SAN JOAQUIN RIVER

Dissolved Oxygen
Total Maximum Daily Load
Stakeholder Process

The Contribution of Algal Biomass to Oxygen Depletion in the San Joaquin River, 1999

P. W. Lehman and C. Ralston, July 23, 2001. Table of Contents

Introduction

Oxygen concentrations below the 5 mg L^{-1} US EPA criterion and 6 mg L^{-1} RWQCB objective have been measured in the lower San Joaquin River Deep Water Channel (DWC) during the fall since the late 1960s (Brown and Caldwell 1970; USBR et al. 1974; CDWR 1989-1995). Low dissolved oxygen concentration has been measured in the routine monthly monitoring program in the San Joaquin River began in the 1970s by the CA Department of Water Resources, CA Department of Fish and Game and the U.S. Bureau of Reclamation. In addition, low dissolved oxygen concentration has been measured by the CA Department of Water Resources during a routine bimonthly dissolved oxygen monitoring study done in conjunction with placement of a rock barrier at the Head of Old River during the fall (CA Department of Water Resources 1989 - 1995).

Initial concerns regarding eutrophication as a cause of the low dissolved oxygen concentration in the San Joaquin River lead to development of a series of computer models of the San Joaquin River that identified key variables including streamflow, light extinction and algal biomass as important controlling factors (Di Toro et al. 1971). These key variables are still considered to be important today (Jones and Stokes 1998) and are included in a more recent management model that focuses on the relative contribution of discharge from the City of Stockton and upstream algal biomass on the oxygen depletion in the Stockton DWC (Chen 1997). Because managing the water quality in this portion of the river is of such great importance economically, new models are continually being developed (Rajbhandari 1995). Yet, the knowledge produced by these models and increased regulations on point source discharge have not eliminated the dissolved oxygen problem.

The purpose of this study was to obtain new and more detailed measurements on the vertical and horizontal variation of oxygen depletion in the DWC and the relative contribution of local and non-local sources of oxygen demand from algal biomass during fall 1999. This information will be used to assist design of a comprehensive field and modeling study in fall 2000.

Methods

Historical data – Historical data analyses was conducted using the CDWR fall dissolved oxygen monitoring program data. These data consist of bimonthly top and bottom measurements of dissolved oxygen concentration taken at approximately 1-mile intervals at channel navigation lights between Prisoners Point and the Turning Basin (Fig. 1). In some years water temperature was also taken. Additional water quality data was obtained from the CDWR compliance monitoring discrete and continuous monitoring programs from the Interagency Ecological Study Program (IEP) database.

Water quality conditions **-** Biweekly vertical profiles of dissolved oxygen, water temperature and specific conductance were taken at 0.5 to 1.5 mile intervals in the DWC between Prisoners Point and the Turning Basin at channel navigation lights. The sampling interval was shortened to 0.5 mile when dissolved oxygen concentration reached below 6 mg L^{-1}. This usually occurred between Light 19 and the Turning Basin**,** an 11.5 mile study reach (Fig. 1). Measurements were taken with a Sea-Bird Electronics 9/11 unit vertical profiler at 1 cm depth intervals between July 27 and December 7, 1999. Dissolved oxygen concentration was calibrated with concurrent measurements of dissolved oxygen using the Winkler dissolved oxygen wet chemistry technique. All measurements were taken on slack after ebb tide. In addition, a continuous longitudinal profile of specific conductance, water temperature, turbidity and chlorophyll *a* fluorescence was made at 1-m depth between Prisoner's Point and the Turning Basin using a through-hull pump system.

Fig. 1. Sampling stations in the Stockton Deep Water Channel.

Slide 1

Net material transport – Net daily transport studies were conducted on August 26 and September 23, 1999 at three stations: Light 43, Channel Point at station 51 and the Turning Basin at Light 50 (Fig. 1). Water samples from 1-m depth and 1-m off the bottom were collected for $BOD_{(10\ day)}$, $CBOD_{(10\ day)}$, ammonia, nitrate, orthophosphate, total phosphorus, organic nitrogen, total organic carbon, dissolved organic carbon, chloride and chlorophyll *a* concentration at each station and tide. Water samples for $BOD_{(10\ day)}$, and $CBOD_{(10\ day)}$ were kept cold (4^oC) and in the dark until analysis within 24hr. Detection limits were 3 mg L^{-1} in August and 1 mg L^{-1} in September. Water samples for chlorophyll *a* and phaeophytin concentration were filtered through 0.45 *u*m pore size glass fiber filters and filters were frozen until analysis (APHA 2000). Water samples for dissolved ammonia, nitrate plus nitrite, chloride and orthophosphate were filtered through a 0.45 um pore size Nucleopore filter and the filtrate was frozen until analysis or analyzed within 48 hr (EPA 1983). Unfiltered water samples for total phosphorus, total Kjeldahl nitrogen (TKN) and volatile (VSS) and total (TSS) suspended solids were kept cold at 4^oC until analysis within 24 hr (EPA 1983; APHA 2000). Dissolved organic carbon (DOC) was measured from the filtrate of water samples passed through a 0.45 um pore-size glass fiber filter in a stainless steel filtration apparatus. DOC filtrate and unfiltered total organic carbon (TOC) water samples were treated with phosphate buffer and analyzed within 24 hr (APHA 2000). All laboratory analyses were analyzed following the QA/QC procedures of the Department of Water Resources Bryte Chemical Laboratory. These included 10% replication of all samples.

In addition to the discrete water samples, vertical profiles were made at each tide of specific conductance, pH, water temperature and dissolved oxygen concentration using YSI instrumentation. Flow velocity was measured hourly for 12 hours at each station using an acoustic doppler current profiling (adcp) unit attached to a boat. Flow velocity for the rest of the tidal day was estimated using the phase and amplitude pattern of tidal stage data collected at Light 43.

This discrete sampling program was supplemented by continuous measurements of dissolved oxygen, chlorophyll *a* fluorescence, water temperature, specific conductance and pH monitored at Light 43 and at station 55 at Mossdale by CDWR as a part of their compliance-monitoring program. These monitoring systems are serviced every 10 days.

Community production rate – Community production rate was measured by the change in dissolved oxygen concentration (mg/L) in 4-hr light and dark bottle incubations of channel water in the euphotic zone at 1m and aphotic zone at 3 m on September 23 at Light 43. Chlorophyll *a* concentration during this study was 5-9 ug L^{-1}. The measured specific production rate was 15 ug O_2 (ug chlorophyll *a*)$^{-1}$ hr^{-1} and measured specific respiration rate was 2 ug O_2 (ug chlorophyll *a*)$^{-1}$ hr^{-1}.

Analysis

Oxygen deficit - Oxygen deficit values were calculated by channel segment and each segment contained a sampling station. The oxygen deficit at each depth was calculated as the difference between measured dissolved oxygen concentration and oxygen concentration at saturation, 5 mg L^{-1} or 6 mg L^{-1}. Oxygen saturation was a function of water temperature and salinity and was determined from standard tables (Colt 1984). The average oxygen deficit in each channel segment was calculated as the product of the volume of the channel segment and the average oxygen deficit determined from the depth profile for that station. Segment volumes were determined by multiplying the length of the channel segment by the cross sectional area of 4338 m^2. This cross sectional area was derived from measurements taken just upstream of Smith Canal on August 26, 1999, adjusted for tide. The average and total oxygen deficit for the entire study reach was based on the combined values of these channel segments. Historical oxygen deficit values were calculated in the same fashion, but only surface and bottom dissolved oxygen concentrations were available.

Algal oxygen demand – The net daily algal oxygen demand (kg O_2 day^{-1}) in each channel segment of the study reach was estimated as the sum of the net oxygen production in the photic zone and respiration in the aphotic zone over 24 hr. Net oxygen production in the photic zone during the daytime was estimated by multiplying the specific production rate (mg O_2 (mg chlorophyll *a*) $^{-1}$ hr^{-1} times the chlorophyll *a* concentration (mg) in the channel, adjusted to a 12-hr period. Oxygen depletion in the photic zone during the nighttime and in the aphotic zone during both the daytime and nighttime was calculated as a product of chlorophyll *a* concentration in the channel (mg) and the specific respiration rate (mg O_2 (mg chlorophyll *a*) $^{-1}$ hr^{-1}), adjusted to the appropriate time interval. The net oxygen demand from algal biomass in the study reach was the sum of the photic and aphotic one oxygen demand in each segment. Chlorophyll *a* concentration was estimated from longitudinal profiles of surface chlorophyll *a* fluorescence.

For comparison, specific rates of primary production and respiration were also estimated from equations from net production rate (Cole and Cloern 1987) and respiration rate (Rudek and Cloern 1996) equations developed for San Francisco Bay.

Net tidal-day transport was calculated as the hourly flow velocity (cm s^{-1}) multiplied times the concentration of each water quality variable measured on each tide over 25 hr. Values were integrated over a 30-min time step and the daily sum of these integrated values was used to estimate the net daily material transfer (flux) at each station.

Historical dissolved oxygen concentration

Low dissolved oxygen concentration has characterized the upstream end of the Stockton DWC near Light 43 since the 1970s. Monthly average dissolved oxygen concentration ranged from 4.82 mg L^{-1} to 7.81 mg L^{-1} between August and November since the 1970s (Table 1). Among the decades, concentration minima occurred in either September or October and reached as low as 1 mg L^{-1}. The frequency of dissolved oxygen concentration below 5 mg L^{-1} and 6 mg L^{-1} varied among the decades and was higher by at least a factor of 2 in the 1970s and 1990s compared with the 1980s. Dissolved oxygen concentration was higher in the 1990s compared with the 1970s when the frequency of values below 5 and 6 mg L^{-1} decreased for all months. The relatively high dissolved oxygen concentration in the 1980s was probably caused by high streamflow during these years that included the period of record high precipitation in 1982-1983 and a flood in 1986.

Table 1. Dissolved oxygen concentrations measured in the Stockton Deep Water Channel between 1970 and 1990 between Light 19 and Light 48.

1970's			1980's			1990's		
DO in Channel (excluding TB)			DO in Channel (excluding TB)			DO in Channel (excluding TB)		
August	-	Average	August	7.35	Average	August	5.92	Average
	-	SD		1.28	SD		1.34	SD
	-	Min		4.2	Min		2.7	Min
	-	Max		9.5	Max		8.3	Max
	-	Freq <5 mg/L		4%	Freq <5 mg/L		27%	Freq <5 mg/L
	-	Freq <6 mg/L		17%	Freq <6 mg/L		49%	Freq <6 mg/L
September	4.82	Average	September	6.95	Average	September	6.28	Average
	2	SD		1.64	SD		1.46	SD
	1.4	Min		2.3	Min		1.9	Min
	11.9	Max		12.8	Max		9.9	Max
	57%	Freq <5 mg/L		10%	Freq <5 mg/L		21%	Freq <5 mg/L
	74%	Freq <6 mg/L		27%	Freq <6 mg/L		40%	Freq <6 mg/L
October	5.38	Average	October	7.35	Average	October	6.61	Average
	1.48	SD		0.96	SD		1.75	SD
	2.3	Min		4.6	Min		1.3	Min
	9.3	Max		11.4	Max		9.2	Max
	40%	Freq <5 mg/L		1%	Freq <5 mg/L		21%	Freq <5 mg/L
	63%	Freq <6 mg/L		9%	Freq <6 mg/L		29%	Freq <6 mg/L
November	6.86	Average	November	7.31	Average	November	7.71	Average
	1.55	SD		0.28	SD		1.23	SD
	3.35	Min		6.9	Min		4.9	Min
	9.8	Max		7.9	Max		10.8	Max
	12%	Freq <5 mg/L		0%	Freq <5 mg/L		1%	Freq <5 mg/L
	33%	Freq <6 mg/L		0%	Freq <6 mg/L		11%	Freq <6 mg/L

Monthly average dissolved oxygen concentration was similar in the Turning Basin and in the DWC, but half of the average dissolved oxygen concentration values were less than 6 mg L^{-1} in the Turning Basin compared with only a few in the DWC (compare Tables 1 and 2). The frequency of average dissolved oxygen concentration less than 5 mg L^{-1} or 6 mg L^{-1} varied among the decades and was greater than 50% in the 1970s and 1990s, but less than 50% in the 1980s. The improvement in the dissolved oxygen concentration between the 1970s and 1990s was less in the Turning Basin than in the DWC.

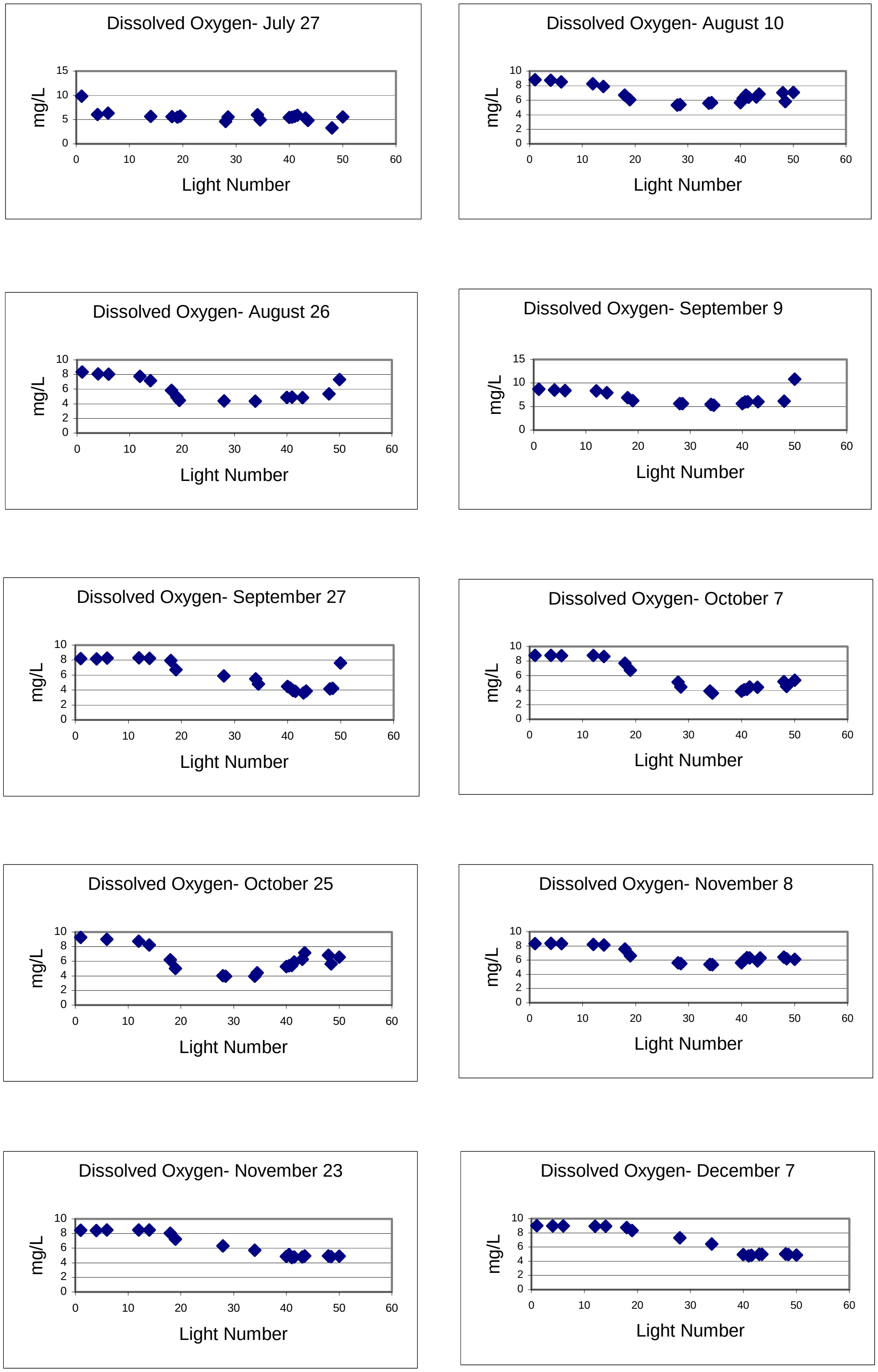
Table 2. Dissolved oxygen concentration measured in the Turning Basin between 1970 and 1990.

1970's			1980's			1990's		
DO in Turning Basin			DO in Turning Basin			DO in Turning Basin		
August	-	Average	August	7.4	Average	August	5.82	Average
	-	SD		3.15	SD		4.52	SD
	-	Min		5	Min		0	Min
	-	Max		12	Max		15.4	Max
	-	Freq <5 mg/L		25%	Freq <5 mg/L		46%	Freq <5 mg/L
	-	Freq <6 mg/L		50%	Freq <6 mg/L		64%	Freq <6 mg/L
September	4.18	Average	September	7.35	Average	September	5.94	Average
	2.6	SD		3.66	SD		3.74	SD
	1.2	Min		1.4	Min		0.2	Min
	9.2	Max		12.3	Max		14.4	Max
	67%	Freq <5 mg/L		27%	Freq <5 mg/L		50%	Freq <5 mg/L
	67%	Freq <6 mg/L		36%	Freq <6 mg/L		56%	Freq <6 mg/L
October	4.34	Average	October	7.71	Average	October	5.91	Average
	2.61	SD		2.7	SD		2.62	SD
	1	Min		4.3	Min		1.8	Min
	8.6	Max		14	Max		11.4	Max
	67%	Freq <5 mg/L		7%	Freq <5 mg/L		42%	Freq <5 mg/L
	78%	Freq <6 mg/L		20%	Freq <6 mg/L		58%	Freq <6 mg/L
November	5.54	Average	November	7.25	Average	November	6.87	Average
	1.52	SD		1.06	SD		2.09	SD
	3.72	Min		6.5	Min		2	Min
	7.8	Max		8	Max		11.1	Max
	55%	Freq <5 mg/L		0%	Freq <5 mg/L		14%	Freq <5 mg/L
	64%	Freq <6 mg/L		0%	Freq <6 mg/L		36%	Freq <6 mg/L

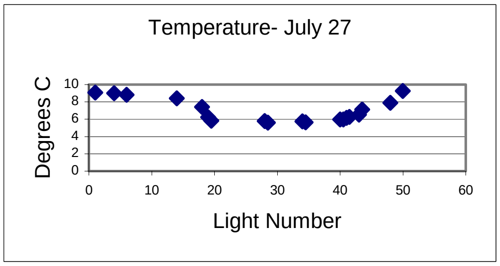
The 1999 Field Study in the Stockton Deep Water Channel

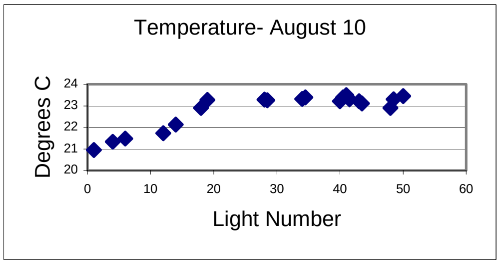
Horizontal and vertical profiles – Average dissolved oxygen concentration below 5 mg L^{-1} or 6 mg L^{-1} characterized the DWC between Light 19 and the entrance of upper San Joaquin River at Light 48 between July and December 1999 (Fig. 2 a). Horizontal profiles of specific conductance, water temperature, dissolved oxygen concentration and optical backscatter suggested the water quality in this reach of the river differed from the reach seaward of Light 18 (Fig. 2 a-d). Specific conductance greater than 400 uS cm^{-1} and high turbidity suggest the water quality conditions at Light 18 to Light 48 were similar to those in the upper San Joaquin River where specific conductance and averaged 600 uS cm^{-1}.

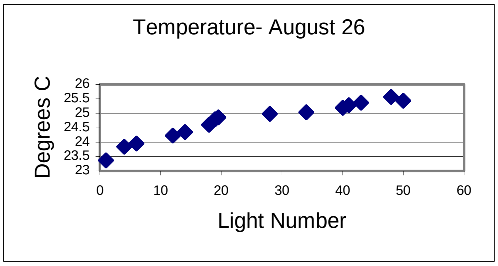
Fig. 2 a-d. Horizontal profiles of water quality variables between Prisoner's Point and the Turning Basin 1999. Code a) dissolved oxygen, b) water temperature, c) specific conductance and d) optical backscatter.

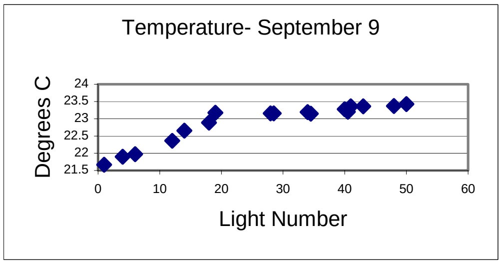


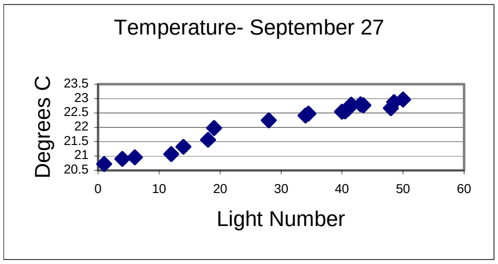
b)

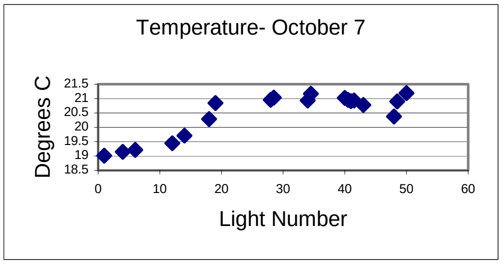

Temperature- July 27
Degrees C
10
8
6
4
2
0
0
10
20
30
40
50
60
Light Number

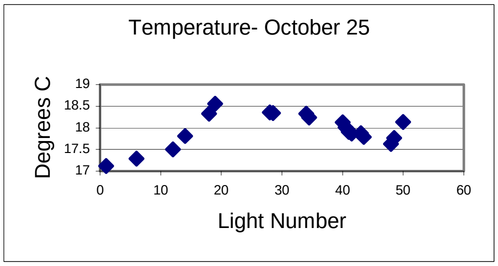

Temperature- August 10
Degrees C
24
23
22
21
20
0
10
20
30
40
50
60
Light Number

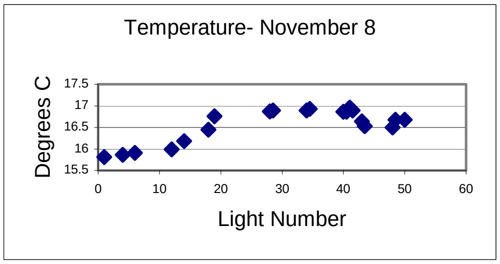

Temperature- August 26
Degrees C
26
25.5
25
24.5
24
23.5
23
0
10
20
30
40
50
60
Light Number

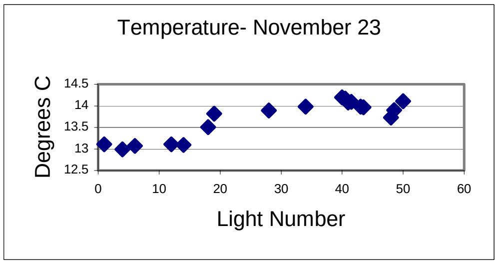

Temperature- September 9
Degrees C
24
23.5
23
22.5
22
21.5
0
10
20
30
40
50
60
Light Number

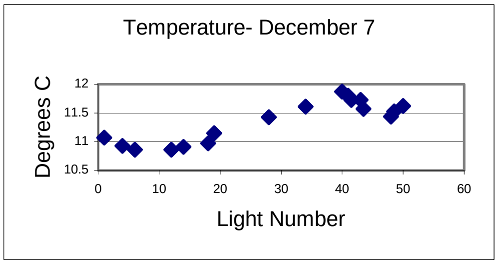

Temperature- September 27
Degrees C
23.5
23
22.5
22
21.5
21
20.5
0
10
20
30
40
50
60
Light Number


Temperature- October 7
Degrees C
21.5
21
20.5
20
19.5
19
18.5
0
10
20
30
40
50
60
Light Number

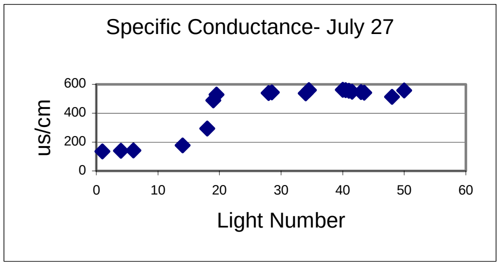

Temperature- October 25
Degrees C
19
18.5
18
17.5
17
0
10
20
30
40
50
60
Light Number

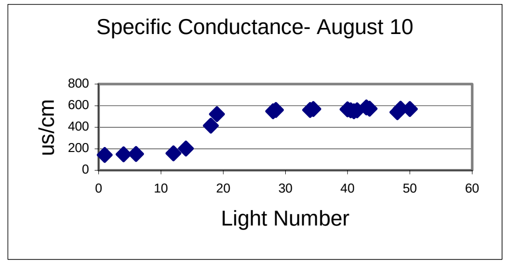

Temperature- November 8
Degrees C
17.5
17
16.5
16
15.5
0
10
20
30
40
50
60
Light Number

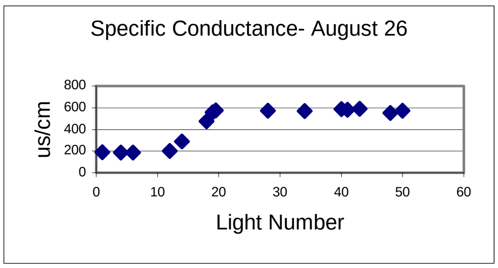

Temperature- November 23
Degrees C
14.5
14
13.5
13
12.5
0
10
20
30
40
50
60
Light Number

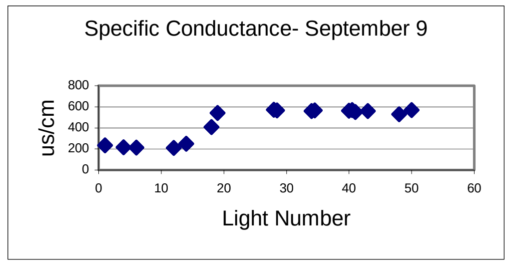

Temperature- December 7
Degrees C
12
11.5
11
10.5
0
10
20
30
40
50
60
Light Number

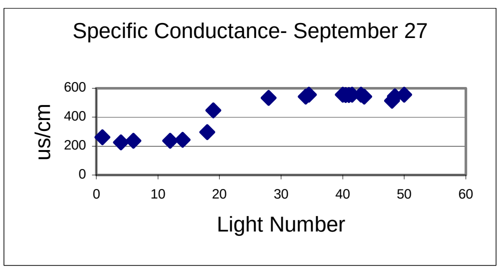
c)

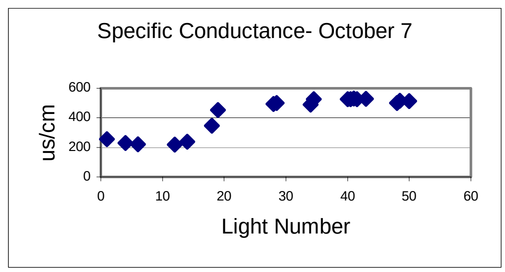

Specific Conductance- July 27
us/cm
600
400
200
0
0 10 20 30 40 50 60
Light Number

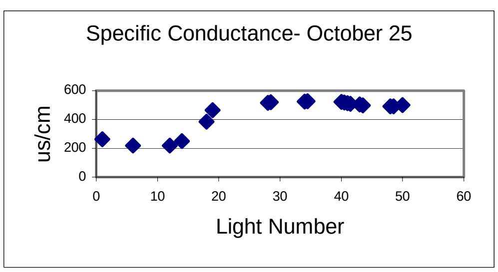

Specific Conductance- August 10
us/cm
800
600
400
200
0
0 10 20 30 40 50 60
Light Number

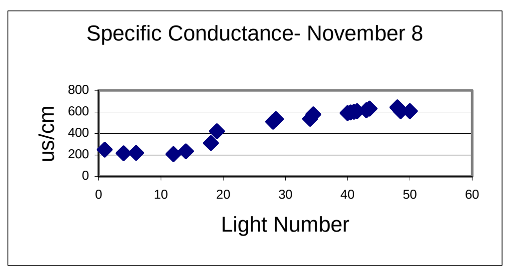

Specific Conductance- August 26
us/cm
800
600
400
200
0
0 10 20 30 40 50 60
Light Number

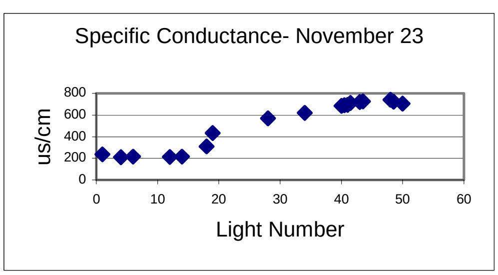

Specific Conductance- September 9
us/cm
800
600
400
200
0
0 10 20 30 40 50 60
Light Number

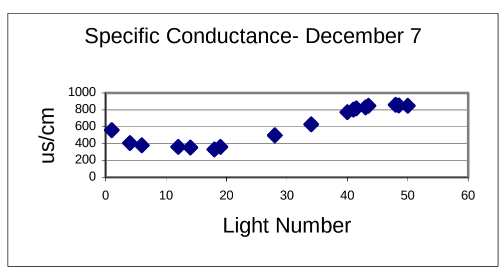

Specific Conductance- September 27
us/cm
600
400
200
0
0 10 20 30 40 50 60
Light Number


Specific Conductance- October 7
us/cm
600
400
200
0
0 10 20 30 40 50 60
Light Number

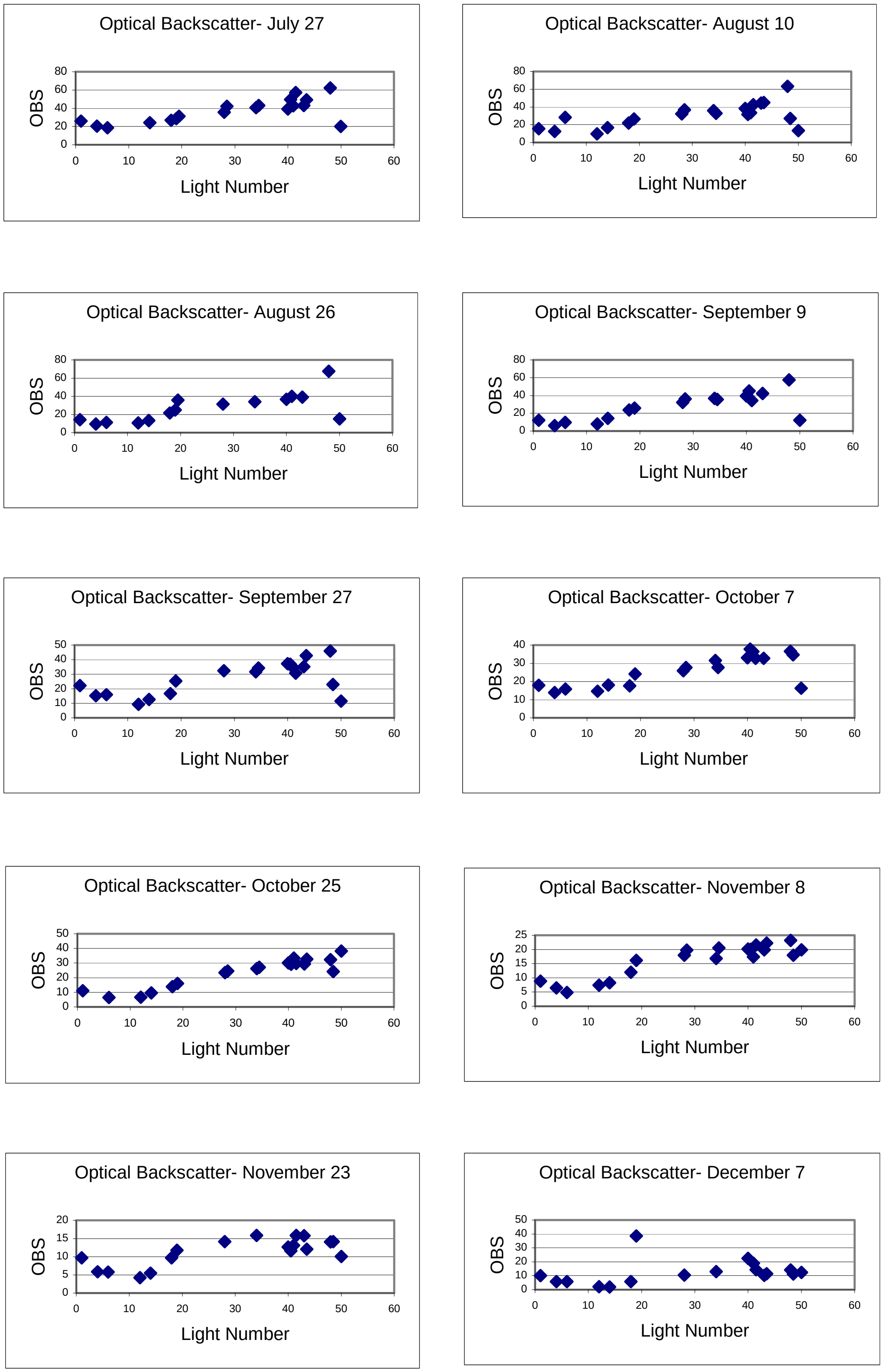

Specific Conductance- October 25
us/cm
600
400
200
0
0 10 20 30 40 50 60
Light Number


Specific Conductance- November 8
us/cm
800
600
400
200
0
0 10 20 30 40 50 60
Light Number


Specific Conductance- November 23
us/cm
800
600
400
200
0
0 10 20 30 40 50 60
Light Number


Specific Conductance- December 7
us/cm
1000
800
600
400
200
0
0 10 20 30 40 50 60
Light Number

d)


Optical Backscatter- July 27
OBS
Light Number
Optical Backscatter- August 10
OBS
Light Number
Optical Backscatter- August 26
OBS
Light Number
Optical Backscatter- September 9
OBS
Light Number
Optical Backscatter- September 27
OBS
Light Number
Optical Backscatter- October 7
OBS
Light Number
Optical Backscatter- October 25
OBS
Light Number
Optical Backscatter- November 8
OBS
Light Number
Optical Backscatter- November 23
OBS
Light Number
Optical Backscatter- December 7
OBS
Light Number

Low dissolved oxygen concentration was measured near the bottom in the study reach and a strong vertical gradient characterized stations near the upstream boundary of the DWC and Turning Basin (Fig. 3). The vertical oxygen gradient was associated with a 1-2 ^{o} C decrease in water temperature, but specific conductance remained constant (Fig. 4 a,b).

Low dissolved oxygen concentration in the DWC was partially a function of high water temperature throughout the water column. Average water temperature upstream of Light 19 was 22-25.5^{o}C and highest near the upstream boundary at Light 43, where the oxygen depletion was most severe (Fig. 2 b). High water temperature reduced the dissolved oxygen saturation concentration in this reach to between 8.7 mg L^{-1} (22^{o}C) and 8.2 mg L^{-1} (25.5^{o}C). However, additional oxygen demand kept dissolved oxygen concentration well below these saturation values (Fig. 2 a).

Fig. 4 Vertical profiles of dissolved oxygen concentration in the Stockton Deep Water Channel.

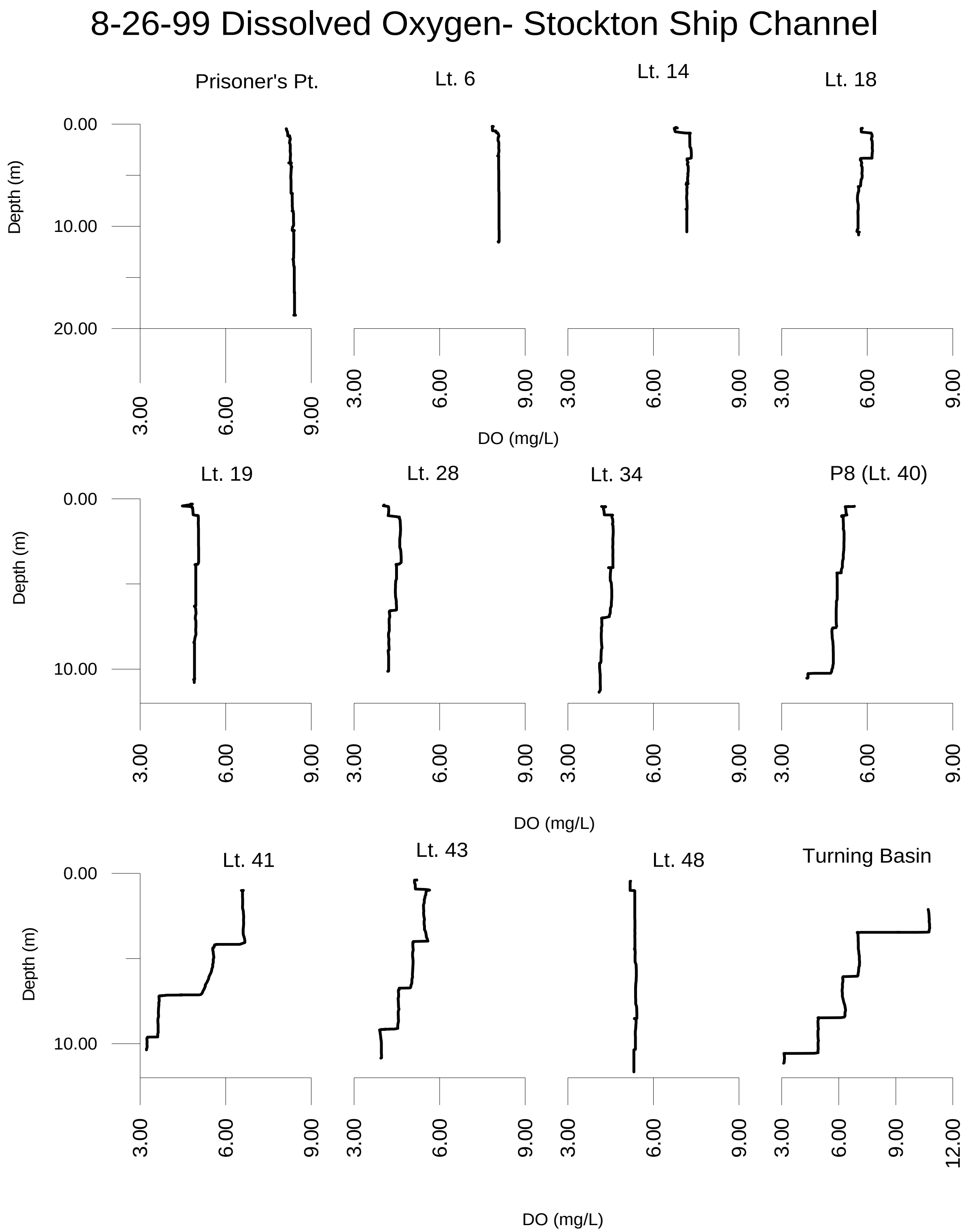
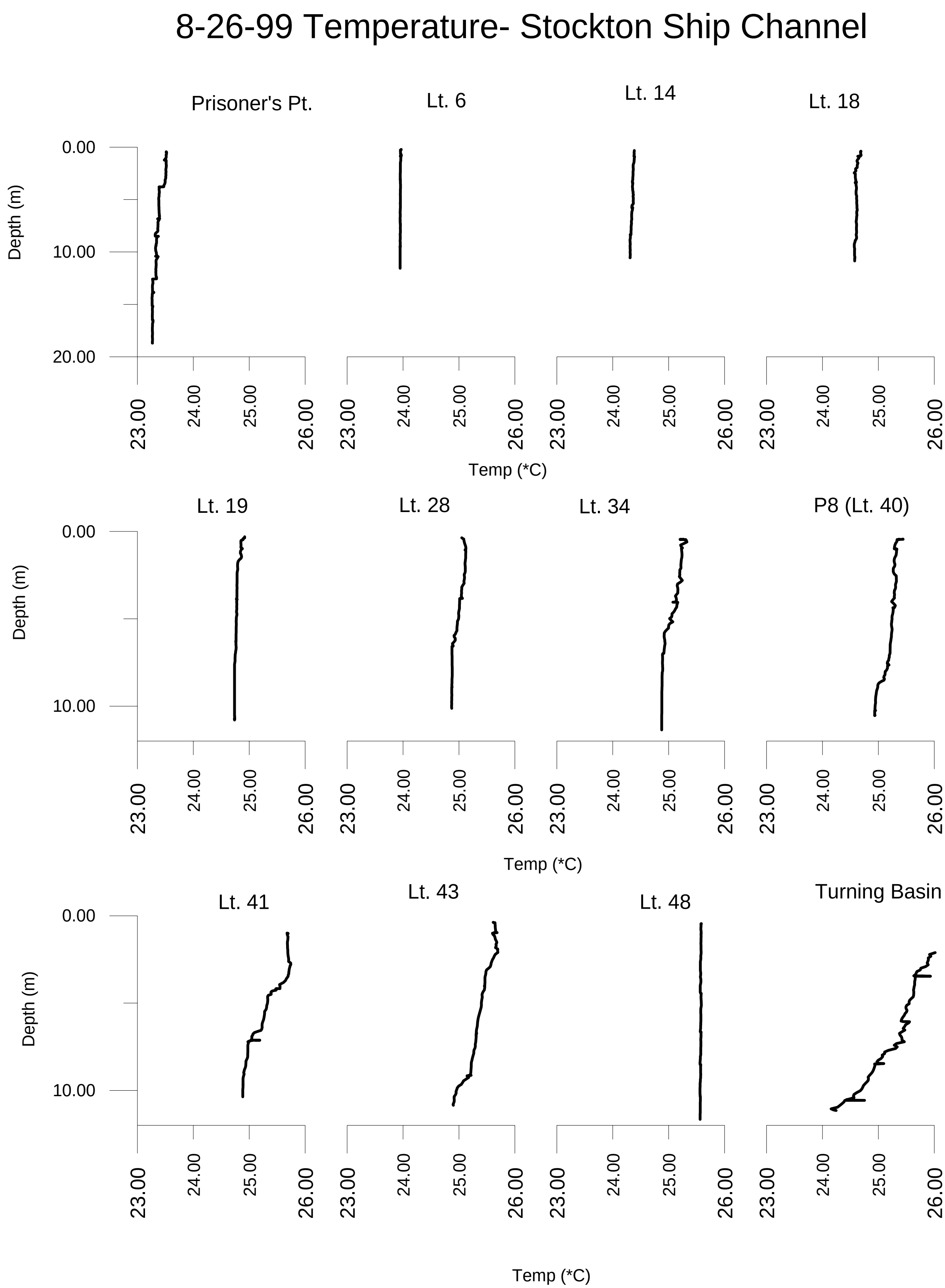


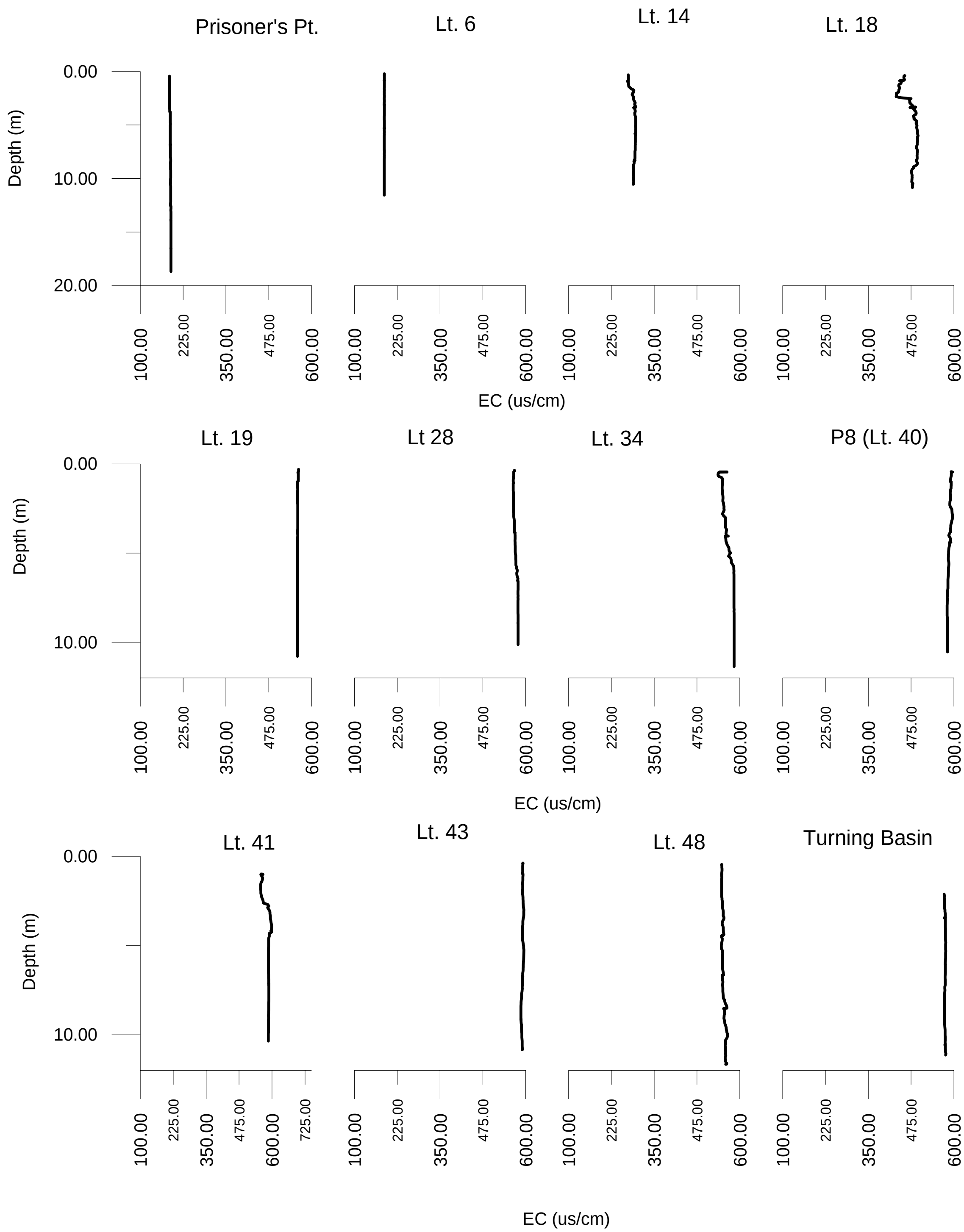
Fig. 4. Vertical profiles of a) water temperature and b) specific conductance.

a)



b)

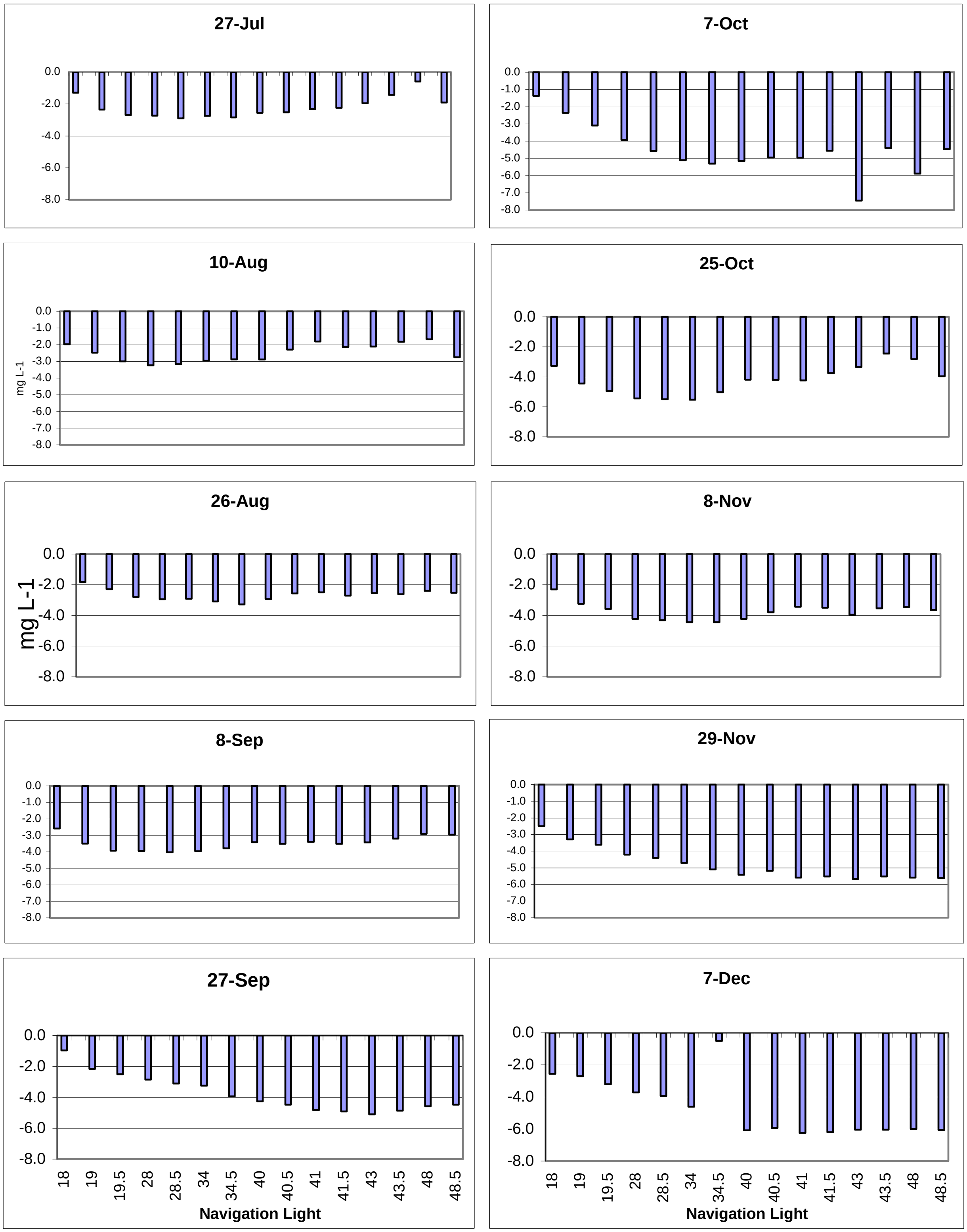
8-26-99 Specific Conductance- Stockton Ship Channel



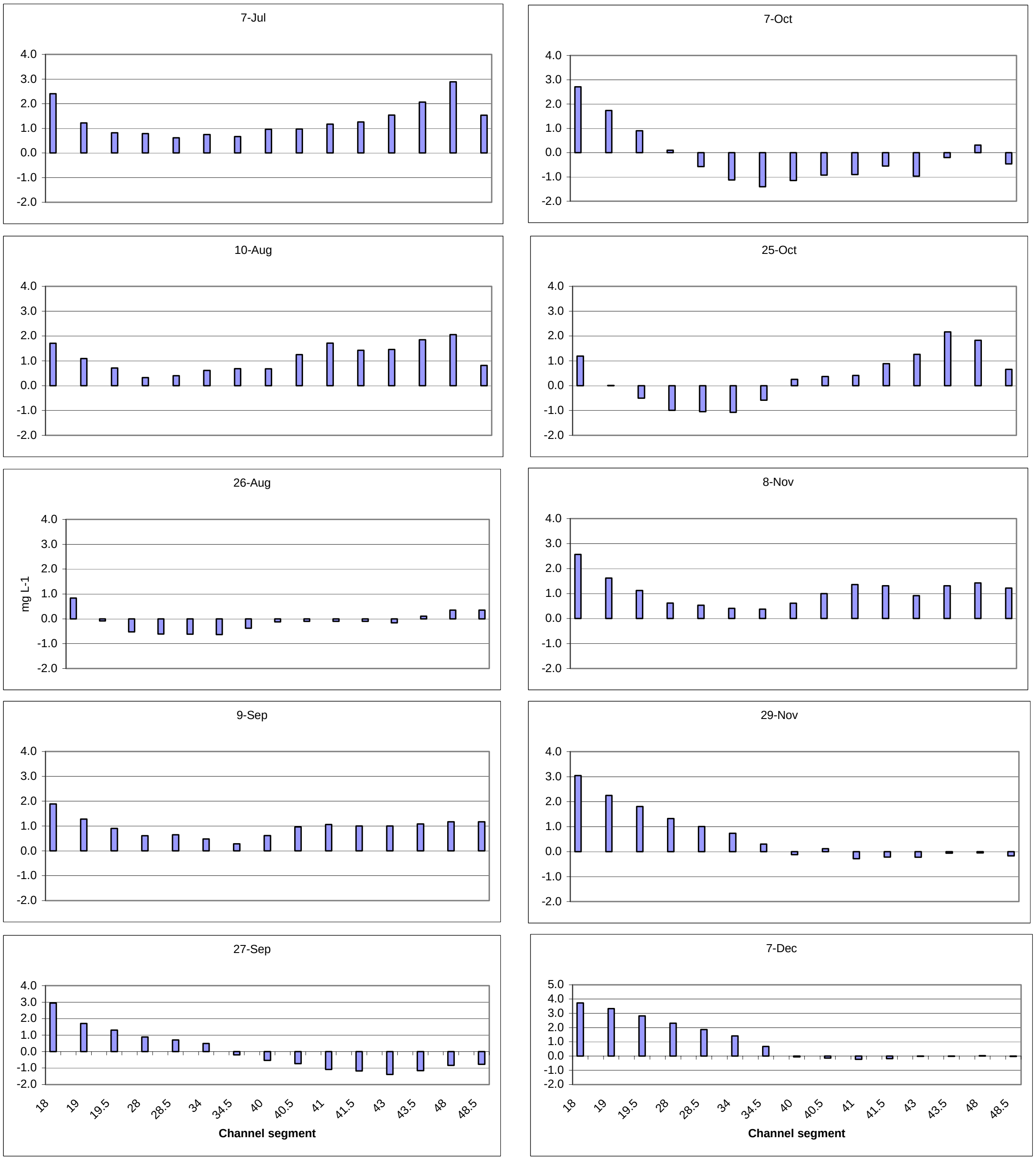
Oxygen deficit - The total oxygen deficit from saturation was consistently negative between July and December in the study reach (Fig. 5 a). The deficit ranged from less than 1 mg L^{-1} to near 8 mg L^{-1} and was usually between 2 mg L^{-1} and 4 mg L^{-1} . The oxygen deficit for 5 mg L^{-1} was often positive, particularly at the seaward edge of the boundary, and didn't exceed 1.5 mg L^{-1} (Fig. 5b). The deficit was variable within each month. For example, the deficit was positive by 1-2 mg L^{-1} on Sept 9, but negative by 1-2 mg L^{-1} for landward segments of the study reach by Sept 27. A similar pattern occurred for Aug 10 and Aug 26 and Nov 8 and Nov 29. The oxygen deficit from 6 mg L^{-1} was often negative by 1 mg L^{-1} and reached a maximum deficit of 2.5 mg L^{-1} in late Sep and early Oct (Fig. 5 c). Although individual segments within the study reach had a negative deficit the net deficit in the channel was usually positive for 5 mg L^{-1} and only slightly negative for 6 mg L^{-1} (Table 3).

Figure 5. Oxygen deficit from a) saturation, b) 5 mg L^{-1} and c) 6 mg L^{-1} within the DWC between July and December 1999.

a)



b)


7-Jul
7-Oct
10-Aug
25-Oct
26-Aug
8-Nov
9-Sep
29-Nov
27-Sep
7-Dec
mg L-1
18
19
19.5
28
28.5
34
34.5
40
40.5
41
41.5
43
43.5
48
48.5
Channel segment

c)

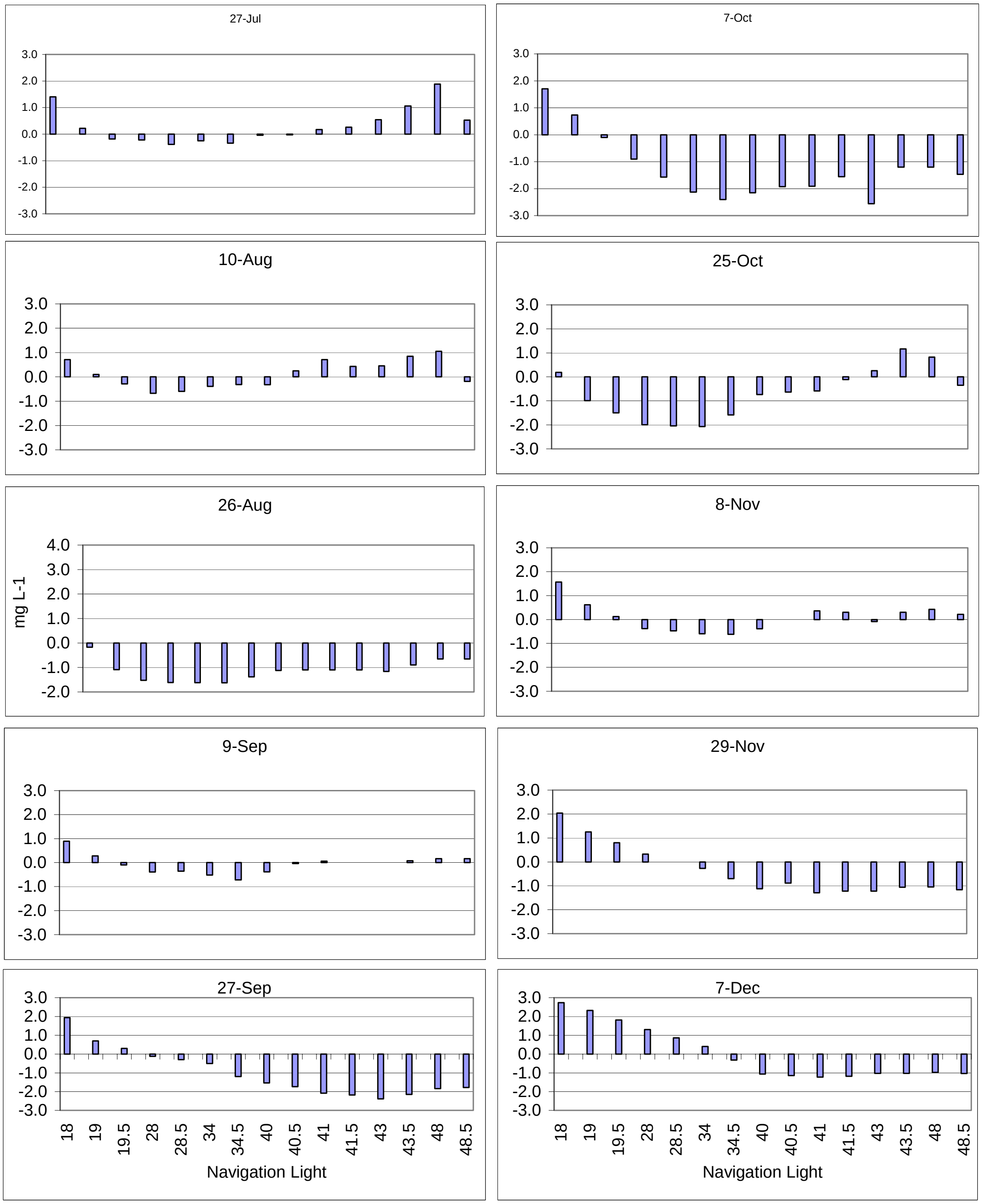

27-Jul
7-Oct
10-Aug
25-Oct
26-Aug
8-Nov
9-Sep
29-Nov
27-Sep
7-Dec
mg L-1
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
4.0
18
19
19.5
28
28.5
34
34.5
40
40.5
41
41.5
43
43.5
48
48.5
Navigation Light
Navigation Light

Fig. 6. Horizontal profiles of surface chlorophyll *a* concentration in the DWC.

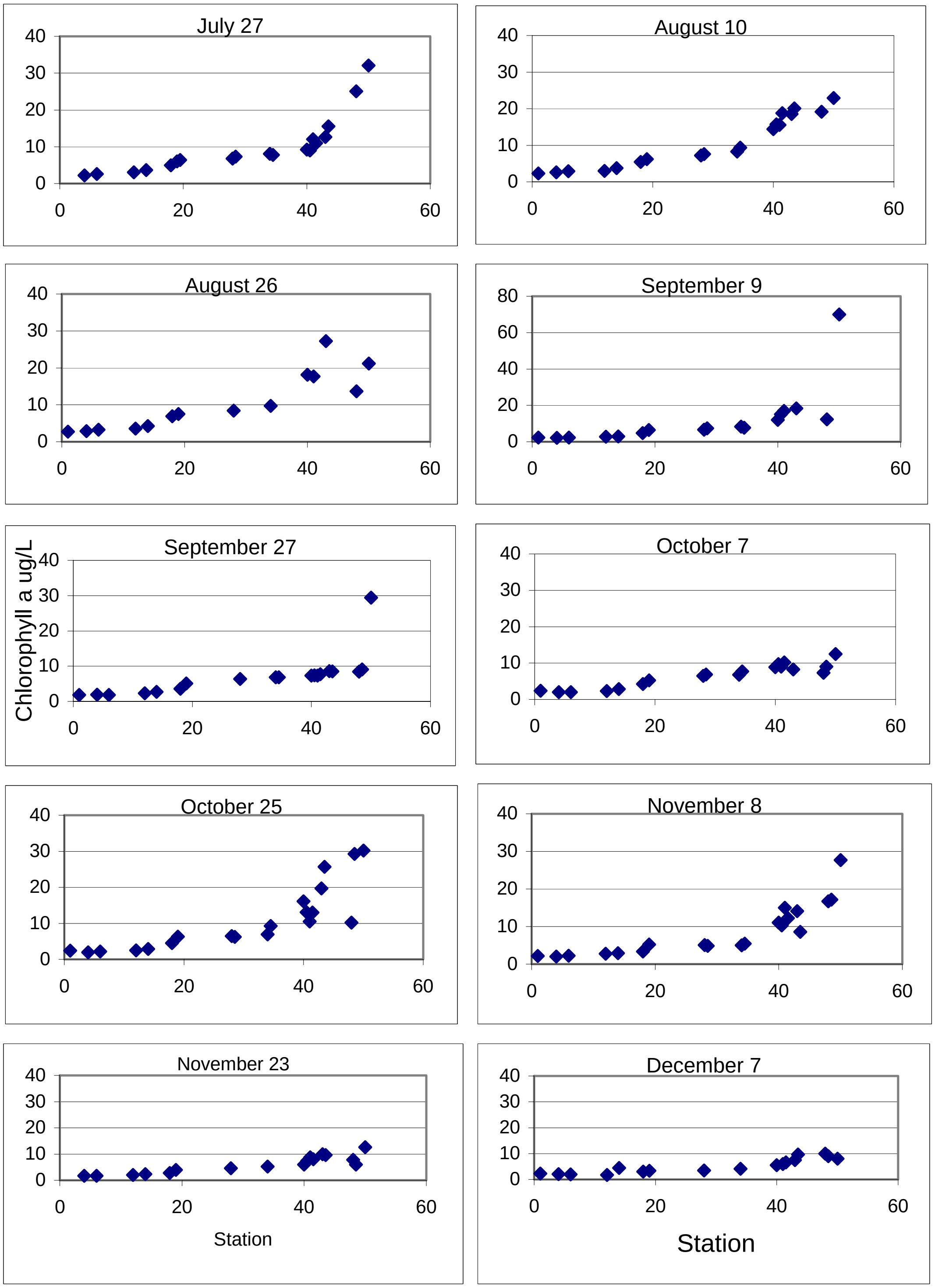


Table 3. Total oxygen demand as deviation from saturation, 5 mg L^{-1} and 6 mg L^{-1} between Disappointment Slough at Light 19 and the upper San Joaquin River at Light 48 for July to December 1999.

	Average Temperature °C	Average Dissolved Oxygen mg L^{-1}	Deviation from Saturation mg L^{-1}	Deviation from 5.0 mg L^{-1}	Deviation from 6.0 mg L^{-1}
27-Jul	23.95	6.31	-2.2	1.3	0.3
10-Aug	23.24	6.15	-2.5	1.1	0.1
26-Aug	25.09	4.88	-3.5	-0.1	-1.1
09-Sep	23.23	5.91	-2.7	0.9	-0.1
27-Sep	22.51	4.86	-3.7	0.0	-1.0
07-Oct	20.85	4.77	-4.5	-0.2	-1.2
25-Oct	18.08	5.38	-4.2	0.3	-0.7
08-Nov	16.76	6.08	-3.8	1.0	0.0
23-Nov	13.94	5.53	-4.8	0.6	-0.4
07-Dec	11.53	5.93	-4.7	1.0	0.0

The oxygen deficit measured in 1999 was similar to that measured previously in both the dry year 1991 (a) and the wet year 1995 (b) (Table 4).

Table 4. Oxygen deficit in the DWC in August and September between Light 19 and Light 48 a) 1991 and b) 1995.

Aug-91

	Average Temperature (C)	Average Dissolved Oxygen (mg/L)	Oxygen deficit from saturation mg L^{-1}	Oxygen deficit from 5.0 mg/L mg L^{-1}	Oxygen deficit from 6.0 mg/L mg L^{-1}
Segment 18		6.6	0.0	0.7	0.3
Segment 19		6.4	0.0	0.6	0.2
Segment 19.5					
Segment 28		5.6	0.0	0.3	-0.2
Segment 28.5					
Segment 34		4.8	0.0	-0.1	-0.6
Segment 34.5					
Segment P8		4.6	0.0	-0.2	-0.7
Segment P8.5					
Segment 41		4.3	0.0	-0.3	-0.8
Segment 41.5					
Segment 43		3.8	0.0	-0.6	-1.0
Segment 43.5					
Segment 48		3.8	0.0	-0.6	-1.0
Segment 48.5			0.0	0.0	0.0

Sep-91	Average Temperature (C)	Average Dissolved Oxygen (mg/L)	Oxygen deficit from saturation mg L^{-1}	Oxygen deficit from 5.0 mg/L mg L^{-1}	Oxygen deficit from 6.0 mg/L mg L^{-1}
Segment 18	24	6.9	-0.7	0.9	0.4
Segment 19	24	6.7	-0.8	0.8	0.3
Segment 19.5					
Segment 28	24	5.9	-0.9	0.4	-0.1
Segment 28.5					
Segment 34	24	5.3	-1.0	0.1	-0.3
Segment 34.5					
Segment P8	24	4.4	-1.3	-0.3	-0.8
Segment P8.5					
Segment 41	24	4.2	-1.5	-0.4	-0.8
Segment 41.5					
Segment 43	25	3.8	-1.4	-0.5	-1.0
Segment 43.5					
Segment 48	25	3.8	-2.1	-0.6	-1.0
Segment 48.5					

b.

Aug-95	Average Temperature (C)	Average Dissolved Oxygen (mg/L)	Oxygen deficit from saturation	Oxygen deficit from 5.0 mg/L	Oxygen deficit from 6.0 mg/L
Segment 18	25.3	5.4	-1.3	0.2	-0.3
Segment 19	25.3	5.2	-1.4	0.1	-0.4
Segment 19.5					
Segment 28	25.3	4.7	-1.6	-0.2	-0.6
Segment 28.5					
Segment 34	25.3	4.6	-1.7	-0.2	-0.7
Segment 34.5					
Segment P8	25.5	5	-1.5	0.0	-0.5
Segment P8.5					
Segment 41	25.5	5	-1.5	0.0	-0.5
Segment 41.5					
Segment 43	25.8	5.3	-1.3	0.1	-0.3
Segment 43.5					
Segment 48	25.3	5.6	-1.2	0.3	-0.2
Segment 48.5					

Sep-95	Average Temperature (C)	Average Dissolved Oxygen (mg/L)	Oxygen deficit from saturation	Oxygen deficit from 5.0 mg/L	Oxygen deficit from 6.0 mg/L
*Segment 18	23.5	5.9	-1.2	0.4	0.0
Segment 19	24	5.7	-1.2	0.3	-0.1
Segment 19.5					
Segment 28	23	5.5	-1.4	0.2	-0.2
Segment 28.5					
Segment 34	23	5.6	-1.4	0.3	-0.2
Segment 34.5					
Segment P8	23	6	-1.2	0.5	0.0
Segment P8.5					
Segment 41	23	6	-1.2	0.4	0.0
Segment 41.5					
Segment 43	23.5	6.9	-0.7	0.8	0.4
Segment 43.5					
Segment 48	23	5.8	-1.3	0.3	-0.1
Segment 48.5					

The magnitude and location of the oxygen deficit in the study reach was strongly influenced by algal photosynthesis. For example, the oxygen deficit from 5 mg L^{-1} was negative for most of the segments of the study reach on Nov 23 when chlorophyll *a* concentration in the DWC was below 10 ug L^{-1}. In contrast, most of the landward channel segments had positive oxygen deficit values on Nov 8 near the when chlorophyll *a* concentration was 10-20 ug L^{-1} (Figs. 5 and 6).

Algal biomass contributed up to 10% of the total oxygen deficit and up to100 % of the oxygen deficit for 5 mg L^{-1} and 6 mg L^{-1}in the DWC during fall 1999 in the study reach. The average algal biomass in the study reach was 243 kg (Table 5 a). Over the course of a day this algal biomass produced an additional 20 to 72 kg day^{-1} of chlorophyll *a*, an increase of 14-22%. Although this algal photosynthesis caused a net production of oxygen in the photic zone, the photic zone was shallow (0.5 m Secchi disk depth) compared with the total depth of 11.8 m. As a result, most of the phytoplankton in the water column was in the dark where only respiration occurs. This excess of respiration over photosynthesis produced an average net oxygen demand in the study reach of between 3829 to 7391 kg O_2 day^{-1}; equivalent to 0.19 to 0.36 mg L^{-1}.

These values for algal net production and respiration rate are only estimates because the dissolved oxygen light and dark bottle method measures the net production and respiration of both algae and bacteria. In order to assess the potential contribution of algae alone on the community production rates, measured community production and respiration rates were compared with values calculated using equations derived for San Francisco Bay (Table 5b). Algal net production rate estimates were similar for modeled and measured values (Table 5 b).

Table 5. Estimated chl a biomass and photosynthetic production rates for the DWC between Light 19 and Light 48. Specific production rates were based on a) light and dark bottle dissolved oxygen measurements conducted on Sep 23, 1999 and b) equations for

a)

Date	Chl a in the channel kg	Percent chl produced of that in channel %	Daily production of chl a kg chl day^{-1}	Net photic zone production kg C day^{-1}	Aphotic zone respiration kg C day^{-1}	Net water column production kg C day^{-1}	Oxygen demand kg O_2 day-1	Oxygen demand mg O_2 L^{-1}
27-Jul	275	22	60	2415	-3807	-1392	-4460	-0.22
10-Aug	316	22	69	2776	-4375	-1599	-5126	-0.25
26-Aug	360	20	72	2876	-4988	-2112	-6770	-0.33
09-Sep	273	18	49	1964	-3787	-1823	-5843	-0.28
27-Sep	180	18	32	1293	-2494	-1201	-3848	-0.19
07-Oct	193	18	34	1388	-2676	-1288	-4128	-0.20
25-Oct	309	16	49	1970	-4276	-2306	-7391	-0.36
08-Nov	226	14	31	1260	-3127	-1868	-5986	-0.29
23-Nov	157	14	22	877	-2178	-1301	-4169	-0.20
07-Dec	144	14	20	806	-2000	-1195	-3829	-0.19
mean	243	18	44	1762	-3371	-1608	-5155	-0.25

b)

Date	Chl a in the channel	Percent chl produced of total in channel	Daily production of chl a	Net photic zone production	Aphotic zone respiration	Net water column production	Oxygen demand	Oxygen demand
	kg	%	kg chl day^{-1}	kg C day^{-1}	kg C day^{-1}	kg C day^{-1}	kg O_2 day-1	mg O_2 L^{-1}
27-Jul	275	15	40	1602	-2210	-608	-1949	-0.09
10-Aug	316	12	39	1552	-2365	-813	-2605	-0.13
26-Aug	360	7	24	975	-2531	-1556	-4989	-0.24
9-Sep	273	12	33	1308	-2205	-897	-2876	-0.14
27-Sep	180	12	22	874	-1854	-980	-3141	-0.15
7-Oct	193	11	20	813	-1903	-1090	-3492	-0.17
25-Oct	309	8	25	1010	-2338	-1328	-4256	-0.21
8-Nov	226	7	16	658	-2026	-1368	-4384	-0.21
23-Nov	157	6	10	393	-1768	-1375	-4408	-0.21
7-Dec	144	5	8	301	-1720	-1419	-4548	-0.22
mean	243	10	24	949	-2092	-1143	-3665	-0.18

Although chlorophyll *a* biomass decreased in the DWC between July and December, its impact on the oxygen demand increased in Nov and Dec due to the high respiration produced by decreased day length and solar irradiance near the end of the year (Table 5). However, the oxygen demand from algal biomass was not sufficiently high to account for the large increase in oxygen demand at the end of the year. Net tidal-day transport studies suggest a major source of this oxygen demand was nitrogen.

Phaeophytin concentration, a breakdown product of chlorophyll *a* concentration, was two times higher than chlorophyll *a* concentration in the DWC and tributaries and suggested that decaying algal biomass contributes significantly to the oxygen demand (Table 6). However, the rate of oxygen consumption associated with this phaeophytin concentration is unknown. Instead, high phaeophytin concentration in the tributaries suggested phytoplankton growth and subsequent decomposition upstream influenced the oxygen demand load into the DWC.

Table 6. Pigment biomass and water quality conditions for tributaries to the DWC measured in 1999.

CHANNEL POINT

	Depth (ft)	Diss. Oxygen (mg/L)	Water Temperature (C)	Chlorophyll a (ug/L)	Phaeophytin (ug/L)	NTU
7/27/99	3	9.3	20.5			11
	No Data	No Data	No Data			
8/10/99	3	6.5	23.9	13.7	4.7	11
	24.3	6.9	22.9			
8/26/99	3	No Data	25.6	8.5	11	No Data
	No Data	No Data	25.4	10.3	17.3	
9/9/99	3	6.7	23.4	9.3	11.9	34
	16.4	6.8	23.4			
9/27/99	3	4.8	22.5	4.6	6.4	21
	29	5.1	22.4			
10/7/99	3	5	21.4	5.8	3.8	16
	30.8	6.32	19.5			
10/25/99	3	7.2	18			18
	26.9	7.4	17.5			
11/8/99	3	6.7	16.8	22	5	10
	34.9	6.4	166.4			
11/23/99	3	5	13.7	6	3	10
	18.5	5.1	13.7			
12/7/99	3	4.9	11.4	8	7	11
	33.5	4.9	11.5			

SMITH CANAL

	Depth (ft)	Diss. Oxygen (mg/L)	Water Temperature (C)	Chlorophyll a (ug/L)	Phaeophytin (ug/L)	NTU
7/27/99	3	No Data	No Data			17
8/10/99	3	7.6	23.9	17.8	5.1	18
	8.8	7.6	23.7			
8/26/99	3	5.37	25.9	38.4	7.1	No Data
	6.6	6.22	25.9			
9/9/99	3	6.5	23.7	26.1	5.9	16
9/27/99	3	6.5	24	23.9	5.7	17
10/7/99	3	5.2	21.4			17
10/25/99	3	9.3	18.4			14
11/8/99	3	8	17.9			10
11/23/99	3	4.8	14.2			8
12/7/99	3	5	11.8			9

CALAVERAS RIVER

	Depth (ft)	Diss. Oxygen (mg/L)	Water Temperature (C)	Chlorophyll a (ug/L)	Phaeophytin (ug/L)	NTU
7/27/99	3	12.1	26.7			17
	No Data	No Data	No Data			
8/10/99	3	6.32	23.3	12.7	4.6	16
	12.7	6.59	23.2			
8/26/99	3	3.76	25.6	11.6	4.5	No Data
	18.3	4.46	25.1			
9/9/99	3	6.4	24.1	9.9	4.4	13
	12.7	6.8	23.6			
9/27/99	3	9.1	23.1	18.2	5.2	12
	18.3	5.3	22.4			
10/7/99	3	6.8	21.6			10
	12.2	6.2	20.8			
10/25/99	3	5.2	18.1			15
	20.8	5.3	17.9			
11/8/99	3	6.5	17.4			9
	14.9	5.8	16.9			
11/23/99	3	4.6	14.2			10
	19.5	4.6	14.1			
12/7/99	3	5	11.9			12
	19.3	4.9	11.9			

TURNING BASIN

	Depth (ft)	Diss. Oxygen (mg/L)	Water Temperature (C)	Chlorophyll a (ug/L)	Phaeophytin (ug/L)	NTU
7/27/99	3	10.8	25.4			9
	38.09	7	23.7			
8/10/99	3	8.1	24.1	22.9	5.6	7
	37.5	5.1	23			
8/26/99	3	8..6	25.8	21.2	5.5	No Data
	36.6	3.1	24.2			
9/9/99	3	13	24.9	64.4	7.3	5
	36.8	6.5	22.4			
9/27/99	3	8.4	23.3	32.2	7.7	6
	35.8	5	22.6			
10/7/99	3	5.7	21.6	13.6	3.8	7
	37.1	4.1	20.5			
10/25/99	3	11	19			6
	37.8	3.7	17.6			
11/8/99	3	7.1	17.1	45	4	7
	39.4	6.1	16.4			
11/23/99	3	5	14.5	9	3	7
	37.7	5.6	13.6			
12/7/99	3	4.9	11.7	5	4	7
	39.1	4.8	11.5			

LIGHT 14- DOWNSTREAM BOUNDARY

	Depth (ft)	Diss. Oxygen (mg/L)	Water Temperature (C)	Chlorophyll a (ug/L)	Phaeophytin (ug/L)	NTU
07/27/1999	3	8.4	22.3			11
	37	8.4	22			
08/10/1999	3	8	22.3	3.8	3.8	10
	36.7	8.2	22			
08/26/1999	3	7.3	24.4	4.2	3.8	No Data
	34.6	7.2	24.4			
09/09/1999	3	7.7	22.9	2.9	3.7	7
	36.2	8	22.6			
09/27/1999	3	8.2	21.4	2.7	3.7	6
	29.6	8.2	21.3			
10/07/1999	3	8.7	19.8			7
	34.8	8.5	19.7			
10/25/1999	3	8.2	18			3
	36.7	8.4	17.7			
11/08/1999	3	8.1	16.3			4
	36.9	8.2	16.1			
11/23/1999	3	8.5	13.2			6
	36.4	8.5	13			
12/07/1999	3	8.9	11			7
	36.6	9	10.9			

Tributary and local sources of algal biomass – Chlorophyll *a* concentration *u*g L^{-1} was higher at Smith Canal and the Turning Basin than Channel Point, the Calaveras River and Light 24 near Turner Cut (Table 6). Dissolved oxygen concentration above 5 mg L^{-1} at Channel Point, Smith Canal, the Calaveras River and Light 14 suggests net photosynthesis was sufficient to oxygenate tributary sources despite high algal biomass. In contrast, near the bottom dissolved oxygen was consistently less than 5 mg L^{-1} in the Turning Basin, where high algal biomass at the surface was associated with a deep water column that would limit oxygenation from photosynthesis and surface aeration. An evaluation of the load of algal biomass and oxygen demand from these sources is not yet possible because of a lack of flow velocity data.

Table 7. Comparison of discrete chlorophyll *a* concentration measured at Vernalis and continuous fluorometric measurements of chlorophyll *a* concentration at Mossdale for August and September 1999.

Date	Vernalis		Mossdale	
	chlorophyll ug/L	phaeophytin ug/L	chlorophyll ug/L	phaeophytin ug/L
8/5/99	48	18	41.1	15.4
8/12/99	33	18	38.1	15
8/19/99	38	13	34.1	14.3
8/26/99	25	12	27.6	12.1
9/2/99	40	13	28.4	13.4
9/9/99	33	15	25.8	13
9/16/99	22	15	31.1	13.8
9/23/99	22	16	21	10.5
9/30/99	28	10	25.2	12.9

Vernalis may be a poor station for calculation of upstream load. Chlorophyll *a* concentration at Vernalis and Mossdale was similar during the fall (Table 7). However, chlorophyll *a* concentration was approximately a factor of 2 lower between Mossdale and Channel Point, where the upper San Joaquin River entered the DWC (Table 8 and 9). This decrease may be caused by algal decay processes. Most of the pigment biomass that entered the DWC at Channel Point was phaeophytin. A 1.1-1.2 mg L^{-1} decrease in total organic carbon between Vernalis and Channel Point supported the loss of chlorophyll *a* and phaeophytin in the channel if the carbon/ pigment ratio was 40 (Table 9). The decrease could be a function of sedimentation because suspended solids also decreased by a factor of 2 between Mossdale and Channel Point.
(Table 8)

Table 8. Comparison of chlorophyll a and phaeophytin concentrations (ug L^{-1}) measured at Vernalis, Mossdale and Channel Point in August and September.

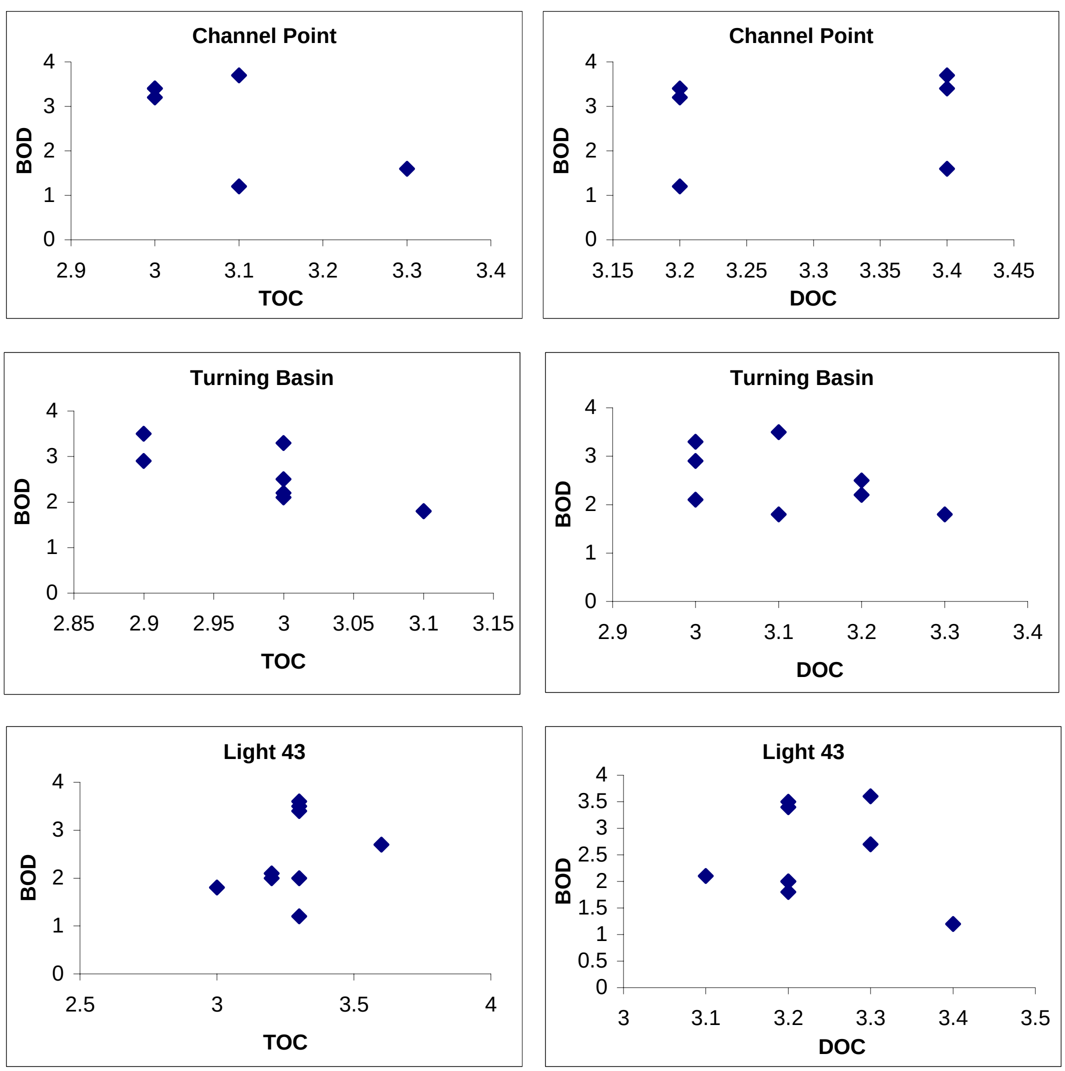
	Vernalis		Mossdale		Channel Pt.	
	chl	phae	chl	phae	chl	phae
26-Aug	27	14	27.65 + 7.86	12.07 ± 1.85	8.46 ± 0.94	11.00 ± 4.15
23-Sep	22	16	20.96 ± 2.88	10.50 ± 0.68	8.70 ± 3.81	7.79 ± 0.40

Table 9. Comparison of surface water quality conditions at Vernalis and Channel Point measured on August 26 and September 23, 1999.

	26-Aug		23-Sep	
Variable	Vernalis	Channel Point	Vernalis	Channel Point
BOD mg/L	2.50	< 3.00	4.30	1.80
CBOD mg/L	<1	< 3.00	2.00	2.40
Total organic carbon mg/L	4.40	3.20	4.10	3.00
Dissolved organic carbon mg/L	3.60	2.60	3.80	2.60
Particulate organic carbon mg/L	0.80	0.60	0.30	0.40
Total suspended solids mg/L	87.00	26.00	107.00	49.00
Volatile suspended solids mg/L	< 5.00	3.00	7.60	6.00
Nitrate plus nitrite mg/L	1.70	2.00	2.10	2.20
Ammonia mg/L	< 0.50	0.18	< 0.10	0.35
Orthophosphate mg/L	0.15	0.15	0.14	0.14
Total phosphate mg/L	0.30	0.22	0.25	0.20
Total Kjeldahl nitrogen mg/L	3.40	1.00	1.60	1.00
chlorophyll a ug/L	27.00	7.00	22.00	9.00
phaeophytin ug/L	14.00	4.00	16.00	18.00
chlorophyll a as carbon mg/L	1.08	0.28	0.88	0.36
total pigment as carbon mg/L	1.64	0.44	1.52	1.08

Chlorophyll *a* plus phaeophytin concentration comprised less than half of the total organic carbon and its correlation with BOD was poor for most stations. Most of the organic carbon among stations was dissolved and was associated with a low BOD (Table 12). BOD decreased with total organic carbon concentration at the Turning Basin and Channel Point and with dissolved organic carbon concentration at the Turning Basin (Fig. 7). The association between BOD and both total and dissolved organic carbon was poor at Light 43. This inconsistent correlation between BOD and chlorophyll *a* concentration suggested more than algal biomass at Channel Point and Light 43 influenced BOD. In contrast, a good correlation between chlorophyll *a* concentration and BOD suggested most of the BOD was produced by algae at the Turning Basin.

Fig. 7. Association between BOD (mg L-1), TOC (mg L-1) and DOC (mg L-1) measured on September 23, 1999.



Net daily transport – Net tidal-day transport studies conducted in August and September indicated about 65% of the organic carbon, 40-60% of the volatile suspended solids and at least 60% of the nitrogenous and 60% of the carbonaceous oxygen demand transported downstream past Light 43 came from the upper San Joaquin River (Table 10 a, b). Total algal biomass transported from the San Joaquin River at station 51 near Channel Point accounted for 40-90 % of the chlorophyll *a* biomass transported seaward past Light 43. The daily load of algal biomass into the DWC from the upper San Joaquin River was equivalent to 46-100% of the chlorophyll *a* produced in the DWC from in situ growth on Aug 26 and Sep 23 in the study reach. The total pigment load was much higher when phaeophytin was included. Phaeophytin concentration was nearly two times higher than chlorophyll *a* concentration at both the channel and main stem stations.

Table 10. Net tidal day material transfer (kg day^{-1}) at three stations in the lower San Joaquin River on a) August 26, 1999 and b) September 23, 1999.

a)

Material	Light 43	Channel Point	Turning Basin
BOD 10 day	ND	ND	ND
CBOD 10 day	ND	ND	ND
TOC	10571	6915	-528
DOC	8513	5570	-940
ammonia	751	575	13
nitrate	6278	4291	49
TKN	3056	2237	-754
ortho-P	461	368	14
total P	834	595	-78
VSS	17723	6915	-3090
TSS	125732	103833	-8136
chlorophyll	24	22	-30
phaeophytin	47	36	-3

b)

Material	Light 43	Channel Point	Turning Basin
BOD 10 day	3942	-760	582
CBOD 10 day	2327	1474	88
TOC	9730	6481	1332
DOC	8153	4619	1069
ammonia	626	2751	9
nitrate	7074	4118	734
TKN	2917	3463	450
ortho-P	208	260	35
total P	649	400	126
VSS	16365	9958	8101
TSS	171076	91429	14026
chlorophyll	29	11	9
phaeophytin	46	19	5

The net transport of algal biomass from each source differs when both chlorophyll *a* and phaeophytin concentration are considered. The net transport of phaeophytin concentration exceeded the net transport of chlorophyll *a* biomass at Channel Point and Light 43 and was higher at both these stations compared with the Turning Basin. When both pigments were included, the Turning Basin accounted for 18% of the seaward transport past Light 43 compared with 40% from Channel Point.

The oxygen demand from ammonia transported from the upper San Joaquin River was high. In August, the ammonia transported from Channel Point was equivalent to 70% of the ammonia exported at Light 43 and produced a direct oxygen demand of 2588 kg day^{-1}. The load of ammonia from upstream increased 5 fold in September. However, ammonia transported into the DWC exceeded that transported downstream at Light 43 by about 2,000 kg day^{-1}. If nitrification of this additional ammonia occurred in the DWC upstream of Light 43, it would have produced an oxygen demand of 9562 kg day^{-1}. Nitrification of this ammonia was supported by higher nitrate downstream load at Light 43 than Channel Point. The sum of nitrate and ammonia concentration exported at Light 43 was equal to the sum of these nutrient inputs from Channel Point and the Turning Basin.

Non-ammonia nitrogen load was also high and exceeded ammonia load in August. Non-ammonia nitrogen is calculated as TKN minus dissolved ammonia concentration and assumes the amount of ammonia attached to suspended sediments is small. Note that TKN does not measure nitrate and nitrite. In August, non-ammonia nitrogen downstream load at station 51 was over 2 times higher than the ammonia load and accounted for most of the TKN load at station 43. As expected, ammonia load at Channel Point was nearly 5 times higher in September when ammonia load from the Stockton RWCF is high and comprised nearly all of the TKN downstream load. Interestingly, the downstream ammonia load at Light 43 was small compared with the nitrogenous load.

Preliminary data suggest the Turning Basin could be either a source or sink of inorganic and organic material to the DWC (Table 10 a, b). In August, the daily material transport was mostly upstream into the Turning Basin, but this amount was only a small amount compared to the material transported downstream past Light 43. In September, the Turning Basin was a net source of material into the DWC, and contributed up to 20% of the inorganic and organic matter transported downstream at Light 43. The transport of chlorophyll *a* biomass into the DWC from the Turning Basin was similar to that transported into the DWC from the upper San Joaquin River at Channel Point and to 20-50% of that transported downstream past Light 43. These loads need further evaluation. Hourly ADCP velocity values were highly variable for the Turning Basin.

Summary

Current conditions

Dissolved oxygen concentration below the EPA 5 mg L^{-1} and RWQCB 6 mg L^{-1} standard has been measured in the DWC since the 1970s. Decadal comparisons suggest these below standard concentrations are ongoing, but were somewhat lower in the 1980s when streamflow was high. The frequency of low dissolved oxygen concentration decreased somewhat in the 1990s in the DWC, but has changed little in the Turning Basin.
Oxygen deficit calculated from vertical and horizontal profiles taken in 1999 indicated that oxygen depletion occurred along a longer reach of the river than previously suggested. A negative oxygen deficit was measured for both 5 mg L^{-1} and 6 mg L^{-1} from Light 19 to the Turning Basin. Like previous years the worst oxygen depletion was measured between Buckley Cove at Light 40 and the Turning Basin.

Water quality data suggest the study reach between Light 19 and the entrance of the upper San Joaquin River at Light 48 was most similar to the upper San Joaquin River and differed from seaward locations. The study reach was characterized by higher specific conductance, water temperature, chlorophyll *a* concentration and turbidity and lower dissolved oxygen concentration than seaward stations
Oxygen depletion usually occurred throughout the water column in the study reach and was accompanied by a strong vertical oxygen gradient at the landward boundary of the study reach and in the Turning Basin. This oxygen depletion was associated with a decreasing water temperature gradient of 1^{o}C in the DWC and 2 ^{o}C or more in the Turning Basin.

Oxygen Demand from algal biomass

Estimates of oxygen demand from algal biomass reached 0.36 mg L^{-1} of oxygen demand in the DWC and accounted for up to 100% of the oxygen deficit from 5 mg L^{-1} and 6 mg L^{-1}. Specific production and respiration rates used to estimate these values were probably low. The measured specific production rate of 15 mg O2 (mg chlorophyll *a*) $^{-1}$ hr^{-1} in September was at the low end of the range of values measured in the channel during the 1980s, 13.5-32.0 mg O2 (mg chlorophyll *a*) $^{-1}$ hr^{-1} (Lehman 1990). Specific production rate measured in the 1970s was much lower than in the 1980s at 2 mg O2 (mg chlorophyll *a*) $^{-1}$ hr^{-1} and may be a function of a long 24-hr incubation time (Lehman 1990). The measured specific production rate in this study was similar to the 16.5 mg O2 (mg chlorophyll *a*) $^{-1}$ hr^{-1} estimated from equations developed for San Francisco Bay of (Cole and Cloern 1987). It is likely that the estimated net production in this study was low because the values in this study were influenced by high respiration by nitrifying bacteria.

The measured specific respiration rate of 1-2 mg O_2 (mg chlorophyll *a*)$^{-1}$ hr^{-1} estimated from calculated respiration rates for San Francisco Bay (Rudek and Cloern 1996) were similar to the 2 mg O_2 (mg chlorophyll *a*)$^{-1}$ hr^{-1} measured for this study. Because most of the water column is below the photic zone, small differences in the respiration rate may have a large effect on the estimated oxygen demand.

The contribution of both chlorophyll *a* and phaeophytin concentration may be important in determining the importance of algal biomass to oxygen demand from tributary sources. The net daily transfer of chlorophyll *a* concentration into the DWC from the Turning Basin matched that from the upper San Joaquin River in September, but the net transfer of phaeophytin was 3 times lower. The contribution of total algal biomass may also important for a full evaluation of the net seaward transport from the DWC, where the net transport of phaeophytin past the main stem station was two fold higher than for chlorophyll *a*. Future field and modeling studies will need to consider the relative transport of both live and decaying algal biomass to the oxygen demand. Tracer studies will be needed to determine the relative contribution of live and decaying algal biomass from tributaries and local sources to oxygen demand.

Algal load calculated from Vernalis may be a poor estimate of upstream load to the DWC. The total algal biomass transported into the DWC from the upper San Joaquin River past Channel Point was two 2 times smaller than the chlorophyll *a* concentration measured at Mossdale and Vernalis.

The association between organic carbon and BOD $_{(10day)}$ was variable and chlorophyll *a* concentration comprised only a small fraction of the total organic carbon measured at each station.

Net daily transport

The upper San Joaquin River at Channel Point was a major source of oxygen demand and organic and inorganic material to the DWC. The net daily transport of material from the upper San Joaquin River past Channel Point was at least 40% of the material transported downstream past Light 43. The net tidal day downstream load at Light 43 was usually than could be caused by the upper San Joaquin River alone and suggests other sources are important.

The Turning Basin contributed some of the organic and inorganic carbon and oxygen demand transported downstream at Light 43. In August, the net transport or organic and inorganic material was primarily upstream into the Turning Basin. This net transport was small and removed less than 20% of the nutrients and organic carbon in the DWC. In September, the net material transport was downstream from the Turning Basin and contributed less than 20% of the inorganic and organic material and oxygen demand to the DWC. The net transport of volatile suspended solids comprised nearly half of the downstream transport at Light 43. Chlorophyll *a* concentration contributed up to 30% of the VSS exported downstream. Low net flows made determination of material transfer from the Turning Basin to the DWC uncertain.

The net transport of oxygen demand associated with nitrogenous material from the upper San Joaquin River past Channel Point into the DWC was high. In August, ammonia downstream transport at Channel Point was 575 kg day^{-1} and was equivalent to an oxygen demand of 2588 kg O_2 day^{-1}. This ammonia accounted for 76% of the downstream ammonia transported past Light 43, but was only a small fraction of the nitrogenous load measured as TKN. In September, ammonia transported past Channel Point was 5 times higher and accounted for most of the TKN. Higher nitrate load at Light 43 than Channel Point suggested this ammonia was rapidly converted to nitrate by nitrification.

Recommendations

Persistence of the oxygen depletion in the DWC over the last 30 years despite RWQCB load restrictions and flow augmentation with the head of Old River barrier suggests both field and modeling studies are needed to identify the major causal mechanisms of this problem.

More spatially and temporally intense information is needed to characterize the oxygen depletion in the DWC and its persistence near the bottom between Light 19 and Light 48.

High frequency information is needed on the seasonal variation in oxygen demand produced by algal growth in the DWC, algal load from upstream and nitrification of ammonia and non-ammonia sources.

Frequent net transport studies are needed upstream of the DWC to verify the lower organic and inorganic load into the DWC from upstream when computed for Channel Point just upstream of the DWC versus Mossdale or Vernalis farther upstream. These measurements are also needed to verify the seasonal shift in ammonia and non-ammonia nitrogenous load from upstream. Continuous fluorometry measurements would greatly assist development of a more accurate net daily transfer rate for algal biomass at these stations.

The relative contribution of organic material to the oxygen demand should be addressed in future studies by making comparisons of CBOD and total BOD measurements with chlorophyll a, TOC, DOC, VSS, phaeophytin, TKN and ammonia concentration.

Tracer studies are needed to identify algal and nonalgal sources of carbon and nitrogen.

Load and flow information is needed to quantify the contribution of the Turning Basin load to the DWC because it has high algal biomass and low dissolved oxygen concentration near the bottom.

Information is needed on the influence of light on algal growth in the DWC because light is the primary limiting factor in the DWC and upstream.

Citations

Brown, K. and D. Caldwell. 1970. Main water quality control plant 1969 enlargement and modification study. Part 2. Benefits of proposed tertiary treatment to San Joaquin River water quality. Technical Report to the City of Stockton. Brown and Caldwell Consulting Engineers.

California Department of Water Resources. 1989-1995. Water Quality Conditions in the Sacramento-San Joaquin Delta. Environmental Services Office, Department of Water Resources, Sacramento, CA.

Chen, C. W. 1997. Evaluation of alternatives to meet the dissolved oxygen objectives of the lower San Joaquin River. Systech Engineering, Inc., 3180 Crow Canyon Place, Suite 260, San Ramon, CA 94583.

Cole, B. and J. E. Cloern. 1987. An empirical model for estimating phytoplankton productivity in estuaries. Marine Ecology Progress Series 36:299-305.

Colt, J. 1984. Computation of Dissolved Gas Concentrations in Water as Functions of Temperature, Salinity, and Pressure. American Fisheries Society Special Publication 14, Bethesda, MD.

Di Toro, D. M, D. J. O'Connor and R. V. Thomann. 1971. A dynamic model of the phytoplankton population in the Sacramento-San Joaquin Delta, p. 131-180. *In* Nonequilibrium Systems in Natural Water Chemistry. Adv. Chem. Ser. 196, Amer. Chem. Soc., Washington, DC.

U. S. Environmental Protection Agency (US EPA). 1983. Methods for Chemical Analysis of Water and Wastes. Washington, DC. Technical Report EPA-600/4-79-020.

Jones and Stokes Associates. 1998. Potential solutions for achieving the San Joaquin River dissolved oxygen objectives. Jones & Stokes Associates, 2600 V Street, Suite 100, Sacramento, CA 95818.

Lehman, P. 1990. Hypothesis 2: Changes in phytoplankton growth rate produced the post-drought decline in chlorophyll *a* concentration, pages 27-28. In Evaluation of selected biological factors that may have contributed to the drought and post-drought decline in chlorophyll *a* concentration. Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary. Technical Report 22.

Rajbhandari, H. 1995. Dynamic simulation of water quality in surface water systems utilizing a Lagrangian reference frame. Dissertation, University of California, Davis, CA 95616.

Rudek, J. and J. E. Cloern. 1996. Planktonic respiration rates in San Francisco Bay, pages 289-304. *In* J. T. Hollibaugh (ed.) San Francisco Bay: The Ecosystem. Pacific Division of the American Association for the Advancement of Science. San Francisco, CA 94118.

USBR and CARA. 1977. U. S. Bureau of Reclamation and California Resources Agency. Delta-Suisun Bay Ecological Studies. Biological methods and data for 1968-1974.