Table 8 also contains the estimated $BOD_u$ loads for each of the major tributaries and along the SJR upstream of Mossdale. These loads were calculated based on the measured summer average $BOD_{10}$ concentrations reported by Foe, *et al.* (2002) in the Strawman analysis, multiplied by the summer average flows at each of the measuring points, times 0.65 to convert $BOD_{10}$ to $BOD_5$, times 3.0 to convert $BOD_5$ to ultimate BOD, times 5.4 to convert the units to lbs/day. As evidenced from this table, the SJR at Lander coupled with Salt and Mud Sloughs' discharges add substantial $BOD_u$ to the SJR. This is manifested as 40,000 to 50,000 lbs/day of $BOD_u$ in the SJR at Patterson. At the SJR at Maze the $BOD_u$ increased to 60,000 to 73,000 lbs/day. At Mossdale, there is further increase to 90,000 to 120,000 lbs/day of $BOD_u$. The eastside rivers (Merced, Tuolumne and Stanislaus), which are major contributors of flow, are not major sources of $BOD_u$. These results are in agreement with the above-discussed findings that the measured BOD is correlated with planktonic algal chlorophyll and that the eastside rivers are not major sources of phytoplankton for the SJR.

McGahan (pers. comm., 2002) has questioned the cause of the significant increase in the planktonic algal chlorophyll and $BOD_u$ loads that occurs between the discharges of Mud and Salt Sloughs and the SJR at Lander, and the SJR at Patterson. This issue has been reviewed further, with respect to whether there are significant additional sources of algae/BOD between the Mud/Salt Slough discharges and the SJR at Patterson. It was found that Los Banos Creek discharges to Mud Slough below where Mud Slough gaging and monitoring has been conducted. Therefore, Los Banos Creek is a potential source of algae and BOD to Mud Slough that is not reflected in the Mud Slough loads.

Dahlgren (2002) collected samples of Los Banos Creek during the summer 2000. It was found that the average planktonic algal chlorophyll in the Creek waters during the summer was about 11 μg/L, while at the same time, Mud Slough planktonic algal chlorophyll averaged 45 μg/L. Quinn (pers. comm., 2002) estimates that the summer (June through September) average flow of Los Banos Creek is about 9 cfs. Based on this information, Los Banos Creek is not a major contributor to the planktonic algal loads and their associated BOD to the SJR upstream of Patterson.

Dileanis (pers. comm., 2002) of the USGS has provided estimates of the chlorophyll plus pheophytin and $BOD_{10}$ added to the SJR during 2001 between where the Merced River enters the SJR and the SJR at Patterson. One sample per month was taken from the three tributaries that discharge to the SJR between the Merced River and the SJR at Patterson (Harding Drain, Orestimba Creek and Spanish Grant Drain) during the period July through October 2001. Using an average of the USGS data for 2001 for each of these tributaries between July and October, it is found that about 10,000 lbs of $BOD_u$ have been contributed by these tributaries to the SJR at Patterson. Therefore, the increase in $BOD_u$ between the Mud and Salt Slough discharges and Patterson due to algal growth in the SJR and other sources of BOD is about 34,000 lbs of $BOD_u$. This compares to a summed load of about 16,000 lbs of $BOD_u$ from Mud Slough, Salt Slough, SJR at Lander Avenue and the Merced River. Therefore, the $BOD_u$ load between the upstream tributary discharges (Mud and Salt Sloughs) and Patterson about doubled in the summer/early fall of 2001.

Dileanis (pers. comm., 2002) has indicated that the travel time of the SJR from Highway 165 (Lander Avenue) to Patterson is about 50 hours (about 2 days). This is based on the dye-tracer studies of Kratzer and Biagtan (1997). Foe (pers. comm., 2002) has estimated the travel times during the summer 2001 between Salt Slough's discharge to the SJR and Patterson as 1.7 days, Mud Slough and Patterson as 1.1 days, and the SJR at Lander Avenue and Patterson as 1.8 days. He points out that the gaging stations on Mud and Salt Sloughs are upstream of the discharge point to the SJR, and therefore there could be another half a day or so travel time within the tributaries before reaching the SJR. It is evident that there is from 1.5 to 2 days' travel time between the Mud and Salt Slough discharges to the SJR, and Patterson. Bowie, *et al*. (1985) have indicated that a review of the literature on algal doubling times in laboratories and waterbodies shows that the range is from about 0.2 to 3, with many doubling times on the order of 1 to 2 days. Since Foe, *et al*. (2002), found an apparent doubling time for algae in the upper SJR of about 38 to 47 hours (1.6 to 2 days), it is apparent that the increase in $BOD_u$ between Mud and Salt Slough and the SJR at Lander Avenue discharges and that found at the SJR at Patterson can readily be accounted for based on algal growth and the inputs from other tributaries between these two locations, with algal growth being the dominant cause of the increased algae and BOD in the SJR at Patterson.

Based on the information provided by Dileanis (pers. comm., 2002), it is found that the ratio of $BOD_{10}$ to planktonic algal chlorophyll for Orestimba Creek and Spanish Grant Drain is significantly different than this same ratio for Harding Drain. Harding Drain has a much higher BOD to chlorophyll ratio than Orestimba Creek and Spanish Grant Drain. This indicates that Harding Drain, which represents about 80 percent of the total BOD load from these three tributaries, has other causes of BOD than planktonic algae. This might be expected, based on the fact that Harding Drain receives city of Turlock domestic wastewaters, which contain CBOD and ammonia. Further, there are upstream dairies that could be contributing wastewaters to Harding Drain. There is need to further investigate the sources of BOD in Harding Drain.

It is of interest to see that the summer 2000 flows, which are approximately twice the flows in 2001, contained increased $BOD_u$ as measured along the River and at Mossdale. The comparison between the $BOD_u$ measured at Mossdale for 2000 and 2001 of 120,000 and 93,000 lbs/day, respectively, with the three years' summer average of the city of Stockton's BOD data collected at Mossdale (67,000 lbs/day) (Figure 15), shows a substantial difference between the two values. This difference is a result of the Figure 15 box model calculations being based on the use of flow of the SJR into the DWSC to estimate the Mossdale load that reaches the DWSC from upstream sources. The Table 8 values, however, use the Vernalis flow to estimate the total load at Mossdale. The difference between the two is the amount of the load that is diverted down Old River below Mossdale.

The potential significance of summer irrigation return flows has been examined by Foe, *et al.* (2002). According to Foe, *et al*., summer irrigation return flows were about 20 percent of the flow at Vernalis. In 2000 Foe, *et al.* used chlorophyll concentrations from Orestimba Creek as representative of algal concentrations from irrigation return flows. In 2001 the USGS measured chlorophyll at a number of sites in the Central Valley including Orestimba Creek. Statistically, all of the westside tributaries had about the same concentrations of planktonic algal chlorophyll as Orestimba Creek. Foe, *et al.* (2002) conclude that the data from Orestimba Creek is broadly representative of agricultural irrigation tailwater returns.

When the average Orestimba chlorophyll concentration is multiplied by 20 percent of the flow at Vernalis the calculated load of algae and their associated BOD is not a significant part of the total load measured in the SJR at Vernalis. Multiple regression of all the data collected from SJR tributaries shows that ammonia, DOC, etc., are important in explaining tributary-to-tributary variations in chlorophyll and BOD. However, examination of the data collected at Mossdale shows that the concentrations of chlorophyll and pheophytin are the only significant factors causing oxygen demand. Foe (pers. comm., 2002) interprets this to mean that the BOD constituents from other sources of BOD in the tributaries have been largely oxidized by the time they arrive at Mossdale, leaving algae as the primary source of BOD at Mossdale.

One of the issues of particular concern is the role of growth of algae in the SJR between where Mud and Salt Sloughs discharge to the SJR and the algae/$BOD_u$ at Mossdale. If there was no growth of algae in the SJR between where Mud and Salt Sloughs enter the SJR and Vernalis/Mossdale, then the eastside rivers would dilute the planktonic algal chlorophyll present in the River. However, it appears, from the chlorophyll concentrations found along the SJR, that the amount of growth that occurs about equals the amount of low-algal water added from the eastside rivers during the summer and early fall months. This finding supports the Foe, *et al.* (2002) algal growth model discussed in the Strawman, which shows that there was an apparent doubling of the algal population every day and a half to three days during the study period. Hutton (2002) is conducting modeling studies of flow and algal growth dynamics in the SJR upstream of Mossdale in which the DWR DSM-2 flow model will be expanded to include a water quality component. This modeling will be done in cooperation with CALFED-funded HydroQual modeling. The results of this modeling are not expected to be available for about a year.

The pattern (see Figure 17) that evolved from both the Foe, *et al.* (2002) Strawman analysis and the USGS/UCD data presented by Dileanis (2002) of the mainstem and tributary monitoring of the SJR during the summer/fall 2000-2001 is one of Mud and Salt Sloughs, as well as the SJR at Lander Avenue discharging (containing) high concentrations of planktonic algae. The planktonic algae measured as chlorophyll is correlated with the BOD of the sample. These algae develop in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds based on nutrients discharged to the tributaries within the watershed. As the waters in the SJR travel over the three-or-so-day travel time from Mud and Salt Slough discharge points just upstream of where the Merced River enters the SJR to Vernalis/Mossdale, there is additional algal growth based on the algal populations that are present in the headwaters near where Mud and Salt Sloughs enter the SJR. The net result is that from 50 to at times as much as 80 percent of the planktonic algae and BOD at Mossdale has its origin in the discharges from Mud and Salt Sloughs and the SJR at Lander Avenue.

As discussed below, during the irrigation season (May through September), part of the algal load present in the SJR upstream of Vernalis is diverted by the 30 or so percent of the SJR ag diversions (reported by Quinn and Tulloch, 2002). These diversions change the total load of algae at various locations in the SJR by removing total algal load from the River. They do not change the concentrations of algae in the River. The eastside rivers add low-algal water to the SJR, and thereby increase the total flow of the SJR. The additions tend to dilute the planktonic algal concentrations in the SJR from those present just upstream of where an eastside river enters the SJR; however, since the mixture of the eastside rivers coupled with the upstream SJR waters still contain significantly surplus available forms of nitrogen and phosphorus derived from upstream sources, there is substantial growth of planktonic algae in the SJR.

Since the eastside rivers during the summer and fall tend to be low in turbidity (suspended solids), they would tend to dilute the turbidity within the SJR, thereby promoting algal growth in the SJR because of the potential for increased light penetration below where the eastside rivers enter the SJR. At this time, the potential role of the low turbidity in the eastside rivers in allowing greater algal growth has not been investigated. Dileanis (pers. comm., 2002) has indicated that he is investigating this area and will report on it at a later time. His initial findings include that the Secchi depth (a measure of light penetration) in the SJR increases from the Merced River location to Vernalis. The suspended solids in the River decrease from the Mud and Salt Slough discharge area to Vernalis. This increased water clarity would likely be due to the input of low turbidity water from the eastside rivers that would tend to reduce the light limitation governing algal growth in the SJR, promoting even greater growth of algae than that which occurs in the upstream parts of the SJR near the Merced River.

<u>IEP Database Review</u>. E. Van Nieuwenhuyse (2002) conducted a statistical analysis of the 19 years of data that have been collected as part of the Interagency Ecological Program (IEP) monitoring of the Delta and its tributaries, to evaluate the effects on Delta water quality of South Delta water exports to Central and Southern California. This monitoring program was started in 1983. It has consisted of detailed monitoring of certain parameters at selected locations, such as the continuous monitoring station on the SJR at the northern end of Rough and Ready Island. There has also been monthly sampling of the water near this location for a variety of parameters, including planktonic algal chlorophyll. In addition, there has been monitoring of the SJR at Vernalis. This database is an almost unequaled database for long-term record of monitoring of waterbodies in California. The database used by Van Nieuwenhuyse (2002) is an independent database from that used by Foe, *et al.* (2002) in the Strawman analysis and by Dileanis (2002) in developing Figures 18 and 19.

Van Nieuwenhuyse (2002) examined all data collected in the IEP monitoring program that are potentially relevant to the DO depletion situation in the SJR DWSC. This included the winter/spring data, as well as the summer/fall data. The parameters on which he focused were those that are potentially influential in causing DO depletion within the DWSC. These include planktonic algal chlorophyll at Vernalis, the city of Stockton=s reported ammonia discharges to the SJR just upstream of the DWSC and planktonic algal concentrations present in the SJR just downstream of Rough and Ready Island. He also used the Rough and Ready Island continuous monitoring data to examine the DO depletion that occurs at this location. These data were used as an index to DO depletion that occurs throughout the DWSC.

As discussed elsewhere in this synthesis report, the DO monitoring that occurs at the DWR Rough and Ready Island continuous monitoring station provides a reasonable assessment of the DO depletion that occurs in the upper part of the DWSC near Rough and Ready Island with respect to the upper part of the water column. It does not properly reflect the magnitude of DO depletion that occurs near the bottom of the DWSC. It also does not address the situations where, during higher flows of the SJR through the DWSC, the point of maximum DO depletion occurs further downstream of Rough and Ready Island. These issues are discussed further by Foe, *et al.* (2002) and elsewhere in this synthesis report, with particular reference to the monitoring that has been conducted by DWR in the Hayes cruises.

One of Van Nieuwenhuyse's (2002) conclusions is that there is a strong correlation between DO depletion at Rough and Ready Island (from this database) and the planktonic algal chlorophyll that is present in the SJR at Vernalis. This conclusion is the same as that reported by Foe, *et al.* (2002), using a different database.

Another important conclusion is that the city of Stockton ammonia discharges to the SJR are correlated to DO depletion at Rough and Ready Island. Van Nieuwenhuyse (2002) further concluded that increases in the flow of the SJR at Vernalis tended to reduce the magnitude of DO depletion at Rough and Ready Island. These conclusions from the IEP database are all in accord with the results of the past three years' studies by the TAC.

Leland, *et al.* (2001) reported on the distribution of algae in the San Joaquin River relative to nutrient supply, salinity and other factors. They found that the phytoplankton in the San Joaquin River were primarily centric diatoms, and indicated that the growth of these phytoplankton was found to be limited more by light and flow regime than nutrient supply. Lehman (2002) has reported that the SJR upstream of Vernalis frequently shows substantial changes in the types of algae that are present in the River over short periods of time. These changes may be due to variable inputs of upstream water from the Mud and Salt Slough and SJR at Lander Avenue watersheds, which contain different types of algae that are manifested in the SJR as patches of a certain type of algae that are carried downstream.

Additional information on phytoplankton dynamics and planktonic algal chlorophyll in the Delta has been provided by Ball (1987). Further, Jassby and Cloern (2000) have presented a review of the significance of organic matter, which is principally algal and other sources, as part of the trophic structure of the Delta. Woodard (2000) has reviewed the TOC and DOC data that have been collected over the years in the tributaries to the Delta and within the Delta. These various studies all point to the SJR upstream of Mossdale being an important source of organic carbon for the Delta, and that an appreciable part of this organic carbon is in the form of algae and algal remains (detritus).

***SJR Water Diversions***. The SJR DWSC monitoring data collected over the years in the Hayes cruises, the data collected in the past three years as part of the CALFED-supported studies and the water quality modeling data discussed above and below have all shown that flow of the SJR through the DWSC is a dominant factor in influencing DO depletion in the DWSC. The flow of the SJR through the DWSC is highly dependent on upstream reservoir releases of water and upstream diversions of water. Lee and Jones-Lee (2000a) reviewed the information available on the upstream diversions of the SJR and its tributary flows that are influencing DO depletion in the DWSC. As discussed by Lee and Jones-Lee (2000a), 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. There are basically two types of diversions that need to be considered. One of these is headwater diversions, and the other is diversions that take place within the Valley floor. The magnitude of each type of diversion is summarized below.

Table 9, from Lee and Jones-Lee (2000a), summarizes the State Water Resources Control Board information on water diversions in the SJR watershed. This table shows that the Central Valley Project (CVP) diverts about a million ac-ft/yr from the South 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.

**Table 9**
**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 WPRS 1980)

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 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.

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 exacerbate the SJR DWSC DO problem to the extent that they divert SJR water at Old River.

In addition to diversion of SJR and its tributary waters, which reduce the flow of the eastside rivers into the SJR, there are appreciable diversions of the SJR along its length from the Merced River to the DWSC. Quinn and Tulloch (2002) have reported on their assessment of these diversions. They report that during 1999, 2000 and 2001, the Patterson Irrigation District, West Stanislaus Irrigation District, El-Solyo Water District and Banta Carbona Water District divert about 500 cfs from the SJR during the months of May through August. The Patterson diversion is located near Patterson, California, about 1,000 ft downstream of the SJR Patterson gage. The West Stanislaus Irrigation District intake is located between Patterson, California, and where the Tuolumne River discharges to the SJR. The El-Solyo intake is located just downstream of the SJR Maze gage. The Banta Carbona Water District intake is located between Vernalis and Mossdale.

The three upstream of Vernalis diversions, during the summer divert an average of about 400 cfs. In September, the total irrigation/water districts' diversion of water decreased to about 188 cfs, while in October, diversions amounted to about 50 cfs. With a SJR flow at Vernalis during the same period of about 1,000 to 2,000 cfs, the irrigation districts' diversions diverted between 25 and 50 percent of the SJR flow at Vernalis/Mossdale. Some of this diverted irrigation water is returned to the SJR in tailwater returns. Quinn and Tulloch (2002) estimate that during July the irrigation return waters to the SJR represent about 60 cfs, which is about 15 percent of the water diverted.

Quinn (pers. comm., 2002) indicated that the CVRWQCB estimates the groundwater inflow to the SJR to be about 4.7 cfs/mile. Therefore, in the SJR reach from Patterson to Vernalis (about 15 river miles) the groundwater would add about 70 cfs to the SJR flow. Additional information on the quantity and quality of groundwater inflow to the SJR has been provided by Phillips, *et al.* (1991).

If it is assumed that the SJR water that is diverted contains about 6 mg/L of $BOD_{10}$, the total BOD load removed from the SJR by the ag diversions is about 31,500 lbs/day. This represents a substantial reduction in the total $BOD_u$ load that is diverted from the SJR by ag diversions. Therefore, the ag irrigation diversions are detrimental to the DO problem within the DWSC to the extent that these diversions reduce the flow of the SJR through the DWSC. However, these ag diversions are beneficial to the DO problem in the DWSC as a result of removing a substantial algal ($BOD_u$) load from the DWSC.

***Significance of Stormwater Runoff***. The low-DO problem within the DWSC primarily occurs during the summer/fall. Since the DWSC reach of concern where low-DO problems occur is about the first seven miles of the Channel downstream of the Port, and since this reach has a hydraulic residence time of a few days to 30 or so days, depending on the SJR flow through the DWSC, the loads of oxygen demand of primary concern are those that enter the DWSC during the summer and early to mid-fall. Winter and spring SJR flows and associated oxygen demand loads to the DWSC generally do not lead to low-DO problems in the DWSC. As discussed by Foe, *et al.* (2002) there are exceptions to this situation; however, they are significantly less frequent than those that occur during the summer and fall.

The short residence times of the critical reach of the DWSC of a few days to a couple of weeks have important implications with respect to some potential sources of oxygen demand, such as those associated with stormwater runoff from urban, agricultural and rural lands. Since, typically, there is little or no significant rainfall runoff during the summer and early fall, stormwater runoff from urban and agricultural lands is not a significant source of oxygen demand that causes the primary low-DO problems of concern within the DWSC. An exception to this can occur during mid-fall, such as during October-November, when there are stormwater runoff events that could bring runoff-associated oxygen demand constituents into the SJR and DWSC, that lead to DO depletion below the water quality objective. There is need to examine whether some of the low-DO problems that occur in the DWSC during the fall are potentially related to an increased oxygen demand load to the SJR from upstream of Mossdale stormwater runoff from ag, urban or riparian land sources, or directly to the DWSC from urban runoff from Stockton. This is an area that has not been adequately investigated at this time.

***Upstream Wastewater/Urban Stormwater Sources***. The oxygen demand loads of the city of Stockton's discharge of about 45 cfs of treated domestic wastewaters to the SJR just upstream of where the SJR enters the DWSC have been quantified. Of particular importance is the City's discharge of elevated concentrations of ammonia which can exert a significant oxygen demand in the DWSC. There are, however, a number of upstream of Mossdale municipal and commercial/industrial wastewater sources that have the potential to add oxygen demand to the SJR and thereby, increase the DO depletion problem in the DWSC. Quinn and Tulloch (2002) have reviewed the existing information on these sources.

With the exception of Manteca (6 mgd) and Turlock (10.4 mgd), the CVRWQCB NPDES wastewater discharge permits for municipal and industrial discharges in the SJR watershed above Vernalis generally prohibit wastewater discharges to the SJR and its tributaries during the summer and early fall. According to Tulloch (pers. comm., 2002), Los Banos and Merced wastewaters do not reach the SJR. Modesto's NPDES wastewater discharge permit requires that it discharge its wastewaters to land irrigation systems during the summer and early fall. These land irrigation systems do not have direct discharge to the SJR or its tributaries. There may, however, be groundwater transport of nutrients, especially nitrate, from the wastewater irrigation areas to the SJR or its tributaries during the summer months. Tracy discharges is wastewaters to the South Delta, which at this time do not enter the SJR DWSC. That situation could change if the reverse-flow pumping of South Delta waters into the SJR via Old River is initiated. Further, according to Foe (pers. comm., 2002), Lathrop and Mountain House have proposed NPDES permits which would provide for discharges of wastewaters to the SJR upstream of the DWSC.

As with ag land stormwater runoff, the lack of rainfall during the summer and early fall prevents stormwater runoff from municipal and industrial areas in the SJR watershed from being a major contributor to summer and fall loads of oxygen demand materials to the SJR and its tributaries. As discussed above, however, mid-fall rain could transport oxygen demand materials from municipal and industrial areas in stormwater runoff that could add to the mid- to late fall low-DO problems in the DWSC.

Generally, it can be concluded that since the large municipalities in the SJR watershed, upstream of Vernalis, such as Modesto and Merced, do not discharge domestic wastewaters to the SJR or its tributaries during the summer and early fall months, these municipalities are not major direct causes of the low-DO problem in the DWSC.

***Significance of the Mud and Salt Slough and SJR Upstream of Lander Avenue Watersheds***. Evaluation of the data collected in the summer/fall of 2000 and 2001 of the SJR upstream of Vernalis has shown that two of the SJR tributaries, Mud Slough and Salt Slough, and the SJR upstream of Lander Avenue (Highway 165) are the primary sources of algae that ultimately, after several days of transport with additional growth in the SJR, lead to the high algal related oxygen demand that causes DO depletion below the water quality objective in the DWSC. At times, up to about 80 percent of the oxygen demand load to the DWSC at Mossdale is derived from these three sources.

McGahan (pers. comm., 2002) has provided the following information on the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds. The "Grassland Drainage Area" is only a small portion of the watershed that discharges out Mud and Salt Slough into the San Joaquin River. The Grassland Drainage Area is a 97,000-acre agricultural area with 40,000 acres of subsurface drains that discharges out the San Luis Drain. All of this flow goes into Mud Slough, along with other flows outside of the Grassland Drainage Area. Flows from the Grassland Drainage Area in water year 2000 were 31,260 acre-feet. The total flows from Mud and Salt Slough were 235,490 acre-feet. The Grassland Drainage Area therefore discharged 13 percent of the flow from these two combined sites, and this does not include the flow contribution from the San Joaquin River at Lander Avenue (Hwy 165).

The Mud and Salt Slough watersheds are an important source of other pollutants, including selenium, boron, and salt (TDS). According to McGahan (pers. comm., 2002), the flows from the Grassland Drainage Area have been reduced significantly (47 percent from historical flows) due to the current selenium reduction program over the last five-year period. It will be important in developing the TMDLs to manage the water quality problems in discharges from the Mud and Salt Slough watersheds to integrate the various control programs for selenium, boron and TDS with nutrient/algae control programs so that they do not exacerbate the low-DO problem in the DWSC.

Thus far, studies conducted by Stringfellow and Quinn (2002) within the Mud and Salt Slough watersheds during the summer/fall 2000 have shown that the primary source of algal nutrients (nitrogen and phosphorous compounds) that lead to high algal concentrations/loads at the mouths of Mud and Salt Sloughs where they enter the SJR, is water derived from agricultural activities. These studies show that, at least during the summer/fall of 2001, the public and private wildlife refuges were not major sources of nutrients and algae compared to the agricultural drain waters during the summer months. A study of ag-drain and tailwater discharges to the SJR upstream of the DWSC indicated that these discharges of tailwater during the summer/early fall irrigation season may not be important sources of oxygen demand that lead to low-DO problems in the DWSC.

Johnston, *et al.* (1965) made measurements of the nitrogen and phosphorus content of tile drainage waters in the San Joaquin Valley near Fresno, California. While the purpose of their study was to investigate the losses of fertilizer, it provides information on the potential for tile drain waters to serve as a source of nutrients which can lead to algal growth problems and thereby develop oxygen demand in the waters downstream of the tile drains. Johnston, *et al.*, studied tile drains from 11 systems on the west side of the San Joaquin Valley, including seven in Fresno, three in Merced and one in Stanislaus County. Based on the study of a number of different tile drain systems, Johnston, *et al.*, reported that the nitrogen content of the drainage effluent ranged from 2 to 14 mg/L N. The phosphorus concentrations in tile drain water ranged from 0.053 to 0.23 mg/L P.

While Johnston, *et al.*, characterized the phosphorus losses as small compared to the fertilizers applied, the concentrations of both N and P in the tile drain waters are sufficient to represent a potentially significant source of nutrients which would stimulate the growth of algae. This particular situation is of concern in the Mud and Salt Slough watershed areas, where discharges from the tile drains potentially represent a starting point for the development of the algae that become the important seed to cause Mud and Salt Sloughs to have high concentrations of algal-derived oxygen demand.

Kratzer and Shelton (1998) reviewed the studies conducted by them and others in the late 1980s on the sources of nutrients and suspended sediment in the surface waters of the San Joaquin River watershed. They reported that the approximate nutrient concentrations in ag irrigation tailwater (surface return flow) were nitrate at 6 mg/L N, ammonia at 0.1 mg/L N, orthophosphate at 0.2 mg/L P and total phosphorus at 0.4 mg/L P. Subsurface agricultural drainage (tile drains) was reported by Kratzer and Shelton, based on the California Department of Water Resources (1975) report, to contain nitrate at 25 mg/L N, ammonia at 0.2 mg/L N, orthophosphate at 0.05 mg/L P and total phosphorus at 0.1 mg/L P. These results are in agreement with those reported by Johnston*, et al.* (1965). It is evident that ag tailwater and tile drain water can contain sufficient N and P to stimulate substantial growth of planktonic algae. The Mud and Salt Slough watershed tailwater and tile drain water will need to be investigated with regard to their contribution of nutrients that stimulate the growth of algae in the headwaters of the Mud and Salt

Slough watersheds, that in turn lead to the high concentrations of algae and BOD at the point where Mud and Salt Sloughs discharge to the SJR.

***Eastside Rivers***. The Tuolumne, Stanislaus, and Merced Rivers (eastside of the SJR rivers), bring high-quality Sierra Nevada mountain-derived waters into the SJR. These eastside rivers have been found to have a low algal and oxygen demand content. The addition of eastside river water to the SJR in the summer and fall can be a major asset to controlling the low-DO problem in the DWSC, since this low algal content water dilutes the high algal content water of the SJR, and thereby reduces the concentration/load of oxygen demand to the DWSC.

***City of Stockton Wastewaters***. The city of Stockton wastewater discharges of elevated ammonia at times can be a significant contributor to the low-DO problem in the DWSC. As discussed above, at times, the city of Stockton's wastewater oxygen demand load, which is principally in the form of ammonia, has been found to represent about 50 percent of the total BOD load to the DWSC. The CVRWQCB has recently adopted a revised NPDES wastewater discharge permit for the city of Stockton that limits the monthly average ammonia concentration in the effluent to 2 mg/L for aquatic life toxicity reasons. The permit may be appealed to the State Board. If the permit is upheld, then the oxygen demand load reduction would result in up to a 20,000 lbs/day $BOD_u$ reduction.

**Water Quality Modeling**

Several modeling approaches have been used in this study of oxygen demand sources and their impacts on the DO in the DWSC. They include spreadsheet mass-balance box-model calculations, which relate oxygen demand loads to DO deficit in the DWSC. The results of these box model calculations were presented above. A similar box-model approach was used by Foe, *et al.* (2002) to determine the major sources of oxygen demand that enter the SJR upstream of Mossdale. Further, statistical evaluation of the 19-year IEP database has been conducted by Van Nieuwenhuyse (2002). The results of his studies have been presented above. Also, an estimate has been made of the expected algae and BOD concentrations in the DWSC that should be present if all of the algae within the DWSC developed in the DWSC. These results are presented in a subsequent section.

***Evaluation of Oxygen Demand Rate Constants.*** Litton (2001, 2002) and Foe, *et al*. (2002) have conducted long-term BOD tests. Litton (2002) has used these results to characterize the BOD exertion during the BOD test. Typically, the BOD reaction is formulated as a first-order exponential reaction, where the instantaneous rate of BOD decay is proportional to the BOD remaining in the sample. This relationship is described by Chapra (1997), Thomann and Mueller (1987) and Bowie*, et al*. (1985), and is shown in equation (4).

$$dL/dt = -kL \tag{4}$$

Where L is the amount of BOD remaining to be oxidized.

This equation integrates to

$$L = L_0 \times e^{-kt}$$

Where $L_0$ is the initial amount of BOD in the sample at the beginning of the test, and
k is the BOD exertion rate constant, with units of "per day."

Litton (2002) has indicated that the ratio of $BOD_u$ to $BOD_5$ is

$$BOD_u/BOD_5 = 1/(1 \; ! \; e^{-k \times 5}) \qquad (5)$$

Where $BOD_u$ is the ultimate (long-term) BOD in the sample.

Litton's 2001 BOD exertion rate constants and associated multipliers are shown below in Table 10.

**Table 10**
**2001 Mean and Standard Deviation of the First-Order BOD Decay Constants at 20EC**

| **Location** | **k at 20EC ($d^{!1}$)** | | **$BOD_u/BOD_5$** |
|---|---|---|---|
| | **mean** | **std. dev.** | |
| | BOD / CBOD / NBOD | BOD / CBOD / NBOD | BOD / CBOD / NBOD |
| San Joaquin River | 0.087 / 0.11 / 0.057 | 0.019 / 0.022 / 0.017 | 2.8 / 2.4 / 4.0 |
| DWSC | 0.094 / 0.11 / 0.076 | 0.034 / 0.023 / 0.038 | 2.7 / 2.4 / 3.2 |

From Litton (2002)

According to Litton, a reasonable $BOD_u/BOD_5$ multiplier for the DWSC 2001 data is estimated to be 2.75 at 20ºC. The multiplier for CBOD is 2.4, which was estimated from nitrogen-inhibited BOD bottle data.

Chen and Tsai (2002a) have reported using a $BOD_5$ decay constant of 0.1 per day, a $BOD_u$ to $BOD_5$ ratio of 2.54, an ammonia decay constant of 0.05 per day and a DO to ammonia ratio of 4.57. According to Bowie, *et al.* (1985), the Chen and Tsai values are typical of what are normally used in oxygen demand modeling. They are, however, somewhat higher than those found by Litton for the SJR and the DWSC during 2001. It is unclear at this time if the differences are sufficient to cause significant deviations between the loads of oxygen demand to the DWSC and the DO responses found, compared to those predicted by the Chen and Tsai modeling.

Since the BOD measurements are made at 20ºC, there is need to correct the rate of BOD exertion for the impact of temperature on this rate. Normally, the impact of temperature on BOD rate constants is corrected through the equation (6):

$$k_T = k_{20}\theta^{(T-20)} \qquad (6)$$

Where $k_T$ is the rate constant at temperature T,
$k_{20}$ is the rate constant at 20ºC, and
θ is an empirical coefficient.

The typical value of θ used in BOD modeling is 1.047. Since temperatures as high as 28ºC are sometimes found in the DWSC, a 20ºC 0.1 rate constant becomes 0.144 at 28ºC. As a result, a $BOD_u$ of 10 mg/L at Channel Point would exert over a 10-day period about 6.3 mg/L of oxygen demand at 20ºC, while at 28ºC, the BOD exerted would be 7.5 mg/L. Since most of the time there is not an eight-degree temperature differential between 20ºC and the DWSC temperature, the magnitude of temperature impact on BOD exertion in the DWSC is a fraction of a mg/L.

As discussed above, there is concern that assessing the BOD of algae in a five-day test may underestimate the long-term BOD of the water. Fitzgerald (1964) reported that assessing the BOD of algae often shows a significant lag between the start of the test and the initiation of oxygen depletion. Fitzgerald's studies showed that this lag-time was the period of time over which the algae die in the BOD bottle. This period can be several days to several weeks, depending on the type of algae and other factors. Examination of the long-term BOD tests that Litton (2001, 2002) and Foe*, et al.* (2002) conducted showed a smooth regression from the beginning of the test – i.e., no lag.

***Deterministic Modeling of Oxygen Demand Load-Response Relationships for the DWSC.*** The DWSC and the SJR, almost to Vernalis, are part of a freshwater tidal system where tidal flows, ranging from 2,000 to about 4,000 cfs, occur through the DWSC each day. In addition, there is the downstream flow of the SJR through the DWSC which can range from a negative (upstream) flow to a few thousand cfs downstream. This creates a highly complex flow system that must be properly modeled in order to assess the impacts of altered oxygen demand load from various sources on DO depletion in the DWSC.

In the mid-1990's, the city of Stockton contracted with Systech Engineering (Dr. Carl Chen) to develop a model that could be used to predict the impact of the City's domestic wastewater discharges to the SJR, just upstream of the DWSC, on the dissolved oxygen resources within the DWSC. The city of Stockton model (Schanz and Chen, 1993; Chen and Tsai, 2002a) of the SJR, near the DWSC and the DWSC, is a deterministic model that describes the tidal and net SJR flow through the DWSC and attempts, through a set of differential equations, to describe the processes that govern DO depletion in the DWSC as a function of oxygen demand loads. This model was reviewed by the US EPA (1999a) and found to be of appropriate structure. With the initiation of these DO TMDL studies, the Chen model was modified so that it more appropriately matched the DO depletion found in the summer/fall 1999 studies. Chen and Tsai (2002a) have reported on the modeling results obtained during the TAC studies. Generally, there was some agreement with the general trends between the measured DO depletion at various times and locations in the DWSC and the Chen model simulations of the DO during the summer/fall 1999. There were also some deviations between the tuned model simulation results and the field data to which the model was tuned.

The improved Chen model, developed to simulate the 1999 data, was used to simulate the dissolved oxygen conditions in the DWSC found during the summer/fall 2000. Again, the model which had been tuned to 2000 results showed some similarity between the simulated values and the measured values. However, in both 1999 and 2000, there were times when there was relatively poor agreement between the modeled simulated results and the DO within the DWSC. Similar problems occurred for other modeled constituents, such as nitrogen and phosphorus compounds, planktonic algal chlorophyll and several other parameters.

In the original CALFED proposal submitted in January 2001 to support the summer/fall 2001 studies, funding was budgeted to expand the Chen modeling of the DWSC through the use of a real-time or near real-time forecasting modeling approach. From information that was to be developed through the monitoring program of the loads of oxygen demand present at Mossdale from SJR upstream sources and discharged to the SJR by the city of Stockton, attempts were to be made to determine whether the Chen model properly predicted the DO depletion that was occurring in the DWSC. Since this was to be a forecasting modeling approach, discrepancies between the predicted DO depletion and the measured DO depletion were to be used to modify the Chen model to more properly simulate the field observations. Through this interactive forecasting modeling approach, it was felt that by the fall 2001, a somewhat better simulation of DO depletion for certain oxygen demand loads would be achieved. Unfortunately, the CALFED Science Program chose not to support further work with the refinement of the Chen model during the summer/fall 2001. This means that little progress has been made in modeling oxygen demand load to the DWSC DO response in the DWSC during 2001 and thus far in 2002.

One of the issues of concern to the CALFED Science Program management and their peer review panel that reviewed the SJR Low-DO Directed Action proposal submitted in January 2001, was the belief that DO depletion in the DWSC could not be adequately modeled with a one-dimensional model of the Chen model type. Since, at times, there is short-term thermal stratification that occurs within the DWSC, which is apparently related to somewhat lower dissolved oxygen in the near-sediment waters, it was suggested that the modeling of oxygen demand load DO depletion in the DWSC must be done with a two-dimensional model. It appears, however, that the Science Program peer review panel did not adequately consider the highly transitory nature of the thermal stratification that occurs, and that its impact represents only a small part of the DWSC volume that is of concern with respect to DO depletion within the DWSC.

For the two-dimensional modeling to be meaningfully applied, a substantial ongoing monitoring program of temperature profiles must be established, operated and maintained to provide the input data for the two-dimensional model. Initially, the monitoring of temperature profiles will have to involve the use of a comprehensive array of thermister chains and flow measurements. It is likely that, over time, the number and location of these measurements can be reduced to a few key measurements at certain locations.

Without this information, the two-dimensional model will have to be reduced to a one-dimensional model, assuming that it is a mixed system with occasional short-term periods of stratification that are sometimes associated with greater-than-normal DO depletion. It should also be noted that, once the two-dimensional model has been developed, it is going to have to be tuned and then verified through yet to be developed monitoring. It is not possible to use the two-dimensional model on the existing database, because the drivers for the two dimensions (i.e., temperature/density profiles) do not exist at the frequency and locations where it will be critical to have this information. Therefore, it is likely to be at least three, and possibly five, years before a properly evaluated two-dimensional model is available for use to predict the DO deficit in the DWSC as a function of oxygen demand loads to the DWSC.

CALFED has contracted with HydroQual, a modeling firm in New Jersey, and Stanford University faculty, with the assistance of University of California, Davis, faculty, to develop two-dimensional models of oxygen demand DO depletion for the DWSC. At this time, the scopes of work for this modeling effort are being developed. While these models, if successful, may be of assistance in describing oxygen demand load DO relationships in the DWSC, which would account for the short-term thermal stratification that leads to slightly greater DO depletion in the near-bottom waters at various times and locations in the DWSC, the current CALFED Science Program modeling effort will be of limited value to helping the SJR DO TMDL Steering Committee and the CVRWQCB in formulating the initial implementation approach for managing low-DO in the DWSC, since the modeling results were significantly delayed beyond the time the Steering Committee and the CVRWQCB needed results for formulation of the TMDL and its allocation among stakeholders, which must take place by June 2003.

In winter 2001-02, CALFED approved a limited amount of funds to support Chen to use his current model to predict DO depletion in the DWSC, compared to the actual depletion that occurred in the summer/fall 2001. While graphical presentation of the modeling simulation compared to some of the data collected on the DWSC during the summer/fall 2001 has been made available, a report covering the results of this modeling effort is not yet available. The graphical presentation (Chen and Tsai, 2002b) of the results shows that the Chen model, tuned to 2000 studies results, continued to have significant problems in properly simulating the DO depletion at various times and locations within the DWSC. *(A section devoted to a review of Russ Brown's comments on Chen's 2001 modeling results will be added when they become available.)*

Rajbhandari (2001) of the Department of Water Resources is developing a modification of the DSM-2 model for prediction of DO depletion in the DWSC. Further work on this model is being conducted by DWR.

A factor that influences the reliability of simulating DO depletion in the DWSC from the measured oxygen demand loads is that the various investigators, such as two different groups in DWR and the city of Stockton, who are making measurements of DO and other parameters in the DWSC during the summer and fall, sometimes show differences between each of their measured values at approximately the same time and location. A comparison of the city of Stockton with the Hayes cruise DO measurements in the summer/fall of 2000 showed that the city of Stockton and the DWR Hayes monitoring of the DWSC DO were consistently about a mg/L different at about the same time and location. The Hayes DO measurements were about a mg/L higher than the city of Stockton DO measurements. This difference occurred in the DO 5 to 6 mg/L range, which is the critical range for these measurements. The mg/L difference in this range could be the difference between violating or not violating the water quality objective.

In an effort to determine if there was a systematic error between the city of Stockton and the Hayes cruise data DO measurements, a special QA/QC study on DO measurements was conducted in the summer 2001. These results, as reported in a subsequent section, do not show such an error. The differences between the 2000 Hayes cruise data and the city of Stockton measurements of DO are apparently related to the fact that the city of Stockton DO measurements are made at mid-depth, while the Hayes cruise data measurements are made near the surface. Frequently the DWSC surface DO concentrations are a mg/L or more higher than at mid-depth. The Chen and Tsai (2002a) model results predict a mid-depth DO, and should agree with the city of Stockton measurements, and be somewhat different than the surface water DO measurements made during the Hayes cruises.

An issue of particular concern to many of the stakeholders in the SJR DWSC watershed, who potentially face spending large amounts of funds to control the oxygen demand problem, is whether the current Chen model is sufficiently reliable to provide guidance on how best to manage the low-DO problem in the DWSC. If the TMDL allocation shows that the ag interests in the Mud and Salt Slough watersheds need to reduce their nutrients that become algae at the mouths of these sloughs by a certain amount, say 25 percent, is this estimate reliable plus or minus five percent, or 20 percent? At this time, an answer to this issue is not available.

Lee and Jones-Lee (2000a), in their discussion of the modeling in their "Issues" report, delineated the importance of the model being expanded to include addressing low-DO episodes. At this time, the Chen model more or less predicts a mid-depth DO in the water column. While under certain conditions, it is possible to tune the model so that the data points and the simulation match fairly well, at other times the simulation does not match the data well. Part of this is due to the scatter in the data. Another part is due to the inability of the model to properly track constituents such as ammonia and organic nitrogen. Lee and Jones-Lee (2000a) recommended that an effort be devoted to examining the relationship between the average concentration of DO in the water column predicted by the model and the excursions above and below this prediction, based on actual data obtained at various locations in the DWSC. This recommended evaluation has not been done, with the result that the model has yet to come to grips with a number of major issues in properly simulating DO in the DWSC water column and at various locations in the DWSC.

Now that the CVRWQCB staff have proposed a Phase I TMDL implementation target, the modeling should be designed to make predictions of how altered loads achieve that target, at all locations and times where low DO occurs in the Deep Water Ship Channel. The modeling needs to be expanded to stations nearer Turner Cut, since at times, especially under high flow, the maximum oxygen depletion is shifted downstream to the Turner Cut region.

Another issue that needs to be addressed is whether the thermal stratification that occurs near the surface and the DO stratification that often occurs near the bottom can be modeled within the financial resources that are available for data gathering. The existing database is not adequate to build a model that has any potential reliable predictive capability in addressing these issues.

It is also not clear whether the problems with the model being able to be tuned to the whole dataset for a particular situation are due to the variability of the input parameters or fundamental problems with the modeling processes. It is apparent that, in order to potentially make the modeling effort more reliable, a much more comprehensive monitoring program of the oxygen demand loads to the DWSC and the DO responses to these loads as a function of parameters that influence responses must be obtained. There is need to plan the monitoring program for the Phase I implementation, to develop the database needed so that, during Phase I, the modeling can be improved.

It is important to understand that the current HydroQual modeling will not likely eliminate many of the significant problems that are found with the Chen modeling, since the database upon which to build the HydroQual model to address issues of concern, does not exist. Further, because of the way the funding has developed, there will be limited (if any) additional data collected which can be input to the HydroQual model. As a result, the HydroQual model will likely provide little in the way of improvement in predictive capability than the current Chen model. This will result in the Phase I TMDL and its allocation having to be based largely on the Strawman analysis and intuition about what the members of the SJR DO TMDL Steering Committee feel may be occurring in the Deep Water Ship Channel with respect to oxygen demand load-DO response relationships.

***Application of the Streeter-Phelps Model.*** As part of the Strawman analysis, Foe, *et al*., (2002) have applied the Streeter-Phelps equation/model to helping to understand DO depletion in the DWSC. This equation relates the oxygen demand load to a riverine waterbody to the DO depletion that will occur downstream of the introduction of the load. It is traditionally used to predict the impact of domestic wastewater discharges of BOD on the DO concentrations in a river. The original Streeter-Phelps equation is a simplistic model, which incorporates dissolved oxygen depletion due to a BOD load with reaeration of the waterbody through atmospheric surface aeration. These two processes are modeled as first-order processes, where the rate of BOD exertion is proportional to the BOD concentration, and the rate of reaeration is proportional to the oxygen deficit from saturation. The typical oxygen profile downstream of a BOD load is a curvilinear relationship, where at the minimum DO, the rate of DO depletion equals the rate of reaeration. This point is referred to as the point of inflection in the DO sag relationship.

Foe, *et al.* (2002) used the unmodified Streeter-Phelps model to examine how the point of inflection in the DWSC would change with changes in flow of the SJR through the DWSC. The changes in flow affect the travel time of the oxygen demand constituents through the critical reach of the DWSC. Using the flow-travel time relationship developed by Brown (2002a), as shown in Figure 7, and the city of Stockton's measured BOD concentrations at Channel Point, as well as the DO deficit from saturation measured at this location, Foe, *et al.* (2002) simulated the location of the point of inflection for DO depletion in the DWSC. In order to make the unmodified Streeter-Phelps equation fit the observed data, based on city of Stockton monitoring and the DWR Hayes cruises, Foe, *et al.* (2002) found it necessary to use a BOD exertion rate constant of 0.25 per day. This is over 2.6 times the BOD exertion rate constant measured by Litton (2002) of 0.094 per day.

As discussed by Bowie, *et al.* (1985), Chapra (1997) and Thomann and Mueller (1987), many of those who utilize the Streeter-Phelps equation have found it necessary to incorporate a variety of other factors in order to be able to reliably simulate DO depletion downstream of a BOD source. Of particular importance in many situations is sediment oxygen demand, algal growth/ photosynthesis and respiration and, in some systems, particulate BOD settling. The unmodified Streeter-Phelps equation used by Foe, *et al.* (2002) does not include a variety of factors that are known to influence DO concentrations in the DWSC. Litton (2002) has reported that a significant part of the BOD removal in the DWSC is related to particulate BOD settling.

Some of the observations made by Foe, *et al.* (2002) utilizing the unmodified Streeter-Phelps relationship include that, on the average, the $BOD_5$ concentrations measured by the City at Channel Point are lowered by 0.06 mg/L for each hundred cfs increase in SJR flow through the DWSC.

Foe, *et al.* (2002) indicated that the point of inflection for the oxygen sag curve occurred 0.2 to 0.3 mile further downstream with each hundred cfs increase in SJR flow through the DWSC. In a comparison between their Streeter-Phelps-predicted point of inflection with its actual location, based on city of Stockton and DWR cruise data, showed that this point was consistently about 2.5 miles further upstream than it actually occurred.

Foe, *et al.* (2002) examined the effect of changing the temperature on the oxygen profiles simulated from the unmodified Streeter-Phelps. Overall, Foe, *et al*. (2002) found that higher temperatures tend to cause greater DO depletion at the point of inflection.

Using the unmodified Streeter-Phelps approach for a 10 to 13 mg/L $BOD_u$ and a flow of 1,000 cfs, Foe, *et al.* (2002) predicted that the Channel will need between 3,300 and 8,500 lbs/day of additional DO, respectively, to avoid violations of the water quality objective. These amounts are in general agreement with the average conditions (2,300 lbs/day) that were found in the box model calculations presented previously, which were based on the average conditions that have occurred over the past three years. Further, they are in general agreement with, but somewhat lower than, Brown's (2002b) estimate of needed aeration (10,000 lbs/day).

***Estimating Algal Growth Within the DWSC.*** There is concern about the potential influence of algae that develop in the DWSC on oxygen depletion in the DWSC. Lehman, *et al.* (2001) reported that the increase in algal biomass in the DWSC was up to 100 kg chlorophyll *a* per day (220 lbs/day), and that, at this rate, the DWSC algal biomass development is similar to the upstream daily loads of algal biomass to the DWSC. It is of interest to evaluate the expected growth of algae in the DWSC based on its morphological, hydrological and nutrient characteristics. An estimate of this growth can be obtained from the Vollenweider-OECD eutrophication modeling results reported by Jones and Lee (1986) and Lee and Jones-Lee (2001a, b). Based on empirical data collected from over 750 waterbodies located throughout the world, it is possible to estimate the amount of algae that should develop in the DWSC. This estimate is based on a normalized available phosphorus load to the DWSC, considering its morphology (mean depth) and hydrology (hydraulic residence time). This normalized phosphorus load translates to an average in-waterbody phosphorus concentration. The average available phosphorus concentration in the DWSC during the summer months is about 0.1 mg/L P. Using the Jones-Lee and Lee updated relationship between normalized phosphorus load and planktonic algal chlorophyll, it is found that the DWSC should develop about 10 to 15 µg/L of chlorophyll *a* by the time the water reaches Turner Cut, when the SJR flow through the DWSC allows at least a 10-day travel time between Channel Point and Turner Cut.

Examination of the city of Stockton data for station R7 (just upstream of Turner Cut) shows that frequently during the summer/fall of 2000 and 2001, the planktonic algal chlorophyll at this location is from 5 to 17 µg/L – i.e., in the range of the expected planktonic algal chlorophyll based on Vollenweider-OECD modeling results. This concentration of planktonic algal chlorophyll translates, according to the relationship shown in Appendix D, to 1 to 2 mg/L $BOD_5$. These are the typical concentrations of $BOD_5$ measured by the city of Stockton during 2000 and 2001 at Turner Cut. Therefore, it can be concluded that the DWSC is growing algae in accord with the growth of algae that typically occurs in waterbodies located throughout the world.

Assuming 1 mg/L $BOD_5$ in the Channel due to in-Channel algal growth and the Channel volume, it is found that algal growth in the Channel could represent on the order of 120,000 lbs of $BOD_u$. Using a 10-day travel time through the Channel, the algal growth would amount to about 12,000 lbs/day of $BOD_u$. It is evident that the primary source of oxygen demand for the Channel, when the city of Stockton's discharges contain a few mg/L ammonia N, is upstream sources, since on the average the algal $BOD_u$ loads to the Channel are on the order of 67,000 lbs/day at Mossdale.

An issue that needs to be considered in applying the Vollenweider-OECD eutrophication modeling approach to the DWSC is that significant new algal biomass in the DWSC arising from algal growth would be primarily found in the lower parts of the Channel near Turner Cut. It is the experience of the authors that long, thin waterbodies like the DWSC should be modeled with a "plug-flow" modeling approach, where maximum algal biomass will occur at the downstream end of the waterbody. The net result is that most of the algal growth that occurs in the DWSC is likely exported from the DWSC to the Central Delta at Turner Cut and Columbia Cut.

It is important to recall that any algal growth that occurs in the DWSC is accompanied by oxygen production, where, unless the surface waters of the DWSC become oversaturated with respect to DO and there is loss of the photosynthetically produced oxygen to the atmosphere, the oxygen produced by the algal growth is available to satisfy the oxygen demand associated with it. Typically, the near-surface waters of the DWSC are found to be undersaturated with respect to dissolved oxygen. A possible exception could occur in late afternoon, during periods of intense photosynthesis in the upper one to two feet of the DWSC. Further studies are needed to determine if there are periods during the afternoon when there is short-term supersaturation of DO in the surface waters of the DWSC.

An issue that has not been addressed in these studies, as well as in the modeling, is the potential for zooplankton and clam grazing of algae that could significantly impact phytoplankton concentrations. Since zooplankton grazing can significantly impact phytoplankton populations over short periods of time, and since clam harvesting of zooplankton has been found to be an important factor in influencing phytoplankton populations within the Delta (Foe, pers. comm., 2002) it is possible that some of the unexplained changes in concentrations of phytoplankton in the SJR upstream of the DWSC and within the DWSC could be due to zooplankton and clam grazing of phytoplankton. Litton (pers. comm., 2002) has reported that there are large numbers of clams in the DWSC sediments near Turner Cut. Current measurements and modeling have not measured or incorporated the potential for zooplankton and clam grazing of phytoplankton as a factor that could influence phytoplankton populations in the SJR upstream of the DWSC and within the DWSC.

Since there are pulses of pesticide-caused zooplankton toxicity present in the SJR and DWSC, it is possible that pesticides discharged from agriculture in irrigation tailwater and discharged from urban areas in stormwater runoff to the SJR and the DWSC influence zooplankton populations, which in turn influence phytoplankton populations. These situations could explain some of the changes in phytoplankton concentrations that are found in the SJR and DWSC.

**South Delta Barrier Modeling Results**

During the course of the study, it became evident that the operation of the South Delta Channel barriers (see Figure 5) was important in influencing the amount of SJR flow at Vernalis that was diverted into Old River for export to Central and Southern California versus allowed to continue down the SJR into the DWSC. The South Delta has three main channels which convey water from the SJR through Old River to the State and Federal Project export pumps in the South Delta. These channels have rock barriers installed each spring to help control water levels within these channels. CALFED, as part of the Record of Decision, is obligated to replace the temporary rock barriers with permanent mechanical barriers. Hildebrand (pers. comm., 2001) suggested to the SJR DO TMDL Steering Committee and TAC that it may be possible to provide additional water to the SJR DWSC by auxiliary low-head, reverse-flow pumping of South Delta water over the permanent barriers.

In order to investigate this situation, one of the CALFED 2001 Low-DO Directed Action projects was devoted to modeling water flow through the South Delta in order to assess the feasibility of the use of auxiliary flow pumps across South Delta flow barriers to increase the flow of the SJR through the DWSC. Nader (2002) has issued a summary report on this modeling effort. While at this time the modeling effort is not complete, the initial results indicate that it is potentially technically and economically feasible through low-head, reverse-flow pumping across the permanent barriers to add substantial South Delta water to the SJR via Old River that would pass through the DWSC.

The initial modeling has shown that the auxiliary reverse-flow pumping would significantly improve the relatively poor water quality that now exists in the South Delta, associated with the temporary rock barriers creating relatively stagnant waterbodies in some of the channels. The improvement in water quality would arise from the fact that the reverse-flow pumping over a permanent barrier would largely pump high quality Sacramento River water that is diverted from its course toward being exported to Central and Southern California via the State and Federal

Projects. At this time, during the summer, the water in the South Delta is largely San Joaquin River water which has high algal concentrations and experiences DO concentations below the water quality objective.

One of the potential benefits of low-head reverse-flow pumping across the South Delta barriers is the ability to stabilize the flow of the SJR through the DWSC. Flow stabilization would eliminate some of the significant changes in SJR flow through the DWSC that, under certain conditions, can lead to severe DO depletion. Further, stabilized flow would be an asset to managing aeration in the DWSC.

There are a number of issues that need to be addressed before the reverse-flow pumping approach could be adopted. These include the potential impacts of the approximately 200 cfs of ag drain water that is discharged to the South Delta each summer from agricultural activities in the South Delta. This ag drain water would contain a number of potential pollutants that could cause adverse impacts on water quality in the South Delta and the SJR below where Old River intersects with the SJR. Also of concern is that the city of Tracy currently discharges its domestic wastewaters to a South Delta channel. Other developing cities will likely propose to follow a similar approach. The municipal wastewater loads to the South Delta could cause significant water quality problems in the South Delta. There is need for a multi-year water quality monitoring/modeling project to evaluate the potential water quality problems associated with the reverse-flow pumping of water across the permanent barriers when they are installed.

**QA/QC Issues**

One of the issues of concern in any study of this type is the reliability of the database developed upon which management decisions involving expenditures of large amounts of funds will be based. Each of the PIs generating data in this study followed standard QA/QC procedures for their respective organizations. Duplicate samples, spikes and in some cases, split sample comparisons were made. Some of the PIs have reported the results of the QA/QC program in their data reports. In general it is believed that the data generated in this study is neither worse nor better than the typical water quality data generated in studies of this type.

In an attempt to try to address two specific QA/QC issues, the project PI, G. F. Lee (2001a), organized a proposed QA/QC program, which was to enable the investigators making similar measurements to compare the results. A study of this type on DO measurements was conducted in July 2001 at the DWR Rough and Ready Island station. The results of this study have been reported by Stringfellow (2001). His report and other information on the QA/QC program is available on the SJR TMDL website, www.sjrtmdl.org. The DO measurements made by the various investigators all agreed with each other, as well as agreed with the DWR Rough and Ready Island monitoring station results. It became clear that, at least under those conditions, the various investigators could measure DO reliably. As of yet, the data collected in the summer/fall of 2001 have not been made available/examined so that a comparison between the results of the various investigators for measurements of DO and other parameters could be conducted.

Another parameter of particular concern with respect to reliability of measurements, is the planktonic algal chlorophyll. During the July 2001 QA/QC study at Rough and Ready Island, each of the investigators making chlorophyll measurements were to make measurements from a single sample. As of this time, the results of these measurements have not been reported. It has been found, however, that Dahlgren of the University of California, Davis, used a different chlorophyll extraction procedure using methanol than the other investigators who extracted the chlorophyll with acetone. Dahlgren is not part of the TAC studies and therefore, has not been involved with the TAC in planning, implementing and reporting of the results. He has, however, significantly contributed to this project through making his data available prior to their publication.

**DO Water Quality Objectives**

As discussed by Lee and Jones-Lee (2000a), there has been considerable discussion about the appropriate dissolved oxygen water quality objective for the Deep Water Ship Channel (DWSC) that will protect the beneficial uses of the Channel, upstream waters and the Delta without unnecessary expenditures for DO depletion control. The current Central Valley Regional Water Quality Control Board Basin Plan objective (CVRWQCB, 1994) for dissolved oxygen is that the concentration of DO at any location in the Deep Water Ship Channel between Channel Point and Disappointment Slough shall not be less than 6 mg/L between September 1 and November 30, and 5 mg/L between December 1 and August 31. Gowdy and Foe (2002) have recently reviewed the origin of these objectives. The 6 mg/L value is related to some extent to the State Water Resources Control Board's perceptions of the concentration of dissolved oxygen needed in the Deep Water Ship Channel to not inhibit fall-run Chinook salmon through the Deep Water Ship Channel to their spawning areas upstream. The 5 mg/L objective relates to protection of aquatic life. It coincidentally is similar to, but not the same as the US EPA (1986, 1987) recommended water quality criterion for protection of aquatic life, since the US EPA allows averaging of DO concentrations in meeting the objective, and low DO concentrations to occur near the sediment water interface.

The DO TMDL target for the DWSC is an extremely important value that could influence large expenditures for oxygen demand constituent control in the watershed, aeration of the DWSC and/or enhanced flow of the SJR through the DWSC.

Gowdy and Foe (2002) have proposed that the TMDL would be implemented with a phased approach, where during the initial phase, the following issues will be addressed:

- *"further development of source and linkage analysis to refine allocations of responsibility and source control measures;*
- *study of the effectiveness of initially implemented alternatives in meeting the interim DO performance goal;*
- *design of improvements to implemented initial phase alternatives as necessary to meet final Basin Plan DO objective; and*
- *an examination of the technical basis for the Basin Plan DO objective and, if appropriate, modification of the objective through the required State and Regional Board processes."*

They indicate that the number of TMDL phases and specific actions in each phase will be defined as part of the TMDL implementation plan that will be developed after June 2003. Gowdy and Foe (2002) did not define the length of the initial phase of the TMDL.

During the initial phase of the TMDL implementation, Gowdy and Foe (2002) have proposed as the interim DO water quality target that,

> *"Between June 1 and November 30 dissolved oxygen shall not be less than 5.0 mg/l measured as a 7-day mean of daily minimums, with no daily minimum below 3.0 mg/l. The Basin Plan objective of 5.0 mg/l will be applicable between December 1 and May 31."*

Based on a review of the literature (see Lee and Jones-Lee, 2000a), this proposed interim TMDL goal would not be expected to significantly adversely impact the aquatic life resources of the DWSC. It would be protective of fish and other aquatic life from death caused by low DO. It would represent a reduced rate of growth of fish and some other forms of aquatic life when the DO is less than about 5 mg/L. The reduced rate of growth of fish that would occur for DO between 3 mg/L and 5 mg/L for a seven-day period would not likely be significantly adverse to the fisheries and other aquatic life resources of the DWSC and connected waterbodies.

During the final phase of the TMDL implementation, which could be from five to ten years after June 2003, the DO TMDL target would become the CVRWQCB water quality objective. It is possible that, by the time the final phase of the TMDL implementation is initiated, the CVRWQCB water quality objective for the DWSC may be changed from the current 5 mg/L during December 1 through August 31 and 6 mg/L between September 1 through November 30. Also, rather than the current absolute minimum of no exceedance of these objectives, a daily averaging of the DO concentrations, reflecting photosynthetically caused diel variations in DO, where early morning concentrations in the surface waters are significantly lower for a few hours than late afternoon concentrations, would be used in assessing compliance with the water quality objective. This approach is acceptable to the US EPA and is the approach followed in a number of states (Delos 1999).

Another possible change in the current CVRWQCB DO water quality objective that is acceptable by the US EPA and many states is an allowance of DO depression near the bottom, reflecting the effect of the sediment oxygen demand associated with eutrophic waters. Highly fertile waterbodies throughout the world, which have excellent fisheries, routinely experience DO depletions near the sediments.

From a review of how the 6 mg/L water quality objective was developed for the DWSC (see Gowdy and Foe, 2002, and Lee and Jones-Lee, 2000a), it can be concluded that changing the 6 mg/L objective to the US EPA national water quality criteria of 5 mg/L is likely technically justified. The California Department of Fish and Game studies reported by Hallock, *et al.* (1970) concluded that DO concentrations less than 5 mg/L could potentially inhibit upstream migration of the fall run of Chinook salmon through the DWSC. However, as they point out, it was not clear whether this inhibition was due to high water temperatures and/or loss of home stream water signal during the same time the DO was less than 5 mg/L.

Another issue of concern is whether DO depletion below the 6 mg/L concentration near the bottom waters, but above this value in the mid-water column and surface waters, are inhibitory to Chinook salmon migration to home stream waters during the fall. There is need for further studies to understand the role of DO concentrations less than 6 mg/L as a migratory barrier to the fall run of Chinook salmon. As part of gaining acceptance for stakeholders' expenditures of funds to control the low-DO problem in the DWSC, it will be important to justify the significant additional expenditure for aeration or oxygen demand constituent control from the watershed based on appropriately conducted studies that show the fall run of Chinook salmon through the DWSC is in fact inhibited by DO concentrations less than 6 mg/L.

In December 2001, the State Water Resources Control Board held a workshop devoted to discussion of the current understanding of the recovery of the Chinook salmon and other anadromous fish populations in the Central Valley waterbodies. This workshop was attended by G. F. Lee. About 10 years ago, the fisheries' managers and the State Water Resources Control Board established a 10-year goal of doubling the anadromous fish populations in the Central Valley. At this meeting a variety of factors was discussed by the participants as potentially impacting the success of increasing the anadromous fish populations. DO was not one of the parameters mentioned by any of the participants. It appears that the "experts," as well as those responsible for managing/enhancing the anadromous fish populations, consider a variety of other factors, including water temperature, habitat, water diversions, ocean harvesting, etc., as more important than dissolved oxygen water quality objective violations in the Deep Water Ship Channel. The interaction of these various factors is poorly understood. Further, it is not clear that the populations of many of the anadromous fish have changed significantly since the enhancement program was initiated approximately 10 years ago.

A major factor influencing the populations of anadromous fish is the available flows and, in particular, wet and dry years. This greatly complicates understanding the changes that have taken place in the anadromous fish populations, since the initial baseline period was during a drought period, and the last few years have been fairly wet years. There seemed to be general consensus at this workshop that everything should be left alone in order to allow another 10 years or so to see if the enhancement programs that are in place are, in fact, significantly enhancing the populations. This could be an impetus for not changing the 6 mg/L DO water quality objective to 5 mg/L, even though the 6 mg/L is not based on a technically valid assessment of the effect of DO on Chinook salmon migration through the DWSC.

**Implications of Technical Studies For Managing the DWSC Low-DO Problem**

The results of the three-year technical studies of the DWSC and its watershed provide useful information on the technical allocation of responsibility for control of the low-DO problem that occurs in the DWSC. A summary of these issues is presented below.

***Port of Stockton***. As discussed above, if the Deep Water Ship Channel had not been constructed and the SJR downstream of the Port of Stockton had the same depth as upstream, there would be few, if any, low-DO problems in the seven miles of the SJR upstream of Turner Cut. The "Port of Stockton" is responsible for the existence of the Deep Water Ship Channel, and therefore, has a responsibility for controlling low DO in the Deep Water Ship Channel by helping fund oxygen demand control programs and/or aeration. Since the maintenance of the Deep Water Ship Channel by the US Army Corps of Engineers is mandated by Congress as part of a national program for dredged channel maintenance, and since continued maintenance of this Channel continues to contribute to the low-DO problem in the DWSC, the Corps of Engineers/US Congress should have considerable responsibility for helping to solve the low-DO problem in the DWSC.

If the Channel were not maintained it would shoal (become shallower) within a few years. This would eventually lead to increased oxygen demand assimilative capacity as the volume and residence time of the DWSC, between Stockton and Turner Cut, decreases. Eventually, the SJR downstream of Stockton would have the same ability to transport high algal oxygen demand loads as now occurs upstream of the Port. The CVRWQCB staff has indicated that the Port and its stakeholders could likely find that their need to obtain maintenance-dredging permits from the Central Valley Regional Water Quality Control Board could be used to help convince the Port and its stakeholders that they need to become a responsible stakeholder to help correct the problem caused by the creation of the Port and its associated Deep Water Ship Channel. This in turn could lead to causing Congress to fund, as part of the annual maintenance dredging appropriation, corrective measures for the low-DO problem.

There is precedent for this in that, as part of deepening the Deep Water Ship Channel from 30 to 35 feet, that took place several years ago, the Corps of Engineers installed an aeration device near Channel Point for the purpose of correcting the loss of oxygen demand assimilative capacity associated with channel deepening (see discussion by Nichol and Slinkard 1999; US EPA, 1971; USA COE, 1988). The Sacramento Corps District is responsible for operation and maintenance of this aeration system. Basically, there is need for Congress to make the funding available to address the larger picture associated with ongoing navigational depth management of the first seven miles of the DWSC below the Port of Stockton.

***Supplemental Aeration.*** As part of gaining permission from the CVRWQCB to deepen the DWSC from 30 to 35 feet, the Corps of Engineers installed two jet aerators at the Port of Stockton. These aeration devices were designed to compensate for the increased oxygen demand caused by the increased depth of the water column in the DWSC. However, they were not evaluated with respect to whether the design characteristics were, in fact, achieved. It has been found by Brown (2002b) that one of the aerators is operating at about 80 percent and the other is operating at about 25 percent of design. According to Foe (pers. comm., 2002), the agreement between the Corps and the CVRWQCB requires that the Corps run the aerators when the DO falls below 5.2 mg/L anywhere in the DWSC as measured by the city of Stockton weekly runs between September 1 and November 30.

Brown (2002b) has conducted a review of alternative aeration technologies. Brown (2002b) has reported that there are several alternative aeration approaches that show promise to add sufficient DO to the DWSC to control the low-DO problem. He provided general review of the basic methods that are used to artificially increase oxygen content of waterbodies. These include air bubble diffusers using air or pure oxygen, hollow fiber membranes, waterfalls or cascades, pressure side-stream aeration, and water fans. Brown provides some general characteristics of each of these approaches for providing additional oxygen to waterbodies. He estimates that the cost of adding oxygen to a waterbody is on the order of about $0.10/lb.

As discussed above in the "Box Model Calculations" section, based on the last three years' data, on average about 2,300 lbs/day of DO needs to be added to the DWSC to prevent DO depletion below the water quality objective. There are times, however, when much larger amounts of oxygen will be needed. Brown (2002b), using a different approach for calculating oxygen deficit below the water quality objective, indicated that in 2001 an aeration device that delivered 10,000 lbs/day of DO would satisfy the DO deficit during the summer. He concludes that about the same amount would likely have been needed in 1999 and 2000. The amount of aeration needed to meet the WQO will be dependent on the SJR DWSC flow, where increased flow will require greater amounts of aeration. Further, increased flow will affect the locations where aerators should be placed.

At this time, there is need for a comprehensive engineering evaluation of the use of aeration to control the low-DO problem in the DWSC. This evaluation should lead to several years of large-scale pilot studies to examine the technical feasibility and associated costs of using one or more aeration approaches to solve the low-DO problem in the DWSC. Eventually, through the pilot studies, it will be possible to design, construct and operate an aeration system to control the low-DO problem to meet the interim and final TMDL DO target goal. It is likely that aeration will be part of an overall management plan which will utilize a combination of upstream oxygen demand load control, managed SJR flow through the DWSC and selective aeration of the DWSC to control the low-DO problem.

***South Delta Barrier Reverse-Flow Pumping.*** At this time, the barriers in the South Delta are manually operated. CALFED has committed to the installation of automatic tidal barriers, which are reported to better manage flows in the South Delta channels, to eliminate the low water levels that occur now, associated with export pumping of South Delta water to Central and Southern California. As discussed above, it has been proposed that the operation of the barriers can be conducted in such a way as to increase the flow of the SJR through the DWSC. Hildebrand (pers. comm., 2002) proposed that barrier operations, coupled with low-head, reverse-flow pumping over the barriers, can be conducted in such a way as to export water from the South Delta into the SJR via Old River. This, in turn, would shorten the hydraulic residence time of oxygen-demanding materials added to the DWSC, potentially resulting in less DO depletion in the DWSC. It has been found by Nader (2002) that low-head, reverse-flow pumping is technically feasible in providing South Delta water to the SJR DWSC. There is, as discussed above, a number of issues that need to be addressed in connection with developing this proposed approach to helping solve the low-DO problem in the DWSC.

The Strawman results from Foe, *et al.* (2002), as well as the observations made from the Hayes cruise data on the impact of flow on the low DO in the DWSC over the past 15 years, and the box model calculations presented herein, have raised questions about the ability of supplemental flow to the DWSC to control the low-DO problems. There is no issue that SJR flows greater than about 2,000 cfs through the DWSC will control the low-DO problem in the first seven miles below the Port of Stockton in the DWSC by exporting the oxygen demand loads into the Central Delta before they can be exerted in the DWSC. At this time there is not a readily discernable relationship between SJR flow through the DWSC between about 500 and 1,500 cfs and DO depletion in the DWSC. While the Chen and Tsai (2002a) modeling presents a generalized relationship between SJR DWSC flow and DO depletion in the DWSC, the DWSC monitoring data, such as those presented herein based on the city of Stockton's monitoring as well as those developed in the Hayes cruises, raise questions about the reliability of the Chen model results. This is an issue that has not been resolved at this time.

The Nader (2002) modeling has predicted that reverse-flow, low-head pumping over the permanent South Delta barriers would improve water quality in the South Delta as a result of introducing Sacramento River water into the South Delta. It is desirable that the supplemental flow into the SJR should be of a low oxygen demand content and thereby dilute the oxygen demand in the SJR waters that enter the DWSC. While this appears to be feasible, there are other South Delta water quality issues that are not well understood. There are a number of South Delta water quality issues that need to be addressed before the barrier reverse-flow pumping approach can be adequately evaluated. There is need for further studies on the hydraulics of the South Delta, with particular reference to how the permanent barriers would impact the water quality that is occurring in the South Delta and the quality of water that would be exported from the South Delta to the SJR via Old River.

***Mud and Salt Slough and SJR Upstream of Lander Avenue Watersheds.*** The significance of the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds as a source of algae/oxygen demand material for the DWSC could require that stakeholders in these watersheds develop control programs that can control the growth of algae in the Sloughs' watersheds and the SJR upstream of Lander Avenue. The Mud and Salt Slough watersheds are already under regulatory constraints for control of selenium. According to McGahan (pers. comm., 2002), the regulatory controls have resulted in a reduction of selenium loads discharged by Mud Slough by 56 percent over the last five years. The flow from the Mud Slough watershed has been reduced by 47 percent during this period. The Mud and Salt slough watersheds will also likely come under regulatory control of total salt (TDS) and boron (CVRWQCB, 2002b). Further, it is possible that, as a result of the TMDL to control oxygen demand loads in the SJR watershed, the discharges of nutrients in the Mud and Salt Slough watersheds, as well as to the SJR upstream of Lander Avenue, that lead to the development of algae that cause violations of the DO water quality objective in the DWSC, will need to be reduced/controlled.

The algae control program should be designed to reduce the algal-related oxygen demand loads that enter the SJR from Mud and Salt Sloughs and the SJR upstream of Lander Avenue as opposed to nutrient control programs that are arbitrary across-the-board nutrient reductions irrespective of their contributions to the water quality problem. As discussed by Lee (2001b) and Lee and Jones (1998), this approach requires a good understanding of nutrient and algal growth dynamics from where the nutrients are first discharged until the algae enter the DWSC and cause DO depletion below the WQO.

At this time there is essentially no understanding of the specific sources of nutrients in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds that develop into algae that grow to a sufficient extent, within the Mud and Salt Slough watersheds as well as the SJR upstream of Lander Avenue watershed, to lead to high algal concentrations/loads in the SJR upstream of where the Merced River enters the SJR. It is the growth of algae, based primarily on the nutrients derived from these watersheds, that ultimately become the high algal-caused oxygen demand loads that have been found in the SJR at Mossdale. The initial focus of the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds' oxygen demand load control program should be on gaining an understanding of algal growth dynamics and nutrient sources in these watersheds. This understanding can then potentially be used to control the algal populations that are present in the SJR upstream of where the Merced River enters the SJR. The needed studies will require several years of detailed, selective monitoring in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds to develop an information base on which to begin to formulate potential oxygen demand control programs.

SFEI (2002) has recently published the 1999-2000 annual report for the Grassland Bypass Project. This report contains information pertinent to monitoring within the Mud and Salt Slough watersheds. At this time, there is extensive monitoring being conducted for temperature, pH, EC, TSS, selenium, boron, sediments, selenium uptake by biota, and aquatic life toxicity to fish larvae, zooplankton and algae. As recommended by the SJR DO TMDL Steering Committee (Lee, 2001c), the current monitoring program in the Mud and Salt Slough watersheds needs to be significantly expanded to include the various forms of nitrogen and phosphorus compounds that serve as algal nutrients, as well as planktonic algal chlorophyll, pheophytin and BOD. Further, each of the sub-watersheds within the Mud and Salt Slough and SJR at Lander Avenue watersheds should be monitored for some of these parameters, as well as flow, at various locations to define the specific sources of nutrients and algae that ultimately become the high concentrations at the mouths of Mud and Salt Sloughs and in the SJR at Lander Avenue.

It should be understood, as discussed by Lee (2001b), that controlling algal nutrients (nitrogen and phosphorus) from agricultural activities will be difficult and could be quite expensive compared to the profit margins that many parts of ag are experiencing today. Lee and Jones-Lee (2001a, b) reviewed the literature summarizing the experience of nutrient control programs from agricultural sources in other parts of the country, such as in the Great Lakes region and in the Chesapeake Bay watershed. Sharpley (2000) and Logan (2000) have summarized the experience of attempting to control algal nutrients in agricultural runoff in the Chesapeake Bay and the Lake Erie watersheds. As summarized by Lee (2001b), the nutrient control programs that have been conducted over the past 15 to 20 years in these areas have thus far failed to be highly effective in controlling nitrogen and phosphorus inputs to these waterbodies. It has been reported by Sprague, *et al.* (2000) that the major nutrient reductions that have occurred in the Chesapeake Bay watershed are associated with the cessation of agricultural activities in parts of the watershed.

Lee (2001b) has reviewed many of the issues that need to be considered in developing a technically valid cost-effective algae/nutrient control program in the SJR watershed. As he discussed, the approach should focus on controlling the nutrients that are specifically responsible for the algal biomass (BOD load) that causes DO depletion below the water quality objective in the DWSC. From the information available, it is concluded that available algal phosphorus control in the Mud and Salt Slough headwaters could have the potential of limiting algal growth in these waters and thereby reducing the biomass of algae that are discharged by these tributaries to the SJR. Stringfellow and Quinn (2002) and Foe, *et al.* (2002) have reported that the concentrations of algal available phosphorus in Mud Slough near its mouth where it joins with the SJR, are sufficiently depressed to be near algal growth-rate limiting. If that situation can be promoted throughout the Mud and Salt Slough watersheds, as well as the SJR upstream of Lander Avenue, then the algal seed which ultimately develops into a large algal biomass at Mossdale could potentially be controlled sufficiently to reduce the algal-caused oxygen demand that enters the DWSC.

Stringfellow and Quinn (2002) reported that algal growth in the San Luis drain, which is a concrete-lined channel that carries ag drain water from the 97,000-acre Grassland Drainage Area to Mud Slough, shows a doubling in algal biomass in about one to two days. This is in accord with the expected algal growth under light-limited conditions. It is also similar to the apparent algal doubling rates reported by Foe, *et al.* (2002). There is an important difference between the Foe, *et al*. (2002) doubling rates and those of Stringfellow and Quinn in that the Stringfellow and Quinn doubling rates are the true doubling rates while the Foe doubling rates reflect the algal doubling but also water diversions and low algal water import to the SJR. The Foe, *et al.* (2002) doubling rates are not true doubling rates but are the apparent doubling rates reflecting changes in the hydrologic characteristics of the SJR.

In conducting a nutrient control program in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds, it would be important to focus on algal nutrients such as nitrate and soluble ortho P and not total P. Lee, *et al*. (1980) have reported that large amounts of the agriculturally derived phosphorus in stormwater runoff is often in particulate forms, where most of the phosphorus is not available to support algal growth. This situation may not apply to ag-derived tailwater and subsurface drain water. Lee and Jones-Lee (2002a, b) have discussed nutrient control issues associated with agricultural sources. These discussions provide information pertinent to the control of nutrients and algae in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds.

***Allocation of Oxygen Demand Loads in Sub-Watersheds***. It is possible that the CVRWQCB will assign allowable oxygen demand loads to each of the SJR tributaries as part of implementation of the TMDL. It will then become the responsibility of the stakeholders in each SJR tributary watershed, as well as those that discharge directly to the SJR in ag drains, to develop approaches for controlling their oxygen demand discharges to meet the CVRWQCB-allowed oxygen demand load from a tributary.

It will likely require several years of study and considerable funding before an allocation of responsibility for control of oxygen demand sources that occur at the tributary's point of discharge to the SJR can be developed. Only when this information is available and is implemented into a management plan, can there begin to be effective control of oxygen demand sources within the SJR DWSC watershed. The initial phase of the DO TMDL implementation plan will need to be devoted largely to gaining an understanding of oxygen demand sources and their potential control within each of the SJR tributaries' watersheds. It will be important in developing these programs to be certain that the control of oxygen demand in the watershed is appropriately tied to oxygen demand that leads to DO depletion below a WQO within the DWSC.

***Ag Diversions***. Agricultural diversions of SJR water along its course between where Mud and Salt Sloughs enter the SJR and the DWSC can, during the irrigation season, divert significant amounts of water and associated oxygen demand for irrigation. This tends to reduce the magnitude of the Mud and Salt Slough and SJR upstream of Lander Avenue oxygen demand loads that ultimately reach the DWSC. These diversions have been considered in the Foe, *et al.* (2002) Strawman analysis in estimating the significance of this area's algal related oxygen demand as a cause of DO depletion problems in the DWSC.

One of the most significant diversions of SJR water occurs into Old River, where the waters are exported via the State and Federal Projects to Central and Southern California. At times, most of the water in the SJR that reaches Old River is diverted into Old River for export. This diversion, while reducing the magnitude of the algal related oxygen demand loads that are present in the SJR at Mossdale that reach the DWSC which is beneficial to the DWSC, adversely impacts the flow of the SJR through the DWSC, thereby increasing the hydraulic residence time of the residual oxygen demand loads to the DWSC. The low flow conditions of a few hundred cfs of SJR flow through the DWSC, compared to about 600 to 2,000 cfs that typically occurred during the 1999, 2000 and 2001 study period, resulted in some of the most significant oxygen depletions in the DWSC found during the studies. DO concentrations of about 2 mg/L were found during one occasion of this type.

***Eastside Rivers***. The flow of eastside rivers (Tuolumne, Stanislaus, and Merced Rivers) into the SJR can be a major factor in reducing the oxygen demand derived from the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds, that leads to low-DO problems in the DWSC, as a result of diluting the elevated SJR algal concentrations that are present upstream of where the eastside rivers enter the SJR. This conclusion is particularly important since, as discussed by Lee and Jones-Lee (2000a), the San Joaquin River watershed is predicted to double in population over the next 20 years. Such doubling can only occur if additional water supplies are developed to serve this population. It appears now that there would likely be opposition to the use of any eastside river water to serve as a domestic supply for any new populations or any additional growth in the Central Valley or in the San Joaquin River watershed because of the potential adverse impacts on the flow of the eastside rivers to the SJR, which tends to dilute the oxygen demand present in the SJR from upstream watershed sources.

**Issues that Need to be Resolved**

There are a number of key issues that evolve from the conceptual models for the sources and impacts of oxygen demand on the DO resources of the SJR DWSC that need to be resolved. With respect to the constituents responsible for the DO depletion in the DWSC, the key issue is what are the constituents primarily responsible for DO depletion below water quality objectives in the DWSC. Of equal importance is the origin of these constituents.

***Oxygen Demand Dynamics in the SJR DWSC Watershed.*** A major issue that needs to be addressed in formulating a technically valid, cost-effective DO depletion control program for the DWSC is an understanding of the dynamics of oxygen demand development and changes in the oxygen demand that occur in the SJR during transport into the DWSC. There are a variety of factors that influence oxygen demand concentrations/loads within the SJR upstream of the DWSC. These include the growth of algae in the SJR tributaries, the growth of algae in the mainstem of the SJR, the diversion of algae and other oxygen demand constituents from the SJR and its tributaries for use in the watershed for irrigated agriculture and for refuge/duck club operations, and the decay of the oxygen demand that occurs in transport from where it is first developed until the waters enter the DWSC. These various processes need to be modeled to develop a quantitative relationship between oxygen demand/algae that develop in the SJR that is ultimately discharged into the DWSC.

One of the most important factors influencing the fate of oxygen demand from the upper parts of the watershed is the diversion of waters from the SJR and its tributaries for irrigated agriculture. Further, the role of the eastside rivers (Stanislaus, Tuolumne and Merced) in providing low-algae and low-nutrient waters to the SJR, thereby diluting the upstream oxygen demand/algae, needs to be understood. Understanding these processes under various SJR flow regimes and seasonal characteristics is essential to assigning an appropriate allocation of oxygen demand load responsibility to the stakeholders/dischargers and water diverters within the SJR watershed. This understanding must be gained for each of the individual tributary watersheds, as well as the overall SJR watershed. Understanding the dynamics of oxygen demand from its first introduction or development within the SJR tributaries, and the fate of the oxygen demand within the tributary and in the SJR prior to reaching the DWSC, is essential to appropriate allocation of responsibility for the DO depletion within the DWSC. This understanding of the dynamics of oxygen demand development, transport and fate upstream of the DWSC must be addressed for the various seasons (monthly), especially during the late spring, summer and fall. Further, it needs to consider how the wet-year versus dry-year conditions within the SJR watershed influence oxygen demand dynamics within the DWSC watershed.

An issue that will need to be considered in developing nutrient control programs within the SJR watershed is the potential adverse impact of such programs on the fisheries resources of the Delta. Lee and Jones (1991) have shown that there is an inverse relationship between fish production in waterbodies and their nutrient loads. Since there is an interest in improving the fisheries of the Delta, controlling nutrient inputs to the Delta from its tributaries could prove to be detrimental to Delta fisheries. This issue will need to be evaluated as part of any nutrient management program within the Delta and its tributaries.

***City of Stockton Wastewater Discharges.*** The wastewater discharges from the city of Stockton are, at times, potentially significant sources of oxygen demand for the DWSC. In addition to the residual BOD present after treatment, the wastewaters, at times, can contain high concentrations of algae that develop in the City's treatment ponds. While at times the City filters its effluent to remove many of the algae, at other times discharges of algae occur. This adds to the algal load within the DWSC. Another component of the City's wastewater discharges is the ammonia content, where traditionally, beginning in September through the fall, the wastewater ponds discharge high concentrations of ammonia to the SJR. In the summer 2001, however, the City's wastewater ponds discharged ammonia at high concentrations all summer long. This is an unusual pattern; however, it contributed to the oxygen demand load in the early and late summer. Another factor to consider with the City's wastewater discharges is that they are not constant, but are often shut off over the weekends, and then are allowed to occur again on Monday. This discharge pattern could be influencing the oxygen depletion within the DWSC. The impacts of this discharge pattern on DO depletion in the DWSC need to be evaluated.

It is proposed by the CVRWQCB that the city of Stockton reduce the ammonia discharges to the SJR because of the potential for these discharges to cause toxicity to aquatic life (US EPA, 1999b). There is need to evaluate the degree of control that the City must exercise to eliminate toxicity issues relative to the control of ammonia needed to control ammonia-caused significant oxygen demand that influences DO depletion in the DWSC.

***DO "Crashes" in the DWSC.*** One of the most significant issues that will need to be understood is the origin of the DO "crashes," where, for what appears to be short periods of time, unusually low DO occurs at certain locations in the DWSC. At times there will be short-term DO depletions to relatively low levels -- i.e., 2 mg/L. These DO "crashes" are particularly significant since they may ultimately become the controlling DO depletions that must be managed. At this time, the causes of the DO crashes are not understood.

Some of the factors that may be responsible for the DO crashes include unusually high short-term oxygen demand loads or other factors, such as decreased light penetration associated with increased turbidity or color, that influence how oxygen demand discharged to the DWSC influences DO depletion within the Channel. There is need for intensive field studies involving more frequent monitoring of sources and DO depletion than has been conducted in the past three years. Such studies should be designed to understand and thereby control the DO crash episodes that occur occasionally in the DWSC.

As discussed above, there are a number of issues related to the variability of the oxygen demand loads present in the SJR at Mossdale and discharged by the City to the SJR upstream of Channel Point in influencing the variability of oxygen depletion measured a week to two weeks later at various locations in the DWSC. A lagrangian approach needs to be adopted where load-response relationships are examined at various locations within the DWSC as a function of travel time to the location of interest. This approach needs to consider the tidal-induced longitudinal mixing that occurs within the DWSC that would smooth the variable load inputs to the SJR to minimize high-frequency variability in oxygen depletion and exported loads of oxygen demand and oxygen deficits at Turner Cut. There is need for high-frequency sampling at various locations within the DWSC to determine the variability in DWSC response parameters to upstream oxygen demand loads. At this time, this issue has not been addressed.

***DO Depletion Within the South and Central Delta.*** At times, large amounts of oxygen demand are delivered to the South Delta through the diversion of SJR water into Old River. It is known that there are DO depletions below the water quality objective in the South Delta. It is unclear as to the cause of these DO depletions. Are they related to the diversion of oxygen demand, principally algae, from the SJR into Old River? What influence does the city of Tracy's wastewater discharges or South Delta channel algal growth have on the current water quality problems in the South Delta channels?

Another factor is how will these DO depletions in the South Delta be influenced by the installation and operation of the permanent barriers that CALFED is proposing to install in the South Delta. Also of concern is the influence of the proposed increased export of South Delta water through the State and Federal Projects, which again will cause manipulations of the oxygen demand and flows in the SJR down Old River and through the DWSC. Any major changes in the flow patterns from what exist now need to be carefully evaluated before the changes take place, to be certain that the problems that now occur because of diversions and export pumping of water from the Delta do not make the DO depletion problem in the SJR worse than it already is.

Under high flow conditions of the SJR through the DWSC, appreciable amounts of oxygen demand in the form of algae, ammonia and organic nitrogen are diverted into the Central Delta through the cross-SJR DWSC flow of the Sacramento River that arises from the export pumping of South Delta waters to Central and Southern California. No work has been done thus far on the DO depletions in the Central Delta. It needs to be done before any plan to modify the SJR flow through the DWSC is implemented through the discharge of South Delta water through the DWSC. This proposed flow management plan also needs to be evaluated with respect to the quality of the water that would be discharged to the SJR DWSC from the South Delta via Old River.

***Oxygen Demand Dynamics Between Mossdale and Channel Point***. Foe, *et al.* (2002), as part of the Strawman analysis, have addressed the issue of whether there are unusual or unexpected changes in oxygen demand that occur between the SJR at Mossdale and the DWSC at Channel Point. Confusing information has been presented on this issue, where claims of large amounts of oxygen demand disappearance occurred in this reach of the San Joaquin River. There are questions, however, about the reliability of that assessment, based on the ability to reliably conduct a mass balance in the tidal part of the DWSC at Channel Point. Measurements at Channel Point reflect dependence on tidal stage and direction, inputs from the SJR DWSC downstream of this location, inputs from the upstream SJR and inputs from the Port of Stockton's Turning Basin. The Turning Basin has significantly different surface and bottom water characteristics than the main body of the DWSC near Rough and Ready Island. Channel Point is an extremely difficult area to properly monitor and understand factors influencing algae and oxygen demand concentrations in samples taken from this location. In order to properly characterize the concentrations of constituents at Channel Point, an extensive sampling and flow measurement program far beyond those that have been conducted thus far is needed to be able to reliably claim that there are unexpected or unusual concentrations of oxygen demand constituents in samples taken from Channel Point.

As shown in Figure 7, at 1,000 cfs of SJR flow through the DWSC there is about a 1.5-day travel time between Mossdale and Channel Point, while at 600 cfs the travel time between these two points is about 2.5 days. During a one- to two-day travel time between Mossdale and Channel Point, significant changes in the oxygen demand, algae, etc., would not be expected. Foe, *et al.* (2002) have shown that the changes that occur in oxygen demand between Vernalis and Mossdale are in accord with what would be expected, where there is increased algal growth in the SJR between these two locations. Quinn and Tulloch (2002) have pointed out that there is a major ag diversion (Banta Carbona) of SJR water between Vernalis and Mossdale. According to Quinn (pers. comm., 2002) during July 2001, the Banta Carbona diversion represented about 200 cfs. This water district, therefore, has the potential to divert a substantial part of the oxygen demand load present in the SJR at Vernalis and thereby reduce the total load that is present at Mossdale. Overall, it does not appear that there is any unusual behavior of oxygen demand loads present at Vernalis that cause the concentrations at Mossdale, or for that matter at Channel Point, to be significantly different from what is expected.

**Development of a TMDL and Its Technical Allocation**

The overall conclusion is that there is an adequate information base now to establish a Phase I TMDL and to allocate the oxygen demand load responsibility for the discharge of oxygen-demanding constituents that influence DO depletion in the DWSC, to the SJR DWSC tributary mouths. Substantial additional work will need to be done during Phase I to refine the TMDL, especially under altered meteorological/hydrological conditions, and to improve on the predictive capability of the city of Stockton/Chen model to define the occasional excursions of DO below the normal DO depletion in what are characterized as "crashes."

The monitoring of the past two years has defined the magnitude of the loads of oxygen demand from each of the major tributaries to the SJR and the changes in these loads along the SJR from the Mud and Salt Slough area down to Mossdale. Therefore, at least during moderately wet years, the expected oxygen demand loads at various locations within the SJR watershed above Mossdale, have been defined at the major tributary mouths. The magnitude of the loads will likely change during drought years. The overall conclusions, with respect to Mud and Salt Sloughs and the SJR upstream of Lander Avenue being dominant sources of oxygen demand, will not likely change. The Central Valley Regional Water Quality Control Board and, for that matter, the Steering Committee will not be able to allocate oxygen demand loads to a greater degree of refinement than to the mouths of the major tributaries to the SJR until such time as detailed oxygen demand load studies have been conducted in each of the major tributary watersheds.

The allocation of oxygen demand load among stakeholders within a particular tributary watershed will require several years of detailed monitoring within the sub-watershed, coupled with developing a sub-watershed stakeholder structure that would enable the stakeholders in a sub-watershed to work together to develop an allocation process which could control the oxygen demand loads from their respective sources to meet the allocated load at the tributary discharge point to the SJR. The development of this information is at least several years away. The modeling that is funded by CALFED does not address this issue. The TMDL will need to be conducted in a phased approach where the first phase will be largely devoted to obtaining additional information on the specific sources of oxygen demand in the Mud and Salt Slough and SJR upstream of Lander Avenue watersheds and their potential for control.

Further, the initial phase of the TMDL will need to be devoted to pilot studies of aeration of the DWSC to control the low-DO problem. In addition, an engineering evaluation of the potential to achieve at least control of flow, if not enhanced flow, of the SJR through the DWSC will need to be conducted during the initial phase of the TMDL implementation.

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

**Guidance on Monitoring Program During Phase I Implementation**

With the development of the first phase of the total maximum daily load (TMDL) implementation program, there will be need to establish a long-term monitoring program designed to assess the effectiveness of the implementation program and, most importantly, to continue to gather information on the factors controlling the development of oxygen demand in the SJR DWSC watershed and its depletion of DO in the Deep Water Ship Channel. A specific project should be developed which reviews the existing data on the characteristics of the oxygen demand loads, their sources and the impacts on DO resources within the DWSC for the purpose of developing a TMDL Phase I monitoring program. The objectives of this program should be clearly defined. It should be designed and developed with adequate funding to meet the appropriate objectives.

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