ISSUES IN DEVELOPING THE SAN JOAQUIN RIVER, CA, DO TMDL: BALANCING POINT AND NONPOINT OXYGEN DEMAND/NUTRIENT CONTROL[1]

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ABSTRACT

In 1994, the Central Valley Regional Water Quality Control Board (CVRWQCB) classified the San Joaquin River (SJR) Deep Water Ship Channel (DWSC), located near Stockton, California, as Clean Water Act 303(d) "impaired" because dissolved oxygen (DO) concentrations routinely fell below the water quality objective (standard) (WQO) in the 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 the CVRWQCB staff would take back control for development of the TMDL control plan.

This paper presents an overview of the DWSC DO depletion problem and many of the issues that need to be considered by the Steering Committee/CVRWQCB in developing a technically valid, cost-effective TMDL that will enable compliance with the DO WQO. This is a synopsis 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).

KEYWORDS

San Joaquin River, Dissolved Oxygen (DO), Total Maximum Daily Load (TMDL), Phytoplankton.

BACKGROUND

As part of developing the Port of Stockton (Port), a navigation channel was dredged in the SJR through the Delta to Stockton (Figure 1). 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

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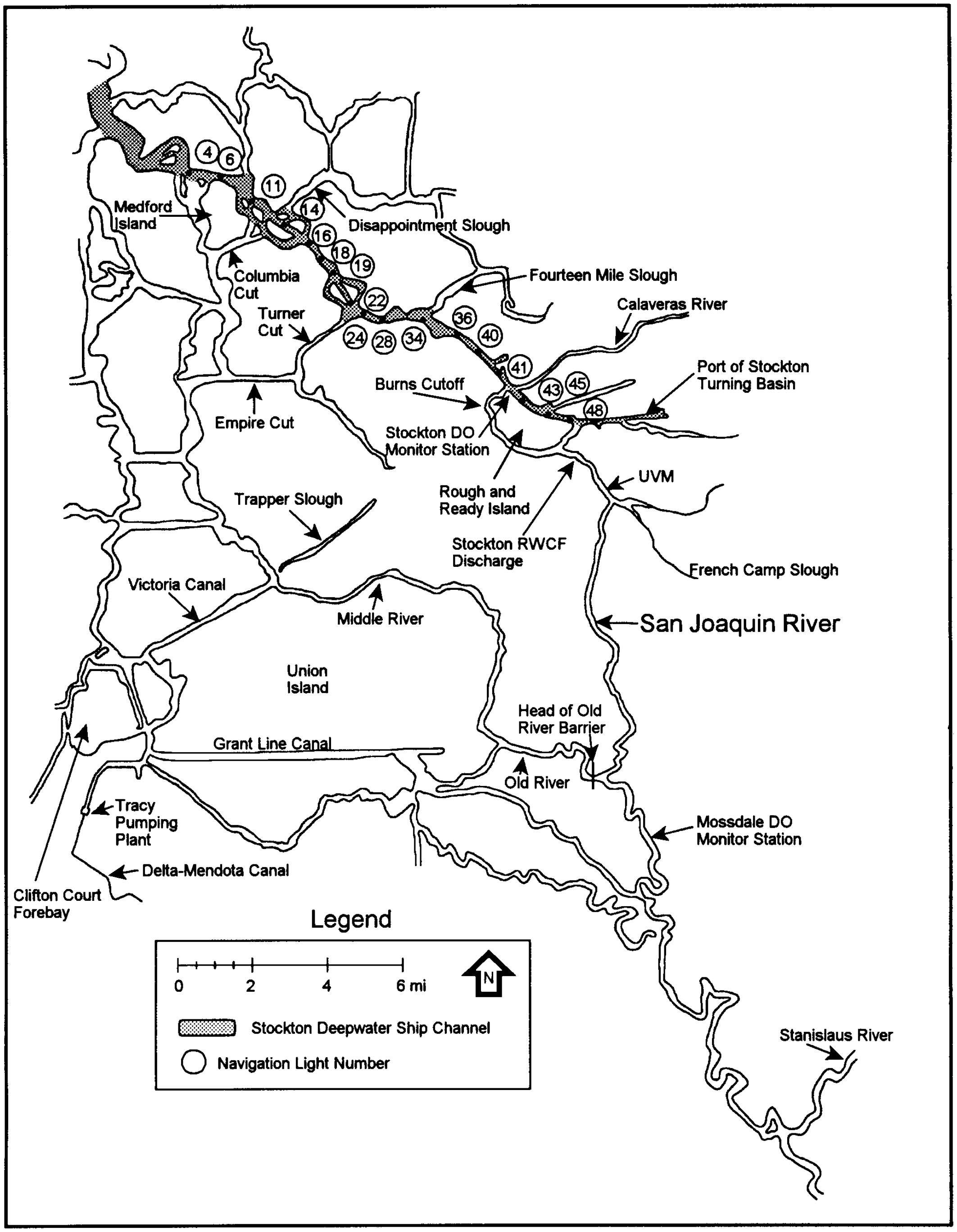
Figure 1 - Location of water quality stations and navigation lights on the San Joaquin River in the vicinity of Stockton



cfs tidal influenced flow. The summer/fall 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 of Stockton, 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 relatively short hydraulic residence time of the DWSC (see Figure 8) 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 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 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 low DO problem in the SJR DWSC is a long-standing problem that has existed for at least 30 years (Bain, *et al*., 1968).

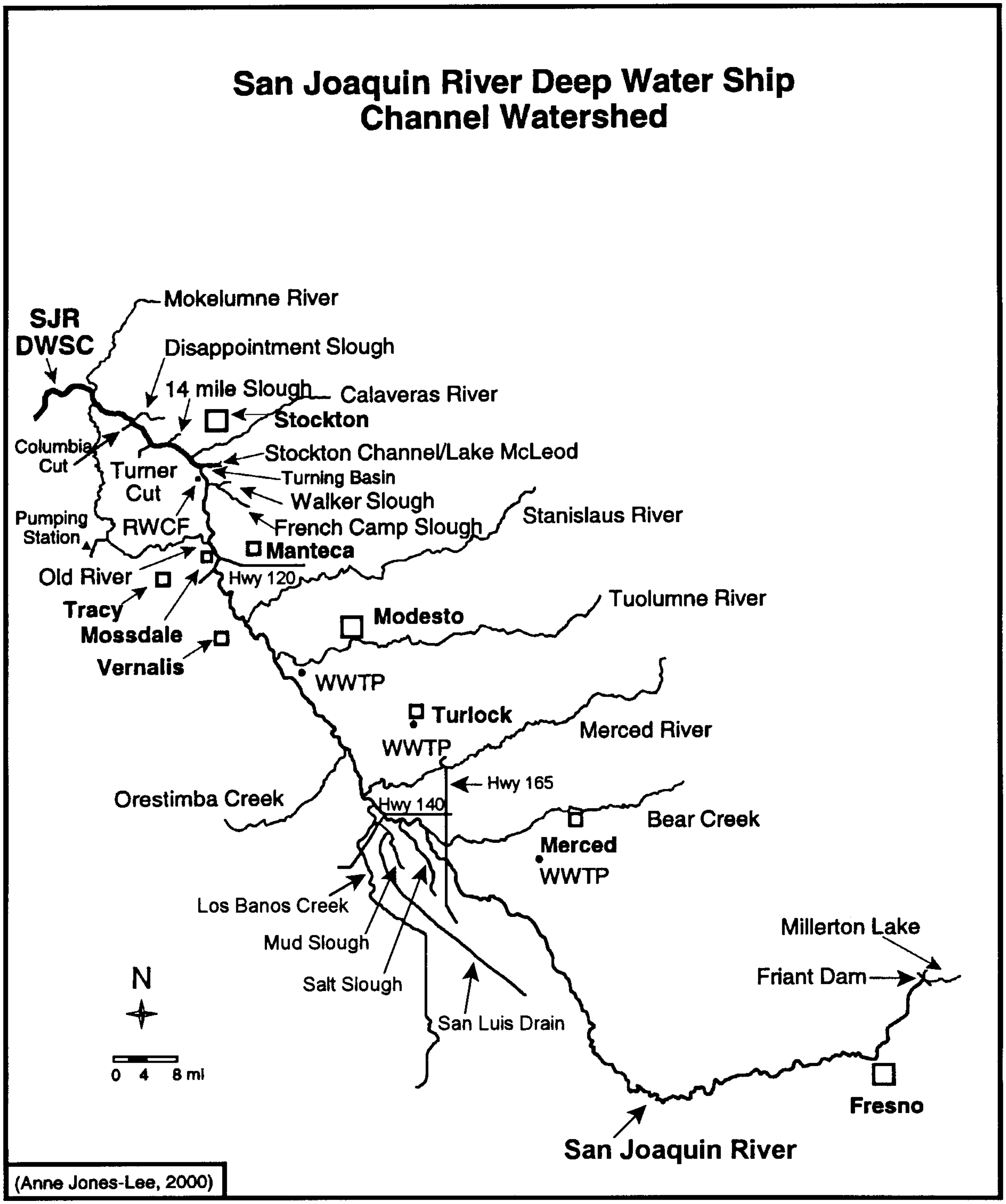
The DO water quality objective during September through November is 6 mg/L and during December through August is 5 mg/L. The 5 mg/L WQO is based on the US EPA national water quality criterion for protection of aquatic life. The 6 mg/L WQO was adopted by the State Water Resources Control Board in order to prevent lower DO from inhibiting the upstream migration of Chinook salmon. 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 Sierra Nevada mountains, flows through the agricultural Central Valley and 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. As shown in Figure 2, the SJR drains the Central Valley between Fresno and Stockton. It has a 7,345 sq mi watershed that contains 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 and has numerous dairies and feedlots. The current estimated urban population in this watershed is approximately two million and, at a rate of growth of 2 percent/yr, is expected to double to about four million by 2040.

The COE (1988), as part of the deepening of the DWSC, discussed many of the factors affecting dissolved oxygen depletion in the DWSC. As they discuss, upon entering the San Joaquin Valley floor, the SJR water quality deteriorates due to agricultural, municipal and industrial stormwater runoff, wastewater discharges; municipal, industrial, dairy and animal feed lot/husbandry activities and natural/riparian wetland runoff/ drainage. In addition to adding

Figure 2


San Joaquin River Deep Water Ship Channel Watershed
SJR DWSC
Mokelumne River
Disappointment Slough
14 mile Slough
Calaveras River
Stockton
Columbia Cut
Turner Cut
Stockton Channel/Lake McLeod
Turning Basin
Walker Slough
French Camp Slough
Stanislaus River
Pumping Station
RWCF
Manteca
Old River
Hwy 120
Tracy
Mossdale
Vernalis
Modesto
Tuolumne River
WWTP
Turlock
WWTP
Merced River
Hwy 165
Orestimba Creek
Hwy 140
Bear Creek
Merced
WWTP
Los Banos Creek
Mud Slough
Salt Slough
San Luis Drain
Millerton Lake
Friant Dam
N
0 4 8 mi
Fresno
San Joaquin River
(Anne Jones-Lee, 2000)

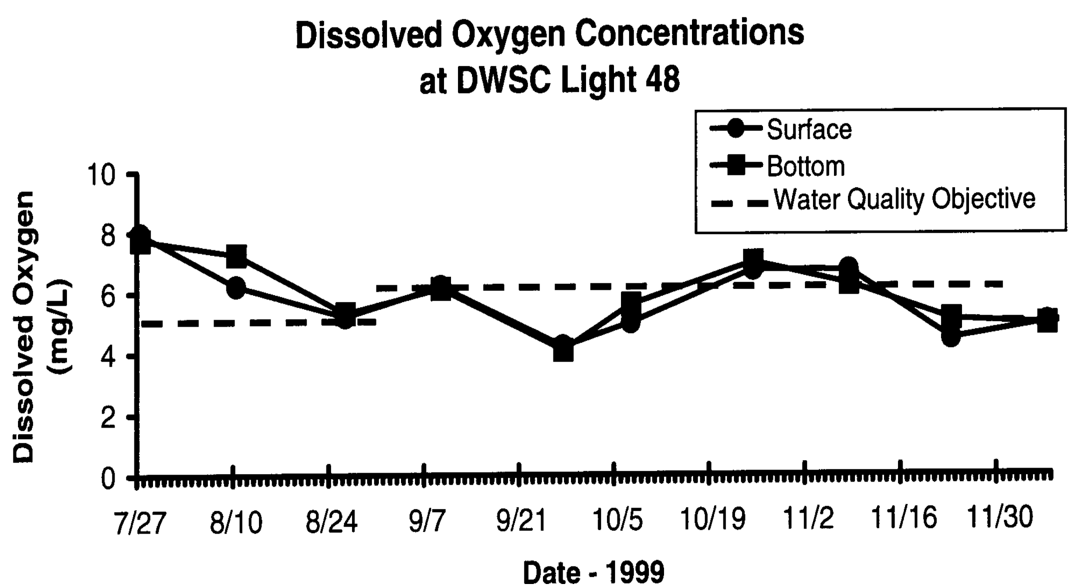
oxygen-requiring substances (carbonaceous and nitrogenous biochemical oxygen demand - BOD), the discharges contribute substantial amounts of nutrients (N and P compounds) which can support algal growth. The death of these algae are a source of oxygen demand in the DWSC when SJR at Vernalis flows represent 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 contributes to the oxygen demand that is present at Vernalis and, under certain SJR flow/diversion conditions, exerts oxygen demand in the DWSC. 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 summer. The death of these algae in the DWSC is believed to be one of the primary sources of DWSC oxygen demand.

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 is presented in Figure 3. Station 48 (see Figure 1) is in the Port of Stockton Turning Basin. Station 41 is near the downstream end of Rough and Ready Island which is about 2 miles from the point where the SJR enters the DWSC at the Port of Stockton. Station 18 is about 10 miles downstream of this point.

Figure 3 - DWSC DO Data Summer/Fall 1999
Adapted from DWR - Lehman (2000)



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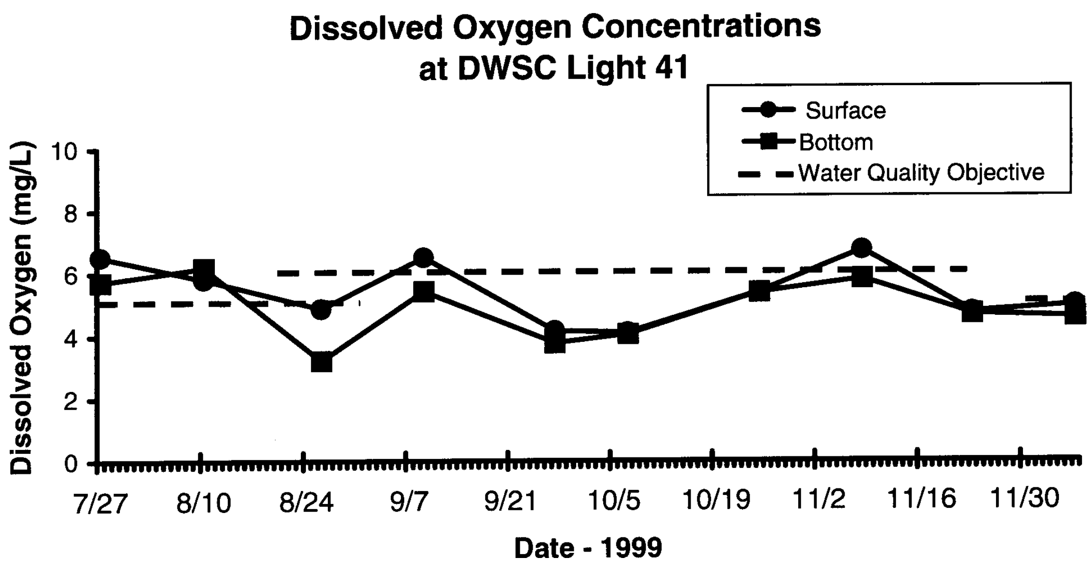

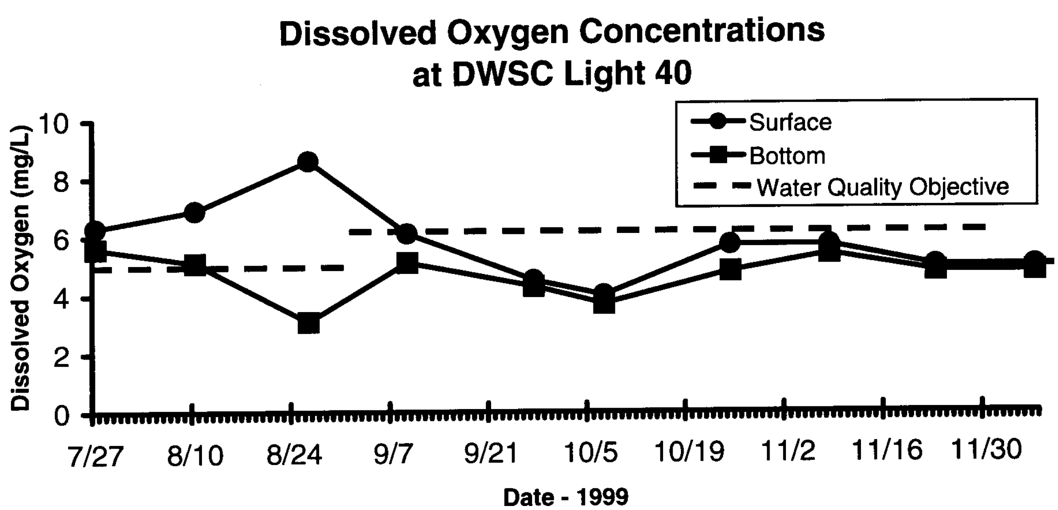

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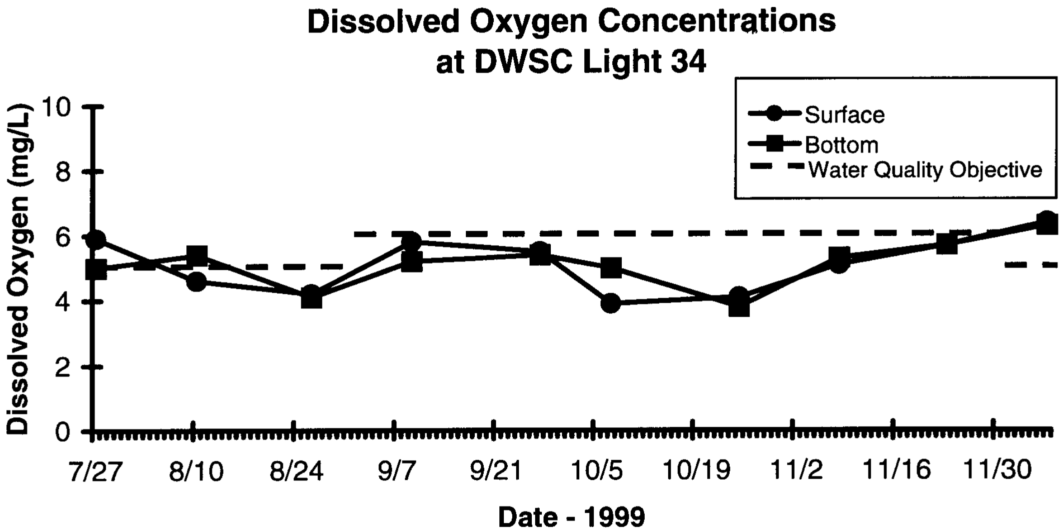
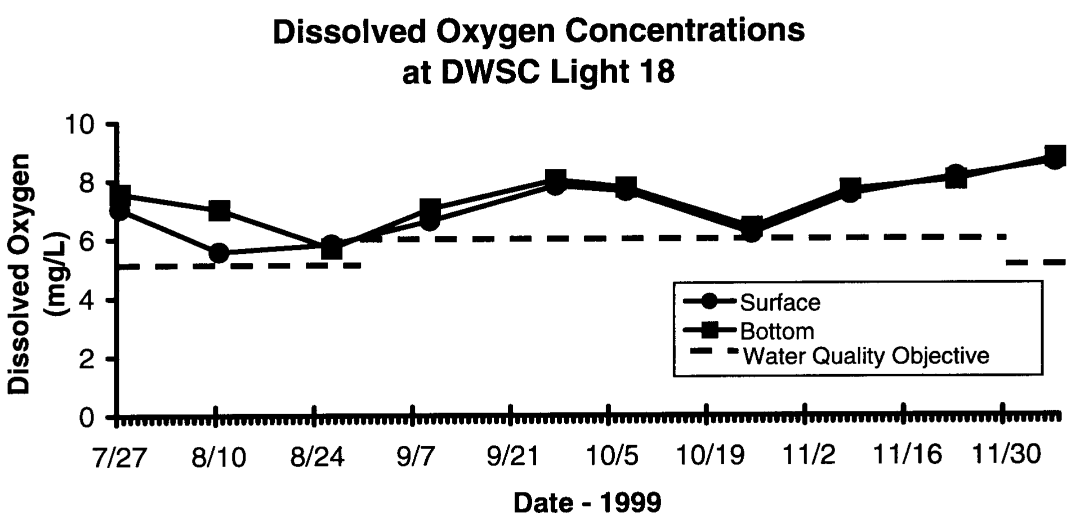


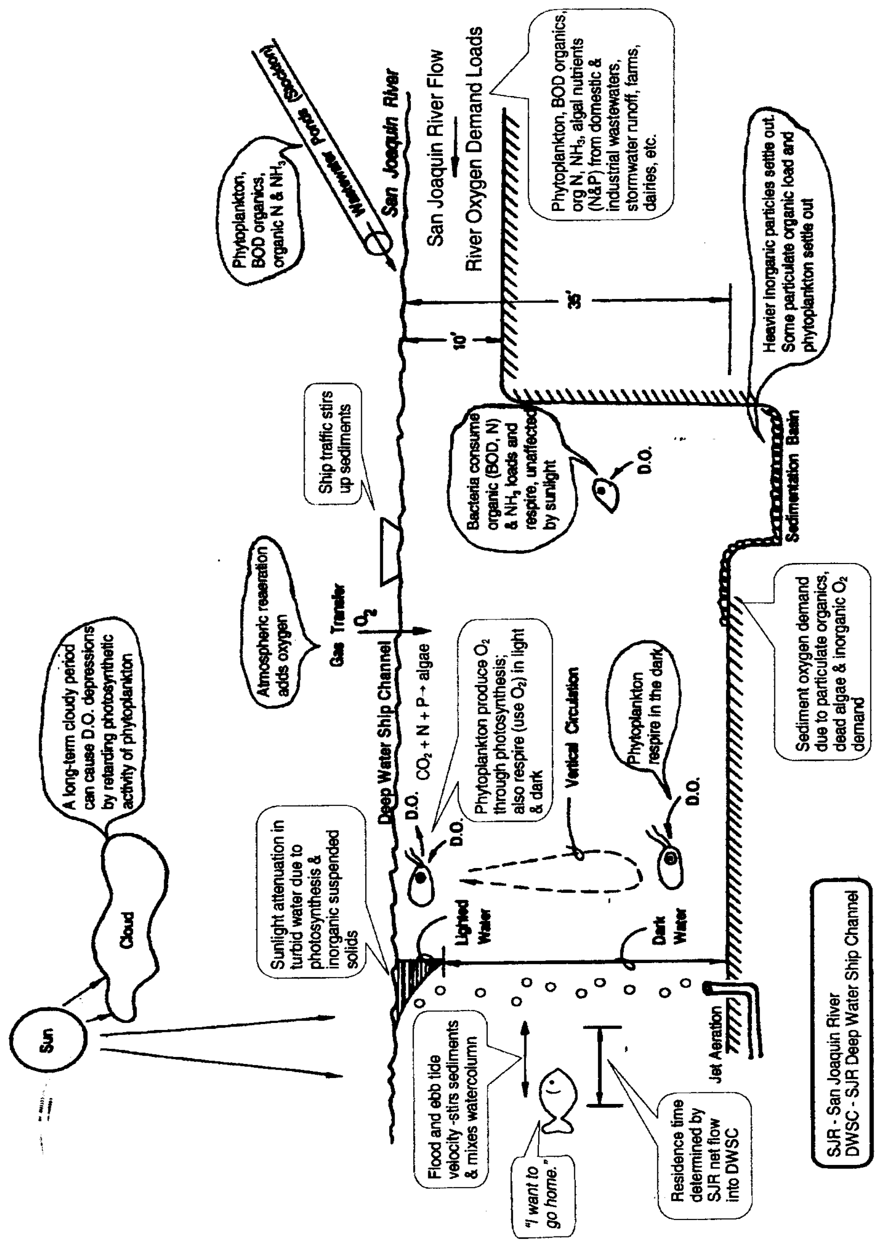


It was found that the DO concentrations in the DWSC decreased to below the WQO of 5 mg/L in August and 6 mg/L during September through early December 1999. During August and most of September the SJR flow into the DWSC was about 900 cfs. In late September through October the SJR flow into the DWSC ranged 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. According to the US EPA (1999), ammonia at these concentrations and the SJR DWSC temperature and pH is toxic to many forms of aquatic life over a period of exposure of about 30 days 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.

FACTORS INFLUENCING DISSOLVED OXYGEN DEPLETION IN THE DWSC

The processes/factors governing DO depletion in the DWSC are presented in Figure 4. 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.

Figure 4



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

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.

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 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 1 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.

Figure 6 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. 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.

Figure 5

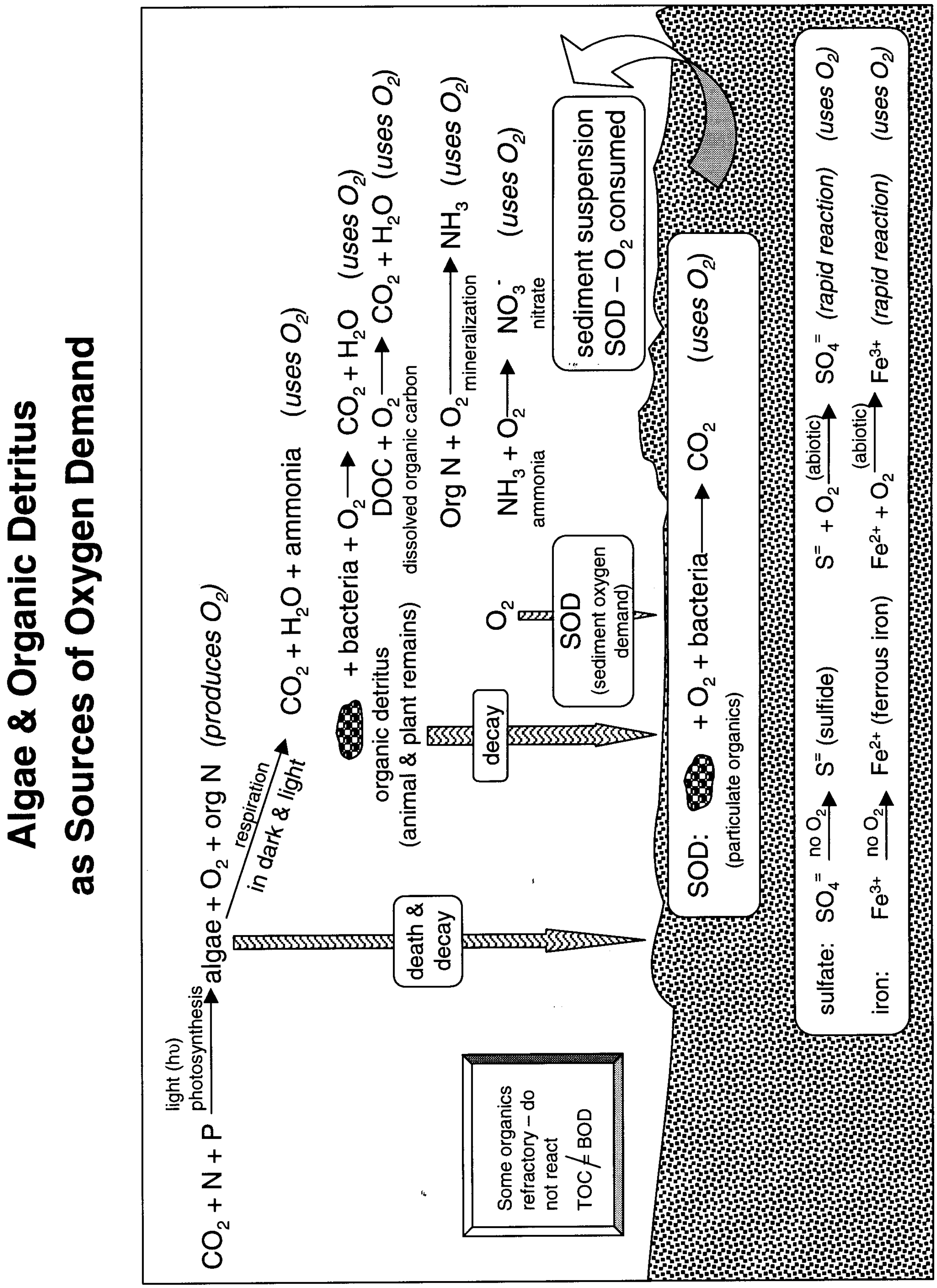
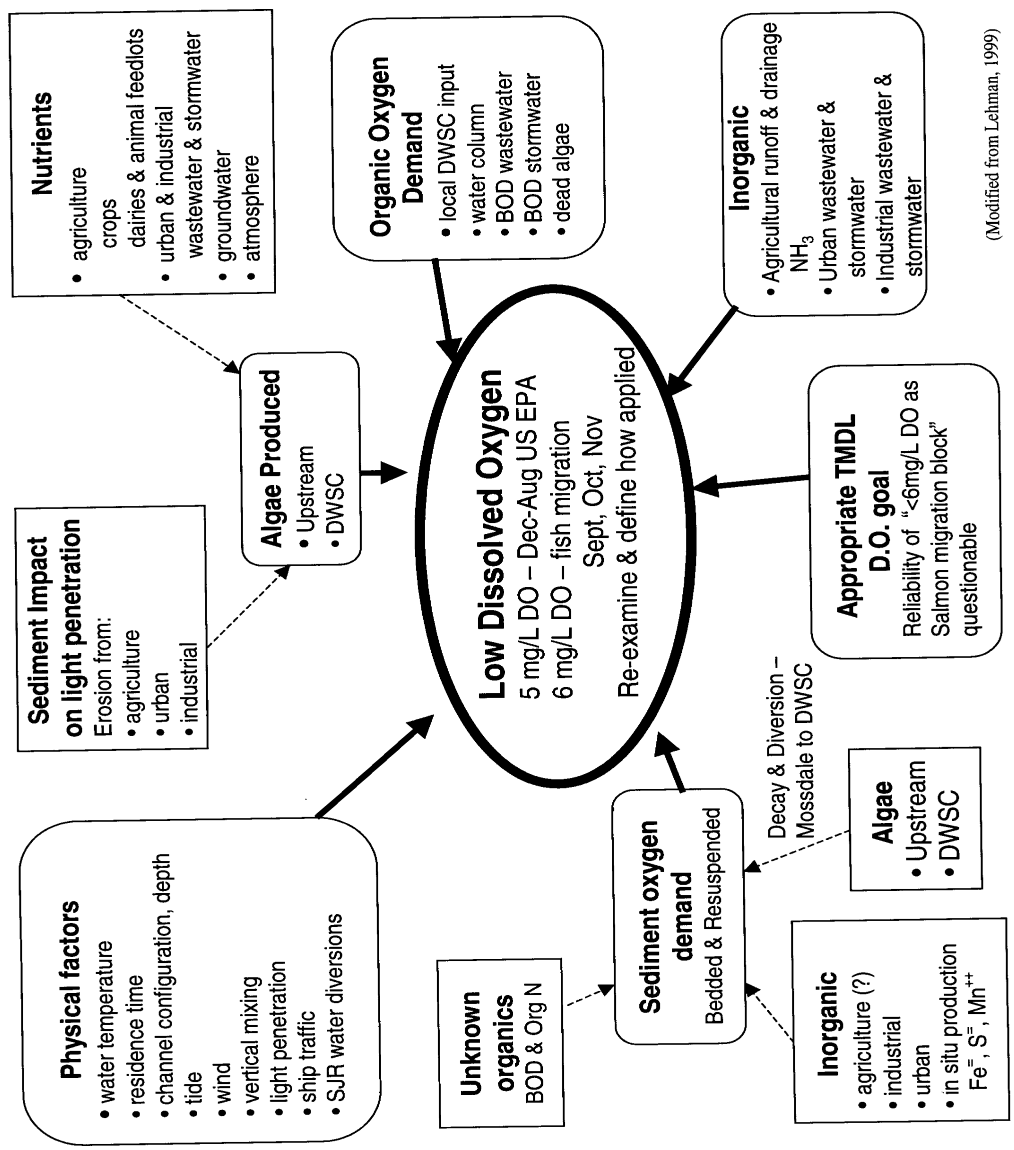


Figure 6 - Factors Influencing Dissolved Oxygen Depletion in the SJR DWSC



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 6 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 6 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.

The various factors listed in Figure 6 are being investigated in year-2000 and year-2001 studies of the DWSC. These studies will develop the information needed to incorporate the factors influencing DO depletion into the oxygen demand load DO depletion response model that has been developed for the DWSC (Chen and Tsai, 1996, 1997).

OXYGEN DEMAND BOX MODEL CALCULATIONS

Figure 7 and Table 1 present the results of box model calculations of the major sources of oxygen demand during the summer/fall 1999. Lee and Jones-Lee (2000) provide the details on the approach used to develop the information in Table 1. In general, they are based on measured concentrations of oxygen demand constituents and flow, summed to yield a total daily load of oxygen demand from each major source.

August 1999

Based on the August 1999 SJR and DWSC monitoring, it is found that the total ultimate 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. 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.

The box model calculations for September 1999 are similar to those for August 1999. 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 SJR flow and its associated oxygen demand load was largely diverted into 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.

Figure 7

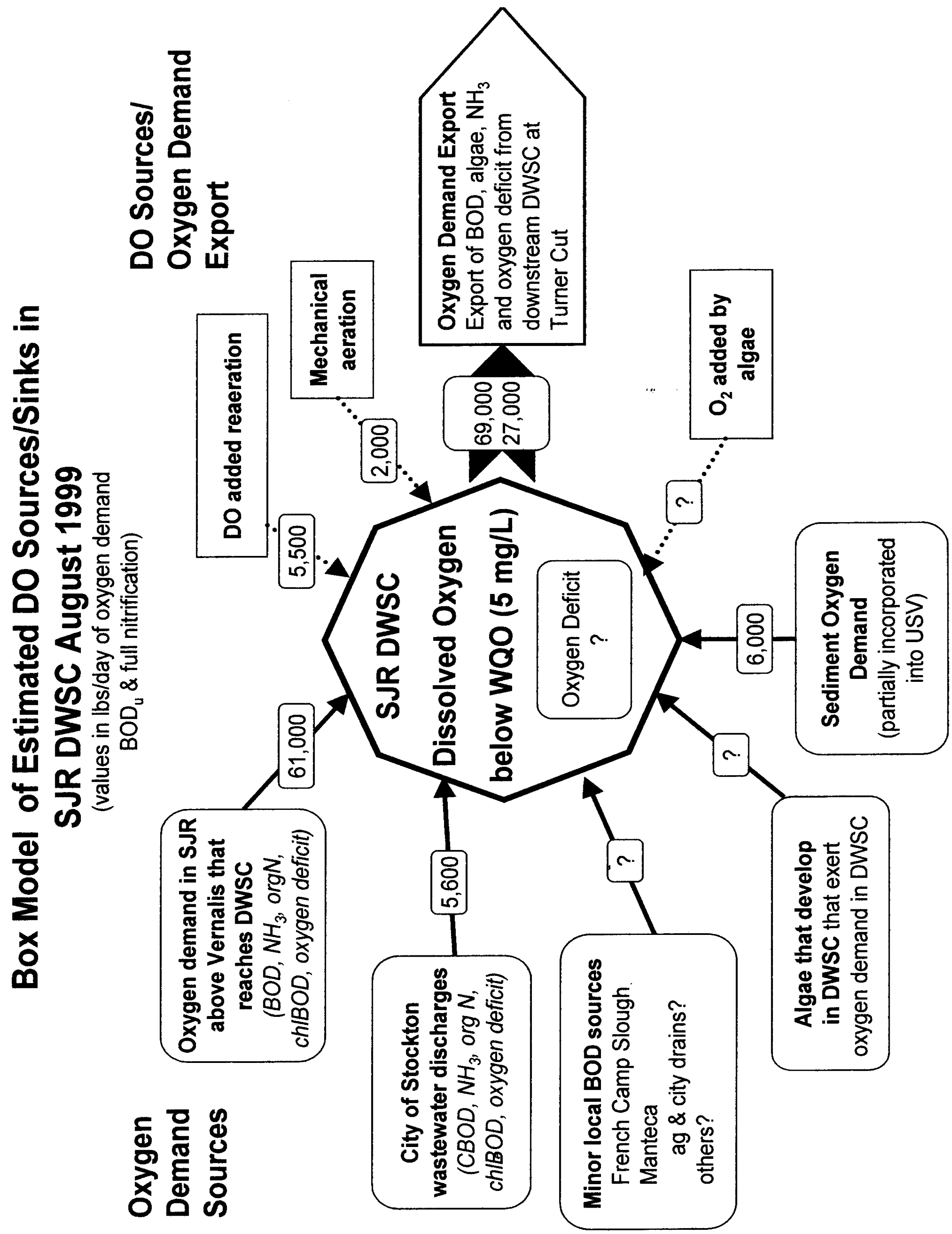


Table 1 - Box Model Calculations of Oxygen Demand Sources/Sinks for the San Joaquin River During Summer/Fall 1999

Source	BOD_u (lbs/day)				
	August	September	October		
SJR DWSC Net 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	?	?	?

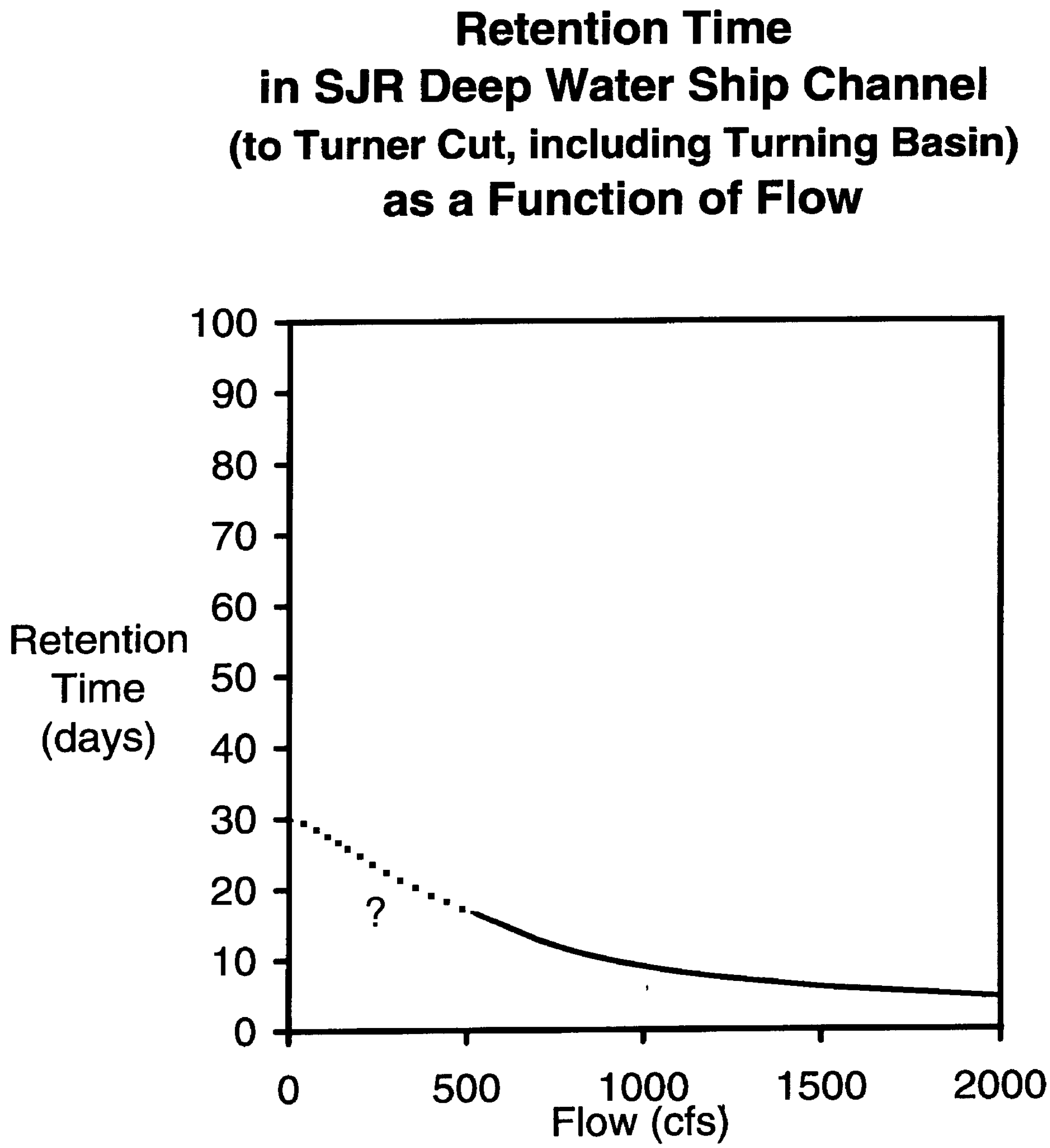
These results demonstrate that the upstream diversions of SJR water are important in determining the source of the oxygen demand loads contributed to the DWSC. These results also show that it will be necessary to expand the TMDL load analysis to the SJR watershed upstream of Vernalis. Both carbonaceous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

Figure 8 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).

As shown in Figure 8, the hydraulic residence time of water/oxygen demand that enters the DWSC is highly dependent on SJR flow through the DWSC. The first 15 miles of the DWSC can have a hydraulic residence time that varies from about 5 days at a net downstream flow of 2,000 cfs to about 30 days at 100 cfs.

Figure 9 presents a summary of the sources of oxygen-demanding materials in the DWSC. On the right side of Figure 9 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.

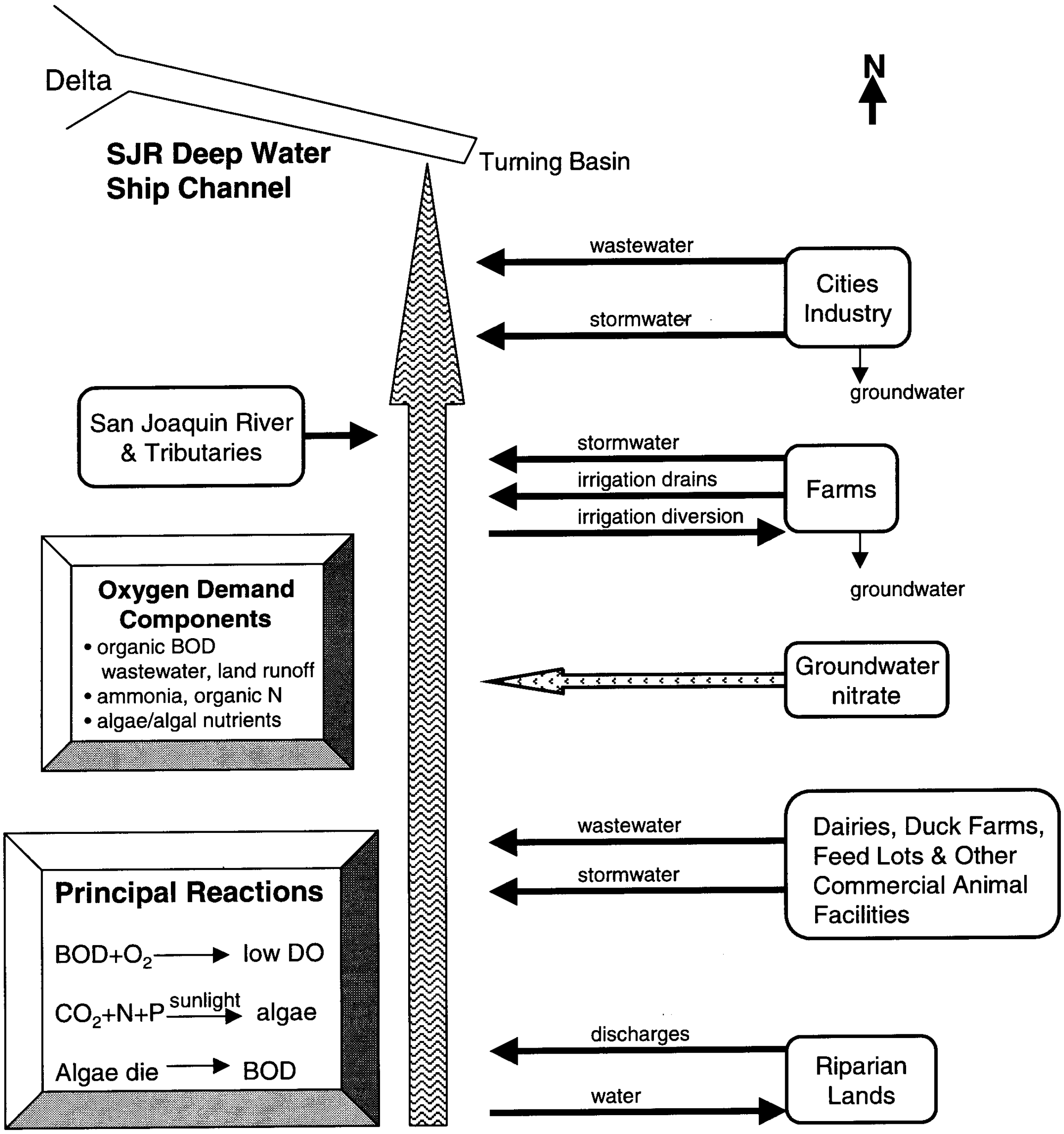
Figure 8



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.

Figure 9

Sources/Sinks of Oxygen Demand in SJR-DWSC Watershed



San Joaquin River

There is particular concern about the agricultural 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, 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 seasonal wetlands 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.

During 2000 and 2001 detailed studies are being conducted on the amounts of nutrients and oxygen-demanding materials present in the DWSC and its major tributaries. This information, when available, will help better define the relative significance of each of the sources of nutrients/oxygen demand shown in Figure 9.

RELATIONSHIP BETWEEN ALGAL NUTRIENT CONCENTRATIONS AND ALGAL BIOMASS

Since algae have been found to be important sources of oxygen demand within the DWSC, it is of interest to explore the possibility of controlling nutrient inputs to the SJR and DWSC as a means of controlling phytoplankton growth and their associated oxygen demand. 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.

Jones-Lee and Lee (2001) have recently summarized the existing information of the relationship between nutrient concentrations/loads and planktonic algal development in waterbodies. As they discuss, 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. Recent data indicate that the Secchi depth in the SJR upstream of Vernalis and within the DWSC is much lower than would be expected based on phytoplankton controlling light penetration. These results indicate that suspended inorganic and organic sediments are likely playing an important role in determining the amount of algae that develop within the SJR and DWSC.

Figure 10 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 11 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.

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 30 and 100 of that needed by the algae, for P and N, respectively. 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.

Figure 10

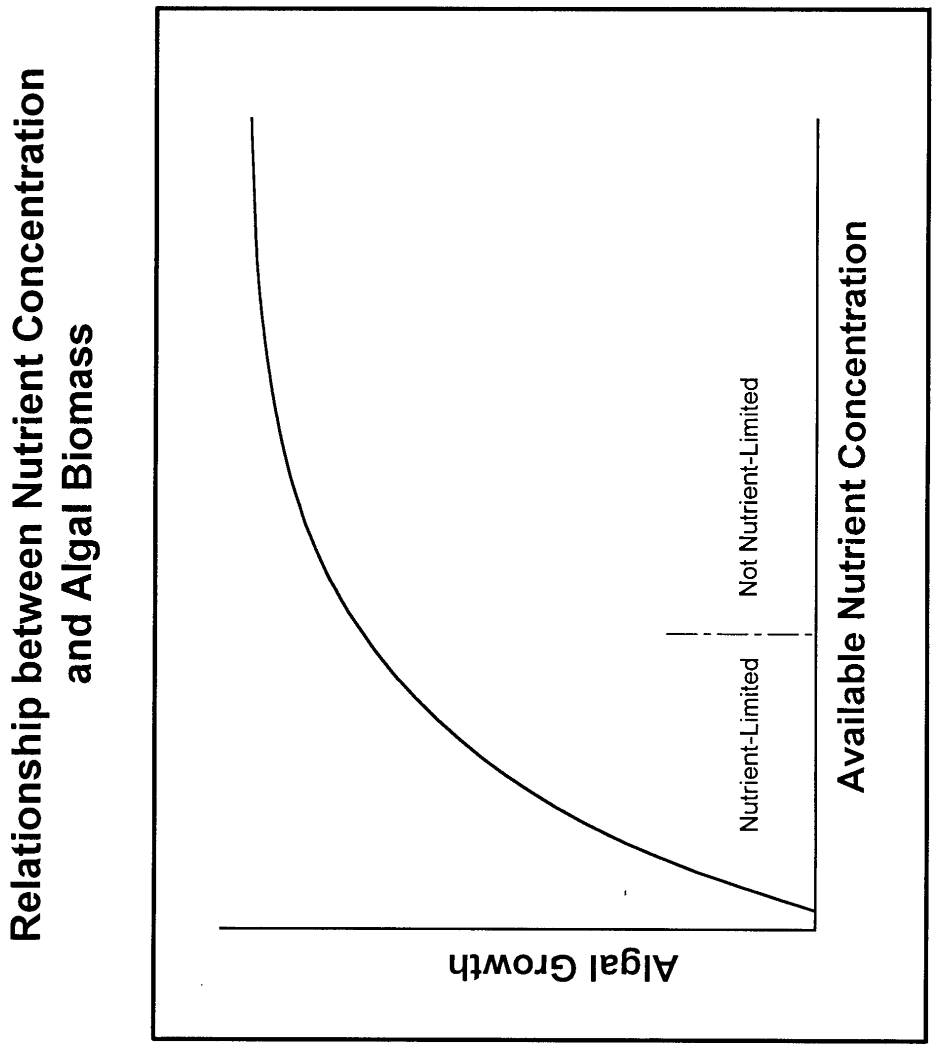
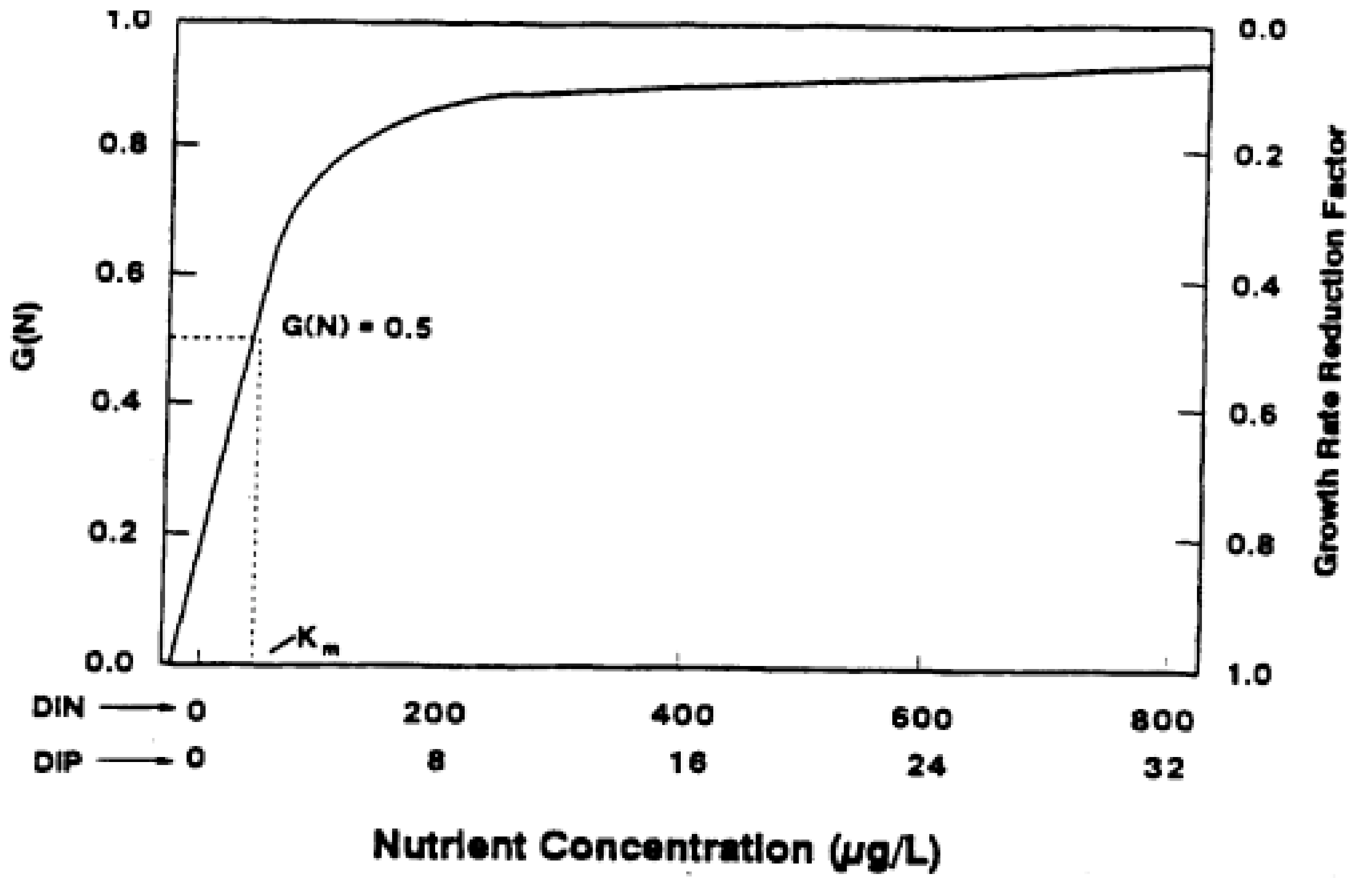


Figure 11



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

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 often 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 11 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.

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 2. 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 in the San Joaquin River above Vernalis, which exert an oxygen demand within the DWSC.

As listed in Table 2, 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. These studies are being conducted during 2000 and 2001.

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 2 - Responsibility for SJR DWSC DO Depletion Below Water Quality Objective

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.

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 and not violate the DO WQO of 5 mg/L. Since that time, the SJR DWSC has been deepened by an additional five feet which further reduces the oxygen demand assimilative capacity of the DWSC. Further, the Brown and Caldwell estimated allowable BOD_u load did not include the safety factor required in TMDL development. Work is currently underway as part of a "Strawman" effort to develop preliminary estimates of the allowable oxygen demand load to the DWSC considering the impact of SJR flow through the DWSC on DO depletion for a given oxygen demand load.

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 concern that these high SJR flows lead to DO depletion elsewhere in the central Delta. Similarly, the diversion of SJR flow into 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 provided $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. A Directed Action proposal in the amount of $2 million per year for two years has been submitted to CALFED by the SJR DO TMDL Steering Committee to continue field studies devoted to determining the relationships between the discharge of oxygen demanding substances to the DWSC and the DO depletion that occurs for a particular oxygen demand load to the DWSC as a function of SJR flow through the DWSC.

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. According to Delos (2000), the US EPA does not have a policy on this issue.

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 among stakeholders.

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 an 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).

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