.9 mg/L	
DO Saturation at 23 C: 8.6 mg/L	
DO Deficit: 0.7 mg/L	
Average DO Deficit added to SJR DWSC:	**3,500 lbs/day**
Average temperature during October at SJR Vernalis: 18.1 C	
Average DO during October at SJR Vernalis: 8.4 mg/L	
DO Saturation at 18 C: 9.5 mg/L	
DO Deficit: 1.1 mg/L	
Average DO Deficit added to SJR DWSC:	

Table 3 (continued)

Assumed flow of 150 cfs: **890 lbs/day**
Assumed flow of 400 cfs: **2,400 lbs/day**
Assumed flow of 1,000 cfs: **6,000 lbs/day**

Total Oxygen Demand Load added to SJR DWSC from SJR at Vernalis

August 1999: **61,000 lbs/day**
September 1999: **70,000 lbs/day**
October 1999 (assumed SJR UVM flow of 150 cfs): **6,300 lbs/day**
October 1999 (assumed SJR UVM flow of 400 cfs): **17,000 lbs/day**
October 1999 (assumed SJR UVM flow of 1,000 cfs): **42,450 lbs/day**

City of Stockton Wastewater Treatment Plant
Based on Information Provided by Jones & Stokes (2000)

Average Stockton Flow into SJR

August:	31 mgd,	48 cfs
September:	26 mgd,	40 cfs
October:	28 mgd,	43 cfs

Average BOD Loading from Stockton
Average CBOD_5 from Stockton, August 1999: 1,234 lbs/day
This translates to an ultimate CBOD_u of 1,234 x 2.5 = **3,000 lbs/day**
Average CBOD_5 during August from Stockton was 4.2 mg/L
Average CBOD_5 from Stockton, September 1999: 1,266 lbs/day
This translates to an ultimate CBOD_u of 1,266 x 2.5 = **3,100 lbs/day**
Average CBOD_5 during September from Stockton was 5.5 mg/L
Average CBOD_5 from Stockton, October 1999: 861 lbs/day
This translates to an ultimate CBOD_u of 861 x 2.5 = **2,100 lbs/day**
Average CBOD_5 during October from Stockton was 3.6 mg/L

Average monthly Ammonia N and TKN from Stockton
(Based on correcting for nitrification in BOD_5 test, which was 40% of the BOD_5)

Average Ammonia during August from Stockton: 3.4 mg/L N
Average OrgN during August from Stockton: 1.7 mg/L N
Average TKN during August from Stockton: 5.1 mg/L N ⇒ 1,320 lbs/day
Average Nitrogen-caused oxygen demand (NBOD_u)/2.5 from Stockton: **2,400 lbs/day**

Average Ammonia during September from Stockton: 12.7 mg/L N
Average OrgN during September from Stockton: 2.6 mg/L N
Average TKN during September from Stockton: 15.3 mg/L N ⇒ 3,300 lbs/day
Average Nitrogen-caused oxygen demand (NBOD_u)/2.5 from Stockton: **6,000 lbs/day**

Table 3 (continued)

Average Ammonia during October from Stockton: 20.7 mg/L N
Average OrgN during October from Stockton: 3.0 mg/L N
Average TKN during October from Stockton: 23.7 mg/L N ⇒ 5,500 lbs/day
Average Nitrogen-caused oxygen demand (NBOD$_u$)/2.5 from Stockton **9,900 lbs/day**

Average Dissolved Oxygen Deficit from Stockton
Average temperature during August: 25 C
Average DO during August: 7.4 mg/L
DO Saturation at 25 C: 8.3 mg/L
DO Deficit in Stockton Effluent: 0.9 mg/L
Average DO Deficit from Stockton: **230 lbs/day**

Average temperature during September: 25 C
Average DO during September: 7.5 mg/L
DO Saturation at 25 C: 8.3 mg/L
DO Deficit in Stockton Effluent: 0.8 mg/L
Average DO Deficit from Stockton: **173 lbs/day**

Average temperature during October: 20 C
Average DO during October: 8.4 mg/L
DO Saturation at 20 C: 9.1 mg/L
DO Deficit in Stockton Effluent: 0.7 mg/L
Average DO Deficit from Stockton: **162 lbs/day**

Total Oxygen Demand Load from Stockton
August 1999: **5,600 lbs/day**
September 1999: **9,300 lbs/day**
October 1999: **12,200 lbs/day**

Oxygen Demand of French Camp Slough
No Information for August and September

October King (2000) based on two measurements
Average BOD$_5$: 2 mg/L, average flow 46 cfs ⇒ 500 lbs/day
BOD$_u$ x 2.5 ⇒ **1,250 lbs/day**

Average TKN: 0.9 mg/L N ⇒ 224 lbs/day
NBOD$_u$/2: 224 x 4.5/2 ⇒ **503 lbs/day**

DO Deficit? No information is available

Total Oxygen Demand: **1,750 lbs/day**

Table 3 (continued)

DWSC Sediment Oxygen Demand

Chen & Tsai (2000) model: **6,000 lbs/day**

Note: 1 g O_2/m^2/day SOD over 1,000 ac = 9,000 lbs/day SOD

Algae that Develop in DWSC that Become Oxygen Demand in DWSC - Oxygen Added to DWSC by Algal Photosynthesis

It is assumed that algae that develop in the DWSC does not add to DWSC oxygen demand. DWSC developed algal produced oxygen is assumed equal to oxygen demand of DWSC produced algae, which is balanced by their oxygen demand and export across the downstream boundary.

Atmospheric Reaeration

Chen & Tsai (2000) model: **5,500 lbs/day**

Mechanical Reaeration

COE (1988): potential **2,000 lbs/day**

There were times during August and October when the aerator was not operating.

Oxygen Demand/Deficit Exported from DWSC

Chen and Tsai (2000) modeling results

CBOD exported across lower DWSC boundary	5,000 lbs/day	12,500 lbs/day
NH_3-N exported across lower DWSC boundary	1,880 lbs/day	8,460 lbs/day
Chlorophyll exported across lower DWSC boundary	58 lbs/day	5,800 lbs/day
Total		**26,800 lbs/day**

Alternative Approach for estimating oxygen demand export

Using SJR DWSC flow times the estimated concentration of BOD_u, OrgN, NH_3, O_2 deficit, it is possible to estimate the amount of oxygen demand that is exported past the critical reach of the DWSC. Calculations using this approach are presented below:

August

BOD_5: Assumed 5 mg/L ⇒	59,400 lbs/day BOD_u	
NH_3 + OrgN: Assumed 0.5 mg/L N ⇒	5,300 lbs/day $NBOD_u$	
DO deficit from saturation: Assumed 1 mg/L ⇒	4,750 lbs/day	
Total		**69,400 lbs/day**

September

BOD_5: Assumed 4 mg/L ⇒	50,220 lbs/day BOD_u
NH_3 + OrgN: Assumed 0.5 mg/L N ⇒	5,650 lbs/day $NBOD_u$

Table 3 (continued)

DO deficit from saturation: Assumed 1 mg/L ⇒ 4,750 lbs/day
Total **60,600 lbs/day**

October Assumed flow of 150 cfs
BOD$_5$: Assumed 6 mg/L ⇒ 12,150 lbs/day BOD$_u$
NH$_3$ + OrgN: Assumed 0.7 mg/L N ⇒ 1,275 lbs/day NBOD$_u$
DO deficit from saturation: Assumed 2 mg/L ⇒ 1,620 lbs/day
Total **15,000 lbs/day**

The difference between the Chen and Tsai estimated export and the estimated export based on concentrations and flows presented above may be due to the difference in the and ultimate BOD calculations from 5-day BOD values. Chen and Tsai are using a value of 1.5 to relate BOD$_5$ to BOD$_u$. The calculations presented in this report use 2.5, which better matches the data obtained for the SJR and DWSC.

Import from Downstream Boundary

Chen and Tsai (2000) provided information on the range of loads of oxygen-demanding materials that would be imported to the DWSC from the Sacramento River and downstream Delta areas. At an SJR flow of 1,000 cfs and an oxygen demand concentration of 1 mg/L, Chen and Tsai estimate that about 700 lbs/day of oxygen demand is added to the DWSC from downstream sources.

At an assumed flow of 500 cfs and 1 mg/L oxygen demand concentration, the estimated oxygen demand added from downstream sources is 900 lbs/day.

If the concentration of oxygen demand is 10 mg/L and the flow is:

1,000 cfs	7,300 lbs/day of oxygen demand imported from downstream sources
500 cfs	9,000 lbs/day of oxygen demand imported from downstream sources

Mass Balance (lbs/day)

Oxygen Demand			**DO Sources/Export**	
August		**DWSC Deficit ?**		
USV	61,000		Reaeration	5,500
Stockton	5,600		Aerator	2,000
			Export	69,400?
Total	**66,600**			**77,000**
September		**DWSC Deficit ?**		
USV	70,000		Reaeration	5,500
Stockton	9,300		Aerator	2,000
			Export	60,600?
Total	**79,300**			**68,000**

The information presented in Figures 15, 16, 18, 19 and 20 and Table 3 shows that during the times that there is appreciable SJR flow into the DWSC, the upstream of Vernalis BOD and ammonia/orgN in the San Joaquin River are significant sources of oxygen demand for the DWSC. However, when the SJR is largely diverted through Old River, the algal and other oxygen demand load that is present at Vernalis is apparently a small part of the BOD load to the DWSC. Under SJR low flow conditions into the DWSC, especially during the fall, a significant part of the oxygen demand discharged to the DWSC is apparently derived from City of Stockton wastewater discharges of ammonia.

The overall conclusion from the box model calculations is that the nitrogen and phosphorus loads contributed to the San Joaquin River above Vernalis that result in algal biomass and ammonia/orgN that is present in the SJR at Vernalis are significant sources of oxygen demand for the DWSC under essentially all conditions except those where the SJR flow in the DWSC is less than a few hundred cfs.

In evaluating oxygen demand sources, it is important to consider that the SOD may, in some -- possibly a large -- part, have already been included in the upstream of Vernalis loads that reach the DWSC. Since that BOD load appears to be due, to a substantial extent, to algae and detritus, a part of that load, upon reaching the DWSC, would be exerted in the water column. Another part of the upstream of Vernalis algal/detritus load would contribute to the sediment oxygen demand load. At this time, the relative significance of freshly settled algal cells/detritus as a cause of SOD, versus accumulated oxygen demand that exists within the sediments due to the conversion of oxidized forms of iron and sulfur to reduced forms (ferrous iron and sulfide(s)), has not been quantified; however, it appears that the primary oxygen demand of the DWSC is associated with biochemical processes that take place within the water column.

Impact of Ammonia Discharges on DWSC Oxygen Resources

Ammonia, through nitrification reactions which involve certain bacteria converting ammonia to nitrite and nitrate, can consume appreciable oxygen. One mg/L of NH_3 when fully oxidized to nitrate, will consume about 4.5 mg/L of dissolved oxygen. Beginning in June 1999, Lee and Jones-Lee (2000a) were involved in a study concerned with ammonia concentrations and their impacts in the Wine Slip in the Port of Stockton.

The Wine Slip (See Figure 21) is a ship loading/unloading area that is immediately adjacent to the DWSC near where the SJR enters the DWSC. CALAMCO is an ammonia distribution facility that is located in the Port of Stockton. Weekly monitoring of Wine Slip water for its ammonia concentrations has been conducted as part of CALAMCO's NPDES permit requirements, associated with the use of Wine Slip water for once-through heating of ammonia. Further, monthly ammonia analyses have been conducted by CALAMCO as part of its NPDES permit requirements, involving sampling Wine Slip water and nearby Deep Water Ship Channel water (Table 4). Lee and Jones-Lee (2000a) have recently reported the results of these studies.

Figure 21

Aerial Photo of Port of Stockton & Vicinity Showing CALAMCO and Study Sampling Locations

Table 4
Location of San Joaquin River Deep Water Ship Channel Sampling Stations

Station Number	Location
R1	Deep Water Ship Channel 100 yds east of Wine Slip
R2	End of Wine Slip near CALAMCO's intake and discharge
R3	Deep Water Ship Channel 100 yds west of Wine Slip
R4	San Joaquin River one quarter mile upstream of Deep Water Ship Channel
R5	Roth Road, about a mile downstream of Mossdale
R6	Mossdale

The CALAMCO data (Tables 5 and 6) show that between June and September 1999, the ammonia concentrations in the Wine Slip and nearby Deep Water Ship Channel, as well the water pumped by CALAMCO from the Wine Slip were less than 0.3 mg/L NH_3 At the end of September and throughout October, November and December 1999, the Wine Slip waters, as well as the Deep Water Ship Channel waters, showed significant increases in the ammonia concentrations. Beginning in November, the concentrations of ammonia were about 1.2 to 1.4 mg/L NH_3 in the Wine Slip and nearby Deep Water Ship Channel; however, the concentration of total ammonia in the San Joaquin River where it discharges to the Deep Water Ship Channel was 2.1 mg/L NH_3. In December the concentrations of ammonia in the CALAMCO intake and discharge waters as well as in the Wine Slip ranged from 3.1 to 3.5 mg/L NH_3.

A sample of the San Joaquin River taken near Channel Point at R4 contained 4.4 mg/L NH_3. That sample had an un-ionized ammonia concentration of 0.1 mg/L NH_3. However, samples taken at R5, Roth Road, and R6, Mossdale, had total ammonia concentrations of about 0.3 and <0.2 mg/L NH_3. The DeltaKeeper (see Lee and Jones-Lee, 2000b) found ammonia concentrations in the SJR where it enters the DWSC and downstream near the Rod and Gun Club on the order of 3.4 to 3.9 mg/L N on December 28, 1999, and January 20, 2000. These data show that the high ammonia concentrations found by CALAMCO for similar monitoring locations extended through at least mid-January 2000.

Based on the data provided by Jones and Stokes (2000), the City of Stockton's wastewater ponds were discharging about 4 mg/L ammonia-N in August 1999. By November, the wastewater treatment plant ponds were discharging ammonia to the SJR at a concentration of about 21 mg/L NH_3. Considering the typical flows of the wastewater treatment plant ponds (40 to 50 cfs) and the low flows of the SJR below Mossdale (200 cfs), the concentrations of ammonia in the SJR as it enters the DWSC are projected to be between 3 to 4 mg/L NH_3. These were the concentrations that were found in the CALAMCO and DeltaKeeper monitoring of the lower SJR.

Table 5 Ammonia Concentration CALAMCO Wine Slip Intake Water

Date		Ammonia mg/L NH_3
JAN	01/07/99	<1
	01/14/99	<1
	01/21/99	1.9
	01/28/99	<1
FEB	02/04/99	<1
	02/11/99	<1
	02/18/99	<1
	02/26/99	<1
MAR	03/04/99	<1
	03/11/99	<1
	03/18/99	<1
	03/25/99	<1
APRIL	04/01/99	<1
	04/08/99	<1
	04/15/99	<1
	04/22/99	<1
	04/29/99	<1
MAY	05/06/99	<1
	05/13/99	<1
	05/20/99	<1
	05/27/99	<1
JUNE	06/03/99	<1
	06/10/99	<1
	06/17/99	<1
	06/24/99	<1
JULY	07/01/99	<1
	07/08/99	0.2
	07/15/99	0.3
	07/22/99	0.2
	07/29/99	0.3
AUG	08/05/99	<0.2
	08/12/99	0.2
	08/18/99	<0.2
	08/26/99	0.2
SEPT	09/02/99	<0.2
	09/09/99	0.3
	09/16/99	<0.2
	09/23/99	<0.2
	09/30/99	0.3
OCT	10/07/99	0.9
	10/14/99	0.7
	10/21/99	0.2
	10/28/99	0.4
NOV	11/04/99	0.7
	11/11/99	1
	11/18/99	1.8
	11/24/99	2.5
DEC	12/2/99	1.7
	12/9/99	3.3
	12/16/99	3.3

Table 6
Wine Slip, Deep Water Ship Channel and San Joaquin River Monitoring, 1999

Date	Location	Ammonia (mg/L NH_3)	pH	Temp (F)
June 10	R-1	<1	8.1	64
June10,	R-2	<1	8.0	65
June 10	R-3	<1	8.1	64
June 10	R-4	<0.2	7.3	76
July 7	R-1	<0.2	7.5	79
July 7	R-2	<0.03	7.6	80
July 7	R-3	<0.02	7.8	80
July 7,	R-4	<0.2	7.3	76
August 30	R-1	<0.2	8.3	82
August 30	R-2	<0.2	8.3	80
August 30	R-3	<0.2	8.0	78
August 30	R-4	<0.2	8.2	80
Sept 15	R-1	<0.2	8.5	82
Sept 15	R-2	<0.2	8.3	81
Sept 15	R-3	<0.2	8.7	83
Sept 15	R-4	<0.3	8.1	81
Oct 13	R-1	<0.4	8.7	78
Oct 13	R-2	<0.7	8.5	77
Oct 13	R-3	<0.7	8.7	76
Oct 13	R-4	<0.8	7.9	72
Nov 11	R-1	1.2	7.7	61
Nov 11	R-2	1.3	7.7	60
Nov 11	R-3	1.4	7.8	61
Nov 11	R-4	2.1	7.8	61
Dec 8	R-1	3.6	7.9	55
Dec 8	R-2	3.5	7.9	55
Dec 8	R-3	3.6	7.9	55
Dec 8	R-4	4.4	8.0	56
Dec 8	R-5	<0.2	7.8	55
Dec 8	R-6	0.3	7.7	55

Examination of the CALAMCO ammonia data (Tables 5 and 6), as well as the data provided by the DeltaKeeper, shows that during the summer through September, the concentrations of ammonia found in the DWSC and lower SJR near where it enters the DWSC were less than 1 mg/L NH_3. However, beginning in October, and especially November 1999 through mid-January 2000, the concentrations of ammonia in the DWSC and lower SJR ranged from 2 to 4 mg/L NH_3. These concentrations of ammonia are of concern due to both exerting an oxygen demand, as well as toxicity to aquatic life.

The US EPA (1999a) has recently released its revised ammonia water quality criteria. As shown in Table 7, the total ammonia criterion value depends on the temperature and pH of the water. At high temperatures and pH values, a greater percentage of the total ammonia is in a toxic un-ionized form.

Table 7
Ammonia Water Quality Criteria

Total Ammonia (mg/L N)

pH	**Temperature (C)**			
	16	**20**	**24**	**28**
7.0	5.4	4.1	3.2	2.5
7.5	4.0	3.1	2.4	1.8
8.0	2.2	1.7	1.3	1.0
8.5	1.0	0.8	0.6	0.4

US EPA December 1999

Total ammonia concentrations in the SJR and DWSC were found to be on the order of 2 to 3.5 mg/L N during November 1999; therefore, at the pH and temperature of the DWSC waters that occurred in fall 1999 (pH greater than about 7.5 to 8.5 and temperatures 18 to 24 C) the ammonia concentrations found in these waters would be expected to be toxic to some forms of aquatic life. This toxicity will likely be enhanced by low DO concentrations, since ammonia is known to be more toxic at low DO concentrations.

The Department of Water Resources maintains a continuous dissolved oxygen monitoring station for the DWSC at Rough and Ready Island near Burns Cutoff. As shown in Figure 4, Burns Cutoff is just downstream of where the SJR enters the DWSC. A review of the DO monitoring data for the DWR Burns Cutoff monitoring station (see subsequent section Figure 29) shows that significantly depressed dissolved oxygen concentrations were found during October, November and December 1999. This severely low DO coupled with the elevated ammonia is likely toxic to some forms of aquatic life in the DWSC near Rough and Ready Island. As shown by the box model calculations (Figures 18, 19 and 20), the City of Stockton's domestic wastewater ammonia discharges are a likely significant source of the oxygen demand under low to moderate SJR flow (less than about 500 cfs) into the DWSC that caused the low DO in late fall 1999.

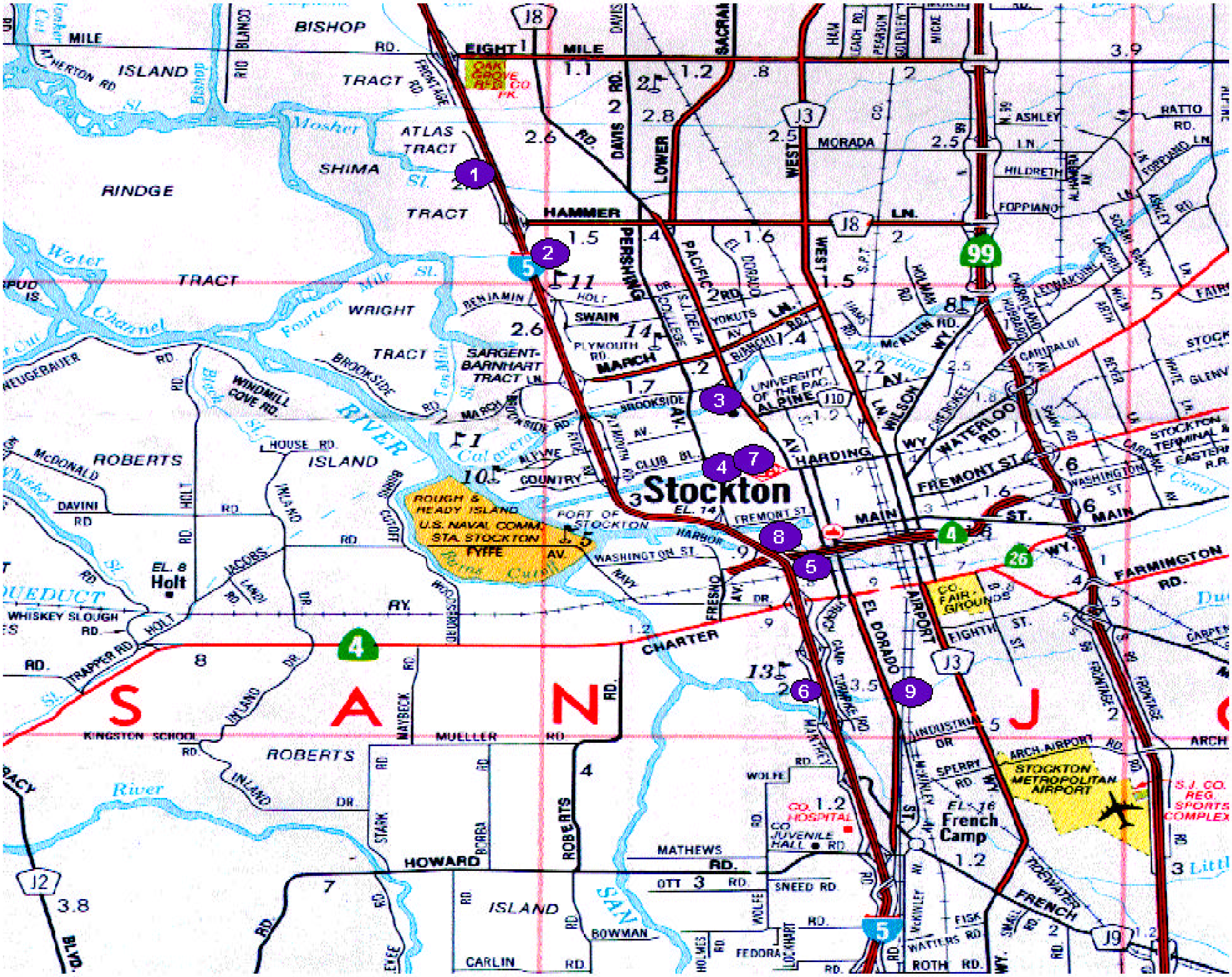
Not only was there sufficient ammonia present in the DWSC to be toxic to some forms of aquatic life when the temperature was about 20 C and the pH was greater than about 8, but also the ammonia was adding to the oxygen-demanding materials present in the DWSC to cause/contribute to significant dissolved oxygen depletions below the water quality objective of 6 mg/L during October and November, and 5 mg/L during December. While it has been known for many years that, beginning in late summer, the City of Stockton oxidation ponds lose their ability to remove ammonia from the domestic and industrial wastewaters that are treated by these ponds, the consequences of this situation with respect to DO depletion and aquatic life toxicity have not been adequately investigated.

Stockton Sloughs as Local Sources of Oxygen Demand

One of the issues that will need to be addressed in the SJR DO TMDL development and implementation is the potential role of DWSC local sources of oxygen demand on the DO depletion problem below WQOs that occurs each summer and fall within the DWSC. As used herein, "local" means discharges below Mossdale. Of particular concern is the potential role of nearby discharges that could contain oxygen demand materials. As discussed above, one of the local sources of oxygen demand is French Camp Slough. King (2000), based on a limited study conducted in October 1999, found that French Camp Slough could contribute potentially significant amounts of oxygen demand to the DWSC under conditions of low SJR flow into the DWSC. There are a number of other sloughs/discharges that are of potential importance as local oxygen demand sources. These include the City of Stockton sloughs. These sloughs are tidal freshwater drainage ways that collect stormwater runoff from the City of Stockton. They also have a dry weather flow component that is adding constituents to the sloughs, which would, to some extent, be transported to the DWSC.

During November 1999, the DeltaKeeper (1999) monitored DO and several other water quality parameters in the DWSC, as well as several City of Stockton sloughs. The sampling stations used in the DeltaKeeper studies are presented in Figure 22. Table 8a presents the Stockton Slough monitoring data that have been collected by the DeltaKeeper during the fall and winter 1999-2000. Examination of Table 8a shows that DO concentrations of less than 2 mg/L were found on several occasions in Mormon Slough, Five Mile Slough, Mosher Slough, and Smith Canal. Table 8b presents the Stockton Slough monitoring data developed by the DeltaKeeper for the fall of 1996. These data show that this low DO problem in the Stockton sloughs has been occurring in other years.

Figure 22



DeltaKeeper Dissolved Oxygen Sampling Sites -November 1999

1 Mosher Slough - Mariner's Drive bridge at I-5
2 Five-Mile Slough - at Plymouth Road bridge
3 Calaveras River - at Woods Bridge, north of UOP campus
4 Smiths Canal - at Pershing Avenue bridge
5 Mormon Slough - at Lincoln Street bridge
6 Walker Slough - at Manthey Road bridge and I-5 (Van Buskirk Park)
7 Smiths Canal - at Yosemite Street
8 Mormon Slough - at Turning Basin
9 Walker Slough - upstream from confluence with Duck Creek

Table 8a
Dissolved Oxygen Concentrations in Stockton Sloughs during November 1999 and January-February 2000

Mosher Slough

Date	Time	Depth (ft)	Temp (C)	DO mg/L	DO % Sat.[2]	Spec Cond[3]	Tide	Notes
11/8/99	850	3.4	14.5	8.5	86	66	low	½ rain 11/7-11/8
11/9/99	845	2.9	14.7	4.0	39	78	low	
11/10/99	1020	1.5	14.7	2.3	23	108	low	
11/11/99	1015	1.2	14.8	1.4	14	120	low	blackish brown
11/12/99	920	1.3	15.2	1.6	16	138	incoming	
11/13/99	925	1.3	15.3	1.8	18	123	incoming	
11/14/99	950	1.3	15.3	1.9	19	125	incoming	
11/15/99	920	1.3	15.3	2.5	25	142	incoming	
11/16/99	915	1.2	14.8	2.4	23	150	incoming	
11/17/99	1013	1.5	15.3	3.3	33	95	incmg/mid	
11/18/99	925	1.5	13	1.3	12	93	incmg/low	
11/19/99	850	0.6	11.8	2.0	19	104	outg/vlow	
11/20/99	830	1.3	12.7	6.4	60	57	outg/low	
11/21/99	745	1.5	12.7	5.3	50	133	outg/low	
11/22/99	900	1.2	10.1	5.5	49	131	outg/low	
11/23/99	900	1.4	10.5	4.9	44	137	outg/mid	
11/24/99	910	1.1	11	4.6	41	146	outg/low	
1/14/00	922	1	9.4	8.6	75	225	incoming	day after rain
1/19/00	904	1	11.7	6.1	57	104	low/outgoing	rain
1/20/00	1016	1	12.1	4.8	45	121	low/outgoing	rain
1/21/00	959	1	11	3.9	35	140	low/outgoing	no rain
1/22/00	958	1	11.3	4	37	161	low/outgoing	no rain
1/23/00	1012	1.5	11.6	5.5	50	147	low/outgoing	rain
1/25/00	1544	1	13.1	9.3	88	154	low/outgoing	no rain - fast, muddy flow
1/26/00	1433	0.5	12	5.9	54	199	low/outgoing	no rain
1/27/00	1442	1.5	11.5	7.4	68	184	low/outgoing	no rain
1/28/00	1411	1.5	11.6	6.3	58	194	low/outgoing	rain
2/1/00	850	1	11.1	5.4	49	139	low/outgoing	day after rain
2/2/00	1735	1	12.5	4.1	38	177	low/outgoing	no rain
2/3/00	1040	1	10.5	8.6	77	173	low/outgoing	rain
2/4/00	914	1	11.8	6.4	59	158	low/outgoing	day after rain
2/7/00	904	1	11.7	3.8	35	185	low/outgoing	3 days after rain

Five Mile Slough

Date	Time	Depth (ft)	Temp (C)	DO (mg/l)	DO% Sat	Spec Cond	Tide	Notes
11/8/99	915	1.1	14.5	6.	59	328	low	½ rain 11/7-8
11/9/99	900	0.3	13.6	0.8	8	251	low	
11/10/99	1040	0.8	14.8	1.9	19	356	low	
11/11/99	1030	0.5	15.2	3.1	31	309	low	blackish brown
11/12/99	930	1.1	14.6	2.6	26	326		
11/13/99	945	1.2	14.6	4.8	47	282	incoming	
11/14/99	1000	1.1	15.3	6	60	295	incoming	

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[2] Percent dissolved oxygen saturation

[3] Specific Conductivity in µmhos/cm at 20 C

Table 8a (continued)

11/15/99	935	1.1	15.8	6.5	66	317		
11/16/99	930	0.8	15.2	4.8	48	329		
11/17/99	1026	1	14.6	4	39	181	high/slack	
11/18/99	950	1	12.8	3	28	199	slack	
11/19/99	905	1	11	3.8	36	214	mid/outg	
11/20/99	850	0.9	12	2.9	29	126	low	
11/21/99	800	0.9	12.7	3.9	36	162	mid/incmg	
11/22/99	916	1.1	10	6.2	55	182	mid	
11/23/99	915	1.0	10.3	6.9	62	210	slack/high	
11/24/99	925	1.3	10.2	7.8	69	238	mid	
1/14/00	922	1	9.4	8.6	75	225	incoming	day after rain
1/19/00	918	1	11.8	2.4	22	150	low/outgoing	rain – oil sheen
1/20/00	1036	1	12.2	2.4	23	151	low/outgoing	rain – oil sheen
1/21/00	1012	1	10.8	2.4	21	144	low/outgoing	no rain
1/22/00	1012	1	11.7	2.8	26	178	low/outgoing	no rain
1/23/00	1026	1.5	11.5	8.7	80	67	high	rain
1/25/00	1414	1	14.6	6.7	66	109	low/outgoing	day after rain
1/26/00	1500	1	13	5.2	49	74	low/outgoing	no rain
1/27/00	1452	0.5	13	4.4	42	81	low/outgoing	no rain
1/28/00	1424	0.5	12	5.5	52	103	low/outgoing	rain
2/1/00	902	1	10	4.7	42	94	low/outgoing	day after rain
2/2/00	1719	0.5	13.6	4.2	40	96	low/outgoing	no rain – duckweed
2/3/00	935	1	10.5	8.6	77	173	low/outgoing	rain
2/4/00	930	1	11.5	6.1	57	86	low/outgoing	day after rain
2/7/00	915	0.5	11.4	4.6	42	107	low/outgoing	3 days after rain

Walker Slough

Date	Time	Depth (ft)	Temp (C)	DO mg/L	DO % Sat	Spec Cond	Tide	Notes
11/8/99	1115	1.3	15.4	6.4	64	287	low	½ rain 11/7-8
11/9/99	945	1.7	14.5	4.7	46	359	low	
11/10/99	1200	1.1	15.5	5.7	58	330	low	
11/11/99	1140	1.3	15.7	5.3	54	380	low	
11/12/99	1115	1.2	15.2	5.1	50	429	outg	
11/13/99	1115	1.3	15.2	7	70	457	outg	
11/15/99	1050	1.2	15.6	6.4	54	448	incmg	
11/16/99	1045	1.2	15.3	5.7	57	408	incmg/mid	heavy brown scum
11/17/99	1150	1.1	15.5	5.6	56	400	incmg/mid	oil circles
11/18/99	1105	1.1	14	5.9	57	351	incmg/low	
11/19/99	1225	1.1	12.5	5.6	53	390	incmg/low	rain
11/20/99	1110	0.7	13	5.6	53	185	low/slack	
11/21/99	1020	0.6	11.8	4.7	43	260	low/slack	
11/22/99	1045	0.7	9.1	7.0	61	277	incm/low	
11/23/99	1035	1.4	9.5	7.3	64	329	outg/vlow	
11/24/99	1055	1.2	9.9	7.3	64	376	outg/low	
1/14/00	1100	1	9.3	10	88	706	high/incoming	day after rain
1/19/00	1039	1	11.9	4.9	46	256	low/slack	rain
1/20/00	1153	1	12.1	5.2	49	241	low/incom	rain
1/21/00	1135	1	11.1	5.6	51	215	low/outgoing	no rain
1/22/00	1117	1	12.1	6	56	222	low/outgoing	no rain
1/23/00	1128	1	11.8	9.1	84	163	low/outgoing	rain

Table 8a (continued)

1/25/00	1544	1	13.1	9.3	88	154	low/outgoing	no rain
1/26/00	1610	1	13	9.4	89	88	low/outgoing	no rain
1/27/00	1610	1.5	12.6	9.3	88	108	low/outgoing	no rain
1/28/00	1637	1	11.3	8.2	75	140	low/outgoing	rain
2/1/00	1008	1	10.2	8	71	168	low/outgoing	day after rain
2/2/00	1559	1	12.5	9.5	89	205	slack/outgoing	no rain
2/3/00	1040	1	10.5	8.6	77	173	low/outgoing	rain
2/4/00	1053	1	11.3	8.4	77	152	low/outgoing	day after rain
2/7/00	1045	1	10.9	9.7	87	108	low/outgoing	3 days after rain

Mormon Slough

Date	Time	Depth (ft)	Temp (C)	DO mg/L	DO % Sat	Spec Cond	Tide	Notes
11/8/99	1050	1.2	15.7	8.3	83	84	low	½ rain 11/7-8
11/10/99	1135	1	16	1.3	14	165	low	
11/11/99	1130	1.1	15.9	0.7	8	185	low	blackish brown
11/12/99	1100	1.4	15.6	0.5	4.8	264	outg	
11/13/99	1100	1.5	15.5	0.6	6	269	incmg	
11/15/99	1030	1.2	15.7	2.2	22	335	incmg	
11/16/99	1030	1.1	15.4	2.0	20	349	outg	
11/17/99	1135	1.4	15.4	1.0	10	293	incmg/mid	
11/18/99	1040	1.4	14.2	0.7	7	245	incmg/mid	
11/19/99	1205	1.5	13	1.5	14	270	incmg/mid	
11/20/99	1050	1.2	14.1	3.5	34	115	incmg/low	
11/21/99	1005	1.0	13.3	2.6	25	149	low/slack	
11/22/99	1021	0.6	11.6	3.4	31	162	outg/vlow	
11/23/99	1020	1.0	10.8	3.2	29	172	slack/vlow	
11/24/99	1045	1.2	11.1	3.6	33	196	slack/low	
1/14/00	1045	1	9.5	4	35	749	high/slack	day after rain
1/99/00	1022	1	12.2	4.3	40	117	low/outgoing	rain
1/20/00	1138	1	12	3.4	32	318	low/incoming	rain
1/21/00	1120	1	11.7	3.1	29	322	low/outgoing	no rain
1/22/00	1102	1	11.8	2.8	26	456	low/outgoing	no rain
1/23/00	1117	1	11.8	9.6	89	72	low/outgoing	rain
1/25/00	1527	1	13.7	5.9	57	182	low/outgoing	no rain – oily bubbles
1/26/00	1552	1.5	12.7	4.0	38	113	low/outgoing	no rain
1/27/00	1343	1.5	12.4	3.5	33	219	low/outgoing	no rain
1/28/00	1623	1	11.6	3.4	32	281	low/outgoing	rain
2/1/00	955	1	10.6	3.1	28	305	low/outgoing	day after rain
2/2/00	1624	1.5	12.9	4.8	45	385	slack/outgoing	no rain
2/3/00	1025	1	11.3	3.7	34	336	low/outgoing	rain
2/4/00	1037	1	12.1	4.0	37	192	low/outgoing	day after rain
2/7/00	1035	1	12.1	2.7	25	278	low/outgoing	3 days after rain

Smith Canal

Date	Time	Depth (ft)	Temp (C)	DO mg/L	DO % Sat	Spec Cond	Tide	Notes
11/8/99	1020	3.1	15.7	7.7	77	272	Low	½ rain 11/7- 8
11/9/99	930	0.9	15.6	0.4	4	334	low	
11/10/99	1115	1.3	15.9	1.5	15	327	low	
11/11/99	1105	1.3	15.8	1.7	17	356	low	blackish brown
11/12/99	1045	1.4	15.8	2.9	29	411	outgoing	

Table 8a (continued)

11/13/99	1045	1.3	15.4	3.4	35	359	incoming	
11/15/99	1015	1.4	15.3	3.5	35	388	incoming	
11/16/99	1015	1.4	15.3	2.9	29	393	incom/mid	
11/17/99	1104	1.2	15	2.3	23	390	incom/mid	
11/18/99	1025	1.2	14.3	1.6	16	375	incom/low	
11/19/99	1150	1.3	13.6	1.8	18	296	incmg/mid	
11/20/99	1020	1.1	13.5	1.6	16	268	incmg/Iow	
11/21/99	950	1.4	13.3	0.7	6	279	low/slack	
11/22/99	1001	1.3	11.9	1.1	10	292	outg/low	
11/23/99	955	1.5	10.8	1.4	13	327	outg/vlow	
11/24/99	1012	1.5	11.2	1.7	15	352	outg/Iow	
1/14/00	1026	1	9.1	3.9	34	718	high/slack	day after rain
1/19/00	1004	1	11.4	5.2	48	359	low/outgoing	rain
1/20/00	1122	1	11.6	4.0	37	405	low/incoming	rain
1/21/00	1058	1	11	3.6	33	419	low/outgoing	no rain
1/22/00	1048	1	11.4	3.3	30	449	low/outgoing	no rain
1/23/00	1101	2	11.8	5.7	52	331	low/outgoing	rain
1/25/00	1501	1	13.1	8.7	83	100	low/outgoing	no rain
1/26/00	1537	1	12.9	7.0	6	60	low/outgoing	no rain
1/27/00	1357	1	12.2	5.4	50	86	low/outgoing	no rain
1/28/00	1609	1	12.4	4.8	45	121	low/outgoing	rain
2/1/00	938	1	11.1	3.5	32	169	low/outgoing	day after rain
2/2/00	1640	1	12.4	3.8	35	215	slack/outgoing	no rain
2/3/00	1010	1	11.3	3.6	33	184	low/outgoing	rain
2/4/00	1015	1	11.7	4.4	41	171	low/outgoing	day after rain
2/7/00	1018	1	11.9	3.2	30	208	low/outgoing	3 days after rain

Calaveras River

Date	Time	Depth (ft)	Temp (C)	DO mg/L	DO % Sat	Spec Cond	Tide	Notes
11/8/99	1000	2.2	14.9	9.1	90	101	low	½" rain 11/7-11/8
11/9/99	915	1.1	14.6	4.8	47	126	low	
11/10/99	1055	0.8	14.9	4.0	40	136	low	
11/11/99	1050	1.9	14.8	3.5	35	151	low	blackish brown
11/12/99	1030	2.1	15.0	2.9	29	153		
11/13/99	1030	2.1	14.8	3.2	32	133	outgoing	
11/14/99	1020	2.0	14.9	3.4	34	137	incoming	
11/15/99	1000	2.1	15.0	3.9	39	152	incoming	
11/16/99	1015	2.2	14.9	4.2	42	161	incoming	
11/17/99	1050	1.4	14.7	5.4	54	176	incom/mid	
11/18/99	1010	1.4	14.0	4.8	47	175	incmg/low	
11/19/99	920	2	13	5.1	48	175	incmg/vlow	
11/20/99	850	1.0	12.9	8.6	82	160	incmg/low	
11/21/99	830	0.6	12.7	7.2	68	169	incmg/low	
11/22/99	951	1.5	11.5	7.6	70	169	outg/low	
11/23/99	935	2.0	10.9	8.2	75	182	outg/vlow	
11/24/99	1000	2.1	10.6	8.4	76	187	outg/low	
1/14/00	1009	1	9.5	4.6	40	212	high/incoming	day after rain
1/19/00	942	1	11.8	8.8	81	170	low/outgoing	rain
1/20/00	1100	1	12.1	9.9	92	199	low/outgoing	rain
1/21/00	1044	1	11.4	9.9	91	177	low/outgoing	no rain

Table 8a (continued)

1/22/00	1032	1	11.3	10.2	93	198	low/outgoing	no rain
1/23/00	1047	1	12.1	10.2	95	152	low/outgoing	rain
1/25/00	1440	1	12.7	10.3	97	198	low/outgoing	no rain
1/26/00	1524	1	12.6	10.7	100	118	low/outgoing	no rain
1/27/00	1422	1	12.1	11.0	103	149	low/outgoing	no rain
1/28/00	1555	1	11.2	11.1	101	191	low/outgoing	rain
2/1/00	924	1	10.3	11.5	103	229	low/outgoing	day after rain
2/2/00	1655	1	11.5	11.6	106	189	slack/outgoing	no rain
2/3/00	1000	1	11.2	11.8	107	205	low/outgoing	rain
2/4/00	955	1	11.4	11.7	107	198	low/outgoing	day after rain
2/7/00	940	1	11.1	11.7	42	107	low/outgoing	3 days after rain

Table 8b
Monitoring of Stockton Sloughs, 1996

Mosher Slough

Date	Time	Depth (ft)	Temp (C)	DO (mg/l)	DO %	Spec Cond	Tide	Weather
10/15/96	1405	1.5	16.3	9.3	97	274	Out-Low	Clear
10/29/96	1250	1.3	13.6	9.9	96	215	Out-Low	Raining
10/29/96	1307	2.4	13.5	9.7	95	215	Out-Low	Raining
10/30/96	1345	1.8	13.4	9.4	90	253	Out-Low	Partly Cloudy
10/31/96	1447	2.4	13.1	5.5	54	224	Out-Low	Overcast
11/1/96	1010	3.6	13.1	4.1	39	233	In-High	Sunny
11/1/96	1643	2.3	13.1	6.5	62	180	Out-Low	Clear
11/1/96	1648	2.3	13.5	5.7	55	202	Out-Low	Clear
11/2/96	1400	2.8	13.1	5.8	56	242	Out-High	Overcast
11/3/96	1615	2.8	12.4	6.0	56	190		Partly Cloudy
11/8/96	1105	2.2	12.7	8.0	75	219	Low-In	Clear and Warm

Five Mile Slough

Date	Time	Depth (ft)	Temp (C)	DO (mg/l)	DO %	Spec Cond	Tide	Weather
10/15/96	1425	1.6	22.3	9.4	110	838	Out-Low	Clear
10/29/96	1335	1.4	13.9	9.5	84	365	Out-Low	Raining
10/30/96	1404	1.7	13.9	5.9	60	165	Out-Low	Partly Cloudy
10/31/96	1504	2.2	14.2	0.86	8.5	255	Out-Low	Overcast
11/1/96	1143	1.9	13.3	0.31	2.9	288	In-High	Sunny
11/1/96	1705	2.0	14.6	0.25	2.5	285	Low	Clear
11/2/96	1345	2.0	15.0	0.55	5.5	339	Out-High	Overcast
11/3/96	1630	2.1	15.5	4.2	42	391		Partly Cloudy
11/8/96	1120	1.7	13.7	10.6	102	452	Low-In	Clear and Warm

Smith Canal

Date	Time	Depth (ft)	Temp (C)	DO (mg/l)	DO %	Spec Cond	Tide	Weather
10/15/96	1500	5.1	20.9	9.3	107	1393	In-Low	Clear
10/15/96	1500	2.0	21.6	11	126	1383	In-Low	Clear
10/29/96	1645	4.8	13.8	10	97	966	In	Raining
10/30/96	1432	3.4	14.1	6.7	69	384	Out-Low	Partly Cloudy
10/31/96	1535	3.5	13.6	0.6	5.6	387	Out-Low	Partly Cloudy
11/1/96	1237	4.9	13.1	0.3	3.3	533	Out-High	Sunny
11/1/96	1734	3.7	13.5	0.2	2.1	466	In-Low	Clear

Table 8b (continued)

11/2/96	1441	4.2	13.0	0.3	2.6	470	Out-High	Partly Cloudy
11/3/96	1655	4.3	12.8	0.2	2.4	473		Partly Cloudy
11/8/96	1138	5.8	12.2	2.7	26	602	Low-In	Clear and Warm

Calaveras River

Date	Time	Depth (ft)	Temp (C)	DO (mg/l)	DO %	Spec Cond	Tide	Weather
10/15/96	1444	3.7	21.1	6.7	79	959	Out-Low	Clear
10/29/96	1525	6.3	13.8	9.1	88	549	In-Low	Raining
10/30/96	1541	4.6	13.1	7.7	77	486	In-Low	Partly Cloudy
10/31/96	1707	3.3	13.8	2.4	23	487	In-Low	Partly Cloudy
11/1/96	1550	3.1	13.3	1.0	10	323	Out-Low	Clear
11/1/96	1557	6.4	13.0	1.0	9.5	303	Out-Low	Clear
11/1/96	1600	11.0	12.8	0.9	8.9	296	Out-Low	Clear
11/2/96	1552	3.3	13.3	1.2	12	333	Out-Low	Partly Cloudy
11/2/96	1559	6.4	13.3	1.2	12	333	Out-Low	Partly Cloudy
11/2/96	1605	11.3	13.3	1.2	11	332	Out-Low	Partly Cloudy
11/8/96	1020	5.0	12.6	5.3	50	429	Low-In	Clear and Warm
11/8/96	1028	9.2	12.4	4.9	46	427	Low-In	Clear and Warm

Duck Creek

Date	Time	Depth (ft)	Temp (C)	DO (mg/l)	DO %	Spec Cond	Tide	Weather
10/15/96	1515	1.7	20.4	12.3	140	462	In-Low	Clear
10/29/96	1715	2.9	13.1	8.8	84	385	In	Raining
10/30/96	1500	1.6	14.4	6.2	62	411	In-Low	Partly Cloudy
10/31/96	1555	2.0	14.4	4.1	40	380	Low	Partly Cloudy
11/1/96	1300	3.6	13.8	3.1	30	471	Out-High	Sunny
11/1/96	1800	2.7	14.2	4.6	45	416	In-Low	Clear
11/2/96	1507	3.4	14.3	5.6	50	451	Out-High	Partly Cloudy
11/3/96	1718	3.2	14.1	6.3	62	485		Partly Cloudy
11/8/96	1145	2.1	12.8	8.2	77	616	Low-In	Clear and Warm

Chen and Tsai (2000) conducted a limited study of dissolved oxygen depletion in Smith Canal (which is one of the Stockton sloughs) after stormwater runoff events. The purpose of this study was to evaluate the reasons for the dissolved oxygen depression in Smith Canal that occurs after stormwater runoff. Smith Canal is a dead-end slough connected to the San Joaquin River opposite Rough and Ready Island. It receives stormwater inflow from an urban area of Stockton. During or soon after a stormwater runoff event, the water quality in Smith Canal is sufficiently deteriorated so that fish kills have occurred. Smith Canal has a drainage area of 3,300 ac., with 50 percent residential, 18 percent commercial and 26 percent streets. The institution and industrial activities occupy about six percent. In the late 1990s the City of Stockton conducted a multi-year monitoring program to measure stormwater input and water quality response in Smith Canal.

In the Chen and Tsai (2000) studies, the dissolved oxygen in Smith Canal decreased to about 1 mg/L about two days after initiation of the stormwater runoff event. It was found that the sediments in Smith Canal had an oxygen demand of about 0.3 g/ft^2/day, which translates to about 3 g/m^2/day, which is in the high range of SOD for waterbodies.

Chen and Tsai (2000) applied the Stockton SJR DO Model to the DO depletion that occurs after runoff events. The Stockton SJR DO Model was modified to include sediment scour transport and deposition of scoured particles. Further, a routine was added to the model to account for the oxygen demand of the scoured sediments. Chen and Tsai (2000) were able to tune the model so that it tracked reasonably closely the DO depletion. They concluded that the primary cause of DO depletion at the dead-end part of Smith Canal was constituents present in the urban stormwater discharged to this point. They also concluded that the primary cause of dissolved oxygen depletion is the scour of the sediments and the oxygen demand associated with the sediments.

Chen and Tsai (2000) found that the BOD_5 in stormwater runoff to Smith Canal ranged from 12 to 19 mg/L. They concluded that the BOD was not the cause of the DO depletion that occurs in Smith Canal, that the cause for this depression was due to scouring and resuspension of sediments from the channel (Smith Canal) bottom, as well as scouring and resuspension of sediments present in the storm sewers that discharge to Smith Canal. It was found that the DO in Smith Canal recovered from the depression more than five days after the storm. They concluded that the impact of DO depletion was on aquatic life within Smith Canal and there was little impact on the San Joaquin River Deep Water Ship Channel into which Smith Canal discharges.

The City of Stockton study is important to the SJR DO TMDL development and implementation, since it provides data on the chemical characteristics of urban stormwater runoff. Table 9 presents the median event mean concentrations of various constituents in the stormwater runoff.

Table 9
Median Event Mean Concentrations of Various Constituents in the Stockton Stormwater Runoff

Constituents	Units	Residential (n=30)	Commercial (n=11)	Industrial (n=10)
Hardness	mg/L	21	17	39
TSS	mg/L	51	90	211
TDS	mg/L	65	52	101
BOD	mg/L	13	12	19
Coliform	MPN/100	1.45e5	1.09e5	1.07e5
Fecal	MPN/100	2.45e4	1.66e4	9.37e3
TKN	mg/L	2.1	2.0	2.7
Nitrate	mg/L	0.46	0.55	0.82
Total N	mg/L	2.61	2.52	3.59
Ammonia-N	mg/L	0.54	0.73	0.70
Total P	mg/L	0.365	0.35	0.67

(adapted from Chen and Tsai, 1999)

It is of interest to find that the stormwater runoff from Stockton contained about 0.5 mg/L of nitrate, presumably as NO_3, although not specified in the table, and about 0.5 mg/L of ammonia nitrogen. The total Kjeldahl nitrogen, which is the organic nitrogen plus ammonia, was about 2 to 3 mg/L N. The total phosphorus content was about 0.4 mg/L P. Unfortunately, no measurements of soluble ortho-P were made. The five-day BODs ranged from 12 to 19 mg/L. The suspended solids ranged from about 50 to about 200 mg/L. The conclusion from this is that the stormwater runoff in Stockton has a significant potential to cause fertilization of waterbodies; however, when examined compared to the concentrations of nitrogen and phosphorus in the DWSC during the summer and fall, it would actually dilute the concentrations in the channel.

It would be of interest to compare the N and P export coefficients derived from the City of Stockton Smith Canal watershed studies to those reported by Rast and Lee (1983) for urban areas located in various parts of the US. At this time, there is insufficient information available to estimate nutrient export coefficients for the City of Stockton stormwater runoff. It is believed that this data could be developed from the City of Stockton's NPDES permit-related stormwater runoff monitoring required as part of the City having a population greater than 100,000. As discussed in a subsequent section of this report, Rast and Lee (1983) reported average urban area nutrient export coefficients of about 0.25 g/m^2/year N and 0.1 g/m^2/year P.

In July 1999 Camp, Dresser and McKee (CDM, 1999) issued a technical memorandum entitled, "Assessment of Water Quality Data from Smith Canal," which is appended to the Chen and Tsai (2000) report. This memorandum is designed to be a follow-up to the work of Chen and Tsai. In addition to examining the results of the Chen and Tsai studies, CDM also conducted a review of the past City of Stockton stormwater monitoring and Smith Canal water quality characteristic data. The CDM review primarily focused on the water quality characteristic monitoring of the Smith Canal that the City of Stockton has done over recent years. This monitoring included continuous recording of several parameters, including dissolved oxygen, water depth, pH, specific conductivity, and temperature.

CDM (1999) reported, based on a review of both winter and summer data on Smith Canal, that low DOs were also encountered during summer non-stormwater runoff event periods. Generally, poorer water quality was found during the wet season. CDM reported large diel variations in DO of about 2 to sometimes as large as 10 mg/L, indicating high levels of algal photosynthesis and microbial respiration.

Lehman (2000) collected data on Smith Canal and Calaveras River water quality characteristics during August and September 1999 as part of the SJR DO TMDL TAC fall 1999 studies. She reported DOs below the water quality objectives for Smith Canal; however, the Calaveras River just upstream of where it enters the DWSC had DO concentrations during August and September below WQOs. Lehman also reported chlorophyll and phaeophytin concentrations for Smith Canal and Calaveras River. The concentrations ranged from about 5 µg/L to almost 40 µg/L, with the majority of the values in the 10 to 20 µg/L range.

It is evident that there is need to determine if the water quality conditions that exist in the Stockton sloughs during the summer and fall influence the dissolved oxygen depletion problem that exists in the DWSC, and vice versa - whether the low DO conditions in the DWSC aggravate the poor water quality conditions that have been found in the Stockton sloughs. While the dissolved constituents of stormwater runoff to the Stockton sloughs are not likely a significant cause of the DWSC summer-fall DO depletion problems, it is possible that the particulate oxygen demand from the City of Stockton stormwater runoff is a factor contributing to the SOD of the DWSC.

TMDL DO Concentration Goals

One of the most important components of the TMDL development process is the establishment of the TMDL goal.. Typically the TMDL goal is the elimination of WQO violations and full protection of beneficial uses. The CVRWQCB (1994) Basin Plan requirements for maintaining DO in the region of interest's waters are the following:

> ***"Dissolved Oxygen Water Quality Objective***
>
> *Within the legal boundaries of the Delta, the dissolved oxygen concentration shall not be reduced below:*
>
> *"6.0 mg/L in the San Joaquin River (between Turner Cut and Stockton, 1 September through 30 November); and 5.0 mg/L in all other Delta waters except for those bodies of water which are constructed for special purposes and from which fish have been excluded or where the fishery is not important as a beneficial use."*

A worst-case, most strict/protective interpretation of the DO WQO implementation requires that the DO concentration shall not be less than the objective by any amount more than once every three years at any location and time. It is the experience of the authors that the strict, worst-case implementation of the DO WQO is not applied in this manner by states or the US EPA. It is possible that an "average" DO concentration be established as the TMDL DO objective to reflect the ± 1 to 2 mg/L diel changes in surface waters due to algal photosynthesis and microorganism respiration. An "average" DO concentration could also consider the near sediment water interface sediment oxygen demand which causes DO depletion in the water column. How the dissolved oxygen WQO is defined will influence how millions of dollars will be spent in controlling oxygen demand loads to the SJR DWSC to achieve the DO TMDL goal.

The US EPA (1976, 1986, 1987), the National Academies of Science and Engineering (1973) and the American Fisheries Society (AFS, 1979) have conducted detailed reviews of the impact of dissolved oxygen concentrations on aquatic life. A copy of the information provided by the US EPA (1976, 1986, 1987), NAS/NAE (1973) and AFS (1979) is provided in Appendix F. These reviews have served as the basis for the US EPA's current dissolved oxygen national water quality criterion of 5 mg/L. They provide background information pertinent to understanding the development of the US EPA (1987) "Goldbook" DO criteria. The US EPA (1986) "Ambient Water Criteria for Dissolved Oxygen," (freshwater) presents the information used by the US EPA to develop the 1987 national criterion of 5 mg/L. The US EPA (1987) provides guidance on how this criterion is to be implemented with respect to some aspects of averaging DO concentrations found in a waterbody.

The US EPA (1986) has indicated that the primary impact of DO concentrations below 5 mg/L but above about 3 to 4 mg/L is a reduced rate of fish growth. DO concentrations below about 3 to 4 mg/L are acutely toxic (lethal) to some forms of fish. Generally, the studies that have been conducted on the impact of low DO concentrations on rate of fish growth were conducted over extended periods of time. The conditions that exist in the DWSC of part of the day or several days to a few weeks of DO concentrations below 5 mg/L but above 4 mg/L have not been evaluated to determine the impact on fish growth rates. The water quality – beneficial use impairment significance associated with DO excursions below 5 mg/L, that can occur due to algal diel photosynthetic activities, as well as the DO depletions near the sediment water interface, needs to be examined to assess the improvement in the beneficial uses of the San Joaquin River DWSC and the Delta associated with achieving oxygen demand control so that the DO depletion within the DWSC does not violate the WQO at any time and location. Also the adverse impact of average water column DO concentrations below 5 mg/L but above about 4 mg/L for a few days to a few weeks such as occurs in the DWSC needs to be evaluated.

The issue of how the DO water quality objective should be applied has been a long-term problem for regulatory agencies and dischargers. Delos (1999) of the US EPA, Criteria and Standards, Washington DC headquarters has indicated that at this time the US EPA does not provide guidance on how to consider diel (night/day) DO changes and changes with depth, especially near the sediment water interface, in implementing the DO water quality standard. A survey of the practice of other states in implementing the DO water quality standard should be conducted to examine how the US EPA Regions have allowed states to average DO concentrations in implementing the criterion. This information could be important in establishing the range of conditions that have been allowed for averaging diel DO concentrations and those near the sediment water interface relative to the water column.

An important aspect of the SJR DWSC DO TMDL development is a critical evaluation of the validity of the 6 mg/L DO water quality objective adopted by the SWRCB in 1994 as a significant barrier to Chinook salmon migration to their home waters within the SJR watershed. The 1970s studies conducted by the Department of Fish and Game (Hallock, *et al*., 1970) stated in the abstract that,

> *"Salmon avoided water with less than 5 ppm dissolved oxygen by staying farther downstream until the oxygen block cleared. Temperatures over 66° F. had a similar but less sharply defined effect."*

Further, the Recommendations section of the report stated,

"RECOMMENDATIONS

To insure adequate upstream passage for San Joaquin salmon, the following should be provided:

- *a. A minimum positive flow past Stockton of 400 cfs of San Joaquin water, or enough to raise the dissolved oxygen level to 5 ppm, after October 1, whichever is greater, and*
- *b. A minimum positive flow in the San Joaquin River past Turner Cut (consider 200 cfs as a first approximation).*
- *c. A barrier at the head of Old River whenever it appears to be needed, but that barrier should never be a total block to salmon migrating up Old River.*

d. Release of water from the Delta-Mendota Canal into the San Joaquin River above Mossdale when necessary, but only when the Old River barrier is in place.

The above flows past Stockton and Turner Cut are considered to be minimal, and should be exceeded whenever San Joaquin run-off permits."

There appears to be a contradiction between the current CVRWQCB Basin Plan requirement of a minimum 6 mg/L DO between September 1 and November 30, which is supposed to be based on the Hallock, *et al*. (1970), report, and the information provided in this report. There is need to clarify why the State Water Resources Control Board changed the recommendation of Hallock, *et al*., from a 5 mg/L minimum DO to 6 mg/L.

The inhibition of Chinook salmon migration studies need to be redone in light of current DWSC characteristics and technologies associated with doing such studies to determine if there is a significant inhibition of the Chinook salmon migration that occurs in late summer and fall that is due to DO depletions below 6, or even 5, mg/L. The water quality characteristics in the 1970s within the SJR DWSC were likely significantly different from those that are being experienced today. In the 1970s, there could readily have been a variety of other factors which co-occurred with low DO (low flow, high temperatures, etc.) which were the real cause of the apparent Chinook salmon migration inhibition. Of particular concern would be toxicants which were discharged at that time from municipal and industrial wastes or agricultural runoff, including pesticides, which inhibited Chinook salmon migration or constituents which caused the salmon to lose its ability to find its home waters, especially under low-flow conditions, where the chemical signal of the home waters is weak.

Mesick (2000a,b) has recently reviewed the "Factors that Limit Fall-Run Chinook Salmon in the San Joaquin River Tributaries." Based on his review, there is a relatively poor understanding of how each of the factors that could limit Chinook salmon migration during the fall actually impact the migration. There is need to critically examine the apparent contradiction that is occurring today, where a fall run of Chinook salmon is being found in San Joaquin River tributaries under conditions where these salmon must have passed through or around the DWSC at times when the DO was less than 6 mg/L. It is possible that the salmon are bypassing the DWSC through Old River. This needs to be investigated as part of determining how the fall run of salmon that is occurring relates to low dissolved oxygen and other conditions within the DWSC.

Sommer (1999) of the DWR reported on studies that he is conducting on the fall migration of Chinook salmon in the Yolo Bypass Toe Drain. While Chinook salmon are migrating up the Toe Drain to Putah Creek during the fall, unfortunately, no information is available on whether the DO concentrations in the Toe Drain waters were below 6 mg/L. Based on the characteristics of these waters, it is likely that DOs less than 6 mg/L occur in the Toe Drain, especially in the early morning hours. This is an area where expansion of the DWR (Sommer) studies to include DO measurements could provide information that would be of assistance in determining whether DO depletions below 6 mg/L are a significant barrier to the homing of Chinook salmon.

It is possible that the costs of achieving the worst-case 6 mg/L WQO at any SJR DWSC location and time may be so great as to preclude achieving this TMDL goal. Under these conditions, a modification of the designated beneficial uses of the critical reach of the DWSC to allow an “average” DO WQO to be established may be appropriate, especially if it is found that a substantial fall run of Chinook salmon occurs under the current conditions.

The issue of implementing the 5 mg/L DO WQO near the sediment water interface is an area that also needs attention. Many waterbodies have sediments that naturally have zero DO just below the sediment water interface. This situation can occur under limited mixing in the water column just above the sediment water interface. Typically any DO depletion at any depth including that at the sediment water interface could be interpreted as a violation of the 5 mg/L WQO. Such an interpretation would lead to an unachievable TMDL goal. Further no state is known to use this strict interpretation. There is need for the SJR DO TMDL Steering Committee/stakeholders to work with the CVRWQCB, SWRCB, and the US EPA Region 9/ Washington DC to develop an appropriate TMDL DO goal for the SJR DO TMDL.

C. Foe of the CVRWQCB has indicated that the CVRWQCB plans to work with the fisheries resource agencies (CA Department of Fish and Game, National Marine Fisheries, the Fish and Wildlife Service, the US EPA Region 9 and others, as appropriate) in conducting a review of the appropriate approach for developing a SJR DWSC TMDL DO goal and its implementation with respect to diel changes in DO and changes near the sediment water interface.

Review of the Stockton SJR DO Model

The Schanz and Chen (1993) Stockton SJR DO Model of the relationships between oxygen demand loads to the DWSC and DO depletion in the DWSC was developed to guide the City of Stockton and regulatory agencies on the amount of treatment needed of the City's domestic wastewaters prior to discharge to the SJR. The complex character of the oxygen demand load - oxygen depletion response relationships that exist for the SJR DWSC makes the use of this type of model essential. This modeling approach uses a set of differential equations that represent the dominant processes that govern the relationship between oxygen demand loads to a waterbody and the DO depletion below saturation. Each equation has a rate constant (coefficient) that determines the rate of the reaction/process. The input of oxygen demand load and other information and the selection of appropriate modeling coefficients with the simultaneous solution of the equations leads to predictions of the oxygen depletion that will occur in the system being modeled. Included within the modeling coefficients are the relationships of how the processes are influenced by temperature of the water. Temperature can have a significant impact on the rate of some of the processes that influence how an oxygen demand load impacts DO concentrations.

While there are other types of modeling approaches including microcosms, these types of models are not reliable for predicting the oxygen demand constituent load control needed to achieve a specified DWSC DO concentration The Stockton SJR DO modeling approach is typical of the modeling approaches used today to address complex oxygen demand load DO concentration relationships. This modeling approach is the approach that the US EPA and others recommend (Ambrose *et al.*, 1988, 1993a,b; US EPA 1997; Chapra 1997). The US EPA (1997) and Bowie *et al*. (1985), have compiled the rate constants that are typically used in this type of modeling. A key component of model development is adjusting the modeling coefficients (tuning) so that there is good agreement between the model output and field collected data. Normally the tuning of the model involves the selection of modeling coefficients that are in the range of the typically "acceptable" range of values. Usually there are a range of model coefficients that can be used to cause the model output to match the field data.

One of the issues of concern is the verification of the model's reliability in predicting how the DO depletion will change if the oxygen demand or other factors that influence DO depletion such as flow and channel geometry are changed. While models of this type can be tuned to data sets for the system being investigated, there is no way to verify *a priori* that the model will reliably predict oxygen concentrations if the load of oxygen-requiring substances is changed. This results in the need to use a phased TMDL implementation approach. The recommended approach involves tuning the model to best fit the existing load - response data to develop a Phase I TMDL. This TMDL is adjusted for a margin of safety and is adopted as the oxygen demand load reduction that must be shared among all stakeholders.

The allocated oxygen demand loads are implemented and an intensive monitoring program is initiated to determine if the WQO is met. If not, the model is refined with the new information obtained during the Phase I monitoring and a revised TMDL is developed. The Phase II oxygen demand loads are implemented and the system is again monitored. If the WQO is not achieved in Phase II then a Phase III and possibly IV will be needed. The phased approach leads to model verification about five years after the allowable loads are fully implemented. For the SJR DWSC DO depletion, the model verification will likely take place in about ten years from now. While this approach has considerable uncertainty, it is the current state of science/engineering in TMDL development. Further, this approach is in accord with approaches that are typically being used today and supported by CALFED of "adaptive management," where the information obtained through further studies under conditions where a management program has been implemented are used to adjust this program to most cost-effectively manage the water quality problem of concern.

The CVRWQCB requested that the US EPA Region 9 review the Stockton SJR DO Model. Dannel and Tate of the US EPA (1999b) reported that they found, based on SJR DWSC 1991 data, that the Schanz and Chen (1993) Stockton SJR DO Model provided good agreement between DWSC measured characteristics and the model results. They commented that there are a number of areas where there is need for further clarification and model refinement. Examination of the model results (Chen and Tsai, 2000) for the DO depletion that occurred in the DWSC during August and September 1999, using August and September oxygen demand loads, showed that the model tended to be about 1 mg/L high in simulating the predicted DO compared to the measured DO. Further, there were a number of situations where the model results did not predict the measured DO very well. Some measured DO data were several mg/L different (usually lower) from the model's simulated values. These modeling runs were based on using the model tuned to 1991 conditions with 1999 load and flow information. It is evident that there is need to refine and tune the model so that it better predicts the DO depletions over the different flow and oxygen demand load conditions that are occurring now.

A sensitivity analysis of the Stockton SJR DO Model should be conducted to evaluate those components of the model that are most critical to properly coupling oxygen demand loads and DO depletion as a function of other factors that influence this coupling, such as SJR flow. The results of a sensitivity analysis in which the various input parameters and modeling coefficients are varied within expected ranges and the model output is examined with respect to how changes in the input variables and coefficients affect output can be used to guide areas that need additional attention in both field studies and model refinement/tuning.

In addition to considering changes in modeling coefficients that were recommended by Dannel and Tate (US EPA, 1999b) there is need to review the differences in the modeling coefficients used in the Stockton SJR DO Model and those reported by Litton (2000). Also of concern is the Stockton SJR DO Model use of a factor of 1.5 between BOD_5 and BOD_u. Litton (2000) recommends that this factor be 2.5. This difference may be due to the algae and ammonia/orgN as a source of oxygen demand.

These issues need to be reviewed with appropriate changes made in the model. There will likely be need for additional laboratory and field data on these relationships before they can be resolved. A suggested approach for Stockton SJR DO Model refinement is presented below.

Previous Estimates of Allowable Oxygen Demand Loads

Brown and Caldwell (1970) issued a report entitled “City of Stockton; Main Water Quality Control Plant; 1969 Enlargement and Modification Study; Part 2; Benefits of Proposed Tertiary Treatment to San Joaquin River Water Quality.” A review of this report shows that essentially all of the issues that were addressed in the fall 1999 Technical Advisory Committee rough-cut analysis had previously been addressed by Brown and Caldwell in 1970.

Brown and Caldwell’s (1970) report was devoted to evaluating the allowable oxygen demand load to the San Joaquin River Deep Water Ship Channel. This report addresses many of the same issues that were addressed by the TAC in 1999. Brown and Caldwell clearly established that upstream of Vernalis was a significant cause of oxygen depletion within the DWSC. Further, using a modeling approach that was somewhat similar to the Stockton SJR DO Model, although not as sophisticated, they established that the allowable oxygen demand load (ultimate BOD) was about 50,000 lbs/day to avoid violations of the 5 mg/L DO WQO for the SJR DWSC.

Brown and Caldwell (1970) discussed the residence time flow issues that are important to evaluating the impact of oxygen demand loads on DO depletion in the DWSC. They reported that the planktonic algal chlorophyll in the SJR at Vernalis typically ranged from about 50 µg/L to over 200 µg/L. They used a sediment oxygen demand of 1 g/m^2/day in their calculations and reported a DWSC photic zone, where photosynthesis could take place, of about 4.5 feet.

The studies of McCarty (1969) conducted in the late 1960s, that were discussed earlier in this report, established that the ultimate BOD for the SJR at Vernalis and in the DWSC was expressed over at least a 30-day period. This was the approach used in the Brown and Caldwell modeling of DWSC oxygen demand/DO depletion relationships. Similar results had been previously reported by Ball (1987) and recently by King (2000) and Litton (2000), as part of the current studies.

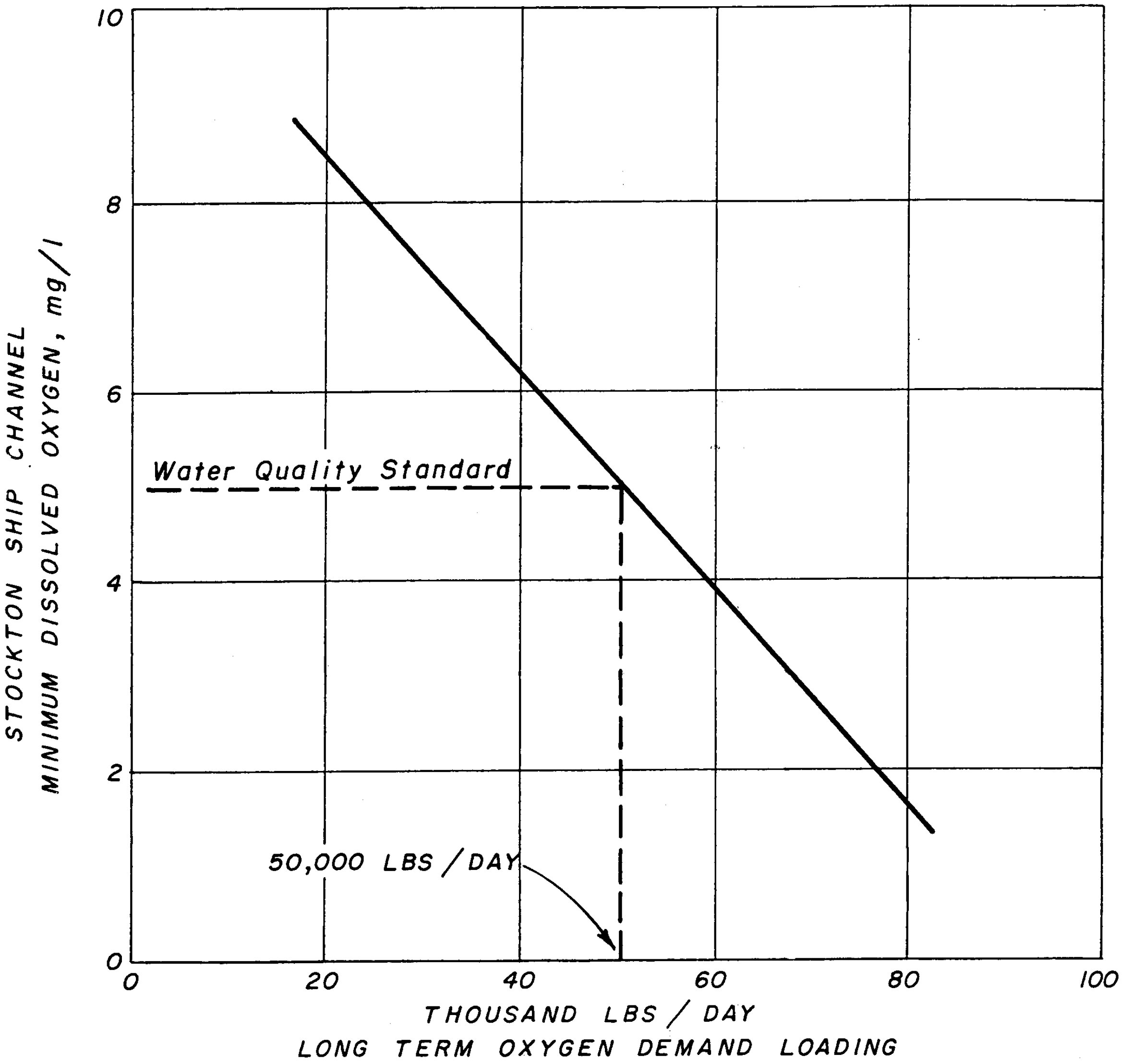
Using the relationship developed by Brown and Caldwell between allowable dissolved oxygen concentrations in the DWSC and BOD_u (see Figure 23), it is found that meeting the 6 mg/L DO objective would have an allowable oxygen demand load of about 40,000 lbs/day. At the time of the Brown and Caldwell study, the DWSC had a depth of 30 feet (this was prior to the dredging to 35 feet), and the City of Stockton was discharging domestic wastewaters which contained high levels of BOD in the form of algae. The city was not then filtering the wastewater effluent to remove the algae before discharge to the SJR. At that time, Brown and Caldwell reported that the daily oxygen demand load during the summer-fall was about 100,000 lbs/day of long-term BOD. The estimated load during August-September 1999 was 70,000 to 80,000 lbs/day. The difference is primarily related to the improved wastewater treatment practiced by the City of Stockton that is occurring today, compared to the late 1960s. Some of this difference may also be due to improved agricultural practices within the SJR watershed.

From the information that has evolved out of the development of this issues report, it appears that a Phase I TMDL allowable load of oxygen-demanding materials on the order of 30,000 to 40,000 lbs/day will need to be established. This Phase I load must include the US EPA required “safety factor” associated with TMDL development. Based on the September-October 1999 data for oxygen demand load DO depletion response, it appears that some of the dischargers of oxygen demand and nitrogen and phosphorus upstream of Vernalis face reducing their discharge loads by at least 50 percent during early summer through November. For now, this magnitude of reduction of oxygen demand load to the DWSC should be considered an initial planning purpose value, which will be refined when the Stockton SJR DO (Chen) model is appropriately modified and tuned to the range of the 1990s data.

As discussed in this report, even with a 50 percent reduction in nitrogen, phosphorus, and BOD loads from various sources, the residual oxygen demand load may be excessive enough, under certain SJR into DWSC flow regimes, to cause violations of the worst-case application of the 5 and 6 mg/L DO water quality objective. As has been indicated, it is extremely important that an understanding of the relationship between flow into the DWSC and oxygen depletion below a WQO within the DWSC be established in the near future. This relationship will help guide the development of studies that will provide the information needed to guide the development of programs to eliminate WQO violations in the most cost-effective manner. With information that documents how flow impacts DO depletion below a WQO for a certain magnitude of oxygen demand load and season, it may be possible to adjust SJR flow into the DWSC to reduce the magnitude of worst-case DO depletion.

Figure 23

Adapted from Brown and Caldwell (1970)



Assimilative Capacity of the San Joaquin River, Turner-Cut to Turning Basin

While the allowable oxygen demand load is dependent on the amount of SJR flow at Vernalis that enters the DWSC and the season (i.e., summer versus late fall), for initial planning purposes, until such time as flow control assurances can be provided, it will likely be necessary to assume worst-case flow conditions as one of the conditions that will have to be met in establishing the Phase I TMDL allowable oxygen demand load. Also, in developing the Phase I TMDL, it will likely be necessary to assume that the control of the oxygen demand load to the DWSC from external sources will need to eliminate worst-case DO depletion. Further review of the summer-fall 1999 data developed by Lehman and Ralston (Lehman, 2000) shows that DO depletion near the sediment water interface is often the worst-case situation.

Recommended Approach for Developing Oxygen Demand SJR DWSC TMDL

One of the objectives of the rough-cut (initial) oxygen demand source/impact analysis of SJR DWSC loads is to develop guidance on the approach that the SJR TAC should follow in developing the TMDL of oxygen demand substances for the SJR DWSC. The development of the total oxygen demand TMDL is the primary task of the SJR DO TMDL Technical Advisory Committee. Rather than proceed to collecting additional data with the support of the CALFED grant and other sources of funding, and then develop the TMDL based on the additional data, it is recommended that the current information be used to develop a first-cut TMDL. Once the initial TMDL has been established, then work can begin on defining the relative significance of each of the oxygen demand sources that must be included in the implementation of the TMDL. Of particular importance is developing an understanding of how oxygen demand loads from a particular source in the SJR DWSC watershed influence the oxygen depletion in the DWSC.

Focusing on TMDL development will reveal additional information needed to formulate the TMDL to eliminate the DO depletions below the water quality objective. This information will be used to formulate the studies that are needed to refine the TMDL oxygen demand loads. The proposed approach would focus the CALFED and other funds available on those areas which are determined, based on the current information, to be of the greatest importance to controlling the DO depletion problem in the DWSC.

The components of the recommended approach for future TAC activities focusing on TMDL development and implementation are presented below.

- The SJR TAC should appoint a small modeling subcommittee to work with Chen to refine the current Stockton SJR DO Model so that it better simulates the DO depletions that have occurred in the 1990s.

  Particular attention should be given to relating SJR algal loads and City of Stockton BOD/NH_3/orgN loads to the DWSC as a function of SJR flow into the DWSC. It should be possible to develop a relationship between SJR UVM flow into the DWSC, chlorophyll/BOD concentrations at Vernalis, City of Stockton BOD and NH_3/orgN concentrations and oxygen demand load to the DWSC.

- The SJR TAC should work with the CVRWQCB and the State Water Resources Control Board (SWRCB), US EPA Region 9, CA Department of Fish and Game, National Marine Fisheries, the Fish and Wildlife Service and others, as appropriate, to resolve the issue of worst-case DO WQO implementation versus the average water column/time of day DO depletion as the TMDL DO goal.

  Since this issue is not likely to be easily resolved, there will be need to develop a relationship between the average DO depletion calculated by the Stockton SJR DO Model and the worst-case time of day and water column depth depletion.

  The results of this activity should enable calculation of the relationship between oxygen demand loads to the DWSC as a function of dominant factors (flow, chlorophyll/BOD at Vernalis and the City of Stockton BOD/NH_3/orgN loads) and the average and worst-case DWSC DO depletion. Special studies may be needed to collect some of these data.

Initiation of TMDL Oxygen Demand Load Allocation

Since it will likely be early 2001 before a preliminary TMDL of oxygen-demanding substances will be developed, it is suggested that the SJR DO TMDL Steering Committee should begin to discuss the allocation of the oxygen demand loads among stakeholders, using a "straw man" TMDL load. It is suggested, based on the 1999 studies and the Brown and Caldwell (1970) studies, that an oxygen demand load to the SJR DWSC of about 30,000 lbs/day of BOD_u be used as the "straw man." It is understood that this value is a starting point for discussions and will likely change somewhat as additional information is obtained through the CALFED and other studies.

The SJR DO TMDL stakeholders who discharge oxygen demand and/or nutrients to the SJR or its tributaries should start to discuss how the SJR total BOD_u load at Vernalis can be reduced from about 100,000 lbs/day to about 30,000 lbs/day. Initially, this loading should be allocated based on an SJR DWSC flow of about 250 cfs, 1,000 cfs and 1,500 cfs. Further, consideration should be given to loadings in late August-early September. Consideration should also be given to mid- to late October, when the BOD_u loading from upstream of Vernalis is less, due to reduced planktonic algal concentrations. This information should be used by the Steering Committee/stakeholders to start discussions of how the loads under these conditions would be allocated among stakeholders.

Initially, the "straw man" discussions of load allocation should be based on the assumptions that a load of oxygen demand and/or nutrients from any point in the watershed is equally significant to the load that enters the DWSC. As information is obtained on the decay of BOD and diversion of water, nutrients, BOD and algae from the SJR, then the allocations can be refined to reflect changes that take place from the point of discharge of the BOD and nutrients to the DWSC. Similarly, as information is developed on the conversion of the nutrients into algae, this information can be factored into the load allocation.

Once a tentative allocation has been established, then discussions should be initiated on oxygen demand/nutrient "pollutant" trading among stakeholders. As additional information is obtained through the CALFED and other studies, the allocated loads can be adjusted based on this information.

Managing Nutrient Export in the SJR DWSC Watershed

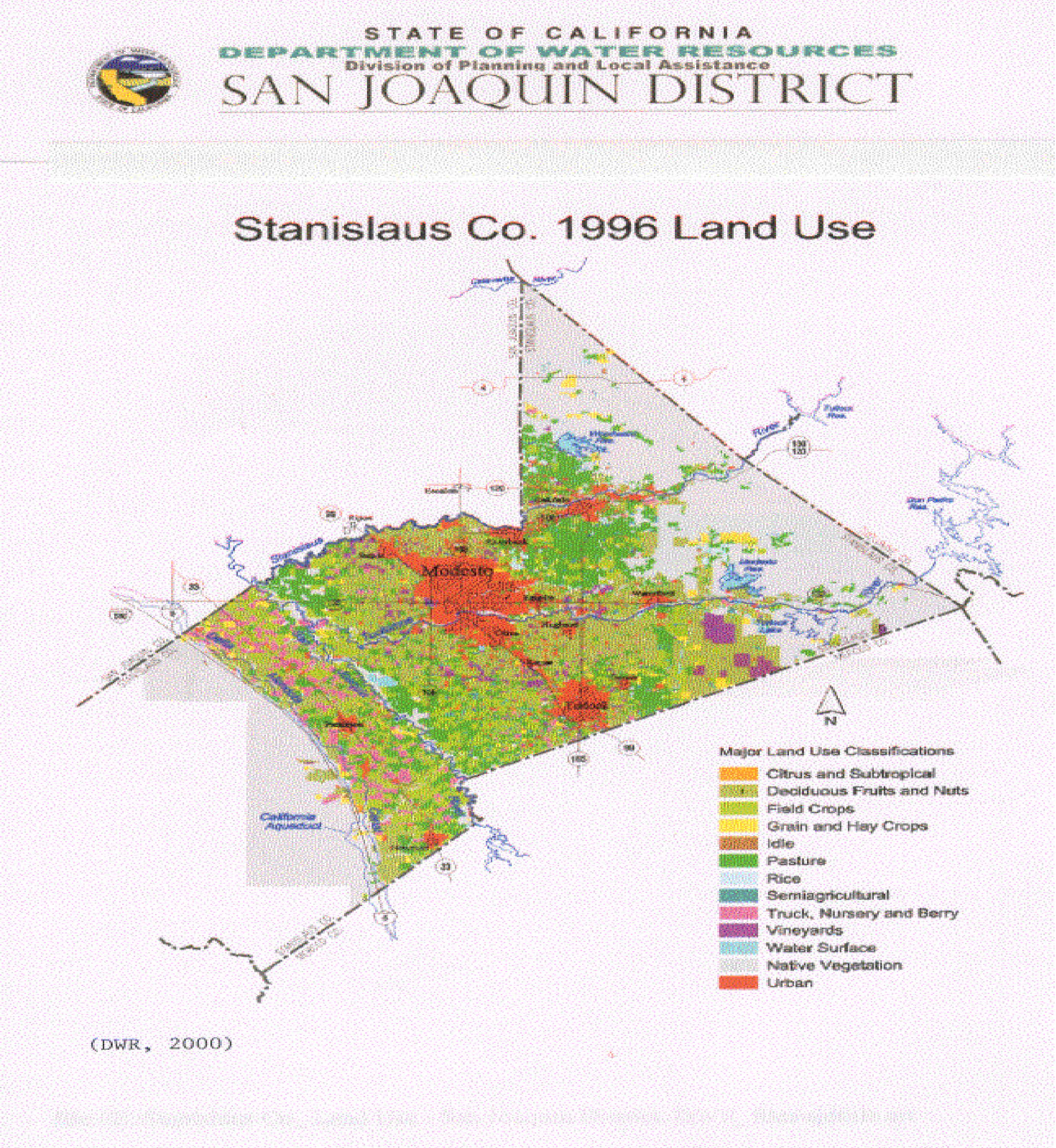
Because of the importance of algae that develop in the SJR above Vernalis in causing dissolved oxygen depletion below WQOs in the DWSC, it will be important to explore developing aquatic plant nutrient (nitrogen and phosphorus) control programs in the SJR watershed above Vernalis. Lee and Jones-Lee (1999) have recently presented a paper devoted to "Strategy for Managing Waterbody Excessive Fertilization (Eutrophication) to Achieve TMDL Goals." This paper presents information on issues that need to be considered in managing excessive growths of algae in waterbodies. As discussed in this paper, nutrients are derived from both point (domestic and industrial wastewaters and stormwater runoff) and non-point sources such as agricultural and riparian land stormwater runoff and discharges such as irrigation return flows (tailwaters). Figures 24, 25 and 26 present DWR diagrams showing land use for 1995 and 1996 within Stanislaus, Merced and Fresno Counties. (These figures can best be viewed using the "View", "Zoom" feature.) Table 10 provides a breakdown of the summer land use acreage for Stanislaus, Merced, Fresno and San Joaquin Counties.

Examination of Figure 24 and Table 10 for Stanislaus County shows that there were appreciable areas of field crops, pasture, fruits and nuts, grain and hay crops present in 1996. DWR estimated that in the summer of 1996 about 378,000 acres of Stanislaus County was devoted to irrigated crops, with about 150,000 acres devoted to corn. The cultivation of almonds represented about 90,000 acres, with pasture representing about 63,000 acres. Approximately 15,000 acres of Stanislaus County were devoted to dairies, feedlots, and farmsteads. In 1996 DWR estimated that there were 61,000 acres of urban area in Stanislaus County, which are located primarily in Modesto and Turlock. Modesto manages much of its stormwater runoff through infiltration wells into the groundwater system. DWR's estimate of native lands present in Stanislaus County during 1996 was 254,000 acres.

Figure 25 and Table 10 present 1995 summer land use within Merced County. DWR estimated that in the summer of 1995 about 525,000 acres of Merced County were devoted to irrigated crops, with about 88,000 acres devoted to cotton. The cultivation of almonds represented about 85,000 acres, with pasture representing about 60,000 acres. Corn cultivation in Merced County in 1995 represented about 58,000 acres. Approximately 18,000 acres of Merced County in 1995 were devoted to dairies, feedlots and farmsteads. In 1995 DWR estimated that there were 40,000 acres of urban area in Merced County, which are located primarily in Merced, Atwater and Livingston. DWR's estimate of native lands present in Merced County during 1995 was about 380,000 acres.

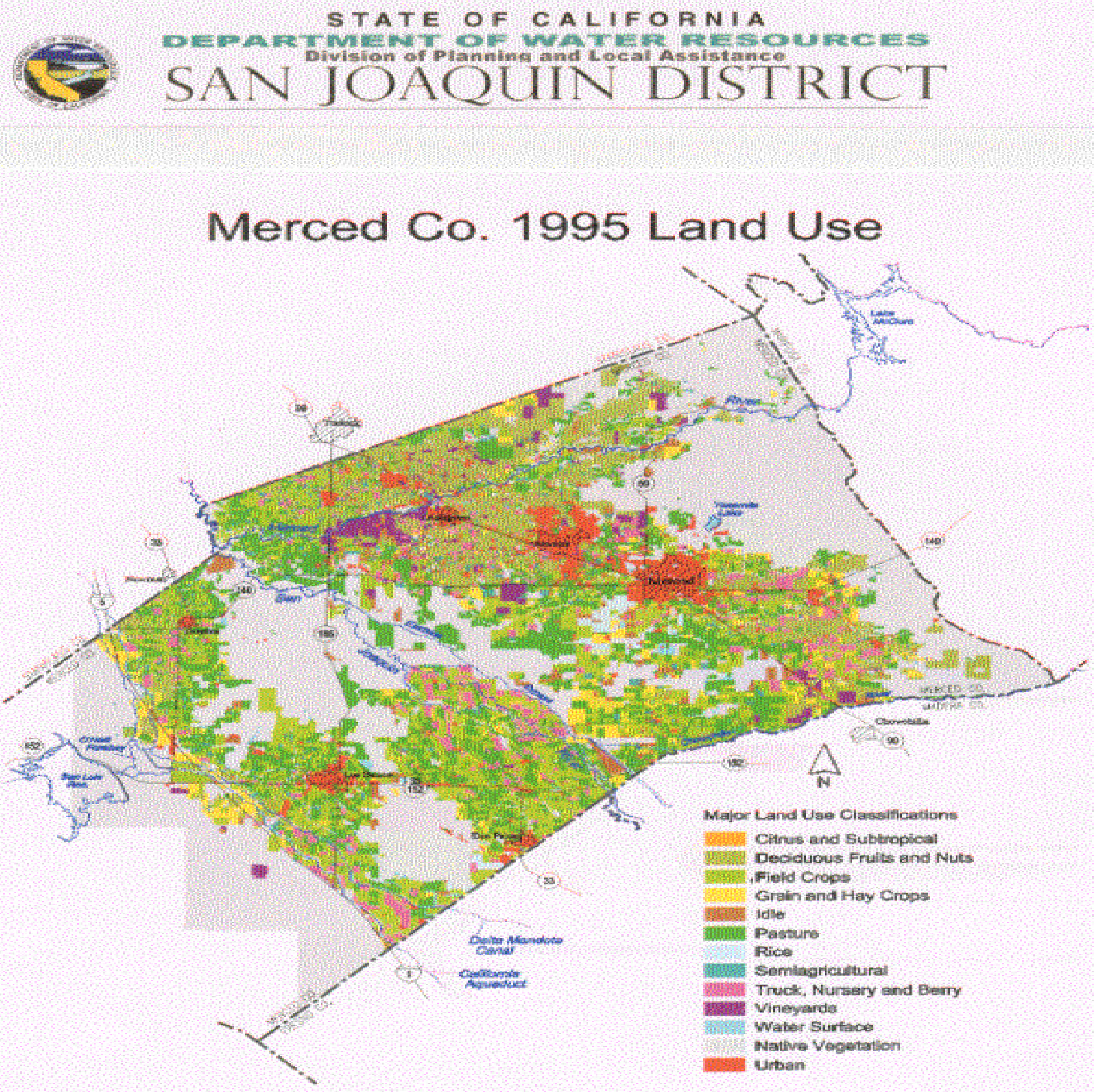
Figure 26 presents the land use diagram for Fresno County during 1994. Table 10 shows the dominant land uses within this county during that year. Only a small part of Fresno County stormwater runoff drains to the San Joaquin River. Included within this drainage is runoff from Fresno during major storm events. Small storm events within Fresno are infiltrated into groundwaters. At this time, the fraction of Fresno County that drains to the San Joaquin River is not known. The dominant crops produced in Fresno County during 1994 were cotton, tomatoes, and vineyards. Approximately 14,000 acres of Fresno County in 1994 were devoted to dairies, feedlots and farmsteads. The urban area represented 140,000 acres, with native lands occupying about 206,600 acres.

Figure 24



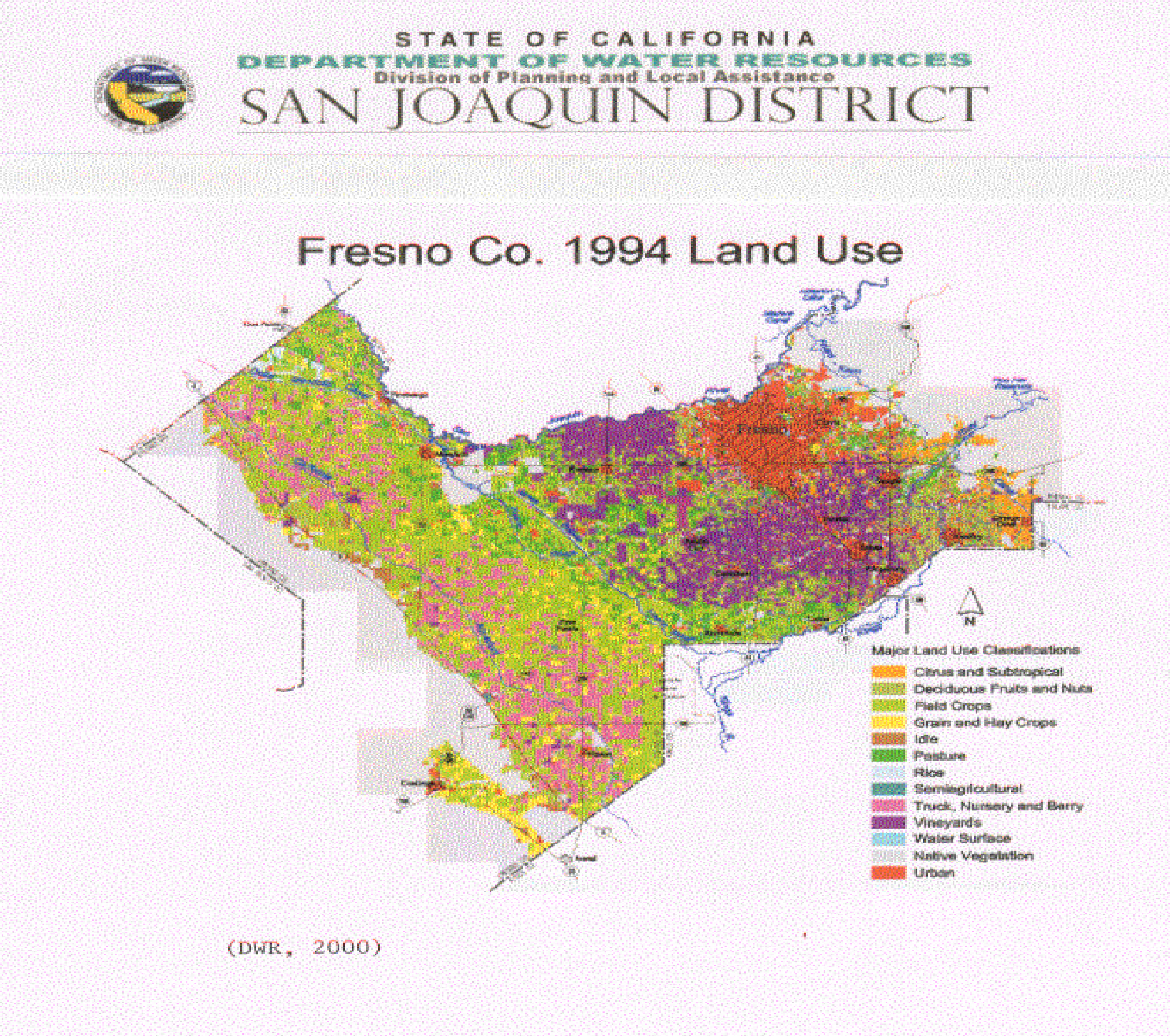
(DWR, 2000)

Figure 25



(DWR, 2000)

Figure 26



(DWR, 2000)

Table 10
Summary of Land Use Within the DWR San Joaquin District

Stanislaus County 1996 Summer Land Use

Land Use	Acres
Irrigated crops	378,000
Farmsteads, feedlots, and dairies	15,000
Urban Areas	61,000
Native Vegetation	254,000

Merced County 1995 Summer Land Use

Land Use	Acres
Irrigated crops	525,000
Farmsteads, feedlots, and dairies	17,600
Urban Areas	39,600
Native Vegetation	380,600

Fresno County 1994 Summer Land Use

Land Use	Acres
Irrigated crops	646,000
Farmsteads, feedlots, and dairies	13,600
Urban Areas	140,000
Native Vegetation	206,600

San Joaquin County 1996 Summer Land Use

Land Use	Acres
Irrigated crops	585,000
Farmsteads, feedlots, and dairies	9,400
Urban Areas	86,700
Native Vegetation	241,000

A similar figure to Figures 24, 25 and 26 was not available for San Joaquin County. Table 10 presents 1996 summer land use within San Joaquin County. DWR estimated that in the summer of 1996 about 585,000 acres of San Joaquin County were devoted to irrigated crops, with about 107,000 acres devoted to fruits and nuts and 42,000 acres devoted to tomatoes. The cultivation of corn represented about 89,000 acres, with pasture representing about 61,000 acres. Approximately 9,400 acres of San Joaquin County in 1996 were devoted to dairies, feedlots and farmsteads. In 1996 DWR estimated that there were 86,700 acres of urban area in San Joaquin County, which are located primarily in Stockton. DWR’s estimate of native lands present in San Joaquin County during 1996 was about 241,000 acres. Only part (small?) of San Joaquin County stormwater runoff is tributary to the SJR DWSC. It will be necessary to define the land uses in the DWSC watershed to be able to estimate the potential significance of this county as a source of N and P and oxygen demand for the DWSC.

Rast and Lee (1983) have discussed the use of nutrient export coefficients for estimating the amounts of nutrients derived from various types of land use within a waterbody’s watershed. Table 11 presents a summary of the nutrient export information developed by Rast and Lee (1983). Based on a study of about 100 watersheds located across the US, as part of the 1970s studies conducted by the US EPA in the International Organization for Economic Cooperation and Development (OECD) eutrophication studies, they report that the export of phosphorus compounds on a mass per unit area per year basis increased by a factor of about five to ten as a result of converting forest and grassland areas to row crop agriculture. The data base for these values was primarily based on non-irrigated agriculture in those areas of the country where there is precipitation during the summer.

Rast and Lee found another factor of five to ten increase in the amount of phosphorus derived from urban areas compared to row crop agriculture. The amount of nitrogen exported per unit area from agriculture and urban areas is about the same. The animal manure data presented in Table 11 is based on Wisconsin dairies where the manure is spread on the land during the summer and winter. The winter spreading of manure is applied to frozen soil which results in high nutrient export in the spring thaw period.

Table 11
Amounts of Nitrogen and Phosphorus Contributed from Various Sources

Source	Nitrogen	Phosphorus	Units
Domestic Wastewater	3.2	0.9	kg/person/yr
Urban Drainage	0.5 (0.25[a])	0.1	$g/m^2/yr$
Rural/Agriculture	0.5 (0.2[a])	0.05	$g/m^2/yr$
Forest	0.3 (0.1[a])	0.01–0.001	$g/m^2/yr$
Manured Land (100 cows/mi^2, 15 tons manure/cow/yr)	0.34	0.11	$g/m^2/yr$
Drained Marsh	10.1	4.5	g/m^2
Rainfall and Dry Fallout	2.4	0.02	$g/m^2/yr$[b]

a = For Western US Waterbodies
b = Waterbody Area
(after Rast and Lee, 1983)

One of the areas that will need attention in the future as part of defining nutrient sources within the SJR DWSC watershed is the assessment of the amount of nitrogen and phosphorus derived from various types of land use. The land use nutrient export values presented by Rast and Lee (1983) need to be evaluated for the SJR DWSC watershed. It should be possible, through special studies at selected locations, to develop nutrient and BOD export coefficients from various types of land use within the SJR DWSC watershed. These export coefficients can then be extrapolated to the complete SJR DWSC watershed, based on current land use information within the watershed.

Typically it is possible to estimate the N and P derived from a waterbody's watershed by multiplying the area of the dominant types of land use by the export coefficients listed in Table 11. Using this approach it is estimated that urban areas in the SJR DWSC would contribute about 700,000 lbs/yr of N and 200,000 lbs/yr of P to the SJR. Agricultural lands would be estimated to contribute about 2 million lbs/yr of N and 5,000 lbs/yr of P to the SJR.

The wastewater N and P values presented in Table 11 are the typical concentrations of N and P in domestic wastewaters after conventional secondary treatment. Kratzer and Shelton (1998) indicate that the SJR watershed had a 1990 population of about 600,000 with a domestic wastewater flow excluding Stockton of about 60 cfs. Stockton wastewater flow is currently about 45 cfs. Based on this information domestic wastewaters in the SJR DWSC watershed contribute about 4 to 5 million lbs/yr of N and about 2 million lbs/yr of P to the SJR and its tributaries. It is understood that only part (fall, winter and spring) of Modesto wastewaters are discharged to the SJR.

Table 11 does not list nitrate contributed to surface water via groundwater discharge. Kratzer and Shelton (1998) estimated that subsurface agricultural drainage to the SJR was about 66 cfs. The concentrations of nitrate in this drainage were about 25 mg/L N. According to Kratzer (2000) the groundwater input of nitrate to surface waters occurs primarily in the grasslands area where the nitrate is derived from natural sources. N. Quinn (personal communication, 2000) has indicated that there have been significant changes in the discharges from the grasslands/wetlands areas since the time of the Kratzer studies in the late 1980s, which have likely affected the amounts of groundwater and nutrients contributed to the SJR upstream of Vernalis. It will be important to examine the potential for irrigated agriculture and land disposal of domestic and industrial wastewaters to cause groundwater pollution by nitrate that leads to surface water pollution in various parts of the SJR watershed. Phillips, *et al.* (1991) have provided information on the quantity and quality of groundwater inflow to the San Joaquin River. The information of Phillips, *et al.*, needs to be updated to the current situation. In those areas where potentially significant nitrate loads to the SJR are derived from groundwater discharge, it will be necessary to investigate the source of this nitrate and control it at the source. Further, it may be necessary to treat the groundwater with the high nitrate to reduce the nitrate load to the SJR from groundwater discharge to surface waters.

There is need to determine the N and P export coefficients for major types of land use in the SJR watershed. This should be one of the major areas of study during 2000. As discussed elsewhere in this report, it will be important, however, to develop nutrient export coefficients for various types of land use on a per month basis, in order to focus on those sources of nutrients that are added to the SJR and its tributaries during late spring, summer and fall.

One of the major areas of future activities will need to be determining the losses/diversions of N and P within the SJR watershed that are exported from a particular location in the watershed and the DWSC. Not only will there be need to determine the amounts that are lost but also the factors that control this loss.

Kratzer and Shelton (1998) provided information on the 1990 fertilizer application in the SJR watershed above Vernalis. They reported that about 51,000 tons/yr of N and 7,300 tons/yr of P were used during 1990. They also reported that about 66,000 tons/yr of N and 17,000 tons/yr of P were in manure produced in the SJR watershed. Based on information provided by

Kratzer and Shelton (1998), 1990 domestic wastewater produced in the SJR watershed above Vernalis is estimated to contain about 1,000 tons/yr N and 2,500 tons/yr P. Based on relative flows, Stockton wastewaters would be expected to be producing and discharging about 60 percent of the upstream of Vernalis N and P loads.

One of the areas of particular concern in the SJR watershed is the rapidly increasing urban population within this watershed. Table 12 shows that between 1990 and 2000, the population of the four counties (or parts thereof) that make up this watershed has increased at a rate of about 2%/yr. The California Department of Finance has projected the populations within these counties until 2040. These projections are presented in Table 13. It is projected that the urban populations within the counties that contribute water/nutrients/BOD will approximately double over the next 40 years. This increased population could have an impact on the SJR DWSC DO through increased wastewater discharges and increased stormwater runoff. Further, the increased population will increase the need for water supplies and its associated consumptive use. Under the current TMDL requirements, increased loads of constituents that contribute to violations of the water quality standards are not allowed. This TMDL limitation could readily impact future population increases within the SJR watershed.

Table 12
San Joaquin River Watershed Populations

County	4-1-1990	1-1-2000	~ increase/yr
San Joaquin[1]	480,628	566,600	1.8%
Stanislaus	370,522	441,400	1.9%
Merced	178,403	210,100	1.8%
Fresno[2]	667,490	805,000	2.1%
Total	1,697,043	2,023,100	1.9%

1. Part of the San Joaquin County population is not in SJR critical reach DWSC watershed.
2. Part of the Fresno County population is not in SJR watershed.

(From www.dof.ca.gov/html/demograp/Hist_E-4.xls)

Table 13
San Joaquin River Watershed Projected Populations

County	1990	2000	2010	2020	2030	2040
San Joaquin[1]	483,817	579,712	725,868	884,375	1,060,442	1,250,610
Stanislaus	375,069	459,025	585,519	708,950	846,998	998,906
Merced	180,182	215,256	264,420	319,785	385,120	460,120
Fresno[2]	673,608	811,179	953,457	1,114,403	1,308,767	1,521,360
Total	1,712,676	2,065,172	2,529,264	3,027,513	3,601,327	4,230,996

1. Part of the San Joaquin County population is not in SJR critical reach DWSC watershed.
2. Part of the Fresno County population is not in SJR watershed.

(From www.dof.ca.gov/html/demograp/p1.xls)

There are a variety of N and P sources that will need to be investigated and potentially controlled to reduce the algal-related oxygen demand load to the DWSC. The future work on nutrient load estimates will need to focus not on the annual total loads but on those loads that cause the growth of algae that cause oxygen depletion below the WQO in the DWSC. These loads will likely occur in late spring, summer and early fall.

Because of the importance of upstream of Vernalis oxygen demand loads influencing DO depletion in the DWSC, it is recommended that a rough-cut analysis of these loads and their fate from the point of release from the land (discharge) and the SJR at Vernalis be conducted in the immediate future. This rough-cut analysis of current information on loads and their fate can help define the studies that need to be done to assess the importance of loads from any particular type of land use activity and location and the oxygen demand load that is present at SJR Vernalis. Kratzer, as part of the current CALFED grant, is developing a rough-cut analysis of the existing information on nutrient and BOD loads to the SJR upstream of Vernalis.

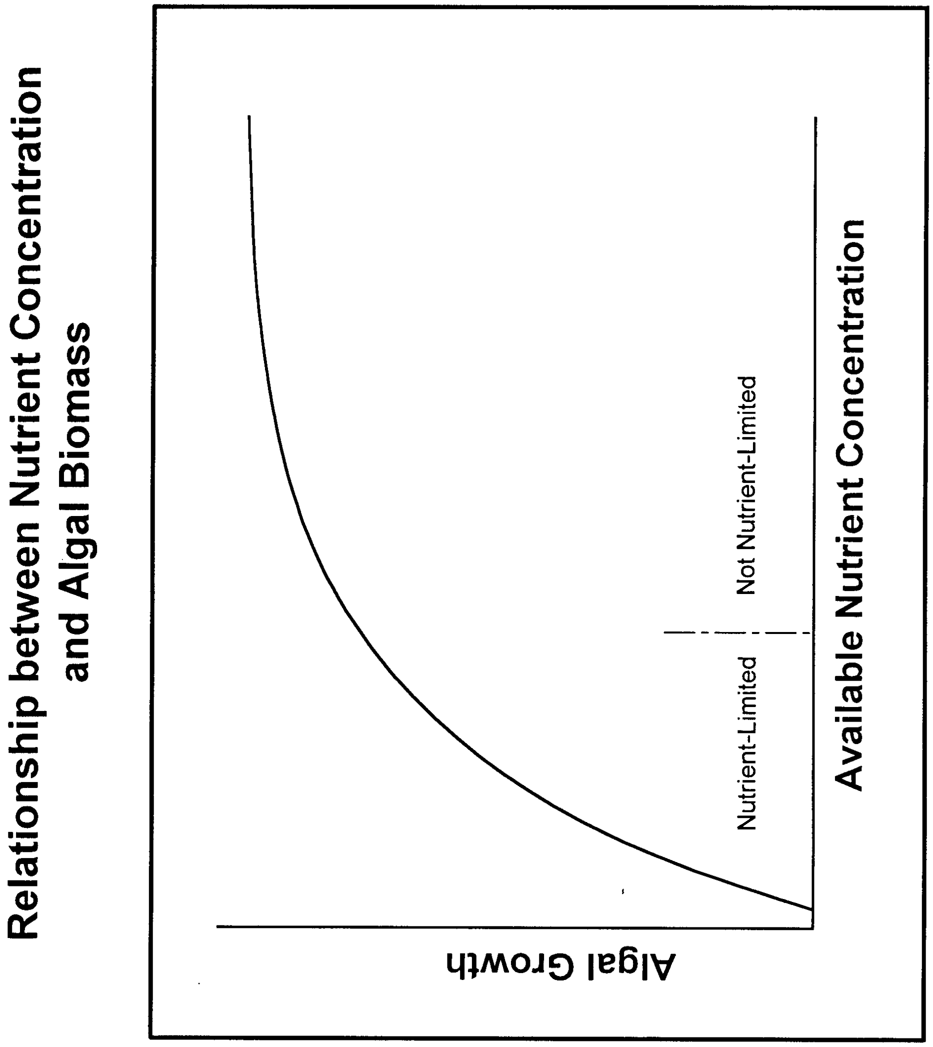
Relationship between Algal Nutrient Concentrations and Algal Biomass

A key component of any algal biomass control program is the development of the relationship between available nutrient concentrations in a waterbody and the amount of algae that develop in the waterbody. The first step in developing an algal control program is to assess which nutrient (nitrogen or phosphorus) is either limiting algal biomass or can be made to limit the amount of algae that develop in a waterbody. Typically, while for most of the US east of the Rocky Mountains, available phosphorus is the element most likely to limit algal growth (biomass), on the West Coast nitrogen is the element most likely to limit algal biomass.

For nitrogen, the algal-available forms are ammonia and nitrate and organic nitrogen that converts to ammonia. Only part of various sources of organic nitrogen convert to ammonia. For phosphorus, it is the soluble orthophosphate that is the form that is readily available for algal growth. Most of the particulate phosphorus is not available to algae. Based on the information available at this time, both algal-available nitrogen and phosphorus are present in both SJR and DWSC waters in considerable surplus of algal needs. The present algal production is most likely limited by light penetration and not nutrients.

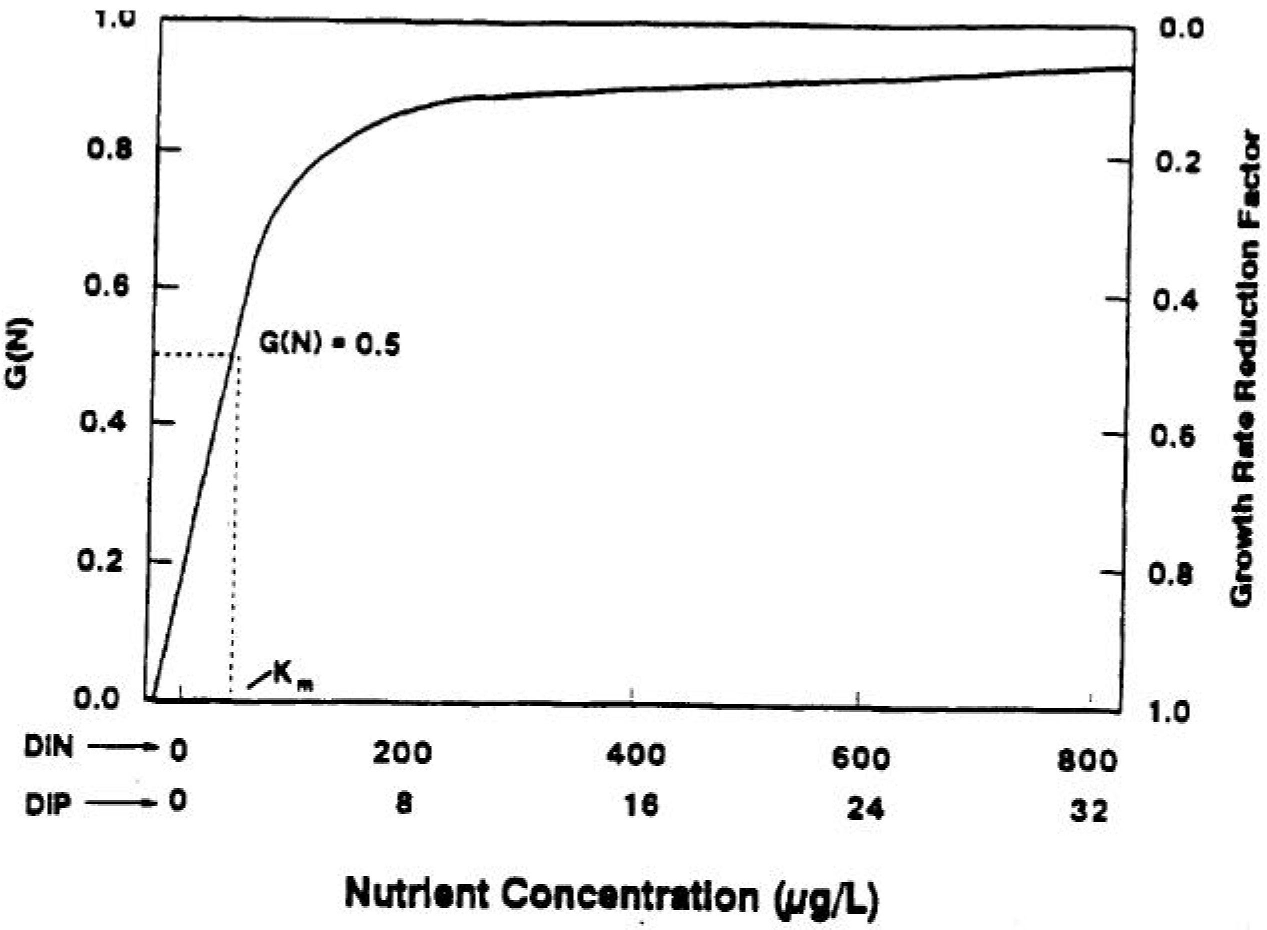
Figure 27 shows the typical relationship that exists for the nutrient (nitrogen or phosphorus) that is most likely to limit the amount of algal biomass that is present in a waterbody. Figure 28 shows the typical algal-available N and P concentrations that are found to limit algal growth rates. At low concentrations of a potentially limiting nutrient, the rate of growth and ultimately the amount of algae that develop are proportional to the concentration of the limiting nutrient. However, at high concentrations, the amount of algae that develop is independent of the nutrient concentration. This is likely the situation in the SJR and DWSC.

Figure 27



Relationship between Nutrient Concentration and Algal Biomass

Figure 28



EFFECT OF NUTRIENTS ON ALGAL GROWTH
(After Ambrose et al., 1993a)

Where:
G(N)= Algal growth rate/day
DIN = Inorganic nitrogen (nitrate, nitrite and ammonia plus the orgN that converts to ammonia)
DIP = Dissolved soluble orthophosphate plus the particulate P that converts to soluble inorganic P
Km = half saturation (Michaelis constant) µg/L

A review of the concentrations of nitrate plus ammonia and soluble orthophosphate present in the SJR at Vernalis, as well as in the DWSC, over the late summer and fall shows that, typically, the concentrations of inorganic nitrogen were on the order of about 2 mg/L (2,000 µg/L) N. Soluble ortho-P concentrations were about 0.15 mg/L (150 µg/L) P. While both concentrations were surplus of growth rate-limiting concentrations needed for algal growth, it is of interest to find that the ratio of inorganic nitrogen to soluble ortho-P during peak biomass was about 13 to 1 on a mass basis. Based on algal stoichiometry, algal composition is balanced with respect to N to P content at 7.5 to 1 on a mass basis, 16 to 1 on a molar basis. The nitrogen to phosphorus ratio in the SJR, both upstream of the DWSC and within the DWSC, that is available to support additional algal growth is surplus by a factor of almost two of that needed by the algae. In other words, if there were not severe light limitation, primarily due to self-shading and inorganic turbidity from erosional materials, the algae would ultimately become limited by the soluble ortho-P content of the water, not nitrogen. This situation is somewhat unusual for the west coast (California), in that usually the ratios are in favor of nitrogen limitation over phosphorus. However, in this case, the limitation, if there were not light-limiting conditions, would be for phosphorus. This has important implications for managing the excessive algal growth that is occurring in the SJR at Vernalis as well as downstream. First and foremost, since it is somewhat easier to control phosphorus in wastewaters and in land runoff than nitrogen in the form of nitrate, this means that the algal biomass control program should focus on phosphorus control.

There is some experience in controlling phosphorus from land runoff in the Midwest and eastern US. In the Midwest, as part of controlling excessive fertilization of the Great Lakes, where algal growth is phosphorus-limited, the agricultural interests in much of the Lake Erie watershed have been practicing phosphorus control from agricultural runoff and domestic wastewater discharges for over 20 years. An International Joint Commission for the Great Lakes report on the experience of controlling phosphorus in land runoff in the Great Lakes watershed has recently been published (Logan, 2000). Logan reports that there have been significant changes in farming practices in some of the Great Lakes watersheds. Of particular interest is the adoption of the “no-till” cultivation approach. While this approach can be effective in controlling erosion from agricultural lands, according to Logan, it may have little impact on nitrogen and dissolved phosphorus export from these lands.

In the Chesapeake Bay region, the states surrounding Chesapeake Bay have been practicing both nitrogen and phosphorus control for about 15 years. Recently, Sharpley (2000) has edited the proceedings of a 1998 conference devoted to agriculture and phosphorus management in the Chesapeake Bay. One of the areas that needs attention in the SJR watershed is to examine the experience in other parts of the country with respect to phosphorus control to see what could potentially be expected in the SJR watershed. The Sharpley edited publication is a result of the Chesapeake Bay program’s Scientific and Technical Advisory Committee conference, held in April 1998. It presents the findings and views of farmers and bay resource users/managers, focusing on the impact of phosphorus on Chesapeake Bay, the sources and transport of agricultural phosphorus within the Chesapeake Bay watershed, development of an integrated nutrient management planning program in the Chesapeake Bay watershed and future trends for phosphorus management in the Chesapeake Bay watershed. Chesapeake Bay has been experiencing excessive fertilization for a number of years, recently, due to the growth of *Psiesteria piscicida*, an algal dinoflagellate. This organism is toxic to fish.

The Chesapeake Bay watershed is similar to the SJR watershed, in that a major agricultural activity within the watershed is commercial animal husbandry which includes, in the case of the SJR watershed, dairies. Manure from animal husbandry operations has a much higher phosphorus-to-nitrogen ratio than needed by plants. Several years ago, the regulatory agencies in the Chesapeake Bay watershed established a goal of reduction of phosphorus and nitrogen loadings by 40 percent by 2000. Thus far, this goal has not been achieved.

Examination of Figure 28 shows that to achieve growth rate limiting conditions for phosphorus requires that the soluble orthophosphate be present at less than about 5 µg/L P. With the concentrations of soluble ortho-P typically present in the DWSC and SJR during peak biomass in excess of 100 µg/L P, this means that there has to be about a twenty-fold decrease in the algal-available P present in the water that is growing the excessive algae (SJR above Vernalis and within the DWSC). Based on the Chesapeake Bay experience of a 40 percent reduction as a goal after about 15 years, it appears that it may be difficult, if not impossible, to control phosphorus, and for that matter, nitrogen inputs to the SJR watershed from agricultural sources and achieve significant reductions in the algal biomass that leads to oxygen demand in the DWSC.

There are approximately 90 million people in the world whose domestic wastewaters are treated for phosphorus removal as part of a eutrophication management program (Lee and Jones, 1988). As they discuss, typically, 90 to 95 percent of the phosphorus in domestic wastewaters can be removed for a few cents per person per day for the population served by the domestic wastewater treatment plant. If the control of phosphorus becomes the focal point of an effort to try to manage the excessive fertilization of the DWSC watershed, then the municipalities that discharge wastewaters to the SJR DWSC watershed could find that they will need to control phosphorus in their domestic wastewaters.

The City of Stockton situation, with respect to the need to initiate nutrient control, has several special considerations that will need to be addressed. Since the nutrients, excluding ammonia, discharged by Stockton do not contribute to the algal load added to the DWSC, the issue of whether there is need to control these nutrients, such as by practicing phosphorus removal in the wastewater discharges, becomes that of whether removal of 90 to 95 percent of the phosphorus in Stockton's wastewater effluent would limit algal growth within the DWSC that is significant to the DO depletion problem below WQOs. As discussed herein, it is unclear at this time what the significance of algal growth within the DWSC is with respect to causing significant adverse impacts on the dissolved oxygen resources within the critical reach of this channel. These issues will need to be carefully evaluated.

Relationship between SJR Flow into the DWSC and DO Depletion: Initial Assessment

As part of the review of the King (2000) report on the oxygen demand loads that were present in the SJR at Vernalis during August and September 1999, it was found that there was apparently a significant decrease in the ultrasound velocity meter (UVM) measured SJR flow into the DWSC during late September. Also there was a significant decrease in the dissolved oxygen concentration in the DWSC at the DWR dissolved oxygen continuous monitoring station off of Rough and Ready Island during October. As discussed herein, it was found through independent studies, that ammonia concentrations in the SJR downstream of where the City of Stockton discharges its domestic wastewaters and within the upper part of the DWSC were on the order of 3 to 4 mg/L N during November and December 1999. The elevated concentrations of ammonia were not found in the SJR near Mossdale, suggesting that they did not originate from upstream.

During October 1999 the City of Stockton reported discharging ammonia to the SJR at concentrations on the order of 20 to 23 mg/L N. It appears that the elevated ammonia concentrations that occurred in the DWSC during late fall 1999 were the result of City of Stockton's discharge of elevated ammonia, and low SJR flow past the City of Stockton's wastewater discharge. This situation, coupled with the low UVM-measured SJR flow at the end of September, led to obtaining additional 1999 flow and DO information for the purpose of understanding how low SJR flow into the DWSC influences DO depletions within the DWSC. Presented herein is additional information that has been acquired that discusses these issues. This discussion represents an initial assessment of the relationships between DO and SJR flow into the DWSC relative to DO depletions below WQOs. Further work may reveal additional information that will be helpful to understand how flow, season, upstream of Vernalis oxygen demand loads, and City of Stockton wastewater discharge loads impact DO depletion within the DWSC.

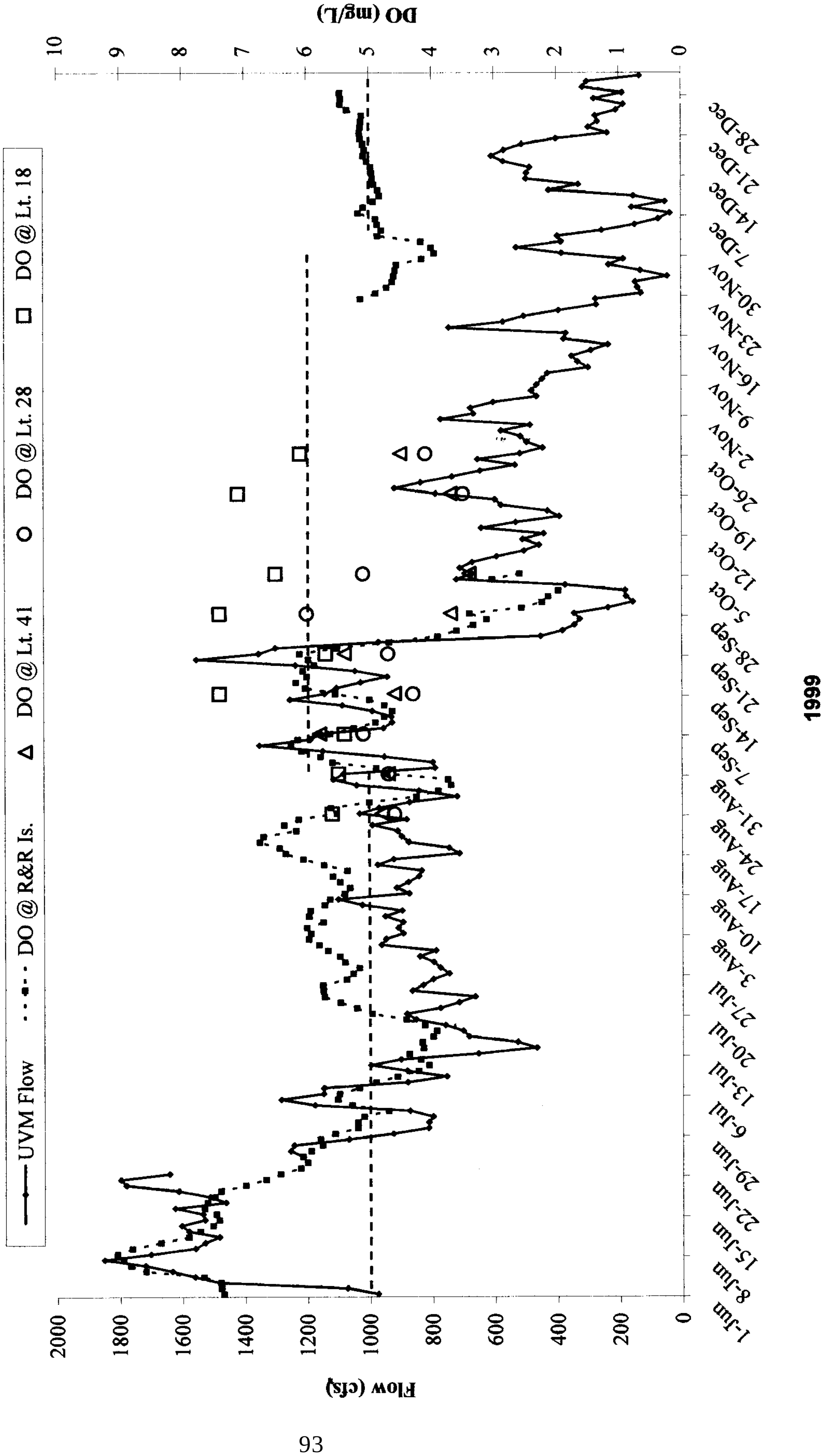
1995-98 DWSC DO and SJR Flow

King of the CVRWQCB has recently provided updated and expanded DWSC DO and SJR flow information for 1995-1999. The DO information presented in Figure 29 is from the Rough and Ready Island continuous monitoring station which measures DO concentrations about two feet below the surface. Also, selected surface water monitoring data taken as discrete samples is presented in Figure 29. The location of the sampling stations is presented in Figures 4 and 30. The SJR flow information presented in Figure 29 is the UVM-measured flow that was developed by R. Oltmann of the USGS. Appendix D provides a table of these data and Delta export flow data. Examination of Figure 29 shows that during 1999 there was a period in mid-July when the DO in the surface waters of the DWSC near Rough and Ready Island was below the water quality objective of 5 mg/L. At the same time, the SJR flow into the DWSC decreased to about 500 cfs. These data show that with a lower flow at a time when the City of Stockton's wastewater discharges are estimated to contain less than 2 mg/L of ammonia based on the August 1999 data reported by the City, the DO in the surface waters of the DWSC near Rough and Ready Island violated the 5 mg/L WQO.

Figure 29 shows that when the SJR UVM flow increased to about 1,000 cfs, the DO at this location increased above the 5 mg/L WQO. In late July when the flow decreased to about 600 cfs, the DO dropped again, but did not decrease below the 5 mg/L WQO. These results point to the need to expand the examination of DO depletion in the DWSC to cover the summer months, as well as at other times when the SJR flow into the DWSC is less than about 1,000 cfs.

During the period of the TAC studies in August and September 1999, when the SJR flow into the DWSC was between 800 and 1,000 cfs, the DO concentrations at the Rough and Ready Island monitoring station were typically above the 5 mg/L WQO that applies to August. However, by late September, when the SJR flows decreased to about 100 cfs, there was a precipitous drop in the dissolved oxygen concentrations in the surface waters down to about 2

Figure 29



San Joaquin River average daily flow and DO levels for June through December, 1999. Flow measured by UVM near Santa Fe RR crossing; DO measured by the Stockton continuous monitoring station at Rough and Ready Island and at selected navigation lights.

Figure 29 (continued)

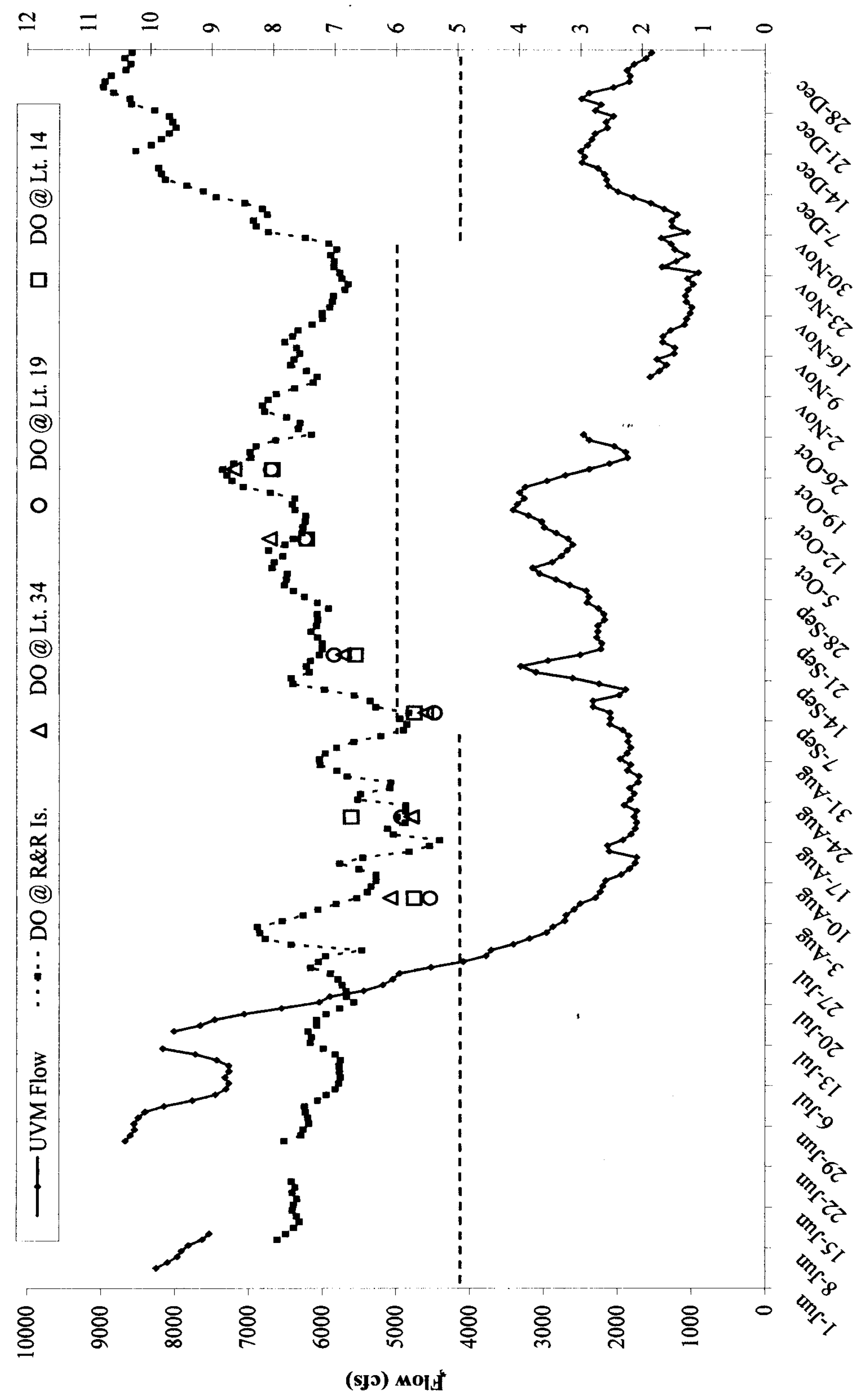


Figure 29 (continued)

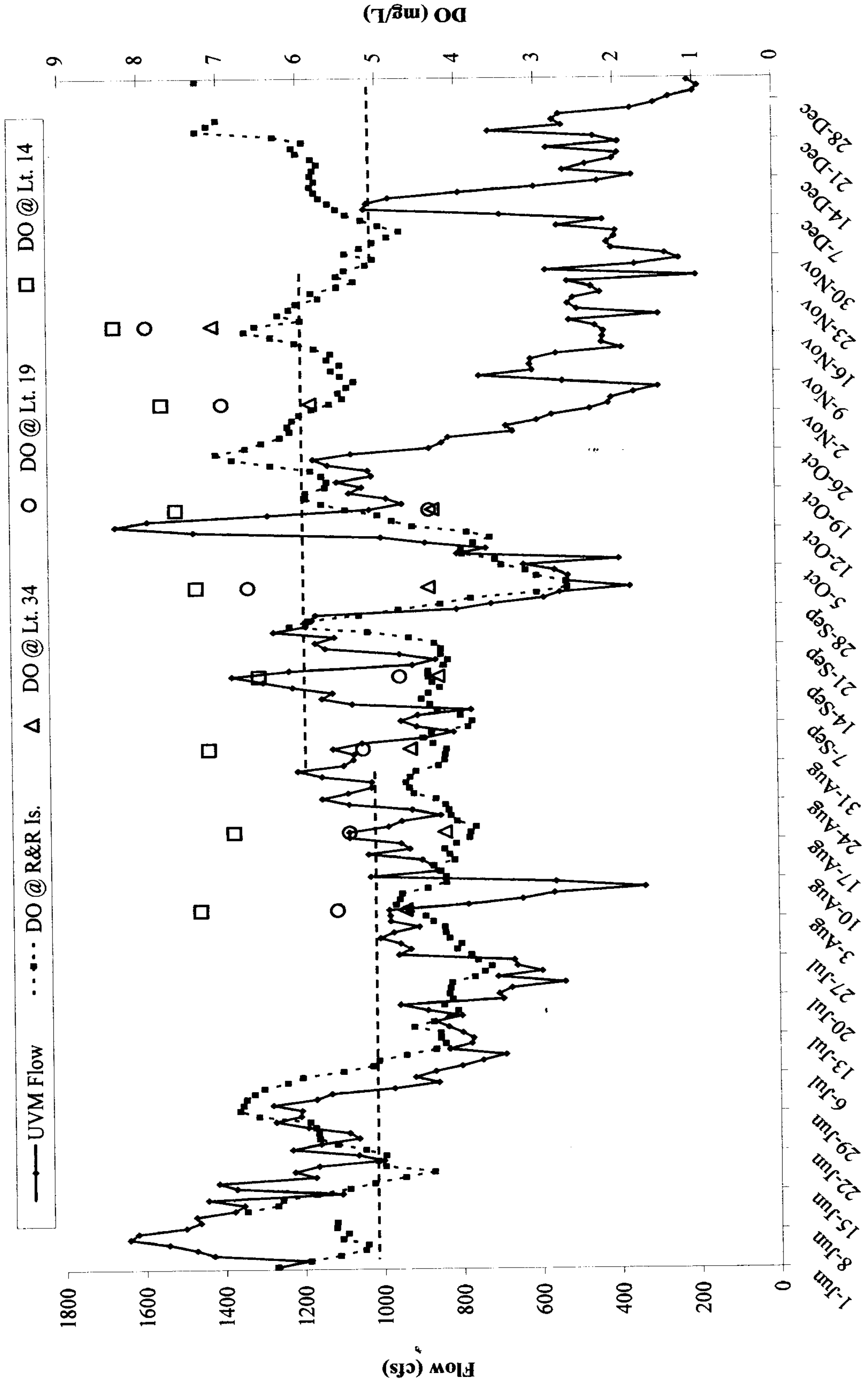


Figure 29 (continued)

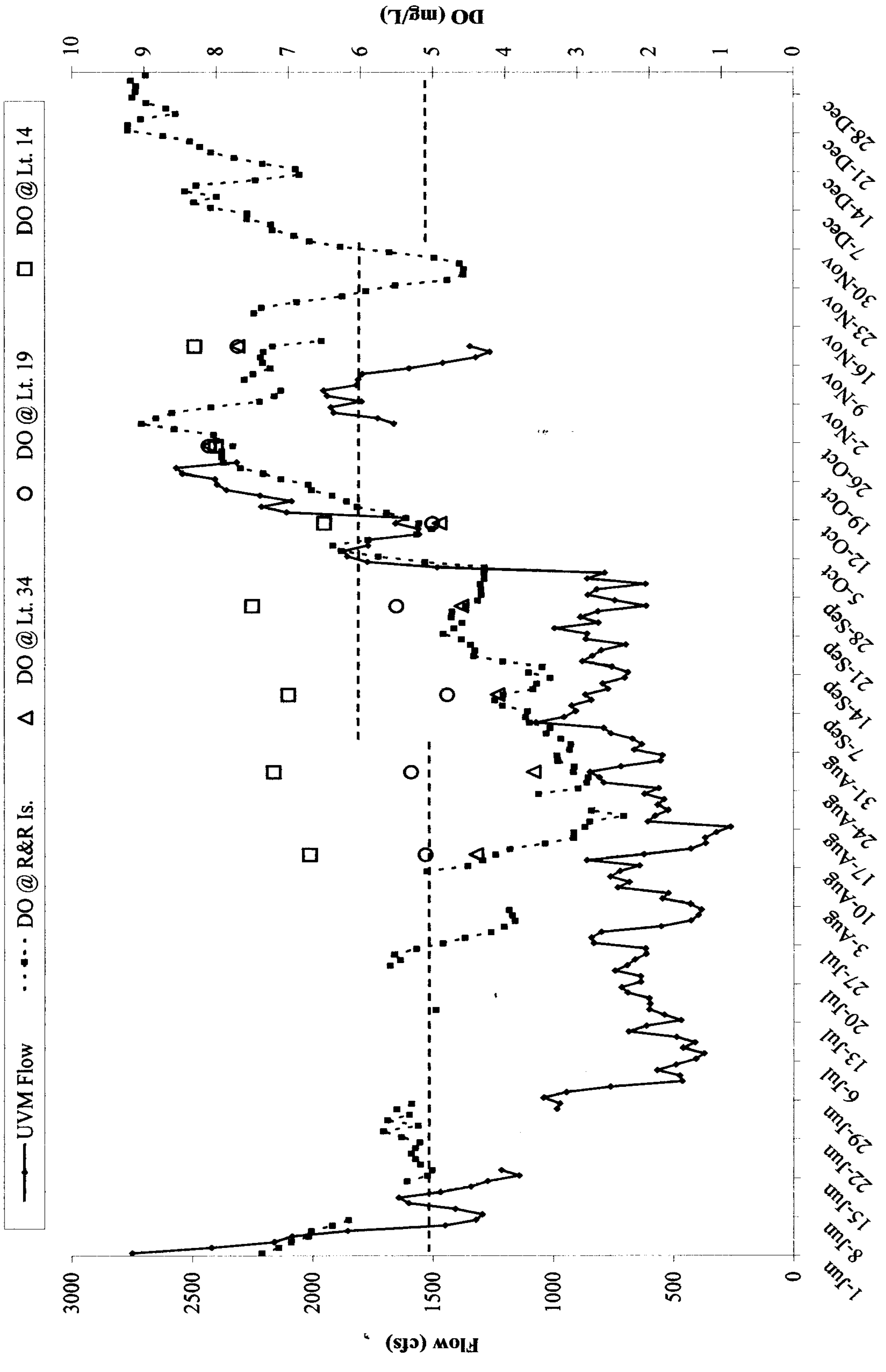
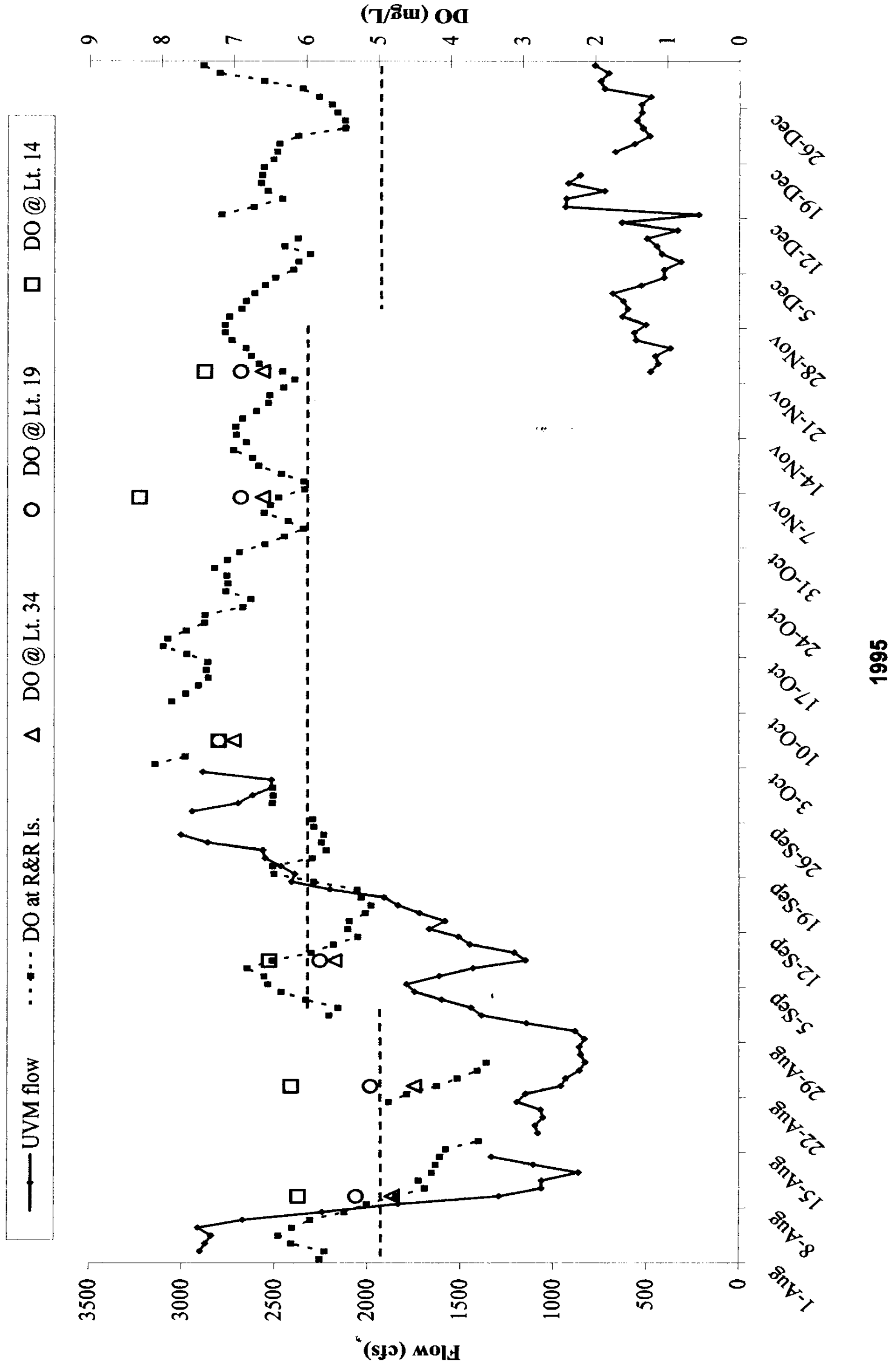


Figure 29 (continued)



mg/L in the DWSC near Rough and Ready Island. During this time, the City of Stockton was discharging ammonia at about 20 mg/L N.

The DWR monitoring data of dissolved oxygen at the Rough and Ready Island station from early October through the end of November are not available. However, DWR conducts independent synoptic cruises of the DWSC in the summer and fall, which include measurements of dissolved oxygen in the water column at selected locations at the surface and near the bottom. During October when the Rough and Ready Island monitoring station data were not available, DWR cruise data for this period (see Figure 29) show that there were violations of the 6 mg/L DO WQO in the DWSC on October 7 and 26, and November 8 and 23.

During the period from the beginning of October through the end of December, the SJR flows into the DWSC varied between essentially 0 and about 1,000 cfs. At the end of November, the dissolved oxygen concentrations were less than the 6 mg/L water quality objective applicable to this time, and at several times in December they were below the 5 mg/L WQO.

The 1998 flow and DO data provide an interesting comparison to 1999, where the SJR flows into the DWSC in 1998 from June through early August ranged from 2,000 to about 8,000 cfs. They remained at about 1,800 to 2,000 cfs during August and September. During this time, there were no violations of the DO WQO at the Rough and Ready Island surface water monitoring station. During October 1998 the flows of the SJR into the DWSC ranged from about 2,000 to about 3,400 cfs. Again, there were no violations of the 6 mg/L WQO at the Rough and Ready Island surface water monitoring station. During late November and early December 1998 the flows in the SJR into the DWSC decreased to about 1,000 to 1,300 cfs, with the DO concentrations in the DWSC near Rough and Ready Island well above the WQO.

From these results, it appears that flows on the order of 2,000 cfs, independent of the season, shorten the hydraulic residence time of the DWSC so that violations of the WQO did not occur at the Rough and Ready Island monitoring station. However, as discussed below (see Figure 33) there were DO water quality objectives violations in both surface and near bottom waters of the DWSC further downstream from Rough and Ready Island.

The SJR flow into the DWSC DO relationships shown in Figure 29 for 1995-97 shows similar patterns as the 1999 and 1998 data. When the SJR flows dropped below about 2,500 cfs there is a potential for the DO in the DWSC to decrease below the WQO. The data presented in Figure 29 does not show the DO concentrations that are present near the sediment water interface. Figure 14 shows that DO depletion at the DWR Rough and Ready Island surface water continuous monitoring station do not reflect worst case conditions for DO depletions. There can be DO depletions at other locations especially near the sediment water interface where DO depletions are greater than at the DWR Rough and Ready station

In order to try to understand the cause of the significant fluctuations in the UVM flows of the SJR into the DWSC, Foe of the CVRWQCB obtained from the USGS (Rick Oltmann) the export flows from the Delta for the fall of 1999. These flows are presented in Table 14 for October, November and December 1999, and in Appendix D. Examination of the October, November and December data shows that the San Joaquin River at Vernalis had a flow that was fairly constant, ranging from about 1,600 cfs to about 2,500 cfs. The significant changes that occurred in the UVM-measured SJR flow into the DWSC during this period were not due to changes in the flow of the SJR at Vernalis.

Table 14
Delta Outflow - Fall 1999

(Flows determined by USGS, in cfs)

October 1999

Date	VNS	FPT	CLFT CT	Tracy	CCC	Outflow
1	2,101	14,733	6,679	4,169	70	4,876
2	2,211	14,340	6,675	4,131	64	4,490
3	2,203	14,472	6,675	4,129	56	4,225
4	2,265	14,096	6,572	4,196	76	4,371
5	2,394	13,988	6,050	4,181	86	4,638
6	2,383	13,864	6,676	4,275	119	3,883
7	2,385	14,131	6,475	4,312	119	3,990
8	2,359	14,269	6,544	4,251	111	4,209
9	2,417	14,388	6,679	4,230	117	4,161
10	2,475	14,349	6,677	4,227	120	4,394
11	2,525	14,093	6,675	4,222	119	4,419
12	2,510	13,916	4,325	4,229	120	6,554
13	2,402	13,188	5,984	4,231	119	4,715
14	2,379	12,204	6,465	4,207	119	3,500
15	2,394	11,509	6,675	4,261	119	2,215
16	2,426	11,046	5,987	4,280	119	2,215
17	2,457	10,597	5,000	4,239	117	2,768
18	2,610	10,625	2,997	4,241	119	4,383
19	2,570	10,689	2,997	4,238	119	4,578
20	2,502	10,817	3,510	4,243	119	4,104
21	2,487	10,866	3,476	4,255	119	4,176
22	2,542	10,597	3,489	4,294	93	4,138
23	2,527	10,423	4,000	4,301	63	3,463
24	2,468	10,881	3,473	4,286	62	3,828
25	2,428	10,831	3,494	4,276	62	4,210
26	2,407	10,923	3,490	4,288	63	4,114
27	2,387	11,117	3,451	4,285	64	4,207
28	2,399	11,281	3,474	4,294	62	4,361
29	2,431	11,814	3,490	4,272	66	5,498
30	2,392	12,134	3,286	4,246	63	6,324
31	2,385	12,172	3,124	4,431	64	6,541

VNS	San Joaquin River at Vernalis
FPT	Sacramento River at Freeport
CLFT CT	State water project export pumps at Clifton Court
Tracy	Federal water project export pumps at Tracy
CCC	Contra Costa Canal export
Outflow	Delta Outflow to San Francisco Bay

Table 14 (continued)

November 1999

Date	VNS	FPT	CLFT CT	Tracy	CCC	Outflow
1	2,444	12,239	2,614	4,248	85	7,205
2	2,357	11,628	3,032	4,251	112	6,863
3	2,399	11,417	3,989	4,254	117	4,411
4	2,469	11,370	3,998	4,268	117	4,213
5	2,580	11,766	3,990	4,241	97	4,240
6	2,591	11,516	3,998	4,236	62	4,774
7	2,461	11,474	3,990	4,172	61	4,624
8	2,395	12,357	4,497	4,248	62	6,446
9	2,364	12,836	4,996	4,295	60	9,042
10	2,312	13,010	5,996	4,235	62	8,616
11	2,264	13,403	4,999	4,276	63	9,660
12	2,269	13,808	4,995	4,252	61	10,005
13	2,288	14,174	5,642	4,259	62	7,251
14	2,257	14,088	5,497	4,271	62	5,491
15	2,216	14,460	5,201	4,263	67	5,651
16	2,266	13,782	3,351	4,272	66	7,833
17	2,222	14,400	4,651	4,165	66	7,615
18	2,165	14,133	5,159	4,172	63	7,700
19	2,137	14,368	5,600	4,190	60	6,964
20	2,109	15,495	6,396	4,175	60	8,814
21	2,104	15,609	6,241	4,162	60	10,325
22	2,090	16,447	6,066	4,205	81	8,918
23	2,059	17,072	6,628	4,167	99	9,189
24	2,009	16,440	6,676	4,092	76	9,809
25	1,991	15,775	6,177	4,048	99	7,079
26	1,982	15,114	6,672	4,016	101	5,701
27	1,950	14,902	6,676	4,048	99	4,936
28	1,957	14,598	6,353	4,056	101	4,950
29	1,957	14,452	5,986	4,132	78	4,976
30	1,972	14,903	5,475	4,176	100	5,223

VNS	San Joaquin River at Vernalis
FPT	Sacramento River at Freeport
CLFT CT	State water project export pumps at Clifton Court
Tracy	Federal water project export pumps at Tracy
CCC	Contra Costa Canal export
Outflow	Delta Outflow to San Francisco Bay

Table 14 (continued)

December 1999

Date	VNS	FPT	CLFT CT	Tracy	CCC	Outflow
1	2,001	15,898	5,345	4,175	99	6,933
2	1,893	17,144	5,815	4,093	106	7,590
3	1,862	19,055	5,606	4,042	72	9,041
4	1,836	18,790	5,559	4,017	60	10,930
5	1,828	18,186	5,536	4,024	56	10,610
6	1,832	17,676	6,677	4,016	63	7,698
7	1,808	17,379	6,671	4,023	44	7,153
8	1,791	17,080	6,678	4,027	38	6,794
9	1,790	16,753	6,672	4,022	38	6,484
10	1,788	17,018	3,291	1,739	25	12,933
11	1,796	17,755	3,290	828	37	14,102
12	1,776	17,907	3,298	828	38	14,848
13	1,748	17,786	791	678	39	17,623
14	1,726	17,780	792	714	40	17,443
15	1,707	17,788	794	716	40	16,261
16	1,727	17,512	797	708	40	16,266
17	1,742	17,113	800	711	40	16,001
18	1,743	16,659	787	713	40	15,666
19	1,748	16,358	796	713	34	15,202
20	1,705	15,953	1,291	715	27	14,422
21	1,688	15,464	2,300	716	0	13,035
22	1,669	15,424	3,294	714	1	11,549
23	1,630	15,324	4,293	715	2	10,545
24	1,639	15,326	2,999	3,274	0	9,151
25	1,644	15,290	2,999	3,945	3	8,534
26	1,659	15,256	3,989	3,925	1	7,534
27	1,649	15,415	3,996	3,918	27	7,538
28	1,618	15,249	4,501	4,012	40	7,073
29	1,600	14,948	5,300	4,024	40	6,132
30	1,599	14,729	5,347	4,024	21	5,832
31	1,581	14,393	6,822	4,093	1	4,148

VNS	San Joaquin River at Vernalis
FPT	Sacramento River at Freeport
CLFT CT	State Water Project export pumps at Clifton Court
Tracy	Federal Water Project export pumps at Tracy
CCC	Contra Costa Canal export
Outflow	Delta Outflow to San Francisco Bay

Table 14 shows that the flows of the Sacramento River at Freeport during October through December 1999 ranged from about 10,000 to 19,000 cfs. The flow of the Sacramento River is of some importance to DO depletion within the DWSC, primarily through its impact on dilution of the SJR flow in the vicinity of Disappointment Slough/Columbia Cut (see Figure 3). From the current information, it would not be expected that the changes in the Sacramento River flow from October through December would have significantly impacted the DO depletion that occurred during this time in the DWSC.

Table 14 presents the export flows for the State and Federal Water Project pumps. During October and November, the State Water Project exported at Clifton Court about 2,600 to 6,000 cfs. The Federal Water Project pumps at Tracy exported about 4,000 to 4,200 cfs during this time. During December, for the period December 13 through 19, the State and Federal Projects' exports of Delta water were significantly curtailed. Based on information provided at the Bay-Delta Modeling Forum Hydrodynamic Modeling Workshop held on February 4, 2000, this curtailment was associated with an effort to protect spring run yearling salmon.

Table 14 also presents the amounts of export at the Contra Costa Canal, which varied from 0 to slightly over 100 cfs during October through December. The outflow from the Delta through San Francisco Bay was estimated during this period to range from about 2,200 cfs to about 17,000 cfs, with the latter values occurring when the State and Federal Projects curtailed their export during mid-December.

Based on initial examination of the Delta water export data, there does not appear to be any relationship between the low SJR flows into the DWSC and exports of Delta water, either through the State or Federal Water Projects, or to San Francisco Bay. It appears that the low flows and their associated low DO values are primarily controlled by the amount of water present in the SJR at Vernalis that is diverted into the Old River Channel. Since, as discussed below, the head of Old River barrier was not installed in 1999, the change in flow that occurred at the end of September 1999 was not associated with removal of that barrier. However, as discussed in a subsequent section, the change in flow appears to be related to the removal of the temporary barrier on Grant Line Canal (see Figure 4).

The amount of SJR flow at Vernalis that is diverted into Old River is controlled by the head of Old River barrier. This is a temporary barrier that is installed to divert San Joaquin River flow at Vernalis down the original channel for the purpose of maintaining flow for fish migration. The head of Old River barrier was not installed during 1999, with the result that an appreciable part of the SJR flow at Vernalis was allowed to flow into Old River. This flow carried with it an appreciable oxygen demand load into the South Delta.

A review of the 1995-99 data presented in Figure 29 shows, relative to the magnitude of DO depletion below a WQO, that DO depletion in the surface waters at the DWR Rough and Ready continuous monitoring station occurs in events that are associated with decreased SJR flow into the DWSC. Most of the DO depletion occurrence events are associated with SJR flow into the DWSC in the range of 300 to 1,000 cfs. The range of DO depletion for a particular flow typically was 1 to 2 mg/L below the applicable WQO. There were several DO depletion events with an extreme DO depletion below the WQO of 3 to 4 mg/L. These occurred with SJR flows of less than about 400 cfs.

There were situations where there were SJR flows into the DWSC below 1,000 cfs where the DO was not depleted below the WQO. These types of situations occurred more commonly in the fall than the summer. It appears that the lower oxygen demand load associated with reduced algal biomass that is expected in the fall, coupled with the lower temperatures during this time, reduce the magnitude of the DO depletion in the fall.

It is evident that SJR flows into the DWSC greater than about 1,500 cfs greatly reduced the DO depletion in the DWSC below the WQO. An SJR flow past Stockton into the DWSC greater than about 2,500 cfs was not associated with a DO depletion below the WQO for the DWR Rough and Ready Island surface monitoring station. However, as shown in Figure 14, there were DO depletions at other locations in the DWSC in the surface waters and especially in the bottom waters that are of a greater magnitude than those that occur in the surface waters at the DWR surface water monitoring station.

The 1995-99 data did not include the SJR flow reversal conditions that occurred in the drought years of the early 1990s. These conditions existed when the SJR flow into Old River was greater than the SJR flow at Vernalis. As a result there is SJR DWSC flow "upstream" through the DWSC into Old River. Under these conditions, the upstream of Vernalis oxygen demand loads are all diverted into Old River. Hayes and Lee (2000) (Appendix E) provided 1994 DO data for the DWSC during an SJR flow reversal year. The net daily flow past Stockton was –717 to +168 cfs during August and September and –308 to +301 cfs during October and November 1994. The DO depletion data during this period was shifted upstream to the Rough and Ready Island/Channel Point area. DO depletions of 1 to 2 mg/L below the WQO occurred during this time. In this case, the oxygen demand that caused the DO depletion was derived from City of Stockton and other local sources, including channel SOD and DWSC and nearby channels/sloughs-produced algae. The downstream into the DWSC tidal excursion of City of Stockton oxygen demand alone and/or combined with other local sources was evidently sufficient to cause DO depletion near Channel Point below the WQO.

The DWR DWSC 1995-99 DO and SJR flow data, coupled with the Lehman (2000) 1999 DWSC data provide considerable insight into the impact of SJR flow into the DWSC on the magnitude of DO depletion. It is evident that SJR flow into the DWSC is a dominant factor that controls how an oxygen demand of a certain magnitude impacts DO depletion in the DWSC. It is clear that there are also other factors that impact the DO depletion such as temperature, season, oxygen demand load, and possibly type of oxygen demand, etc. An important conclusion from these initial results is that SJR flow into the DWSC above 2,500 cfs, with even high oxygen demand loads present in the SJR at Vernalis, greatly reduces the magnitude of DO depletion in the DWSC. This is apparently due to the shortened residence times of the upstream of DWSC oxygen demand loads in the DWSC.

The DO depletion that would normally occur further downstream associated with higher flows in a typical river situation apparently do not occur in the SJR DWSC because of the cross-Delta flow caused by state and federal water projects' export of water in the south and southwest Delta. This export draws Sacramento River water across the SJR DWSC, reducing the length of the DWSC that experiences DO depletion below the WQO. As shown in the box model calculations presented previously, several tens of thousands of pounds per day of BOD_u are exported downstream of Disappointment Slough/Columbia Cut under flows of around 1,000 cfs. With flows of 2,000 cfs, much larger daily export of oxygen demand into the central Delta will occur.

An issue that has not been addressed in the SJR DO depletion studies is whether the diversion of SJR flows down Old River, with its high upstream of Vernalis oxygen demand loads, leads to DO depletions in the South Delta channels/canals that violate a DO WQO. Similarly under high-flow conditions, the high oxygen demand load that enters the DWSC and is transported through the DWSC at Disappointment Slough/Columbia Cut and therefore is exported into the central Delta by the Sacramento River cross-Delta flow, leads to low DO conditions in the central Delta that have not yet been recognized/reported.

There is discussion of developing/operating central Delta tidal barriers to optimize water quality/fisheries associated with "channeling" the Sacramento River through the Delta to the Projects' export pumps. Based on discussions at the Bay Delta Modeling Forum meeting held in February 2000, the situation that developed in the fall of 1999, where poor drinking water quality and adverse conditions to fisheries occurred, requires that a different approach be taken to Sacramento River flow control through the Delta. The operation of the tidal barriers could influence the potential impact of the SJR DWSC oxygen demand loads on central Delta DO depletion. At this time, CALFED is undertaking a major review of the operation of a Delta Cross-Channel barrier, which would enable Sacramento River water to be imported to the central and southern Delta while inhibiting larval fish in this water from entering this area of the Delta. There appears to be a significant problem with larval fish survival in the central Delta. By operating a Cross-Channel barrier as a function of tide stage in such a way as to inhibit importing larval fish, it may be possible to allow Sacramento River water to enter the Cross-Channel (see Figure 3) and protect larval fish. It is essential that all CALFED, DWR, USBR and Fish and Wildlife Service plans for managing Delta flow carefully evaluate the impact of these Delta flow manipulations on DO resources in the DWSC and the central and South Delta.

The DO depletion studies of the SJR DWSC need to be expanded to insure that Delta inflow and within-Delta flow manipulations do not cause DO depletion that would normally occur in the DWSC to occur at other locations in the Delta. There is need to determine the fate of the over 100,000 pounds/day of ultimate BOD that is introduced into these areas under certain SJR/Delta flow regimes. It is important to understand these situations as soon as possible since they could become important factors in limiting the approaches that can be used to control the impacts of oxygen demand on Delta aquatic life resources.

DO Depletion along the DWSC during 1995-99

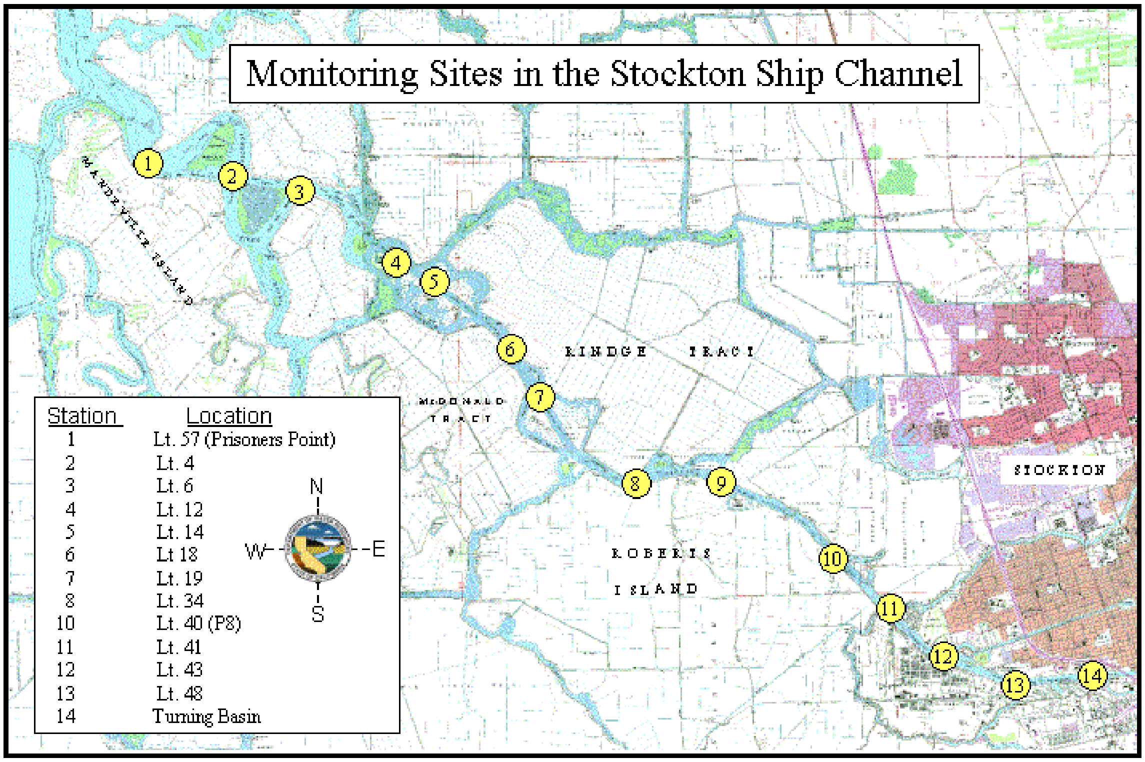
In order to examine the relationship between the DO measurements in the surface waters of the DWSC at Rough and Ready Island and the DO depletions in the surface and near-bottom (1 meter off top and bottom) waters at other locations in the DWSC between the Turning Basin and Turner Cut/Disappointment Slough, the data that DWR (Steve Hayes and group) has been collecting on DO concentrations within the DWSC was obtained. Hayes and Lee (2000) have recently presented a summary of the DWR data on the relationship between DO depletion in the DWSC and wet and dry flow years. Their review is included as Appendix E. The discussion presented below provides additional detail on these issues. Figure 30 presents a map of the DWR sampling stations used in these studies. Figure 31 through Figure 35 present the DO profiles that DWR obtained along the DWSC during 1995 through 1999.

Figure 30 shows that DWR Station 11 is close to where the DWR continuous DO monitor is located. Station 13 is near where the SJR enters the DWSC at Channel Point. Station 14 is the Port of Stockton Turning Basin. Disappointment Slough is located in the vicinity of Stations 4 and 5, with Turner Cut being located between Stations 7 and 8.

Examination of Figure 31 for the fall 1999 DWR monitoring of dissolved oxygen near the surface and the bottom of the DWSC shows that during October and November dissolved oxygen concentrations in the surface and bottom waters of the DWSC were typically below the 6 mg/L WQO. As low or lower concentrations of dissolved oxygen occurred in the surface and bottom waters during October and early November near Turner Cut compared to Station 11, where the DWR DO continuous monitoring station at Rough and Ready Island is located. While typically the surface and near-bottom dissolved oxygen concentrations were the same at each location outside of the Turning Basin, there were some occasions during 1999 where there was about 0.5 mg/L difference between the surface and bottom DO values. On October 26, there was a significant difference between the surface and bottom water DO in the Turning Basin.

Overall, it can be concluded from the 1999 data presented in Figure 31 that the DWR monitoring of DO in the surface waters near Rough and Ready Island is an indication of the DO depletion problems below WQOs that are occurring, although at times lower DOs were found in

Figure 30



surface and bottom waters just upstream of Turner Cut than at the Rough and Ready Island station.

Figure 32 presents the results of the DWR monitoring of dissolved oxygen in the DWSC during August 1998 through October 1998. During this period, there were at least 2,000 cfs of SJR flow into the DWSC. During this period the DO concentrations in the DWSC at the Rough and Ready Island surface water monitoring station did not violate WQOs. However, examination of Figure 32 shows that while the Station 11 (Rough and Ready Island) DO measurements were above the WQOs, there were WQO violations for Stations 5 through 9 in September 1998. Therefore, even a flow of 2,000 cfs is not adequate to prevent DO depletion in the DWSC below WQOs. The elevated flows that occurred in 1998 pushed the oxygen sag (maximum depletion) further downstream from a location just above Turner Cut to just above Disappointment Slough.

As in 1999, except for the Turning Basin, the surface and bottom water DO concentrations at the various stations were similar in 1998, indicating that the DWSC is fairly well vertically mixed at all locations except within the Turning Basin.

Figure 33 presents the August through November 1997 DWSC DWR monitoring data. Examination of Figure 33 shows that during August 1997 there were significant violations of the 5 mg/L WQO in both surface and bottom waters. Further, on several occasions during August and September, the DO depletion in the bottom waters was greater than that in the surface waters. Again, at some times, there were marked differences in the DO concentrations of the surface and bottom waters of the Turning Basin.

The SJR flow (see Figure 29) into the DWSC during 1997 was lower than during 1998, which accounts, in part, for the greater DO depletions below WQOs that occurred during 1997.

The September, October and November 1997 data show that the 6 mg/L WQO was violated over considerable distances in the DWSC, typically starting at about Channel Point or just downstream, down to about halfway between Turner Cut and Disappointment Slough. Note that the horizontal lines on this figure which were drawn by DWR for the 5 mg/L WQO for September, October and November should have been drawn at 6 mg/L, with the result that the visual perception of the DO depletion is even greater than that shown by the figure.

Figure 34 presents the 1996 DWSC DO monitoring of the DWSC. The data obtained show that during August, September and early October there were violations of the DO WQOs for these periods. By late October through the November monitoring run, the DO in the DWSC surface and bottom waters was above the 6 mg/L WQO.

There were also several of the monitoring runs in 1996 where there were significant differences between the surface and bottom waters' DO concentrations. Again, on many occasions, the surface and bottom waters of the Turning Basin had significantly different DO concentrations, but this did not always occur. Of particular interest is that while August 12 and September 10 showed marked differences between the surface and bottom water DO concentrations within the Turning Basin, the August 27 data showed little difference. As discussed herein, because of the importance of low DOs near the bottom in establishing the TMDL, it will be important to understand why, for the Turning Basin and at other locations in the DWSC, the DO near the bottom is lower than the surface waters, yet two weeks later, the two are the same. The factors that control the mixing that eliminates the lower DO near the bottom need to be understood and, if possible, enhanced.

The 1995 DWR monitoring of the DWSC (Figure 35) for August 5 and 23, 1995, showed that while the surface waters were above the 5 mg/L WQO, the bottom waters were below this value. September 8 showed violations of the 6 mg/L DO WQO for both surface and bottom waters over considerable distances of the DWSC. October 6, November 6 and November 22 had dissolved oxygen concentrations in the surface and bottom waters, except for the Turning Basin, just at or above the 6 mg/L WQO. The Turning Basin on several occasions had significant DO depletions near the bottom that were not reflected in the surface waters.

Initial Overall Assessment of SJR Flow on DWSC DO Depletion

Overall, based on this initial assessment of the current information, it is evident that SJR flow into the DWSC plays a significant role in DO depletions below the WQO. Further, there are month-to-month and year-to-year variations in DO depletions below WQOs which cannot be explained based on the SJR flow information available. It is evident, however, that even an SJR flow of 2,000 cfs through the DWSC will not prevent DO WQO violations.

It is likely that a more detailed evaluation of existing data on flow and other characteristics of the DWSC will help elucidate some of the factors controlling the relationship between an oxygen demand load from upstream of Vernalis versus the City of Stockton and other local sources. It is also evident that a detailed examination of the existing data would provide guidance on the specific studies that should be conducted within the DWSC and upstream that will be needed to develop a technically valid, cost-effective dissolved oxygen management plan for the DWSC. A high priority should be given to a critical in-depth examination of the relationship between flow and other factors that are suspected to influence DO depletion within the DWSC below the WQOs.

SJR Water Diversions

A significantly different flow regime and DO depletion pattern would exist within the SJR DWSC if there were not such large diversions of water from the SJR and its tributaries upstream of the DWSC. Table 15 shows that the Central Valley Project (CVP) diverts about a million ac ft/yr from the Delta. To the extent that this diversion results in increased SJR flow into Old River, it diverts water from the SJR that could flow through the DWSC. Further, according to the SWRCB (1999c), the City of San Francisco diverts about 240,000 ac ft/yr of water from the Tuolumne River as part of the City's water supply that is based on the Hetch Hetchy Reservoir on the Tuolumne River. This diversion directly impacts the flow of the SJR into the DWSC. In addition, SWRCB estimates that the Turlock and Modesto Irrigation Districts divert another almost 1 million ac ft/yr of Tuolumne River water, which also adversely affects the flow of the SJR into the DWSC. Part of that water, however, is returned to the SJR watershed above the DWSC in irrigation return water.

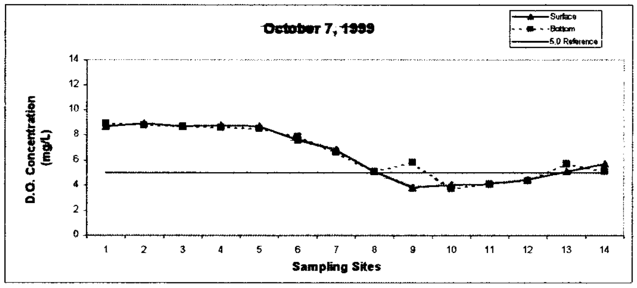
(The figures presented below are derived essentially in the form that DWR made them available. Greater resolution on the following figures can be obtained through the use of a zoom expansion by 200%)

Figure 31

Dissolved Oxygen Concentrations in the Stockton Ship Channel for October - December 1999

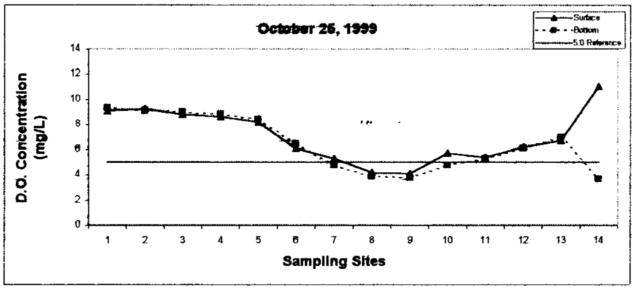
October 7, 1999

Sites	Surface	Bottom	5.0 Referenc	Surf-temp	Bot-temp
1	8.7	8.9	5	19.1	19
2	8.9	8.8	5	19.1	19.1
3	8.7	8.7	5	19.2	19.2
4	8.8	8.6	5	19.5	19.4
5	8.7	8.5	5	19.8	19.7
6	7.6	7.9	5	20.5	20.1
7	6.8	6.6	5	21	20.8
8	5.1	5.1	5	21.1	20.9
9	3.8	5.8	5	21.3	20.3
10	4	3.7	5	21.2	20.9
11	4.1	4.1	5	21	21.8
12	4.4	4.3	5	20.9	20.8
13	5.1	5.7	5	20.5	19.9
14	5.7	5.1	5	21.6	20.5



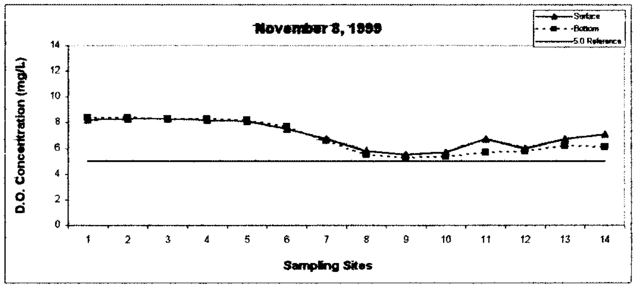
October 25, 1999

Sites	Surface	Bottom	5.0 Referenc	Surf-temp	Bot-temp
1	9.1	9.3	5	17.2	17.1
2	9.2	9.1	5	17.3	17.2
3	8.8	9	5	17.4	17.3
4	8.6	8.8	5	17.6	17.5
5	8.2	8.4	5	18	17.7
6	6.1	6.5	5	18.8	18.2
7	5.3	4.8	5	18.9	18.4
8	4.2	3.9	5	18.6	18.3
9	4.1	3.8	5	18.8	18.2
10	5.7	4.8	5	18.9	18
11	5.4	5.3	5	18	17.9
12	6.2	6.1	5	18	17.7
13	6.7	7	5	17.9	17.4
14	11	3.7	5	19	17.6



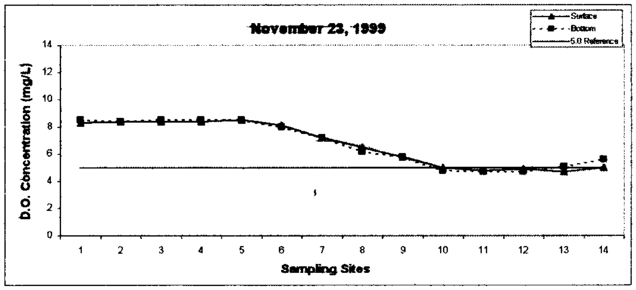
November 8, 1999

Sites	Surface	Bottom	5.0 Referenc	Surf-temp	Bot-temp
1	8.2	8.4	5	15.8	15.8
2	8.3	8.4	5	15.9	15.8
3	8.3	8.3	5	16	15.9
4	8.2	8.3	5	16	16
5	8.1	8.2	5	16.3	16.1
6	7.5	7.7	5	16.6	16.4
7	6.7	6.6	5	17	16.7
8	5.8	5.5	5	17.1	16.8
9	5.5	5.3	5	17.1	16.8
10	5.7	5.4	5	16.9	16.8
11	6.7	5.7	5	17.6	16.7
12	6	5.8	5	16.7	16.6
13	6.7	6.2	5	16.9	16.4
14	7.1	6.1	5	17.1	16.4



November 23, 1999

Sites	Surface	Bottom	5.0 Referenc	Surf-temp	Bot-temp
1	8.3	8.5	5	13.1	13.1
2	8.4	8.4	5	13	13
3	8.4	8.5	5	13.1	13
4	8.4	8.5	5	13.2	13
5	8.5	8.5	5	13.2	13
6	8.1	8	5	13.6	13.5
7	7.2	7.2	5	14	13.8
8	6.5	6.2	5	14	13.9
9	5.8	5.8	5	14.1	13.9
10	5	4.8	5	14.4	14.2
11	4.8	4.7	5	14.2	14
12	4.9	4.7	5	14.1	13.9
13	4.7	5.1	5	13.8	13.6
14	5	5.6	5	14.5	13.6



December 7, 1999

Sites	Surface	Bottom	5.0 Referenc	Winkler	YSI Temp
1	9.97	9.84	5	10.2	11.1
2	9.76	9.74	5	9.9	10.9
3	9.86	9.81	5	10.2	10.9
4	9.69	9.73	5	10.1	11
5	9.8	9.67	5	9.8	11
6	9.75	8	5	9.9	11
7	9.17	9.06	5	10.1	11.2
8	8.39	8.15	5	8.9	11.4
9	7.36	7.01	5	7.1	11.6
10	5.73	5.33	5	5.6	11.9
11	5.43	5.08	5	5.7	11.9
12	5.67	5.32	5	5.4	11.8
13	5.7	5.52	5	5.8	11.5
14	5.33	5.07	5	5.6	11.7

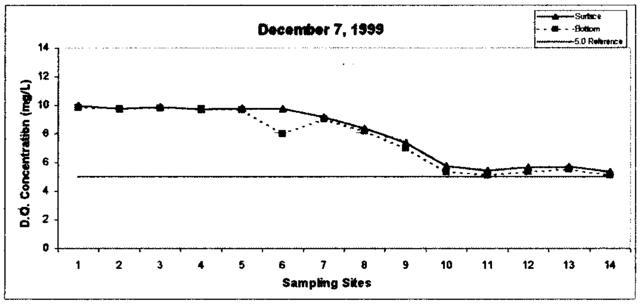


Figure 32

Dissolved Oxygen Concentrations in the Stockton Ship Channel for August through October 1998

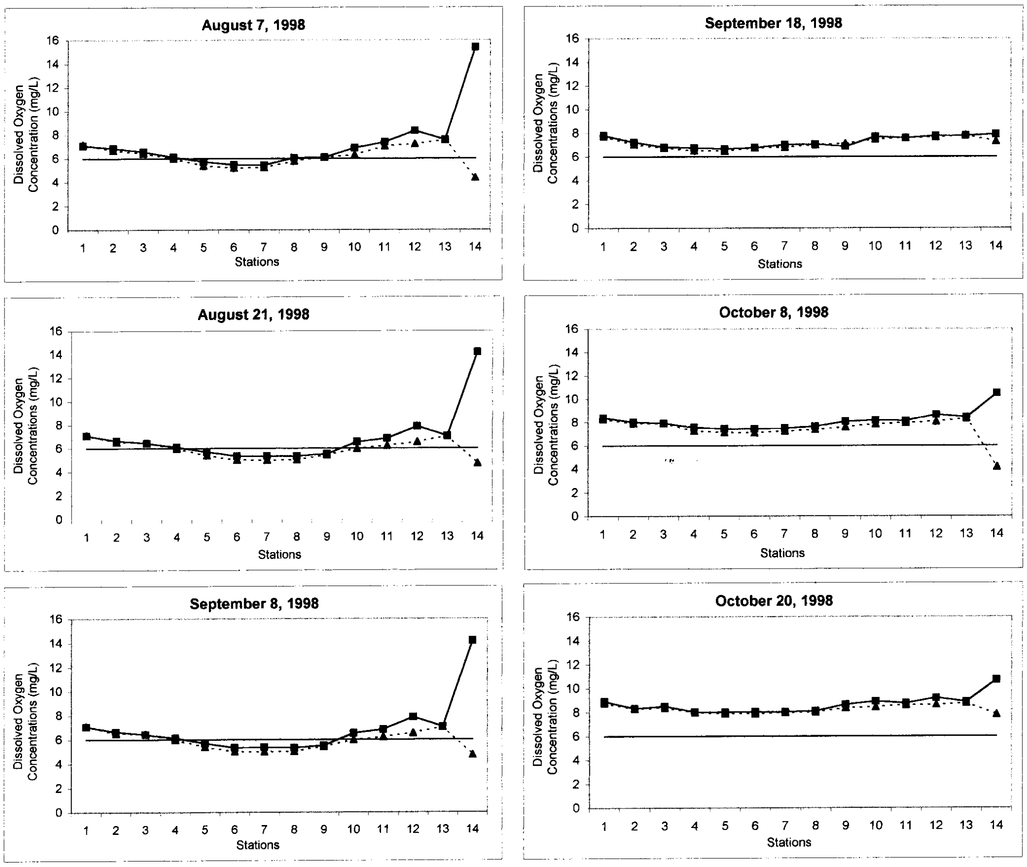


Figure 33

Dissolved Oxygen Concentrations in the Stockton Ship Channel for August through November 1997

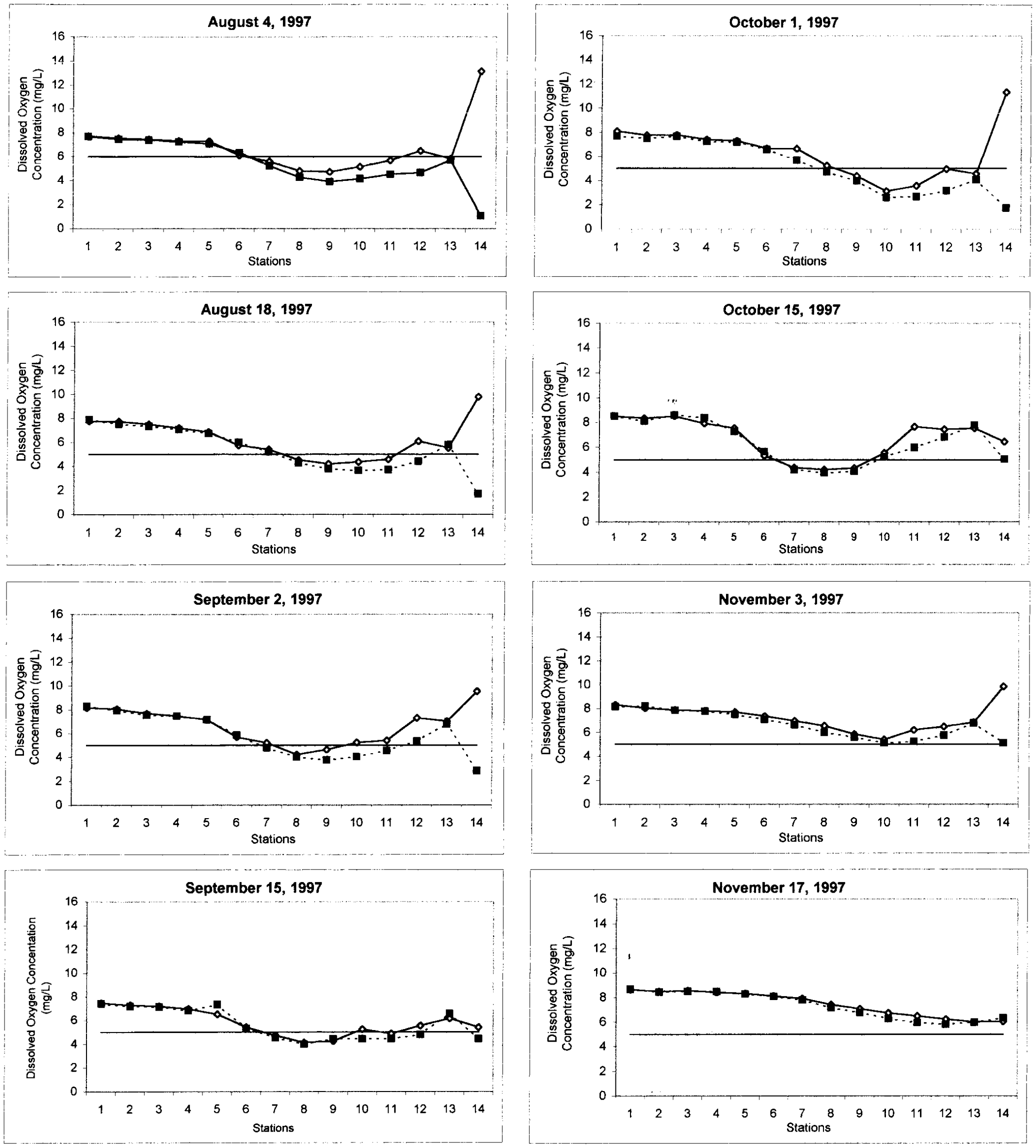


Figure 34

This is the raw data and graphics for the 1996 dissolved oxygen runs. The values were obtained through the Winkler method (except for 9/26/96).

August 12, 1996 Dissolved Oxygen Run

Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	7.2	7.6
Lt. 4	7.2	7.2
Lt. 6	7.2	7
Lt. 12	6.7	6.7
Lt. 14	6.7	6.7
Lt. 18	5.7	5.9
Lt. 19	5.1	4.9
Lt. 28	4.4	4.1
Lt. 34	4.4	3.8
P8	4.8	3.8
Lt 41	5.7	4
Lt. 43	5.3	3.6
Lt. 48	4.7	4.7
Turn. Basin	12.1	2.3

August 27, 1996 Dissolved Oxygen Run

Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	7.8	7.8
Lt. 6	7.6	7.7
Lt. 14	7.5	7.2
Lt. 19	5.4	5.2
Lt. 34	3.9	3.6
P8	4.1	3.5
Lt. 41	4.3	3.9
Lt. 43	5.2	4
Lt. 48	4.7	4.6
Turn. Basin	8.7	7.8

September 10, 1996 Dissolved Oxygen Run

Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	7.8	7.8
Lt. 6	7.6	7.4
Lt. 14	7	6.9
Lt. 19	4.8	4.6
Lt. 34	4	3.4
P8	4.9	3.8
Lt. 41	5.7	4.2
Lt. 43	6.2	4.2
Lt. 48	6	5.7
Turn. Basin	12.3	0.8

September 26, 1996 Dissolved Oxygen Run
(Hydrolab data)

Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	7.9	7.7
Lt. 4	7.8	7.6
Lt. 6	7.8	7.8
Lt. 12	7.7	7.7
Lt. 14	7.5	7.4
Lt. 18	6.1	6.1
Lt. 19	5.5	5.2
Lt. 28	4.6	4.4
Lt. 34	4.6	4.1
P8	4.7	4.5
Lt 41	5.2	4.7
Lt. 43	5.8	5.1
Lt. 48	6.6	6.3
Turn. Basin	7.1	2.7

October 11, 1996 Dissolved Oxygen Run

Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	7.6	7.6
Lt. 4	7.9	7.7
Lt. 6	7.4	7.5
Lt. 12	7.4	7.4
Lt. 14	6.5	6.5
Lt. 18	5.4	5.4
Lt. 19	5	4.9
Lt. 28	4.8	4.6
Lt. 34	4.9	4.7
P8	4.9	5
Lt 41	6	5.1
Lt. 43	6.2	6.1
Lt. 48	6.7	6.8
Turn. Basin	7.3	4.1

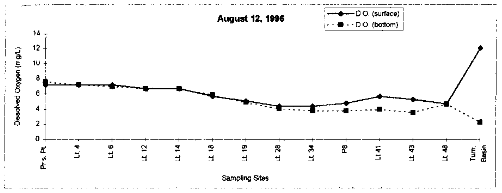
October 25, 1996 Dissolved Oxygen Run

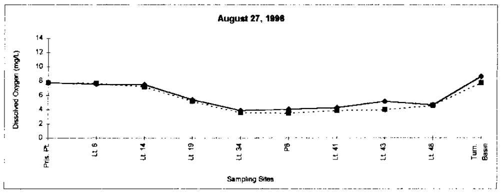
Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	9.2	9.2
Lt. 4	9.1	9.1
Lt. 6	8.9	9
Lt. 12	8.8	8.8
Lt. 14	8.6	8.6
Lt. 18	8.5	8.6
Lt. 19	8.5	8.5
Lt. 28	8.6	8.5
Lt. 34	8.5	8.6
P8	8.5	8.2
Lt 41	8.3	8.4
Lt. 43	8.4	8.5
Lt. 48	8.6	8.6
Turn. Basin	8.1	7.9

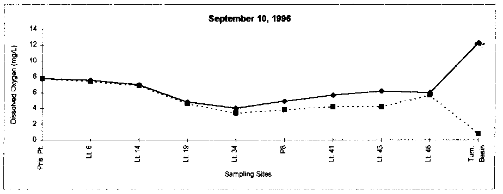
November 12, 1996 Dissolved Oxygen Run

Sampling Sites	D.O. (surface)	D.O. (bottom)
Pris. Pt.	9.2	9.2
Lt. 4	9	8.9
Lt. 6	9	9
Lt. 12	9.1	8.8
Lt. 14	8.6	8.5
Lt. 18	8	7.7
Lt. 19	7.7	7.5
Lt. 28	7.5	7.5
Lt. 34	7.6	7.5
P8	8.2	7.7
Lt 41	8.4	7.8
Lt. 43	8.5	8.1
Lt. 48	8.4	8.2
Turn. Basin	11.1	7

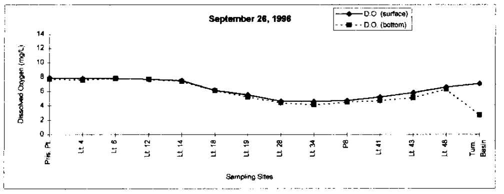
Dissolved Oxygen Sampling in the Stockton Ship Channel in 1996, p.1

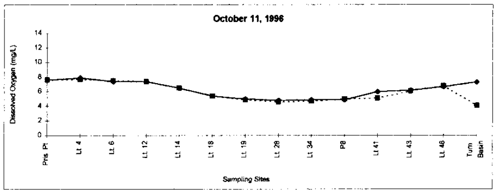


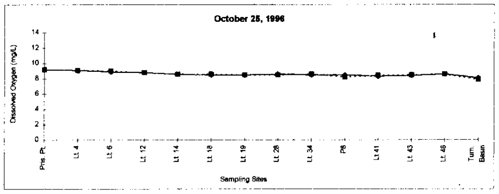




Dissolved Oxygen Sampling in the Stockton Ship Channel in 1996, p.2







Dissolved Oxygen Sampling in the Stockton Ship Channel in 1996, p.3

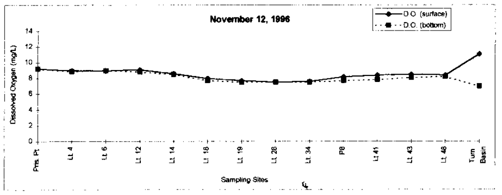


Figure 35

Dissolved Oxygen Concentrations in the Stockton Ship Channel for August through November 1995

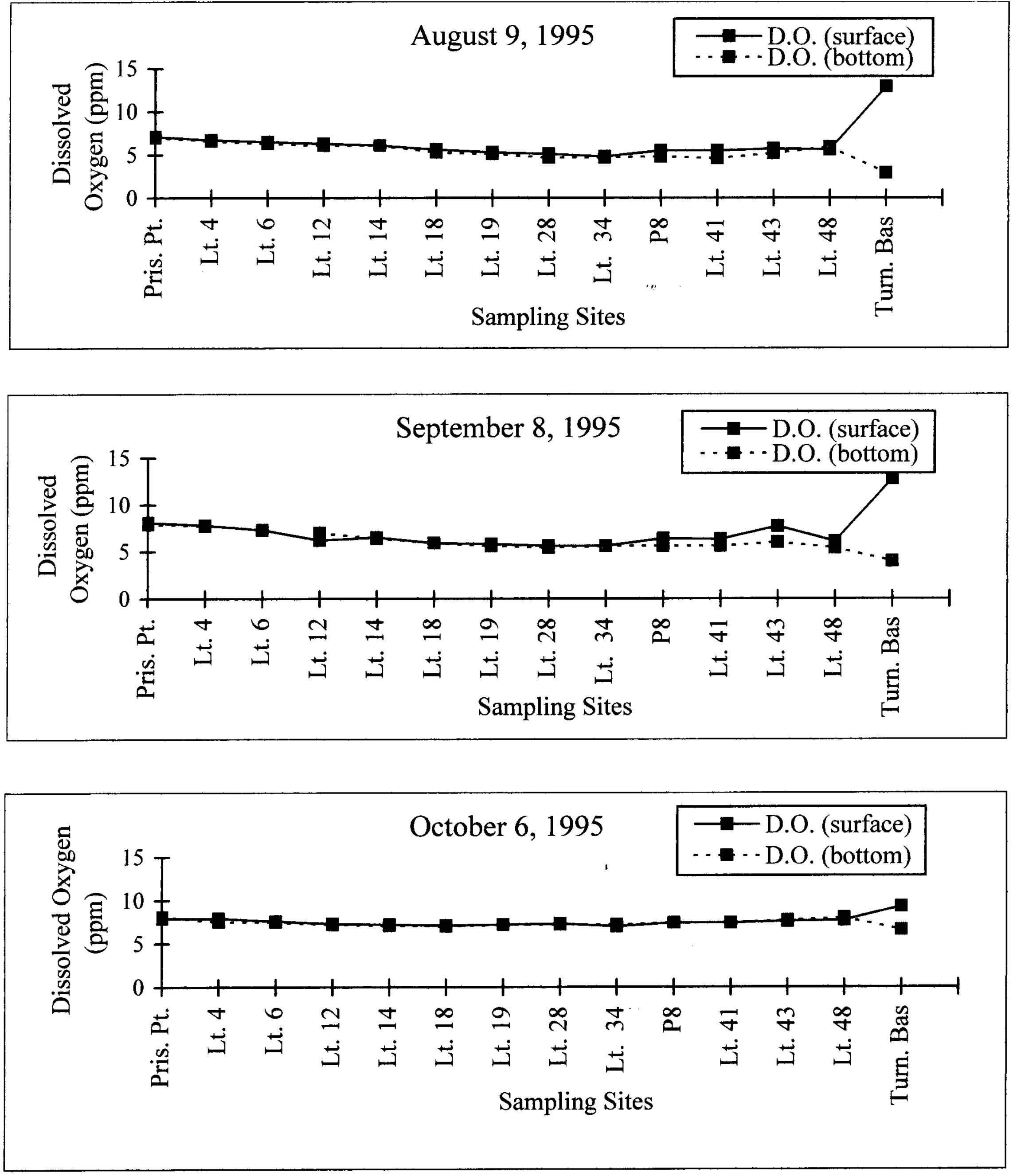
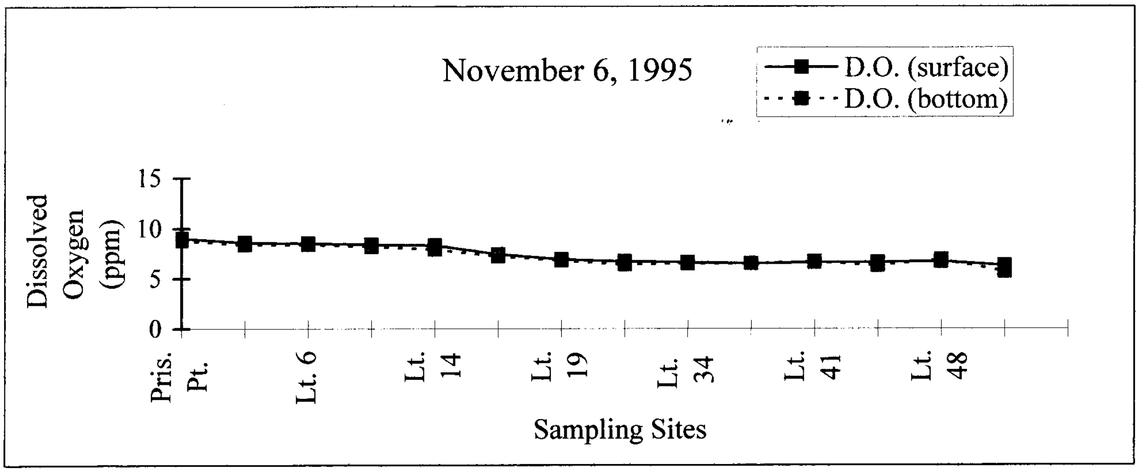


Figure 35 (continued)



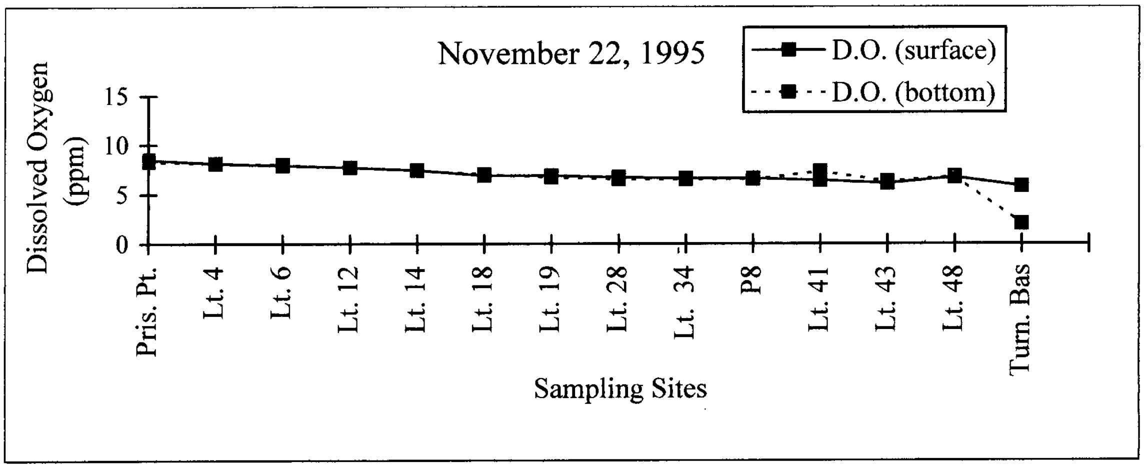


Table 15: Summary of Reduction in Runoff of San Joaquin River at Vernalis from Pre-CVP to Post-CVP

Year Type & Period	Effect of All Post-CVP Upstream Development on Runoff At Vernalis		Effect of CVP on Runoff at Vernalis		
	Reduction in Runoff (acre-ft)[1]	Post-CVP Reduction as Percent of Pre-CVP Actual Runoff	Reduction in Runoff (acre-ft)[1]	Reduction at Vernalis as Percent of Pre-CVP Flow	Reduction at Vernalis as Percent of Post-CVP Flow
DRY					
April – September	417,000	68[2]	6,000	1.4	3.0
Full Year	519,000	45	168,000[3]	11	13
BELOW NORMAL					
April – September	1,064,000	60[2]	386,000	22[2]	55
Full Year	1,219,000	44[2]	543,000	20[2]	35
ABOVE NORMAL					
April – September	1,732,000	57	440,000	15	40
Full Year	1,400,000	28	768,000	15	25
WET					
April – September	1,000,000	19	554,000	15	10
Full Year	1,168,000	13	771,000	9	12
AVERAGE OF ALL YEARS					
April – September	1,053,000	40	345,000	13	24
Full Year	1,076,000	24	553,000	12	19

1. From Tables 2, 4, 6, 8, 10, 12, 14, 16 (For these tables, refer to original document)
2. Pre-CVP "actual" is assumed to be post-CVP actual plus pre-CVP to post-CVP loss per Tables 4, 6, 10
3. Corrected for difference in pre-CVP and post-CVP unimpaired flow

(Table from Water and Power Resources Service 1980)

In summary, the City of San Francisco, irrigation districts and the municipal diversions, to the extent that their diversion results in consumptive use of the diverted water, i.e., the water is not returned to the SJR upstream of the DWSC, adversely impact the SJR flow into the DWSC. The State and Federal Water Projects also adversely impact the SJR DWSC DO problem to the extent that they divert SJR water at Old River. However, it is likely that if the Projects' SJR water that is exported from the Delta were to pass through the DWSC before export, this could be beneficial to reducing the magnitude of the DO depletion in the DWSC for a particular oxygen demand load. This is because it would reduce residence time in the DWSC, reducing the amount of material oxidized.

There are potentially significant adverse impacts to some South Delta water users of not diverting part of the SJR flow at Vernalis into Old River. Tracy, as a municipal wastewater discharger in the South Delta, needs SJR flow through Old River to dilute its wastewater discharges. Without this dilution, Tracy would need to provide a higher degree of treatment of its wastewaters before discharge to the South Delta waters.

The irrigation districts in the South Delta also need SJR water to dilute the salt that builds up within the South Delta waters due to upstream sources and local South Delta discharges. There is also a problem with recirculation/build-up of the salts within the South Delta through the Federal Water Project pumps at Tracy when SJR water is diverted into Old River. Further, there is a problem at times with the Federal Water Project exporting South Delta water at a sufficient rate so that South Delta water users find that, under low tide, the water levels within the channels are sufficiently low that channel water is not available for pumping for irrigation purposes and for some recreational activities, such as boating.

The current water flow problems of the South Delta are long-standing problems that are still being addressed by the Bureau of Reclamation and DWR. DWR Central District (1988) published "South Delta Water Management Program," which describes these problems and some of the approaches being considered to manage them. One of these approaches involves the construction of a number of tide gates within the South Delta to manage the flow in such a way as to minimize flow problems. The tide gates include the Middle River tide gate, Old River tide gate, Grant Line tide gate, and the Tom Paine Slough siphons.

According to A. Hildebrand (2000, personal communication) the reason why some SJR Vernalis water must enter Old River is not only to dilute Tracy domestic wastewater discharges, but also to assist in maintaining flushing flows and adequate water depths for operation of agricultural diversions and for boating in shallow channel reaches. Otherwise, these channels are often sucked dry by the export pumps in the absence of the three tidal barriers. When the three tidal barriers are allowed to operate, the amount of water which must enter Old River is small. When permanent operational tide gate barriers are installed which open on the rising tide and close, with boat locks, during the ebb tide, this will minimize the amount of SJR flow at Vernalis that must be diverted into Old River to avoid South Delta problems of low water and inadequate dilution. The Grant Line barrier can be operated to spill water during a portion of the ebb tide, when necessary to dilute Tracy's domestic wastewater discharges. According to A. Hildebrand, this is only likely to be necessary during one ebb tide every second or third day. The tidal barriers also greatly reduce the need for flushing flows, because they keep the San Joaquin River salt load (about 400,000 tons/yr) from entering Old River.

Another aspect of the SJR diversion situation is that, to the extent that diversions of SJR water occur at Old River, they reduce the upstream of Vernalis load of oxygen-demanding materials discharged to the DWSC. However, the Old River diversions concurrently increase the significance of local DWSC and especially the City of Stockton's wastewater discharges as causes of oxygen depletion within the DWSC.

According to King (2000, personal communication), the Grant Line Canal temporary barrier was removed on September 23, 1999. This removal corresponds to the drop in daily net flow of the SJR into the DWSC from about 900 cfs to about 150 cfs, shown in Figure 29. It is apparent that how the South Delta barriers are operated can have a significant impact on the SJR flow into the DWSC, which, in turn, will impact the oxygen demand load into the DWSC and the DO depletion that occurs from this load.

The TMDL for oxygen demand loads to the DWSC will likely need to be broken down into a seasonal and, for each season, a flow component. It is likely that a more thorough review of SJR DWSC flow and DO depletion will yield information that can provide guidance on the magnitude of oxygen demand loads to the DWSC during the summer (July through September) and fall (October through December) at SJR into DWSC flows in the low (less than 500 cfs), moderate (500 to 1,500 cfs) and higher (greater than 1,500 cfs) ranges. The fall flow ranges will likely need to consider how the control of ammonia toxicity from the City of Stockton's wastewater discharges will influence the oxygen demand loads that can be allowed from other sources and not cause violations of a WQO.

It is evident that the management of the flow barriers in the South Delta at Old River and other locations has considerable significance to a number of stakeholders. There is need to understand how the operation of these barriers impacts flows and DO depletion within the DWSC, as well as water quality within the South Delta. It is clear that the current efforts of CALFED to develop altered flow patterns within and possibly around the Delta need to incorporate a careful evaluation of how altering flows into, through and around the Delta impacts the dissolved oxygen depletion problem that occurs within the DWSC.

SJR DWSC Low DO Responsible Entities

There are many responsible entities for the dissolved oxygen depletion problems that are occurring in the SJR DWSC. A listing of the currently identified entities/activities that influence the dissolved oxygen concentrations in the SJR DWSC is presented in Table 16. Based on the box model calculations, as well as the Stockton SJR DO modeling results, it is concluded that there are several major sources of oxygen demand for the DWSC. These include agricultural and municipal activities that contribute either oxygen demand or nutrients that develop into algae which exert an oxygen demand within the DWSC above the San Joaquin River at Vernalis.

As listed in Table 16, there are a number of potentially significant oxygen demand and nutrient sources upstream of Vernalis, such as agricultural runoff/drainage, and wastewaters from municipalities, industry, dairies and other animal husbandry operations, etc. While Kratzer and Shelton (1998) provided a report on the nutrients and suspended sediment loads to the SJR, the data upon which the loads were calculated were derived from 1972 to 1990. Agricultural practices, wastewater management approaches/loads, etc., within the DWSC watershed have changed over the past 10 to 15 years. Because of the importance of upstream-of-Vernalis oxygen demand loads as contributors to DO depletion in the DWSC during the times that more than a few hundred cfs of SJR-at-Vernalis flow enters the DWSC (i.e., when there are limited diversions of SJR flow at Old River), a high priority for future DO TMDL studies should be given to defining the major upstream-of-Vernalis oxygen and nutrient sources that contribute to dissolved oxygen concentrations below the WQO that occur within the DWSC during late summer and fall.

The nutrient and oxygen demand loads from the DWSC watershed should be assessed on a monthly basis in order to determine the oxygen demand and nutrient loads that actually contribute to the summer and fall DWSC DO depletion problem. There are substantial oxygen demand and nutrient loads from within the DWSC watershed, both upstream and downstream of Vernalis, that are associated with the high winter flows that apparently do not contribute oxygen demand and nutrients to the DWSC that are important in causing DO depletion below water quality objectives. The winter and at least early spring flows associated with stormwater runoff and wastewater discharges within the DWSC watershed transport oxygen demand and algal nutrients through the DWSC during the period of the year (winter/spring) that does not contribute to the DWSC DO depletion problem. This situation arises from high flows and therefore short residence times within the DWSC, low temperatures which slow down the rate of BOD exertion and the rate of algal growth, as well as limited daily duration of sunlight which reduces the rate of algal growth.

Table 16
Responsibility for SJR DWSC DO Depletion Below Water Quality Objective

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Sources of Oxygen Demand
- NPDES Permittees
  - Municipal and Industrial Wastewater Discharges and Stormwater Runoff
    - City of Stockton and other municipalities
  - Dairies and other Animal Husbandry Operations, Including
    - Feedlots, Hogs, Horses, Chickens
  - Industry
- Non-Point Runoff/Discharge of Oxygen Demand
  - Agricultural Lands, Irrigation Drainage, and Stormwater Runoff
  - Non-NPDES Permitted Urban Stormwater Runoff
  - Riparian Lands
- Pollution of Groundwater that Leads to Nitrate Discharge to Surface Waters
  - Agriculture
  - Dairies and other Animal Husbandry
  - Land Disposal of Municipal Wastewaters
  - Urban Areas

DWSC Geometry
- Port of Stockton/Those who benefit from commercial shipping to Port
  - Channel depth impacts oxygen demand assimilative capacity
- Ship Traffic that Stirs Sediments into Water Column that Increases SOD

SJR DWSC Flow
- All entities that divert water from the SJR above the DWSC, as well as those that alter the SJR flow pattern through the Delta
  - Municipal and Agricultural Diversions

Future Urban Development in Watershed
- How will future development in the SJR DWSC be controlled so that the increased oxygen demand and nutrients associated with urban development will not cause future low DO problems in the DWSC?

In making the evaluation of the influence of season in transporting materials to the DWSC that influence DO depletion, it will be important to assess whether any of the winter/spring transported organic detritus (plant and animal remains) and algae associated with these flows are deposited within the DWSC and thereby become part of a sediment oxygen demand that influences DO concentrations during the following summer/fall. A key area of future studies will be an evaluation of the sources of particulates that exert an oxygen demand as part of the DWSC SOD. Of particular concern is the role of organic detritus derived from the watershed that becomes part of the DWSC sediment oxygen demand.

Foe (2000, personal communication) has suggested that it may be appropriate to periodically during the course of the year conduct some long-term BOD tests and determine how much oxidation occurs after 60 days. Foe indicates that this will likely be a small amount, when compared to the oxidation that occurs during the first 10 days. If so, then it can be concluded that material brought in 60 days earlier is of little importance in contributing SOD and can be ignored.

Significance of SJR Diversions above DWSC

The box model calculations and the Stockton SJR DO Model both show the importance of the impact of the water diversions that take place at Old River in influencing the DO depletion problem within the DWSC. Major diversions of SJR water at Old River significantly change how oxygen demand from the watershed impacts the dissolved oxygen concentrations within the DWSC. This situation is primarily associated with significantly increasing the residence time of the SJR inputs to the DWSC. This increased residence time provides more time for the oxygen demand, including the algae that enters the DWSC, to exert their oxygen demand within the DWSC before export across the downstream boundary of the DWSC.

As shown in Figure 9 at 1,000 cfs, the residence time within the DWSC where significant oxygen depletion is occurring is about 10 days. At 100 cfs, the residence time within the DWSC is estimated to be on the order of 30 days. Under a 10-day residence time, a larger fraction of the oxygen demand associated with carbonaceous BOD, nitrogenous BOD, and algae is exported from the DWSC before it can exert its full oxygen demand potential. Under a 30-day residence time, most of the CBOD and NBOD added to the DWSC would be exerted within the DWSC. It will be important to evaluate whether the exported oxygen demand and algae cause significant oxygen demand problems within the central Delta. It is possible that the mixing of the high quality Sacramento River water with the DWSC exported SJR water dilutes the oxygen demand sufficiently so that DO depletion below WQOs does not occur. This needs to be evaluated.

The increased residence time within the DWSC associated with low SJR flow into the DWSC also provides increased time for algal growth within the DWSC. While the algae that develop in the DWSC produce oxygen through photosynthesis in the upper several feet of the DWSC, the settling and death of algae within the DWSC add to the dissolved oxygen depletion problems that occur within the DWSC. At this time, the significance of algal growth within the DWSC as a cause of oxygen demand that exacerbates the DO depletion problems occurring in late summer and fall is poorly understood. This is an area that needs attention during future DO TMDL studies.

One of the consequences of large SJR diversions at Old River during late summer and fall is that the upstream-of-Vernalis oxygen demand and algal nutrient loads are largely diverted down Old River. As a result, the relative significance of upstream-of-Vernalis oxygen demand, algal loads downstream of Mossdale, and other DWSC local sources, changes. This situation was demonstrated during 1999, when the flow of the SJR into the DWSC decreased from about 1,000 cfs to about 150 cfs in late September. As shown in the box model calculations, the upstream-of-Vernalis loads decreased significantly, while the City of Stockton, French Camp Slough, and other local sources of oxygen demand became the dominant sources of constituents that were contributing to the low DO problems that occurred in the DWSC during October. During October 1999, the DO in the DWSC near Rough and Ready Island decreased to about 2 mg/L, the lowest values found during the 1999 study period. The DWSC low dissolved oxygen situation seems to have persisted at times through November and into December.

During SJR higher flow conditions (i.e., greater than about 1,000 cfs) into the DWSC, when the City of Stockton's wastewater ponds are controlling the release of ammonia, the oxygen demand associated with the City of Stockton's wastewater discharges is a small part of the oxygen demand load to the DWSC. However, under low SJR flow conditions of less than a few hundred cfs into the DWSC, the City of Stockton wastewater sources and other local oxygen demand sources become dominant. The significance of the City's wastewater discharges is greatly increased during the fall, when the City's wastewater treatment plant fails to remove the ammonia from the effluent and the DWSC flow is low.

It is evident that how the flow of the SJR into the DWSC is altered by diversions at Old River is important in determining how oxygen demand loads and nutrients discharged to various parts of the DWSC watershed impact the depletion of dissolved oxygen below water quality objectives. This situation makes the diversion of SJR flow at Old River a major factor in determining the oxygen demand and algal-related BOD assimilative capacity of the DWSC. The major diversions of SJR water during summer and fall should cause those who divert this water to become responsible entities for helping to correct the low DO problems in the DWSC that are associated with the diversions.

It will be possible to translate the cost of diverting a certain amount of SJR water down Old River into dollars of increased cost for removal of oxygen demand that will need to be borne by the stakeholders in the DWSC watershed. Basically, there is an equivalency between cfs diverted and the cost of oxygen demand removal from various types of sources at various locations within the DWSC watershed. These costs then will need to be compared to the costs of installing and operating aerators as an alternative to removal of oxygen demand substances in the tributary waters to the DWSC. Ultimately, the SJR DO TMDL Steering Committee will need to try to develop a balance of these various costs to develop the most technically valid, cost-effective approach for controlling the oxygen depletion below the WQO within the DWSC.

Influence of DWSC Channel Depth

The development of the Port of Stockton and its continuing activities, which led to the development of the Deep Water Ship Channel as a means by which ocean-going ships can use the Port, causes the "Port," including all of those who benefit from the reduced cost of shipping goods to and from the Port of Stockton, to be a responsible entity to the DWSC DO depletion problem. Since the San Joaquin River above the DWSC does not experience significant DO depletion problems due to algal and other oxygen demand loads, it is reasonable to assume that if the Port of Stockton/Deep Water Ship Channel did not exist, i.e., if the SJR below the Port of Stockton had a depth of about 10 feet, there would not likely be the significant DO problems that are now being found in the DWSC just downstream of the Port of Stockton.

Chen and Tsai (2000) estimated that, if the DWSC returned to its normal depth of about 10 feet, this would cause about 1 mg/L increase in dissolved oxygen in the DWSC during August and September 1999. For much of the time during these months, this additional dissolved oxygen of about 1 mg/L would eliminate the violations of the water quality objectives. The Port/those who benefit from maintaining the Deep Water Ship Channel are responsible entities for contributing to the dissolved oxygen depletions below the water quality objectives. As with diverted SJR flow, the deepening of the ship channel from its natural depth can be converted to a cost of additional removal of oxygen demand materials by the oxygen demand dischargers within the DWSC watershed. These costs will need to be considered as part of assigning responsibility for the DO depletion problem that exists within the DWSC for any season and range of SJR flows into the DWSC.

There is discussion about deepening the DWSC from its current 35-foot navigation depth to 40 feet. The implementation of this deepening will cause additional depletion of dissolved oxygen within the DWSC over that currently experienced for a particular oxygen demand and flow regime. USA COE (1988) discussed the factors that must be considered in evaluating how deepening the navigation channel from 30 to 35 feet influences the dissolved oxygen resources within the DWSC. It is important to understand that only part of the SJR below the Port of Stockton would be deepened. The navigation channel at any location represents only part of the cross-section of the SJR. Most of the channel depth will not be changed; therefore, the adverse impacts of channel deepening are restricted to just those areas of the channel where deepening actually occurs. These issues are discussed by USA COE (1988).

Impact of City of Stockton Ammonia Discharges on a Shallow DWSC

At this time no evaluation has been made as to whether the City of Stockton's wastewater discharges to the SJR during the fall under low-flow conditions would cause violations of dissolved oxygen water quality objectives within the SJR if the Deep Water Ship Channel did not exist, i.e., the SJR had a depth of 10 feet throughout the Delta. The City of Stockton residual CBOD, and especially the ammonia/NBOD, could represent a sufficiently large oxygen demand load to cause a 10-foot-deep SJR below the current Port of Stockton to experience DO depletions below the water quality objective of 6 mg/L during September-November. This would be especially true under low-flow conditions.

Ammonia Toxicity Issues

The situation that occurred in October-November 1999, where the City of Stockton's wastewater discharges of ammonia caused sufficient ammonia to be present in the SJR and DWSC to be toxic to some forms of aquatic life, will need to be controlled. There is need to better understand the ammonia/orgN assimilative capacity of the DWSC, to avoid toxicity problems during the fall. Basically, if the approaches used in other parts of the US for controlling ammonia-caused toxicity are implemented so that the un-ionized ammonia in the SJR and DWSC does not exceed about 0.02 mg/L NH_3, then the City of Stockton wastewater ammonia discharges to the SJR will need to be significantly curtailed, especially under conditions where the SJR flows above Mossdale are largely diverted down Old River. These diversions are therefore significantly impacting the amount of ammonia that the City of Stockton can discharge to the SJR and avoid both the toxicity problem and the DO depletion problem.

It is important to understand that the ammonia-caused toxicity and the DO depletion problems, while both related to total ammonia discharges to the DWSC, are not directly related to each other. For any given total ammonia discharge, there is a certain amount of oxygen demand that is directly related to the total ammonia concentration in the water. As discussed previously, for ammonia-caused toxicity problems, the un-ionized ammonia, which is the primary toxic fraction, is a function of the temperature and pH of the water.

One of the issues that will need to be considered is how the City of Stockton, in controlling the ammonia toxicity problem (which is a function of fall SJR flow into the DWSC and the total ammonia concentrations added to the SJR), will influence the oxygen demand that occurs in the DWSC each fall due to the residual ammonia loads. This is an area that will need attention as part of determining the allowable oxygen demand load from watershed sources to meet the water quality objective during the fall period when the City of Stockton has problems controlling the ammonia concentrations in its wastewater effluent.

Overall Assessment of Responsibility

Therefore, it can be concluded that there are two major responsible entities for the low DO problems within the DWSC that are not contributors of oxygen demand constituents. All water diverters that manipulate the flows of the San Joaquin River just above where it enters the DWSC, as well as the Port of Stockton and those who benefit from the Port's Deep Water Ship Channel, are contributors to the DO depletion problems that occur each summer and fall in the DWSC. There are also a number of other contributors to these problems that discharge oxygen-demanding materials and/or algal nutrients that develop into algae that enter the DWSC that are responsible entities for the current DO depletion problems.

One of the major objectives of future SJR DO TMDL studies will need to focus on determining the relative significance of each source of oxygen demand/nutrients, as well as the role of water diversions and the maintenance of the DWSC channel navigation depth in influencing DO depletion in the DWSC below water quality objectives. This information will be vital to assigning responsibility and therefore allocation of the funding that will be needed to control the low DO problems that occur in the DWSC each summer and fall.

Aeration of the Deep Water Ship Channel

While the control of the low DO problems will likely focus to a considerable extent on controlling algal nutrients and oxygen-demanding materials that are generated within the DWSC watershed that contribute to the low DO in the DWSC below water quality objectives, there is need to evaluate the potential costs and benefits of solving the low DO problem through aeration of the DWSC. The USA COE (1988) and Nichol and Slinkard (1999) concluded that about 2,000 lbs/day of dissolved oxygen could be added to the DWSC in the vicinity of where the SJR enters the DWSC through a single jet aerator. This is the amount of dissolved oxygen that was computed to be needed to compensate for deepening of the navigation part of the SJR to increase the depth of the Deep Water Ship Channel from 30 to 35 feet, at an SJR flow of about 1,000 cfs.

The aeration of the ship channel is potentially a method of significantly mitigating the impact of the oxygen demand and nutrient discharges to the DWSC, as well as the reduced flows and deeper ship channel, which lead to dissolved oxygen depletions below the water quality objective. There is need to fully evaluate the use of both air and pure oxygen as a means of preventing dissolved oxygen depletions from occurring below the water quality objective in various parts of the DWSC. This evaluation should include the cost of installation and, especially, operation of the aerators.

It is conceivable that the responsible entities for the DO depletion could reach an agreement on how to fund control of oxygen demanding substances and nutrients to the extent that control at the source can be readily achieved, as well as the construction and operation of a DWSC aeration system. These are issues that will need to be addressed by the SJR DO TMDL Steering Committee as part of development of an implementation plan to control the DO depletions below water quality objectives within the DWSC. As discussed herein, there is considerable need for high-quality technical information that will serve as a basis for defining the total maximum daily load of various types of oxygen demand from various sources within the DWSC watershed as a function of seasonal SJR flow into the DWSC. This information will serve as a foundation for Steering Committee deliberations on TMDL development and implementation.

Balancing Oxygen Demand Load Reductions through Source, Flow, and DWSC Geometry Control

As discussed herein, the oxygen demand assimilative capacity of the DWSC is dependent on the amount of flow of the SJR into the DWSC, as well as the geometry-depth of the DWSC. While it is appropriate to require reasonable efforts at controlling aquatic plant nutrients and oxygen demand constituents in wastewater discharges and irrigation return flows, it may not be possible through “reasonable efforts” to reduce the oxygen demand loads to the DWSC at their source so that the dissolved oxygen within the DWSC does not at any location and any time violate the water quality objective.

It is possible that if there were no irrigated agriculture and domestic wastewater discharges to the San Joaquin River during late spring, summer, and fall, the dissolved oxygen concentrations in the DWSC would at certain times of the day, especially early morning and near the sediment water interface, violate the DO water quality objective. This situation could occur under certain flow conditions where the residence time of the water within the DWSC would be sufficient for the residual oxygen demand and nutrients that would enter the DWSC to cause a violation of water quality objectives.

There are many eutrophic (excessively fertile) waterbodies that derive their nutrients from natural sources. These waterbodies experience dissolved oxygen depletions below water quality objectives, especially near the sediment water interface. The DWSC, during high SJR diversion/low DWSC inflow conditions, resembles a 35-foot-deep lake, which could have excessive DO depletion compared to water quality objectives. It will be important, as part of oxygen demand load DO depletion response modeling, to assess whether DO depletion below water quality objectives would be expected, based on natural nutrient and oxygen demand inputs that would be occurring from the SJR DWSC watershed if there were no irrigated agriculture and no municipal and industrial wastewater/stormwater runoff in this watershed. Further, it will be important to examine how diversion of SJR waters upstream of the DWSC impacts how the naturally derived nutrients and oxygen demand, as well as those derived from the activities of man within the watershed, influence the magnitude of DO depletions relative to the WQO.

It is possible that agricultural interests cannot afford to control nutrient export from their lands in the irrigation return flows and still be economically viable. While some reductions in nitrogen and phosphorus export from agricultural lands can be achieved through BMPs at moderate costs, the magnitude of the reductions that may be needed to prevent excessive algal growth in the San Joaquin River above Vernalis, as well as in the DWSC, may be such that irrigated agriculture within the DWSC watershed will have to be greatly curtailed, and even terminated. There is such a large surplus of nitrogen and phosphorus compounds within the SJR at Vernalis and DWSC, that reducing nitrogen and phosphorus inputs to the SJR and its tributaries could require extraordinary, highly expensive nutrient control programs.

A similar situation exists with respect to the City of Stockton and other municipal wastewater discharges and stormwater runoff. Fortunately, at this time it appears that much of the stormwater runoff from urban areas and agricultural areas does not cause DO depletions that violate water quality objectives.

As discussed in the Recommendations for Future Studies section of this report, there is need to understand the coupling between oxygen demand loads derived from natural and anthropogenic (man-made) sources as they impact DO depletion within the DWSC at various times and locations, and the impact of the diversions of SJR water at various times, as well as the geometry of the DWSC. This information will be critical to ultimately developing the balance of oxygen demand source control, flow control, and channel geometry that will evolve into the DO TMDL management plan. While it may not be possible, under current water rights regulations, to require that existing SJR diverters modify their diversions so that it is economically feasible for irrigated agriculture and municipalities to achieve reasonable oxygen demand control, this information will be important in influencing future diversions of SJR water and manipulations of Delta flow patterns that could influence DO depletion within the DWSC.

It will be important to evaluate whether the current attempts to reestablish anadromous fisheries (Chinook salmon and other migratory fish) in the tributaries of the SJR under the conditions where dissolved oxygen concentrations in the DWSC below 6 mg/L at any time and location cannot occur during September through November are potentially economically feasible without drastic changes in diversions, flow regimes, and/or channel geometry. These issues need to be thoroughly evaluated and understood by the Steering Committee and the CVRWQCB in establishing the DO management plan for the DWSC as part of the DO TMDL development program.

Recommendations for Future Studies

Presented below is a summary of the recommended studies/activities that should be initiated to provide the technical base of information needed for the SJR DWSC DO TMDL development and oxygen demand load allocation. This presentation is divided into high priority issues that should begin to be addressed during 2000, and important but lower priority items that should be addressed in subsequent years if additional funding becomes available, provided that all of the high priority items have been adequately addressed.

The development of this suggested priority study area listing reflects the current situation that there is a short period of time (1.5 years) and limited funding (CALFED - $866,000 for one year, plus potential additional funding to be obtained) available and potentially available to develop the information that the SJR DO TMDL Steering Committee and the CVRWQCB will need to develop the initial total maximum daily load of oxygen-demanding substances that can be added to the SJR DWSC and not cause violation of the dissolved oxygen WQO within the DWSC.

Further, both the Steering Committee and the CVRWQCB will need to define the relative significance of each of the major oxygen demand sources within the SJR DWSC watershed during this two-year period. Based on this source information and the projected TMDL, a waste load (NPDES-permitted sources) and load (non-NPDES permitted sources) allocation will be developed by the Steering Committee/CVRWQCB. The high priority items presented below reflect the need of the Steering Committee and the CVRWQCB for certain information upon which to develop the initial allowable load allocation of oxygen-demanding materials within the SJR DWSC watershed.

Developing this information associated with cost estimates of controlling oxygen demand loads from a particular type of source to a certain degree will provide the information needed to begin oxygen demand load trading among types of sources. Further, this information can serve as the basis to consider how such factors as export of water from the SJR above the DWSC, manipulations of water flows within the Delta that affect oxygen demand exerted within the DWSC and the impact of the development of the 35-foot navigation channel within the DWSC that has significantly changed the oxygen demand assimilative capacity of the SJR within the first ten to fifteen miles below the City of Stockton should be incorporated into the dissolved oxygen depletion management plan. This information will serve as the basis for developing a technically valid, cost-effective program that appropriately blends oxygen demand load reductions, altered SJR DWSC flows and channel geometry into a management plan that can be implemented as Phase I of the TMDL.

It is important to understand that incorporation of DWSC aeration and possibly other approaches for controlling DO depletion within the DWSC for any total oxygen demand load/flow regime will likely have to be based on finding funding to construct and operate the aeration, etc., systems. There will be need for the kind of information that is suggested as high priority in this discussion in order to assess the relative cost of controlling oxygen demand constituents at their source, versus controlling DO depletions within the DWSC through aeration or other approaches. Almost certainly, there will be some combination of oxygen demand source control, flow modification, aeration and some combination of other factors that will ultimately be incorporated into the TMDL implementation plan. It is essential that, over the next 1.5 years, the technical base for developing the information needed by the Steering Committee and the CVRWQCB be developed.

In September 1999, in response to questions raised by members of the Steering Committee on how agricultural, dairy, urban and other stakeholders should proceed with developing implementation plans for controlling oxygen demand export from their properties/activities, Lee (1999) provided a discussion, "Recommendations to the San Joaquin River Watershed Agricultural and Urban Communities on Participation in the San Joaquin River Deep Water Ship Channel Low DO TMDL Development." This discussion has been appended to this report as Appendix B.

At the time of developing this discussion last September, it was somewhat unclear as to the role of oxygen demand derived from upstream of Vernalis SJR watershed in influencing DO depletion within the DWSC. The summer/fall 1999 studies, coupled with the box model calculations have demonstrated that moderate to high SJR flow into the DWSC during summer and fall carries with it sufficient oxygen-demanding materials derived from the SJR watershed above Vernalis to cause DO depletions below water quality objectives within the DWSC. Further, the algal nutrients discharged to the SJR and its tributaries above Vernalis that develop into algae that are present at Vernalis are an important component of the oxygen demand that has been found at Vernalis.

It is clear that managers of upstream of Vernalis oxygen demand sources of algal nutrients and oxygen demand constituents need to immediately begin to evaluate, over the range of possible oxygen demand load reductions (25, 50, 75 and 90 percent), the cost of achieving the load reductions at their source. The cost for annual load reductions as well as the monthly (May through November) load reduction cost should be assessed. This cost information will be essential in developing the final oxygen demand load allocation for the various flow conditions that can occur within the DWSC. This cost information, in turn, is essential to developing technically valid oxygen demand load/flow trading programs. This information needs to be developed over the next six months so that it is available when the Steering Committee begins about six months from now to develop its recommended oxygen demand load allocations to the CVRWQCB.

In some instances, it may be necessary to do studies to determine the cost and effectiveness of various best management practices (BMPs) for control of the export of oxygen-demanding substances, including nutrients, from various types of land use/sources, to various degrees. There is need for each of the stakeholder constituent groups, such as urban stormwater managers, agricultural crop-type (commodity) growers, domestic wastewater discharges, etc., to develop reports that can be presented to the Steering Committee within six months on the cost of controlling oxygen-demanding constituents at their source to various degrees.

It is understood that the Phase I DWSC DO depletion management plan will have considerable uncertainty in some of the components that are designed to control the low DO problem within the DWSC. In accord with conventional phased TMDL development/ implementation, the initial Phase I management plan will need to be modified after about five years following the essentially full implementation of the oxygen demand load reductions and modifying factors such as flow diversions/manipulations. The recommended five-year monitoring program will be needed to observe the year-to-year variability of how oxygen demand loads and flows impact the DO depletion within the DWSC.

The modification of the management plan that would be incorporated into Phase II would be based on a comprehensive, detailed monitoring/study program that would take place during the Phase I implementation program to determine the reliability of the initial TMDL and its allocation in achieving the water quality objectives within the DWSC. Since it is likely to take several years from when the Phase I implementation plan is adopted to accomplish significant oxygen demand load reductions, it is likely that the Phase II review, which would follow the Phase I period of initial implementation and monitoring, would begin eight to ten years from when the initial TMDL is developed. During the start-up and five-year monitoring of the effectiveness of the Phase I management plan, it will be important to refine the oxygen demand load/response modeling to more appropriately incorporate the new information gained from the subsequent studies into the model's predictive reliability.

Because of the complexity of the oxygen demand load, flow and other factors that influence DO depletion within the DWSC, there could be need for a Phase III that will not only adjust the Phase II load allocations and factors, but will also account for the significant changes that will likely take place in the SJR DWSC watershed over the next 20 years.

If there were more than 1.5 years in which the information needed for TMDL development and implementation could be developed, and if there were substantially greater funding than is potentially available today, then many of what are listed below as lower priority study areas could/should be undertaken. It is possible that, through the proposed high priority studies, it will be found that some of the lower priority studies should be assigned a higher priority for funding. It is also certain that, as the high priority studies are undertaken, additional high priority funding areas will be identified that will need to be addressed in TMDL development and implementation.

The assignment of priorities to proposed project areas should be based on a critical review of the value of the information that will be gained from conducting the studies in achieving the desired goal of providing reliable technical guidance to the Steering Committee and CVRWQCB on TMDL development, allocation and implementation. A proponent of a particular study should bring to the Technical Advisory Committee information in support of the study, with representative data of the type that could be developed from the study, showing how the development of this data/information is essential to TMDL development and oxygen demand source allocation.

High Priority Issues that Should be Addressed Beginning in 2000

Oxygen Demand Sources

One of the highest priorities for studies should be devoted to defining DWSC oxygen demand sources that originate upstream and downstream of Vernalis that cause DO depletion below a WQO in the DWSC.

Upstream and Downstream of Vernalis. There is need to quantify the oxygen demand and algal nutrients added to the SJR and its tributaries upstream and downstream of Vernalis that impact violations of the DO water quality objective (WQO) in the SJR DWSC. The relative significance of each of the types of oxygen demand,

- nutrients that develop into algae,
- carbonaceous biochemical oxygen demand (CBOD),
- nitrogen-based (ammonia and organic nitrogen) biochemical oxygen demand (NBOD),
- detritus (land- and water-associated plant and animal organic remains)
- other types of oxygen demand,

in the SJR DWSC watershed should be a primary focus of the water quality characteristic monitoring that will begin in spring/summer 2000. The sources of oxygen demand should include,

- agricultural land runoff and drainage,
- municipal and industrial wastewater and stormwater discharges/runoff,
- dairies, feed lots and other animal husbandry discharges/runoff,
- discharges/releases of nitrate and other nitrogen compounds to groundwater that discharge nitrate to surface waters,
- releases of nutrients and oxygen demand from riparian lands and other natural sources,
- other sources, including atmosphere.

An area of particular concern is the oxygen demand associated with agricultural drainage. Long-term BOD measurements should be made of ag drainage at various locations within the SJR watershed to assess whether this drainage during mid- to late summer and fall contributes a significant amount of oxygen demand to the SJR.

The importance of the diversion of SJR water during the mid-summer and fall as a means of removing BOD and algae from the River needs to be evaluated. Since many of the diversions are not gaged/metered, it may be necessary to conduct a number of dye tracer studies to determine how much of the dye injected at an upstream location reaches a downstream location. Studies of the type that Kratzer and Biagtan (1997) conducted need to be conducted at several locations within the SJR and its tributaries to determine the amount of SJR water and oxygen-demanding substances, including algae and nutrients, that are diverted in each major reach of the SJR and its major tributaries.

The estimated oxygen demand loads should be developed on a monthly basis so that it will be possible to relate oxygen demand loads at various times of the year to dissolved oxygen depletion within the DWSC. The ultimate goal of this monitoring should be to develop oxygen demand export coefficients for various types of land use within the SJR DWSC watershed. From this type of information, it should be possible, along with information on land use, to estimate the relative significance of various types of DWSC oxygen demand loads from various parts of the watershed. Particular attention must be given in developing the below Vernalis oxygen demand load estimates to reliably assessing the loads as influenced by tidal flows.

The first phase of this effort should be devoted to compiling the existing data and the development of a "rough cut" analysis of the nutrient and oxygen demand sources in the SJR watershed at Vernalis. This analysis should be conducted immediately to help guide the studies that are needed to define how to best manage the upstream of Vernalis oxygen demand loads that will need to be managed to achieve the required DO in the DWSC.

Modeling Algal Nutrient Dynamics

A major study area that needs immediate attention is the modeling of the relationship between nutrients added to the SJR or one of its tributaries and algae that develop in the SJR/tributary that are transported to the SJR at Vernalis, as well as to the DWSC. There is need to understand the growth dynamics of algae relative to nutrient concentrations within the SJR and its tributaries to a sufficient degree so that predictions can be made of the amounts of nutrient reduction that will have to take place at various locations upstream of Vernalis in order to achieve an algal-related oxygen demand at Vernalis and the DWSC. This modeling will not only have to incorporate algal growth/death dynamics within the river systems, but also the water diversions/additions to the rivers that can impact algal nutrient and algal concentrations at Vernalis and in the DWSC.

Aeration of the DWSC

There is need to evaluate the potential costs and benefits of solving the low DO problem, at least in part, through aeration of the DWSC. Studies should be conducted to evaluate the use of both air and pure oxygen as means of preventing dissolved oxygen depletions from occurring below the water quality objective in various parts of the DWSC. This evaluation should include the cost of installation and, especially, operation of the aerators. An area that needs particular attention as a potential candidate for aeration is the Port of Stockton Turning Basin. The purpose of this aeration would be to mix the water in order to eliminate the low dissolved oxygen that frequently occurs near the sediment water interface, as well as to eliminate the oxygen deficit below the WQO. The evaluation of aeration should include an assessment of the potential negative impacts of aeration on water quality, such as stimulating additional algal growth within the waterbody.

Recommended Approach for Developing the SJR DWSC Oxygen Demand TMDL

Presented in another section of this report is a discussion of the recommended approach for developing the SJR DWSC oxygen demand TMDL. The activities outlined in that section should be a high priority for funding of future studies.

Monitoring of SJR Vernalis, City of Stockton Wastewater Oxygen Demand Loads and the Characteristics of the DWSC

An expanded, comprehensive monitoring program of the oxygen demand loads and their component parts should be conducted at Vernalis through the spring, summer and fall to better understand the magnitude and characteristics of this load as a function of SJR flow, season and other factors/activities within the watershed that could influence oxygen demand loads.

A much more comprehensive monitoring of the water quality characteristics of the DWSC needs to be conducted to more adequately define the impact of vertical, longitudinal, lateral, diel and tidal changes in the DWSC at selected locations upstream, near Turner Cut and near Disappointment Slough.

Impact of SJR DWSC Flow on DWSC Residence Time

Because of the importance of SJR flow into the DWSC of less than about 500 cfs in impacting the residence time of water and, therefore, oxygen demand load in the DWSC, it is important to gain a better understanding of how the residence time of water within the DWSC depends on SJR flow into the DWSC. This information will, in conjunction with information on oxygen demand kinetic (rate) data, be used to estimate the fate/persistence of oxygen demand within the DWSC, as well as the amount of the oxygen demand added to the DWSC that is exported across the DWSC downstream boundary, as a function of oxygen demand load of various types and SJR flow into the DWSC.

Review of Summer/Fall 1999 DWSC Water Quality Characteristic Data

Several studies were conducted during the summer and fall of 1999 that generated considerable data on the characteristics of the DWSC and the upstream of Vernalis loads of oxygen demand. The complete Department of Water Resources (DWR) DWSC database collected from July through November needs to be compiled and critically reviewed. This review will provide information to help understand the oxygen demand dynamics within the DWSC during the summer and fall. It will likely reveal areas that need further study.

Ammonia Discharges by the City of Stockton

While it has been known for many years that, beginning in late summer, the City of Stockton wastewater treatment plant oxidation ponds lose their ability to remove ammonia from the domestic and industrial wastewaters that are treated by these ponds, the consequences of this situation with respect to DO depletion and aquatic life toxicity have not been adequately investigated. Studies need to be conducted to determine the water quality significance from both an aquatic life toxicity and a dissolved oxygen depletion below WQO perspective associated with the City of Stockton's discharges of ammonia/organic nitrogen to the SJR during late summer and fall.

An issue of particular importance is understanding how Stockton's control of aquatic life toxicity associated with the discharge of ammonia to the SJR that results in un-ionized ammonia concentrations within the SJR DWSC above 0.02 mg/L NH_3 would impact DO depletions within the DWSC below water quality objectives.

Application of the Dissolved Oxygen Water Quality Objective

The issue of how the DO water quality objective should be applied is a long-term problem for regulatory agencies and dischargers. Delos (1999) of the US EPA Criteria and Standards Washington DC headquarters has indicated that at this time the US EPA does not provide guidance on how to consider diel (night/day) DO changes and changes with depth, especially near the sediment water interface, in implementing the DO water quality standard. A survey of the practice of other states in implementing the DO water quality standard should be conducted.

Validity of 6 mg/L DO Water Quality Objective

An important aspect of the TMDL development is a critical evaluation of the validity of the 6 mg/L DO water quality objective adopted by the SWRCB in 1994 as a significant barrier to Chinook salmon migration to their home waters within the SJR watershed. The 1970s studies conducted by the Department of Fish and Game (Hallock, *et al*., 1970) do not support a 6 mg/L DO water quality objective and are not adequate to cause agricultural, commercial and municipal interests to spend the large amounts of funds that may be needed to control the oxygen demand loads to the DWSC so that they do not cause violations of the DO WQO based on inhibition of Chinook salmon migration.

With respect to the water quality significance of DO depletions below 5 mg/L, the water quality significance, in terms of impaired beneficial uses, associated with DO excursions below 5 mg/L that can occur due to algal diel photosynthetic activities, as well as the DO depletions near the sediment water interface, needs to be examined to assess the improvement in the beneficial uses of the San Joaquin River DWSC and the Delta associated with achieving oxygen demand control so that the DO depletion within the DWSC does not violate the WQO at any time and location.

Relationship between SJR DWSC Flow and DO Depletions below WQOs

The 1998-1999 flow/dissolved oxygen depletion relationships discussed herein demonstrate the importance of SJR flow into the DWSC on influencing how a particular oxygen demand load to the DWSC results in a DO depletion below a WQO. As expected, related to temperature and duration and intensity of sunlight, there is a marked seasonal impact of the flow/WQO violation relationship. The most severe water quality objective violations occurred in October during low flow conditions. Even later in the month when the flows were up around 800 to 900 cfs, the 6 mg/L WQO was violated; however, in December, when the flows were down at a few hundred cfs, similar to what occurred at the end of September and the beginning of October, the dissolved oxygen concentrations in the DWSC were above the WQO of 5 mg/L, as well as 6 mg/L. While no data are available at this time on planktonic algal chlorophyll in the residual SJR flows into the DWSC, they would be expected to be low, indicating that the upstream of Vernalis oxygen demand is likely significantly less at that time than during August and September.

The DWR data collected every two weeks on the dissolved oxygen concentrations along the DWSC demonstrate that the DO monitoring station at Rough and Ready Island does not necessarily reflect the worst case conditions that occur. Sometimes there is greater DO depletion downstream of that location. This is to be expected, based on a variety of factors, including flow, temperature, type of oxygen demand (i.e., carbonaceous versus nitrogenous BOD), etc. The greater ammonia concentrations that occurred in October, November and December and the lower temperatures would be expected to slow down the rate of BOD exertion. This would be especially true for nitrogenous BOD.

Fate of Oxygen Demand Discharged to Old River and Exported from the DWSC at Disappointment Slough/Columbia Cut

Under certain SJR flow regimes, large amounts of oxygen demand (in excess of 100,000 lbs/day) are discharged into Old River that were derived from SJR upstream of Vernalis sources. At this time, no information is available on whether this high oxygen demand load down Old River is causing DO depletion below a WQO. This is an area that needs investigation in 2000 and for several years.

Under high SJR into DWSC flow regimes, large amounts of oxygen demand are exported from the DWSC into the central Delta as a result of the cross-Delta flow of the Sacramento River originating from the State and Federal Projects exporting water from the Delta. At this time, no information is available on whether the export of this oxygen demand into the central Delta is causing DO depletions below a WQO. This is another area that needs attention in 2000 and for several years, since it could mean that the use of high flows to export oxygen demand into the central Delta and thereby reduce the need for oxygen demand dischargers in the SJR DWSC watershed to treat/control oxygen demand in their discharge would not be a viable option.

Changes in Oxygen Demand Loads between Vernalis and the DWSC

An area that needs funding, as additional funds become available, is the assessment/ modeling of algal growth/death/decay in the reach of the SJR between Vernalis and the DWSC. Emphasis should be given to determining the potential changes in oxygen demand load that are present at Vernalis that reach the DWSC, considering water diversions as well as the oxygen demand additions from the City of Stockton wastewater treatment plant, French Camp Slough, agricultural drains and other local oxygen demand sources.

A more comprehensive monitoring of oxygen demand loads and their components at Vernalis and near where the SJR enters the DWSC should be conducted to determine the fate of oxygen demand loads in this reach of the SJR. In addition to properly sampling at appropriate times in the tidal cycle, it will be important to appropriately sample the water column, and especially the near bed load particulates that are carried in the San Joaquin River.

TMDL Study Technical Coordination

There is an urgent need to appoint a highly knowledgeable TMDL development/allocation project coordinator. The experience that has been occurring and continues to occur with the development of the synthesis report covering the summer-fall 1999 studies has demonstrated the need to take a significantly different approach in the operations of the Technical Advisory Committee. A technical leader should be appointed who is highly knowledgeable in the topics pertinent to TMDL development and allocation. This leader should be given sufficient authority so that he/she can act on behalf of the TAC to insure that reports are submitted on time, in an appropriate form, for review by the TAC and others. This technical leader should be knowledgeable in the details of each of the component studies that are being conducted, where he/she can help coordinate these projects and serve as the liaison between the TAC/Steering Committee and the project investigators.

The technical leader should have an assistant who can conduct data review and other tasks associated with day-to-day operations of the TMDL development/allocation. For example, last summer, Dr. Lee pointed out the problems associated with the data that were collected by one of the cities participating in the expanded SJR monitoring program. While there is agreement that there is a problem, no action has been taken, primarily because there is no one responsible for implementing the corrective measures that are needed to insure that the data collected are reliable and in a readily useable form. The technical leader and his/her assistant would have this responsibility on behalf of the TAC/Steering Committee.

Lower Priority Issues that should be Addressed in Subsequent Years if Funding becomes Available and Higher Priority Items have been Adequately Addressed

Algal Dynamics within the DWSC

A secondary but important area for future study, as additional funding becomes available, is gaining an understanding of the algae that develop within the DWSC and its nearby associated waters, such as the Turning Basin and local sloughs, that become oxygen demand within the DWSC and/or are exported from the DWSC critical reach across the downstream boundary. Particular attention needs to be given to assessing whether algal growth within the DWSC is a significant factor in causing dissolved oxygen depletion below water quality objectives. These studies are given a lower priority than the upstream of Vernalis and downstream of Vernalis oxygen demand source definitions listed above.

Long Term Biochemical Oxygen Demand (BOD_u)

Further work needs to be done to better understand the ultimate BOD of the SJR Vernalis waters, City of Stockton wastewater discharges and DWSC waters. Particular attention needs to be given to confirming that the studies of King (2000), Litton (2000). McCarty (1969) and Ball (1987), which show that the BOD_5/BOD_u (five-day BOD/ultimate BOD) ratios for these waters is greater (2.5 to 4) than the conventional domestic wastewater ratio of about 1.5. This information is important in determining the ultimate BOD and, therefore, the amount of oxygen demand that would be exerted in the DWSC under various flow regimes/residence times. This information is essential for developing a more refined assessment of responsibility for the DO depletion below WQOs.

In addition to evaluating the BOD_5 to BOD_u ratio for carbonaceous BOD (CBOD), an evaluation should be made of the organic nitrogen and ammonia nitrification reaction rates to develop reliable estimates of the appropriate approach to convert ammonia and organic nitrogen concentrations to oxygen demand at various times.

Sediment Oxygen Demand (SOD)

The source of oxygen demand in the DWSC sediments should be investigated as a secondary priority for future funding. At this time, the relative significance of freshly settled algal cells/detritus as a cause of SOD, versus accumulated oxygen demand that exists within the sediments due to the conversion of oxidized forms of iron and sulfur to reduced forms (ferrous iron and sulfide), is unknown. As a lower priority issue, this is an area that may need attention if SOD is determined to be a significant factor in causing the DWSC to have dissolved oxygen concentrations below a WQO. This area could become important if it is determined that the management of oxygen demand loads to the DWSC must prevent DO depletion below WQO near the sediment water interface. If this is the situation, then the source of the oxygen demand constituents that control the SOD needs to be better understood.

With respect to SOD measurements, more detailed SOD measurement as currently programmed in the CALFED project will not likely change the TMDL development and implementation. While SOD is a factor in DWSC oxygen depletion, whether the SOD is 1 or 2 $g/m^2/day\ O_2$ will not significantly impact the TMDL and its implementation. Based on the work of Chen and Tsai (2000), the SOD is about equal to reaeration. As the BOD load to the DWSC decreases, the SOD will decrease and the amount of reaeration will also decrease, likely balancing each other to some extent.

The potential benefits of conducting any dome-measured SOD needs to be critically evaluated from the perspective of how refinement of the current SOD estimates would influence decisions on the TMDL of oxygen-demanding substances and/or the allocation of the oxygen demand loads to various sources. It is possible that considerable money can be saved from the current CALFED project's originally proposed budget by not conducting dome measurements of SOD as originally proposed, but instead using these funds for other, higher priority purposes.

Influence of Inorganic Turbidity on Oxygen Depletion within the DWSC

The August-September 1999 studies revealed an unexplained depletion of dissolved oxygen in the DWSC surface waters that appears to correlate to a significant decrease in light penetration. The high turbidity, apparently from erosional materials, appears to have significantly reduced algal photosynthetic production of DO within the surface waters of the DWSC, resulting in a significant depletion in dissolved oxygen that may not have occurred if light penetration had not been inhibited by inorganic turbidity. The relationship between upstream and DWSC locally derived particulate materials which impact light penetration within the DWSC needs to be evaluated.

Relationship of Low DO in Stockton Sloughs versus DO Conditions in the DWSC

As a secondary priority item, studies should be conducted to understand how low DOs in the City of Stockton sloughs impact the DWSC, as well as how the conditions within the DWSC impact the water quality characteristics within the City of Stockton sloughs. It is unknown at this time how much of the low DO problems found in the sloughs is due to tidal transport of low DO waters from the DWSC into the sloughs.

Biomarker Studies

The potential value associated with conducting the originally proposed CALFED grant biomarker studies needs to be critically evaluated in terms of what new, useful information will be gained from these studies that will be helpful in identifying a source of oxygen demand and especially quantifying its significance in causing dissolved oxygen depletions below the water quality objective. While biomarkers can show that constituents derived from dairies, municipal wastewaters and certain other types of sources are present in the DWSC water column and/or sediments, this is already known.

What biomarkers cannot do, which is what is needed, is to show how much of an oxygen demand discharged by a dairy, a city, etc., is present in the DWSC that is influencing DO depletions below the WQO. Without a large study of the relationship between the aqueous environmental chemistry of the biomarker tracer and the oxygen-demanding substances present in a particular source, it is not possible to quantify, through the use of biomarkers, how much of the oxygen demand discharged by a particular source is present in the DWSC at any particular time.

Literature Review

One of the original plans for the CALFED project was the development of a comprehensive literature review and data compilation for all previous studies within the San Joaquin River watershed and the Delta that are in any way related to the characteristics of the DWSC. In light of the shortfall in funding of high-priority items, it is concluded that spending funds for this literature review should be given a lower priority than many of the other areas for which there is need for funding, that are essential for TMDL development and allocation. Each of the funded tasks should conduct a literature review as part of the task activities. As discussed above, there is need, however, to compile the existing information on oxygen demand and nutrient sources for the SJR above Vernalis and their fate within the SJR and its tributaries between the source and the SJR at Vernalis. This information is essential to planning the future studies for oxygen demand allocation in the SJR above Vernalis watershed.

High Priority Study Areas that Need Year 2000 Funding

In the spring of 2000 the SJR DO TMDL TAC assigned study area priorities for CALFED year 2000 funding. There were several study areas that evolved from the "Issues" review that were recommended for high priority year 2000 funding because of their importance in developing background information for TMDL development/allocation that were not included in the TAC recommended projects for CALFED grant year 2000 funding. The total CALFED grant funds were allocated to other high priority projects before several of these areas could be discussed. Basically there are more high priority funding areas than funds provided in the CALFED year 2000 grant. Presented below is a discussion of the areas that need immediate funding that are not now proposed for support in the year 2000 CALFED funding.

Aeration

Studies devoted to providing information on the potential use of aeration to control DWSC DO depletion below a WQO that cannot be economically eliminated by control at the source of the oxygen demand have previously been recommended as a high priority for CALFED year 2000 funding by the TAC. Aeration was one of the high priority study areas that was not included in the spring 2000 TAC-recommended CALFED year 2000 funding because of insufficient high priority funds. Because of the potential importance of the use of aeration to eliminate problem areas such as the Channel - Turning Basin where source control of oxygen demand will not likely be adequate to eliminate WQO DO exceedances, it is very important that work on evaluation of aeration be started as soon as possible. Waiting until 2001 could result in a situation where there will be insufficient time to develop the needed information as part of TMDL allocation in 2001.

There is need to find funding to initiate a comprehensive review of the potential use of aeration as part of the remedy for controlling the DO depletions below a worst case based WQO. Of particular importance is the cost effectiveness of various aeration approaches for controlling DO concentrations in the DWSC under the range of SJR flow conditions that exist in the DWSC.

Evaluation of Impact of SJR Flow on DO Depletion in the DWSC

Another previously recommended high priority area for immediate funding is a comprehensive evaluation of the impact of SJR flow into the DWSC on DO depletion in the DWSC. This issue was not discussed at the spring 2000 TAC funding allocation meeting because of insufficient time. There is an immediate need to critically examine the existing data base to begin to understand how the magnitude and changes in the SJR flow into the DWSC impact the magnitude of DO depletion in the DWSC below a WQO. From this information and likely with some special purpose modeling by Carl Chen with the improved/tuned model, it will be possible to develop a relationship between SJR flow into the DWSC and the DO depletion below a WQO at various locations for a range of oxygen demand loads. This information is essential to enable the SJR DO TMDL Steering Committee to begin to formulate the optimum balance between oxygen demand load control at the sources, aeration and SJR flow control.

Factors Influencing SJR Flow into the DWSC

The significant change in the DO depletion that occurred in late September 1999 associated with the removal of the Grant Line barrier demonstrated the need to fully understand how manipulation of Delta flows into, within and exported from the Delta impacts DO depletion in the DWSC. There is need to evaluate the factors that control Delta flow patterns that impact SJR flow into the DWSC. This information is needed as soon as possible so that the Steering Committee can start to gain the cooperation of those who control Delta flows to minimize the adverse impacts of flow on SJR DWSC DO depletion.

Sediment Oxygen Demand

A previously recommended area for CALFED year 2000 funding was studies devoted to gaining an understanding of the conditions that control DO depletion near the sediment water interface that occurs at some times and locations. There are insufficient funds in the CALFED year 2000 grant to expand the studies that Dr. G. Litton will be conducting to include the needed studies on why there is DO depletion near the sediment water interface at one time and location and not at the same location a few days later. Since the TMDL goal could be controlled by the low DO that occurs near the sediment water interface, it is essential that these situations be better understood as soon as possible. This understanding could lead to developing control programs that could significantly change the TMDL by changing the magnitude of the worst case DO depletion.

TMDL Goal

At this time the CVRWQCB's DO WQO is 5 mg/L between December 1 and August 31 and 6 mg/L September 1 through November 30. This is implemented as a worst case value where an exceedance of any magnitude more than once every three years is a violation of the WQO. A markedly different TMDL for oxygen-demanding substances' load to the DWSC would likely occur if an "average" DO WQO were selected as the TMDL goal rather than the worst case DO near the sediment water interface or for the surface waters at the minimum of the diel algal photosynthesis/microbial respiratory cycle. There is need to work with the CVRWQCB, DFG, other regulatory agencies and the public (environmental groups) in exploring the possibility of developing a DO TMDL goal other than the worst case WQO. Consideration should be given to evaluating how the beneficial uses of the waters/resources are impacted by the DO concentrations below a worst case WQO in the DWSC. This activity needs to be started immediately to provide adequate time to use this information in the TMDL development.

TMDL Development and Implementation

At this time, considerable CALFED funds are devoted to conducting technical studies that can serve as a basis for TMDL development and allocation. It has become apparent that substantial funding is going to be needed for one or more individuals to work with those conducting the technical studies and the Steering Committee to translate the results of the technical studies into information that can be used by the Steering Committee. Also, there is going to be need for funding to develop reports covering technical issues that are not now being covered by CALFED studies. As an example, there are no funds to conduct studies which would develop a report designed to assess the current state of information on groundwater discharged to the SJR and its tributaries as a source of nitrate that leads to algal development in the SJR.

Another area that needs immediate funding is for someone highly knowledgeable in water quality data development and its utilization to work with the cities doing the special purpose monitoring of their effluent and the San Joaquin River in the vicinity of their wastewater discharges to evaluate the reliability of these data and to convert them to a suitable form for data storage and retrieval.

Need for Additional Funding

There is need to immediately obtain additional funding to address these and other issues that will evolve during 2000 and 2001 that cannot be funded by CALFED either because of inadequate funds or because these project areas are not eligible for CALFED funding. If there is interest in developing work in these topic areas, a subcommittee of the TAC should be formed to develop budgets for each of these project areas.

Other Pending or Future Regulatory Activities that could Influence SJR DO TMDL Stakeholders

According to the State Water Resources Control Board's 305(b) list of impaired waterbodies (SWRCB 1999a,b), the San Joaquin River is considered impaired upstream of or within Stockton because of boron, chlorpyrifos, DDT, diazinon, electrical conductivity, Group A pesticides, selenium and unknown toxicity. Further, the Stockton Deep Water Ship Channel is listed because of dioxin, furans, and PCBs. Delta Waterways are listed because of organic enrichment/low DO and mercury. The Lower Merced and Stanislaus Rivers are listed because of chlorpyrifos, diazinon, and Group A pesticides. Two of the City of Stockton sloughs (Five Mile Slough, and Mosher Slough) are listed because of the organophosphate pesticides chlorpyrifos and diazinon. TMDLs will have to be developed to eliminate these listings. With the possible exception of the Delta Waterways listing, which is not defined with respect to location, all of the other TMDLs needed for the current 305(b) listing will likely be conducted independently of the TMDL to control the low DO in the Deep Water Ship Channel.

CALFED, working with the domestic water supply exporters of Delta water, is organizing, through the Delta Drinking Water Council and the Drinking Water Constituents Workgroup, a number of studies on sources of constituents that are discharged to the Delta which impair the use of Delta water for domestic water supply purposes. The two constituents of greatest concern are total organic carbon/dissolved organic carbon (TOC/DOC) and total dissolved solids (TDS). The TDS is being addressed through the 305(b) listing of the San Joaquin River by electrical conductivity, which is a measure of TDS.

Pizzi and Rodgers (2000) have recently summarized the US EPA Disinfectant/ Disinfection By-Products Rule. This regulation will require additional treatment for waters with a calculated quarterly running average TOC greater than 2 mg/L. Recently, CALFED (2000) has recommended, in "California's Water Future: A Framework for Action," that the TOC in Delta waters be controlled to 3 mg/L. It is possible that within a few years, as the US EPA implements these new drinking water regulations, since the TOC/DOC concentrations in the San Joaquin River are above the concentrations that are considered adverse to the use of this water for domestic water supply purposes, without additional treatment the San Joaquin River throughout this watershed could be classified as an impaired waterbody, which would set in motion the 303(d) listing and the need to control TOC/DOC in land runoff and wastewater discharges to the SJR and its tributaries.

While considerable difficulties are expected in achieving control of oxygen-demanding materials from the SJR watershed so that they do not cause DO depletions in the DWSC below the water quality objective at any location and time, the situation with respect to control of TOC could be much more difficult. There is need to understand the sources of TOC and how best to control them. Lee and Jones (1991a,b) have discussed this issue with respect to the Delta serving as a domestic water supply source. It will be important for the SJR DO TMDL Steering Committee and Technical Advisory Committee to closely coordinate with the CALFED Delta Drinking Water Constituents Workgroup activities. There may be an opportunity for joint monitoring, which could be beneficial to both groups.

A related but independent issue that could influence nutrient control within the Delta watershed, including the San Joaquin River watershed, is the need to control nitrogen and/or phosphorus discharges to the Delta or its tributaries that lead to excessive aquatic plant (water hyacinth) growth within the Delta. Recently, the DeltaKeeper has filed suit for the purpose of requiring that the California Department of Boating and Waterways obtain a permit from the CVRWQCB to use aquatic herbicides for control of water hyacinth. This suit is designed to cause the Department of Boating and Waterways and the CVRWQCB to conduct an in-depth, critical review of the current Boating and Waterways hyacinth control program.

One of the issues that could evolve from this situation is that the CVRWQCB could list the Delta as an impaired waterbody due to excessive growths of water hyacinth. Such a listing could result in the need to develop a nutrient control program for all upstream of the Delta sources, as well as within Delta sources of nitrogen and phosphorus. Such a program could require even greater control of N and/or P within the San Joaquin River watershed than that needed to control algae which contribute to the DO depletion problems below a WQO within the DWSC.

Support for a nutrient control program could be obtained from the domestic water supply exporters of Delta water. As discussed by Lee and Jones (1991a,b), many of the municipal water utilities that export Delta water, that also store this water in a reservoir before use, encounter excessive growths of algae in the storage reservoir that cause tastes and odors, shorten filter runs, and in some instances, increase trihalomethane precursor concentrations. Reducing the nutrient concentrations in the exported Delta waters would reduce the magnitude of these types of problems.

There is concern, however, about the low primary productivity within the Delta which is claimed to be possibly responsible for reduced fish production. Lee and Jones (1991c) have discussed the relationship between nutrient loads to waterbodies and the fish biomass produced within the waterbodies. Reducing the nutrient input to Delta waters would reduce the primary production and adversely affect fish production.

An example of this type of situation occurred in Lake Erie, where in the 1960s Lake Erie was claimed to be “dying” because of excessive algal growth. However, during its “death” the lake had outstanding fisheries. In order to control the excessive algae in Lake Erie, a comprehensive phosphorus management program in Lake Erie’s watershed was initiated. This program has been effective in reducing excessive algal growth within the lake. It has also adversely affected fish production within the lake. Fishermen are now advocating adding phosphorus back to the lake to improve the fisheries.

Lee and Jones (1991a) found that planktonic algal growth within the Delta was often less than that which should develop within the Delta based on nutrient load eutrophication response of waterbodies throughout the world. This reduced planktonic algal chlorophyll compared to that expected appeared to be related to the color of Delta waters arising from the leaching of TOC from peat soils on the Delta islands. This color decreased light penetration more than the self-shading that normally occurs in waterbodies due to phytoplankton.

There may also be a situation where the time the water enters the Delta with its associated nutrients and when it is exported from the Delta can be sufficiently short (on the order of a week) that the algae do not have adequate time to develop to the maximum planktonic algal biomass based on the algal-available nutrients. This situation is supported by the fact that a substantial part of the aquatic plant primary production in the Delta is manifested in the growth of water hyacinth, a floating macrophyte whose growth is not influenced by the color of the water.

Another factor that is sometimes said to influence primary production/algal biomass within the Delta is the harvesting of the phytoplankton by clam beds that have developed in some parts of the Delta. These clam beds cover some Delta channel bottoms and could be responsible for substantial removal of phytoplankton from the overlying waters. (Foe, Personal Communication, 2000*)*

There is need to understand the relationship between nutrient loads to the Delta and the impacts of the nutrients on water quality, as well as fisheries and other aquatic life resources. There will be need to balance the adverse impacts of nutrients as they impact beneficial uses of waters for domestic water supply and recreational purposes, with fisheries production.

Another situation that could affect the need to control nitrogen and phosphorus in runoff and discharges into the SJR watershed is the US EPA's current efforts to develop nutrient (N and P) numeric water quality criteria. US EPA (1998) in its "Water Quality Criteria and Standards Plan – Priorities for the Future" proposed to develop N and P concentration-based criteria for lakes, reservoirs, estuaries and streams to prevent excessive fertilization of these waterbodies. Recently, the US EPA (2000) has released its "Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs." This and similar manuals that are being developed for other types of waterbodies provide guidance on the agency's proposed approach for developing nutrient-based water quality criteria. At this time, the Agency is suggesting that total phosphorus concentrations above 0.01 mg/L P and total nitrogen concentrations (nitrate, ammonia and orgN) above 0.15 mg/L N frequently contribute to excessive growths of aquatic plants in waterbodies. Since these concentrations are well below the concentrations that are typically found in the SJR and the DWSC, it is possible that these waterbodies could be listed as 303(d) impaired waterbodies, which would require nutrient control to control phosphorus and nitrogen below the recommended values. This control would likely need to focus on annual control, and not just summer/fall control, as appears to be needed for the control of algae that develop within the SJR that contribute to DO depletion below the water quality objective. If this situation develops, this could greatly increase the cost of N and/or P control within the SJR watershed.

It could develop that the SJR upstream of Vernalis dischargers will have to implement N and P control programs for point and nonpoint sources to meet ambient water quality criteria that the Agency (US EPA) develops and requires that the state adopt independent of SJR DWSC DO TMDL requirements. There are significant questions about the US EPA's proposed approach for developing the nutrient criteria. Lee and Jones-Lee (1998) have discussed some of the problems with this approach that could readily lead to over-regulation. It will be important for all N and P dischargers in the SJR watershed to follow the US EPA nutrient criteria development, as well as the adoption of these criteria by the State Water Resources Control Board.

Conclusions and Recommendations

This section presents a summary of the current state of knowledge of the sources, magnitude of their significance, and impacts of oxygen-demanding materials derived from the SJR DWSC watershed as they impact DO depletions below the WQO in the DWSC. It also discusses some of the other factors, such as SJR flow into the DWSC, and navigation channel depth, that adversely impact the oxygen demand assimilative capacity of the DWSC. Further, recommendations are made on some of the studies/activities that will need to be addressed as part of developing and implementing a technically valid, cost-effective SJR DO TMDL management plan.

Current DO Depletion Problems in the DWSC

It was confirmed through the late summer and fall 1999 studies conducted by the TAC that significant dissolved oxygen depletions below the 5 and 6 mg/L water quality objectives are continuing to occur. This is a long-standing, well documented problem that is now beginning to be addressed through the CWA 303(d) listing of the DWSC as an impaired waterbody. This listing has initiated the development of the SJR DWSC DO TMDL development and implementation.

Sources of Oxygen Demand

It has been found that the oxygen demand sources for the SJR DWSC include algae and other oxygen-demanding materials present in the SJR at Vernalis that are not diverted through Old River or are not consumed before they reach the DWSC. In addition to the carbonaceous BOD, a significant component of the oxygen demand above Vernalis and at other locations, especially the City of Stockton's domestic wastewater discharges to the SJR, is the total Kjeldahl nitrogen (ammonia plus organic N) present in the water. While the concentrations of organic N are generally only from 0.5 to 2 mg/L N, when converted to ammonia and nitrified, they can represent significant oxygen demand because of the 4.5 factor relating the ammonia concentrations to DO consumption in the nitrification reactions.

It is also found that the ratio of carbonaceous BOD_5/BOD_u is about 2.5 rather than the typical domestic wastewater ratio of 1.5. Further, it is estimated that about 30 days is needed to achieve BOD_u for the samples of SJR water taken at Vernalis, as well as the City of Stockton's wastewater discharges. Normally, the period of time to achieve BOD_u for domestic wastewater samples is expected to be about 20 days. The increased time and ratio of BOD_5 to BOD_u is thought to be due to the fact that the BOD in the samples is composed to a considerable extent of algae and their detrital remains, other sources of detritus, as well as the nitrification reactions.

Impact of SJR Flow/Diversion

The diversion of SJR water present at Vernalis down the Old River channel near Mossdale is a major factor controlling the oxygen demand load that is present at Vernalis that enters the DWSC. The diversion can, at times, be sufficiently great to cause reversal of flow in the SJR upstream through the DWSC. Further, and more commonly, the Old River diversions can reduce the SJR net downstream flow so that only a few hundred cfs enter the DWSC from upstream sources. Under these conditions, the hydraulic residence time of water within the DWSC is increased to about 30 days, while at a flow of about 1,000 cfs, the residence time is about 10 days.

Diversions of SJR water that normally would flow through the DWSC down Old River channel, as well as to the City of San Francisco and other municipalities and irrigation districts, can amount to about 2 million ac ft/yr. This is equivalent to about 3,000 cfs. These diversions significantly adversely impact the oxygen demand assimilative capacity of the DWSC. Another significant factor affecting the oxygen demand assimilative capacity is the navigation channel constructed in the San Joaquin River from San Francisco Bay through the Delta to the Port of Stockton. This channel increases the hydraulic residence time and therefore the magnitude of dissolved oxygen depletion that occurs within the critical reach of the DWSC. This reach extends from the Port of Stockton downstream to about Turner Cut/Disappointment Slough, some 10 to 15 miles. Within this reach, frequent significant dissolved oxygen depletions below the WQO occur during summer, fall, and at some other times during low flow conditions.

The cross-SJR DWSC channel flow of the Sacramento River water that occurs at Disappointment Slough/Columbia Cut arising out of the State and Federal Water Projects exporting Delta water limits the distance that the SJR DWSC DO depletion problem extends downstream, to about Disappointment Slough.

City of Stockton Wastewater Discharges

In 1999 the City of Stockton's wastewater discharges during August and most of September of oxygen-demanding materials to the SJR just upstream of where the SJR enters the DWSC represented a small part of the total oxygen demand load to the DWSC. During this time, the SJR flows into the DWSC were on the order of 900 cfs. The major cause of oxygen demand load was upstream of Vernalis-derived oxygen demand constituents that were not diverted through Old River. At the end of September, the flows of the SJR entering the DWSC decreased to about 150 cfs for a period of about a week.

Starting in August and increasing through September into October, the concentrations of ammonia in the City of Stockton's wastewater discharges to the SJR increased from about 2 mg/L N to about 20 mg/L N. By October, the ammonia concentrations in the City of Stockton's wastewater discharges were sufficient, especially under low SJR flow conditions, to be a significant source of oxygen demand and contribute to dissolved oxygen depletion in the DWSC.

Significance of Ammonia as a Toxicant and Source of Oxygen Demand

Monitoring of the lower SJR and the upper DWSC showed that during November and early December the ammonia concentrations in the SJR below Stockton's wastewater discharges and within the upper DWSC were 3 to 4 mg/L N. These concentrations of ammonia not only represent a potentially significant source of oxygen demand for the DWSC, but also would be toxic to many forms of aquatic life. During the period October through December, dissolved oxygen concentrations in the DWSC surface waters near Rough and Ready Island decreased to about 2 mg/L. The combination of these very low dissolved oxygen concentrations and the high ammonia could lead to severely toxic conditions for many forms of aquatic life.

Stockton SJR DO Model and TMDL Development

The Stockton SJR DO Model, which was tuned to 1991 SJR flow and oxygen demand conditions, generally predicted the amount of oxygen depletion that was found in the DWSC during August and September 1999. This model needs to be tuned to higher flow conditions and expanded to incorporate a number of other factors that influence DO depletion in order to more closely simulate dissolved oxygen depletion within the DWSC as a function of oxygen demand loads of various types from various sources. After modification and tuning, this model will likely be found to be sufficiently reliable to develop a Phase I TMDL for oxygen-demanding substances that can be added to the DWSC and not cause violations of a WQO. It is acknowledged that this Phase I TMDL has considerable uncertainty, which will likely need to be adjusted in a Phase II TMDL that should be developed about 5 years after the Phase I TMDL oxygen demand load allocations have been essentially fully implemented.

This five-year period would be used to monitor the oxygen demand load/DO depletion relationship within the DWSC as a function of flow conditions and other factors that influence these relationships. The Phase II TMDL may have to be followed by a Phase III TMDL, which would be formulated in about 20 years.

DO Concentration TMDL Goal

One of the most significant issues that needs to be resolved as part of developing the TMDL for Phase I and subsequent phases is the implementation approach for the WQO objective. If the CVRWQCB's DO WQO of 5 mg/L during December through August and 6 mg/L for September through November is implemented in a strict manner, not to be violated by any amount at any location and time, the TMDL will likely have to be substantially lower than if an "average" WQO DO concentration is used as the TMDL goal. This average WQO would need to consider both the diel (night/day) algal photosynthetic and microbial respiration in the surface waters of the DWSC, which can cause a several mg/L change in the DO concentration each day, as well as the DO depletion that can occur just above the sediment water interface due to sediment oxygen demand.

Reliability of the 6 mg/L DO WQO

A major area that should be addressed as part of developing an appropriate dissolved oxygen concentration TMDL goal is a critical evaluation of the reliability of the 6 mg/L water quality objective adopted by the State Water Resources Control Board and the CVRWQCB for the DWSC during September-November in order to protect Chinook salmon migration to their upstream spawning areas in the SJR tributaries during the fall. The 1970 studies of the California Department of Fish and Game are not adequate to justify large-scale expenditures by various stakeholders for oxygen demand, flow, and channel geometry control to achieve the 6 mg/L WQO. These studies need to be redone more adequately and reliably with respect to identifying what role, if any, DO excursions below 6 mg/L within the DWSC have in blocking the homing tendencies of Chinook salmon. It appears that fall runs of Chinook salmon are occurring now, where they are reaching their home waters during the time when there are DO depletions within the DWSC below the 6 mg/L WQO. These apparent contradictions between existing conditions within the DWSC and Chinook salmon homing need to be resolved.

Sediment Oxygen Demand

The Stockton SJR DO Model for the SJR DWSC predicts/uses an SOD of about 1 g O_2/m^2/day. This value includes some of the “local” oxygen demand sources for the DWSC. It is in the range of normal SOD values typically found for conditions like those that exist within the DWSC sediments. The estimated SOD for the DWSC during August and September 1999 was on the order of 6,000 lbs/day. At this same time, the oxygen demand added to the DWSC from upstream of Vernalis and the City of Stockton’s wastewater discharges was on the order of 70,000 to 90,000 lbs/day. Therefore, at this time SOD is not considered to be a significant factor in controlling the dissolved oxygen depletion below water quality objectives within the DWSC, except possibly at certain times and locations, such as the Port of Stockton Turning Basin, near the sediment water interface.

At this time, the nature of the sediment oxygen demand is unclear, especially as it relates to biotic reactions on the particulate organic carbon present in the sediments versus the abiotic reactions involving ferrous iron and sulfide interacting with dissolved oxygen. If the TMDL DO goal is implemented as not to be violated at any place and at any time, including at the sediment water interface, it will be necessary to better understand the origins of the SOD constituents to try to focus on control of particulates that enter the DWSC that become part of the SOD.

Expansion of the SJR DO TMDL Management Program to Upstream of Vernalis

One of the major objectives of the TAC studies conducted during the summer and fall of 1999 was an evaluation of the need to expand the SJR DWSC oxygen demand source identification and quantification to the SJR watershed above Vernalis. Of particular concern is an assessment of the algal nutrient (nitrogen and phosphorus) sources and amounts derived from various types of land use activities within this watershed. At this time, both within the SJR at Vernalis and in the DWSC, during late summer and fall when planktonic algal chlorophyll ranges from 20 to 100 or more µg/L, with typical concentrations of about 30 to 40 µg/L, the concentrations of soluble orthophosphate-P and nitrate-N in the water are in the few tenths to a few mg/L range, respectively. These concentrations are significantly surplus of algal needs for additional growth. Additional growth does not occur, primarily because of light limitation caused by self-shading and inorganic turbidity.

The surplus N and P that occurs during peak algal biomass means that substantial reductions in nitrogen and phosphorus discharges/runoff to the SJR and its tributaries upstream of Vernalis, as well as local sources near the DWSC, will have to occur before there will be major changes in the oxygen demand loads associated with algae development within the SJR above Vernalis, as well as the DWSC. It is possible that the natural nutrient export from the upstream of Vernalis loads of nutrients/oxygen demand, coupled with certain flow conditions into the DWSC, could lead to DO depletions below the WQO.

Because of the residence time within the DWSC being on the order of 10 to 30 days during summer and fall, the key nutrient/oxygen demand loads of concern are those that contribute to the DO depletion problems below water quality objectives during summer and fall. The oxygen demand loads of concern are those that occur in early summer through late fall. Oxygen demand and algal nutrients discharged to the SJR and its tributaries, as well as the DWSC, during the winter and spring apparently do not significantly contribute to the DO depletion problems that occur the following summer and fall.

A major effort of future studies will need to be devoted to defining the amounts of oxygen demand materials and algal nutrients that are discharged from various types of land use within the SJR above Vernalis watershed. Further, there will be need to evaluate how the discharge of nutrients and oxygen demand constituents from irrigated and non-irrigated agriculture, municipalities, industries, dairies, feedlots, and other animal husbandry activities, and riparian lands at various locations within the SJR watershed leads to the development of algae, detritus, and other oxygen-demanding materials that are present at Vernalis and that enter the DWSC. This will require a substantial flow and algal nutrient/algal biomass modeling effort.

Significance of Algal Growth in the DWSC and its Associated Nearby Waters

At this time, the role of algae that develop within the DWSC as a source of oxygen demand that leads to significant WQO violations is not understood. There is additional algal growth within the DWSC, which is a contributor to not only oxygen demand throughout the water column but also photosynthetically produced DO in the surface waters. The net balance of oxygen production versus oxygen demand is not understood. This is an area that will need investigation as part of future studies.

Another area that will need investigation is the interrelationship between the low dissolved oxygen concentrations that are being found in late fall and winter, as well as possibly at other times in the Stockton sloughs, and the DO depletion problems that occur within the DWSC. These sloughs are tidal, and therefore receive DWSC water with each tidal cycle. During November-December 1999 and January 2000, several of the Stockton sloughs had dissolved oxygen concentrations between 1 and 2 mg/L. These concentrations would be significantly adverse to aquatic life-related beneficial uses of these waters. How much the slough water quality problems influence the DWSC and vice-versa will need to be investigated as part of managing the DO depletion problems of the DWSC and its nearby associated waters.

Steering Committee Balancing of Responsibility and Funding

The SJR DO TMDL Steering Committee/stakeholders will have a formidable task balancing the control of oxygen demand materials at their source, the influence of SJR flow and especially the diversions down Old River, the navigation depth of the Deep Water Ship Channel, and the magnitude, frequency, and occurrence of DO depletions within the DWSC below the WQO. Agricultural interests and municipalities could face massive expenditures for control of oxygen demand constituents at the source under conditions where SJR flow diversions significantly impact the DO depletion within the DWSC for a particular oxygen demand load.

Aeration of the DWSC

One of the approaches that will need to be evaluated is the use of in-channel aeration as a means of controlling some of the dissolved oxygen depletion problems. Part of the balancing that will need to be achieved will be a balance between control of oxygen demand constituents at their source and the addition of oxygen to the DWSC to mitigate residual oxygen demand constituent DO depletion impacts within the DWSC. Of particular importance in this balancing will be the funding of the construction and especially the long-term operations of the aeration systems.

The SJR DO TMDL Steering Committee will need to explore how to get those entities that do not contribute oxygen demand substances to the DWSC but who significantly influence dissolved oxygen depletion problems within the DWSC through altered flows and/or the presence of the 35-foot navigation channel within the critical reach of the DWSC to fund the control of DO depletion problems within the DWSC. The water diverters/flow manipulators through the Delta, as well as the Port of Stockton and those who benefit from the Port through lower-cost transportation of goods to and from the Port, could become responsible entities for helping to fund oxygen demand source control and/or aeration of the channel.

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Appendix A

A Summary of the Development of the Stakeholder Process and How it Works

Kevin Wolf, Facilitator
SJR DO TMDL Stakeholder Process

Central Valley Regional Water Quality Control Board staff summarized the direction given to the San Joaquin River Dissolved Oxygen TMDL Stakeholder Process in their January 2000 report to the Regional Board as follows:

"In January 1998, the Central Valley Regional Water Quality Control Board adopted a 303(d) list which identified the low dissolved oxygen levels in the San Joaquin River Deep Water Ship Channel as a high priority impairment. Regional Board staff committed to US EPA to develop a report by June 2003 that included all the elements of a Total Maximum Daily Load (TMDL) as required by the Clean Water Act. In addition, the Regional Board must approve a plan that implements actions identified to correct the problem. In April 1999, the Regional Board approved the Regional Cleanup Plan for the Bay Protection and Toxic Cleanup Program. State Board adopted the plan in June and the Office of Administrative Law approved it in November 1999. The Cleanup Plan laid out a strategy for collecting the necessary background information and for developing an implementation plan to correct the problem.

"A key element of the Cleanup Plan was the formation of a Steering Committee composed of local interests to oversee development of the control effort. Primary responsibilities of the Steering Committee were to establish a Technical Advisory Committee, allocate load reductions among dischargers, and recommend to Regional Board staff a time schedule and strategy for implementing the TMDL. The main responsibilities of the Technical Committee were to recommend and undertake scientific studies to aid in the development of the TMDL. This included studies to determine the sources and loads of oxygen requiring substances in the San Joaquin River Basin. Furthermore, the Cleanup Plan stated that no load reductions would be required of NPDES facilities if satisfactory progress was being made on the development of the TMDL. Satisfactory progress was defined as having the majority of studies underway by December 1999 to determine load allocations, and the Steering Committee would likely recommend a TMDL implementation plan, including load allocations, to Regional Board staff by December 2002.

"Dissolved Oxygen TMDL Steering and Technical Advisory Committees have been established and staff believe that the Committees are achieving satisfactory progress on the development of the TMDL report and implementation strategy. The Technical Advisory Committee completed loading studies this past summer to determine the magnitude of oxygen requiring substances originating above and below Vernalis in the San Joaquin Basin. A report is due in January 2000. The Technical Committee also wrote a proposal and was awarded an $860,000 CALFED grant to continue these studies next summer. Staff believe that these studies comprise the majority of work needed to determine the required load reductions in the basin. Finally, the Steering Committee has written a master plan laying out a strategy for developing the implementation plan. The Steering Committee has also voted to try to recommend an implementation plan to Regional Board staff by 2002.

“Staff caution that, while satisfactory progress is presently being achieved on development of the dissolved oxygen TMDL, many difficult and important tasks remain. For next year these include successfully completing the source identification and loading studies and identifying and securing funding to conduct follow-up work in 2001 to evaluate the efficacy and cost-effectiveness of management practices to reduce loads.

“Staff recommend that the Regional Board determine that satisfactory progress has been made in 1999 on the development of the San Joaquin River dissolved oxygen TMDL and that the Regional Board review the program again in December 2000 to ensure that similar progress continues.”

The City of Stockton responded to the stakeholder opportunity and began organizing stakeholder meetings in late 1998. In January 1999, the City retained Kevin Wolf to facilitate the stakeholder process and thus began monthly Steering Committee meetings open to anyone who considered themselves a stakeholder in the dissolved oxygen issue. Beginning with the clarification of the interests of the different stakeholders and a clarification of the goals, the Steering Committee moved quickly in a number of fronts.

A Technical Advisory Committee was formed and wrote a successful proposal for $886,000 in funding from CALFED Category III monies.
(See www.sjrtmdl.org/strategy/funding/calfed/index.html).

The Technical Advisory Committee helped in the development of the rough-cut loading analysis and is making recommendations to the Steering Committee on the prioritization of research, monitoring, and analysis options.

An Executive Committee was formed and meets monthly. Consisting of the Chair, Vice Chair and anyone else interested in attending, the Executive Committee develops proposals for outreach, process, and funding, and writes the agendas for the monthly Steering Committee Meetings. Much of the early work of the Executive Committee was invested in outreach to environmental, city, industrial, and agricultural stakeholding groups.

On July 2, 1999, the Stakeholders adopted a detailed process for making decisions through a consensus-based process. (For more information on how the process works, see www.sjrtmdl.org/stakeholder/process/decision_1999.html).

In the fall of 1999, the Steering Committee began organizing a Pollutant Trading Committee and directed this committee to determine what it would take to develop a pollutant exchange (trading) program. The Committee would help draft the theoretical and practical guidelines, as well principles that the Steering Committee can support.

The Steering Committee continues to meet monthly and consistently has more than 25 people attending. Interest remains high in large part because significant progress is being made and failure of the stakeholder process could create uncertainty and likely cause immediate consequences to a number of the stakeholders.

Appendix B

Recommendations to the San Joaquin River Watershed Agricultural and Urban Communities on Participation in the San Joaquin River Deep Water Ship Channel Low DO TMDL Development

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September 11, 1999 Updated January 14, 2000

At several of the San Joaquin River Deep Water Ship Channel Low DO Steering Committee meetings, representatives of the agricultural community expressed concern about how they should participate in the development of a TMDL for control of the input of constituents that contribute to the low dissolved oxygen (DO) that occurs in the San Joaquin River Deep Water Ship Channel. Similar issues have been raised about the participation of urban community representatives that manage urban stormwater runoff water quality.

At the August 18, 1999, Steering Committee meeting, I suggested that the agricultural community members should develop the information base that is needed to understand the feasibility and cost of controlling nitrate inputs to the San Joaquin River through direct stormwater runoff, irrigation return water (tailwater) and groundwaters that have been polluted by agricultural use of fertilizers or waste management practices that are discharged to surface waters that are part of the San Joaquin River system. The same kind of information needs to be developed by urban communities that face complying with a load allocation/waste load allocation for oxygen- demanding materials that are present in urban area stormwater runoff.

Based on having been involved in similar kinds of situations over the past 35 years, it is my recommendation that each of the agricultural community constituent groups, such as dairies, types of orchards/crops, etc., critically evaluate the potential effectiveness and associated costs of controlling nitrate/ammonia/organic nitrogen and phosphorus (total phosphorus and soluble orthophosphate) in releases from their properties/activities to 25, 50, 75 and 90 percent of the total annual load, as well as the load that occurs monthly from May 1 through November 30 of each year. Similar information needs to be developed by the urban communities associated with nitrate/ammonia/organic nitrogen and phosphorus (total phosphorus and soluble orthophosphate) contributed in urban area stormwater runoff and dry weather flow.

The need to not have to control the nitrogen and phosphorus loads in the late spring, summer, and early fall is based on the possibility that nitrogen and phosphorus inputs to the San Joaquin River system in late fall, winter and early spring may not contribute, to any significant extent, to excessive algal growths and the low DO problem that occurs in the San Joaquin River Deep Water Ship Channel each summer and fall. It is possible that the nitrogen and phosphorus releases from agricultural lands and urban areas during late fall, winter, and early spring are flushed through the San Joaquin River system past the Deep Water Ship Channel into the Delta and therefore are not part of the important nutrient loads that influence low DO during the summer and early fall in the Deep Water Ship Channel area. Although this is likely the case, this is a topic area that needs further review.

As I discussed at the August 18, 1999, Steering Committee meeting, algae are a component of the cause of the low DO that occurs in the Deep Water Ship Channel. There can also be local/upstream inputs of oxygen-demanding materials from domestic wastewater sources through BOD due to biodegradable organics and nitrification of ammonia. While, at this time, the relative significance of each of these sources of constituents that cause or contribute to the low DO problem needs further definition, there can be little doubt that nutrient/nitrogen and/or possibly phosphorus control will be a component of any TMDL low DO control program.

The ultimate implementation policy for the low DO TMDL control program will likely include an algal nutrient control program. Evidence points to the importance of nitrate as the primary nutrient stimulating excessive algal growth within the San Joaquin River system. A likely component of the TMDL will be the control of nitrate and other forms of nitrogen such as ammonia and organic nitrogen from agricultural sources and possibly urban areas.

Phosphorus is included as a nutrient that may need to be controlled based on the finding that even though not limiting algal growth now, it may be easier/cheaper to control phosphorus inputs to the San Joaquin River system than nitrogen inputs. While it appears that there is surplus nitrate and phosphate compared to algal needs for additional growth, the key to controlling the impact of algae on the low DO problem is to cause one of these elements to become a significant growth rate and biomass-limiting nutrient that affects the low DO in the San Joaquin River Deep Water Ship Channel.

The agricultural community crop constituent groups and urban area stormwater runoff management agencies should develop credible reports that discuss the BMPs available, their potential costs for implementation, including construction and operation, and their demonstrated record of effectiveness in controlling nitrate, ammonia and organic nitrogen, and total and soluble orthophosphate exports from their properties/activities. The relative significance of nitrogen compounds versus phosphorus and the potential for controlling algal growth that affects the low DO in the Deep Water Ship Channel will be investigated as part of the planned studies of the San Joaquin River system.

In addition to controlling algal growth and local/upstream municipal and industrial wastewater inputs and agricultural runoff-releases of oxygen-demanding materials such as BOD and ammonia, as well as agricultural crop wastes and animal wastes, consideration will need to be given to aeration of the Deep Water Ship Channel, as well as increasing the flows through the Deep Water Ship Channel as a means of minimizing/controlling the low DO. The ultimate mix of the various approaches between controlling nutrient inputs, local/upstream oxygen-demanding materials from Public-Owned Treatment Works (domestic wastewater treatment plants) (POTWs) and urban/agricultural stormwater runoff and dry weather flow releases, aeration, mixing and increased water throughput to the Deep Water Ship Channel will likely be determined, to a considerable extent by economics.

If the agricultural and urban communities have reliable BMP effectiveness and cost data available in credible reports, they will be in a position to influence, based on a technically valid approach, the ultimate decisions that are made in the wasteload and load allocations and other means of controlling the low DO. It is extremely important that the agricultural and urban communities' reports on possible BMPs to achieve various levels of nitrogen and phosphorus control and their costs be done conservatively, i.e., be uninflated.

Focusing on agricultural and urban releases of nitrogen and phosphorus does not in any way exclude the need for domestic and industrial wastewater nitrogen and phosphorus control. There is, however, considerable information available on the costs of nitrogen and/or phosphorus control in domestic and industrial wastewaters through work that has been done in other parts of the US and the world. At this time, there are about 90 million people in the world that have their domestic wastewaters treated to control phosphorus concentrations for the purpose of reducing algal growth in the receiving waters for the wastewater discharges. There are also a substantial number of domestic and some industrial wastewaters that are treated for nitrogen removal for similar purposes.

It will be important for the agricultural and urban communities to watch closely what is happening in other parts of the country with respect to the development and implementation of nutrient control programs. This is a national problem that is being addressed in many areas including California in the Santa Ana Region, Upper Newport Bay where TMDLs have been adopted for control of nutrients.

Appendix C

San Joaquin River Dissolved Oxygen Cleanup Plan

Condensed from
REGIONAL WATER QUALITY CONTROL BOARD
CENTRAL VALLEY REGION

REGIONAL TOXIC HOT SPOT CLEANUP PLAN

APRIL 1999

Part I

I. INTRODUCTION

In 1989 the California State legislature established the Bay Protection and Toxic Cleanup Program (BPTCP). The BPTCP has four major goals: (1) to provide protection of present and future beneficial uses of the bays and estuarine waters of California; (2) identify and characterize toxic hot spots; (3) plan for toxic hot spot cleanup or other remedial or mitigation actions; (4) develop prevention and control strategies for toxic pollutants that will prevent creation of new toxic hot spots or the perpetuation of existing ones within the bays and estuaries of the State.

This Regional Toxic Hot Spot Cleanup Plan (Cleanup Plan) is intended to provide direction for the remediation or prevention of toxic hot spots in the Central Valley Region (pursuant to Water Code Sections 13390 et seq.). Pursuant to Sections 13140 and 13143 of the Water Code, this Cleanup Plan is necessary to protect the quality of waters and sediments of the State from discharges of waste, in-place sediment pollution and contamination, and any other factor that can impact beneficial uses of enclosed bays, estuaries and coastal waters.

Part III

High Priority Candidate Toxic Hot Spot Characterization
San Joaquin River Dissolved Oxygen Cleanup Plan

Background

Low dissolved oxygen concentrations in the San Joaquin River in the vicinity of the City of Stockton has been identified in Part II of the cleanup plan as constituting a candidate BPTCP hot spot. In January 1998 the Central Valley Regional Water Quality Control Board (Regional Board) adopted a revised 303(d) list which identified low dissolved oxygen levels in the lower San Joaquin River (“Delta waterways”)_as a high priority problem and committed to developing a waste load allocation (TMDL) by the year 2011. The purpose of the Bay Protection Plan is to develop a strategy to collect the information necessary to implement the TMDL.

The San Joaquin River near the City of Stockton annually experiences violations of the 5.0 and 6.0 mg/l dissolved oxygen standard[4]. Violations are variable in time but usually occur over a ten mile River reach between June and November. Dissolved oxygen concentrations in the mainstem can be chronically below the water quality objective and can reach below 2.5 mg/l.

In 1978 the Board adopted more stringent biochemical oxygen demand (BOD) and total suspended solid (TSS) effluent limits for the Stockton Regional Wastewater Control Facility (RWCF) with the intent of reducing or eliminating the low dissolved oxygen conditions in the San Joaquin River. The plant has constructed the necessary additional treatment facilities and has complied with the more stringent effluent limitations. Despite the Cities best efforts, the low dissolved oxygen conditions persist.

The City completed a river model (Schanz and Chen, 1993) assessing the impact of the Stockton RWCF on receiving water quality. Water quality parameters considered included TSS, BOD, ammonia, nitrate and dissolved oxygen. The model suggested that (1) low dissolved oxygen conditions occur in the fall and spring due to a high mass loading of BOD and ammonia, (2) the current Stockton RWCF contributions are a significant portion of the oxygen demand of the River during critical low dissolved oxygen periods and (3) the San Joaquin River would not meet the receiving water dissolved oxygen standards even if the entire discharge from the Stockton RWCF were eliminated from the River.

Taking these facts into consideration, the Board adopted a stricter permit in 1994 requiring the Stockton RWCF to further reduce CBOD and ammonia concentrations. Stockton appealed the permit to the State Board on a variety of grounds including that hydraulic conditions had changed in the River since the Board had considered the permit. The State Board remanded the permit back to the Regional Board for consideration of new Delta flow standards.

In the interim the Stockton RWCF refined the dissolved oxygen model for the River (Chen and Tsai, 1997). The model suggests that the principal factors controlling in-stream oxygen concentration are temperature, flow, upstream algal production, sediment oxygen demand (SOD), and discharge from the Stockton RWCF. Obviously, only one of these factors is within the ability of the Stockton RWCF to control. Solutions to the dissolved oxygen problem will require a more holistic watershed approach. Each factor is described briefly below.

Dissolved oxygen problems are most acute at high temperature in the San Joaquin River in late summer and early fall. Temperature is important because the oxygen carrying

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[4] The 5.0 mg/l standard applies between 1 December and 30 August while the 6.0 mg/l standard is for the period of 1 September through 30 November.

capacity of water decreases with increasing temperature while biotic respiration rates increase. Water temperature is controlled by air temperature and reservoir releases.

Flow of the San Joaquin River at Stockton is regulated by upstream reservoir releases and pumping at the state and federal pumping facilities at Tracy. Net flows at the City of Stockton are often zero or negative in late summer. The lowest dissolved oxygen levels in the River occur during prolonged periods of no net flow.

Algal blooms occasionally develop in the faster moving shallow upper River and are carried down past the City to the deeper slower moving deep- water ship channel. Respiration exceeds photosynthesis here resulting in net oxygen deficits. Upstream algal blooms are controlled by turbidity and nutrient inputs from other NPDES dischargers, the dairy industry, erosion, stormwater runoff, and agricultural inputs.

Finally, the model identified discharge from the Stockton RWCF as contributing to the dissolved oxygen problem. The model indicates that improvements in effluent quality would increase dissolved oxygen levels in the River during critical periods. However, the model confirmed that exceedance of the dissolved oxygen water quality objective would persist if the entire discharge of the Stockton RWCF were removed from the River. The City of Stockton has expressed the concern that the estimated costs for the additional treatment are disproportionate to the benefits and that more cost-effective improvements in dissolved oxygen levels are possible.

Adult San Joaquin fall run Chinook salmon migrate up river between September and December to spawn in the Merced, Tuolumne, and Stanislaus Rivers (Mills and Fisher, 1994). The Basin Plan dissolved oxygen water quality objective was increased from 5.0 to 6.0 mg/l between 1 September and 30 November to aid in upstream migration. The San Joaquin population has experienced severe declines and is considered a ‘species of concern’ by the U.S. Fish and Wildlife Service. Low dissolved oxygen may act as a barrier preventing upstream spawning migration. Also, low dissolved oxygen can kill or stress other aquatic organisms present in this portion of the Delta.

In conclusion, the San Joaquin River near the City of Stockton annually experiences dissolved oxygen concentrations below the Basin Plan water quality objective in late summer and fall. A model has been developed which identifies river flow and temperature, upstream algal blooms, SOD, and discharge from the Stockton RWCF as controlling variables. Only the latter variable is within the ability of the plant to influence. Fall run Chinook salmon migrate upstream during this critical time period.

A. Areal Extent

The areal extent of the water quality exceedance is variable but may in some years be as much as 10 miles of mainstem River. The temporal extent is also variable but can be for as long as 4 months. Dissolved oxygen concentrations are often less than 2.5 mg/l in the mainstem River.

B. Sources

A computer model developed for the Stockton RWCF identified ammonia and BOD as the primary cause of the low dissolved oxygen concentration. The sources are discharges from the Stockton RWCF and surrounding point and non point source discharges. River flow and water temperature were identified as two other variables strongly influencing oxygen concentrations.

C. Summary of Actions

Low dissolved oxygen levels near the City of Stockton in late summer and fall are a well known problem. In 1978 the Regional Board adopted more stringent effluent limits which the RWCF met but these did not correct the in-stream problem. A model developed for the Stockton RWCF suggested that further decreases in effluent BOD and ammonia would improve in-stream dissolved oxygen concentrations during critical periods but would not completely correct the problem. In 1994 the Regional Board further tightened BOD and ammonia permit limits to protect water quality. The permit was appealed to State Board because River hydrology had changed since the permit was adopted. State Board remanded the permit back to the Regional Board to reevaluate the modeling based upon new Delta flow conditions. In the interim, the Stockton RWCF installed a gauge at their discharge point to measure River flow and refined their computer model. The model concluded that the primary factors controlling dissolved oxygen concentration in the critical late summer and fall period were River flow and temperature, upstream algal blooms, SOD, and discharge from the Stockton RWCF. The model also made a preliminary evaluation of placing aerators in the River during critical periods. The results appeared promising. Finally, simulations coupling the dissolved oxygen and the San Joaquin River daily input-output model should be run. It may be possible by coupling the two models to predict exceedances of the Basin Plan dissolved oxygen standard about two weeks in advance. This could be valuable in that it raises the possibility of being able to conduct “real time management” to aid in correcting the problem.

D. Assessment of Actions Required

In January 1998 the Central Valley Regional Board adopted a revised 303(d) list which identified low dissolved oxygen levels in Delta Waterways near Stockton as a high priority impairment. The goal of the TMDL is to ensure that the San Joaquin River achieves full compliance with the Basin Plan Water Quality Objective for dissolved oxygen. To meet this objective, the Central Valley Regional Board intends to develop a strategy for collecting the information necessary to develop a TMDL.

According to the U.S. EPA (1998), "*the goal of the TMDL is the attainment of water quality standards. A TMDL is a written quantitative assessment of water quality problems and the contributing pollutant sources. It specifies the amount of reduction needed to meet water quality standards, allocates load reductions among sources ... and provides the basis for taking actions to restore a water body*".

The U.S. EPA (1998) suggests that the successful development of a TMDL requires information in six general areas: identification of a target, location of sources, quantification of the amount of reduction needed, allocation of loads among sources, an implementation plan and monitoring and evaluation to track results and compliance. Regional Board staff also believe that a seventh element, the formation of a Steering Committee, is needed to help guide the control effort. Each of the elements are described briefly below.

Steering Committee. The Steering Committee shall be composed of representatives from the Stockton RWCF, upstream and adjacent NPDES dischargers, the dairy industry, irrigated agriculture, the environmental community, and state and federal resource agencies. A facilitator/coordinator will be needed to conduct the Steering Committee meetings. A cost estimate for this function is shown in Table 1. The primary role of the Steering Committee will be to establish a Technical Advisory Committee, determine other stakeholders who should be participants on the Steering Committee, review recommendations of the Technical Advisory Committee on what special studies should be performed, how the load reductions should be allocated, and the time schedule and strategy for implementing the TMDL. The Steering Committee will also be responsible for developing a financial plan to secure the funding for collecting the information needed to implement the TMDL.

The responsibilities of the Technical Advisory Committee will be to identify information needs, determine and prioritize special funding needs, recommend load allocations, direct and assist in the review of the Stockton RWCF model, collate and analyze existing data, conduct special studies, critique special study and data analysis results, establish a common data bank, develop cost estimates, draft implementation and monitoring plans, review monitoring data and advise on effectiveness of the implementation plan. Regional Board staff will make final recommendations to the Board about load allocations and the TMDL implementation. If it appears likely that the Steering and Technical Advisory Committees will be unable to make recommendations in a timely fashion, then staff will develop the load allocation and TMDL implementation plan in the absence of this information.\

Target. The target of the TMDL is attainment of the Basin Plan dissolved oxygen water quality objective in the lower San Joaquin River. The dissolved oxygen objective for the time period of 1 September through 30 November is 6.0 mg/l and at all other times is 5.0 mg/l.

Sources and Causes. The Stockton RWCF dissolved oxygen model identified the following factors as the cause of the low dissolved oxygen levels: upstream and adjacent algal blooms, SOD, river flow, discharge from the Stockton RWCF and temperature. It is felt that there is a need for independent validation of the Stockton RWCF dissolved oxygen model. U.S. EPA has committed resources through Tetra Tech to do so. Model evaluation should occur after input has been obtained from both the Steering and Technical Advisory Committees. If validation shows that the model is reliable and that its initial findings are accurate, then the actions listed below are recommended.

Summarize and Compile Data. Collate all pertinent background data on the principle factors which contribute to the dissolved oxygen problem. These include information on all upstream and adjacent point and non-point source BOD and nutrient loads as well as all information on historical dissolved oxygen patterns in the San Joaquin River and changes in fisheries resources that may have been caused by the problem. All information gaps should be identified. Funds necessary for this task are shown in Table 1.

Determine BOD and Nutrient Sources. Collect all additional nutrient and BOD data needed to fill information gaps identified above. This will probably include additional studies on loadings from both local and upstream point and non-point source discharges. In addition, feasibility studies should be undertaken to evaluate the cost and efficacy of load reductions at the most important sources. Funding for this task is identified in Table 1.

Determine Sources and Causes of SOD. The Steering and Technical Advisory Committees will conduct investigations to determine the sources and causes of SOD. Also, feasibility studies will be undertaken to identify the most effective solutions for controlling SOD. Funds necessary for this task are shown in Table 1.

Evaluate Engineered Solutions. The TMDL strategy should include evaluations of creative engineered solutions. At a minimum, the Steering and Technical Advisory Committees should evaluate the feasibility of river aeration and changes in San Joaquin River hydrology. Evaluations of river hydrology may include several options. One is real time management of flows at the head of Old River during critical periods. A second option might be pumping water south through the Delta Mendota Canal for release down Newman Wasteway to augment base flows in the lower San Joaquin River during critical periods. Either option might be significantly enhanced by linking the continuous monitoring data (flow, salinity, temperature, dissolved oxygen and pH) presently collected in the San Joaquin River with measurements of nutrients and chlorophyll to determine sources and timing of high organic loads so that the head of Old River barrier can be operated in an adaptive management framework (Jones and Stokes Associates, 1998). A cost estimate for evaluating these options is shown in Table 1.

Amount of Load Reduction Needed. The load reduction needed is the difference between the load that would fulfill the Basin Plan Water Quality Objective for dissolved oxygen and the load that causes the dissolved oxygen concentrations presently measured in the main channel of the River.

Allocation of Loads Among Sources. The Steering and Technical Advisory Committees will make recommendations on load allocations to Regional Board staff after considering the following: importance of source, cost of correction per unit of dissolved oxygen increase obtained and probability of success of the action. The Steering and Technical Advisory Committees may also consider creative solutions such as funding aeration or hydrologic changes or the development of non-point source management practices. These are suggested as methods for assuring a contribution from other responsible entities who can make no load reductions. Finally, the load allocation process will include a safety factor to account for population growth in the Basin during the next 30 years.

Implementation Plan. While a full discussion of the implementation plan is premature, several facts are worth noting. First, the Steering and Technical Advisory Committees will make recommendations on load reduction allocations and the schedule and funding for implementing the TMDL. Regional Board staff will review these recommendations and propose a dissolved oxygen TMDL to the Board. It is anticipated that Regional Board staff will need about 6 months to review the recommendations and prepare the paperwork for the Basin Plan amendment. Second, the Basin Plan amendment will include load reduction allocations and a time schedule for meeting them. The reductions may necessitate revisions of NPDES permits and development and enforcement of management practices in the agriculture community.

It is anticipated that the TMDL will take three years to develop once funding has been secured. In the interim, the Regional Board will be draft new and revising existing NPDES permits for discharge to the lower San Joaquin River and South Delta. The Clean Water Act requires that NPDES permits contain effluent limits fully protective of receiving water quality, so any permits for discharges to impaired water bodies must contain stringent effluent limits. Where dischargers are a significant contributor to the River's dissolved oxygen problem, improvements in effluent quality may be required prior to completion of the TMDL. For new and expanded discharges, staff will recommend on a case-by-case basis stringent effluent limits to ensure no increase in oxygen demand to the South Delta. The time schedules for implementation of any stricter effluent limits may take into account the TMDL process. However, load reductions from existing dischargers will not be required if satisfactory progress is being made on TMDL development unless it is clear before the process has been completed that the specific load reduction would be required even under the TMDL. It will be assumed that satisfactory progress is being made if the majority of studies to determine load allocations are underway by

December 1999 and, it appears likely, that the Steering Committee will recommend a TMDL implementation plan, including load allocations to Regional Board staff by the year 2002.

Monitoring and Reevaluation. The implementation plan will include monitoring. The purpose of monitoring is to verify compliance with the Basin Plan Dissolved Oxygen Objective. If monitoring demonstrates that the Water Quality Objective is not being met, then additional load reductions will be required. These new load reductions will be implemented after consultation with the Steering and Technical Advisory Committees. An estimate of funds necessary for monitoring is shown in Table 1.

E. An Estimate of the Total Cost to Develop the TMDL

A cost estimate for developing the TMDL is provided in Table 1. Although there are costs to implement this plan there are also benefits. Currently, beneficial uses are being impacted by the low dissolved oxygen levels in the South Delta. The beneficial uses that are being impacted are ESTUARINE HABITAT (EST) and SPORT FISHING (REC 1). Implementation of the plan would increase dissolved oxygen concentrations and minimize or eliminate the impact on beneficial uses.

Table 1. Cost estimates for developing a dissolved oxygen TMDL in the lower San Joaquin River and an estimate of the time required to complete each task.

Task	Cost	Yrs from date funds avail.
Steering Committee		as long as required
Facilitator/Coordinator	$ 12,000[1]	
Problem Statement		
Summarize and compile data	$ 50,000	0.5
Source Analysis		
Validate DO Model	$ 30,000	0.5
Determine BOD and nutrient sources	$ 200,000	2.0
Evaluate feasibility of control options	$ 50,000	
Determine sediment contribution	$ 200,000	2.0
Evaluate feasibility of control options	$ 50,000	
Evaluate engineered solutions	$ 80,000	2.0
Implementation Plan		
TMDL for Regional Board consideration	--	2.5
Monitoring/Reevaluation		annually after TMDL adopted
Monitoring to evaluate load reductions	$ 20,000[1]	

1: per year

F. An Estimate of Recoverable Costs from Potential Dischargers

No immediate funds are available from the discharge community to develop the TMDL. However, once the load reductions are allocated, then the responsible entities will be required to assume the costs of implementation.

G. Two Year Expenditure Schedule Identifying Funds to Implement the Plan that are Not Recoverable from Potential Dischargers.

Clean Water Act 104(b)(3), 106(g), and 319(h) grants are potential sources of funding and have been used in the past by Regional Boards to address such issues. CALFED may also be a source of funding.

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Appendix D
San Joaquin River Flow and Dissolved Oxygen and Export Flows Through the California Aqueduct (CA) and Delta-Mendota Canal (DMC), 1999

	San Joaquin River Flow (cfs)		DWSC RRI DO	Export Flow (cfs)	
June	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	ND	976	7.3	725	2010
2	3227	1074	7.4	730	2007
3	3304	1483	7.4	724	2004
4	3323	1562	7.7	725	2007
5	3353	1634	8.6	724	2010
6	3352	1720	8.8	726	2012
7	3353	1850	8.9	724	2011
8	3338	1703	9.0	724	2643
9	3349	1560	8.8	724	2891
10	3350	1529	8.4	723	2899
11	3283	1484	7.9	216	2896
12	3259	1581	7.7	272	2891
13	3303	1604	7.5	728	2892
14	3357	1530	7.4	727	2882
15	3305	1536	7.5	725	2822
16	3303	1625	7.7	725	2798
17	3272	1463	7.6	777	2791
18	3070	1513	7.5	725	2811
19	2990	1613	7.4	727	ND
20	3080	1780	7.0	725	2862
21	3240	1798	6.7	723	2794
22	3130	1643	6.4	720	2791
23	3124	ND	6.1	721	2796
24	2958	ND	6.0	720	2774
25	2781	1215	6.1	940	2848
26	2706	1256	5.9	1807	3727
27	2734	1244	5.8	1807	4269
28	2781	1069	5.8	1812	4278
29	2628	927	5.6	2920	4305
30	2536	813	5.2	2928	4403
Ave:	3131	1457	7.2	956	2866
S Dev:	255	277	1.1	646	717

	San Joaquin River Flow (cfs		DWSC RRI DO	Export Flow (cfs)	
July	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	2469	813	5.2	5453	3910
2	2349	799	5.1	5773	3753
3	2352	874	4.7	5995	3794
4	2544	1178	5.3	6101	3675
5	ND	1285	5.5	6083	3681
6	2532	1149	5.5	5781	3682
7	2458	1149	5.2	5787	3682
8	2380	880	4.9	5583	3679
9	2293	756	4.6	5672	3529
10	2299	882	4.2	4981	3993
11	2308	998	4.1	4924	4312
12	2384	902	4.2	5488	4313
13	2276	654	4.4	6368	4295
14	2270	467	4.1	6571	4295
15	2181	528	4.2	6571	4295
16	2106	684	4.0	6609	4261
17	2218	702	3.9	5624	4254
18	2249	760	4.1	6406	3666
19	2156	853	4.4	6686	3421
20	1958	882	5.0	6474	3415
21	1975	775	5.2	6452	3939
22	2011	716	5.5	6447	4328
23	1924	664	5.7	6503	4339
24	1874	865	5.7	6508	4326
25	1946	830	5.8	6516	4327
26	2015	798	5.4	6769	4268
27	1928	747	5.3	5138	4379
28	1961	775	5.2	5095	4449
29	1951	796	5.4	5435	4502
30	1942	840	5.5	6260	4524
31	1983	789	5.7	6540	4474
Ave:	2176	832	4.9	6019	4057
S Dev:	208	177	0.6	559	353

	San Joaquin River Flow (cfs)		DWSC RRI DO	Export Flow (cfs)	
Aug	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	2088	964	5.8	3512	4522
2	2066	949	6.0	5070	4221
3	2009	894	5.9	5195	4388
4	1972	909	6.0	6517	4635
5	1894	894	5.7	5758	4549
6	1859	951	6.0	6743	4174
7	1911	897	5.9	6877	4937
8	2023	1024	5.7	6877	4497
9	2027	1101	5.6	6869	4493
10	1910	874	5.4	6799	4464
11	1915	914	5.3	6785	4498

	San Joaquin River Flow (cfs)		DWSC RRI DO	Export Flow (cfs)	
Sept	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	1878	790	4.9	6989	4422
2	1930	797	5.6	4948	4496
3	1918	952	5.8	7350	4500
4	1954	1150	6.1	7051	ND
5	1998	1352	6.3	7053	ND
6	2011	1190	6.1	7080	ND
7	1941	1155	5.6	7100	4408
8	1788	955	5.3	7115	4430
9	1791	928	4.9	7098	4475
10	1855	930	4.8	7092	4453
11	1899	991	4.6	7099	4421

12	1878	877	5.5	6736	4513
13	1879	843	5.6	6751	4545
14	1885	835	5.4	6846	4520
15	1951	975	5.7	6134	4524
16	1976	923	6.1	6415	4521
17	1884	713	6.3	6664	4508
18	1851	747	6.4	6828	4463
19	1899	876	6.8	6901	4500
20	1838	898	6.7	6912	3873
21	1793	911	6.2	6950	3603
22	1945	991	6.4	6958	3607
23	2015	882	6.1	5705	3610
24	1938	1032	5.5	6047	4232
25	1893	970	5.6	6789	4505
26	1876	873	5.0	7194	4456
27	1847	720	4.3	7006	4426
28	1926	843	3.9	7012	4425
29	2035	1042	3.7	6907	4440
30	2063	1116	3.7	6921	4431
31	1929	1084	4.7	7005	4459
Ave:	1935	920	5.6	6506	4372
S Dev:	75	99	0.8	767	305

12	2047	1086	4.8	7120	4459
13	2133	1254	5.0	6932	4454
14	2054	1143	5.5	6885	4457
15	2002	1106	6.0	6930	4150
16	1981	1029	6.2	6990	4635
17	1957	943	6.0	7000	4226
18	2006	1046	6.1	6987	4270
19	2102	1237	5.9	6983	4259
20	2154	1554	6.0	6987	4234
21	2073	1355	6.1	7061	4261
22	2027	1301	5.5	7085	4266
23	1993	972	4.7	6580	4267
24	1967	451	3.9	6584	4283
25	1958	382	3.6	6574	4270
26	1996	343	3.3	6570	4285
27	2108	326	3.1	6458	4276
28	2079	344	3.4	6446	4243
29	1983	235	2.6	6362	4176
30	2027	156	2.2	6349	4177
Ave:	1987	915	5.0	6829	4343
S Dev:	90	375	1.2	444	124

	San Joaquin River Flow (cfs)		**DWSC RRI DO**	**Export Flow (cfs)**	
Oct	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	2101	178	2.1	6503	4266
2	2211	182	2.0	6670	4242
3	2203	372	ND	6627	4218
4	2265	721	3.0	6627	4193
5	2394	671	2.6	6605	4204
6	2383	710	ND	6285	4204
7	2385	670	ND	6561	4187
8	2360	591	ND	6574	4264
9	2417	504	ND	6555	4206
10	2475	455	ND	6555	4194
11	2525	508	ND	6550	4182
12	2510	440	ND	3360	4085
13	2402	641	ND	6635	4150
14	2379	531	ND	6559	4215
15	2394	390	ND	6571	4233
16	2426	428	ND	5908	8240
17	2457	577	ND	5007	8128
18	2610	597	ND	3177	8113
19	2570	787	ND	2975	4108
20	2502	919	ND	3418	4117
21	2487	834	ND	3432	4111
22	2542	734	ND	3463	4116
23	2527	644	ND	3477	4127
24	2468	532	ND	3524	3966
25	2428	651	ND	3402	4150
26	2407	516	ND	3444	3954
27	2387	443	ND	3418	4047
28	2399	495	ND	3448	4162

	San Joaquin River Flow (cfs)		**DWSC RRI DO**	**Export Flow (cfs)**	
Nov	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	2444	770	ND	2957	4220
2	2357	665	ND	3401	4212
3	2399	674	ND	4554	4223
4	2469	601	ND	4529	4215
5	2580	463	ND	3914	4314
6	2591	480	ND	3760	2628
7	2457	463	ND	3589	4138
8	2395	444	ND	4225	4137
9	2364	428	ND	4714	4223
10	2312	298	ND	5735	4237
11	2264	331	ND	4825	4220
12	2269	350	ND	4930	4132
13	2288	288	ND	5697	4118
14	2257	233	ND	5356	3639
15	2216	376	ND	4885	2793
16	2266	369	ND	3405	1938
17	2222	743	ND	5836	1048
18	2165	570	ND	5778	227
19	2137	504	ND	5774	0
20	2109	392	ND	6223	0
21	2104	272	ND	6078	0
22	2090	273	5.1	6044	0
23	2059	129	4.9	6162	0
24	2010	140	4.7	6404	0
25	1991	147	4.6	6406	0
26	1976	44	4.6	6390	0
27	1958	130	4.6	6426	0
28	1957	232	4.6	6408	0

29	2431	514	ND	3198	4213
30	2392	577	ND	3446	4239
31	2385	484	ND	3033	4230
Ave:	2414	558	2.4	4936	4550
S Dev:	108	165	0.5	1595	1204

29	1957	185	4.1	6279	0
30	1971	383	4.0	6006	0
Ave:	2221	379	4.6	5223	2089
S Dev:	191	191	0.4	1088	1979

	San Joaquin River Flow (cfs)		**DWSC RRI DO**	**Export Flow (cfs)**	
Dec	**Vernalis**	**UVM1**	**(mg/L)2**	**CA**	**DMC**
1	2001	527	4.0	5898	0
2	1893	384	4.2	6356	0
3	1862	396	4.9	5313	0
4	1836	254	4.8	5321	0
5	1828	148	4.9	5308	0
6	1832	72	4.9	6742	0
7	1808	35	5.2	6411	0
8	1791	157	5.1	6385	0
9	1790	51	4.9	6226	0
10	1788	152	4.8	3237	0
11	1796	423	4.9	3235	0
12	1776	329	4.9	3309	0
13	1748	496	4.9	2461	0
14	1726	495	5.0	781	0
15	1707	485	5.0	674	0
16	1727	568	5.0	764	0
17	1742	607	5.1	756	0
18	1743	567	5.1	765	0
19	1748	510	5.1	774	0
20	1705	401	5.1	1281	0
21	1688	236	5.1	2224	440
22	1669	297	5.1	3142	292
23	1630	267	5.1	4098	0
24	1639	275	5.1	2902	0
25	1644	208	5.3	2966	0
26	1659	185	5.5	3924	0
27	1649	279	5.4	3823	0
28	1618	189	5.5	4359	0
29	1600	315	ND	5419	0
30	1599	301	ND	6398	0
31	1581	133	ND	6660	0
Ave:	1736	314	5.0	3804	24
S Dev.:	97	163	0.3	2105	93

1 SJR flow into DWSC

2 Surface dissolved oxygen concentration at DWR Rough and Ready Island Monitoring Station

Source: IEP database preliminary data; Vernalis flow data from California Data Exchange Center

Appendix E

A COMPARISON OF FALL STOCKTON SHIP CHANNEL DISSOLVED OXYGEN LEVELS IN YEARS WITH LOW, MODERATE, AND HIGH INFLOWS[5]

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INTRODUCTION

Since 1968, Bay-Delta and Monitoring Section staff and supporting IEP staff have measured dissolved oxygen levels in the Stockton Ship Channel in late summer and early fall. Dissolved oxygen is monitored to determine if placement of the Old River closure is necessary and to monitor conditions during and after placement. This article compares the monitoring results obtained during years with low (1994), moderate (1997), and high (1998) fall inflows into the channel to determine if high inflows significantly improve dissolved oxygen levels within the channel.

Dissolved oxygen monitoring was conducted twice a month by vessel (the *San Carlos*) from August through November of each year. During each of the monitoring runs, 14 sites were sampled from Prisoner's Point in the central Delta (Station 1) to the Stockton Turning Basin (Station 14) (Figure 1). Dissolved oxygen and water temperature data were collected for each site at the top and bottom of the water column during ebb slack tide using traditional discrete (Van Dorn sampler and Winkler titration) and continuous monitoring (Hydrolab model DS-3 multiparameter surveyor) instrumentation.

Typically, dissolved oxygen levels in the eastern Stockton Ship Channel drop below 6.0 mg/L during the late summer and early fall because of low San Joaquin River inflows, warm water temperatures, high BOD, reduced tidal circulation, intermittent reverse flow conditions, and other factors. These low dissolved oxygen levels have been known to cause physiological stress to fish and block upstream migration of salmon in the San Joaquin River. Despite the distinctly different inflows into the eastern channel during the fall of 1994, 1997, and 1998, these conditions persisted. A brief description of the findings for different inflow conditions of each year follows.

1994: A DRY YEAR WITH LOW FALL SAN JOAQUIN RIVER FLOWS

In 1994, average daily flows in the San Joaquin River past Vernalis approached 1,000 cfs in August and September and 1,300 cfs in October and November. Because of the low late summer and early fall San Joaquin River flows, the Old River closure was in place from September 7 through November 30. However, reverse flow conditions in the San Joaquin River past Stockton persisted throughout the late summer and early fall, as average net daily flows past Stockton ranged from -717 cfs to +168 cfs in August and September, and -308 to +301 cfs in October and November. These conditions apparently reduced any improvements attributable to placement of the closure.

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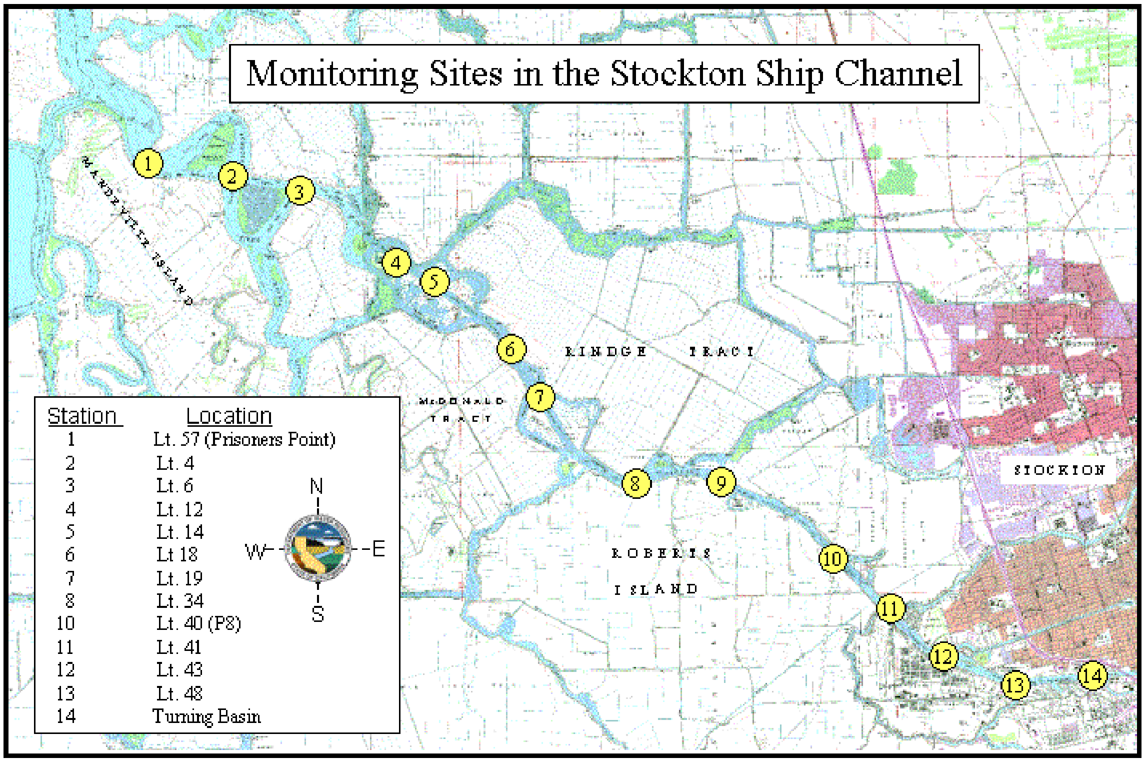
[5] Hayes, S.P and Lee, Jennifer, S., Interagency Ecological Newletter:51-56 Winter (2000)

Because of low inflows into the eastern channel, warm late summer water temperatures (24 to 28 °C), persistent reverse flow conditions past Stockton, and other factors, a dissolved oxygen sag (an area within the channel where levels were 5.0 mg/L or less) developed in the eastern channel in and immediately west of Rough and Ready Island (the Station 9 to 13 area) in August and persisted through early October (Figure 2). The lowest surface and bottom dissolved oxygen levels of 4.0 mg/L and 3.8 mg/L, respectively, were measured at the eastern end of Rough and Ready Island (Station 13) on August 22.

Cooler water temperatures in the channel on October 18 (16 to 19°C) and November 18 (10 to 12°C) and slightly improved flow conditions eliminated the sag area by October 18. Dissolved oxygen levels in the eastern channel fully recovered to levels similar to those in the western channel by November 15.

Figure 1

Dissolved oxygen monitoring sites in the Stockton Ship Channel



Station	Location
1	Lt. 57 (Prisoners Point)
2	Lt. 4
3	Lt. 6
4	Lt. 12
5	Lt. 14
6	Lt 18
7	Lt. 19
8	Lt. 34
10	Lt. 40 (P8)
11	Lt. 41
12	Lt. 43
13	Lt. 48
14	Turning Basin

Cooler water temperatures in the channel on October 15 (17 to 19 °C) and in November (14 to 18 °C), improved fall flow conditions in the San Joaquin River (the average daily flows past Vernalis briefly exceeded 3,000 cfs in mid-October). The elimination of reverse flow conditions past Stockton on October 10 displaced the sag area westward on October 15 and gradually eliminated it in November. The lack of late fall rain in the San Joaquin River drainage basin delayed the full recovery of dissolved oxygen levels in the eastern channel to those historically measured in the western channel during November in previous years.

1997: A WET YEAR WITH MODERATE FALL SAN JOAQUIN RIVER FLOWS

In 1997, average daily flows in the San Joaquin River past Vernalis approached 2,000 cfs in August and September and exceeded 2,000 cfs in October and November. Because of the relatively high average daily flows, the Old River closure was not installed due to overtopping, bank erosion, and other concerns. In spite of the relatively high flows in the San Joaquin River, average daily net flows past Stockton ranged from -466 cfs to +198 cfs in August and September, and reverse flows were not eliminated until early October when flood control related reservoir releases within the drainage basin of the San Joaquin River were initiated.

Because of the relatively low inflows into the eastern channel, warm late summer and early fall water temperatures (22 to 27 °C), late summer and early fall reverse flow conditions past Stockton, and other factors, a dissolved oxygen sag also developed in the eastern channel in and immediately west of the Rough and Ready Island area (Stations 8 through 13) in August and persisted through early October (Figure 3). The lowest surface (3.1 mg/L) and bottom (2.6 mg/L) levels were measured at Buckley Cove (Station 10) on October 1, 1997.

1998: A WET YEAR WITH HIGH FALL SAN JOAQUIN RIVER FLOWS

In 1998, average daily flows in the San Joaquin River past Vernalis ranged from 4,753 to 6,708 cfs from August through October and average daily flows past Vernalis ranged from 1.020 to 2,011 cfs due to the exceptionally wet winter of 1997-1998 and the following cool, wet spring. Because of the exceptionally high flows and the absence of reverse flow conditions past Stockton, a closure across the mouth of Old River was not constructed in fall 1998.

In spite of exceptionally high San Joaquin River inflows into the eastern Stockton Ship Channel, a dissolved oxygen depression occurred in the central channel from Columbia Cut (Station 5) to Fourteen Mile Slough (Station 9) in August and early September (Figure 4). This area of depression is considerably west of the Rough and Ready Island area in the eastern channel where the sag area has historically occurred.

Relatively warm late summer water temperatures measured within the channel in August and early September (22 to 26 C) appear to have contributed to the establishment of the dissolved oxygen depression in the channel in the late summer of 1998. However, at the range of water temperature values experienced in the late summer of 1998, dissolved oxygen levels have been lower (less than 5.0 mg/L) in the eastern channel in previous years.

The high San Joaquin River inflows into the eastern channel immediately east of Rough and Ready Island appear to have been sufficient to push the area of depressed dissolved oxygen levels westward from the historical sag area in the eastern channel to the central portion of the channel. Tidal fluctuations and greater water column mixing within the central portion of the channel may have contributed to the improved dissolved oxygen levels.

By September 18, 1998, the late summer dissolved oxygen depression in the channel was eliminated and by October 20, 1998, full recovery of dissolved oxygen levels to greater than 8.0 mg/L was accomplished throughout the channel due to cooler water temperatures (13 to 18 C in October) and sustained high San Joaquin River inflows into the channel.

CONCLUSIONS

From August through October of 1998, average daily San Joaquin River flows past Vernalis (approximately 6,000 cfs) were six times the flows past Vernalis during the same period in 1994, and three times the flow past Vernalis during the same period in 1997. The significantly higher flows in 1998 did eliminate the dissolved oxygen sag normally present in the eastern channel. However, a dissolved oxygen depression developed within the Stockton Ship Channel in August and early September, when water temperatures were warmest, in spite of the significantly higher flows in 1998. Thus, the 1998 flow conditions apparently contributed to only partial improvement in late summer dissolved oxygen conditions within the channel.

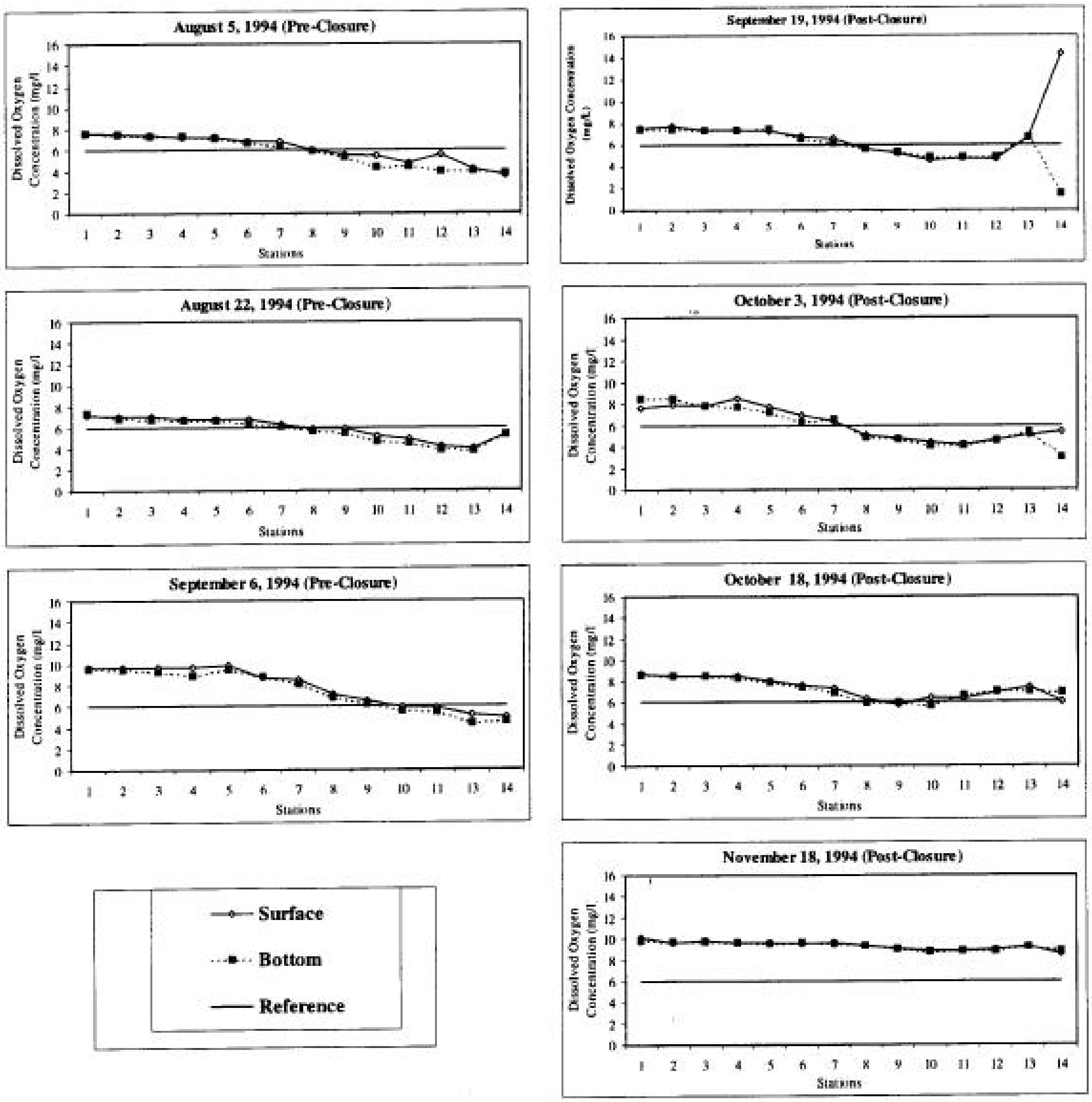
Based on the 1998 dissolved oxygen monitoring results, placement of the closure at the head of Old River may produce marginal results in years with low to moderate fall San Joaquin River inflows. At no time during years with low to average fall flows in the San Joaquin River (such as 1994 and 1997, respectively) would placement of the Old River closure have improved flows sufficiently to duplicate the flow conditions and partial improvement on channel dissolved oxygen levels achieved in fall 1998.

POSTSCRIPT: THE STOCKTON TURNING BASIN IN 1994, 1997, AND 1998

Exceptionally high surface and low bottom dissolved oxygen levels were periodically measured in the Stockton Turning Basin throughout the fall in 1994, 1997, and 1998. During these periods, surface dissolved oxygen levels ranged from 9.6 to 15.4 mg/L and bottom dissolved oxygen levels ranged from 1.5 to 5.6 mg/L. Occasionally, the distinct dissolved oxygen stratification subsided, and surface and bottom dissolved oxygen levels became similar (within 2 to 3 mg/L of each other). These results are typical of all years.

The highly stratified dissolved oxygen conditions periodically detected in the basin during the late summer and early fall of each year appear to be the result of localized biological and water quality conditions occurring in the basin. The basin is at the eastern dead-end terminus of the channel and is subject to reduced tidal activity, restricted water circulation, and increased residence times when compared to the remainder of the channel. As a result, water quality and biological conditions within the basin have historically differed from those within the main channel downstream, and have led to extensive late summer and fall algal blooms and dieoffs. Usually a series of intense algal blooms composed primarily of crytomonads, diatoms, flagellates, and blue-green and green algae are detected. Stratified dissolved oxygen conditions appear to be produced in the water column of the basin by blooms in the following manner: (1) high algal productivity at the surface of the basin produces elevated surface dissolved oxygen levels and (2) dead or dying bloom algae settle out of the water column and sink to the bottom to contribute to high BOD. Bottom dissolved oxygen levels in the basin are further degraded by additional BOD loadings in the area such as regulated discharges into the San Joaquin River and from recreational activities adjacent to the basin. When bloom activity subsides, the dissolved oxygen stratification is reduced, and basin surface and bottom dissolved oxygen levels become less diverse.

Note: The “Reference” Line in the Attached Figures is Not Necessarily the Water Quality Objective.
The WQO is 5 mg/L for August and 6 mg/L for September, October and November.



August 5, 1994 (Pre-Closure)

August 22, 1994 (Pre-Closure)

September 6, 1994 (Pre-Closure)

September 19, 1994 (Post-Closure)

October 3, 1994 (Post-Closure)

October 18, 1994 (Post-Closure)

November 18, 1994 (Post-Closure)

Figure 2 Dissolved oxygen concentrations in the Stockton Ship Channel in 1994

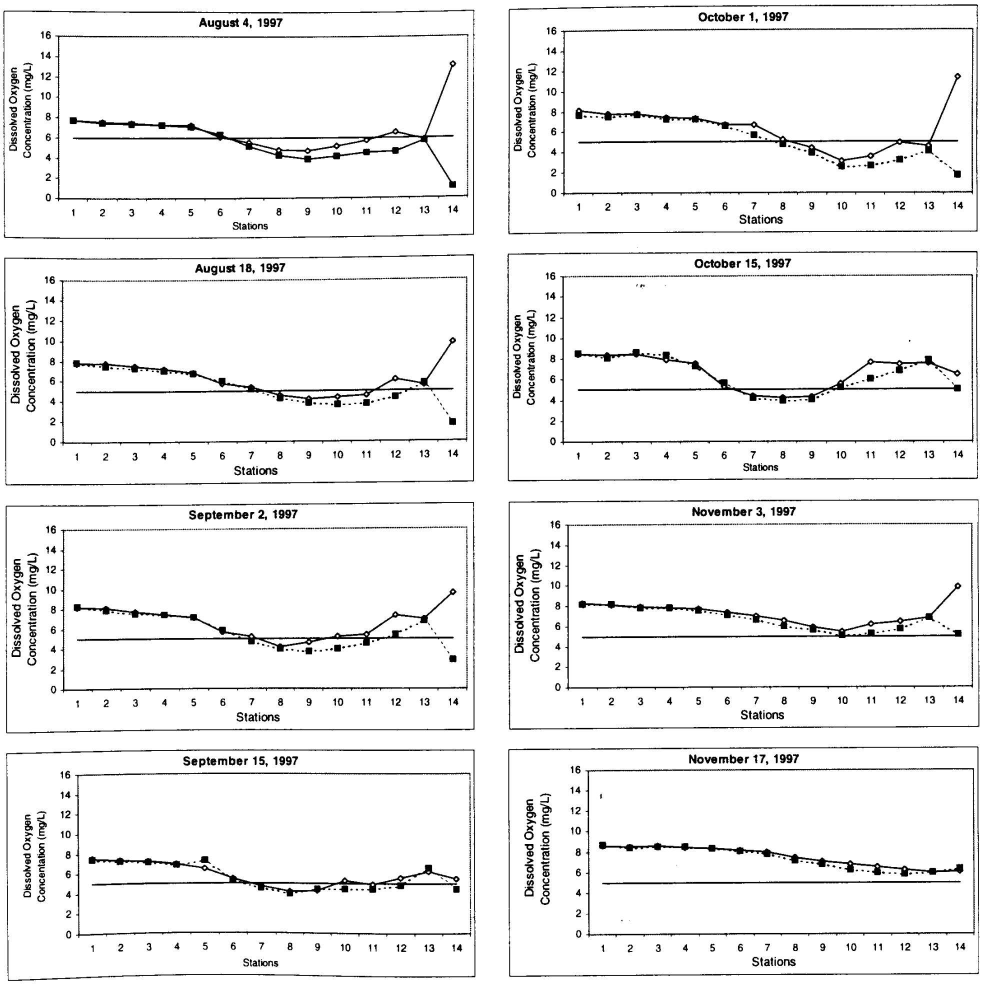
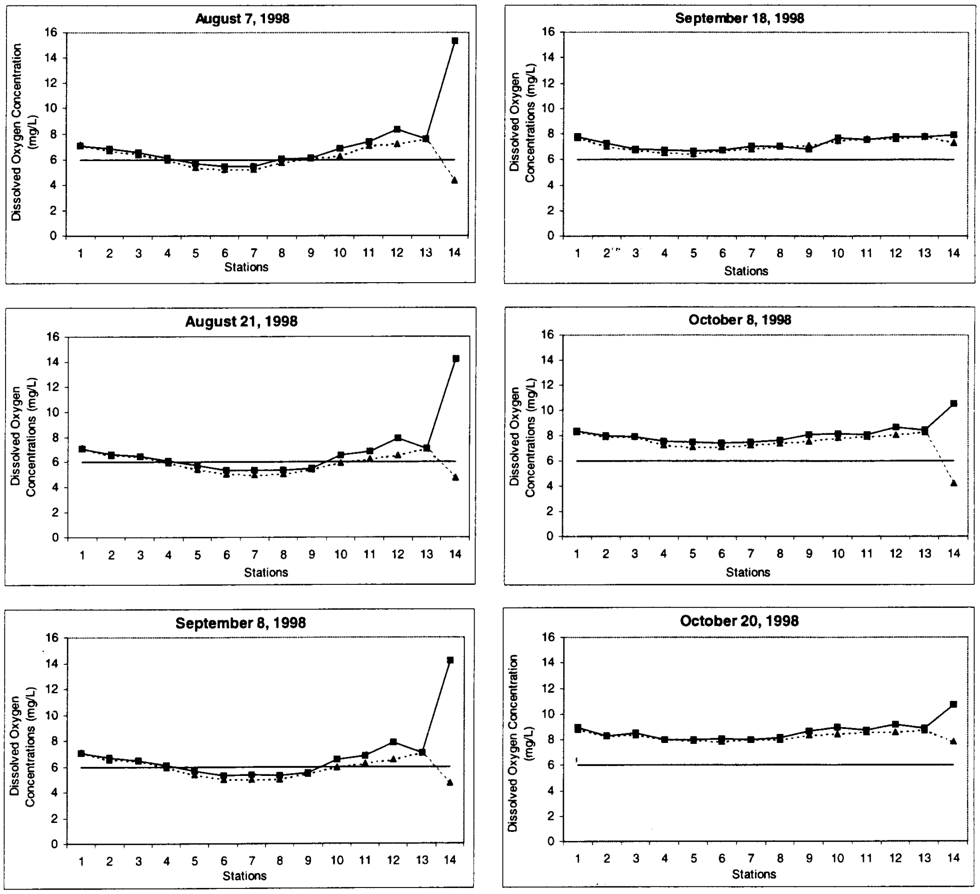


Figure 3 Dissolved oxygen concentrations in the Stockton Ship Channel in 1997



August 7, 1998

August 21, 1998

September 8, 1998

September 18, 1998

October 8, 1998

October 20, 1998

Figure 4 Dissolved oxygen concentrations in the Stockton Ship Channel in 1998

Appendix F

DISSOLVED OXYGEN CRITERIA

QUALITY CRITERIA
FOR
WATER 1986

“GoldBook”

US EPA 1987

DISSOLVED OXYGEN

NATIONAL CRITERIA:

The national criteria for ambient dissolved oxygen concentrations for the protection of freshwater aquatic life are presented in Table 1. The criteria are derived from the production impairment estimates which are based primarily upon growth data and information on temperature, disease, and pollutant stresses. The average dissolved oxygen concentrations selected are values 0.5 mg/L above the slight production impairment values and represent values between no production impairment and slight production impairment. Each criterion may thus be viewed as an estimate of the threshold concentration below which detrimental effects are expected.

Table 1

Water quality criteria for ambient dissolved oxygen concentration.

	Coldwater Criteria				Warmwater Criteria	
	Early Life Stages [1,2]		Other Life Stages		Early Life Stages[2]	Other Life Stages
30-Day Mean	NA[3]		6.5		NA	5.5
7-Day Mean	9.5	(6.5)	NA		6.0	NA
7-Day Mean Minimum	NA		5.0		NA	4.0
1-DayMinimum[4,5]	8.0	(5.0)	4.0		NA	4.0

1 These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/L differential is discussed in the criteria document. For species that have early life stages exposed directly-to the water column, the figures in parentheses apply.

2 Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

3 NA (not applicable).

4 For highly manipulatable discharges, further restrictions apply (see page 37).

5 All minima should be considered as instantaneous concentrations to be achieved at all times.

Criteria for coldwater fish are intended to apply to waters containing a population of one or more species in the family Salmonidae (Bailey *et al*., 1970) or to waters containing other coldwater or coolwater fish deemed by the user to be closer to salmonids in sensitivity than to most warmwater species. Although the acute lethal limit for salmonids is at or below 3 mg/L, the coldwater minimum has been established at 4 mg/L because a significant proportion of the insect species common to salmnonid habitats are 1ess tolerant of acute exposures to low dissolved oxygen than are salmonids. Some coolwater species may require more protection than that afforded by the other life stage criteria for warmwater fish and it may be desirable to protect sensitive coolwater species with the coldwater criteria. Many states have more stringent dissolved oxygen standards for cooler waters, waters that contain either salmnonids, nonsalmonid coolwater fish, or the sensitive centrachid, the smallmouth bass The warmwater criteria are necessary to protect early life stages of warmwater fish as sensitive as channel catfish and to protect other life stages of fish as sensitive as largemouth bass. Criteria for early life stages are intended to apply only where and when these stages occur. These criteria represent dissolved oxygen concentrations which EPA believes provide a reasonable and adequate degree of protection for freshwater aquatic life.

The criteria do not represent assured no effect levels. However, because the criteria represent worst case conditions (i.e., for wasteload allocation and waste treatment plant design), conditions will be better than the criteria nearly all of the time at most sites. In situations where criteria conditions are just maintained for considerable periods the proposed criteria represent some risk of production impairment. This impairment would depend on innumerable other factors. If slight production impairment or a small but undefinable risk of moderate impairment is unacceptable, than one should use the “no production impairment” values given in the document as means and the “slight production impairment” values as minima. The table which presents these concentrations is reproduced here as Table 2.

The criteria do represent dissolved oxygen concentrations believed to protect the more sensitive populations of organisms against potentially damaging production impairment. The dissolved oxygen concentrations in the criteria are intended to be protective at typically high seasonal environmental temperatures for the appropriate taxonomic and life stage classifications, temperatures which are often higher than those used in the research from which the criteria were generated, especially for other than early life stages.

Where natural conditions alone create dissolved oxygen concentrations less than 110 percent of the applicable criteria means or minima or both, the minimum acceptable concentration is 90 percent of the natural concentration. These values are similar to those presented graphically by Doudoroff and Shumway (1970) and those calculated from Water Quality Criteria 1972 (NAS/NAE, 1973). Absolutely no anthropogenic dissolved oxygen depression in the potentially lethal area below the 1-day minima should be allowed unless special care is taken to ascertain the tolerance of resident species to low dissolved oxygen.

If daily cycles of dissolved oxygen are essentially sinusoidal, a reasonable daily average is calculated from the day’s high and low dissolved oxygen values. A time-weighted average may be required if the dissolved oxygen cycles are decidedly non-sinusoidal. Determining the magnitude of daily dissolved oxygen cycles requires at least two appropriately timed measurements daily, and characterizing the shape of the cycle requires several more appropriately spaced measurements.

Once a series of daily mean dissolved oxygen concentrations are calculated, an average of these daily means can be calculated (Table 3). For embryonic, larval, and early life stages, the averaging period should not exceed 7 days. This short time is needed to adequately protect these often short duration, most sensitive life stages. Other life stages can probably be adequately protected by 30-day averages. Regardless of the averaging period, the average should be considered a moving average rather than a calendar-week or calendar-month average.

The criteria have been established on the basis that the maximum dissolved oxygen value actually used in calculating any daily mean should not exceed the air saturation value. This consideration is based primarily on analysis of studies of cycling dissolved oxygen and the growth of largemouth bass (Stewart *et al.*, 1967), which indicated that high dissolved oxygen levels (> 6 mg/L) had no beneficial effect on growth.

Table 2.

Dissolved Oxygen Concentrations (mg/L) Versus Quantitative Level of Effect.

1. <u>Salmonid</u> <u>Waters</u>
    a. Embryo and Larval Stages
        No Production Impairment = 11* (8)
        Slight Production Impairment = 9* (6)
        Moderate Production impairment = 8* (5)
        Severe Production Impairment = 7* (4)
        Limit to Avoid Acute Mortality = 6* (3)
    (*Note: These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/L difference is discussed in the criteria document.)

    b. Other Life Stages
        No Production Impairment =8
        light Production Impairment =6
        Moderate Production Impairment =5
        Severe Production Impairment =4
        Limit to Avoid Acute Mortality =3
2. <u>Nonsalmnonid</u> <u>Waters</u>
    a. Early Life Stages
        No Production Impairment =6.5
        Slight Production Impairment =5.5
        Moderate Production Impairment =5
        Severe Production Impairment =4.5
        Limit to Avoid Acute Mortality =4

    b. Other Life Stages
        No Production Impairment =6
        Slight Production Impairment =5
        Moderate Production Impairment =4
        Severe Production Impairment =3.5
        Limit to Avoid Acute Mortality =3

3. Invertebrates
    No Production Impairment =8
    Some Production Impairment =5
    Acute Mortality Limit =4

Table 3
Sample calculations for determining daily means and 7-day mean dissolved oxygen concentrations (30-day averages are calculated in a similar fashion using 30 days data).

Dissolved Oxygen (mg/L)

Day	Daily Max.	Daily Min.	Daily Mean
1	9.0	7.0	8.0
2	10.0	7.0	8.5
3	11.0	8.0	9.5[b]
4	12.0[a]	8.0	9.5
5	9.0	10.0	8.0
6	11.0	9.0	10.0
7	12.0[a]	10.0	10.5[c]
		57.0	65.0
	1-day Minimum	7.0	
	7-day Mean Minimum	8.1	
	7-day Mean	9.3	

a Above air saturation concentration (assumed to be 11.0 mg/L for this example).
b (11.0 + 8.0)/2.
c (11 0+10.0)/2.

During periodic cycles of dissolved oxygen concentrations, minima lower than acceptable constant exposure levels are tolerable so long as:

1. the average concentration attained meets or exceeds the criterion;
2. the average dissolved oxygen concentration is calculated as recommended in Table 3; and
3. the minima are not unduly stressful and clearly are not lethal.

A daily minimum has been included to make certain that no acute mortality of sensitive species occurs as a result of lack of oxygen. Because repeated exposure to dissolved oxygen concentrations at or near the acute lethal threshold will be stressful and because stress can indirectly produce mortality or other adverse effects (e.g., through disease), the criteria are designed to prevent significant episodes of continuous or regularly recurring exposures to dissolved oxygen concentrations at or near the lethal threshold. This protection has been achieved by setting the daily minimum for early life stages at the subacute lethality threshold, by the use of a 7-day averaging period for early life stages, by stipulating a 7-day mean minimum value for other life stages, and by recommending additional limits for manipulatable discharges.

The previous EPA criterion for dissolved oxygen published in Quality Criteria for Water (US EPA, 1976) was a minimum of 5 mg/L (usually applied as a 7Q10) which is similar to the current criterion minimum except for other life stages of warmwater fish which now allows a 7-day mean minimum of 4 mg/L. The new criteria are similar to those contained in the 1968 "Green Book" of the Federal Water Pollution Control Federation (FWPCA, 1968).

A. The Criteria and Monitoring and Design Conditions

The acceptable mean concentrations should be attained most of the time, but some deviation below these values would probably not cause significant harm. Deviations below the mean will probably be serially correlated and hence apt to occur on consecutive days. The significance of deviations below the mean will depend on whether they occur continuously or in daily cycles, the former being more adverse than the latter. Current knowledge regarding such deviations is limited primarily to laboratory growth experiments and by extrapolation to other activity related phenomena.

Under conditions where large daily cycles of dissolved oxygen occur, it is possible to meet the criteria mean values and consistently violate the mean minimum criteria. Under these conditions the mean minimum criteria will clearly be the limiting regulation unless alternatives such as nutrient control can dampen the daily cycles.

The significance of conditions which fail to meet the recommended dissolved oxygen criteria depend largely upon five factors: (1) the duration of the event; (2) the magnitude of the dissolved oxygen depression; (3) the frequency of recurrence; (4) the proportional area of the site failing to meet the criteria, and (5) the biological significance of the site where the event occurs. Evaluation of an event's significance must be largely case- and site-specific. Common sense would dictate that the magnitude of the depression would be the single most important factor in general, especially if the acute value is violated. A logical extension of these considerations is that the event must be considered in the context of the level of resolution of the monitoring or modeling effort. Evaluating the extent, duration, and magnitude of an event must be a function of the spatial and temporal frequency of the data. Thus, a single deviation below the criterion takes on considerably less significance where continuous monitoring occurs than where sampling is comprised of once-a-week grab samples. This is so because based on continuous monitoring the event is provably small, but with the much less frequent sampling the event is not provably small and can be considerably worse than indicated by the sample. The frequency of recurrence is of considerable interest to those modeling dissolved oxygen concentrations because the return period, or period between recurrences, is a primary modeling consideration contingent upon probabilities of receiving water volumes, waste loads, temperatures, etc. It should be apparent that return period cannot be isolated from the other four factors discussed above. Ultimately, the question of return period may be decided on a site-specific basis taking into account the other factors (duration, magnitude, areal extent, and biological significance) mentioned above. Future studies of temporal patterns of dissolved oxygen concentrations, both within and between years, must be conducted to provide a better basis for selection of the appropriate return period.

In conducting wasteload allocation and treatment plant design computations, the choice of temperature in the models will be important. Probably the best option would be to use temperatures consistent with those expected in the receiving water over the critical dissolved oxygen period for the biota.

B. The Criteria and Manipulatable Discharges

If daily minimum DOs are perfectly serially correlated, i.e., if the annual lowest daily minimum dissolved oxygen concentration is adjacent in time to the next lower daily minimum dissolved oxygen concentration and one of these two minima is adjacent to the third lowest daily minimum dissolved oxygen concentration, etc., then in order to meet the 7-day mean minimum criterion it is unlikely that there will be more than three or four consecutive daily minimum values below the acceptable 7-day mean minimum. Unless the dissolved oxygen pattern is extremely erratic, it is also unlikely that the lowest dissolved oxygen concentration will be appreciably below the acceptable 7-day mean minimum or that daily minimum values below the 7-day mean minimum will occur in more than one or two weeks each year. For some discharges, the distribution of dissolved oxygen concentrations can be manipulated to varying degrees. Applying the daily minimum to manipulatable discharges would allow repeated weekly cycles of minimum acutely acceptable dissolved oxygen values, a condition of unacceptable stress and possible adverse biological effect. For this reason, the application of the one-day minimum criterion to manipulatable discharges must limit either the frequency of occurrence of values below the acceptable 7-day mean minimum or must impose further limits on the extent of excursions below the 7-day mean minimum. For such controlled discharges, it is recommended that the occurrence of daily minimum below the acceptable 7-day mean minimum be limited to 3 weeks per year or that the acceptable one-day minimum be increased to 4.5 mg/L for coldwater fish and 3.5 mg/L for warmwater fish. Such decisions could be site-specific based upon the extent of control and serial correlation.

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Ambient Water Quality Criteria for Dissolved Oxygen

US EPA, 1986
(Goldbook Criterion Document)

FRESHWATER AQUATIC LIFE

I. Introduction

A sizable body of literature on the oxygen requirements of freshwater aquatic life has been thoroughly summarized (Doudoroff and Shumway, 1967, 1970; Warren et al., 1973; Davis, 1975a,b; and Alabaster and Lloyd, 1980). These reviews and other documents describing the dissolved oxygen requirements of aquatic organisms (U.S. Environmental Protection Agency, 1976; International Joint Commission, 1976; Minnesota Pollution Control Agency, 1980) and more recent data were considered in the preparation of this document. The references cited below are limited to those considered to be the most definitive and most representative of the preponderance of scientific evidence concerning the dissolved oxygen requirements of freshwater organisms. The guidelines used in deriving aquatic life criteria for toxicants (Federal Register, 45 FR 79318, November 28, 1980) are not applicable because of the different nature of the data bases. Chemical toxicity data bases rely on standard 96-h LC5O tests and standard chronic tests; there are very few data of either type on dissolved oxygen.

Over the last 10 years the dissolved oxygen criteria proposed by various agencies and researchers have generally reflected two basic schools of thought. One maintained that a dynamic approach should be used so that the criteria would vary with natural ambient dissolved oxygen minima in the waters of concern (Doudoroff and Shumway, 1970) or with dissolved oxygen requirements of fish expressed in terms of percent saturation (Davis, 1975a,b). The other maintained that, while not ideal, a single minimum allowable concentration should adequately protect the diversity of aquatic life in fresh waters (U.S. Environmental Protection Agency, 1976). Both approaches relied on a simple minimum allowable dissolved oxygen concentration as the basis for their criteria. A simple minimum dissolved oxygen concentration was also the most practicable approach in waste load allocation models of the time.

Expressing the criteria in terms of the actual amount of dissolved oxygen available to aquatic organisms in milligrams per liter (mg/l) is considered more direct and easier to administer compared to expressing the criteria in terms of percent saturation. Dissolved oxygen criteria expressed as percent saturation, such as discussed by Davis (1975a,b), are more complex and could often result in unnecessarily stringent criteria in the cold months and potentially unprotective criteria during periods of high ambient temperature or at high elevations. Oxygen partial pressure is subject to the same temperature problems as percent saturation.

The approach recommended by Doudoroff and Shumway (1970), in which the criteria vary seasonally with the natural minimum dissolved oxygen concentrations in the waters of concern, was adopted by the National Academy of Sciences and National Academy of Engineering (NAS/NAE, 1973). This approach has some merit, but the lack of data (natural minimum concentrations) makes its application difficult, and it can also produce unnecessarily stringent or unprotective criteria during periods of extreme temperature.

The more simplistic approach to dissolved oxygen criteria has been supported by the findings of a select committee of scientists specifically established by the Research Advisory Board of the International Joint Commission to review the dissolved oxygen criterion for the Great Lakes (Magnuson et al., 1979). The committee concluded that a simple criterion (an average criterion of 6.5 mg/l and a minimum criterion of 5.5 mg/l) was preferable to one based on percent saturation (or oxygen partial pressure) and was scientifically sound because the rate of oxygen transfer across fish gills is directly dependent on the mean difference in oxygen partial pressure across the gill. Also, the total amount of oxygen delivered to the gills is a more specific limiting factor than is oxygen partial pressure per se. The format of this otherwise simple criterion was more sophisticated than earlier criteria with the introduction of a two-concentration criterion comprised of both a mean and a minimum. This two-concentration criteria structure is similar to that currently used for toxicants (Federal Register, 45 FR 79318, November 28, 1980). EPA agrees with the International Joint Commission's conclusions and will recommend a two-number criterion for dissolved oxygen.

The national criteria presented herein represent the best estimates, based on the data available, of dissolved oxygen concentrations necessary to protect aquatic life and its uses. Previous water quality criteria have either emphasized (Federal Water Pollution Control Administration, 1968) or rejected (National Academy of Sciences and National Academy of Engineering, 1972) separate dissolved oxygen criteria for coldwater and warmwater biota. A warmwater-coldwater dichotomy is made in this criterion. To simplify discussion, however, the text of the document is split into salmonid and nonsalmonid sections. The salmonid-nonsalmonid dichotomy is predicated on the much greater knowledge regarding the dissolved oxygen requirements of salmonids and on the critical influence of intergravel dissolved oxygen concentration on salmonid embryonic and larval development. Nonsalmonid fish include many other coldwater and coolwater fish plus all warmwater fish. Some of these species are known to be less sensitive than salmonids to low dissolved oxygen concentrations. Some other nonsalmonids may prove to be at least as sensitive to low dissolved oxygen concentrations as the salmonids; among the nonsalmonids of likely sensitivity are the herrings (Clupeidae), the smelts (Osmeridae), the pikes (Esocidae), and the sculpins (Cottidae). Although there is little published data regarding the dissolved oxygen requirements of most nonsalmonid species, there is apparently enough anecdotal information to suggest that many coolwater species are more sensitive to dissolved oxygen depletion than are warmwater species. According to the American Fisheries Society (1978), the term "coolwater fishes" is not vigorously defined, but it refers generally to those species which are distributed by temperature preference between the "coldwater" salmonid communities to the north and the more diverse, often centrarchid-dominated "warmwater" assemblages to the south. Many states have more stringent dissolved oxygen standards for colder waters, waters that contain either salmonids, nonsalmonid coolwater fish, or the sensitive centrarchid, the smallmouth bass.

The research and sociological emphasis for dissolved oxygen has been biased towards fish, especially the more economically important species in the family Salmonidae. Several authors (Doudoroff and Shumway, 1970; Davis, 1975a,b) have discussed this bias in considerable detail and have drawn similar conclusions regarding the effects of low dissolved oxygen on freshwater invertebrates. Doudoroff and Shumway (1970) stated that although some invertebrate species are about as sensitive as the moderately susceptible fishes, all invertebrate species need not be protected in order to protect the food source for fisheries because many invertebrate species, inherently more tolerant than fish, would increase in abundance. Davis (1975a,b) also concluded that invertebrate species would probably be adequately protected if the fish populations are protected. He stated that the composition of invertebrate communities may shift to more tolerant forms selected from the resident community or recruited from outside the community. In general, stream invertebrates that are requisite riffle-dwellers probably have a higher dissolved oxygen requirement than other aquatic invertebrates. The riffle habitat maximizes the potential dissolved oxygen flux to organisms living in the high water velocity by rapidly replacing the water in the immediate vicinity of the organisms. This may be especially important for organisms that exist clinging to submerged substrate in the riffles. In the absence of data to the contrary, EPA will follow the assumption that a dissolved oxygen criterion protective of fish will be adequate.

One of the most difficult problems faced during this attempt to gather, interpret, assimilate, and generalize the scientific data base for dissolved oxygen effects on fish has been the variability in test conditions used by investigators. Some toxicological methods for measuring the effects of chemicals on aquatic life have been standardized for nearly 40 years; this has not been true of dissolved oxygen research. Acute lethality tests with dissolved oxygen vary in the extreme with respect to types of exposure (constant vs. declining), duration of exposure (a few hours vs. a week or more), type of endpoint (death vs. loss of equilibrium), type of oxygen control (nitrogen stripping vs. vacuum degassing), and type of exposure chamber (open to the atmosphere vs. sealed). In addition there are the normal sources of variability that influence standardized toxicity tests, including seasonal differences in the condition of test fish, acclimation or lack of acclimation to test conditions, type and level of feeding, test temperature, age of test fish, and stresses due to test conditions. Chronic toxicity tests are typically of two types, full life cycle tests or early life stage tests. These have come to be rather rigorously standardized and are essential to the toxic chemical criteria established by EPA. These tests routinely are assumed to include the most sensitive life stage, and the criteria then presume to protect all life stages. With dissolved oxygen research, very few tests would be considered legitimate chronic tests; either they fail to include a full life cycle, they fail to include both embryo and larval stages, or they fail to include an adequate period of post-larval feeding and growth.

Instead of establishing year-round criteria to protect all life stages, it may be possible to establish seasonal criteria based on the life stages present. Thus, special early life stage criteria are routinely accepted for salmonid early life stages because of their usual intergravel environment. The same concept may be extended to any species that appear to have more stringent dissolved oxygen requirements during one period of their life history. The flexibility afforded by such a dichotomy in criteria carries with it the responsibility to accurately determine the presence or absence of the more sensitive stages prior to invocation of the less stringent criteria. Such presence/absence data must be more site-specific than national in scope, so that temperature, habitat, or calendar specifications are not possible in this document. In the absence of such site-specific determinations the default criteria would be those that would protect all life stages year-round; this is consistent with the present format for toxic chemical criteria.

II. Salmonids

The effects of various dissolved oxygen concentrations on the well being of aquatic organisms have been studied more extensively for fish of the family Salmonidae (which includes the genera Coregonus, Oncorhynchus, Prosopium, Salmo, Salvelinus, Stenodus, and Thymallus) than for any other family of organisms. Nearly all these studies have been conducted under laboratory conditions, simplifying cause and effect analysis, but minimizing or eliminating potentially important environmental factors, such as physical and chemical stresses associated with suboptimal water quality, as well as competition, behavior, and other related activities. Most laboratory studies on the effects of dissolved oxygen concentrations on salmonids have emphasized growth, physiology, or embryonic development. Other studies have described acute lethality or the effects of dissolved oxygen concentration on swimming performance.

A. Physiology

Many studies have reported a wide variety of physiological responses to low dissolved oxygen concentrations. Usually, these investigations were of short duration, measuring cardiovascular and metabolic alterations resulting from hypoxic exposures of relatively rapid onset. While these data provide only minimal guidance for establishing environmentally acceptable dissolved oxygen concentrations, they do provide considerable insight into the mechanisms responsible for the overall effects observed in the entire organism. For example, a good correlation exists between oxygen dissociation curves for rainbow trout blood (Cameron, 1971) and curves depicting the reduction in growth of salmonids (Brett and Blackburn, 1981; Warren et al., 1973) and the reduction in swimming ability of salmonids (Davis et al., 1963). These correlations indicate that the blood’s reduced oxygen loading capacity at lower dissolved oxygen concentrations limits the amount of oxygen delivered to the tissues, restricting the ability of fish to maximize metabolic performance.

In general, the significance of metabolic and physiological studies on the establishment of dissolved oxygen criteria must be indirect, because their applicability to environmentally acceptable dissolved oxygen concentrations requires greater extrapolation and more assumptions than those required for data on growth, swimming, and survival.

B. Acute Lethal Concentrations

Doudoroff and Shumway (1970) summarized studies on lethal concentrations of dissolved oxygen for salmonids; analysis of these data indicates that the test procedures were highly variable, differing in duration, exposure regime, and reported endpoints. Only in a few cases could a 96-hr LC5O be calculated. Mortality or loss of equilibrium usually occurred at concentrations between 1 and 3 mg/l.

Mortality of brook trout has occurred in less than one hour at 10°C at dissolved oxygen concentrations below 1.2 mg/l, and no fish survived exposure at or below 1.5 mg/l for 10 hours (Shepard, 1955). Lethal dissolved oxygen concentrations increase at higher water temperatures and longer exposures. A 3.5 hr exposure killed all trout at 1.1 and 1.6 mg/l at 10 and 20°C, respectively (Downing and Merkens, 1957). A 3.5-day exposure killed all trout at 1.3 and 2.4 mg/l at 10 and 20°C, respectively. The corresponding no-mortality levels were 1.9 and 2.7 mg/l. The difference between dissolved oxygen concentrations causing total mortality and those allowing complete survival was about 0.5 mg/l when exposure duration was less than one week. If the period of exposure to low dissolved oxygen concentrations is limited to less than 3.5 days, concentrations of dissolved oxygen of 3 mg/l or higher should produce no direct mortality of salmonids.

More recent studies confirm these lethal levels in chronic tests with early life stages of salmonids (Siefert et al., 1974; Siefert and Spoor, 1973; Brooke and Colby, 1980); although studies with lake trout (Carlson and Siefert, 1974) indicate that 4.5 mg/l is lethal at 10°C (perhaps a marginally acceptable temperature for embryonic lake trout).

C. Growth

Growth of salmonids is most susceptible to the effects of low dissolved oxygen concentrations when the metabolic demands or opportunities are greatest. This is demonstrated by the greater sensitivity of growth to low dissolved oxygen concentrations when temperatures are high and food most plentiful (Warren et al., 1973). A total of more than 30 growth tests have been reported by Herman et al. (1962), Fisher (1963), Warren et al. (1973), Brett and Blackburn (1981), and Spoor (1981). Results of these tests are not easily compared because the tests encompass a wide range of species, temperatures, food types, and fish sizes. These factors produced a variety of control growth rates which, when combined with a wide range of test durations and fish numbers, resulted in an array of statistically diverse test results.

The results from most of these 30-plus tests were converted to growth rate data for fish exposed to low dissolved oxygen concentrations and were compared to control growth rates by curve-fitting procedures (JRB Associates, 1984). Estimates of growth rate reductions were similar regardless of the type of curve employed, but the quadratic model was judged to be superior and was used in the growth rate analyses contained in this document. The apparent relative sensitivity of each species to dissolved oxygen depletion may be influenced by fish size, test duration, temperature, and diet. Growth rate data (Table 1) from these tests with sa1mon and trout fed unrestricted rations indicated median growth rate reductions of 7, 14, and 25 percent for fish held at 6, 5, and 4 mg/l, respectively (JRB Associates, 1984). However, median growth rate reductions for the various species ranged from 4 to 9 percent at 6 mg/l, 11 to 17 percent at 5 mg/l, and 21 to 29 percent at 4 mg/l.

Considering the variability inherent in growth studies, the apparent reductions in growth rate sometimes seen above 6 mg/l are not usually statistically significant. The reductions in growth rate occurring at dissolved oxygen concentrations below about 4 mg/l should be considered severe; between 4 mg/l and the threshold of effect, which variably appears to be between 6 and 10 mg/l in individual tests, the effect on growth rate is moderate to slight if the exposures are sufficiently long.

Within the growth data presented by Warren et al. (1973), the greatest effects and highest thresholds of effect occurred at high temperatures (17.8 to 21.7°C). In two tests conducted at about 8.5°C, the growth rate reduction at 4 mg/l of dissolved oxygen averaged 12 percent. Thus, even at the maximum feeding levels in these tests, dissolved oxygen levels down to 5 mg/l probably have little effect on growth rate at temperatures below 10°C.

Table 1. Percent reduction in growth rate of salmonids at various dissolved oxygen concentrations expressed as the median value from n tests with each species (calculated from JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Species(number of tests)					
	Chinook Salmon (6)	Coho Salmon (12)	Sockeye Salmon (1)	Rainbow Trout (2)	Brown Trout (1)	Lake Trout (2)
9	0	0	0	0	0	0
8	0	0	0	1	0	0
7	1	1	2	5	1	2
6	7	4	6	9	6	7
5	16	11	12	17	13	16
4	29	21	22	25	23	29
3	47	37	33	37	36	47
Median Temp. (°C)	15	18	15	12	12	12

Growth data from Warren et al. (1973) included chinook salmon tests conducted at various temperatures. These data (Table 2) indicated that growth tests conducted at 10-15°C would underestimate the effects of low dissolved oxygen concentrations at higher temperatures by a significant margin. For example, at 5 mg/l growth was not affected at 13°C but was reduced by 34 percent if temperatures were as high as 20°C. Examination of the test temperatures associated with the growth rate reductions listed in Table 1 shows that most data represent temperatures between 12 and 15°C. At the higher temperatures often associated with low dissolved oxygen concentrations, the growth rate reductions would have been greater if the generalizations the chinook salmon data are applicable to salmonids in general. Coho salmon growth studies (Warren et al., 1973) showed a similar result over a range of temperatures from 9 to 18°C, but the trend was reversed in two tests near 22°C (Table 3). Except for the 22°C coho tests, the coho and chinook salmon results support the idea that effects of low dissolved oxygen become more severe at higher temperatures. This conclusion is supported by data on largemouth bass (to be discussed later) and by the increase in metabolic rate produced by high temperatures.

Effects of dissolved oxygen concentration on the growth rate of salmonids fed restricted rations have been less intensively investigated. Thatcher (1974) conducted a series of tests with coho salmon at 15°C over a wide range of food consumption rates at 3, 5, and 8 mg/l of dissolved oxygen. The only significant reduction in growth rate was observed at 3 mg/l and food consumption rates greater than about 70 percent 01 maximum. In these studies, Thatcher noted that fish at 5 mg/l appeared to expend less energy in swimming activity than those at 8 mg/l. In natural conditions, where fish may be rewarded for energy expended defending preferred territory or searching for food, a dissolved oxygen concentration of 5 mg/l may restrict these activities.

Table 2. Influence of temperature on growth rate of chinook salmon held at various dissolved oxygen concentrations (calculated from Warren et al., 1973; JRB Associates, 1984).

Dissolved Oxygen (mg/L)	Percent Reduction in Growth Rate at					
	8.4°C	13.0°C	13.2°C	17.8°C	18.6°C	21.7°C
9	0	0	0	0	0	0
8	0	0	0	0	2	0
7	0	0	4	0	8	2
6	0	0	8	5	19	14
5	0	0	16	16	34	34
4	7	4	25	33	53	65
3	26	22	36	57	77	100

Table 3. Influence of temperature on growth rate of coho salmon held at various dissolved oxygen concentrations (calculated from Warren et al., 1973; JRB Associates, 1984).

Dissolved Oxygen (mg/L)	Percent Reduction in Growth Rate at					
	8.6°C	12.9°C	13.0°C	18.0°C	21.6°C	21.8°C
10	0	0	0	0	0	0
9	0	0	0	5	0	0
8	0	1	2	10	0	0
7	1	4	6	17	0	6
6	4	10	13	27	0	1
5	9	18	23	38	0	7
4	17	29	36	51	4	19
3	28	42	51	67	6	37

The effect of forced activity and dissolved oxygen concentration on the growth of coho salmon was studied by Hutchins (1974). The growth rates of salmon fed to repletion at a dissolved oxygen concentration of 3 mg/l and held at current velocities of 8.5 and 20 cm/sec were reduced by 20 and 65 percent, respectively. At 5 mg/l, no reduction of growth rate was seen at the slower velocity, but a 15 percent decrease occurred at the higher velocity.

The effects of various dissolved oxygen concentrations on the growth rate of coho salmon (~5 cm long) in laboratory streams with an average current velocity of 12 cm/sec have been reported by Warren et al. (1973). In this series of nine tests, salmon consumed aquatic invertebrates living in the streams. Results at temperatures from 9.5° to 15.5°C supported the results of earlier laboratory studies; at higher growth rates (40 to 50 mg/g/day), dissolved oxygen levels below 5 mg/l reduced growth rate, but at lower growth rates (0 to 20 mg/g/day), no effects were seen at concentrations down to 3 mg/l.

The applicability of these growth data from laboratory tests depends on the available food and required activity in natural situations. Obviously, these factors will be highly variable depending on duration of exposure, growth rate, species, habitat, season, and size of fish. However, unless effects of these variables are examined for the site in question, the laboratory results should be used. The attainment of critical size is vital to the smolting of anadromous salmonids and may be important for all salmonids if size-related transition to feeding on larger or more diverse food organisms is an advantage. In the absence of more definitive site-specific, species-specific growth data, the data summaries in Tables 1, 2, and 3 represent the best estimates of the effects of dissolved oxygen concentration on the potential growth of salmonid fish.

D. Reproduction

No studies were found that described the effects of low dissolved oxygen on the reproduction, fertility, or fecundity of salmonid fish.

E. Early Life Stages

Determining the dissolved oxygen requirements for salmonids, many of which have embryonic and larval stages that develop while buried in the gravel of streams and lakes, is complicated by complex relationships between the dissolved oxygen supplies in the gravel and the overlying water. The dissolved oxygen supply of embryos and larvae can be depleted even when the dissolved oxygen concentration in the overlying body of water is otherwise acceptable. Intergravel dissolved oxygen is dependent upon the balance between the combined respiration of gravel-dwelling organisms, from bacteria to fish embryos, and the rate of dissolved oxygen supply, which is dependent upon rates of water percolation and convection, and dissolved oxygen diffusion.

Water flow past salmonid eggs influences the dissolved oxygen supply to the microenvironment surrounding each egg. Regardless of dissolved oxygen concentration in the gravel, flow rates below 100 cm/hr directly influence the oxygen supply in the microenvironment and hence the size at hatch of salmonid fish. At dissolved oxygen levels below 6 mg/l the time from fertilization to hatch is longer as water flow decreases (Silver et al., 1963; Shumway et al., 1964).

The dissolved oxygen requirements for growth of salmonid embryos and larvae have not been shown to differ appreciably from those of older salmonids. Under conditions of adequate water flow (≥100 cm/hr), the weight attained by salmon and trout larvae prior to feeding (swimup) is decreased less than 10 percent by continuous exposure to concentrations down to 3 mg/l (Brannon, 1965; Chapman and Shumway, 1978). The considerable developmental delay which occurs at low dissolved oxygen conditions could have survival and growth implications if the time of emergence from gravel, or first feeding, is critically related to the presence of specific food organisms, stream flow, or other factors (Carlson and Siefert, 1974; Siefert and Spoor, 1974). Effects of low dissolved oxygen on early life stages are probably most significant during later embryonic development when critical dissolved oxygen concentrations are highest (Alderdice et al.), 1958) and during the first few months post-hatch when growth rates are usually highest. The latter authors studied the effects of 7-day exposure of embryos to low dissolved oxygen at various stages during incubation at otherwise high dissolved oxygen concentrations. They found no effect of 7-day exposure at concentrations above 2 mg/l (at a water flow of 85 cm/hr).

Embryos of mountain whitefish suffered severe mortality at a mean dissolved oxygen concentration of 3.3 mg/l (2.8 mg/l minimum) and some reduction in survival was noted at 4.6 mg/l (3.8 mg/l minimum); at 4.6 mg/l, hatching was delayed by 1 to 2 weeks (Siefert et al., 1974). Delayed hatching resulted in poorer growth at the end of the test, even at dissolved oxygen concentrations of 6 mg/l.

Evaluating intergravel dissolved oxygen concentrations is difficult because of the great spatial and temporal variability produced by differences in stream flow, bottom topography, and gravel composition. Even within the same redd, dissolved oxygen concentrations can vary by 5 or 6 mg/l at a given time (Koski, 1965). Over several months, Koski repeatedly measured the dissolved oxygen concentrations in over 30 coho salmon redds and the overlying stream water in three small, forested (unlogged) watersheds. The results of these measurements indicated that the average intraredd dissolved oxygen concentration was about 2 mg/l below that of the overlying water. The minimum concentrations measured in the redds averaged about 3 mg/l below those of the overlying water and probably occurred during the latter period of intergravel development when water temperatures were warmer, larvae larger, and overlying dissolved oxygen concentrations lower.

Coble (1961) buried steelhead trout eggs in streambed gravel, monitored nearby intergravel dissolved oxygen and water velocity, and noted embryo survival. There was a positive correlation between dissolved oxygen concentration, water velocity, and embryo survival. Survival ranged from 16 to 26 percent whenever mean intergravel dissolved oxygen concentrations were below 6 mg/l or velocities were below 20 cm/hr; at dissolved oxygen concentrations above 6 mg/l and velocities over 20 cm/hr, survival ranged from 36 to 62 percent. Mean reductions in dissolved oxygen concentration between stream and intergravel waters averaged about 5 mg/l as compared to the 2 mg/l average reduction observed by Koski (1965) in the same stream. One explanation for the different results is that the intergravel water flow may have been higher in the natural redds studied by Koski (not determined) than in the artificial redds of Coble’s investigation. Also, the density of eggs near the sampling point may have been greater in Coble’s simulated redds.

A study of dissolved oxygen concentrations in brook trout redds was conducted in Pennsylvania (Hollander, 1981). Brook trout generally prefer areas of groundwater upwelling for spawning sites (Witzel and MacCrimmon, 1983). Dissolved oxygen and temperature data offer no indication of groundwater flow in Hollander’s study areas, however, so that differences between water column and intergravel dissolved oxygen concentrations probably represent intergravel dissolved oxygen depletion. Mean dissolved oxygen concentrations in redds averaged 2.1, 2.8, and 3.7 mg/liter less than the surface water in the three portions of the study. Considerable variation of intergravel dissolved oxygen concentration was observed between redds and within a single redd. Variation from one year to another suggested that dissolved oxygen concentrations will show greater intergravel depletion during years of low water flow.

Until more data are available, the dissolved oxygen concentration in the intergravel environment should be considered to be at least 3 mg/l lower than the oxygen concentration in the overlying water. The 3 mg/l differential is assumed in the criteria, since it reasonably represents the only two available studies based on observations in natural redds (Koski, 1965; Hollander, 1981). When siltation loads are high, such as in logged or agricultural watersheds, lower water velocity within the gravel could additionally reduce dissolved oxygen concentrations around the eggs. If either greater or lesser differentials are known or expected, the criteria should be altered accordingly.

F. Behavior

Ability of chinook and coho salmon to detect and avoid abrupt differences in dissolved oxygen concentrations was demonstrated by Whitmore et al. (1960). In laboratory troughs, both species showed strong preference for oxygen levels of 9 mg/l or higher over those near 1.5 mg/l; moderate selection against 3.0 mg/l was common and selection against 4.5 and 6.0 mg/l was sometimes detected.

The response of young Atlantic salmon and brown trout to low dissolved oxygen depended on their age; larvae were apparently unable to detect and avoid water of low dissolved oxygen concentration, but fry 6-16 weeks of age showed a marked avoidance of concentrations up to 4 mg/l (Bishai, 1962). Older fry (26 weeks of age) showed avoidance of concentrations up to 3 mg/l.

In a recent study of the rainbow trout sport fishery of Lake Taneycomo, Missouri, Weithman and Haas (1984) have reported that reductions in minimum daily dissolved oxygen concentrations below 6 mg/l are related to a decrease in the harvest rate of rainbow trout from the lake. Their data suggest that lowering the daily minimum from 6 mg/l to 5, 4, and 3 mg/l reduces the harvest rate by 20, 40, and 60 percent, respectively. The authors hypothesized that the reduced catch was a result of reduction in feeding activity. This mechanism of action is consistent with Thatcher’s (1974) observation of lower activity of coho salmon at 5 mg/l in laboratory growth studies and the finding of Warren et al. (1973) that growth impairment produced by low dissolved oxygen appears to be primarily a function of lower food intake.

A three-year study of a fishery on planted rainbow trout was published by Heimer (1984). This study found that the catch of planted trout increased during periods of low dissolved oxygen in American Falls reservoir, on the Snake River in Idaho. The author concluded that the fish avoided areas of low dissolved oxygen and high temperature and the increased catch rate was a result of the fish concentrating in areas of more suitable oxygen supply and temperature.

G. Swimming

Effects of dissolved oxygen concentrations on swimming have been demonstrated by Davis et al. (1963). In their studies, the maximum sustained swimming speeds (in the range of 30 to 45 cm/sec) of juvenile coho salmon were reduced by 8.4, 12.7, and 19.9 percent at dissolved oxygen concentrations of 6, 5, and 4 mg/l, respectively. Over a temperature range from 10 to 20°C, effects were slightly more severe at cooler temperatures. Jones (1971) reported 30 and 43 percent reductions of maximal swimming speed of rainbow trout at dissolved oxygen concentrations of 5.1 (14°C) and 3.8 (22°C) mg/l, respectively. At lower swimming speeds (2 to 4 cm/sec), coho and chinook salmon at 20°C were generally able to swim for 24 hours at dissolved oxygen concentrations of 3 mg/l and above (Katz et al., 1958). Thus, the significance of lower dissolved oxygen concentrations on swimming depends on the level of swimming performance required for the survival, growth, and reproduction of salmonids. Failure to escape from predation or to negotiate a swift portion of a spawning migration route may be considered an indirect lethal effect and, in this regard, reductions of maximum swimming performance can be very important. With these exceptions, moderate levels of swimming activity required by salmonids are apparently little affected by concentrations of dissolved oxygen that are otherwise acceptable for growth and reproduction.

H. Field Studies

Field studies of salmonid populations are almost non-existent with respect to effects of dissolved oxygen concentrations. Some of the systems studied by Ellis (1937) contained trout, but of those river systems in which trout or other salmonids were most likely (Columbia River and Upper Missouri River) no stations were reported with dissolved oxygen concentrations below 5 mg/l, and 90 percent of the values exceeded 7 mg/l.

III. Non-Salmonids

The amount of data describing effects of low dissolved oxygen on nonsalmonid fish is more limited than that for salmonids, yet must cover a group of fish with much greater taxonomic and physiological variability. Salmonid criteria must provide for the protection and propagation of 38 species in 7 closely related genera; the non-salmonid criteria must provide for the protection and propagation of some 600 freshwater species in over 40 diverse taxonomic families. Consequently, the need for subjective technical judgment is greater for the non-salmonids.

Many of the recent, most pertinent data have been obtained for several species of Centrarchidae (sunfish), northern pike, channel catfish, and the fathead minnow. These data demonstrate that the larval stage is generally the most sensitive life stage. Lethal effects on larvae have been observed at dissolved oxygen concentrations that may only slightly affect growth of juveniles of the same species.

A. Physiology

Several studies of the relationship between low dissolved oxygen concentrations and resting oxygen consumption rate constitute the bulk of the physiological data relating to the effect of hypoxia on nonsalmonid fish. A reduction in the resting metabolic rate of fish is generally believed to represent a marked decrease in the scope for growth and activity, a net decrease in the supply of oxygen to the tissues, and perhaps a partial shift to anaerobic energy sources. The dissolved oxygen concentration at which reduction in resting metabolic rate first appears is termed the critical oxygen concentration.

Studies with brown bullhead (Grigg, 1969), largemouth bass (Cech et al., 1979), and goldfish and carp (Beamish, 1964), produced estimates of critical dissolved oxygen concentrations for these species. For largemouth bass, the critical dissolved oxygen concentrations were 2.8 mg/l at 30°C, <2.6 mg/l at 25°C, and <2.3 mg/l at 20°C. For brown bullheads the critical concentration was about 4 mg/l. Carp displayed critical oxygen concentrations near 3.4 and 2.9 mg/l at 10 and 20°C, respectively, and goldfish critical concentrations of dissolved oxygen were about 1.8 and 3.5 mg/l at 10 and 20°C, respectively. A general summary of these data suggest critical dissolved oxygen concentrations between 2 and 4 mg/l, with higher temperatures usually causing higher critical concentrations.

Critical evaluation of the data of Beamish (1964) suggest that the first sign of hypoxic stress is not the decrease in oxygen consumption, but rather an increase, perhaps as a result of metabolic cost of passing an increased ventilation volume over the gills. These increases were seen in carp at 5.8 mg/l at 20°C and at 4.2 mg/l at 10°C.

B. Acute Lethal Concentrations

Based on the sparse data base describing acute effects of low dissolved oxygen concentrations on non-salmonids, many non-salmonids appear to be considerably less sensitive than salmonids. Except for larval forms, no non-salmonids appear to be more sensitive than salmonids. Spoor (1977) observed lethality of largemouth bass larvae at a dissolved oxygen concentration of 2.5 mg/1 after only a 3-hr exposure. Generally, adults and juveniles of all species studied survive for at least a few hours at concentrations of dissolved oxygen as low as 3 mg/l. In most cases, no mortality results from acute exposures to 3 mg/l for the 24- to 96-h duration of the acute tests. Some non-salmonid fish appear to be able to survive a several-day exposure to concentrations below 1 mg/l (Moss and Scott, 1961; Downing and Merkens, 1957), but so little is known about the latent effects of such exposure that short-term survival cannot now be used as an indication of acceptable dissolved oxygen concentrations. In addition to the unknown latent effects of exposure to very low dissolved oxygen concentrations, there are no data on the effects of repeated short-term exposures. Most importantly, data on the tolerance to low dissolved oxygen concentrations are available for only a few of the numerous species of non-salmonid fish.

C. Growth

Stewart et al. (1967) conducted several growth studies with juvenile largemouth bass and observed reduced growth at 5.9 mg/l and lower concentrations. Five of six experiments included dissolved oxygen concentrations between 5 and 6 mg/l; dissolved oxygen concentrations of 5.1 and 5.4 mg/l produced reductions in growth rate of 20 and 14 percent, respectively, but concentrations of 5.8 and 5.9 mg/l had essentially no effect on growth. The efficiency of food conversion was not reduced until dissolved oxygen concentrations were much lower, indicating that decreased food consumption was the primary cause of reduced growth.

When channel catfish fingerlings held at 8, 5, and 3 mg/l were fed as much as they could eat in three daily feedings, there were significant reductions in feeding and weight gain (22 percent) after a 6 week exposure to 5 mg/l (Andrews et al., 1973). At a lower feeding rate, growth after 14 weeks was reduced only at 3 mg/l. Fish exposed to 3 mg/l swam lethargically, fed poorly and had reduced response to loud noises. Raible (1975) exposed channel catfish to several dissolved oxygen concentrations for up to 177 days and observed a graded reduction in growth at each concentration below 6 mg/l. However, the growth pattern for 6.8 mg/l was comparable to that at 5.4 mg/l. He concluded that each mg/l increase in dissolved oxygen concentrations between 3 and 6 mg/l increased growth by 10 to 13 percent.

Carlson et al. (1980) studied the effect of dissolved oxygen concentration on the growth of juvenile channel catfish and yellow perch. Over periods of about 10 weeks, weight gain of channel catfish was lower than that of control fish by 14, 39, and 54 percent at dissolved oxygen concentrations of 5.0, 3.4, and 2.1 mg/l, respectively. These differences were produced by decreases in growth rate of 5, 18, and 23 percent (JRB Associates, 1984), pointing out the importance of differentiating between effects on weight gain and effects on growth rate. When of sufficient duration, small reductions in growth rate can have large effects on relative weight gain. Conversely, large effects on growth rate may have little effect on annual weight gain if they occur only over a small proportion of the annual growth period. Yellow perch appeared to be more tolerant to low dissolved oxygen concentrations, with reductions in weight gain of 2, 4, and 30 percent at dissolved oxygen concentrations of 4.9, 3.5, and 2.1 mg/l, respectively.

The data of Stewart et al. (1967), Carlson et al. (1980), and Adelman and Smith (1972) were analyzed to determine the relationship between growth rate and dissolved oxygen concentration (JRB Associates, 1984). Yellow perch appeared to be very resistant to influences of low dissolved oxygen concentrations, northern pike may be about as sensitive as salmonids, while largemouth bass and channel catfish are intermediate in their response (Table 4). The growth rate relations modeled from Adelman and Smith are based on only four data points, with none in the critical dissolved oxygen region from 3 to 5 mg/l. Nevertheless, these growth data for northern pike are the best available for nonsalmonid coldwater fish. Adelman and Smith observed about a 65 percent reduction in growth of juvenile northern pike after 6-7 weeks at dissolved oxygen concentrations of 1.7 and 2.6 mg/l. At the next higher concentration (5.4 mg/l), growth was reduced 5 percent.

Table 4. **Percent reduction in growth rate of some nonsalmonid fish held at various dissolved oxygen concentrations expressed as the median value from n tests with each species (calculated from JRB Associates, 1984).**

Dissolved Oxygen (mg/l)	Species (number of tests)			
	Northern Pike (1)	Largemouth Bass (6)	Channel Catfish (1)	Yellow Perch (1)
9	0	0	0	0
8	1	0	0	0
7	4	0	1	0
6	9	0	3	0
5	16	1	7	0
4	25	9	13	0
3	35	17	20	7
2	--	51	29	22
Median Temp (°C)	19	26	25	20

Brake (1972) conducted a series of studies on juvenile largemouth bass in two artificial ponds to determine the effect of reduced dissolved oxygen concentration on consumption of mosquitofish and growth during 10 2-week exposures. The dissolved oxygen in the control pond was maintained near air-saturation (8.3 to 10.4 mg/l) and the other pond contained mean dissolved oxygen concentrations from 4.0 to 6.0 mg/l depending upon the individual test. The temperature, held near the same level in both ponds for each test, ranged from 13 to 27°C. Food consumption and growth rates of the juvenile bass, maintained on moderate densities of forage fish, increased with temperature and decreased at the reduced dissolved oxygen concentrations except at 13°C. Exposure to that temperature probably slowed metabolic processes of the bass so much that their total metabolic rates were not limited by dissolved oxygen except at very low concentrations. These largemouth bass studies clearly support the idea that higher temperatures exacerbate the adverse effects of low dissolved oxygen on the growth rate of fish (Table 5). Comparisons of Brake's pond studies with the laboratory growth studies of Stewart et al. (1967) suggest that laboratory growth studies may significantly underestimate the adverse effect of low dissolved oxygen on fish growth. Stewart's six studies with largemouth bass are summarized in Table 4 and Brake's data are presented in Table 5. All of Stewart's tests were conducted at 26°C, about the highest temperature in Brake's studies, but comparison of the data show convincingly that at dissolved oxygen concentrations between 4 and 6 mg/l the growth rate of bass in ponds was reduced 17 to 34 percent rather than the 1 to 9 percent seen in the laboratory studies. These results suggest that the ease of food capture in laboratory studies may result in underestimating effects of low dissolved oxygen on growth rates in nature.

Table 5. Effect of temperature on the percent reduction in growth rate of largemouth bass exposed to various dissolved oxygen concentrations in ponds (after Brake, 1972; JRB Associates, 1984).

Temperature (°C)	Percent Reduction in Growth Rate at		
	4.2 ± 0.2 mg/l	4.9 ± 0.2 mg/l	5.8 ± 0.2 mg/l
13.3	0	--	--
13.6	--	--	7
16.3	--	18	--
16.7	--	--	15
18.1	--	19	--
18.6	--	34	--
18.7	18	--	--
23.3	26	--	--
26.7	--	--	17
27.4	31	--	--

Brett and Blackburn (1981) reanalyzed the growth data previously published by other authors for largemouth bass, carp, and coho salmon in addition to their own results for young coho and sockeye salmon. They concluded for all species that above a critical level ranging from 4.0 to 4.5 mg/l, decreases in growth rate and food conversion efficiency were not statistically significant in these tests of relatively short duration (6 to 8 weeks) under the pristine conditions of laboratory testing. EPA believes that a more accurate estimate of the dissolved oxygen concentrations that have no effect on growth and a better estimate of concentration:effect relationships can be obtained by curve-fitting procedures (JCB Associates, 1984) and by examining these results from a large number of studies. Brett and Blackburn added an additional qualifying statement that it was not the purpose of their study to seek evidence on the acceptable level of dissolved oxygen in nature because of the problems of environmental complexity involving all life stages and functions, the necessary levels of activity to survive in a competitive world, and the interaction of water quality (or lack of it) with varying dissolved concentrations. Their cautious concern regarding the extrapolation to the real world of results obtained under laboratory conditions is consistent that of numerous investigators.

D. Reproduction

A life-cycle exposure of the fathead minnow beginning with 1- to 2-month old juveniles was conducted and effects of continuous low dissolved oxygen concentrations on various life stages indicated that the most sensitive stage was the larval stage (Brungs, 1971). No spawning occurred at 1 mg/l, and the number of eggs produced per female was reduced at 2 mg/l but not at higher concentrations. Where spawning occurred, the percentage hatch of embryos (81-89 percent) was not affected when the embryos were exposed to the same concentrations as their parents. Hatching time varied with temperature, which was not controlled, but with decreasing dissolved oxygen concentration the average incubation time increased gradually from the normal 5 to nearly 8 days. Mean larval survival was 6 percent at 3 mg/l and 25 percent at 4 mg/l. Mean survival of larvae at 5 mg/l was 66 percent as compared to 50 percent at control dissolved oxygen concentrations. However, mean growth of surviving larvae at 5 mg/l was about 20 percent lower than control larval growth. Siefert and Herman (1977) exposed mature black crappies to constant dissolved oxygen concentrations from 2.5 mg/l to saturation and temperatures of 13-20°C.Number of spawnings, embryo viability, hatching success, and survival through swim-up were similar at all exposures.

E. Early Life Stages

Larval and juvenile non-salmonids are frequently more sensitive to exposures to low dissolved oxygen than are other life stages. Peterka and Kent (1976) conducted semi-controlled experiments at natural spawning sites of northern pike, bluegill, pumpkinseed, and smallmouth bass in Minnesota. Dissolved oxygen concentrations were measured 1 and 10 cm from the bottom, with observations being made on hatching success and survival of embryos, sac larvae, and, in some instances, larvae. Controlled exposure for up to 8 hours was performed in situ in small chambers with the dissolved oxygen controlled by nitrogen stripping. For all species tested, tolerance to short-term exposure to low concentrations decreased from embryonic to larval stages. Eight-hour exposure of embryos and larvae of northern pike to dissolved oxygen concentrations caused no mortality of embryos at 0.6 mg/l but was 100 percent lethal to sac-larvae and larvae. The most sensitive stage, the larval stage, suffered complete mortality following 8 hours at 1.6 mg/l; the next higher concentration, 4 mg/l, produced no mortality. Smallmouth bass were at least as sensitive, with nearly complete mortality of sac-larvae resulting from 6-hour exposure to 2.2 mg/l, but no mortality occurred after exposure to 4.2 mg/l. Early life stages of bluegill were more hardy, with embryos tolerating 4-hour exposure to 0.5 mg/l, a concentration lethal to sac-larvae; sac-larvae survived similar exposure to 1.8 mg/l, however. Because the most sensitive stage of northern pike was the later larval stage, and because the younger sac-larval stages of smallmouth bass and bluegill were the oldest stages tested, the tests with these latter species may not have included the most sensitive stage. Based on these tests, 4 mg/l is tolerated, at least briefly, by northern pike and may be tolerated by smallmouth bass, but concentrations as high as 2.2 mg/l are lethal.

Several studies have provided evidence of mortality or other significant damage to young non-salmonids as a result of a few weeks exposure to dissolved oxygen concentrations in the 3 to 6 mg/l range. Siefert et al. (1973) exposed larval northern pike to various dissolved oxygen concentrations at 15 and 19°C and observed reduced survival at concentrations as high as 2.9 and 3.4 mg/l. Most of the mortality at these concentrations occurred at the time the larvae initiated feeding. Apparently the added stress of activity at that time or a greater oxygen requirement for that life stage was the determining factor. There was a marked decrease in growth at concentrations below 3 mg/l. In a similar study lasting 20 days, survival of walleye embryos and larvae was reduced at 3.4 mg/l (Siefert and Spoor, 1974), and none survived at lower concentrations. A 20 percent reduction in the survival of smallmouth bass embryos and larvae occurred at a concentration of 4.4 mg/l (Siefert et al., 1974) and at 2.5 mg/l all larvae died in the first 5 days after hatching. At 4.4 mg/l hatching occurred earlier than in the controls and growth among survivors was reduced. Carlson and Siefert (1974) concluded that concentrations from 1.7 to 6.3 mg/l reduced the growth of early stages of the large-mouth bass by 10 to 20 percent. At concentrations as high as 4.5 mg/l, hatching was premature and feeding was delayed; both factors could indirectly influence survival, especially if other stresses were to occur simultaneously. Carlson et al. (1974) also observed that embryos and larvae of channel catfish are sensitive to low dissolved oxygen during 2- or 3-week exposures. Survival at 25°C was slightly reduced at 5 mg/l and significantly reduced at 4.2 mg/l. At 28°C survival was slightly reduced at, 3.8, 4.6, and 5.4 mg/l; total mortality occurred at 2.3 mg/l. At all reduced dissolved oxygen concentrations at both temperatures, embryo pigmentation was lighter, incubation period was extended, feeding was delayed, and growth was reduced. No effect of dissolved oxygen concentrations as iow as 2.5 mg/l was seen on survival of embryonic and larval black crappie (Siefert and Herman, 1977). Other tolerant species are the white bass and the white sucker, both of which evidenced adverse effect to embryo larval exposure only at dissolved oxygen concentrations of 1.8 and 1.2 mg/l, respectively (Siefert et al., 1974; Siefert and Spoor, 1974).

Data (Figure 1) on the effects of dissolved oxygen on the survival of embryonic and larval nonsalmonid fish show some species to be tolerant (largemouth bass, white sucker, black crappie, and white bass) and others nontolerant (channel catfish, walleye, northern pike, smallmouth bass). The latter three species are often included with salmonids in a grouping of sensitive coldwater fish; these data tend to support that placement.

F. Behavior

Largemouth bass in laboratory studies (Whitmore et al., 1960) showed a slight tendency to avoid concentrations of dissolved oxygen of 3.0 and 4.6 mg/l and a definite avoidance of 1.5 mg/l. Bluegills avoided a concentration of 1.5 mg/l but not higher concentrations. The environmental significance of such a response is unknown, but if large areas are deficient in dissolved oxygen this avoidance would probably not greatly enhance survival. Spoor (1977) exposed largemouth bass embryos and larvae to low dissolved oxygen for brief exposures of a few hours. At 23 to 24°C and 4 to 5 mg/l, the normally quiescent, bottom-dwelling yolk-sac larvae became very active and swam vertically to a few inches above the substrate. Such behavior in natural systems would probably cause significant losses due to predation and simple displacement from the nesting area.

G. Swimming

Effects of low dissolved oxygen on the swimming performance of largemouth bass were studied by Katz et al. (1959) and Dahlberg et al. (1968). The results in the former study were highly dependent upon season and temperature, with summer tests at 25°C finding no effect on continuous swimming for 24 hrs at 0.8 ft/sec unless dissolved oxygen concentrations fell below 2 mg/l. In the fall, at 20°C, no fish were able to swim for a day at 2.8 mg/l, and in the winter and 16° no fish swam for 24 hours at 5 mg/l. These results are consistent with those seen in salmonids in that swimming performance appears to be more sensitive to low dissolved oxygen at lower temperatures.

Dahlberg et al. (1968) looked at the effect of dissolved oxygen on maximum swimming speed at temperatures near 25°C. They reported slight effects (less than 10% reduction in maximum swimming speed) at concentrations between 3 and 4.5 mg/l, moderate reduction (16-20%) between 2 and 3 mg/l and severe reduction (30-50%) at 1 to 1.5 mg/l.

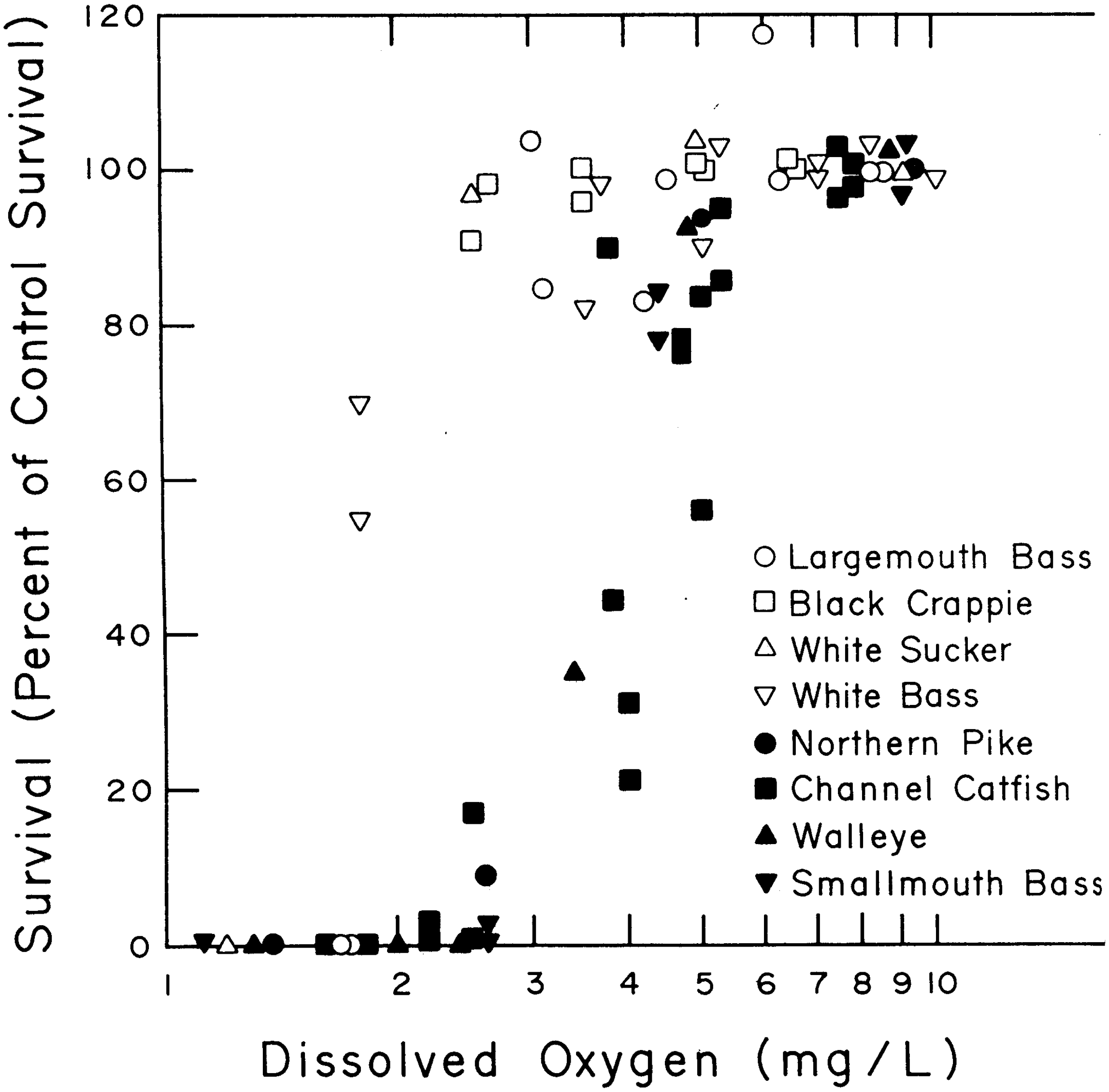

Figure 1. Effect of continuous exposure to various mean dissolved oxygen concentrations on survival of embryonic and larval stages of eight species of nonsalmonid fish. Minima recorded in these tests averaged about 0.3 mg/l below the mean concentrations.

H. Field Studies

Ellis (1937) reported results of field studies conducted at 982 stations on freshwater streams and rivers during the months of June through September, 1930-1935. During this time, numerous determinations of dissolved oxygen concentrations were made. He concluded that 5 mg/l appeared to be the lowest concentration which may reasonably be expected to maintain varied warmwater fish species in good condition in inland streams. Ellis (1944) restated his earlier conclusion and also added that his study had included the measurement of dissolved oxygen concentrations at night and various seasons. He did not specify the frequency or proportion of diurnal or seasonal sampling, but the mean number of samples over the 5-year study was about seven samples per station.

Brinley (1944) discussed a 2-year biological survey of the Ohio River Basin. He concluded that in the zone where dissolved oxygen is between 3 and 5 mg/l the fish are more abundant than at lower concentrations, but show a tendency to sickness, deformity, and parasitization. The field results show that the concentration of 5 mg/l seems to represent a general dividing line between good and bad conditions for fish.

A three-year study of fish populations in the Wisconsin River indicated that sport fish (percids and centrarchids) constituted a significantly greater proportion of the fish population at sites having mean summer dissolved oxygen concentrations greater than 5 mg/l than at sites averaging below 5 mg/l (Coble, 1982). The differences could not be related to any observed habitat variables other than dissolved oxygen concentration.

These three field studies all indicate that increases in dissolved oxygen concentrations above 5 mg/l do not produce noteworthy improvements in the composition, abundance, or condition of non-salmonid fish populations, but that sites with dissolved oxygen concentrations below 5 mg/l have fish assemblages with increasingly poorer population characteristics as the dissolved oxygen concentrations become lower. It cannot be stressed too strongly that these field studies lack definition with respect to the actual exposure conditions experienced by the resident populations and the lack of good estimates for mean and minimum exposure concentrations over various periods precludes the establishment of numerical criteria based on these studies. The results of these semi-quantitative field studies are consistent with the criteria derived later in this document.

IV. Invertebrates

As stated earlier, there is a general paucity of information on the tolerance of the many forms of freshwater invertebrates to low dissolved oxygen. Most available data describe the relationship between oxygen concentration and oxygen consumption or short-term survival of aquatic larvae of insects. These data are further restricted by their emphasis on species representative of relatively fast-flowing mountain streams.

One rather startling feature of these data is the apparently high dissolved oxygen requirement for the survival of some species. Before extrapolating from these data one should be cautious in evaluating the respiratory mode(s) of the species, its natural environment, and the test environment. Thus, many nongilled species respire over their entire body surface while many other species are gilled. Either form is dependent upon the gradient of oxygen across the respiratory surface, a gradient at least partially dependent upon the rate of replacement of the water immediately surrounding the organism. Some insects, such as some members of the mayfly genus, Baetis, are found on rocks in extremely swift currents; testing their tolerance to low dissolved oxygen in laboratory apparatus at slower flow rats may contribute to their inability to survive at high dissolved oxygen concentrations. In addition, species of insects that utilize gaseous oxygen, either from bubbles or surface atmosphere, may not be reasonably tested for tolerance of hypoxia if their source of gaseous oxygen is deprived in the laboratory tests.

In spite of these potential problems, the dissolved oxygen requirements for the survival of many species of aquatic insects are almost certainly greater than those of most fish species. Early indication of the high dissolved oxygen requirements of some aquatic insects appeared in the research of Fox et al. (1937) who reported critical dissolved oxygen concentrations for mayfly nymphs in a static test system. Critical concentrations for six species ranged from 2.2 mg/l to 17 mg/l; three of the species had critical concentrations in excess of air saturation. These data suggest possible extreme sensitivity of some species and also the probability of unrealistic conditions of water flow. More recent studies in water flowing at 10 cm/sec indicate critical dissolved oxygen concentrations for four species of stonefly are between 7.3 and 4.8 mg/l (Benedetto, 1970).

In a recent study of 22 species of aquatic insects, Jacob et al. (1984) reported 2-5 hour LC50 values at unspecified “low to moderate” flows in a stirred exposure chamber, but apparently with no flow of replacement water. Tests were run at one or more of five temperatures from 12 to 30°C; some species were tested at only one temperature, others at as many as four. The median of the 22 species mean LC50s was about 3 mg/l, with eight species having an average LC50 below 1 mg/l and four in excess of 7 mg/l. The four most sensitive species were two mayfly species and two caddisfly species. The studies of Fox et al. (1937), Benedetto (1970), and Jacob et al. (1984) were all conducted with European species, but probably have general relevance to North American habitats. A similar oxygen consumption study of a North American stonefly (Kapoor and Griffiths, 1975) indicated a possible critical dissolved oxygen concentration of about 7 mg/l at a flow rate of 0.32 cm/sec and a temperature of 20°C.

One type of behavioral observation provides evidence of hypoxic stress in aquatic insects. As dissolved oxygen concentrations decrease, many species of aquatic insects can be seen to increase their respiratory movements, movements that provide for increased water flow over the respiratory surfaces. Fox and Sidney (1953) reported caddisfly respiratory movements over a range of dissolved oxygen from 9 to 1 mg/l. A dissolved oxygen decrease to 5 mg/l doubled the number of movements and at 1 to 2 mg/l the increase was 3- to 4-fold.

Similar data were published by Knight and Gaufin (1963) who studied a stonefly common in the western United States. Significant increases occurred below 5 mg/l at 16°C and below 2 mg/l at 10°C. Increases in movements occurred at higher dissolved oxygen concentrations when water flow was 1.5 cm/sec than 7.6 cm/sec, again indicating the importance of water flow rate on the respiration of aquatic insects. A subsequent paper by Knight and Gaufin (1965) indicated that species of stonefly lacking gills are more sensitive to low dissolved oxygen than are gilled forms.

Two studies that provide the preponderance of the current data on the acute effects of low dissolved oxygen concentrations on aquatic insects are those of Gaufin (1973) and Nebeker (1972) which together provide reasonable 96-hr LC50 dissolved oxygen concentrations for 26 species of aquatic insects (Table 6). The two studies contain variables that make them difficult to compare or evaluate fully. Test temperatures were 6.4°C in Gaufin's study and 18.5°C in Nebeker's. Gaufin used a vacuum degasser while Nebeker used a 30-foot stripping column that probably produced an unknown degree of supersaturation with nitrogen. The water velocity is not given in either paper, although flow rates are given but test chamber dimensions are not clearly specified. The overall similarity of the test results suggests that potential supersaturation and lower flow volume in Nebeker's tests did not have a significant effect on the results.

Because half of the insect species tested had 96-h LC5O dissolved oxygen concentrations between 3 and 4 mg/l it appears that these species (collected in Montana and Minnesota) would require at least 4 mg/l dissolved oxygen to ensure their survival. The two most sensitive species represent surprisingly diverse habitats, Ephemerella doddsi is found in swift rocky streams and has an LC5O of 5.2 mg/l while the pond mayfly, Callibaetis montanus, has an LC5O of 4.4 mg/l. It is possible that the test conditions represented too slow a flow for E. doddsi and too stressful flow conditions for C. montanus.

Other freshwater invertebrates have been subjected to acute hypoxic stress and their LC5O values determined. Gaufin (1973) reported a 96-h LC5O the amphipod Gammarus limnaeus of < 3 mg/l. Four other crustaceans were studied by Sprague (1963) who reported the following 24-h LC5Os: 0.03 mg/l, Asellus intermedius 0.7 mg/l, Hyalella azteca 2.2 mg/l, Gammarus pseudo-rnnaeus; and 4.3 mg/l, Gammarus fasciatus. The range of acute sensitivities of these species appears similar to that reported for aquatic insects.

There are few long-term studies of freshwater invertebrate tolerance to low dissolved oxygen concentrations. Both Gaufin (1973) and Nebeker (1972) conducted long-term survival studies with insects, but both are questioned because of starvation and potential nitrogen supersaturation, respectively. Gaufin's data for eight Montana species and 17 Utah species suggest that 4.9 mg/l and 3.3 mg/l, respectively, would provide for 50 percent survival for between 4.4 and 5.0 mg/l and one < 0.5 mg/l. Overall, these data indicate that prolonged exposure to dissolved oxygen concentrations below 5 mg/l would have detrimental effects on a large proportion of the aquatic insects common in areas like Minnesota, Montana, and Utah. Information from other habitat types and geographic locations would provide a broader picture of invertebrate dissolved oxygen requirements.

A more classic toxicological protocol was used by Homer and Waller (1983) in a study of the effects of low dissolved oxygen on Daphna magna. In a 26-d chronic exposure test, they reported that 1.8 mg/l significantly reduced fecundity and 2.7 mg/l caused a 17 percent reduction in final weight of adults. No effect was seen at 3.7 mg/l.

Table 6. Acutely lethal concentrations of dissolved oxygen to aquatic insects.

Species	96-h LC50 (mg/L)	Source*
Stonefly		
Acroneuria pacifica	1.6 (H)**	G
Acroneuria lycorias	3.6	N
Acrynopteryx aurea	3.3 (H)	G
Acrynopteryx parallela	< 2 (H)	G
Diura knowltoni	3.6 (L)	G
Nemoura cinctipes	3.3 (H)	G
Pteronarcys californica	3.9 (L)	G
Pteronarcys californica	3.2 (H)	G
Pteronarcys dorsata	2.2	N
Pteronarcella badia	2.4 (H)	G
Mayfly		
Baetisca laurentina	3.5	N
Callibaetis montanus	4.4 (L)	G
Ephemerella doddsi	5.2 (L)	G
Ephemerella grandis	3.0 (H)	G
Ephemerella subvaria	3.9	N
Hexagenia limbata	1.8 (H)	G
Hexagenia limbata	1.4	N
Leptophlebia nebulosa	2.2	N
Caddisfly		
Brachycentrus occidentalis	< 2 (L)	G
Drusinus sp.	1.8 (H)	G
Hydropsyche sp.	3.6 (L)	G
Hydropsyche betteri	2.9 (21°C)	N
Hydropsyche betteri	2.6 (18.5°C)	N
Hydropsyche betteri	2.3 (17°C)	N
Hydropsyche betteri	1.0 (10°C)	N
Lepidostoma sp.	< 3 (H)	G
Limnophilus ornatus	3.4 (L)	G
Neophylax sp.	3.8 (L)	G
Neothremma alicia	1.7 (L)	G
Diptera		
Simulium vittatum	3.2 (L)	G
Tanytarsus dissimilis	< 0.6	N

* G = Gaufin (1973) – all tests at 6.4°C.
N = Nebeker (1972) – all tests at 18.5°C except as noted/flow 125 ml/min.

** H = high flow (1000 ml/min); L = low flow (500 ml/min).

In summarizing the state of knowledge regarding the relative sensitivity of fish and invertebrates to low dissolved oxygen, it seems that some species of insects and other crustaceans are killed at concentrations survived by all species of fish tested. Thus, while most fish will survive exposure to 3 mg/l, many species of invertebrates are killed by concentrations as high as 4 mg/l. The extreme sensitivity of a few species of aquatic insects may be an artifact of the testing environment. Those sensitive species common to swift flowing, coldwater streams may require very high concentrations of dissolved oxygen. On the other hand, those stream habitats are probably among the least likely to suffer significant dissolved oxygen depletion.

Long-term impacts of hypoxia are less well known for invertebrates than for fish. Concentrations adequate to avoid impairment of fish production probably will provide reasonable protection for invertebrates as long as lethal concentrations are avoided.

V. Other Considerations

A. Effects of Fluctuations

Natural dissolved oxygen concentrations fluctuate on a seasonal and daily basis, while in most laboratory studies the oxygen levels are held essentially constant. In two studies on the effects of daily oxygen cycles the authors concluded that growth of fish fed unrestricted rations was markedly less than would be estimated from the daily mean dissolved oxygen concentrations (Fisher, 1963; Whitworth, 1968). The growth of these fish was only slightly above that attainable during constant exposure to the minimum concentrations of the daily cycles. A diurnal dissolved oxygen pulse to 3 mg/l for 8 hours per day for 9 days, with a concentration of 8.3 mg/l for the remainder of the time, produced a significant stress pattern in the serum protein fractions of red bluegill and largemouth bass but not yellow bullhead (Bouck and Bail, 1965). During periods of low dissolved oxygen the fish lost their natural color, increased their ventilation rate, and remained very quiet. At these times food was ignored. Several times, during the low dissolved oxygen concentration part of the cycle, the fish vomited food which they had eaten as much as 12 hours earlier. After comparable exposure of the rock bass, Bouck (1972) observed similar results on electrophoretic patterns and feeding behavior.

Stewart et al. (1967) exposed juvenile largemouth bass to patterns of diurnally-variable dissolved oxygen concentrations with daily minima near 2 mg/l and daily maxima from 4 to 17 mg/l. Growth under any fluctuation pattern was almost always less than the growth that presumably would have occurred had the fish been held at a constant concentration equal to the mean concentration.

Carlson et al. (1980) conducted constant and diurnally fluctuating exposures with juvenile channel catfish and yellow perch. At mean constant concentrations of 3.5 mg/l or less, channel catfish consumed less food and growth was significantly reduced. Growth of this species was not reduced at fluctuations from about 6.2 to 3.6 and 4.9 to 2 mg/l, but was significantly impaired at a fluctuation from about 3.1 to 1 mg/l. Similarly, at mean constant concentrations near 3.5 mg/l, yellow perch consumed less food but growth was not impaired until concentrations were near 2 mg/l. Growth was not affected by fluctuations from about 3.8 to 1.4 mg/l. No dissolved oxygen related mortalities were observed. In both the channel catfish and the yellow perch experiments, growth rates during the tests with fluctuating dissolved oxygen were considerably below the rate attained in the constant exposure tests. As a result, the fluctuating and constant exposures could not be compared. Growth would presumably have been more sensitive in the fluctuating tests if there had been higher rates of control growth.

Mature black crappies were exposed to constant and fluctuating dissolved oxygen concentrations (Carlson and Herman, 1978). Constant concentrations were near 2.5, 4, 5.5, and 7 mg/l and fluctuating concentrations ranged from 0.8 to 1.9 mg/l above and below these original concentrations. Successful spawning occurred at all exposures except the fluctuation between 1.8 and 4.1 mg/l.

In considering daily or longer-term cyclic exposures to low dissolved oxygen concentrations, the minimum values may be more important than the mean levels. The importance of the daily minimum as a determinant of growth rate is common to the results of Fisher (1963), Stewart (1967), and Whitworth (1968). Since annual low dissolved oxygen concentrations normally occur during warmer months, the significance of reduced growth rates during the period in question must be considered. If growth rates are normally low, then the effects of low dissolved oxygen concentration on growth could be minimal; if normal growth rates are high, the effects could be significant, especially if the majority of the annual growth occurs during the period in question.

B. Temperature and Chemical Stress

When fish were exposed to lethal temperatures, their survival times were reduced when the dissolved oxygen concentration was lowered from 7.4 to 3.8 (Alabaster and Welcomme, 1962). Since high temperature and low dissolved oxygen commonly occur together in natural environments, this likelihood of additive or synergistic effects of these two potential stresses is a most important consideration.

High temperatures almost certainly increase the adverse effects of low dissolved oxygen concentrations. However, the spotty, irregular acute lethality data base provides little basis for quantitative, predictive analysis. Probably the most complete study is that on rainbow trout, perch, and roach conducted by Downing and Merkens (1957). Because their study was spread over an 18-month period, seasonal effects could have influenced the effects at the various test temperatures. Over a range from approximately 10 to 20°C, the lethal dissolved oxygen concentrations increased by an average factor of about 2.6, ranging from 1.4 to 4.1 depending on fish species tested and test duration. The influence of temperature on chronic effects of low dissolved oxygen concentrations are not well known, but requirements for dissolved oxygen probably increase to some degree with increasing temperature. This generalization is supported by analysis of salmon studies reported by Warren et al. (1973) and the largemouth bass studies of Brake (1972).

Because most laboratory tests are conducted at temperatures near the mid-range of a species temperature tolerance, criteria based on these test data will tend to be under-protective at higher temperatures and over-protective at lower temperatures. Concern for this temperature effect was a consideration in establishing these criteria, especially in the establishing of those criteria intended to prevent short-term lethal effects.

A detailed discussion and model for evaluating interactions among temperature, dissolved oxygen, ammonia, fish size, and ration on the resulting growth of individual fish (Cuenco et al., 1985a,b,c) provides an excellent, in-depth evaluation of potential effects of dissolved oxygen on fish growth.

Several laboratory studies evaluated the effect of reduced dissolved oxygen concentrations on the toxicity of various chemicals, some of which occur commonly in oxygen-demanding wastes. Lloyd (1961) observed that the toxicity of zinc, lead, copper, and monohydric phenols was increased at dissolved oxygen concentrations as high as approximately 6.2 mg/l as compared to 9.1 mg/l. At 3.8 mg/l, the toxic effect of these chemicals was even greater. The toxicity of ammonia was enhanced by low dissolved oxygen more than that of other toxicants. Lloyd theorized that the increases in toxicity of the chemicals were due to increased ventilation at low dissolved oxygen concentrations; as a consequence of increased ventilation, more water, and therefore more toxicant, passes the fish's gills. Downing and Merkens (1955) reported that survival times of rainbow trout at lethal ammonia concentrations increased markedly over a range of dissolved oxygen concentrations from 1.5 to 8.5 mg/l. Ninety-six-hr LC5O values for rainbow trout indicate that ammonia became more toxic with decreasing dissolved oxygen concentrations from 8.6 to 2.6 mg/l (Thurston et al., 1981). The maximum increase in toxicity was by about a factor of 2. They also compared ammonia LC5O values at reduced dissolved oxygen concentrations after 12, 24, 48, and 72 hrs. The shorter the time period, the more pronounced the positive relationship between the LC5O and dissolved oxygen concentration. The authors recommended that dissolved oxygen standards for the protection of salmonids should reflect background concentrations of ammonia which may be present and the likelihood of temporary increases in those concentrations. Adelman and Smith (1972) observed that decreasing dissolved oxygen concentrations increased the toxicity of hydrogen sulfide to goldfish. When the goldfish were acclimated to the reduced dissolved oxygen concentration before the exposure to hydrogen sulfide began, mean 96-hr LC5O values were 0.062 and 0.048 mg/l at dissolved oxygen concentrations of 6 and 1.5 mg/l, respectively. When there was no prior acclimation, the LC5O values were 0.071 and 0.053 mg/l at the same dissolved oxygen concentrations. These results demonstrated a less than doubling in toxicity of hydrogen sulfide and little difference with regard to prior acclimation to reduced dissolved oxygen concentrations. Cairns and Scheier (1957) observed that bluegills were less tolerant to zinc, naphthenic acid, and potassium cyanide at periodic low dissolved oxygen concentrations. Pickering (1968) reported that an increased mortality of bluegills exposed to zinc resulted from the added stress of low dissolved oxygen concentrations. The difference in mean LC5O values between low (1.8 mg/l) and high (5.6 mg/l) dissolved oxygen concentrations was a factor of 1.5.

Interactions between other stresses and low dissolved oxygen concentrations can greatly increase mortality of trout larvae. For example, sublethal concentrations of pentachlorophenol and oxygen combined to produce 100 percent mortality of trout larvae held at an oxygen concentration of 3 mg/l (Chapman and Shumway, 1978). The survival of chinook salmon embryos and larvae reared at marginally high temperatures was reduced by any reduction in dissolved oxygen, especially at concentrations below 7 mg/l (Eddy, 1972).

In general, the occurrence of toxicants in the water mass, in combination with low dissolved oxygen concentration, may lead to a potentiation of stress responses on the part of aquatic organisms (Davis, 1975a,b). Doudoroff and Shumway (1970) recommended that the disposal of toxic pollutants must be controlled so that their concentrations would not be unduly harmful at prescribed, acceptable concentrations of dissolved oxygen, and these acceptable dissolved oxygen concentrations should be independent of existing or highest permitted concentrations of toxic wastes.

C. Disease Stress

In a study of 5 years of case records at fish farms, Meyer (1970) observed that incidence of infection with Aeromonas liquefasciens (a common bacterial pathogen of fish) was most prevalent during June, July, and August. He considered low oxygen stress to be a major factor in outbreaks of Aeromonas disease during summer months. Haley et al. (1967) concluded that a kill of American and threadfin shad in the San Joaquin River occurred as a result of Aeromonas infection the day after the dissolved oxygen was between 1.2 and 2.6 mg/l. In this kill the lethal agent was Aeromonas but the additional stress of the low dissolved oxygen may have been a significant factor.

Wedemeyer (1974) reviewed the role of stress as a predisposing factor in fish diseases and concluded that facultative fish pathogens are continuously present in most waters. Disease problems seldom occur, however, unless environmental quality and the host defense systems of the fish also deteriorate. He listed furunculosis, Aeromonad and Pseudomonad hemorrhagic septicemia, and vibriosis as diseases for which low dissolved oxygen is one environmental factor predisposing fish to epizootics. He stated that to optimize fish health, dissolved oxygen concentrations should be 6.9 mg/l or higher. Snieszko (1974) also stated that outbreaks of diseases are probably more likely if the occurrence of stress coincides with the presence of pathogenic microorganisms.

VI. Conclusions

The primary determinant for the criteria is laboratory data describing effect on growth, with developmental rate and survival included in embryo and larval production levels. For the purpose of deriving criteria, growth in the laboratory and production in nature are considered equally sensitive to low dissolved oxygen. Fish production in natural communities actually may be significantly more, or less, sensitive than growth in the laboratory, which represents only one simplified facet of production.

The dissolved oxygen criteria are based primarily on data developed in laboratory under conditions which are usually artificial in several important respects. First, they routinely preclude or minimize most environmental stresses and biological interactions that under natural conditions are likely to increase, to a variable and unknown extent, the effect of low dissolved oxygen concentrations. Second, organisms are usually given no opportunity to acclimate to low dissolved oxygen concentrations prior to tests nor can they avoid the test exposure. Third, food availability is unnatural because the fish have easy, often unlimited, access to food without significant energy expenditure for search and capture. Fourth, dissolved oxygen concentrations are kept nearly constant so that each exposure represents both minimum and an average concentration. This circumstance complicates application of the data to natural systems with fluctuating dissolved oxygen concentrations.

Considering the latter problem only, if the laboratory data are applied directly as minimum allowable criteria, the criteria will presumably be higher than necessary because the mean dissolved oxygen concentration will often be significantly higher than the criteria. If applied as a mean, the criteria could allow complete anoxia and total mortality during brief periods of very low dissolved oxygen or could allow too many consecutive daily minima near the lethal threshold. If only a minimum or a mean can be given as a general criterion, the minimum must be chosen because averages are too independent of the extremes.

Obviously, biological effects of low dissolved oxygen concentrations depend upon means, minima, the duration and frequency of the minima, and the period of averaging. In many respects, the effects appear to be independent of the maxima; for example, including supersaturated dissolved oxygen values the average may produce mean dissolved oxygen concentrations that are leadingly high and unrepresentative of the true biological stress of the dissolved oxygen minima.

Because most experimental exposures have been constant, data on the effect of exposure to fluctuating dissolved oxygen concentrations is sketchy. The few fluctuating exposure studies have used regular, repeating daily cycles of an on-off nature with 8 to 16 hours at low dissolved oxygen and the remainder of the 24 hr period at intermediate or high dissolved oxygen. This is an uncharacteristic exposure pattern, since most daily dissolved oxygen cycles are of a sinusoidal curve shape and not a square-wave variety.

The existing data allow a tentative theoretical dosing model for fluctuating dissolved oxygen only as applied to fish growth. The EPA believes that the data of Stewart et al. (1967) suggest that effects on growth are reasonably represented by calculating the mean of the daily cycle using as a maximum value the dissolved oxygen concentration which represents the threshold effect concentration during continuous exposure tests. For example, with an effect threshold of 6 mg/l, all values in excess of 6 mg/l should be averaged as though they were 6 mg/l. Using this procedure, the growth effects appear to be a reasonable function of the mean, as long as the minimum is not lethal. Lethal thresholds are highly dependent upon exposure duration, species, age, life stage, temperature, and a wide variety of other factors. Generally the threshold is between 1 and 3 mg/l.

A most critical and poorly documented aspect of a dissolved oxygen criterion is the question of acceptable and unacceptable minima during dissolved oxygen cycles of varying periodicity. Current ability to predict effects of exposure to a constant dissolved oxygen level is only fair; the effects of regular, daily dissolved oxygen cycles can only be poorly estimated; and predicting the effects of more stochastic patterns of dissolved oxygen fluctuations requires an ability to integrate constant and cycling effects.

Several general conclusions result from the synthesis of available field and laboratory data. Some of these conclusions differ from earlier ones in the literature, but the recent data discussed in this document have provided additional detail and perspective.

° Naturally-occurring dissolved oxygen concentrations may occasionally fail below target criteria levels due to a combination of low flow, high temperature, and natural oxygen demand. These naturally-occurring conditions represent a normal situation in which the productivity of fish or other aquatic organisms may not be the maximum possible under ideal circumstances, but which represent the maximum productivity under the particular set of natural conditions. Under these circumstances the numerical criteria should be considered unattainable, but naturally-occurring conditions which fail to meet criteria should not be interpreted as violations of criteria. Although further reductions in dissolved oxygen may be inadvisable, effects of any reductions should be compared to natural ambient conditions and not to ideal conditions.

° Situations during which attainment of appropriate criteria is most critical include periods when attainment of high fish growth rates is a priority, when temperatures approach upper-lethal levels, when pollutants are present in near-toxic quantities, or when other significant stresses are suspected.

° Reductions in growth rate produced by a given low dissolved oxygen concentration are probably more severe as temperature increases. Even during periods when growth rates are normally low, high temperature stress increases the sensitivity of aquatic organisms to disease and toxic pollutants, making the attainment of proper dissolved oxygen criteria particularly important. For these reasons, periods of highest temperature represent a critical portion of the year with respect to dissolved oxygen requirements.

° In salmonid spawning habitats, intergravel dissolved oxygen concentrations are significantly reduced by respiration of fish embryos and other organisms. Higher water column concentrations of dissolved oxygen are required to provide protection of fish embryos and larvae which develop in the intergravel environment. A 3 mg/l difference is used in the criteria to account for this factor.

° The early life stages, especially the larval stage, of non-salmonid fish are usually most sensitive to reduced dissolved oxygen stress. Delayed development, reduced larval survival, and reduced larval and post-larval growth are the observed effects. A separate early life stage criterion for non-salmonids is established to protect these more sensitive stages and is to apply from spawning through 30 days after hatching.

° Other life stages of salmonids appear to be somewhat more sensitive than other life stages of the non-salmonids, but this difference, resulting in a 1.0 mg/l difference in the criteria for other life stages, may be due to a more complete and precise data base for salmonids. Also, this difference is at least partially due to the colder water temperatures at which salmonid tests are conducted and the resultant higher dissolved oxygen concentration in oxygen-saturated control water.

° Few appropriate data are available on the effects of reduced dissolved oxygen on freshwater invertebrates. However, historical concensus states that, if all life stages of fish are protected, the invertebrate communities, although not necessarily unchanged, should be adequately protected. This is a generalization to which there may be exceptions of environmental significance. Acutely lethal concentrations of dissolved oxygen appear to be higher for many aquatic insects than for fish.

° Any dissolved oxygen criteria should include absolute minima to prevent mortality due to the direct effects of hypoxia, but such minima alone may not be sufficient protection for the long-term persistence of sensitive populations under natural conditions. Therefore, the criteria minimum must also provide reasonable assurance that regularly repeated or prolonged exposure for days or weeks at the allowable minimum will avoid significant physiological stress of sensitive organisms.

Several earlier dissolved oxygen criteria were presented in the form of a family of curves (Doudoroff and Shumway, 1970) or equations (NAS/NAE, 1973) which yielded various dissolved oxygen requirements depending on the qualitative degree of fishery protection or risk deemed suitable at a given site. Although dissolved oxygen concentrations that risk significant loss of fishery production are not consistent with the intent of water quality criteria, a qualitative protection/risk assessment for a range of dissolved oxygen concentrations has considerable value to resource managers. Using qualitative descriptions similar to those presented in earlier criteria of Doudoroff and Shumway (1970) and Water Quality Criteria 1972 (NAS/NAE, 1973), four levels of risk are listed below:

<u>No Production Impairment</u>. Representing nearly maximal protection of fishery resources.

<u>Slight Production Impairment</u>. Representing a high level of protection of important fishery resources, risking only slight impairment of production in most cases.

<u>Moderate Production Impairment</u>. Protecting the persistence of existing fish populations but causing considerable loss of production.

<u>Severe Production Impairment</u>. For low level protection of fisheries of some value but whose protection in comparison with other water uses cannot be a major objective of pollution control.

Selection of dissolved oxygen concentrations equivalent to each of these levels of effect requires some degree of judgment based largely upon examination of growth and survival data, generalization of response curve shape, and assumed applicability of laboratory responses to natural populations. Because nearly all data on the effects of low dissolved oxygen on aquatic organisms relate to continuous exposure for relatively short duration (hours to weeks), the resultant dissolved oxygen concentration-biological effect estimates are most applicable to essentially constant exposure levels, although they may adequately represent mean concentrations as well.

The production impairment values are necessarily subjective, and the definitions taken from Doudoroff and Shumway (1970) are more descriptive than the accompanying terms "slight, "moderate," and "severe." The impairment values for other life stages are derived predominantly from the growth data summarized in the text and tables in Sections II and III. In general, slight, moderate, and severe impairment are equivalent to 10, 20, and 40 percent growth impairment, respectively. Growth impairment of 50 percent or greater is often accompanied by mortality, and conditions allowing a combination of severe growth impairment and mortality are considered as no protection.

Production impairment levels for early life stages are quite subjective and should be viewed as convenient divisions of the range of dissolved oxygen concentrations between the acute mortality limit and the no production impairment concentrations.

Production impairment values for invertebrates are based on survival in both long-term and short-term studies. There are no studies of warmwater species and few of lacustrine species.

The following is a summary of the dissolved oxygen concentrations (mg/l) judged to be equivalent to the various qualitative levels of effect described earlier; the value cited as the acute mortality limit is the minimum dissolved oxygen concentration deemed not to risk direct mortality of sensitive organisms:

1. <u>Salmonid Waters</u>
    a. Embryo and Larval Stages
        ° No Production Impairment = 11* (8)
        ° Slight Production Impairment = 9* (6)
        ° Moderate Production Impairment = 8* (5)
        ° Severe Production Impairment = 7* (4)
        ° Limit to Avoid Acute Mortality = 6* (3)

    (* Note: These are water column concentrations recommended to achieve the required <u>intergravel</u> dissolved oxygen concentrations shown in parentheses. The 3 mg/l difference is discussed in the criteria document.)

    b. Other Life Stages
        ° No Production Impairment = 8
        ° Slight Production Impairment = 6
        ° Moderate Production Impairment = 5
        ° Severe Production Impairment = 4
        ° Limit to Avoid Acute Mortality = 3

2. Nonsalmonid Waters
    a. Early Life Stages
        - No Production Impairment = 6.5
        - Slight Production Impairment = 5.5
        - Moderate Production Impairment = 5
        - Severe Production Impairment = 4.5
        - Limit to Avoid Acute Mortality = 4

    b. Other Life Stages
        - No Production Impairment = 6
        - Slight Production Impairment = 5
        - Moderate Production Impairment = 4
        - Severe Production Impairment = 3.5
        - Limit to Avoid Acute Mortality = 3

3. Invertebrates
        - No Production Impairment = 8
        - Some Production Impairment = 5
        - Acute Mortality Limit = 4

Added Note

Just prior to final publication of this criteria document, a paper appeared (Sowden and Power, 1985) that provided an interesting field validation of the salmonid early life stage criterion and production impairment estimates. A total of 19 rainbow trout redds were observed for a number of parameters including percent survival of embryos, dissolved oxygen concentration, and calculated intergravel water velocity. The results cannot be considered a rigorous evaluation of the criteria because of the paucity of dissolved oxygen determinations per redd (2-5) and possible inaccuracies in determining percent survival and velocity. Nevertheless, the qualitative validation is striking.

The generalization drawn from Coble's (1961) study that good survival occurred when mean intergravel dissolved oxygen concentrations exceeded 6.0 mg/l and velocity exceeded 20 cm/hr was confirmed; 3 of the 19 redds met this criterion and averaged 29 percent embryo survival. The survival in the other 16 redds averaged only 3.6 percent. The data from the study are summarized in Table 7. The critical intergravel water velocity from this study appears to be about 15 cm/hr. Below this velocity even apparently good dissolved oxygen characteristics do not produce reasonable survival. At water velocities in excess of 15 cm/hr the average percent survival in the redds that haye dissolved oxygen concentrations that met the criteria was 29.0 percent. There was no survival in redds that had dissolved oxygen minima below the acute mortality limit. Percent survival in redds with greater than 15 cm/hr flow averaged 15.6, 6.5, and 0.9 percent for redds meeting slight, moderate, and severe production impairment levels, respectively.

Table 7. Survival of rainbow trout embryos as a function of intergravel dissolved oxygen concentration and water velocity (Sowden and Power, 1985) as compared to dissolved oxygen concentrations established as criteria or estimated as producing various levels of production impairment.

Criteria Estimates	Dissolved Oxygen Concentration mg/L		Percent Survival	Water Velocity, cm/hr	Mean Survival (Flow > 15 cm/hr)
	Mean	Minimum			
Exceeded Criteria	8.9	8.0	22.1	53.7	
	7.7	7.0	43.5	83.2	29.0
	7.0	6.4	1.1	9.8	
	6.9	5.4	21.3	20.6	
Slight Production Impairment	7.4	4.1	0.5	7.2	
	7.1	4.3	21.5	16.3	
	6.7	4.5	4.3	5.4	15.6
	6.4	4.2	0.3	7.9	
	6.0	4.2	9.6	17.4	
Moderate Production Impairment	5.8	3.1	13.4	21.6	
	5.3	3.6	5.6	16.8	6.5
	5.2	3.9	0.4	71.0	
Severe Production Impairment	4.6	4.1	0.9	18.3	0.9
	4.2	3.3	0.0	0.4	
Acute Mortality	3.9	2.9	0.0	111.4	
	3.6	2.1	0.0	2.6	
	2.7	1.2	0.0	4.2	0.0
	2.4	0.8	0.0	1.1	
	2.0	0.8	0.0	192.0	

Based on an average redd of 1000 eggs, these mean percent survivals would be equivalent to 290, 156, 65, 9, and 0 viable larvae entering the environment to produce food for other fish, catch for fishermen, and eventually a new generation of spawners to replace the parents of the embryos in the redd. Whether or not these survival numbers ultimately represent the impairment definitions is moot in the light of further survival and growth uncertainties, but the quantitative field results and the qualitative and quantitative impairment and criteria values are surprisingly similar.

VII. National Criterion

The national criteria for ambient dissolved oxygen concentrations for the protection of freshwater aquatic life are presented in Table 8. The criteria are derived from the production impairment estimates on the preceding page which are in turn based primarily upon growth data and information on temperature, disease, and pollutant stresses. The average dissolved oxygen concentrations selected are values 0.5 mg/l above the slight production impairment values and represent values between no production impairment and slight production impairment. Each criterion may thus be viewed as an estimate of the threshold concentration below which detrimental effects are expected.

Criteria for coldwater fish are intended to apply to waters containing a population of one or more species in the family Salmonidae (Bailey et al., 1970) or to waters containing other coldwater or coolwater fish deemed by the user to be closer to salmonids in sensitivity than to most warmwater species. Although the acute lethal limit for salmonids is at or below 3 mg/l, the coldwater minimum has been established at 4 mg/l because a significant proportion of the insect species common to salmonid habitats are less tolerant of acute exposures to low dissolved oxygen than are salmonids. Some coolwater species may require more protection than that afforded by the other life stage criteria for warmwater fish and it may be desirable to protect sensitive coolwater species with the coldwater criteria. Many states have more stringent dissolved oxygen standards for cooler waters, waters that contain either salmonids, nonsalmonid coolwater fish, or the sensitive centrarchid, the smallmouth bass. The warmwater criteria are necessary to protect early life stages of warmwater fish as sensitive as channel catfish and to protect other life stages of fish as sensitive as largemouth bass. Criteria for early life stages are intended to apply only where and when these stages occur. These criteria represent dissolved oxygen concentrations which EPA believes provide a reasonable and adequate degree of protection for freshwater aquatic life.

The criteria do not represent assured no-effect levels. However, because the criteria represent worst-case conditions (i.e., for wasteload allocation and waste treatment plan design), conditions will be better than the criteria nearly all the time at most sites. In situations where criteria conditions are just maintained for considerable periods, the criteria represent some risk of production impairment. This impairment would probably be slight, but would depend on innumerable other factors. If slight production impairment or a small but undefinable risk of moderate production impairment is unacceptable, then continuous exposure conditions should use the no production impairment values as means and the slight production impairment values as minima.

Table 8. Water quality criteria for ambient dissolved oxygen concentration.

	Coldwater Criteria		**Warmwater Criteria**	
	Early Life Stages[1,2]	Other Life Stages	Early Life Stages[2]	Other Life Stages
30 Day Mean	NA[3]	6.5	NA	5.5
7 Day Mean	9.5 (6.5)	NA	6.0	NA
7 Day Mean Minimum	**NA**	5.0	NA	4.0
1 Day Minimum[4,5]	8.0 (5.0)	4.0	5.0	3.0

[1] These are water column concentrations recommended to achieve the required <u>intergravel</u> dissolved oxygen concentrations shown in parentheses. The 3 mg/l differential is discussed in the criteria document. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.

[2] Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

[3] NA (not applicable).

[4] For highly manipulatable discharges, further restrictions apply (see page 37)

[5] All minima should be considered as instantaneous concentrations to be achieved at all times.

The criteria represent annual worst-case dissolved oxygen concentrations believed to protect the more sensitive populations of organisms against potentially damaging production impairment. The dissolved oxygen concentrations in the criteria are intended to be protective at typically high seasonal environmental temperatures for the appropriate taxonomic and life stage classifications, temperatures which are often higher than those used in the research from which the criteria were generated, especially for other than early life stages.

Where natural conditions alone create dissolved oxygen concentrations less than 110 percent of the applicable criteria means or minima or both, the minimum acceptable concentration is 90 percent of the natural concentration. These values are similar to those presented graphically by Doudoroff and Shumway (1970) and those calculated from Water Quality Criteria 1972 (NAS/NAE, 1973). Absolutely no anthropogenic dissolved oxygen depression in the potentially lethal area below the 1-day minima should be allowed unless special care is taken to ascertain the tolerance of resident species to low dissolved oxygen.

If daily cycles of dissolved oxygen are essentially sinusoidal, a reasonable daily average is calculated from the day’s high and low dissolved oxygen values. A time-weighted average may be required if the dissolved oxygen cycles are decidedly non-sinusoidal. Determining the magnitude of daily dissolved oxygen cycles requires at least two appropriately timed measurements daily, and characterizing the shape of the cycle requires several more appropriately spaced measurements.

Once a series of daily mean dissolved oxygen concentrations are calculated, an average of these daily means can be calculated (Table 9). For embryonic, larval, and early life stages, the averaging period should not exceed 7 days. This short time is needed to adequately protect these often short duration, most sensitive life stages. Other life stages can probably be adequately protected by 30-day averages. Regardless of the averaging period, the average should be considered a moving average rather than a calendar-week or calendar-month average.

The criteria have been established on the basis that the maximum dissolved oxygen value actually used in calculating any daily mean should not exceed the air saturation value. This consideration is based primarily on analysis of studies of cycling dissolved oxygen and the growth of largemouth bass (Stewart et al., 1967), which indicated that high dissolved oxygen levels (> 6 mg/l) had no beneficial effect on growth.

During periodic cycles of dissolved oxygen concentrations, minima lower than acceptable constant exposure levels are tolerable so long as:

1. the average concentration attained meets or exceeds the criterion;

2. the average dissolved oxygen concentration is calculated as recommended in Table 9; and

3. the minima are not unduly stressful and clearly are not lethal.

Table 9 Sample calculations for determining daily means and 7-day mean dissolved oxygen concentrations (30-day averages are calculated in a similar fashion using 30 days data).

Day	**Dissolved Oxygen (mg/l)**		
	Daily Max.	Daily Min.	Daily Mean
1	9.0	7.0	8.0
2	10.0	7.0	8.5
3	11.0	8.0	9.5
4	12.0[a]	8.0	9.5[b]
5	10.0	8.0	9.0
6	11.0	9.0	10.0
7	12.0[a]	10.0	10.5[c]
Σ		57.0	65.0
1-day Minimum		7.0	
7-day Mean Minimum		8.1	
7-day Mean			9.3

[a] Above air saturation concentration (assumed to be 11.0 mg/l for this example).
[b] (11.0 + 8.0) ÷ 2.
[c] (11.0 +10.0) ÷ 2.

A daily minimum has been included to make certain that no acute mortality of sensitive species occurs as a result of lack of oxygen. Because repeated exposure to dissolved oxygen concentrations at or near the acute lethal threshold will be stressful and because stress can indirectly produce mortality or other adverse effects (e.g., through disease), the criteria are designed to prevent significant episodes of continuous or regularly recurring exposures to dissolved oxygen concentrations at or near the lethal threshold. This protection has been achieved by setting the daily minimum for early life stages at the subacute lethality threshold, by the use of a 7-day averaging period for early life stages, by stipulating a 7-day mean minimum value for other life stages, and by recommending additional limits for manipulatable discharges.

The previous EPA criterion for dissolved oxygen published in <u>Quality Criteria for Water</u> (USEPA, 1976) was a minimum of 5 mg/l (usually applied as a 7Q10) which is similar to the current criterion minimum except for other life stages of warmwater fish which now allows a 7-day mean minimum of 4 mg/l. The new criteria are similar to those contained in the 1968 “Green Book” of the Federal Water Pollution Control Federation (FWPCA, 1968).

A. <u>The Criteria and Monitoring and Design Conditions</u>

The acceptable mean concentrations should be attained most of the time, but some deviation below these values would probably not cause significant harm. Deviations below the mean will probably be serially correlated and hence apt to occur on consecutive days. The significance of deviations below the mean will depend on whether they occur continuously or in daily cycles, the former being more adverse than the latter. Current knowledge regarding such deviations is limited primarily to laboratory growth experiments and by extrapolation to other activity-related phenomena.

Under conditions where large daily cycles of dissolved oxygen occur, it is possible to meet the criteria mean values and consistently violate the mean minimum criteria. Under these conditions the mean minimum criteria will clearly be the limiting regulation unless alternatives such as nutrient control can dampen the daily cycles.

The significance of conditions which fail to meet the recommended dissolved oxygen criteria depend largely upon five factors: (1) the duration of the event; (2) the magnitude of the dissolved oxygen depression; (3) the frequency of recurrence; (4) the proportional area of the site falling to meet the criteria; and (5) the biological significance of the site where the event occurs. Evaluation of an event's significance must be largely case- and site-specific. Common sense would dictate that the magnitude of the depression would be the single most important factor in general, especially if the acute value is violated. A logical extension of these considerations is that the event must be considered in the context of the level of resolution of the monitoring or modeling effort. Evaluating the extent, duration, and magnitude of an event must be a function of the spatial and temporal frequency of the data. Thus, a single deviation below the criterion takes on considerably less significance where continuous monitoring occurs than where sampling is comprised of once-a-week grab samples. This is so because based on continuous monitoring the event Is provably small, but with the much less frequent sampling the event is not provably small and can be considerably worse than indicated by the sample.

The frequency of recurrence is of considerable interest to those modeling dissolved oxygen concentrations because the return period, or period between recurrences, is a primary modeling consideration contingent upon probabilities of receiving water volumes, waste loads, temperatures, etc. It should be apparent that return period cannot be isolated from the other four factors discussed above. Ultimately, the question of return period may be decided on a site-specific basis taking into account the other factors (duration, magnitude, areal extent, and biological significance) mentioned above. Future studies of temporal patterns of dissolved oxygen concentrations, both within and between years, must be conducted to provide a better basis for selection of the appropriate return period.

In conducting waste load allocation and treatment plant design computations, the choice of temperature in the models will be important. Probably the best option would be to use temperatures consistent with those expected in the receiving water over the critical dissolved oxygen period for the biota.

B. The Criteria and Manipulatable Discharges

If daily minimum dissolved oxygen concentrations are perfectly serially correlated, i.e., if the annual lowest daily minimum dissolved oxygen concentration is adjacent in time to the next lower daily minimum dissolved oxygen concentration and one of these two minima is adjacent to the third lowest daily minimum dissolved oxygen concentration, etc., then in order to meet the 7-day mean minimum criterion it is unlikely that there will be more than three or four consecutive daily minimum values below the acceptable 7-day mean minimum. Unless the dissolved oxygen pattern is extremely erratic, it is also unlikely that the lowest dissolved oxygen concentration will be appreciably below the acceptable 7-day mean minimum or that daily minimum values below the 7-day mean minimum will occur in more than one or two weeks each year. For some discharges, the distribution of dissolved oxygen concentrations can be manipulated to varying degrees. Applying the daily minimum to manipulatable discharges would allow repeated weekly cycles of minimum acutely acceptable dissolved oxygen values, a condition of probable stress and possible adverse biological effect. If risk of protection impairment is to be minimized, the application of the one day minimum criterion to manipulatable discharges should either limit the frequency of occurrence of values below the acceptable 7-day mean minimum or impose further limits on the extent of excursions below the 7-day mean minimum. For such controlled discharges, it is recommended that the occurrence of daily minima below the acceptable 7-day mean minimum be limited to 3 weeks per year or that the acceptable one-day minimum be increased to 4.5 mg/l for codwater fish and 3.5 mg/l for warmwater fish. Such decisions could be site-specific based upon the extent of control, serial correlation, and the resource at risk.

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Water Quality Criteria 1972

A Report of the Committee on Water Quality Criteria

"BlueBook"

Environmental Studies Board
National Academy of Sciences National Academy of Engineering

Washington, D.C., 1972

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DISSOLVED OXYGEN

Oxygen requirements of aquatic life have been extensively studied. Comprehensive papers have been presented by Doudoroff and Shumway (l967),[89] Doudoroff and Warren (1965),[91] Ellis (l937),[93] and Fry (l960).[94] (Much of the research on temperature requirements also considers oxygen, and references cited in the discussion of Heat and Temperature, p. 151, are relevant here.) The most comprehensive review yet to appear has been written by Doudoroff and Shumway for the Food and Agriculture Organization (FAO) of the United Nations (l970).[90] This FAO report provides the most advanced summary of scientific research on oxygen needs of fish, and it has served as a basis for most of the recommendations presented in this discussion. In particular, it provided the criteria for citing different levels of protection for fish, for change from natural levels of oxygen concentration, and for the actual numerical values recommended. Much of the text below has been quoted verbatim or condensed from the FAO report. Its recommendations have been modified in only two ways: the insertion of a floor of 4 mg/L as a minimum, and the suggestion that natural minima be assumed to be equal to saturation levels if the occurrence of lower minima cannot be definitely established. Doudoroff and Shumway covered oxygen concentrations below the floor of 4 mg/L; however, the 4 mg/L floor has been adopted in this report for reasons explained below.

Levels of Protection

Most species of adult fish can survive at very low concentrations of dissolved oxygen. Even brook trout *(Salvelinus fontinalis)* have been acclimated in the laboratory to less than 2 mg/L of O_2. In natural waters, the minimum concentration that allows continued existence of a varied fish fauna, including valuable food and game species, is not high. This minimum is not above 4 mg/L and may be much lower.

However, in evaluating criteria, it is not important to know how long an animal can resist death by asphyxiation at low dissolved oxygen concentrations. Instead, data on the oxygen requirements for egg development, for newly hatched larvae, for normal growth and activity, and for completing all stages of the reproductive cycle are pertinent. Upon review of the available research, one fact becomes clear: *any* reduction of dissolved oxygen can reduce the efficiency of oxygen uptake by aquatic animals and hence reduce their ability to meet demands of their environment. There is evidently no concentration level or percentage of saturation to which the O_2 content of natural waters can be reduced without causing or risking some adverse effects on the reproduction, growth, and consequently, the production of fishes inhabiting those waters.

Accordingly, no single, arbitrary recommendation can be set for dissolved oxygen concentrations that will be favorable for all kinds of fish in all kinds of waters, or even one kind of fish in a single kind of water. Any reduction in oxygen may be harmful by affecting fish production and the potential yield of a fishery.

The selection of a level of protection (Table III-3) is a socioeconomic decision, not a biological one. Once the level of protection is selected, appropriate scientific recommendations may be derived from the criteria presented in this discussion.

Table III-3
Guidelines for Selecting Desired Type and Level of Protection of Fish Against Deleterious Effects of Reduced Oxygen Concentrations

Level of Protection	**Intended type of protection**	**Possible application**
Nearly Maximum[a]	For virtually unimpaired productivity and unchanged quality of a fishery	Appropriate for conservation areas, parks, and water bodies of high or unique value. Requires, practically speaking, that little or no deoxygenating wastes be added to natural waters. Nor must there be any activities such as unfavorable land use which would reduce O_2 levels.
High	Not likely to cause appreciable change in the ecosystem, nor material reduction of fish production. Some impairment is risked, but appreciable damage is not to be expected at these levels of oxygen.	Could be appropriate for fisheries or aquatic ecosystems of some importance, which should not be impaired by other uses of water.
Moderate	Fisheries should persist, usually with no serious impairment, but with some decrease in production.	Could be used for fisheries which are valued, but must co-exist with major industries or dense human population.
Low	Should permit the persistence of sizeable populations of tolerant species and successful passage of most migrants.[b] Much reduced production or elimination of sensitive fish is likely.	Appropriate for fisheries that have some commercial or recreational value, but are so unimportant compared with other water uses, that their maintenance cannot be a major objective of pollution control. This type of protection should, however, provide for survival of sensitive species in adult or subadult life stages for short periods during the year, if oxygen levels at other times are satisfactory for growth, reproduction, etc.

a. Note that there could be a higher level of protection that would require oxygen to be near natural level at all times, whereas nearly maximum requires only that oxygen should not fall below the lowest level characteristic of the season.

b. But will not protect migrating salmonids, which would require at least a Moderate level of protection, for zones of passage.

Basis for Recommendations

The decision to base the recommendations on O_2 concentration minima, and not on average concentrations, arises from various considerations. Deleterious effects on fish seem to depend more on extremes than on averages. For example, the growth of young fish is slowed markedly if the oxygen concentration falls to 3 mg/L for part of the day, even if it rises as high as 18 mg/L at other times. It could be an inaccurate and possibly controversial task to carry out the sets of measurements required to decide whether a criterion based on averages was being met.

A daily fluctuation of O_2 is to be expected where there is appreciable photosynthetic activity of aquatic plants. In such cases, the minimum O_2 concentration will usually be found just before daybreak, and sampling should be done at that time. Sampling should also take into account the possible differences in depth or width of the water body. The guiding principle should be to sample the places where aquatic organisms actually live or the parts of the habitat where they should be able to live.

Before recommendations are proposed, it is necessary to evaluate criteria for the natural, seasonal O_2 minimum from which the recommendations can be derived. Natural levels are assumed to be the saturation levels, unless scientific data show that the natural levels were already low in the absence of man-made effects.

Certain waters in regions of low human populations can still be adequately studied in their natural or pristine condition. In these cases the minimum O_2 concentration at different seasons, temperatures, and stream discharge volumes can be determined by direct observation. Such observed conditions can also be useful in estimating seasonal minima in similar waters in similar geographical regions where natural levels can no longer be observed because of waste discharges or other man-made changes.

In many populated regions, some or all of the streams and lakes have been altered. Direct determination of natural minima may no longer be possible. In these cases the assumption of year-round saturation with O_2 is made in the absence of other evidence.

Supersaturation of water with dissolved oxygen may occur as the result of photosynthesis by aquatic vegetation. There is some evidence that this may be deleterious to aquatic animals because of gas bubble disease (see Total Dissolved Gases, p. 135).

Despite the statements in previous paragraphs that there is no single O_2 concentration which is *favorable* to all species and ecosystems, it is obvious that there are, nevertheless, very low O_2 concentrations that are *unfavorable* to almost all aquatic organisms. Therefore, a floor of 4 mg/L is recommended except in situations where the natural level of dissolved oxygen is less than 4 mg/L in which case no further depression is desirable. The value of 4 mg/L has been selected because there is evidence of subacute or chronic damage to several fish below this concentration. Doudoroff and Shumway (l970)[90] review the work of several authors as given below, illustrating such damage. Fathead minnows *(Pimephales promelas)* held at 4 mg/L spawned satisfactorily; only 25 per cent of the resultant fry survived for 30 days, compared to 66 per cent survival at 5 mg/L. At an oxygen level of 3 mg/L, survival of fry was even further reduced to 5 per cent (Brungs 1972[101] *personal communication*). Shumway, *et al.* (1964)[98] found that the dry weight of coho salmon *(Oncorhynchus kisutch)* alevins (with yolk sac removed) was reduced by 59 per cent when they had been held at 3.8 mg/L of oxygen, compared to weights of the controls. The embryos of sturgeon *(Acipenser)* suffered complete mortality at oxygen concentrations of 3.0 to 3.5 mg/L, compared to only 18 per cent mortality at 5.0 to 5.5 mg/L (Yurovitskii l964).[100] Largemouth bass *(Micropterus salmoides)* embryos reared at 25 C showed survival equal to controls only at oxygen levels above 3.5 mg/L (Dudley l969).[92]

Efficiency of food conversion by juvenile bass was nearly independent of O_2 at 5 mg/L and higher, but growth rate was reduced by 16.5 per cent at 4 mg/L, and 30 per cent at 3 mg/L (Stewart, *et al.*, l967).[99] Similar reductions in growth of underyearling coho salmon occurred at the same O_2 concentrations (Herrmann, *et al.*, l962).[95] Although many other experiments have shown little or no damage to performance of fish at 4 mg/L, or lower, the evidence given above shows appreciable effects on embryonic and juvenile survival and growth for several species of fish sufficient to justify this value.

Warm- and Coldwater Fishes

There are many associations and types of fish fauna throughout the country. Dissolved oxygen criteria for coldwater fishes and warmwater game fishes are considered together in this report. There is no evidence to suggest that the more sensitive warmwater species have lower O_2 requirements than the more sensitive coldwater fishes. The difference in O_2 requirements is probably not greater than the difference of the solubility of O_2 in water at the maximum temperatures to which these two kinds of fish are normally exposed in summer (Doudoroff and Shumway, 1970).[90] In warmwater regions, however, the variety of fishes and fish habitats is relatively great, and there are many warmwater species that are exceedingly tolerant of O_2 deficiency.

Unusual Waters

There are certain types of waters that naturally have low oxygen content, such as the "black waters" draining swamps of the Southeastern United States. (Other examples include certain deep ocean waters and eutrophic waters that support heavy biomass, the respiration of which reduces O_2 content much of the time.) A special situation prevails in the deep layers (hypolimnion) of some lakes. Such layers do not mix with the surface layers for extended periods and may have reduced O_2, or almost none. Fish cannot live in the deep layers of many such lakes during a large part of the year, although each lake of this kind must be considered as a special case. However, the recommendation that *no* oxygen- consuming wastes should be released into the deep layers still applies, since there may be no opportunity for reaeration for an entire season.

Organisms Other Than Fish

Most research concerning oxygen requirements for freshwater organisms deals with fish; but since fish depend upon other aquatic species for food, it is necessary to consider the O_2 requirements of these organisms. This Section makes the assumption that the O_2 requirements of other components of the aquatic community are compatible with fish (Doudoroff and Shumway, 1970).[90] There are certain exceptions where exceedingly important invertebrate organisms may be very sensitive to low O_2, more sensitive than the fish species in that habitat (Doudoroff and Shumway, l970).[90]

The situation is somewhat more complicated for invertebrates and aquatic plants, inasmuch as organic pollution that causes reduction of O_2 also directly increases food material. However, it appears equally true for sensitive invertebrates as for fish that *any* reduction of dissolved O_2 may have deleterious effects on their production. For example, Nebeker (1972)[97] has found that although a certain mayfly *(Ephemera simulans)* can survive at 4.0 mg/L of oxygen for four days, any reduction of oxygen below saturation causes a decrease in successful transformation of the immature to the adult stage.

Salmonid Spawning

For spawning of salmonid fishes during the season when eggs are in the gravel, there are even greater requirements for O_2 than those given by the high level of protection. (See Table III-3 for description of levels.) This is because the water associated with the gravel may contain less oxygen than the water in the stream above the gravel. There is abundant evidence that salmonid eggs are adversely affected in direct proportion to reduction in O_2. The oxygen criteria for eggs should be about half way between the nearly maximum and high levels of protection.

Interaction with Toxic Pollutants or Other Environmental Factors

It is known that reduced oxygen levels increase the toxicity of pollutants. A method for predicting this interaction has been given by Brown (1968),[88]on and a theoretical background by Lloyd (l961).[96] The disposal of toxic pollutants must be controlled so that their concentrations will not be unduly harmful at prescribed acceptable levels of O_2, temperature, and pH. The levels of oxygen recommended in this Section are independent of the presence of toxic wastes, no matter what the nature of the interaction between these toxicants and O_2 deficiencies. Carbon dioxide is an exception, because its concentration influences the safe level of oxygen. The recommendations for O_2 are valid when the CO_2 concentration is within the limits recommended in the section on CO_2.

Application of Recommendations

As previously stated, the recommendations herein differ in two important respects from those widely used. First, they are not fixed values independent of natural conditions. Second, they offer a choice of different levels of protection of fishes, the selection of any one of which is primarily a socioeconomic decision, not a biological one.

Table III-4 presents guidelines for the protection of fishes at each of four levels. Each column shows the level to which the dissolved O_2 can be reduced and still provide the stated level of protection for local fisheries. The values can be derived from the equations given in the recommendations. These equations have been calculated to fit the curves shown in the figure on page 264 of Doudoroff and Shumway (l970),[90] which serve as the basis of the recommendations. To use Table III-4, the estimated natural seasonal minimum should first be determined on the basis of available data or from expert judgment. This may be taken to be the minimum saturation value for the season, unless there is scientific evidence that losses of O_2 levels prevailed naturally. The word “season” here means a period based on local climatic and hydrologic conditions, during which the natural thermal and dissolved O_2 regime of a stream or lake can be expected to be fairly uniform. Division of the year into equal three-month periods, such as December-February, March-May, is satisfactory. However, under special conditions, the designated seasons could be periods longer or shorter than three months, and could in fact be taken as individual months. The selected periods need not be equal in length.

When the lowest natural value for the season has been estimated, the desired kind and level of protection should then be selected according to the guidelines in Table III-3. The recommended minimum level of dissolved oxygen may then be found in the selected column of Table III-4, or as given by the formula in the recommendation.

Examples

- It is desired to give moderate protection to trout *(Salvelinus fontinalis)* in a small stream during the summer. The maximum summer temperature is 20 C (68 F); the salt content of the water is low and has negligible effect on the oxygen saturation value. The atmospheric pressure is 760 millimeters (mm) Hg. Oxygen saturation is therefore 9.2 mg/L. This is assumed to be the natural seasonal minimum in the absence of evidence of lower natural concentrations. Interpolating from Table III-4 or using the recommended formula, reveals a minimum permissible concentration of oxygen during the summer of 6.2 mg/L. If a high level of protection had been selected, the recommendation would have been 7.8 mg/L. A low level of protection, providing little or no protection for trout but some for more tolerant fish, would require a recommendation of 4.5 mg/L. Other recommendations would be calculated in a similar way for other seasons.

- It is decided to give moderate protection to large-mouth bass *(Micropterus salmoides)* during the summer. Stream temperature reaches a maximum of 35 C (95 F) during summer, and lowest seasonal saturation value is accordingly 7.1 mg/L. The recommendation for minimum oxygen concentration is 5.4 mg/L.

- For low protection of fish in summer in the same stream described above (for largemouth bass), the recommendation would be 4.0 mg/L, which is also the floor value recommended.

- It is desired to protect marine fish in full-strength sea water (35 parts per thousand salinity) with a maximum seasonal temperature of 16 C (61 F). The saturation value of 8 mg/L is assumed to be the natural dissolved oxygen minimum for the season. For a high level of protection, the recommendation is 7.1 mg/L, for a moderate level of protection it is 5.8 mg/L, and for a low level of protection it is 4.3 mg/L.

TABLE III-4
Example of Recommended Minimum Concentrations of Dissolved Oxygen

Estimated natural seasonal minimum concentration of oxygen in water	Corresponding temperature of oxygen-saturated fresh water	Recommended minimum concentration of O_2 for selected levels of protection			
		Nearly maximal	High	Moderate	Low
5	(a) (a)	5	4.7	4.2	4.0
6	46C(a) (115F)(a)	6	5.6	4.8	4.0
7	36C (96.8F)	7	6.4	5.3	4.0
8	27.5C (81.5F)	8	7.1	5.8	4.3
9	21C (69.8F)	9	7.7	6.2	4.5
10	16C (60.8F)	10	8.2	6.5	4.6
12	7.7C (34.7F)	12	8.9	6.8	4.8
14	1.5C (34.7F)	14	9.3	6.8	4.8

a. Included to cover waters that are naturally somewhat deficient in O_2. A saturation value of 5 mg/L might be found in warm springs or very saline waters. A saturation value of 6 mg/L would apply to warm sea water (32C = 90F).

Note: The desired kind and level of protection of a given body of water should first be selected (across head of table). The estimated seasonal minimum concentration of dissolved oxygen under natural conditions should then be determined on the basis of available data, and located ii the left hand column of the table. The recommended minimum concentration of oxygen for the season is then taken from the table. All values are in milligrams of O_2 per liter. Values for natural seasonal minima other than those listed are given by the formula and qualifications in the section on recommendations.

It should be stressed that the recommendations are the minimum values for any time during the same season.

Recommendations

(a) For nearly maximal protection of fish and other aquatic life, the minimum dissolved oxygen in any season (defined previously) should not be less than the estimated natural seasonal minimum concentration (defined previously) characteristic of that body of water for the same season. In estimating natural minima, it is assumed that waters are saturated, unless there is evidence that they were lower in the absence of man-made influences.

(b) For a high level of protection of fish, the minimum dissolved oxygen concentration in any season should not be less than that given by the following formula in which M = the estimated natural seasonal minimum concentration characteristic of that body of water for the same season, as qualified in (a):

$$\text{Criterion}^* = 1.41M - 0.0476M^2 - 1.11$$

(c) For a moderate level of protection of fish, the minimum dissolved oxygen concentration in any season should not be less than is given by the following formula with qualifications as in (b):

$$\text{Criterion}^* = 1.08M - 0.0415M^2 - 0.202$$

(d) For a low level of protection of fish, the minimum O_2 in any season should not be less than given by the following formula with qualifications as in (b):

$$\text{Criterion}^* = 0.674M - 0.0264M^2 + 0.577$$

(e) A floor value of 4 mg/L is recommended except in those situations where the natural level of dissolved oxygen is less than 4 mg/L, in which case no further depression is desirable.

(f) For spawning grounds of salmonid fishes, higher O_2 levels are required as given in the following formula with qualifications as in (b):

$$\text{Criterion}^* = 1.19M - 0.0242M^2 - 0.418$$

(g) In stratified eutrophic and dystrophic lakes, the dissolved oxygen requirements may not apply to the hypolimnion and such lakes should be considered on a case by case basis. In other stratified lakes, recommendations (a), (b), (c), and (d) apply; and If the oxygen is below 4 mg/L, recommendation (e) applies. In unstratified lakes recommendations apply to the entire circulating water mass.

(i) All the foregoing recommendations apply to all waters except waters designated as mixing zones (see section on Mixing Zones p. 112). In locations where supersaturation occurs, the increased levels of oxygen should conform to the recommendations in the discussion of Total Dissolved Gases, p. 139.

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* All values are instantaneous, and final value should be expressed to two significant figures.

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QUALITY CRITERIA FOR WATER
"Redbook"

July 1976

U.S. ENVIRONMENTAL PROTECTION AGENCY,

DISSOLVED OXYGEN

CRITERIA

Aesthetics: Water should contain sufficient dissolved oxygen to maintain aerobic conditions in the water column and, except as affected by natural phenomena, at the sediment-water interface. Freshwater aquatic life: A minimum concentration of dissolved oxygen to maintain good fish populations is 5.0 mg/L. The criterion for salmonid spawning beds is a minimum of 5.0 mg/L in the interstitial water of the gravel.

INTRODUCTION

Dissolved oxygen historically has been a major constituent of interest in water quality investigations. It generally has been considered as significant in the protection of aesthetic qualities of water as well as for the maintenance of fish and other aquatic life. Traditionally, the design of waste treatment requirements was based on the removal of oxygen-demanding materials so as to maintain the dissolved oxygen concentration in receiving waters at prescribed levels. Sophisticated techniques have been developed to predict the dissolved oxygen concentration under various hydrologic, hydrographic, and waste loading conditions (Velz, 1970). Dissolved oxygen concentrations are an important gauge of existing water quality and the ability of a water body to support a well-balanced aquatic fauna.

RATIONALE

The aesthetic qualities of water require sufficient dissolved oxygen present to avoid the onset of septic conditions with their attendant malodorous emissions. Insufficient dissolved oxygen in the water column causes the anaerobic decomposition of any organic materials present. Such decomposition tends to cause the formation of noxious gases such as hydrogen sulfide and the development of carbon dioxide and methane in the sediments which bubble to the surface or which tend to float settled sludge as mats which are composed of various organic materials.

Dissolved oxygen in bodies of water used for municipal water supplies is desirable as an indicator of satisfactory water quality in terms of low residuals of biologically available organic materials. In addition, dissolved oxygen in the water column prevents the chemical reduction and subsequent leaching of iron and manganese, principally from the sediments (Environmental Protection Agency, 1973). These metals cause additional expense in the treatment of water or affect consumers' welfare by causing taste and staining plumbing fixtures and other surfaces which contact the water in the presence of oxygen (NAS, 1974).

Dissolved oxygen also is required for the biochemical oxidation of ammonia ultimately to nitrate in natural waters. This reduction of ammonia reduces the chlorine demand of waters and increases the disinfection efficiency of chlorination (NAS, 1974).

The disadvantage of substantial quantities of dissolved oxygen in water used as a source of municipal water supply is the increased rate of corrosion of metal surfaces in both the water treatment facilities and in the distribution system (NAS, 1974). Such corrosion, in addition to the direct damage, can increase the concentration of iron (and other metals) which may cause taste in the water, as well as staining.

A discussion of oxygen criteria for freshwater fish must take into account these facts: (1) fish vary in their oxygen requirements according to species, age, activity, temperature, and nutritional state; (2) fish are found from time to time and can survive for awhile at oxygen concentrations considerably below that considered suitable for a thriving population; and (3) although there is much literature on the oxygen consumption of fish and the effects of varying oxygen concentrations on behavior and survival, few investigators have employed methods or sought endpoints that can be related with confidence to maintaining a good fish population.

To allow for the differences among requirements affected by species and other variables, the dissolved oxygen criteria are based on the concentration that will support a well-rounded population of fish (Ellis, 1937) as it would occur under natural conditions. A population of fish is composed of different but interdependent species of varying feeding and reproductive habits. Any given population will include game and pan fish (bass, pike, trout, perch, sunfish, crappie), some so-called rough or coarse fish (carp, buffalo, bullhead, sucker, chub), and large numbers of smaller “forage” fish (minnows). Theoretically, it should be possible to base oxygen criteria on the needs of the most sensitive component of such a population, but there is not enough information for this at present; that is why the criterion must be based on oxygen concentrations known to permit the maintenance and well-being of the population as a whole.

The requirement that the data be applicable to naturally occurring populations imposes limits on the types of research that can be used as a basis for the criterion. Aside from a few papers on feeding, growth, and survival in relation to oxygen concentration, very little of the laboratory-based literature has a direct bearing; field data are in general more useful. Field studies have the disadvantage that the numbers of variables encountered in the natural environment (temperature, pH, dissolved solids, food supply, and the like, as well as dissolved oxygen) make it necessary to be conservative in relating fish abundance and distribution to oxygen concentration alone, but enough observations have been made under a variety of conditions that the importance of oxygen concentration seems clear.

Field studies in which fish catches have been related to dissolved oxygen concentrations measured at the same time, indicate that a dissolved oxygen concentration of 3 mg/L is too low to maintain a good fish population (Thompson, 1925; Ellis, 1937; Brinley, 1944), and this finding is supported by laboratory observations that in the vicinity of 3 mg/L and below, feeding is diminished or stopped (Lindroth, 1949; Mount, 1960; Herrmann, *et. al.* 1962) and growth is reduced (Hamdorf, 1961; Itazawa, 1971), even when the lowered oxygen concentration occurs for only part of the day (Stewart, *et al.* 1967).

A dissolved oxygen concentration of 4 mg/L seems to be about the lowest that will support a varied fish population (Ellis, 1937), even in the winter (Thompson, 1925), and for a well-rounded population including game fish it should be above that. Both Ellis (1937) and Brinley (1944) set the minimum for a well-rounded population at 5 mg/L. It should be pointed out, however, that Thompson found the greatest variety of species at 9 mg/L, Ellis found good populations more frequently at 6 than at 5 mg/L, and Brinley reported the best concentrations for game fish populations to be above 5 mg/L. The belief that 5 mg/L is adequate is supported by the fact that the introduced rainbow trout thrives in Lake Titicaca (Everett, 1973) where, because of the altitude, the oxygen concentration in fully saturated water is not over 5 mg/L.

Fish embryonic and larval stages are especially vulnerable to reduced oxygen concentrations because their ability to extract oxygen from the water is not fully developed and they cannot move away from adverse conditions. Although many species can develop at oxygen concentrations as low as 2.5 to 3 mg/L, the effects of a reduced oxygen concentration even as high as 5 or 6 mg/L can cause a partial mortality or at the least retard development (Brungs, 1971; Siefert, *et al.* 1973, 1974, 1975; Carlson, *et al.* 1974; Carlson and Siefert, 1974; Garside, 1966; Gulidov, 1969; Hamdorf, 1961). Unless it is extreme, however, the retardation need not be permanent or detrimental to the species (Brannon, 1965; Eddy, 1972). For most fish, maintaining a minimum 5 mg/L in the water mass in the vicinity of the embryos and larvae should suffice.

Special treatment is required for species such as the salmonids, that bury their fertilized eggs in gravel. The flow through gravel is often slow, especially if siltation has occurred, and if it is slow enough the developing fish and other organisms can easily deplete the oxygen supply enough to cause damage, especially if the concentration in the water is relatively low before it enters the gravel (Cooper, 1965; Coble, 1961; Brannon, 1965). With a permeable gravel and abundant flow 5 mg/L in the overlying water should be enough. This concentration could well be inadequate, however, with a less porous gravel and a slower flow. Since the permeability and flow have so important a bearing on the initial oxygen concentration required to maintain the intragravel concentration, and since these characteristics vary with location, it is proposed that the criterion for salmonid spawning beds be stated as not less than 5 mg/L in the gravel. This would require that the concentration in the water entering the gravel be 5 mg/L or more, increasing as the intragravel flow rate decreased.

Decreased dissolved oxygen levels, if sufficiently severe, can adversely affect aquatic insects and other animals upon which fish feed. Sprague (1963) has evaluated such effects on several crustaceans while others have evaluated caddisfly larvae and stonefly nymphs (Doudoroff and Shumway, 1970). However, many other invertebrates are less sensitive to lowered dissolved oxygen concentrations and may be equally suitable fish food. Doudoroff and Shumway (1970) concluded that as long as dissolved oxygen concentrations remain entirely satisfactory for fish, no material impairment of the food resources for fish ascribable to dissolved oxygen insufficiency will occur.

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A REVIEW OF THE EPA RED BOOK
QUALITY CRITERIA FOR WATER

Edited by the Members of the Red Book Review Steering Committee

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Dissolved Oxygen

EPA Criteria

Aesthetics: Water should contain sufficient dissolved oxygen to maintain aerobic conditions in the water column and, except as affected by natural phenomena, at the sediment-water interface. Freshwater aquatic life: A minimum concentration of dissolved oxygen to maintain good fish populations is 5.0 mg/L. The criterion for salmonid spawning beds is a minimum of 5.0 mg/L in the interstitial water of the gravel.

Reviewers: J.C. Davis (Coordinator), G.I. Bresnick, P. Doudoroff, T.R. Doyle, A.J. Mearns, J.B. Pearce, J.J. Peterka, J.G. Robinson, and D.L. Swanson

I. Criteria

The Red Book criterion, a minimum dissolved oxygen concentration of 5.0 mg/liter for freshwater aquatic life ("good fish populations") and salmonid spawning bed interstitial water is inadequate and unjustified. The proposed minimum pertains to all freshwaters without regard to specific regional variations in physical and chemical regimes or existing natural oxygen levels in aquatic ecosystems which are subject to seasonal and biological variability. The criterion pertains only to freshwaters and salmonid spawning beds and fails to consider the marine environment in any way. The concept of a minimal value is not defined. However, for the purposes of this review it is assumed that the Red Book minimum is a value which may occur at any time or depth in any water body to which the criterion is applied.

II. Introduction

The Red Book Introduction is vague and very general and contributes little of use to the document. A better tactic would have been to make reference to the substantial body of literature concerning dissolved oxygen and aquatic life. Specifically, several thorough review articles should be mentioned (Davis 1975a,b; Doudoroff and Shumway 1970; Warren and Shumway 1964; Warren, *et al.* 1973) and the major findings of those reviews summarized. The Introduction should serve to indicate the scope and breadth of knowledge available on the subject and point out the variance in natural aquatic oxygen regimes which support diverse aquatic life forms. Furthermore, it should point out areas where gaps in our knowledge exist and controversy is evident.

III. Rationale

The Red Book criterion is said to be based primarily upon observations made in the field (mostly those of Ellis and associates) on the relation between observed dissolved oxygen levels at various sample sites and the variety of fish species present. The presence of a "well-rounded fish population" was taken as an indication of satisfactory conditions. Doudoroff and Shumway (1970), pp. 241-247, presented a detailed summary of the inadequacy of Ellis' conclusions, citing deficiencies of the evidence upon which those conclusions were based. It was shown that good mixed fish faunas, as defined by Ellis (1937), actually can occur in warm waters where dissolved oxygen levels do not exceed 4 mg/liter for very long periods, are often below 3.0 mg/liter and sometimes are as low as 1.4 mg/liter or less. But these observations do not prove, of course, that fish production is not seriously impaired in all situations at such low dissolved oxygen levels. The observation cited in the Red Book that rainbow trout thrive in Lake Titicaca at levels not exceeding 5.0 mg/liter oxygen, due to altitude, does not justify the criterion choice. Trout production may be reduced materially at 5.0 mg/liter in other areas possessing naturally high oxygen regimes. In essence, the natural dissolved oxygen regimes of aquatic systems must be considered in development and application of criteria. Failure to consider such natural conditions is open to severe criticism.

The Red Book Rationale makes a major point that much of the laboratory-based information available is of little value and that "aside from a few papers on feeding, growth and survival in relation to oxygen concentration, very little of the laboratory-based literature has a direct bearing." In contrast, it is our opinion that a good deal of laboratory work is relevant and useful. Doudoroff and Shumway (1970) and Davis (1975a,b) reviewed recent information in a thorough and critical way and arrived at criteria based upon such an assessment of the literature. Indeed, we are disturbed by the statement that the Red Book criteria are based almost entirely on field data of a very incomplete nature. A number of laboratory studies have indicated threshold oxygen response levels which influence fish behavior, blood oxygen saturation, metabolic rate, swimming ability, viability of eggs and larvae, egg and larval development, food consumption and growth, circulatory dynamics, ventilation, gaseous exchange and sensitivity to toxic stresses. Some of these various threshold response levels of low oxygen for a number of species lie well above the EPA 5.0 mg/liter criterion (Davis 1975b). Certainly the considerable weight of this evidence should not be ignored or summarily dismissed as irrelevant.

The Red Book dismissal of laboratory-derived oxygen data is inconsistent with the bulk of the entire document. Laboratory results have been used to derive the majority of the criteria in the Red Book because good field information is uncommon, particularly about the marine environment. Thus the Rationale adopted seems to discredit the rest of the document – hardly a consistent approach for a criteria pub1ication!

A major area of disagreement exists in EPA's abandonment of criteria like those presented in the Blue Book (NAS 1973) in favor of the present 5.0 mg/liter minimum value. The disadvantage of the revised criteria is that they now fail to consider natural seasonal conditions in a given water body. Indeed, it is highly unrealistic to prescribe rigid oxygen criteria for waters that may be naturally low in oxygen at some time of the year and may not meet the criteria for natural reasons. Furthermore, the Blue Book criteria [and those of Doudoroff and Shumway (1970) on which the former criteria were based in large part] provided flexibility through the concept of "levels of protection," which allowed for individual judgment and evaluation of risk for given situations where stringent or more relaxed criteria could be utilized as desired. It is our opinion that such flexibility is useful and worthwhile and should be included in criteria recommendations.

The fact that the Red Book fails to consider the growing body of information on marine dissolved oxygen regimes and their impact on fish and invertebrate communities caused concern to a number of reviewers. In the sea, considerable variation in dissolved oxygen levels in the water column is evident, particularly along the coast where phytoplankton blooms, respiration and upwelling processes involving deep, low oxygen water can have a major impact. For example, off the California coast, upwelling can produce DO levels as low as 3-4 mg/liter nearshore (1.2 mg/liter off central California). There are no documented deleterious effects of these low levels on nearshore fish or phytoplankton. Off southern California at 60 m, the depth of most deep ocean outfalls, dissolved oxygen normally ranges between 4 and 5 mg/liter and the maximum biomass of fish can be found at that level (Mearns and Greene 1974; Mearns and Smith 1975). Similar high variability in natural dissolved oxygen regimes with seasonal fluctuations can be found on the Atlantic coast (Segar and Berberian 1976) and may be accentuated in regions of highly polluted estuaries and bays (e.g., New York Bight, Newark Bay, Raritan Bay). There is a great need to evaluate the growing body of information on coastal dissolved oxygen regimes and their impact on ecosystems and include such information in criteria recommendations and their application.

Finally, we are of the opinion that the Rationale dealing with dissolved oxygen requirements in salmonid spawning beds is rather naive and open to criticism. The Red Book specifies that a minimum level of 5.0 mg/liter dissolved oxygen be maintained in interstitial waters of such spawning beds. It should be remembered that interstitial oxygen levels in the gravel are likely to be very different from those in the redds where spawning occurs and will vary from location to location, depending on the porosity of the gravel, current velocity, and oxygen gradient between overlying water and interstitial water. Conceivably, some highly productive spawning beds could fail to meet the EPA criterion. Furthermore, in areas where a high level of dissolved oxygen predominates naturally, the level of 5.0 mg/liter as an oxygen minimum may be a very permissive criterion allowing considerable debilitation of embryos or larvae to occur. Highly valuable aquatic populations could therefore suffer considerable harm when reliance is placed on such a criterion. In many areas, valuable spawning beds require a high level of protection and a major change in the oxygen regime should not be permitted.

IV. References Cited

The reference to Siefert, *et al.* (1974) is incorrect. This should be cited as Siefert and Spoor (1974). A check of the references indicated that other citations were correct. It should be pointed out, however, that only a very small sampling of the available literature appears in the Red Book Rationale and that the references chosen appear to be mostly those which support the argument for a minimum level of 5.0 mg/liter.

V. Reviewers' Discussion

It is our opinion that the decision to dismiss the dissolved oxygen criteria presented in the 1973 Blue Book and substitute a much inferior single minimal value is most ill-advised. We feel this action represents a step backwards and that the decision does not reflect current knowledge. The proposed minimum is not scientifically sound and is based only on a small portion of existing information. The Red Book criterion is viewed as highly confining and dangerously misleading if applied to regimes where oxygen concentrations are normally high.

A minority position, taken by one group of reviewers, was that considerable inadequacies are present in the Blue Book as well as the Red Book. T his group voiced many of the above objections to the Red Book but also expressed dissatisfaction with the following Blue Book items:

– The Blue Book advocacy of a 4 mg/liter "floor value" (viewed as providing inadequate protection in many instances).

– The Blue Book advocacy of using natural "minima" in waters already polluted. There are instances where historic baseline levels cannot be determined (e.g., the Potomac, Hudson, River Rouge, Houston Ship Channel).

– The Blue Book's failure to address the possibility of interaction of reduced dissolved oxygen and the presence of toxicants in receiving waters which may lead to toxicity potentiation or outbreaks of disease in stressed fish populations when low levels of oxygen are permitted.

The minority group advocated use of the Davis (l975a,b) "A" level of protection for freshwater aquatic life based on water temperature and percent saturation (a range of 7.2-10.0 mg/liter over the temperature range 0-25 C). This position, however, does not reflect the recommendations of the review panel as a whole and should be viewed as a more stringent recommendation based upon data for mixed cold freshwater fish populations including salmonids.

VI. Recommendations for Improvement of this Section

We strongly recommend a return to the position, criteria and rationale proposed by Doudoroff and Shumway (1970) or the similar ones presented in the Blue Book.

Appropriate references to the vast body of knowledge used to arrive at those more sensible criteria should be included. We feel the argument based upon selected "field studies" is unsound and requires reexamination in future criteria documents. It is essential that consideration of natural regimes of dissolved oxygen be included in criteria application to specific water bodies--both freshwater and marine. Furthermore, the flexibility inherent in the useful concept of "levels of protection" is encouraged and endorsed.

In considering the above recommendations, it should be noted that the recommendations of Doudoroff and Shumway (1970) do not include an arbitrary minimum of 4.0 mg/liter for naturally oxygen-poor waters nor an unrealistic assumption of a minimum natural dissolved oxygen level equal to the air-saturation value when the natural seasonal minimum is unknown. For these reasons they may be preferable to those presented in the 1973 Blue Book, which are otherwise nearly the same, though differently expressed.

Finally, it is suggested that future criteria documents must make an attempt to include the growing body of information on marine oxygen regimes and their effects on marine ecosystems. It is emphasized that such regimes often exhibit considerable seasonal variability and that natural conditions must be considered when applying criteria to marine water bodies. The Blue Book approach for "unusual waters", p. 132, and "Recommendations (a)", p. 134, could be applied directly to marine waters in lieu of the Red Book minimum.

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