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The contribution of algal biomass to oxygen demand in the San Joaquin River Deep Water Channel, fall 2000

By

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Executive Summary

This report describes the results of research conducted in 2000 to determine the source of algal biomass and its relative contribution to oxygen demand in the San Joaquin River deep water channel downstream of Stockton during the fall. The research was funded by a CALFED Ecosystem Restoration Category III grant #99-B16 to the author and was conducted to obtain information needed by CALFED, the public, government agencies, and San Joaquin River stakeholders to characterize and determine the cause of oxygen depletion in the river.

The research was designed to address the following questions:

- Was the oxygen depletion in the DWC caused by physical stratification that prevented mixing?
- What is the relative contribution of algal biomass from in situ growth and upstream load to oxygen demand in the Stockton Deep Water Channel (DWC) ?
- What is the oxygen demand from algal biomass compared with other oxygen demanding substances?
- Are the load of oxygen demanding substances from Vernalis and Mossdale representative of the load that actually enters the DWC ?
- What mechanisms influence the impact of algal load and growth on oxygen demand?
- How well does the current semi-monthly DWR Channel Program characterize the oxygen conditions and algal biomass in the DWC compared with continuous monitoring?

Research demonstrated the importance of both upstream load and local growth to algal biomass in the DWC between Turner Cut and Navigation Light 48 where the net oxygen demand from algal biomass was 2 to 4 mg/L. The algal load from growth in the DWC was at least half of that from upstream and reached 100-300 kg/day as chlorophyll *a*. Algal biomass was primarily composed of a mixed assemblage of diatoms and was correlated with carbonaceous biochemical oxygen demand, but not total oxygen demand that increased seasonally.

The influence of algal growth on oxygen demand in the DWC was controlled by turbidity. Algal growth was light limited in the DWC where algae achieve about half of the light needed to achieve maximum growth rate. Light limitation was a function of low water transparency produced by high suspended sediment concentration and was strongly influenced by the high retention of both total suspended sediment and volatile suspended solids from upstream in the study reach. Unlike many aquatic environments, algal growth was not limited by macronutrients such as dissolved inorganic nitrogen and orthophosphate that were an order of magnitude higher than limiting levels.

Most of the biochemical oxygen demand in the DWC was produced by nitrogenous material. At Turner Cut, Rough and Ready Island and Channel Point nitrogenous BOD consistently comprised 50% to 80% of the oxygen demand. The discharge of ammonia

from the City of Stockton Regional Control Facility (RWCF) is a known source of nitrogenous oxygen demand in the deep water channel and increases between September and November. Ammonia from the Stockton RWCF probably drives the increase in nitrogenous BOD in September through November. This study also measured consistently high loads of non-ammonia Kjeldahl nitrogen from upstream that were often many times larger than the nitrogen load from ammonia. Nitrogenous material contributed about half of the oxygen demand upstream at Mossdale. Carbon to nitrogen ratios at Mossdale were too low to be produced by algae alone. Total BOD at Turner Cut and Rough and Ready Island in the DWC was significantly correlated with both nitrogenous BOD, total Kjeldahl nitrogen and ammonia concentration. Total BOD was not correlated with carbonaceous oxygen demand in the DWC, as would be expected if the primary source of oxygen demand was from algae.

The enhanced continuous water quality monitoring network developed in 2000 was far superior than discrete measurements at quantifying maxima and minima values and temporal variability of algal load and dissolved oxygen concentration. The continuous monitors measured somewhat lower dissolved oxygen at the bottom than the surface, even in this wet year. In addition, the continuous monitors demonstrated the consistent diel variation of dissolved oxygen of 4 mg/L to 7 mg/L that could affect compliance with the U. S. Environmental Protection Agency and CA Regional Water Quality Control Board standards and management alternatives. Upstream monitoring stations demonstrated the oxygen deficit in the DWC was primarily a function of processes in the channel and not imported from upstream.

Recommendations included: 1) separate the oxygen demand from algal respiration and nitrification of nitrogen by bacteria in growth studies, 2) conduct 2000 studies in a critically dry year when algal biomass, residence time, water temperature and oxygen demand are highest, 3) conduct more thorough studies to quantify the magnitude and identify the causes of decreased algal biomass, material load and biochemical oxygen demand between the upstream load at Vernalis and the deep water channel, 4) further evaluate the influence of both temperature an water transparency on algal growth and 5) gain a better understanding of the relative importance of nitrogenous and carbon load to the oxygen demand throughout the summer and fall.

Table of Contents

Figures

Tables

Table IV-3. Net production rate, respiration rate, oxygen demand and chlorophyll *a* load from algal growth in the DWC calculated from light/dark bottle incubation measurements of community production rate.

Table VI – 4 a. Pearson correlation coefficients calculated among water quality variables measured at Turner Cut station 24 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table VI –4 b . Pearson correlation coefficients calculated among water quality variables measured at Rough and Ready Island station 43 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table VI – 4 c. Pearson correlation coefficients calculated among water quality variables measured at Channel Point station 51 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table VI – 4 d . Pearson correlation coefficients calculated among water quality variables measured at Turning Basin station 50 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table IV-5. Daily net production rate, respiration rate, oxygen demand and chlorophyll *a* load from algal growth in the DWC calculated by equation using chlorophyll *a* concentration, surface irradiance and extinction coefficient.

Table VI – 4 a. Pearson correlation coefficients calculated among water quality variables measured at Turner Cut station 24 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table VI –4 b . Pearson correlation coefficients calculated among water quality variables measured at Rough and Ready Island station 43 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table VI – 4 c. Pearson correlation coefficients calculated among water quality variables measured at Channel Point station 51 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

Table VI – 4 d . Pearson correlation coefficients calculated among water quality variables measured at Turning Basin station 50 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

I. Introduction

History
Hypoxia has occurred in a 10-mile reach of the San Joaquin River deep water channel (DWC) near Stockton during the fall for 30 years (Lehman and Ralston 2000). Dissolved oxygen concentration was often below 5 mg/L which is the U. S. EPA national water quality standard for ecosystem health and caused the lower San Joaquin River to be placed on the U.S. EPA 303d of impaired water bodies. In addition, research by the Department of Fish and Game in 1970 suggested dissolved oxygen concentration less than 6 mg/L may adversely impact upstream migration of fall run Chinook salmon (Brown and Caldwell 1970). This lead the CA Regional Water Quality Control Board (RWQCB) to set an additional dissolved oxygen standard of 6 mg/L during September through November.

In 1998, representatives of the environmental community served the U.S. EPA with an intent to sue because the dissolved oxygen conditions had not been improved despite their 303d listing. The U. S. EPA then set December 2002 as the deadline for completion of an allocation of responsibility or TMDL and implementation plan by the RWQCB. As a part of this process, San Joaquin River stakeholders decided it was in their best interest to develop the TMDL and implementation plan and established the San Joaquin River TMDL steering and technical committees.

The technical committee with direction from the steering committee identified missing information needed to determine the cause and sources of oxygen depletion in the deep water channel and assist development of management models and solution alternatives. These needs lead to a CALFED funded research program in 2000.

This report summarizes field data gathered for CALFED funded research between July and November 2000 to determine the contribution of algal biomass to the oxygen demand in the DWC. The research was designed to address the following questions:

- Was the oxygen depletion in the DWC caused by physical stratification that prevented mixing?
- What is the relative contribution of algal biomass from in situ growth and upstream load to oxygen demand in the Stockton Deep Water Channel (DWC) ?
- What is the oxygen demand from algal biomass compared with other oxygen demanding substances?
- Are the load of oxygen demanding substances from Vernalis and Mossdale representative of the load that actually enters the DWC ?
- What mechanisms influence the impact of algal load and growth on oxygen demand?
- How well does the current semi-monthly DWR Channel Program characterize the oxygen conditions and algal biomass in the DWC compared with continuous monitoring?

Other elements of the fall 2000 research program include measurement of upstream material concentration and load by Dr. C. Kratzer of the U. S. Geological Survey, sedimentation rate by Dr. G. Litton of U. O. P., downstream water quality by the City of Stockton by the City of Stockton and Jones and Stokes Associated and water quality modeling by Dr. Carl Chen of Systech Engineering. The results of these studies are described in individual reports by each research scientist on the **sjrtmdl.org** website and summarized in the report titled "Summary Report: Sources and Causes of Oxygen Depletion in the Stockton Deep Water Channel, fall 2000" by Dr. P. W. Lehman (in preparation)**.**

Current hypothesis

The current hypothesis is that the high load of algal biomass from the upper San Joaquin River and ammonia from the Stockton Municipal discharge combined with high water temperature and long residence is the primary cause of low dissolved oxygen concentration in the DWC (Jones and Stokes Associates 1998).

High average chlorophyll *a* concentration of 100 ug/L in the lower San Joaquin River (Lehman 1996a, b) in the 1970s and a factor of 2 higher concentration upstream (website: iep.water.ca.gov) supported the hypothesis that algal load was responsible for the long-term pattern of low dissolved oxygen concentration in the fall. However, a factor of 4 decrease in chlorophyll *a* concentration in the San Joaquin River (Lehman 1992) after 1970 suggests algal biomass may be less important today than historically.

How much of the oxygen demand in the DWC is currently produced by algal and nonalgal organic matter versus inorganic substances or the relative load of each of these from local and external sources is poorly quantified. A pilot study in 1999 indicated algal load from upstream transport and growth in the channel were probably similar in amplitude but produced less oxygen demand than either ammonia nitrogen or non-ammonia nitrogen sources (Lehman and Ralston 2000).

The purpose of this report is to quantify the load of algal biomass from algal growth in the DWC and the immediate upstream and downstream sources of algal and nonalgal biomass and their potential impact on oxygen demand in the DWC between July and November 2000. The relative contribution of local versus imported algal and nonalgal load to oxygen demand will be estimated from in situ community growth rate measurements and net tidal day load from upstream and downstream continuous and discrete measurements. The potential impact of algal growth on oxygen demand in the severely light limited DWC will be assessed with community growth studies conducted at different light intensities. This research will provide management information needed to assess the relative impact of local and imported sources of organic and inorganic substances and environmental conditions on oxygen demand in the DWC.

II. Water Quality Conditions

Discrete profiles

Discrete vertical and horizontal profiles were used to characterize the spatial and temporal variation of water quality conditions in the DWC during the fall in 2000 and to address the following questions.

> **Question**: What water quality conditions characterized the dissolved oxygen depletion in the DWC during 2000?
> **Answer**: Fall 2000 was relatively cool and dissolved oxygen depletion was restricted to a short portion of the DWC near Rough and Ready Island and occurred over a brief period between August and September.
>
> **Question**: Was the oxygen depletion in the DWC caused by physical stratification that prevented mixing.
> **Answer**: The lack of a strong vertical gradient of specific conductance, water temperature or pH suggests oxygen depletion was not caused by a physical stratification process that blocked mixing.

Methods

Continuous horizontal profiles of specific conductance (*u*S/cm), water temperature (^{o}C), dissolved oxygen concentration (mg/L) and chlorophyll fluorescence (volt) were measured at 1 m depth using a Seabird water quality profiling unit or a Turner fluorometer (chlorophyll fluorescence) during high slack tide between station 1 at Prisoner's Point and station 50 at the Turning Basin in the San Joaquin River (Fig. II-1). Profiles were made semi-monthly between August and November during a dissolved oxygen special study program conducted by the Department of Water Resources. Instrumentation was calibrated daily; dissolved oxygen with Winkler titration and chlorophyll fluorescence to laboratory extracted chlorophyll *a* concentration.

Oxygen deficit values describe the amount of dissolved oxygen in the water column in relation to the 5 mg/L and 6 mg/L standards. The water column oxygen deficit was calculated as the sum of the differences between measured dissolved oxygen concentration and either 5 mg/L or 6 mg/L in each 1 m depth of the water column. A negative oxygen deficit indicated dissolved oxygen had to be added to the water column to reach 5 mg/L or 6 mg/L. A positive deficit indicated dissolved oxygen exceeded what was needed to reach 5 mg/L or 6 mg/L.

Results

Horizontal surface profiles – Horizontal profiles in the summer and fall of 2000 described a wet and cool year compared with 1999 (Lehman and Ralston 2000). Dissolved oxygen concentration was consistently above 5 mg/L between August and November, but briefly decreased to below 6 mg/L in August and September between station 19 and 24 (Fig. II-2). Lowest values were measured between station 19 and 41. Dissolved oxygen concentration was partly a function of water temperature that was usually less than 24^{o}C except in early August (Fig. II-3). The warmest water temperature was often measured near station 19 where specific conductance increased by 200 uS/cm (Fig. II-4). Phytoplankton chlorophyll *a* concentration gradually increased upstream from about 10 ug/L near station 1 to over 70 ug/L at station 50 (Fig. II-5). Peak chlorophyll *a* concentration in the DWC occurred between station 24 and 48 in August and September when the lowest dissolved oxygen concentration was measured. Because water samples were collected at slack after ebb tide, the consistent shift in water quality conditions near station 19 probably indicates station 19 was the downstream boundary of material transport from upstream.

Fig. II-2. Average surface dissolved oxygen concentration measured between Prisoner's Point and the Turning Basin.

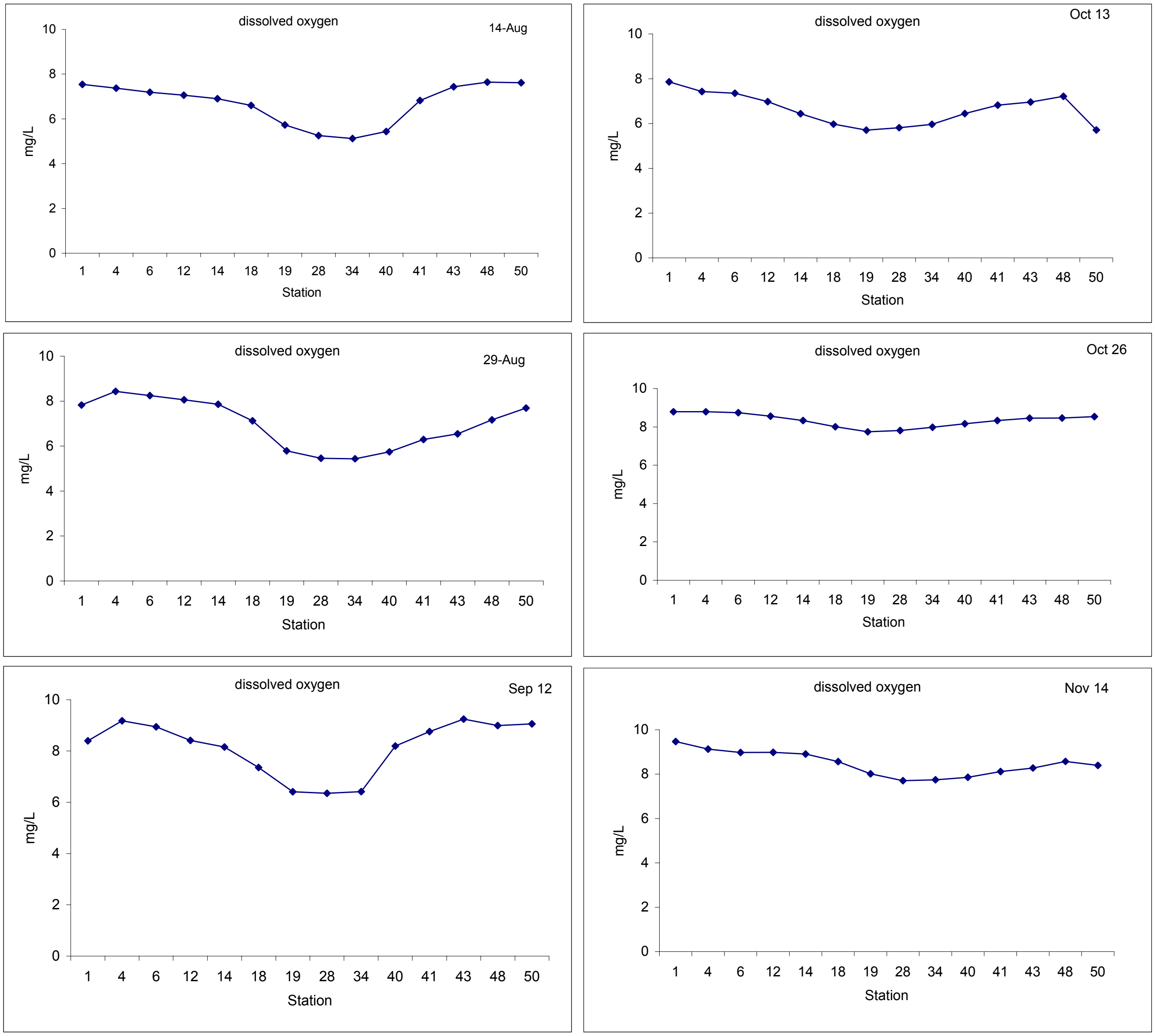

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Fig. II-3. Average surface water temperature measured between Prisoner's Point and the Turning Basin.

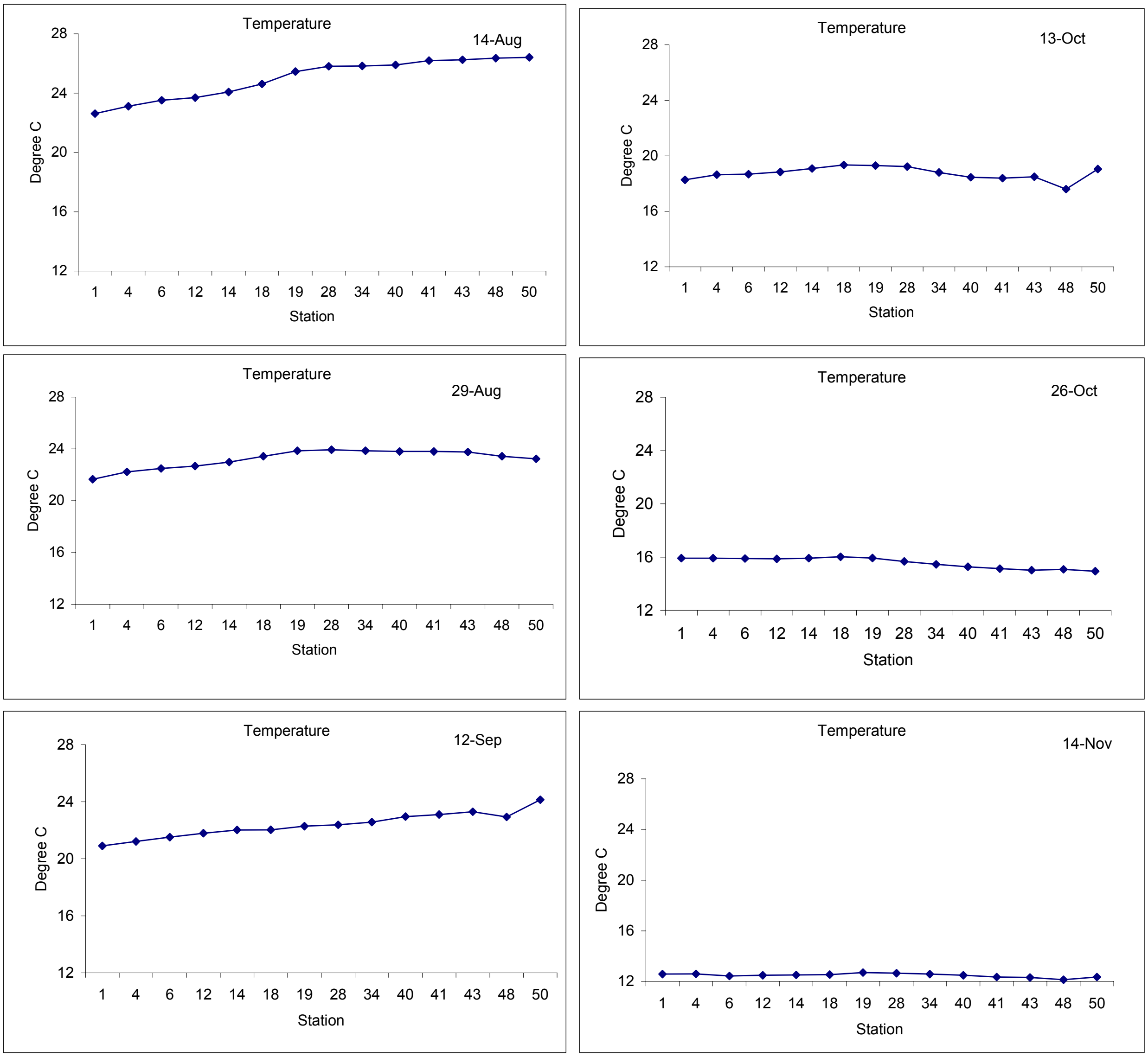


Fig. II-4. Average surface specific conductance between Prisoner's Point and Turning Basin.

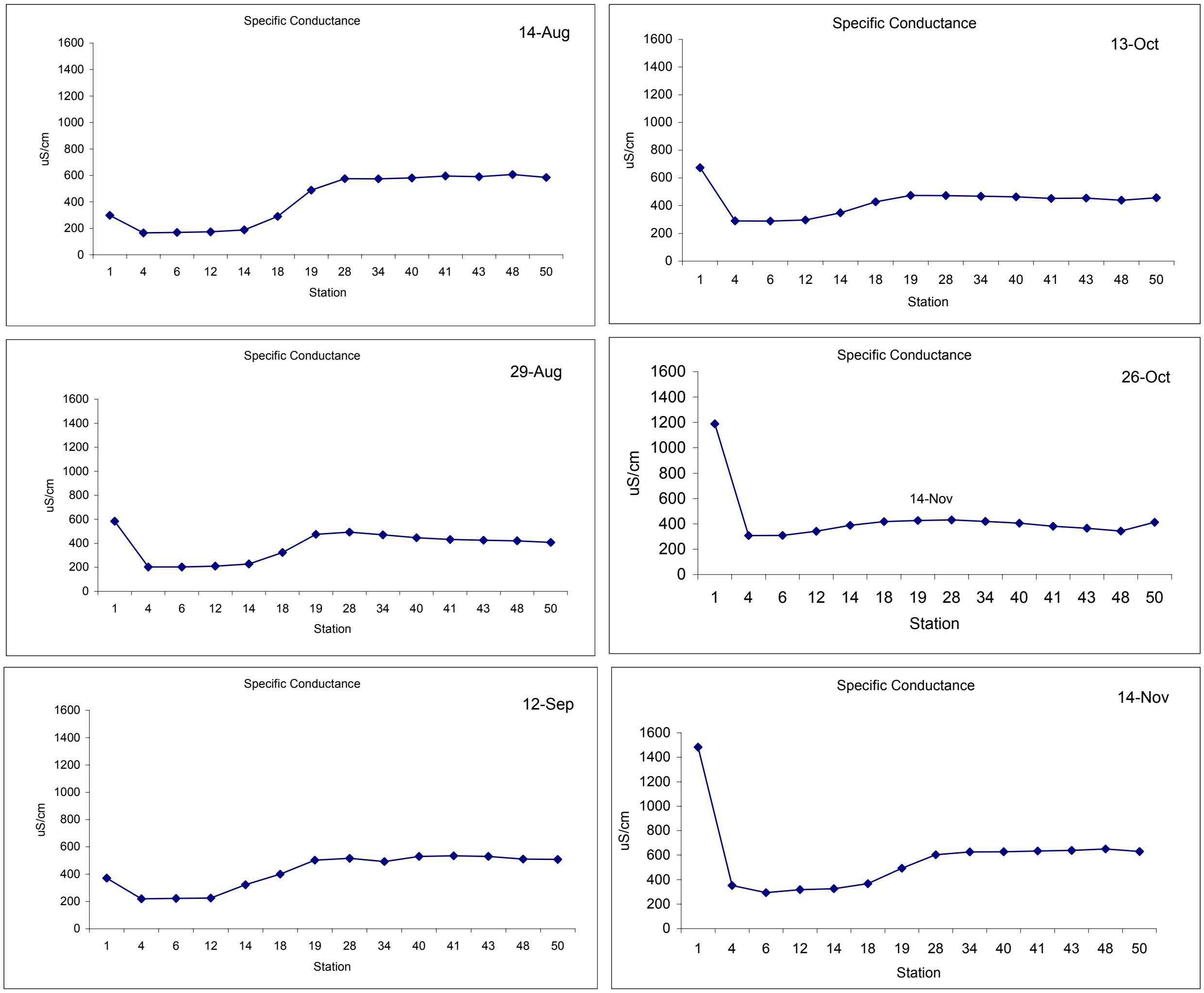
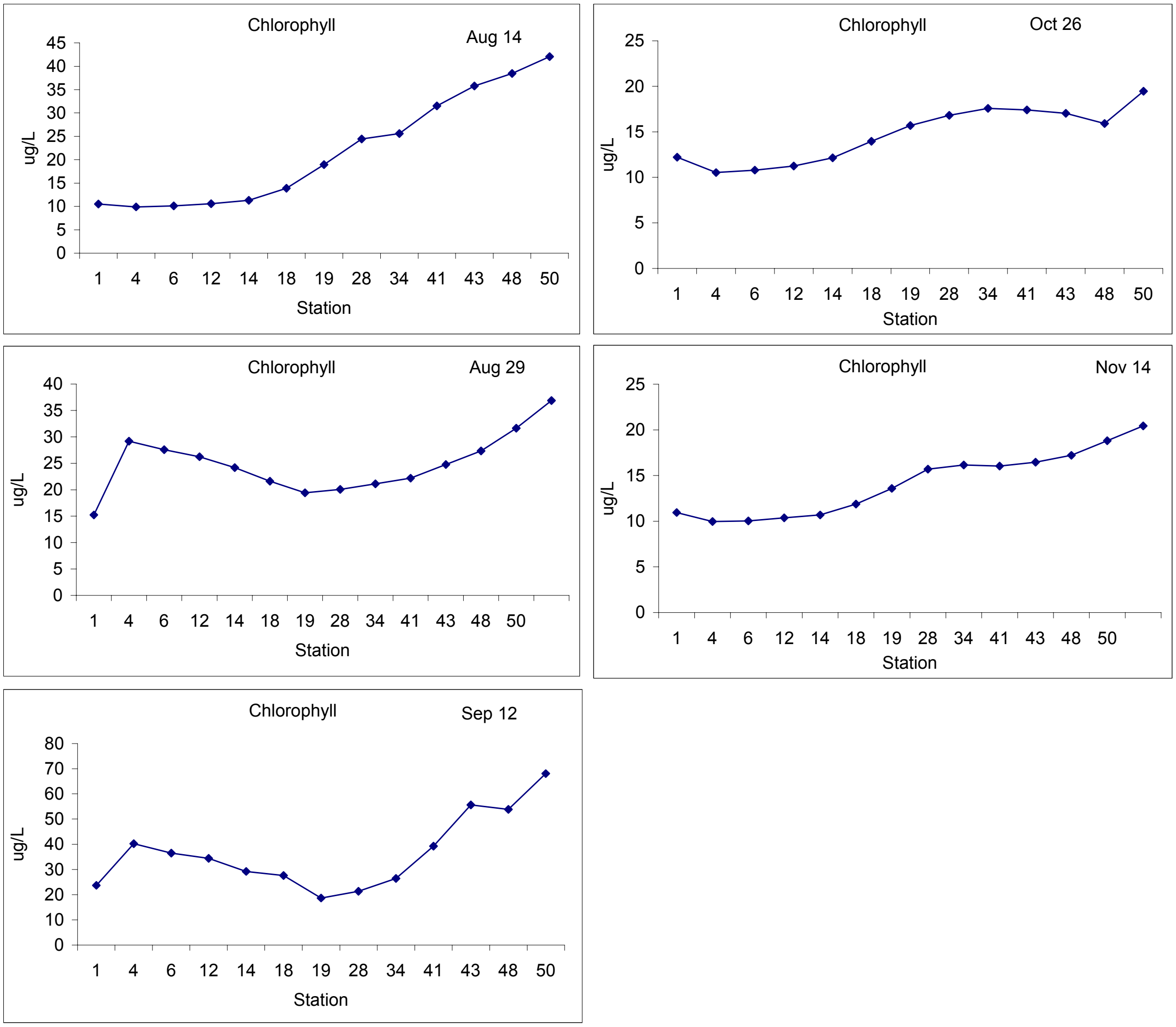


Fig. II-5. Average chlorophyll *a* concentration measured between Prisoner's Point and Turning Basin.



The oxygen deficit of the water column was usually positive or only slightly negative for 5 mg/L (Fig. II-6) and 6 mg/L (Fig. II-7). Negative oxygen deficits were at most 1 mg/L and occurred between July and September at stations 24 through 43. The frequency and spatial extent of negative oxygen deficits was higher for 6 mg/L than 5 mg/L. Positive deficit values were probably a function of the wet and cool conditions in 2000 and contrasted with the frequent negative deficits measured in 1999, a warm and dry year (Lehman and Ralston 2000).

Fig. II-6. Oxygen deficit for 5 mg/L in the water column between Prisoner's Point and Turning Basin.

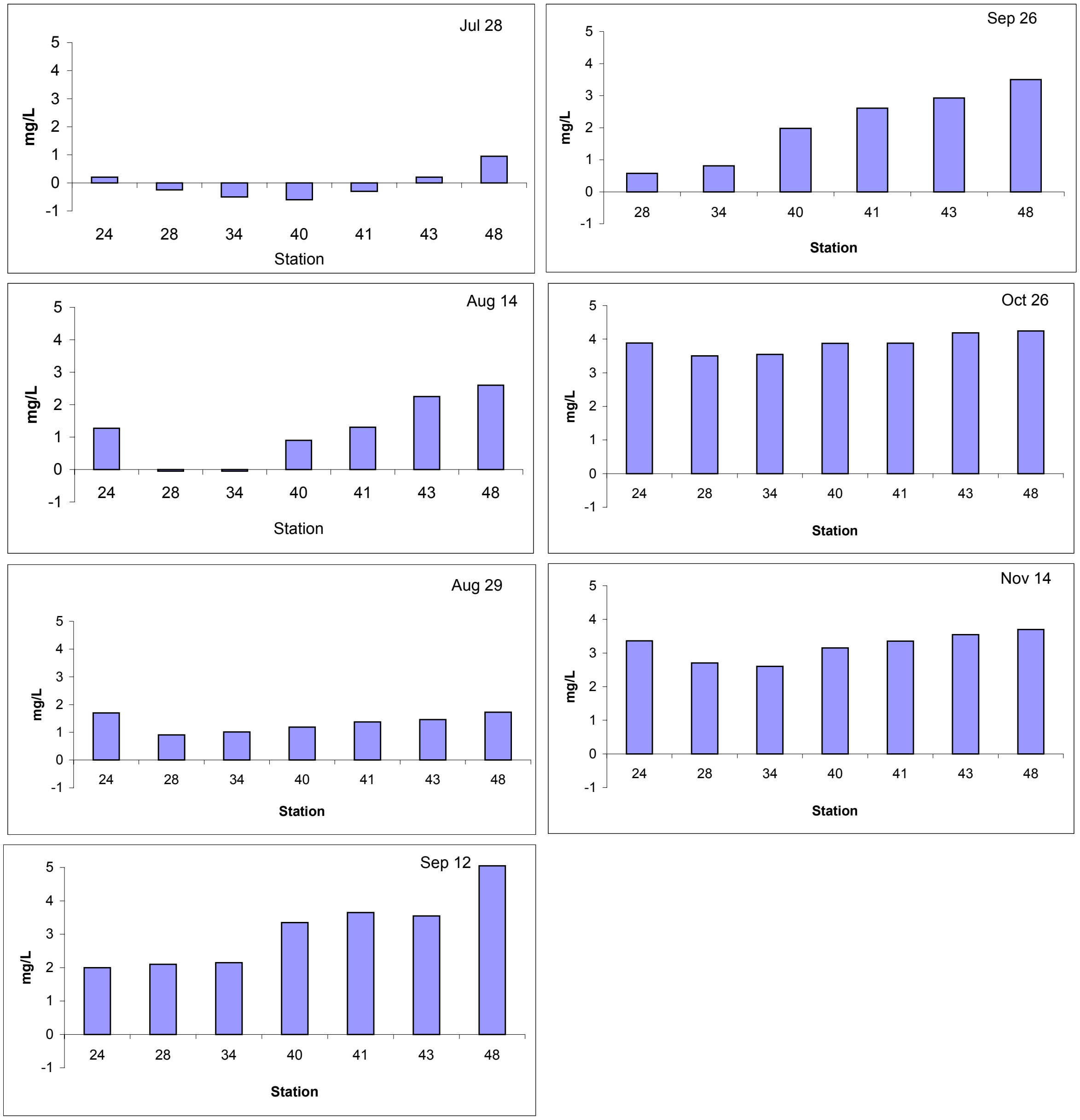
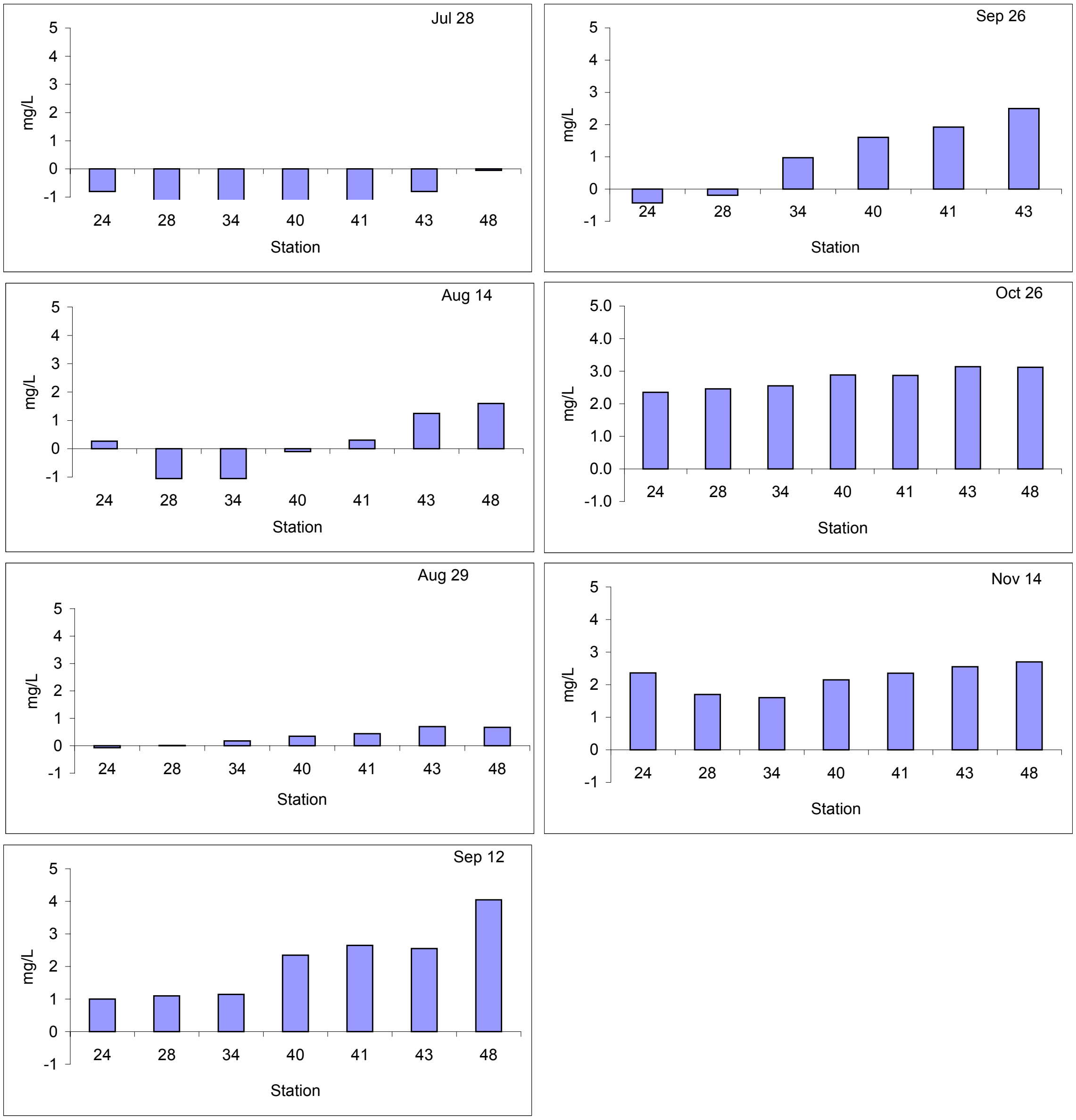


Fig. II-7. Oxygen deficit of the water column for 6 mg/L between Prisoner's Point at station 1 to Turning Basin at station 50.

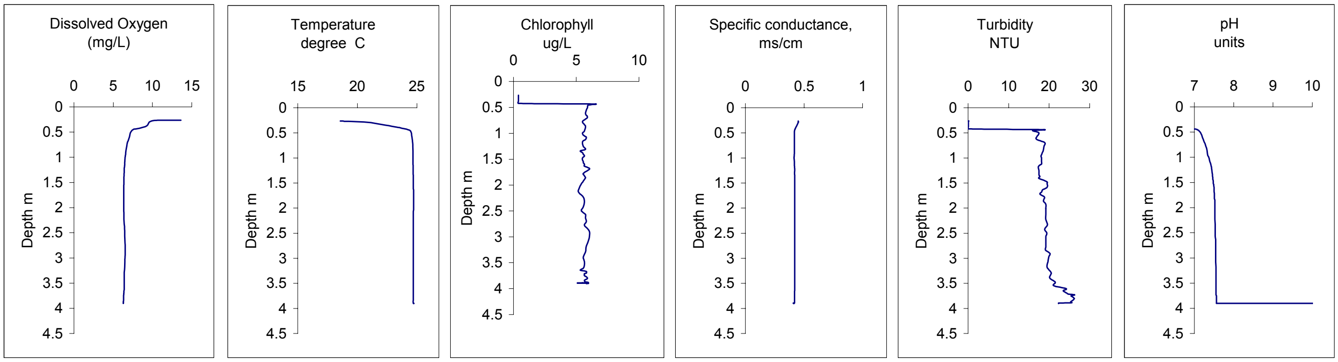


Vertical profiles

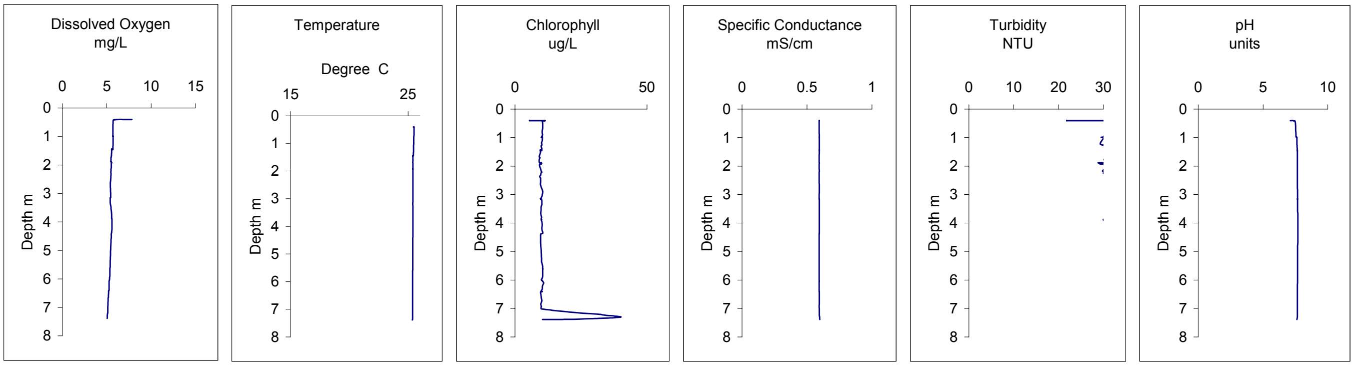
Water quality conditions were usually uniform throughout the water column except dissolved oxygen concentration. Specific conductance and pH were nearly constant with depth and water temperature decreased by at most one degree. Algal biomass was high in the first 0.3 m and slightly lower and constant throughout the rest of the water column. Only dissolved oxygen concentration had a strong vertical gradient that differed by up to 5 mg/L with depth. This gradient occurred between August (Fig. II-8) and October (II-9) between stations 24 and 43. Photosynthesis and aeration probably caused high dissolved oxygen concentration at the surface, but the cause of the low dissolved oxygen near the bottom is unknown. The strongest vertical dissolved oxygen gradient and lowest dissolved oxygen concentration occurred in the Turning Basin, a dead end slough at the upstream end of the study reach. Here dissolved oxygen concentration decreased by 7 mg/L with depth and was as low as 3 mg/L near the bottom. Low dissolved oxygen concentration near the bottom at this station was probably a function of algal decomposition because chlorophyll *a* concentration often reached 100 ug/L or more at the surface and decreased sharply with depth.

Fig. II-8. Vertical profiles for station 24 at Turner Cut (a), station 43 at Rough and Ready Island (b), station 50 at the Turning Basin (c) and station 51 at Channel Point (d) on August 14.

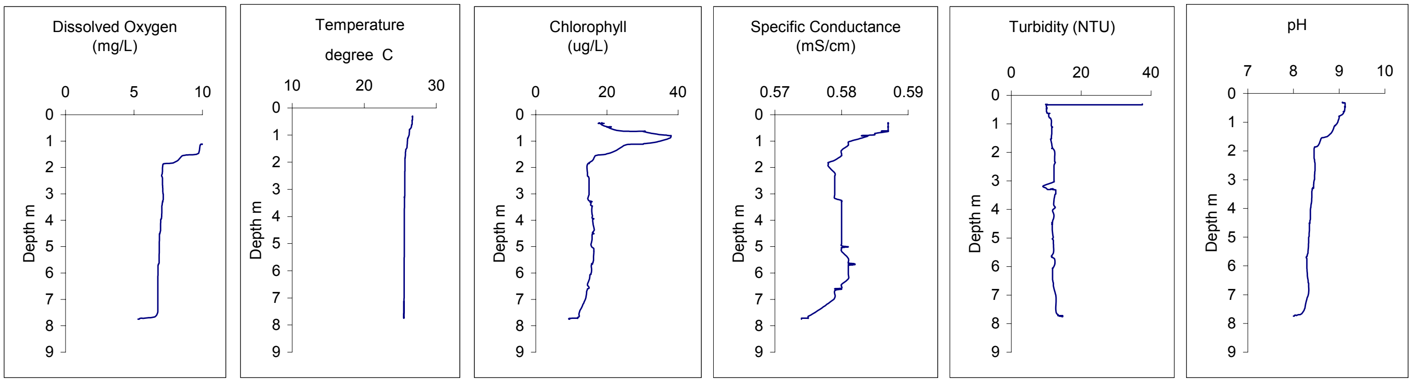
a. Turner Cut



b. Rough and Ready Island



c. Turning Basin



d. Channel Point

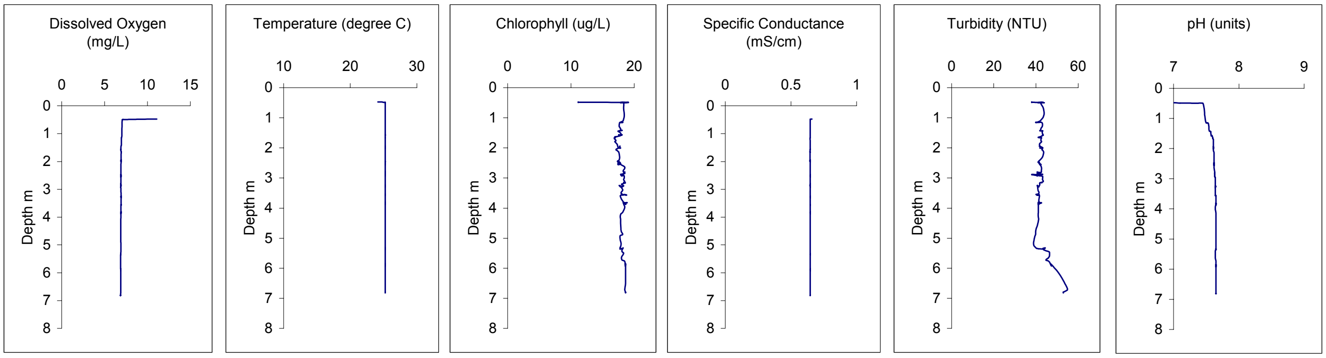
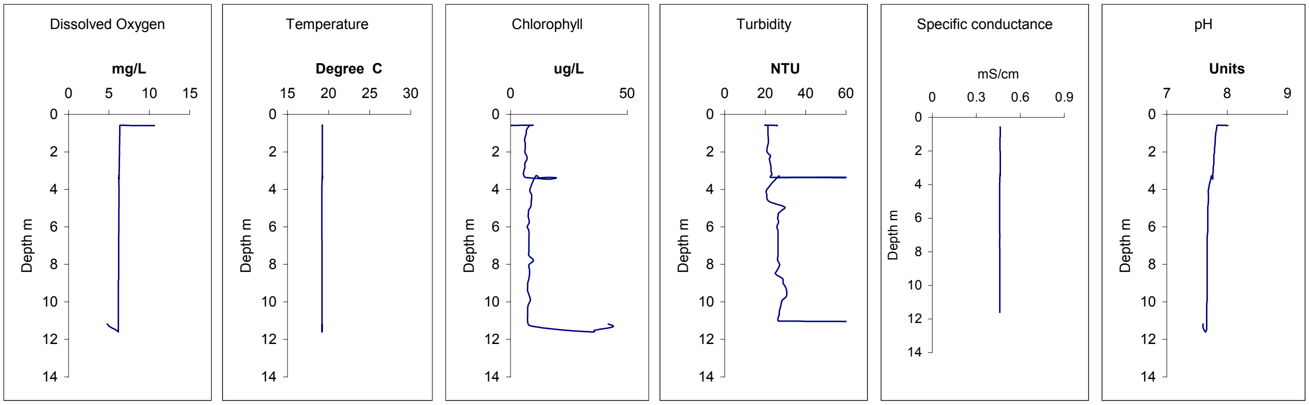
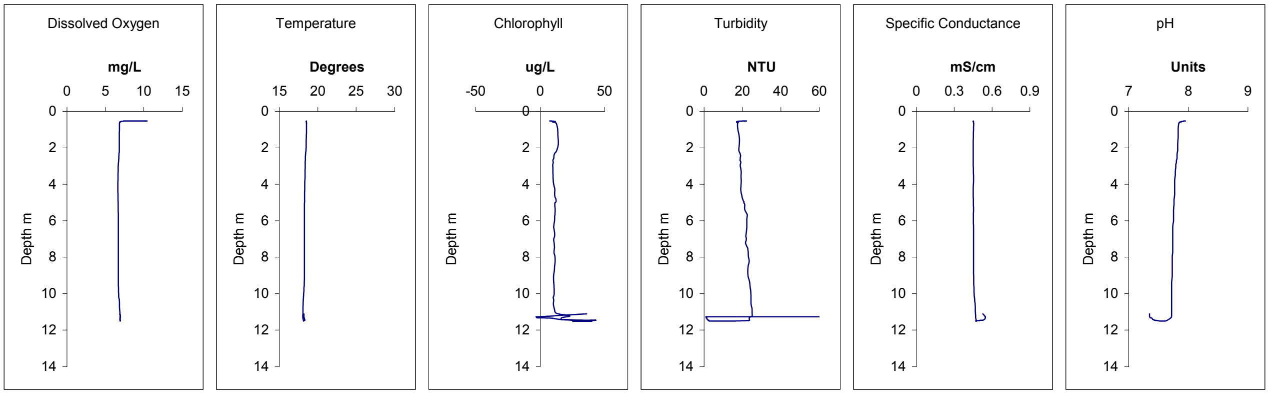


Fig. II-9. Vertical profiles of water quality variables for station 24 at Turner Cut (a), station 43 at Rough and Ready Island (b), station 50 at the Turning Basin (c) and station 51 at Channel Point (d) on October 12.

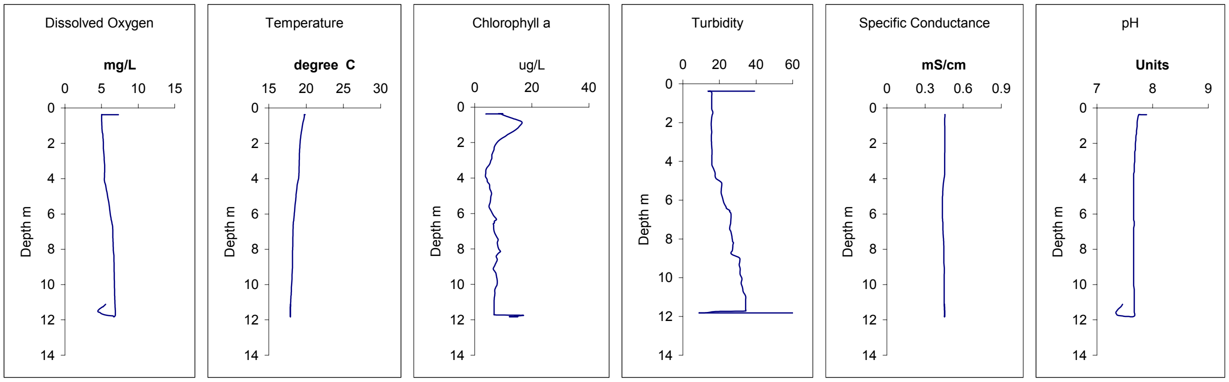
a. Turner Cut



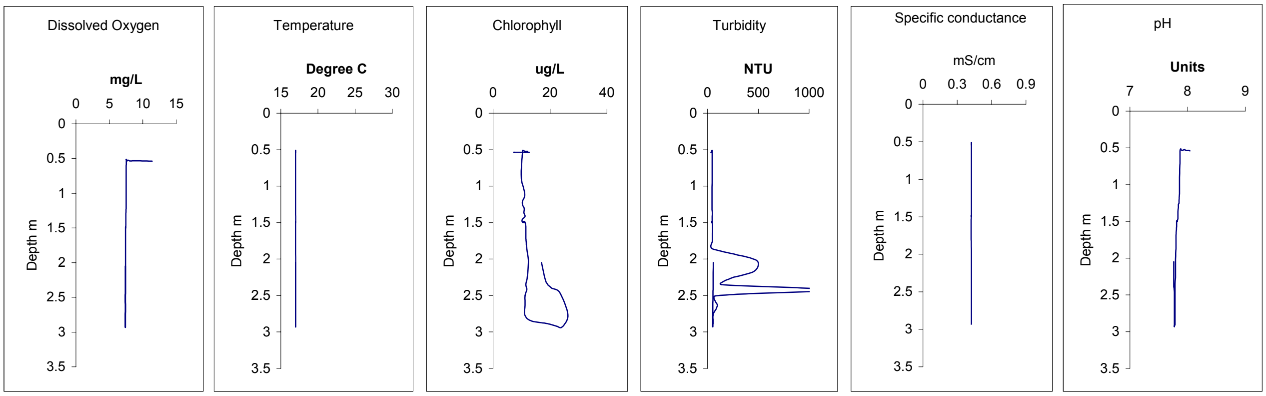
b. Rough and Ready Island station 43.



c. Turning Basin station 50.



d. Channel Point at station 51.



Continuous profiles
Continuous monitors measured water quality variables in the DWC and upstream and downstream sources. These raw data were used to address the question:

> **Question:** How well does the current semi-monthly DWR Channel Program characterize the oxygen conditions and algal biomass in the DWC compared with continuous monitoring?
> **Answer:** Continuous monitoring was superior to discrete monitoring for quantifying daily and seasonal variation and data amplitude.

Methods
Continuous water quality monitoring was conducted at 1 m depth at station 24, station 43, station 50, station 51 and station 55 (Fig. II-1). Water quality measurements were taken with two types of continuous monitoring systems. At stations 43 and 55, measurements were made with a Sneider multiparameter water quality monitoring system operated by the Department of Water Resources (DWR) that measured specific conductance, pH, dissolved oxygen and water temperature. Chlorophyll *a* fluorescence was measured with a Turner 10 fluorometer and calibrated with laboratory analyses of extracted chlorophyll *a* . Solar irradiance was measured at station 43 with an Eppley pyroheliometer.

The DWR continuous monitoring systems were verified every 10 days. In addition, water quality probes were automatically cleaned each day at midnight. The error associated with dissolved oxygen concentration was 0.15-0.20 mg/L. Additional information on the quality assurance and control procedure is available on the website: **iep.water.ca.gov** under DWR continuous water quality monitoring.

Enhancement of the DWR continuous monitoring grid to obtain boundary and near bottom data was a significant part of the CALFED 2000 program. This enhancement was achieved by installing YSI 6600 continuous water quality monitors at the surface of station 24, at the bottom of station 43, and at the surface and bottom of station 50 (Fig. II-1). The YSI 6600 water quality monitors measured turbidity (NTU), specific conductance (uS/cm), dissolved oxygen concentration (mg/L), water temperature (^{o}C) and chlorophyll fluorescence (percent fluorescence) at 15 min intervals. A pulsed dissolved oxygen and fluorescence measuring system and self cleaning mechanisms on the fluorometer minimized the impact of low flow near the probe. Accuracy of the YSI 6600 monitors was verified with a YSI 85 within two week intervals and each machine was calibrated monthly.

Development of the YSI 6600 monitoring system required many steps including instrument selection, equipment purchase, equipment preparation, design and construction of installation and security systems, development of verification and calibration procedures and acquisition of site access permits. Because of these many steps and the late start because of funding delays, the primary effort in year 2000 was to establish the network stations. Each site had different technical and administrative challenges and therefore resulted in different record length.

Future deployment of the YSI 6600 monitoring network will require less preparation time because of the availability of installation systems and operating procedures. However, it is important to note that the longest delay was associated with obtaining access permits at station 24 from the U. S. Coast Guard and at station 50 and station 51 from the Port of Stockton.

Results

Study reach - Water temperature varied by about 2 ^{o}C each day and ranged from 27 ^{o}C to 10^{o}C near the surface (Fig. II-10) and bottom (Fig. II-11) at station 43, the center of the study reach. Specific conductance varied by 50 uS/cm daily and 400 uS/cm seasonally. The decrease in specific conductance in the fall suggested there was a seasonal increase in the exchange of DWC and downstream water.

Average and minimum dissolved oxygen concentration near the surface and bottom were usually above the 5 mg/L and 6 mg/L standards after August in the study reach at station 43. However, average and minimum and bottom concentrations decreased to below either the 5 mg/L or the 6 mg/L standard briefly in September and early October.

Fig. II-10. Continuous water quality data for the surface of station 43 at Rough and Ready Island.

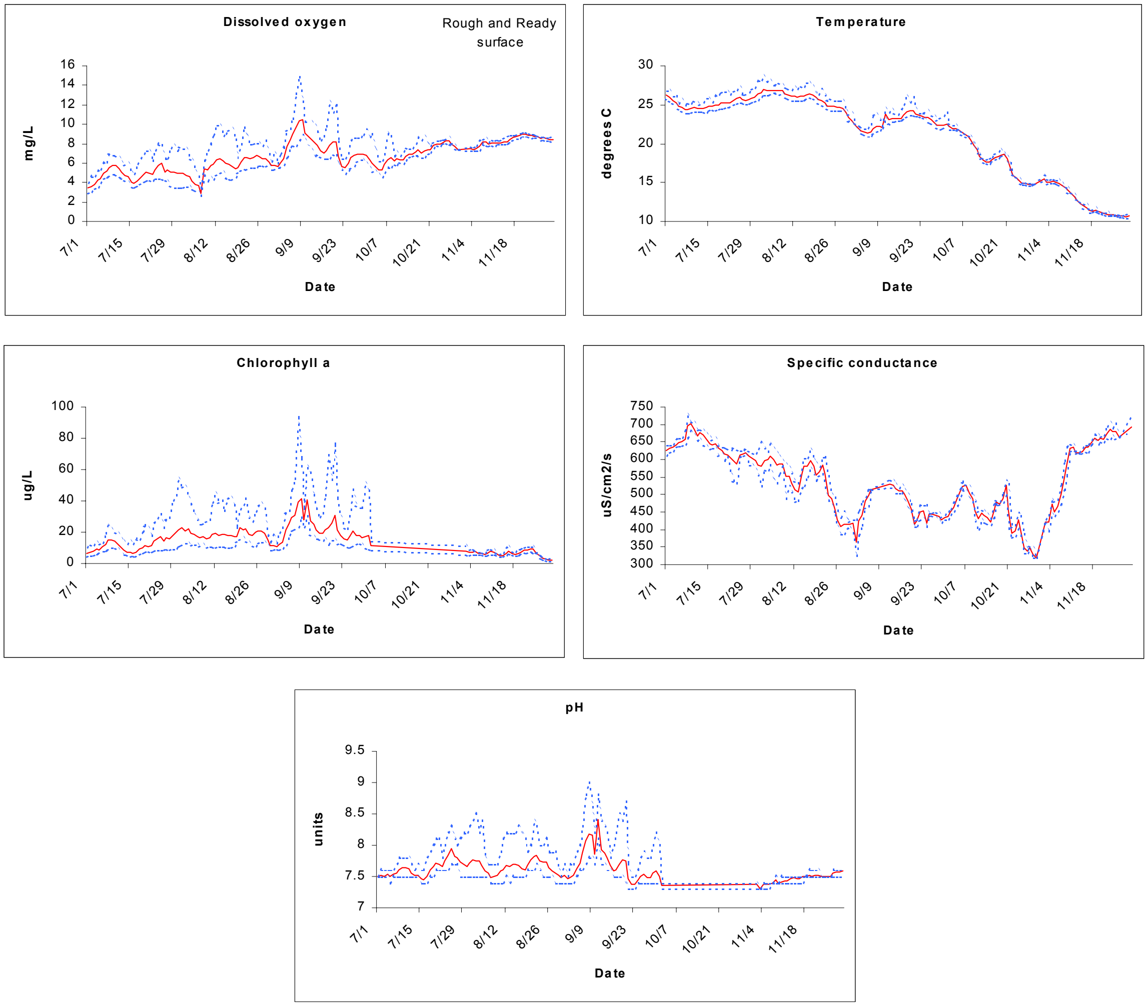


Fig. II-11. Continuous bottom water quality measurements for station 43 at Rough and Ready Island.

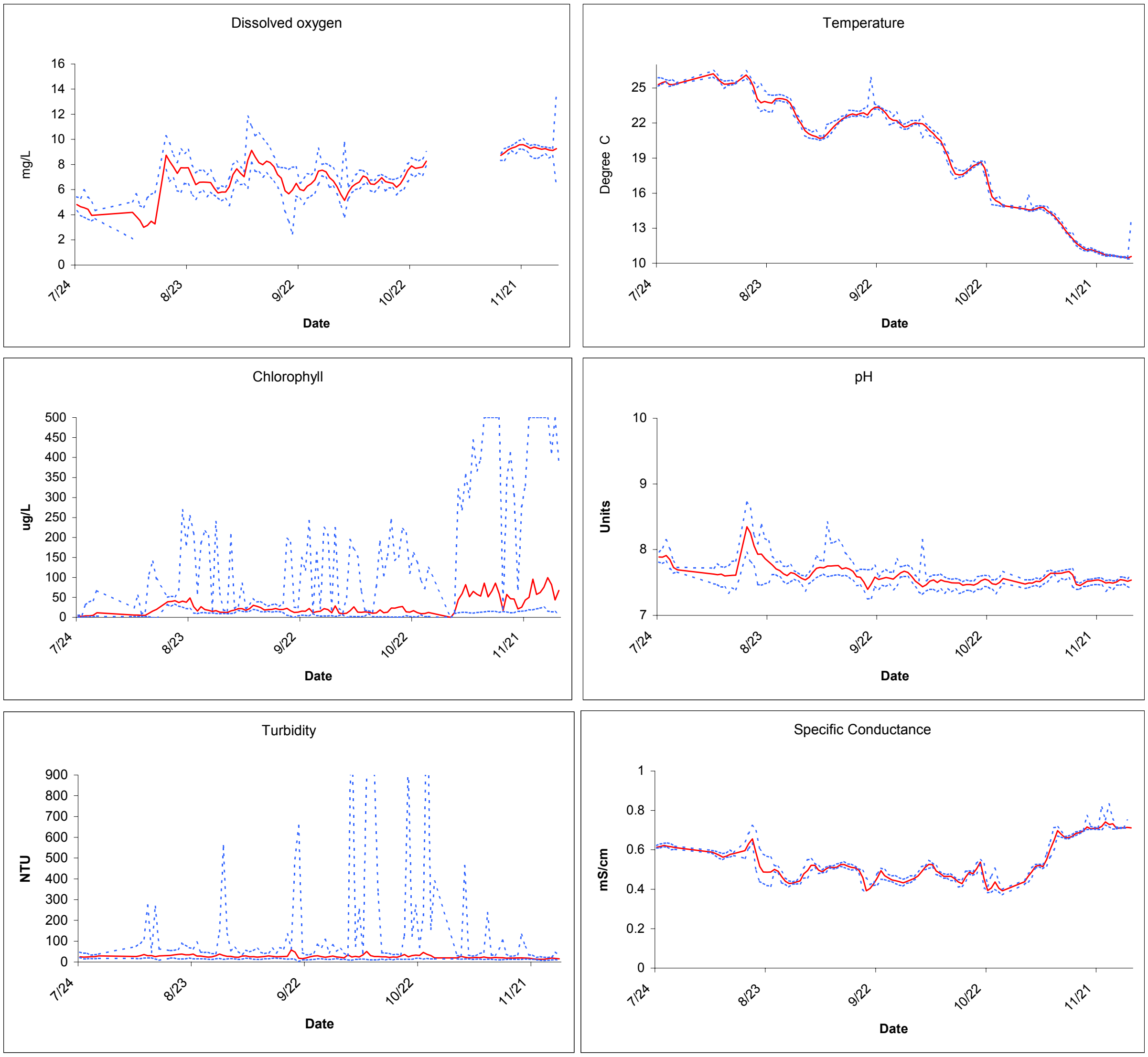


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Fig. II-12. Dissolved oxygen measured at the surface and bottom at station 43, Rough and Ready Island.

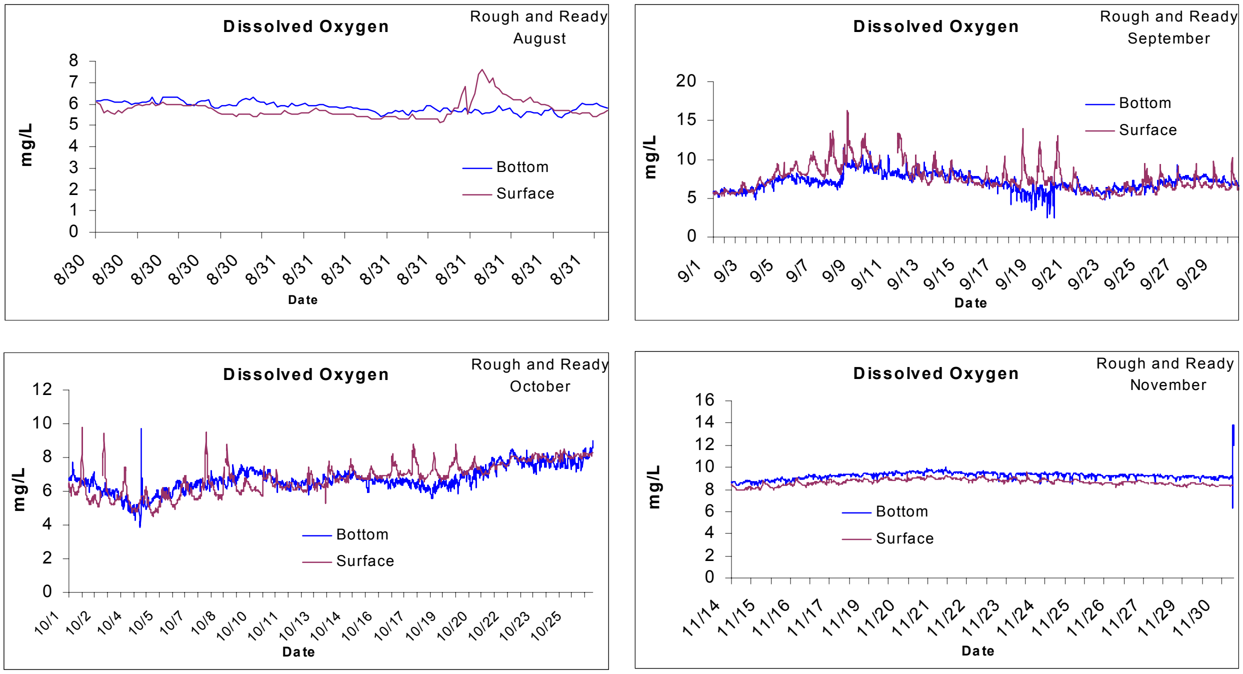
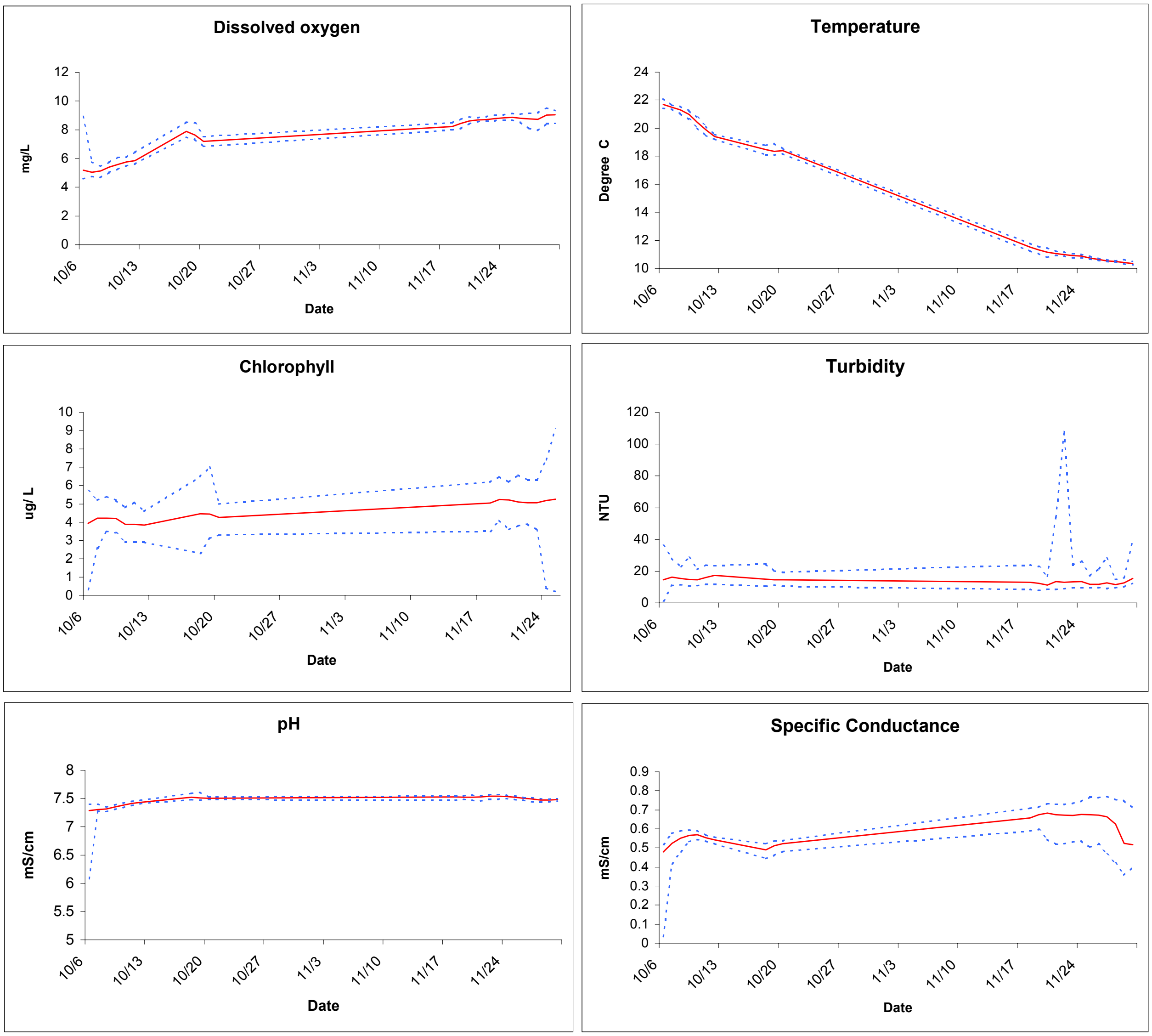


Fig. II-13. Continuous water quality data collected at station 24, Turner Cut.


Dissolved oxygen

Temperature

Chlorophyll

Turbidity

pH

Specific Conductance

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Fig. II-14. Continuous water quality data measured at station 51, Channel Point.

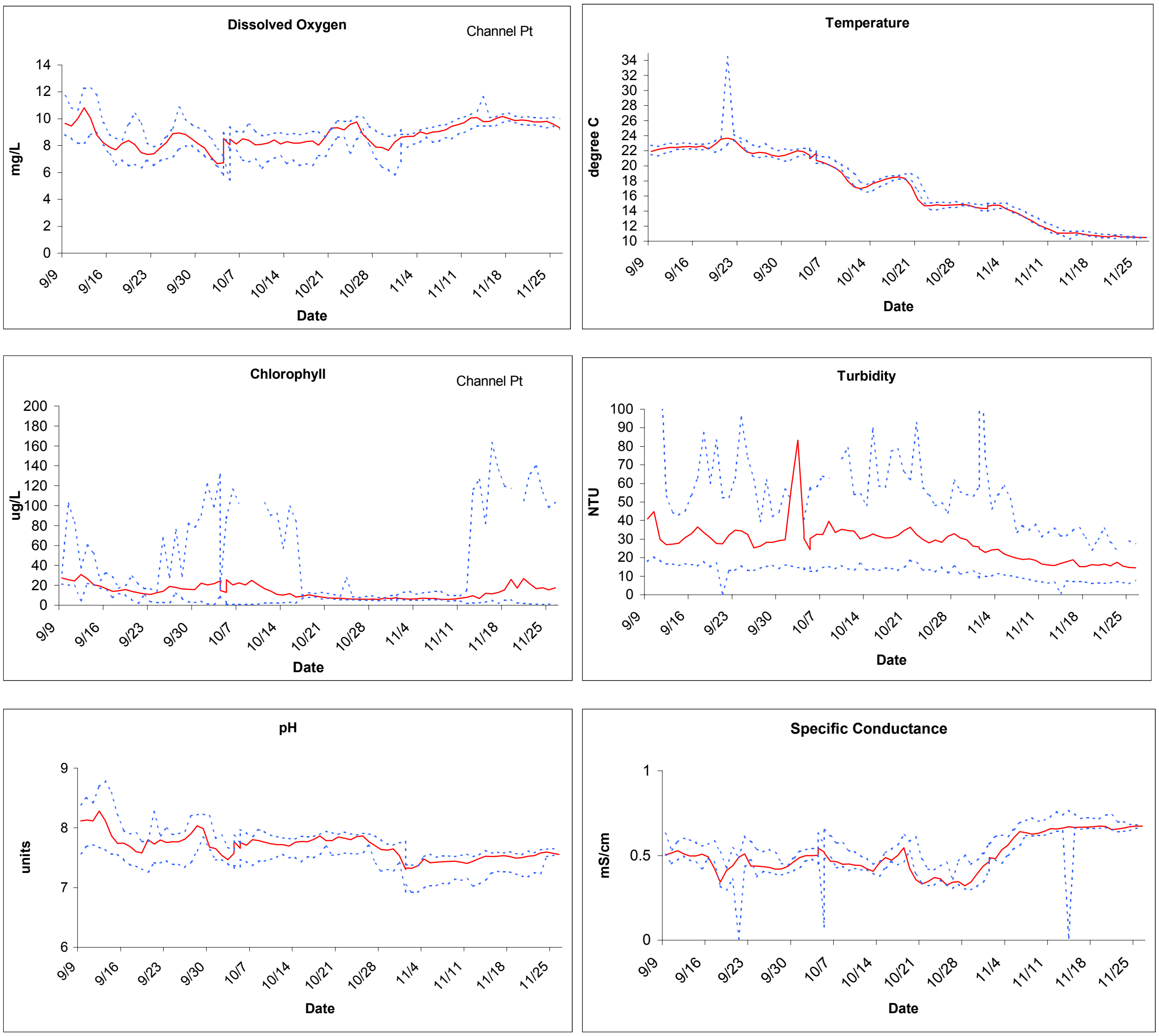

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Fig. II –15. Continuous water quality measurements at Mossdale.

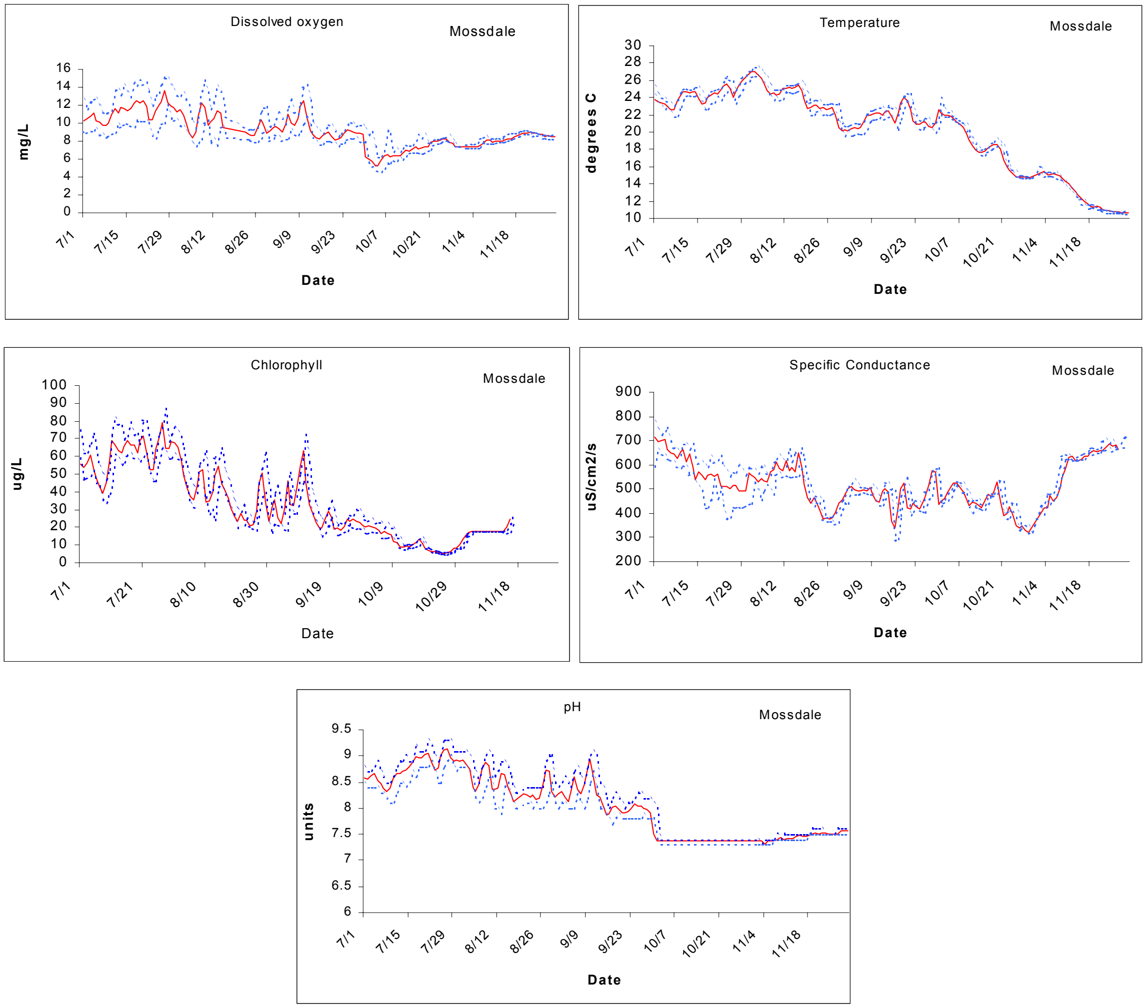


Fig. II-16. Surface continuous water quality data collected at station 50, Turning Basin .

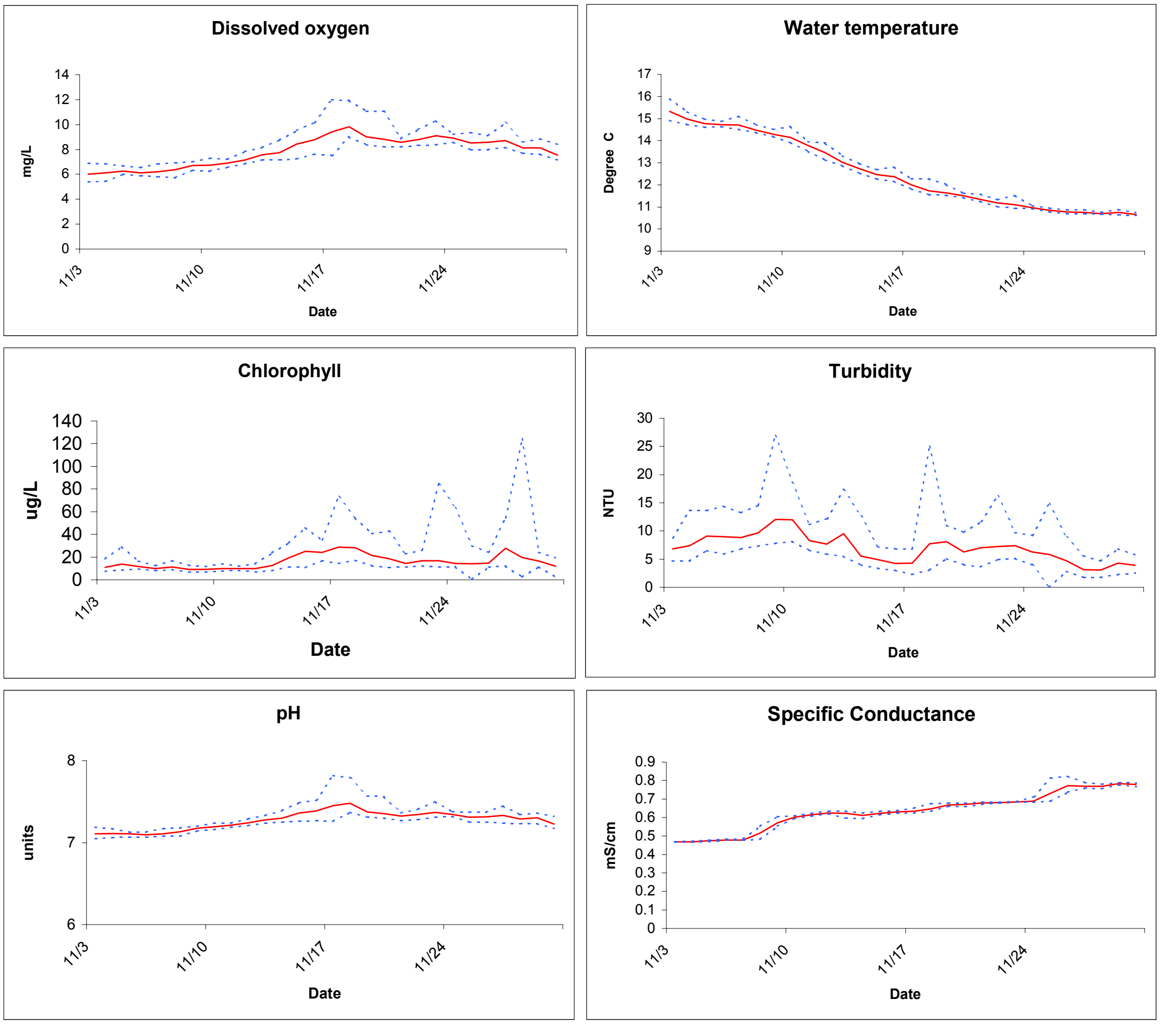
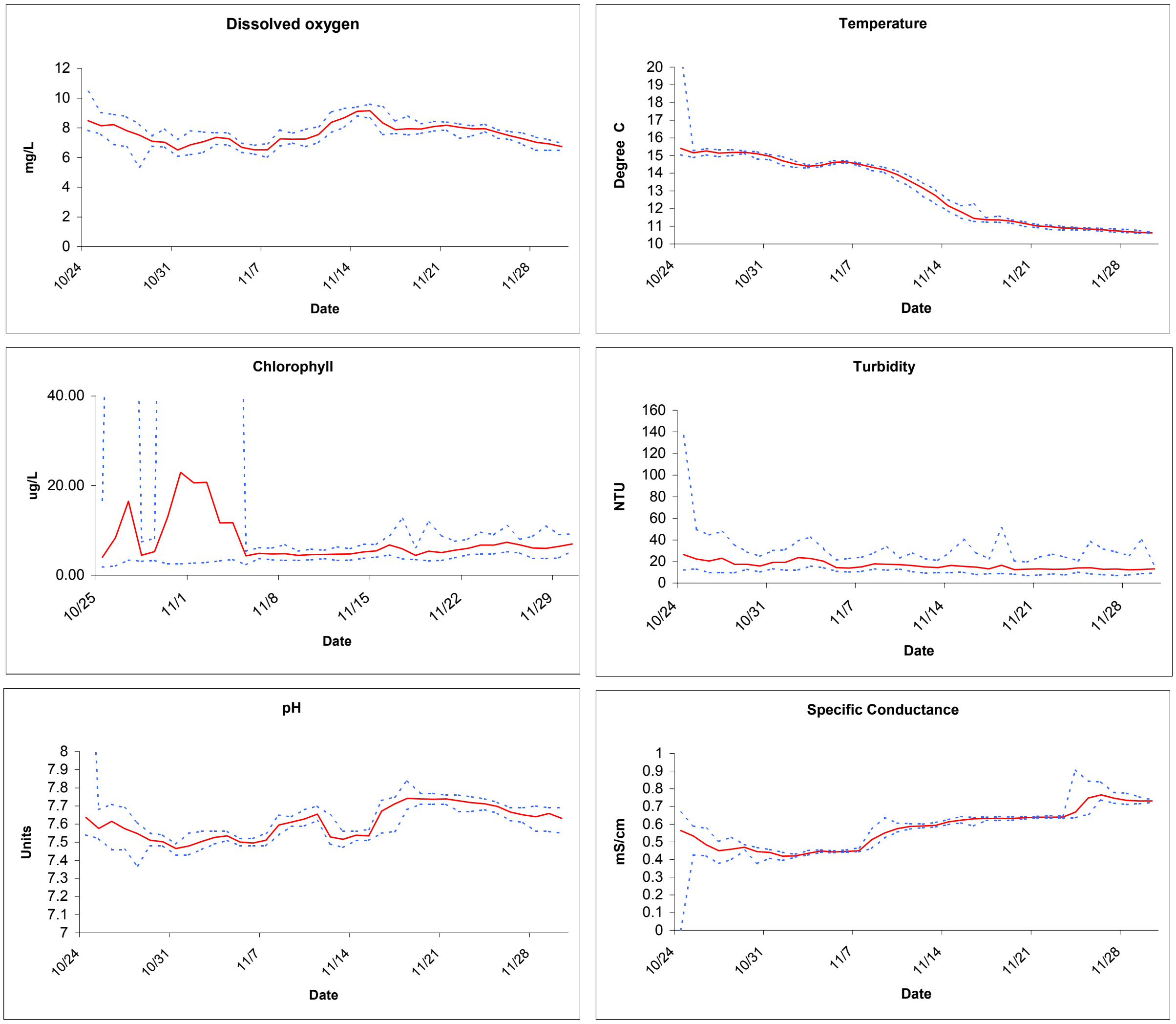


Figure II-17. Near bottom continuous water quality data collected at station 50, Turning Basin.



Dissolved oxygen concentration was lower at the bottom than the surface by up to 7 mg/L, but did not affect compliance with standards for most months except in September and early October when only bottom concentration was below standard values (Fig. II-12).

The diel variation in dissolved oxygen concentration and chlorophyll *a* concentration was similar and positively associated at station 43 (compare Figs. II-10 through II-12). The positive association between dissolved oxygen concentration and chlorophyll *a* concentration was supported by the variation in pH. High daily maximum dissolved oxygen concentration in July and September was associated with high pH. High pH is an indicator of algal photosynthesis which removes carbon dioxide (acidity) from the water during photosynthesis.

Below standard dissolved oxygen concentration also occurred at station 24 near Turner Cut in early October. The coincident below standard dissolved oxygen concentration at station 24 and station 43 demonstrated the severity of this October event (Fig. II-13). This event was probably caused by nonalgal processes because chlorophyll *a* concentration was low at less than 6 mg/L. The coincident low pH also suggested low photosynthetic activity. The water temperature of 19-22^{o}C should have supported dissolved oxygen saturation levels of 9 mg/L.

Upstream – High dissolved oxygen concentration at both upstream station 51 (Fig. II-14) and 55 (Fig. II-15) indicate the upper San Joaquin River was not a direct source of oxygen demand to the DWC. At these stations dissolved oxygen concentration was consistently above 6 mg/L and often supersaturated. The upper San Joaquin River was probably not a source of oxygen demand because of physical differences between the upstream and downstream sections of the river. Depth at the downstream stations in the DWC was 11-12 m and contrasted with shallow stations upstream where maximum water depth was 3-5 m. In the shallow water upstream, vertical mixing to the bottom would support high net oxygen production by algae in the photic zone and the large surface to volume ratio would facilitate high oxygen diffusion at the surface. In addition, slightly lower water temperature upstream increased the capacity for dissolved oxygen concentration. These conditions would have produced a higher dissolved oxygen concentration in the water column upstream then in the DWC despite the high respiration associated with high chlorophyll *a* concentration (compare Figs. II-10 through II-15).

In the Turning Basin at station 50, dissolved oxygen concentration decreased to below 6 mg/L near the surface in November and near the bottom in October and were associated with a chlorophyll a concentration of 20 ug/L and water temperature near 15^{o}C (Figs. II-16 and II-17). The somewhat higher dissolved oxygen at the bottom may be caused by the slight decrease in water temperature and respiration associated with algal biomass with depth.

III. Evaluation of the continuous monitoring network

The enhanced continuous monitoring program provided a more accurate description of diel and seasonal variability and maximum amplitude for each variable than discrete monitoring. Discrete data were unable to describe the 4 mg/L to 7 mg/L diel variation of dissolved oxygen concentration and provided little evidence of below standard concentrations compared with continuous data (compare Figs. II-2 and II10-11). Discrete data did also not describe the factor of 4 or more diel variation in chlorophyll *a* concentration that affects the accuracy of net tidal day load (Fig. II10).

The DWR discrete channel program consistently underestimated the frequency and magnitude of the oxygen deficit because sampling occurred during the middle of the day when dissolved oxygen concentration was near maximum due to algal photosynthesis. The magnitude of this difference was most evident in August and September when diel dissolved oxygen concentration varied by up to 4 mg/L.

Little additional information was gained from the vertical profiles collected by the DWR Channel Program versus the YSI continuous fixed depth measurements because 2000 was a wet and cool year. Dissolved oxygen varied little with depth in the wet year 2000 and contrasted with the dry year 1999 when stratification was strong (Lehman and Ralston 2000). More information is needed during different water-year types to fully evaluate the value of the surface and bottom measurements.

However, the newly installed bottom monitor at station 43 confirmed the persistence of lower dissolved oxygen concentration near the bottom than surface but an absence of severe oxygen depletion at the bottom during the day or night in the DWC. In fact, dissolved oxygen concentration was sometimes slightly higher at the bottom than the surface because of the slightly lower water temperature and algal biomass near the bottom.

The vertical difference between the DWR Shneider surface (1m) monitor and the YSI 6600 bottom monitor (1.6 m from the bottom) were not as large as originally thought. Vertical profile studies done on July 27, 2001 by the San Joaquin River Technical Committee indicated the DWR surface monitor provides a depth integrated sample between 1 and 5.6 m (Stringfellow 2001).

The DWR channel program provided useful information on spatial variation. The continuous horizontal profiles and discrete vertical profiles provided a complete description of the geographical extent of the oxygen depletion during the sampling period. However, these data probably describe the most favorable oxygen conditions and shortest extent of the oxygen depletion because sampling hours are during the middle of the day when oxygen production by algae is highest. A dense network of continuous monitors might provide the most accurate spatial and temporal scale measurements, but this cannot be determined without more comparisons between water-year types.

IV. Load of oxygen demand substances

Community growth rate studies and continuous fluorometry were used to estimate the relative amount of algal biomass in the DWC produced by new growth in the DWC and transported into the DWC the upper San Joaquin River. This information addressed the question:

Question: What is the relative contribution of algal biomass from new growth in the DWC and upstream algal load to oxygen demand in the Stockton Deep Water Channel (DWC)?
Answer: The maximum potential net daily load of algal biomass from new growth in the DWC and transport from upstream were similar in magnitude.

Historical perspective

Chlorophyll *a* concentration, a measure of algal biomass, in the San Joaquin River has measured by the Department of Water Resources and U. S. Bureau of Reclamation on a monthly or semi-monthly basis at 1 m depth since 1970 (iep.water.ca.gov). These data indicate that chlorophyll *a* concentration is currently four times lower in the DWC than in the 1970s and suggests algal biomass may be less important to the dissolved oxygen deficit now than historically (Fig. IV-1). A reduced role of algal biomass to the oxygen deficit in the San Joaquin River was supported by at least a factor of 2 decrease in the algal load at Vernalis, the tidal head of the estuary (Fig. IV-2).

Fig. IV-1. Chlorophyll *a* concentration measured at Rough and Ready Island between 1970 and 2000.

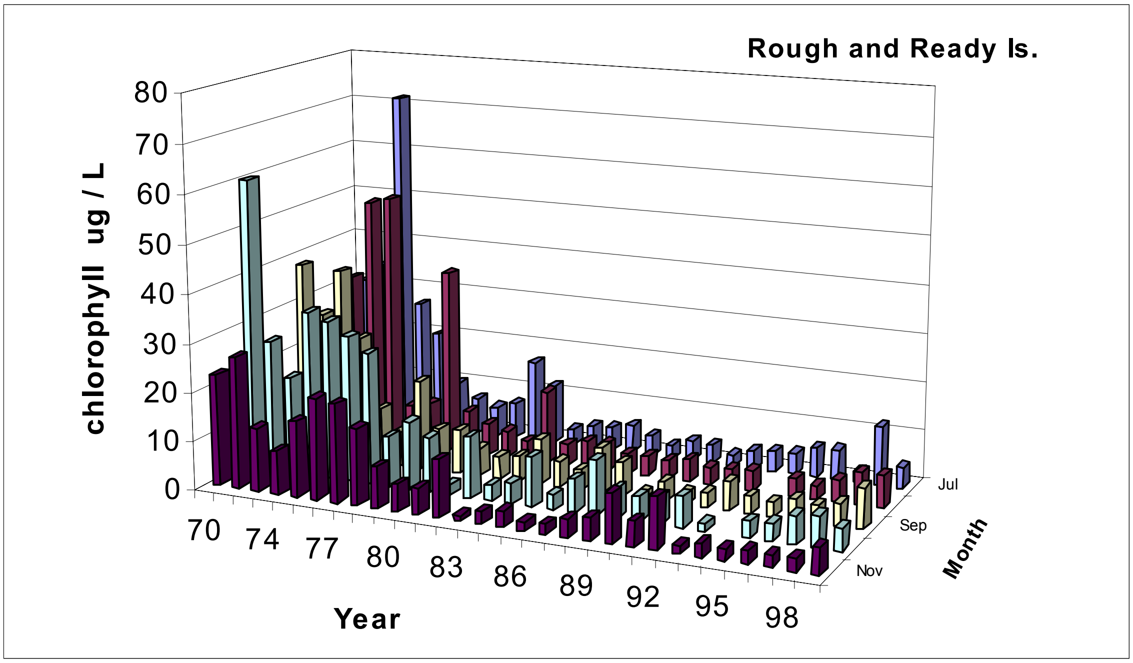
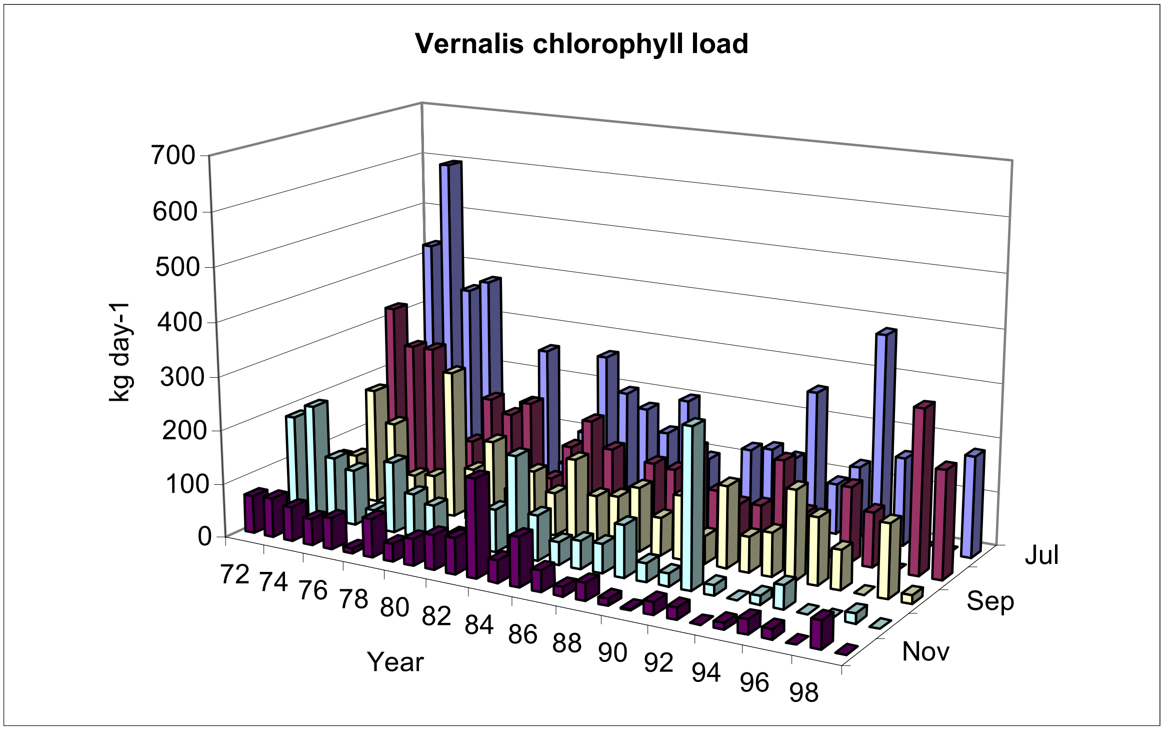


Fig. IV-2. Chlorophyll *a* load calculated for Vernalis between 1970 and 2000.



Growth in the channel

Methods - Community production and respiration rate was measured by dissolved oxygen light and dark bottle in situ incubation. Natural water samples were placed in replicate light and dark bottle glass-stoppered 300 ml B.O.D. borosilicate bottles and incubated in the water column at 1 m and 5 m depth in the DWC for 24 hr (Vollenweider 1972). Sample bottles were maintained at the specified depth in the water column using an incubation rack attached to a buoy that allowed the bottles to stay at constant depth during the daily 1.3 m tide.

The change in dissolved oxygen concentration over the incubation period was determined using Winkler titration. Incubations were stopped in the field by addition of magnanous sulfate and bottles were kept cool and in the dark until titration within 24 hr. Alkaline azide and sulfamic acid were added just before titration with sodium thiosulfate (APHA 1998). Addition of the azide and sulfamic acid just before titration reduced the interference of high organic carbon on the analysis (APHA 1989).

Ancillary water quality measurements included ammonia, nitrate and nitrite, total phosphorus, dissolved orthophosphate, chlorophyll *a*, phaeophytin, total and dissolved organic carbon, total Kjeldahl nitrogen, biochemical oxygen demand (BOD), carbonaceous oxygen demand (CBOD) and phytoplankton species composition. Methods for water quality variables are described in Appendix A. Phytoplankton species were identified using an inverted microscope following settling using the Utermohl method (1958).

Field measurements included vertical profiles of light attenuance using a LiCor quantum sensor and specific conductance, chlorophyll *a* fluorescence, water temperature and turbidity using a YSI 6600 water quality monitor. In addition, continuous solar irradiance (g cal cm2 min) was measured by an Eppley pyroheliometer at station 43.

Specific community production and respiration rates (ug oxygen / ug chlorophyll *a* / hr) estimated the minimum net daily algal production rate (kg oxygen / day) in the photic zone and maximum net daily algal respiration rate (kg oxygen / day) in the aphotic zone. The net algal production rate in the photic zone was estimated as the total mass of chl *a* in the photic zone of the study reach between station 24 and station 48 multiplied by the specific community production rate adjusted to 24 hr. The algal respiration rate in the aphotic zone was calculated in the same fashion as the production rate but specific community respiration rate was used instead of the production rate. The net water column community production (kg oxygen / day) was the sum of the photic and aphotic zone daily production and respiration (negative value). Oxygen demand (mg/L) in the study reach was calculated as the net water column community production divided by the total volume. Chlorophyll a biomass was estimated from horizontal profiles of chlorophyll *a* concentration and assumed a uniform distribution with depth.

The daily load of chlorophyll *a* (kg chlorophyll *a* / day) into the DWC from growth in the photic zone was estimated by conversion of the net community production rate (kg oxygen / day) to carbon using the conversion factor of 0.312 and then to chlorophyll *a* using a carbon: chlorophyll *a* ratio of 40 (Vollenweider 1972).

It is difficult to accurately quantify algal production rate in the DWC because the light/dark bottle technique measures community production and respiration rates that include both phytoplankton and bacterial respiration. This is particularly important in the DWC where high ammonia concentration exerts an oxygen demand from nitrifying bacteria late in the season. The separate contribution of algal growth and respiration to the community production rate was evaluated by comparison of the net daily water column community production rate measured in the DWC with calculated values determined from empirical models using chlorophyll *a* concentration, solar irradiance and light attenuation. Net productivity in the photic zone was calculated from the Cole and Cloern (1987) empirical model for San Francisco Bay algae as follows: $P = (4.6\Psi I_oB)/k$ where P is net primary productivity ($mgC/m^2/day$); I_o is the surface flux of photosynthetically active radiation ($E/m^2/day$); B is phytoplankton biomass as chlorophyll *a* (mg chlorophyll a/m^3); k is the attenuation coefficient (1/m); and Ψ is a constant of 0.69 mg C/mg chlorophyll a/Em^{-2}.

Respiration in the aphotic zone was calculated from the Rudek and Cloern (1996) equation for San Francisco algae when chlorophyll *a* concentration was greater than 9 ug/L as follows: $R = 217.1 + 18.5\ B$ where R is respiration (nmol oxygen/l/hr), B is chlorophyll *a* concentration (ug/L), and 217.1 is a constant.

***Results* -** Measured specific production and respiration rates were high and variable at station 24 and 43 in the DWC (Fig. IV-3). Net community production rates represented a minimum load from algal production that reached at least 35 kg/day to 194 kg/day and was often highest at station 34 and station 40 in the middle of the reach. Oxygen demand from these community production rate measurements reached 1 mg/L at individual stations and totaled 4 mg/L in the reach (Table IV-4).

Average measured net water column production rates were far lower than those calculated from empirical equations and reflected the large respiration rate in natural water samples (Table IV-5). However, higher measured net photic zone production rate suggested algal growth rate was also higher than suggested by modeled values. This difference probably increased seasonally because modeled values were strongly influenced by the seasonal decrease in chlorophyll *a* concentration. Nitrification probably accounted for the high respiration rates in measured values, particularly after August, when ammonia concentration reached over 1 mg/L in the DWC and the ultimate demand was near 7 mg/L (Fig. IV-6). Nitrification resulted in the measured production and respiration rates being close to the minimum and maximum values respectively.

Table IV-3. Net production rate, respiration rate, oxygen demand and chlorophyll load from algal growth in the DWC between station 24 at Turner Cut and station 48 at Light 48 measured from light/dark bottle incubation measurements of community production rate.

Date	net photic zone production rate	aphotic zone respiration rate	net water column production rate	oxygen demand	load chla
	kg O2/ day	kg O2/ day	kg O2/ day	mg O2 / L	kg / day
27-Jul	12051	-18342	-6291	-2.83	94
14-Aug	8930	-10110	-1180	-0.53	70
23-Aug	14140	-22307	-8167	-3.67	110
6-Sep	4900	-14497	-9598	-4.32	38
12-Sep	3416	-16455	-13039	-5.82	27
14-Sep	2384	-11395	-9011	-4.05	19
12-Oct	2758	-8899	-6141	-2.76	22
16-Oct	3462	-5708	-2247	-1.01	27
25-Oct	9872	-7598	2274	1.02	77
26-Oct	2986	-4535	-1549	-0.69	23
7-Nov	1276	-1621	-344	-0.15	10
14-Nov	4462	-4431	31	0.01	35
mean	5886	-10492	-4605	-2	46

Fig. IV-4. Measured oxygen demand in the study reach.

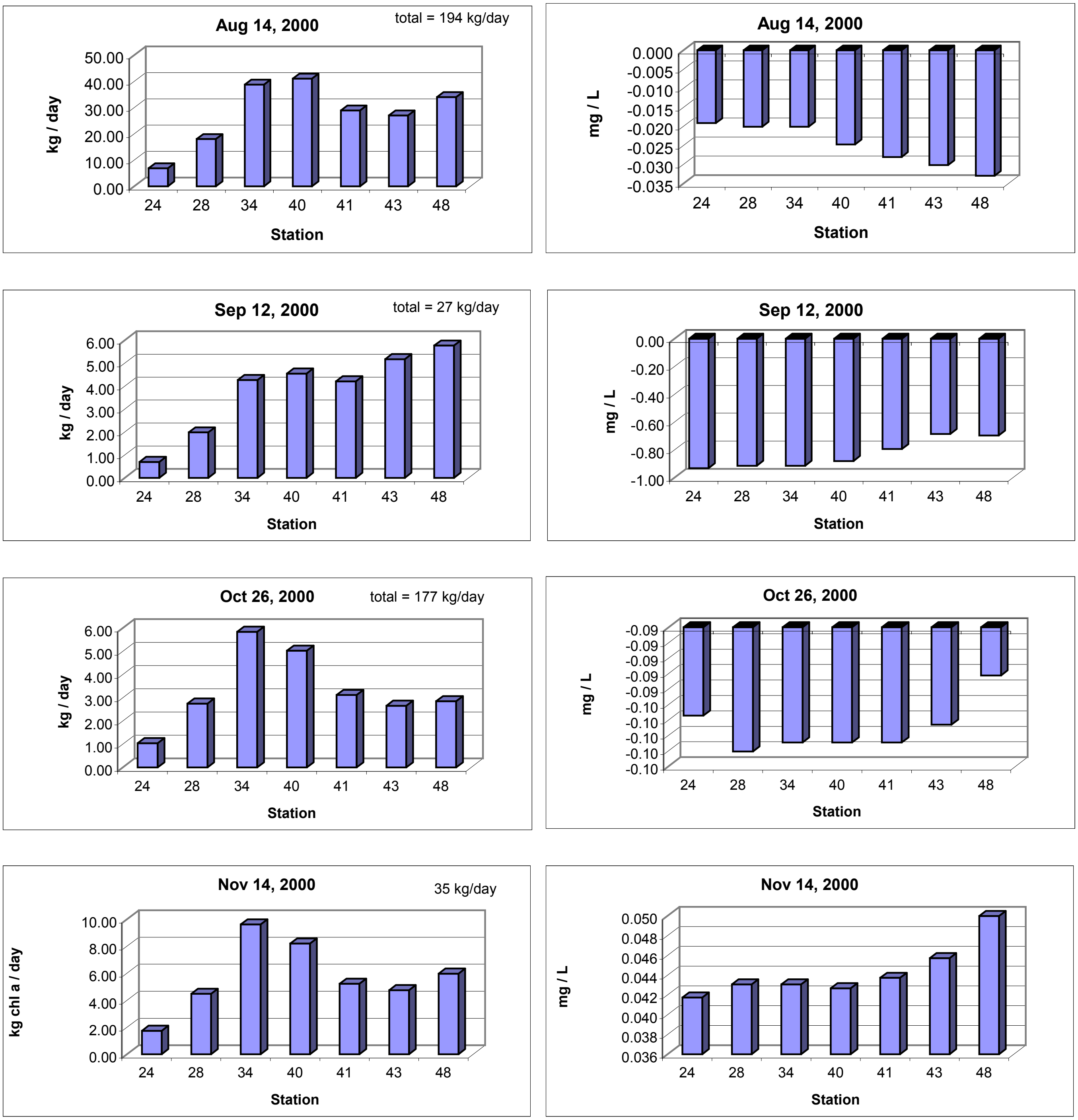
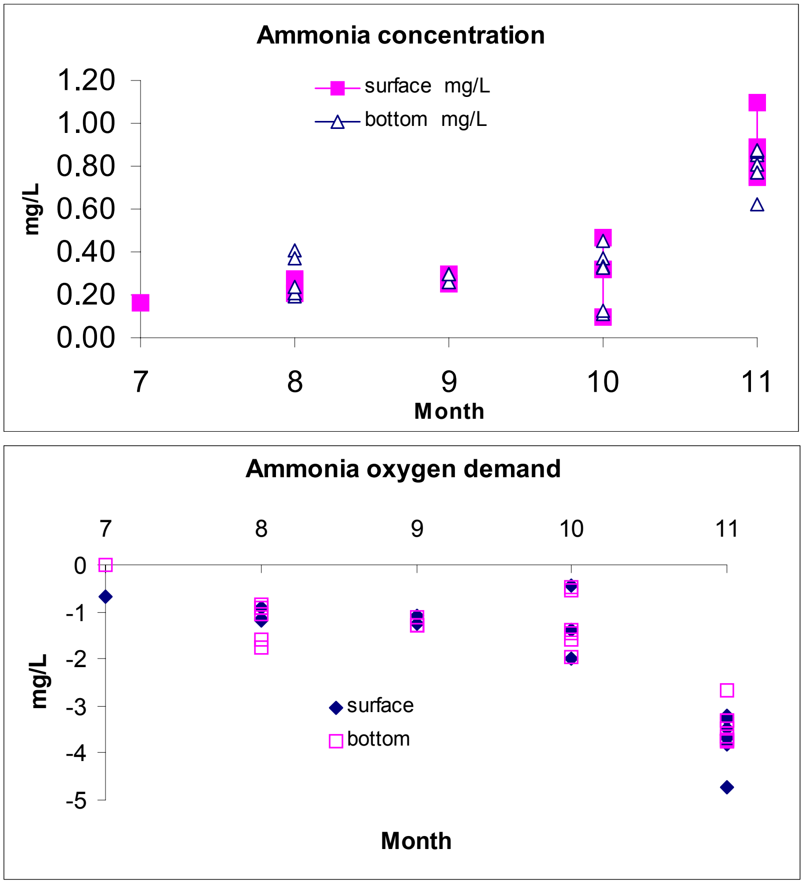


Table IV-5. Daily net production rate, respiration rate, oxygen demand and chlorophyll *a* load from algal growth in the DWC between station 24 at Turner Cut and station 48 at Light 48 calculated by equations using chlorophyll *a* concentration, surface irradiance and extinction coefficient.

Date	net photic zone production rate	aphotic zone respiration rate	net water column production rate	oxygen demand	load chla
	kg O2/ day	kg O2/ day	kg O2/ day	mg O2 / L	kg / day
27-Jul	7272	-3751	3521	0.00	57
14-Aug	12451	-7784	4667	2.11	97
23-Aug	10921	-6224	4697	2.11	85
6-Sep	3756	-5530	-1774	-0.80	29
12-Sep	3896	-7978	-4082	-1.86	30
14-Sep	6797	-4746	2051	0.92	53
12-Oct	2469	-4306	-1836	-0.83	19
16-Oct	1870	-3486	-1616	-0.73	15
25-Oct	1231	-3910	-2679	-1.20	10
26-Oct	2829	-5180	-2351	-1.06	22
7-Nov	923	-3168	-2245	-1.01	7
14-Nov	2450	-4998	-2548	-1.15	19
mean	4739	-5088	-350	-0.29	37

Fig. IV-6. Ammonia concentration and the ultimate oxygen demand from ammonia between July and November in the deep water channel at station 43, Rough and Ready Island.



Tidal load
Tidal loads into the DWC from upstream and downstream were measured in order to access the relative contribution of algal load from growth in the DWC and upstream and downstream sources.

These measurements addressed the following questions:
Question: What is the relative contribution of algal biomass from in situ growth and upstream load to the Stockton Deep Water Channel (DWC) ?
Answer: Algal biomass load from growth in the channel and net tidal transport from the upper San Joaquin River can be similar in magnitude, but varied monthly.

Question: What is the oxygen demand from algal biomass compared with other oxygen demanding substances in the DWC and upstream?
Answer: The potential oxygen demand from carbonaceous BOD and algal respiration in the DWC was smaller than the potential oxygen demand from nitrogenous BOD in the DWC and upstream.

Question: Are the loads of oxygen demanding substances from Vernalis and Mossdale representative of the load that actually enters the DWC ?
Answer: The load of organic oxygen demanding substances including algal biomass, total organic carbon, volatile suspended solids and non-ammonia total Kjeldahl nitrogen into the DWC at Channel Point was lower than expected from measurements at Vernalis and Mossdale. The load of inorganic oxygen demanding substances at Channel Point was higher than expected from Vernalis and Mossdale measurements and was primarily a function of ammonia discharge at the Stockton RWCF.

Methods
The upstream and downstream net transport of algal biomass and associated inorganic and organic materials was estimated by continuous and discrete tidal day measurements. Chlorophyll *a* concentration was estimated from 15 min chlorophyll *a* fluorescence measured with a YSI 6600 water quality meter at station 51 and a Turner fluorometer at station 43 and station 55 (Fig. Map II-1). Chlorophyll *a* concentration (ug/L) was converted to 15 min or hourly load by multiplication with streamflow (L/15 min or L/hour) and daily load was the sum of the 15 min or hourly loads over 25 hr. Streamflow at station 51 was estimated from 15 min flow measured by UVM station and operated by the U. S. Geological Survey just upstream of the Stockton RWCF discharge. Streamflow at station 55 was assumed to be similar to those at station 60 that are estimated from hourly stage data by the CA Department of Water Resources. Streamflow at station 43 was measured by 15 min ADCP measurements.

Tidal day load of nonalgal biomass was estimated from four discrete water samples collected on ebb and flood tide during both spring and neap tide using an ISCO automatic sampler and flow estimates described above. A single discrete water sample was used to estimate load at station 55 and station 60 where tidal exchange is small. Water samples were analyzed for a suite of water quality and biological variables including ammonia, nitrate plus nitrite, orthophosphate, total phosphorus, total and dissolved organic carbon, total and volatile suspended solids, chlorophyll *a*, phaeophytin concentration, BOD and CBOD and phytoplankton species composition and density. Methods for these analyses are listed in Appendix A.

Results

Upstream algal load – Upstream algal load into the DWC was similar in magnitude to the load from algal growth in the DWC (compare Table IV-3 and Fig. IV-7). The net tidal day load of algal biomass into the DWC from station 51 ranged from 10 kg/day to 160 kg/day and was highest between late August and early October.

Fig. IV-7. Net daily chlorophyll *a* load at Channel Point.

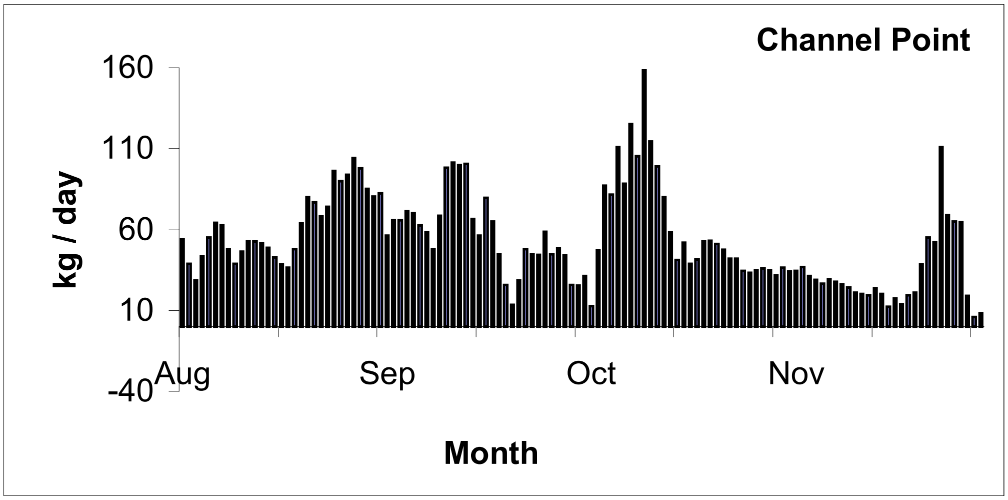
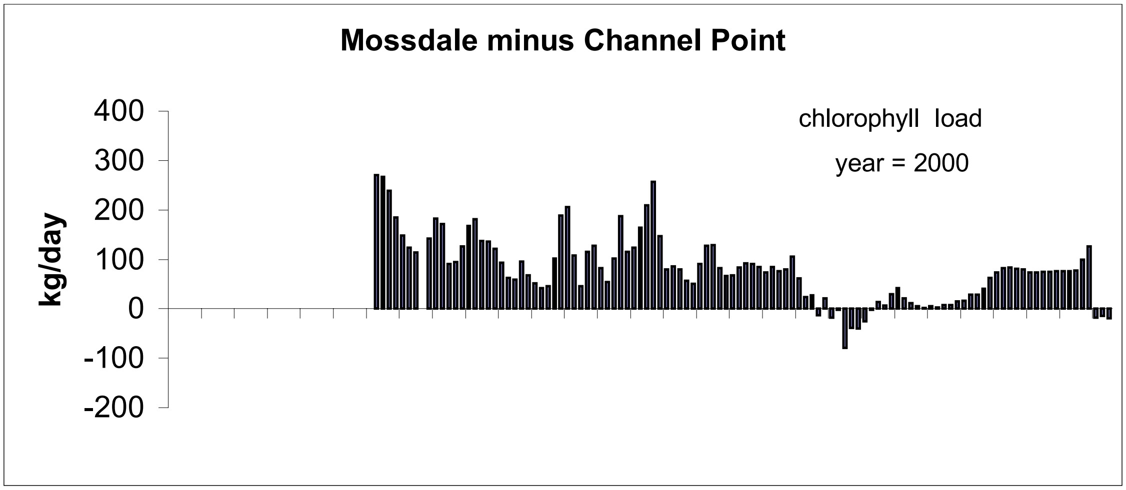
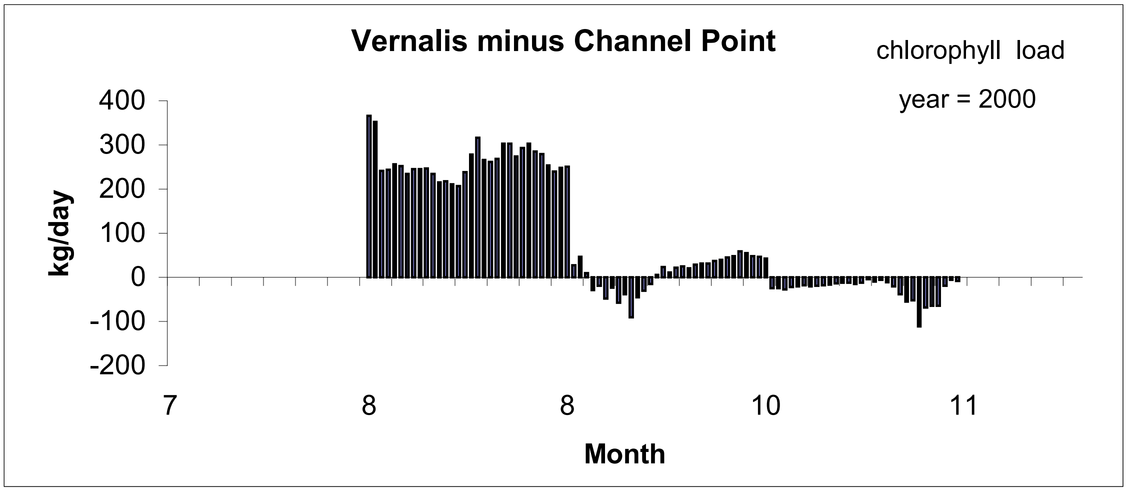
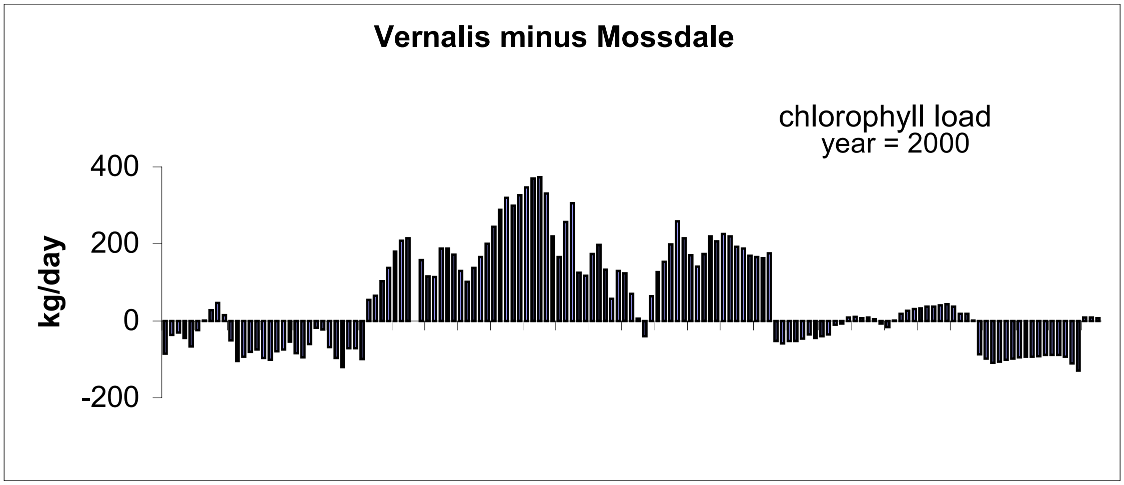


Fig. IV-8. Load difference for upstream stations at Vernalis or Mossdale and Channel Point at the entrance of the DWC.







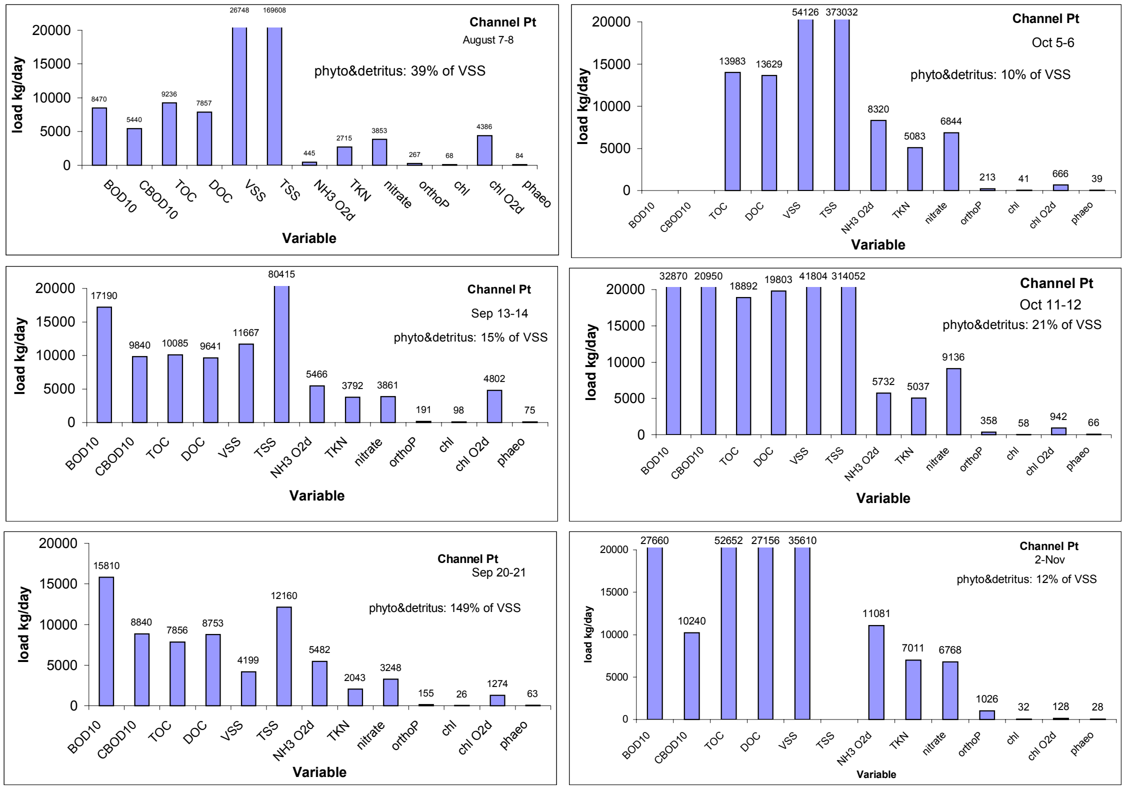
Net tidal day load from Mossdale or Vernlis was a poor estimate of the material load into the DWC from upstream. Net tidal day load from upstream into the DWC was 100-300 kg/day lower when calculated from measurements at station 51 near Channel Point at the entrance of the DWC than from station 55 near Mossdale or station 60 near Vernalis further upstream during August and September (Fig. IV-8). This suggests the upper San Joaquin River was a sink for algal biomass early in the season when most of the algal biomass was lost between station 60 and station 55. Algal load was more similar among upstream stations in October, but was characterized by an increased load between station 60 and station 55 in November.

Non-algal tidal load - The load of algal biomass into the DWC was small compared with the volatile suspended solid load. Chlorophyll *a* and phaeophytin dry weight equivalents were at most 40% of the volatile suspended solids (Fig. IV-9) and most of this algal material was phaeophytin, a surrogate for algal detritus. Chlorophyll *a* derived oxygen demand calculated from measured respiration rate (chl O2d) could have accounted from only a small portion of the total oxygen demand. In addition, most of the organic load into the DWC was dissolved. Nearly 80% of the total organic carbon load was dissolved.

The majority of the upstream oxygen demand was derived from nitrogenous sources. The 10-day carbonaceous BOD load at station 51 was small compared to the total BOD (Fig. IV-9). In contrast, the nitrogenous BOD load or difference between the total BOD and carbonaceous BOD comprised between 50% and 80% of the total and increased seasonally at Channel Point. Nitrification of ammonia from the Stockton RCF contributed to the nitrogenous BOD and may have accounted for a late season increase in total BOD load at Channel Point. Ammonia discharge from the Stockton RWCF increases sharply between September and November (Chen and Tsai 2001). Daily ammonia load increased to over 5,000 kg/day and was associated with ammonia concentrations near 1 mg/L at station 51. Complete conversion of this ammonia to nitrate would require up to 8,000 mg of oxygen at 20 ^{o}C.

The majority of the upstream nitrogenous load was from non-ammonia TKN, assuming ammonia attached to the suspended matter was small. Non-ammonia TKN consists of inorganic and organic material that can be converted to ammonia and does not include nitrate or nitrite. The non-ammonia TKN load at Mossdale was often many times higher than dissolved ammonia and was a fairly constant load over the season. Whether the non-ammonia TKN was particulate or dissolved is unknown. However, total organic carbon: TKN ratios are lower than the value of about 5 that would occur for material of only algal origin.

Fig. IV-9. Net tidal day load measured at Channel Point from tidal water quality measurements.

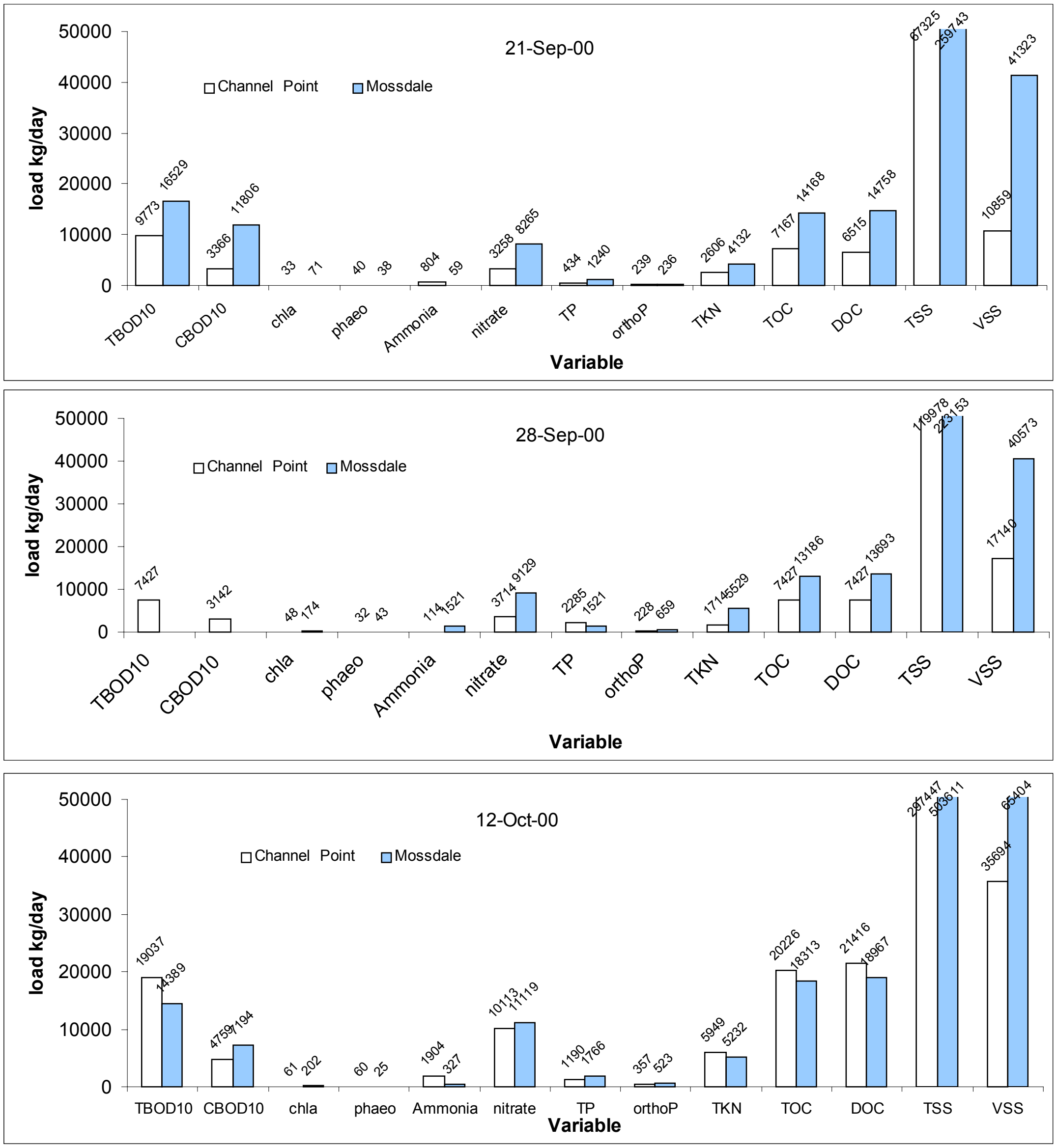


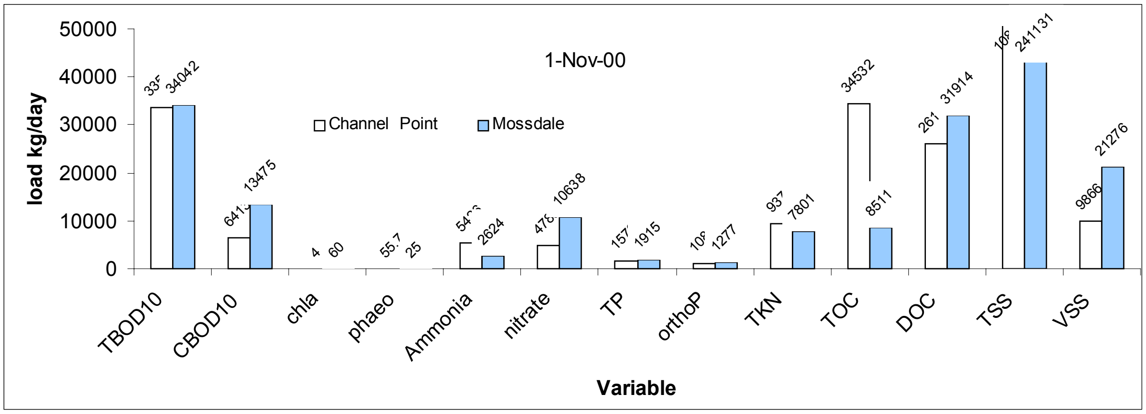
Comparisons of net tidal day load measurements confirmed the loss of organic and inorganic material between station 55 and station 51 suggested by continuous fluorometry data (Fig. IV-10). Total and volatile suspended solids, nitrate, total phosphorus and carbonaceous BOD loads were consistently lower at station 51 than station 55. The cause of this material loss is unknown.

In contrast, total 10 day BOD was higher at station 51 than station 55 in October and November when both ammonia concentration, total Kjeldahl nitrogen and total and dissolved organic carbon were higher at station 51 (Fig. IV-10). The source of this additional oxygen demand was probably the Stockton RWCF that discharges both high loads of ammonia and some organic matter, including chlorophyll a downstream of station 55 late in the fall.

That the San Joaquin River above the DWC was often a sink for algal biomass was supported by comparison of net tidal day loads at station 51, station 55 and station 60 at Vernalis (Fig. IV-11) further upstream.

Fig. IV-10. Comparison of tidal day load at Channel Point station 51 and Mossdale station 55.




1-Nov-00
load kg/day
50000
40000
30000
20000
10000
0
☐ Channel Point
▨ Mossdale
335
34042
641
13475
4
60
55.7
25
54
2624
478
10638
157
1915
109
1277
937
7801
34532
8511
261
31914
109
241131
9866
21276
TBOD10
CBOD10
chla
phaeo
Ammonia
nitrate
TP
orthoP
TKN
TOC
DOC
TSS
VSS
Variable

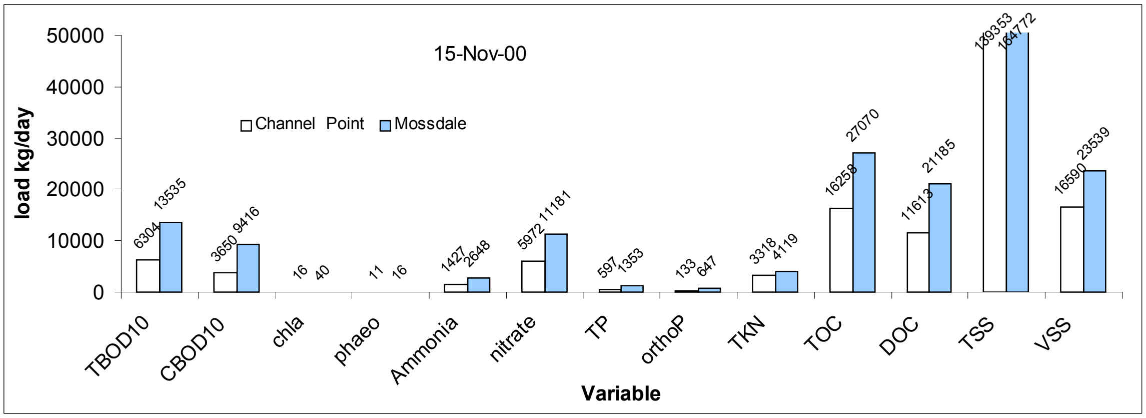
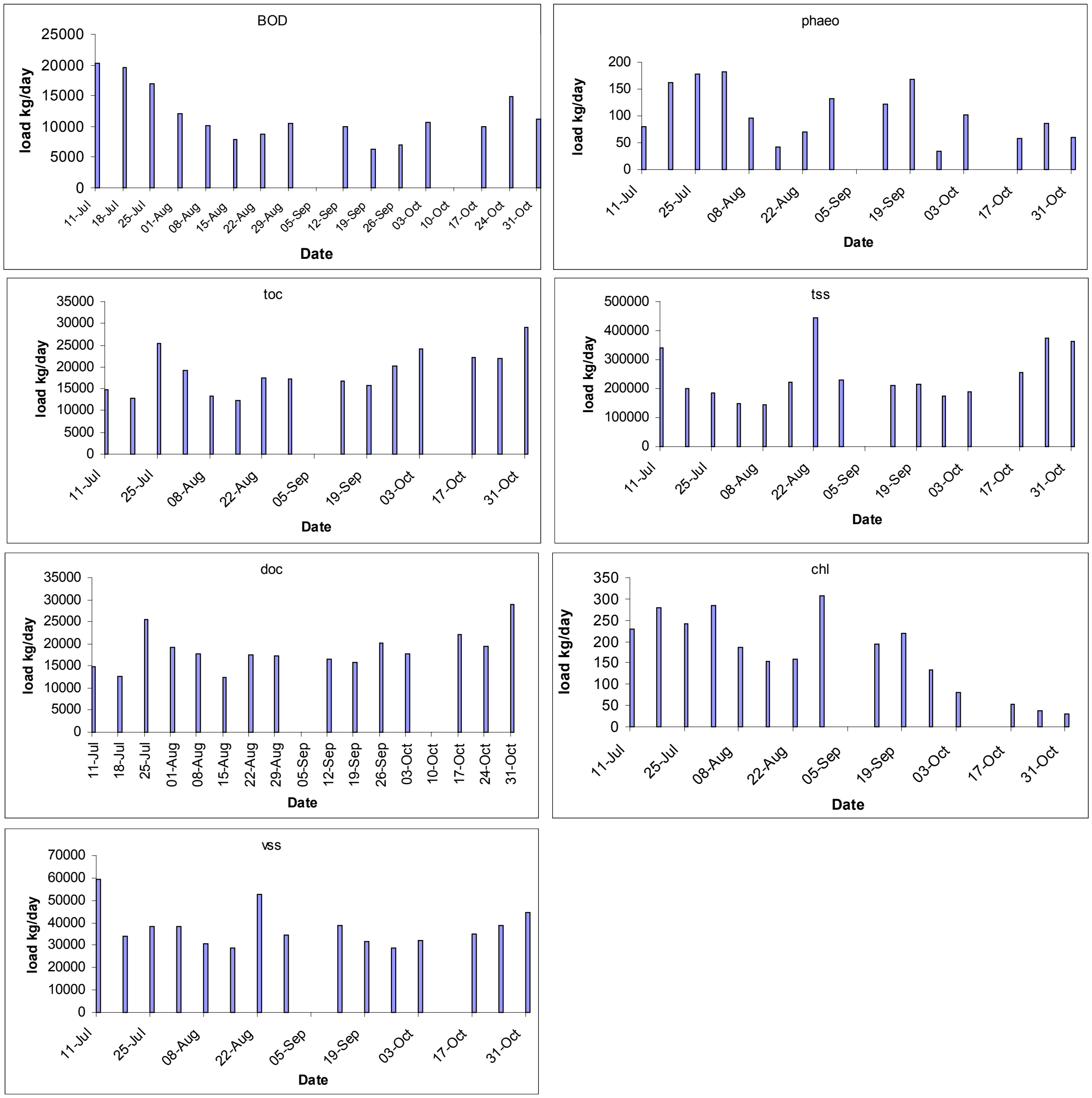

15-Nov-00
load kg/day
50000
40000
30000
20000
10000
0
☐ Channel Point
▨ Mossdale
6304
13535
3650
9416
16
40
11
16
1427
2648
5972
11181
597
1353
133
647
3318
4119
16258
27070
11613
21185
139353
164772
16590
23539
TBOD10
CBOD10
chla
phaeo
Ammonia
nitrate
TP
orthoP
TKN
TOC
DOC
TSS
VSS
Variable

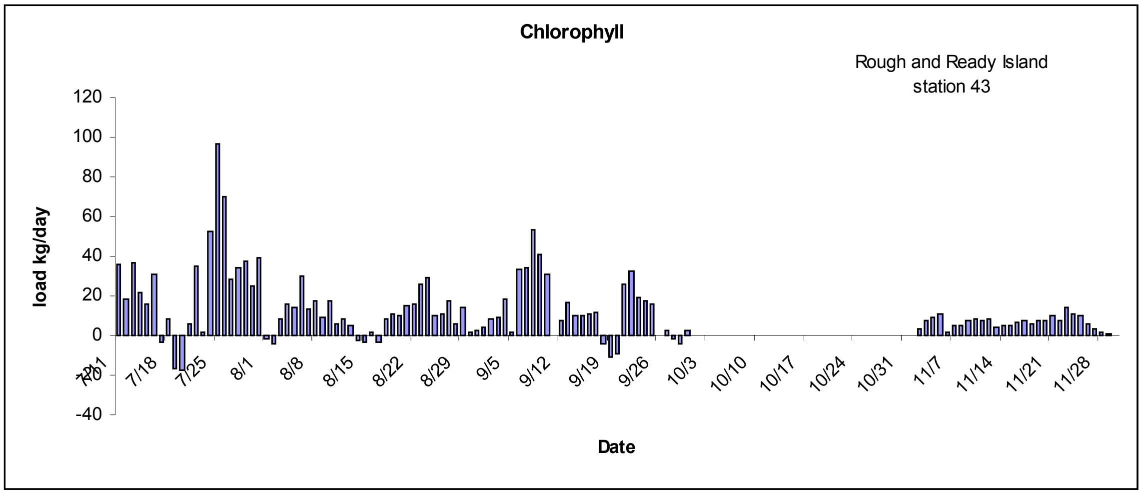
Fig. IV-11. Vernalis tidal day load. Data were collected by the City of Stockton.



Downstream algal load - Net daily downstream export of algal biomass decreased seasonally from near 100 kg/day to 20 kd/day at station 43 (Fig. IV-12). This downstream export was similar in magnitude to load at station 51 upstream and load from algal growth in the DWC (Fig. IV-3 and IV-8). However, unlike upstream, the net export of live algal biomass was usually higher than detrital biomass.

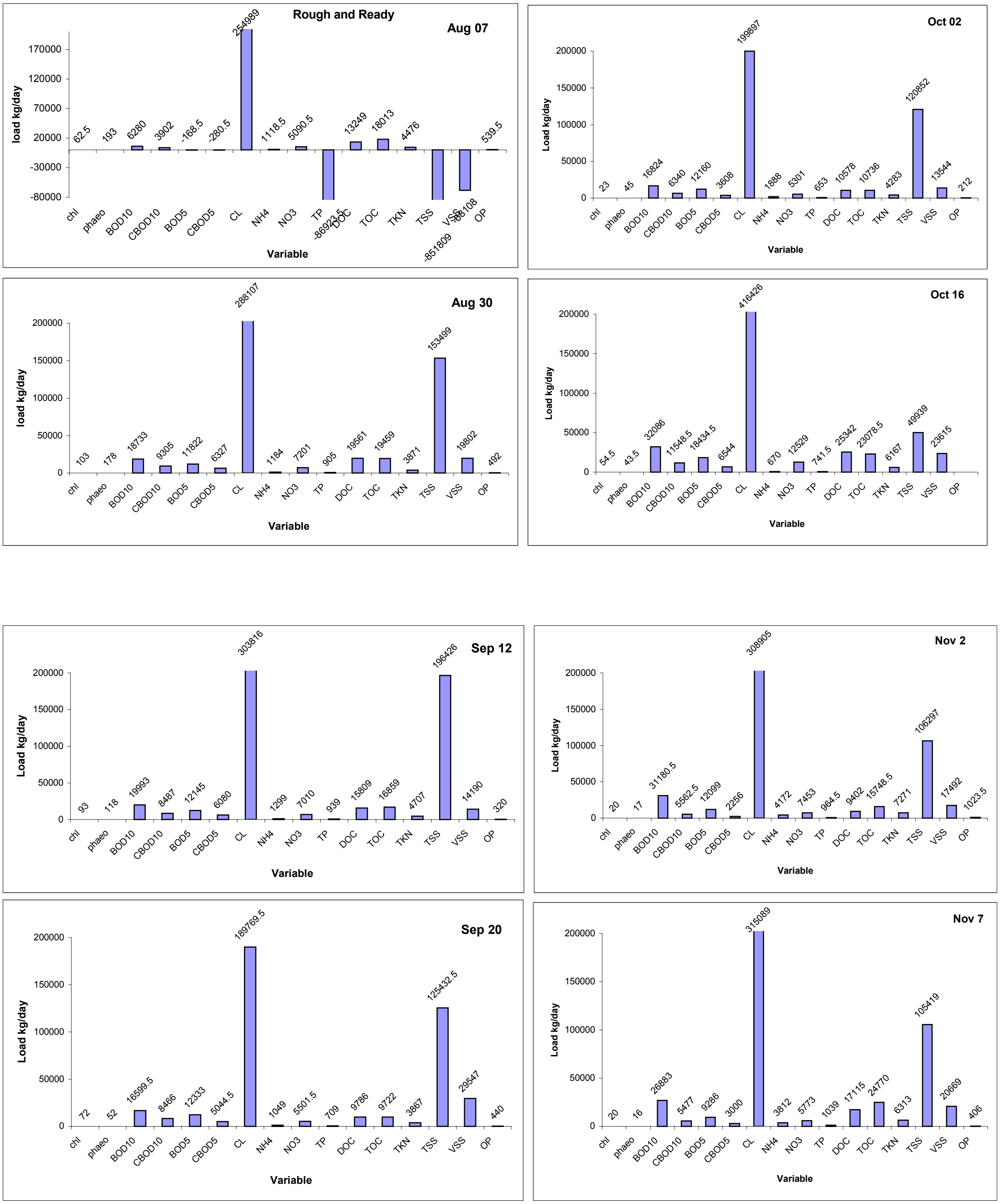
Chlorophyll *a* load was independent of the total suspended solids load that often reached near 200,000 kg/day even though both surface total suspended solids and chlorophyll *a* decreased seasonally (Fig. IV-13). Chlorophyll *a* concentration was also poorly correlated with volatile suspended solids. Volatile suspended solid load was fairly stable throughout the season at 20,000 kg/day, but the percent chlorophyll and phaeophytin was 40% or less and decreased seasonally.

Fig. IV-12. Net daily chlorophyll *a* load calculated from continuous fluorometry and flow data.



Downstream non-algal load - Total BOD10 export at station 43 increased over the season and contrasted with carbonaceous BOD10 that did the reverse (Fig. IV-13). The seasonal increase in total BOD10 was accompanied by a factor of 4 increase in ammonia load. In contrast, the seasonal decrease in carbonaceous BOD10 was accompanied by an increase in total and dissolved organic carbon that suggested carbon was a reduced source of oxygen demand.

Fig. IV-13. Tidal day load calculated for station 43 at Rough and Ready Island based on tidal water quality measurements.



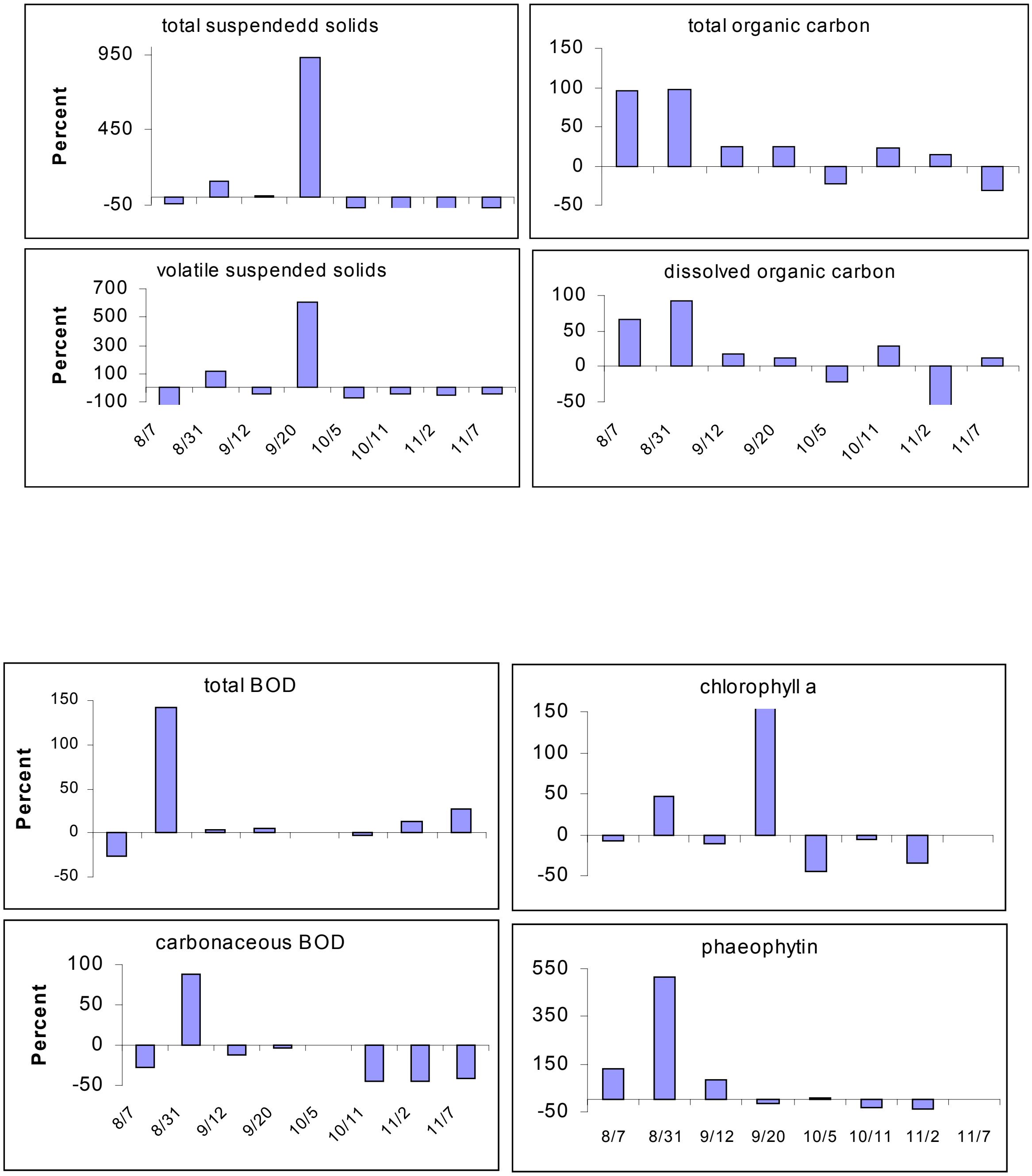
V. Mass balance

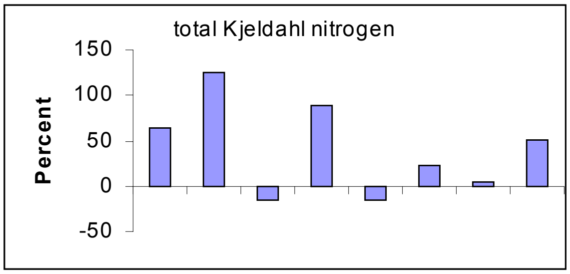
The DWC was usually a sink of both inorganic and organic suspended particulates between station 51 on the upper San Joaquin River and station 43 at Rough and Ready Island (Fig. V-1). The daily net loss of inorganic and organic material usually included total suspended solids, volatile suspended solids, carbonaceous BOD10 and chlorophyll *a* (Fig. V-2). This particulate matter was probably retained in the DWC through settling.

In contrast, the DWC was often a source of total BOD (Fig. V-1). The daily net increase in total BOD was accompanied by an increase in total Kjeldahl nitrogen, ammonia and non-ammonia total Kjeldahl nitrogen. Nitrification of this nitrogen was suggested by the net increase in nitrate, the final product of nitrification. Some of the increase in total BOD was produced by the decomposition of chlorophyll *a* because phaeophytin was exported downstream.

Net load differed somewhat among days, but over the season the DWC was a sink for total suspended solids, volatile suspended solids, carbonaceous BOD and a source of chlorophyll a, total BOD, ammonia, phaeophytin, nitrate, total and dissolved organic carbon, chloride, orthophosphate and total Kjeldahl nitrogen (Fig. V-2).

Fig. V-1. Comparison of net tidal day loads of organic and inorganic materials measured at Channel Point and Rough and Ready Island.




total Kjeldahl nitrogen
Percent
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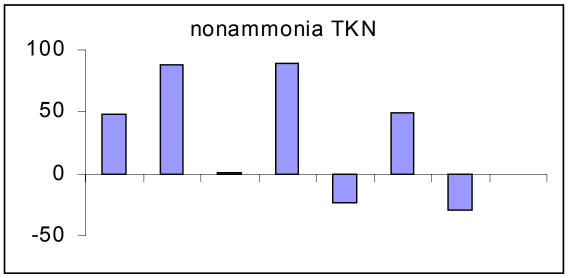
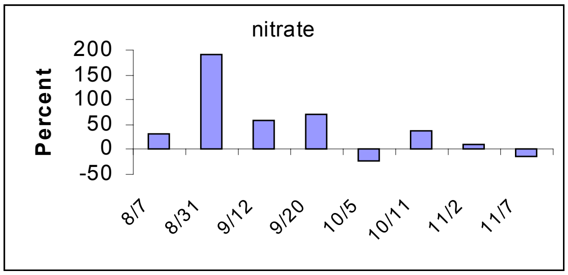
100
50
0
-50


nonammonia TKN
100
50
0
-50


nitrate
Percent
200
150
100
50
0
-50
8/7
8/31
9/12
9/20
10/5
10/11
11/2
11/7

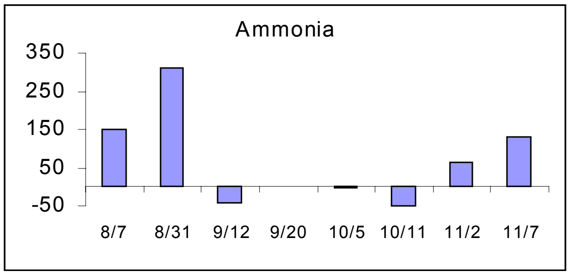
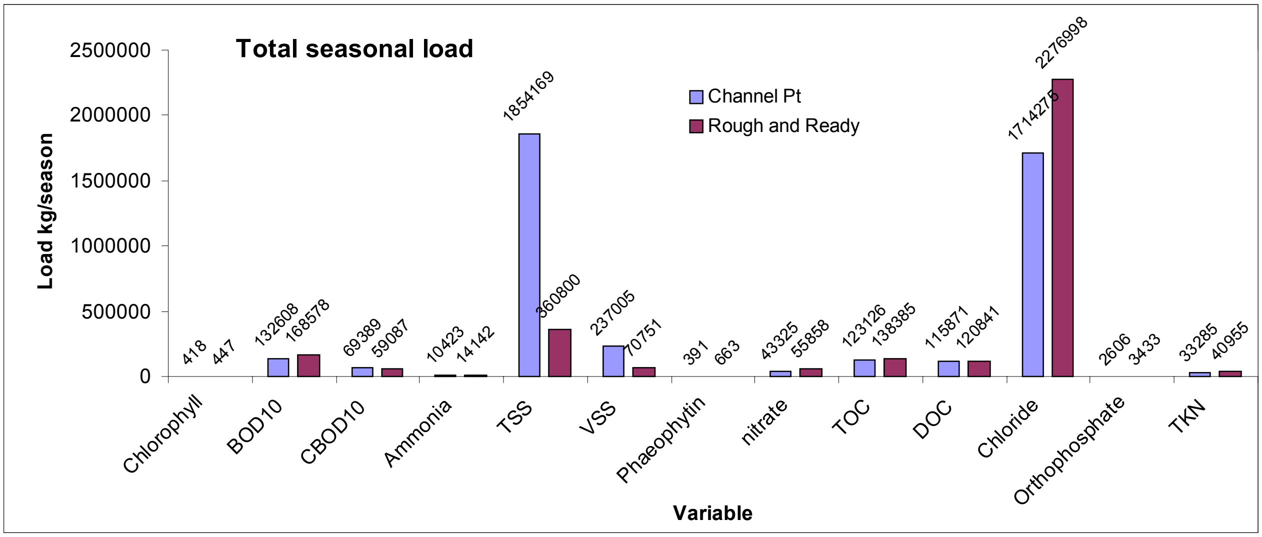

Ammonia
350
250
150
50
-50
8/7
8/31
9/12
9/20
10/5
10/11
11/2
11/7

Fig. V-2. Seasonal totals for the tidal day load calculated from discrete tidal day water quality measurements for station 51 at Channel Point and station 43 at Rough and Ready Island.



VI. Controlling mechanisms

Sources of Oxygen demand

Total, carbonaceous and nitrogenous BOD were compared in order to determine the relative contribution of each to oxygen demand. These comparisons were made in order to address the question:

> **Question:** What is the oxygen demand from algal biomass compared with other oxygen demanding substances?
> **Answer:** The oxygen demand in the DWC was primarily produced by nitrogenous materials and was poorly correlated with algal biomass.

The oxygen demand in total BOD tests was primarily produced by the decomposition of nitrogenous material by nitrifying bacteria or nitrification. Carbonaceous BOD consistently accounted for 1-2 mg/L of the total BOD at stations 24, 43 and 51 and was a small percent of the total BOD that reached 6 mg/L (Fig. VI-1). The carbonaceous BOD decreased seasonally and contrasted with total BOD that increased seasonally.

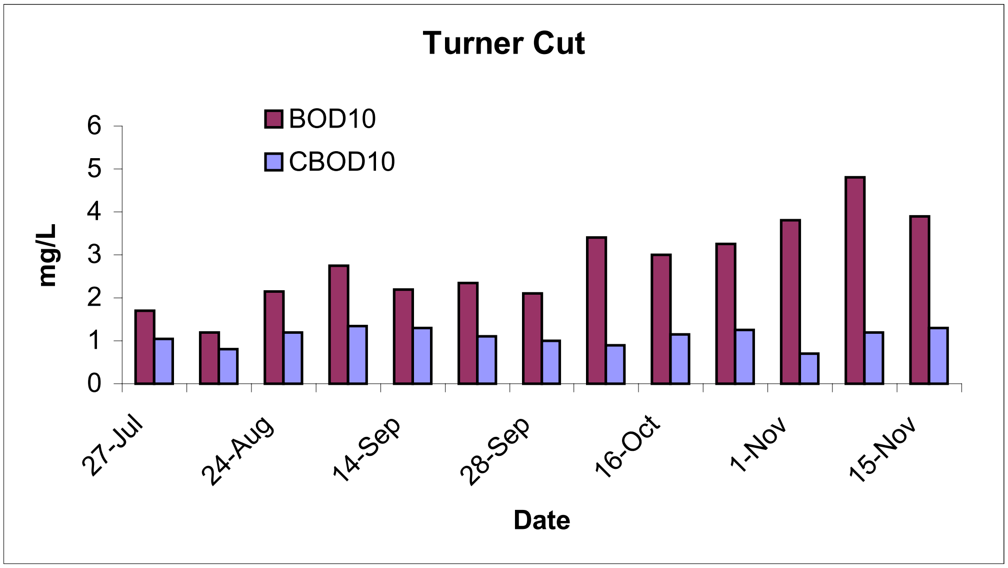
The seasonal increase in total BOD was positively correlated ($p < 0.01$) with ammonia and total Kjeldahl nitrogen at station 24 and station 43 in the DWC and station 51 in the upper San Joaquin River (Fig. VI-2). The importance of ammonia to the seasonal increase in total BOD10 throughout the DWC was supported by both high correlation coefficients and consistent patterns among correlation coefficients at stations 24, 43 and 51 (Tables VI-4 a-c). Total BOD10 was most highly correlated with nitrogenous BOD (NBOD) and ammonia concentration among the 15 variables tested. Ammonia concentration was often high at these stations and seasonally increased with high load from the Stockton Regional Water Control Facility in September through November (Fig. VI-3). Total Kjeldahl nitrogen measures both ammonia and non-ammonia nitrogen sources and increased in association with the seasonal increase in ammonia concentration.

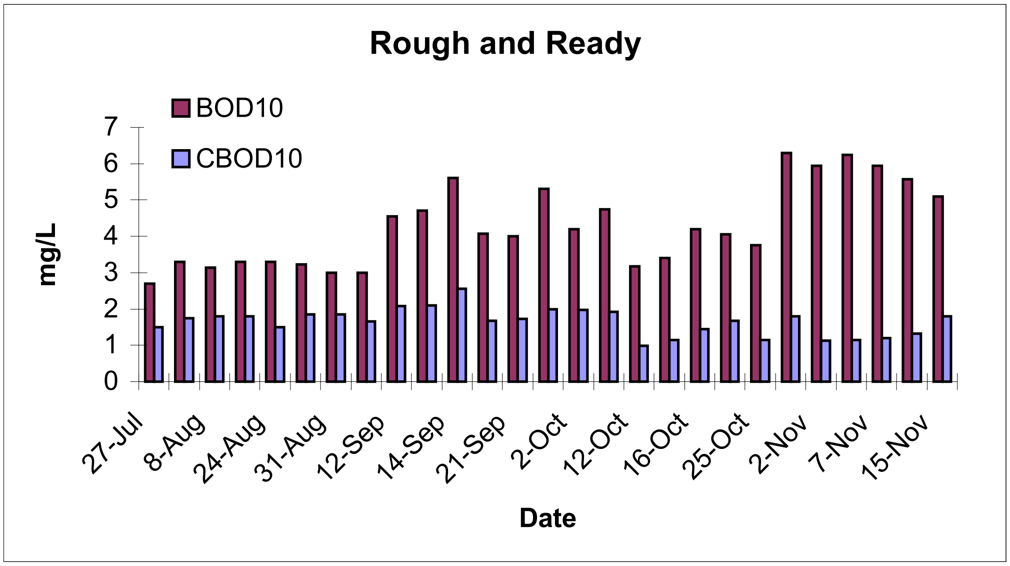
Total BOD10 was not associated with algal biomass at stations 24, 43 or 51 (Table VI-4 a-c). Total BOD, ammonia, nitrogenous BOD and total Kjeldahl nitrogen were negatively or non-significantly correlated with chlorophyll *a* or phaeophytin concentration. Even the correlation between chlorophyll *a* or phaeophytin concentration and carbonaceous BOD was non-significant except at station 43.

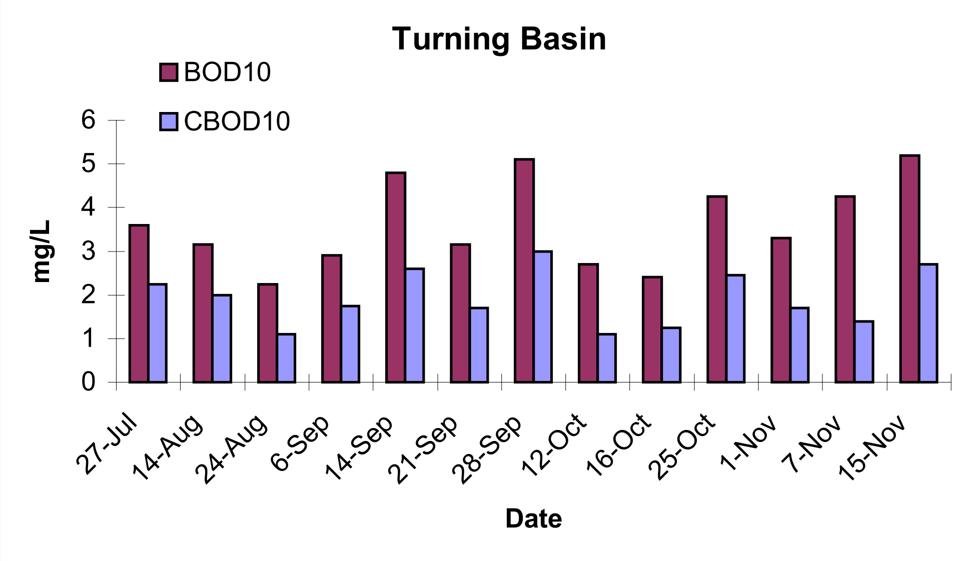
In contrast, total BOD was not significantly correlated with dissolved ammonia concentration at station 50 in the Turning Basin where dissolved ammonia concentration was usually low and oxygen demand was dominated by algal biomass. Ammonia concentration was usually 2 times lower and chlorophyll *a* concentration was 2 times higher at station 50 than downstream in the DWC (Fig. VI-2; Table VI-4 d. Here carbonaceous BOD10 usually comprised over 50% of the total BOD10 and was positively correlated with total BOD, Kjeldahl nitrogen, chlorophyll *a* and phaeophytin concentration.

Settling rate studies confirmed the relatively small contribution of carbonaceous BOD to the total BOD and dominance of nitrogenous BOD to the total BOD in the DWC. In addition, separate BOD tests on suspended particles versus water column samples indicated the total BOD was driven by the soluble phase (G. Litton, personal communication).

Fig. VI-1. Comparisons of total and carbonaceous BOD of water samples in the DWC at Turner Cut and Rough and Ready Island and upstream input stations at Turning Basin and Channel Point. Nitrogenous BOD is the difference between the two.






Turning Basin
BOD10
CBOD10
mg/L
6
5
4
3
2
1
0
27-Jul
14-Aug
24-Aug
6-Sep
14-Sep
21-Sep
28-Sep
12-Oct
16-Oct
25-Oct
1-Nov
7-Nov
15-Nov
Date

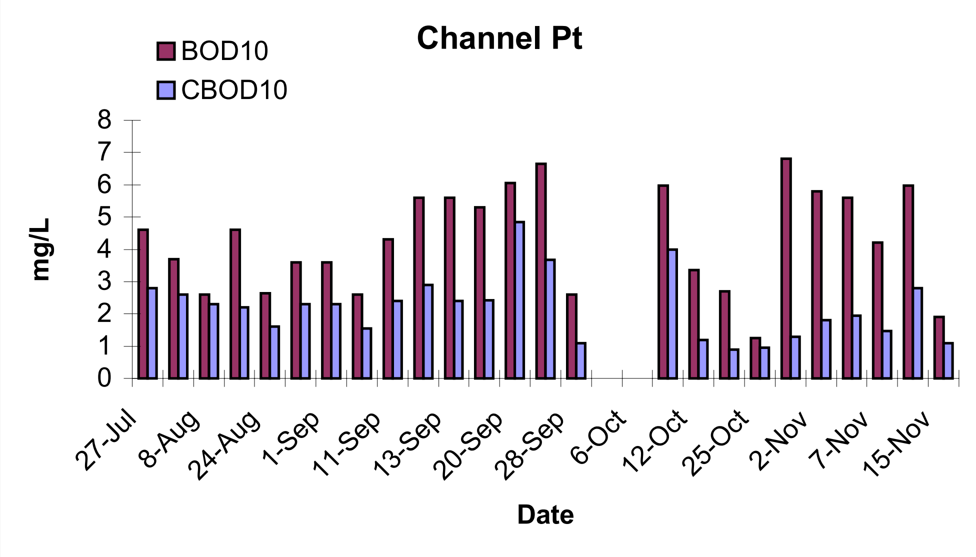
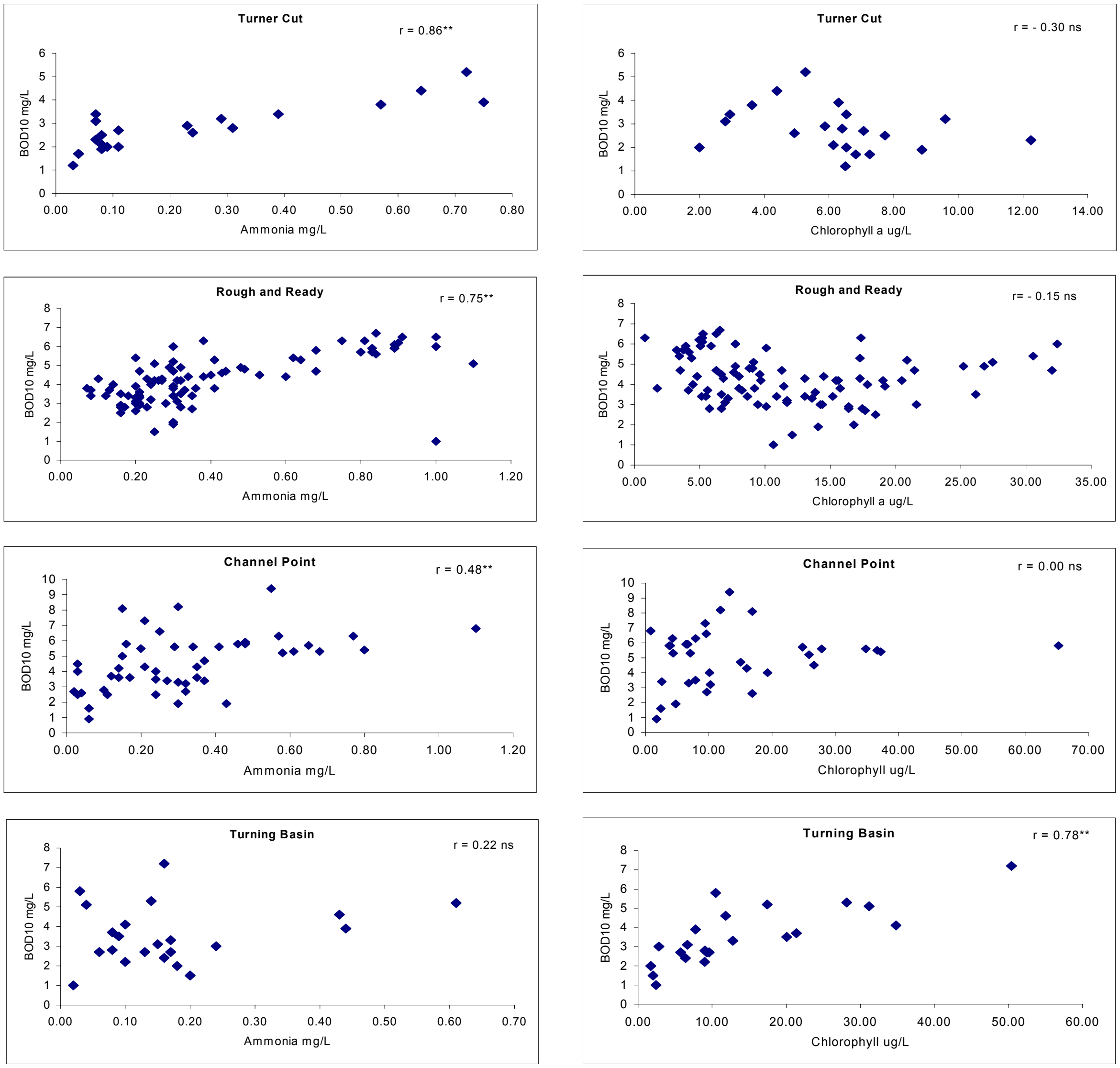

Channel Pt
BOD10
CBOD10
mg/L
8
7
6
5
4
3
2
1
0
27-Jul
8-Aug
24-Aug
1-Sep
11-Sep
13-Sep
20-Sep
28-Sep
6-Oct
12-Oct
25-Oct
2-Nov
7-Nov
15-Nov
Date

Fig. VI-2. Association between total BOD and either ammonia or chlorophyll *a* concentration for four stations in and around the DWC during 2000.



DRAFT

Table VI – 4 a. Pearson correlation coefficients calculated among water quality variables measured at Turner Cut station 24 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

	ammonia	chlorophyll	BOD10	BOD5	CBOD5	CBOD10	chloride	dissolved organic carbon	nitrate	orthophosphate	phaeophytin	total keldahl nitrogen	total organic carbon	total phosphorus	total suspended solids	volatile suspended solids	NBOD10
ammonia			.86					.61			-.69	.76	.58		-.52	-.56	.89
chlorophyll									.46								
BOD10	.86			.62								.77	.65		-.48	-.46	.97
BOD5			.62		.44		-.44										.57
CBOD5				.44		.70											
CBOD10					.70												
chloride				-.44				.57	.56					.46			
dissolved organic carbon	.61		.50				.57				-.62	.61	.76	.68	-.55	-.55	.48
nitrate		.46					.56										
orthophosphate											-.58						
phaeophytin	-.69							-.62		-.58			-.43		.44	.49	-.44
total keldahl nitrogen	.76		.78					.61					.43		-.44	-.48	.78
total organic carbon	.58		.65					.76			-.43	.70		.46	-.65	-.61	.68
total phosphorus								.68									
total suspended solids	-.52		-.48					-.53			.44	-.44				.91	-.55
volatile suspended solids	-.56		-.46					.85			.49	-.48	-.61		.91		-.54
NBOD10	.89		.97		.57			.48			-.44	.77	.68		-.55	-.54	
NBOD5			.51	.88			-.47										.55

Table VI –4 b . Pearson correlation coefficients calculated among water quality variables measured at Rough and Ready Island station 43 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

	ammonia	chlorophyll	BOD10	BOD5	CBOD5	CBOD10	chloride	dissolved organic carbon	nitrate	orthophosphate	phaeophytin	total keldahl nitrogen	total organic carbon	total phosphorus	total suspended solids	volatile suspended solids	NBOD10
ammonia		-.45	.75		-.27	-.26	.42	.71		.23	-.36	.53	.78				.84
chlorophyll	-.45				.52	.58			.34		.53						-.41
BOD10	.75			.47							-.25	.54					.91
BOD5			.47		.51	.44	-.48		-.23								.28
CBOD5	-.27	.52		.51		.79	-.22		-.37			-.26					-.21
CBOD10	-.26	.58		.44	.79				-.31		.44				.45	.45	-.25
chloride	.42			-.48	-.22				.33			.55			.26	.27	
dissolved organic carbon																	
nitrate																	
orthophosphate	.23											.23					
phaeophytin	-.36	.53	-.25			.44						.28		.24	.68	.68	-.44
total keldahl nitrogen	.54		.54		-.26		.55			.23	.28			.35	.53	.52	.51
total organic carbon																	
total phosphorus											.24	.35			.63	.63	
total suspended solids						.45	.26				.67	.53		.63		.99	
volatile suspended solids						.45	.27				.68	.52		.63	.99		
NBOD10	.84	-.41	.91	.28	-.21	-.25					-.44	.51					
NBOD5			.47	.86			-.43				-.28						.44

Table VI – 4 c. Pearson correlation coefficients calculated among water quality variables measured at Channel Point station 51 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

	ammonia	chlorophyll	BOD10	BOD5	CBOD5	CBOD10	chloride	dissolved organic carbon	nitrate	orthophosphate	phaeophytin	total keldahl nitrogen	total organic carbon	total phosphorus	total suspended solids	volatile suspended solids	NBOD10
ammonia		-.34	.48	.46			.39				-.31	.79		.34			.79
chlorophyll	-.34										.58						
BOD10	.48			.89	.38	.74						.33					.69
BOD5			.87			.86											.33
CBOD5	.46		.38						-.35			.29					.39
CBOD10			.74	.86													
chloride	.39								.55			.47					
dissolved organic carbon	.56																
nitrate					-.35		.55									.38	
orthophosphate	.41													.43			
phaeophytin	-.31	.58															-.32
total keldahl nitrogen	.79		.33		.29		.47			.41				.55	.34	.28	.55
total organic carbon																	
total phosphorus	.34									.43		.55			.60	.50	.30
total suspended solids												.34		.60		.91	
volatile suspended solids												.28		.50	.91		
NBOD10	.79		.69	.36	.39						-.32	.55		.30			
NBOD5	-.35			.30	-.89					-.28							

Table VI – 4 d . Pearson correlation coefficients calculated among water quality variables measured at Turning Basin station 50 between July and November 2000. Coefficients are significant at either the 0.05 level (regular type) or 0.01 level (bold type).

	ammonia	chlorophyll	BOD10	BOD5	CBOD5	CBOD10	chloride	dissolved organic carbon	nitrate	orthophosphate	phaeophytin	total keldahl nitrogen	total organic carbon	total phosphorus	total suspended solids	volatile suspended solids	NBOD10	NBOD5
ammonia												.56				-.45	.53	
chlorophyll			.78	.71	.75	.79			-0.50	-0.54		0.46					0.52	
BOD10		0.78		.95	.89	.90			.46	-.71	.52	.63					.82	.43
BOD5		.71	.95		.93	.71			-.52	-.65	.62	.57					.71	.49
CBOD5		.75	.89	.93		.98				.62	.66	.48					.51	
CBOD10		.79	.90	.91	.98					-.60	.68						.50	
chloride												.52						
dissolved organic carbon																		
nitrate		-.50	-.46	-.52														-.47
orthophosphate		-.54	-.71	-.65	-.62	-.60									.45		-.64	
phaeophytin			.52	.62	.66	.68												
total keldahl nitrogen	.56	.46	.63	.57	.48		.52										.72	
total organic carbon																		
total phosphorus															.50			
total suspended solids										.45				.50		.71		
volatile suspended solids	-.45														.71			
NBOD10	.53	.52	.82	.71	.51	.50				-.64		.72						.69
NBOD5			.43	.49					-.47								.69	

Tidal variation

Water quality measurements were compared on each tide during the day in order to determine the impact of tidal day variation on water quality measurements. These data helped to quantify the net tidal day load and answer the questions:

> **Question**: What is the relative contribution of algal biomass from in situ growth and upstream load to oxygen demand in the Stockton Deep Water Channel (DWC)?
> **Question**: What is the oxygen demand from algal biomass compared with other oxygen demanding substances?
> **Answer**: The load of water quality variables varied among tides by a factor of 2 to 4 each day. However, because seasonal variability was also high only ebb and flood tide loads were significantly different for discrete water samples.

Discrete tidal day material export from the DWC was significantly ($p < 0.01$) higher on ebb than flood tide by at least a factor of 2 at station 43. This was true for both spring and neap tide, but there was no significant difference between spring and neap tide.

Light attenuation in water column

Algal growth rates were measured at different light intensities in order to determine the influence of light on the maximum potential for algal growth in the DWC. This is important management information because algae are light limited in the San Joaquin River and management alternatives that affect water clarity could impact algal production rate and the associated oxygen demand. This information was used in the question:

> **Question**: What mechanisms influence the impact of algal load and growth on oxygen demand?
> **Answer**: Light attenuation was an important controlling mechanism for algal growth and oxygen demand. The light in the euphotic zone averaged 18% of surface irradiance. At this low light level algal growth was limited to 25% of its maximum potential.

Method - Algal growth potential at varying light intensities was estimated by dissolved oxygen light/dark bottle incubation of water samples in open-air flow through incubators that utilized ambient surface irradiance and river water to produce the natural diel pattern of light and water temperature. Continuous pumping of water from 1-m depth through the incubator coil system maintained water temperature within 0.5 ^{o}C of ambient water temperature. Light intensity of replicate water samples was varied by a series of screens to achieve zero to 50 percent of surface irradiance. Diel changes in surface irradiance were measured with an Eppley pyroheliometer and LiCor quantum sensor.

Specific community production rates (ug oxygen / ug chl*a* / hr) measured at each light intensity were used to generate photosynthesis versus light curves for each day (Fig. VI-3). The threshold of these curves is the maximum specific production rate or assimilation ratio and indicates the maximum algal growth rate at optimum light intensity. The initial slope of the photosynthesis versus light curve (ug oxygen/ ug chla / hr / umole quanta/ m2 /s) was used to measure algal response rate to increasing light (Platt and Jassby 1976).

Results - Light severely limited algal growth in the deep water channel. Light extinction was rapid and surface irradiance usually decreased to 1% within a depth of 2-m (Fig. VI-4). Algal photosynthesis only occurs in this portion of the water column called the euphotic zone that was about 2-m throughout the season in the study reach between Turner Cut at station 24 and Rough and Ready Island near station 43 (Fig. VI-5). Maximum specific production rate generally decreased from about 20 to 5 ug oxygen/ug chlorophyll *a* / hr (Fig. VI-6) and was commonly associated with a daily average light intensity between 25 and 45% of the surface irradiance (Fig. VI-7). This optimum light intensity was well above the 18% average surface light intensity commonly measured in the euphotic zone at station 43. Both the average maximum specific production rate and initial slope of the photosynthesis versus light curve varied seasonally by a factor of 2 to 3 (Fig. VI-8), but similar initial slopes among stations suggested growth of both upstream and downstream algae were equally influenced by light limitation in the DWC.

Fig. VI-3. Characteristic photosynthesis versus average daily light intensity curve plotted for station 43 near Rough and Ready Island. Specific production rate is in units of ug oxygen/ ug chlorophyll *a* / hour.

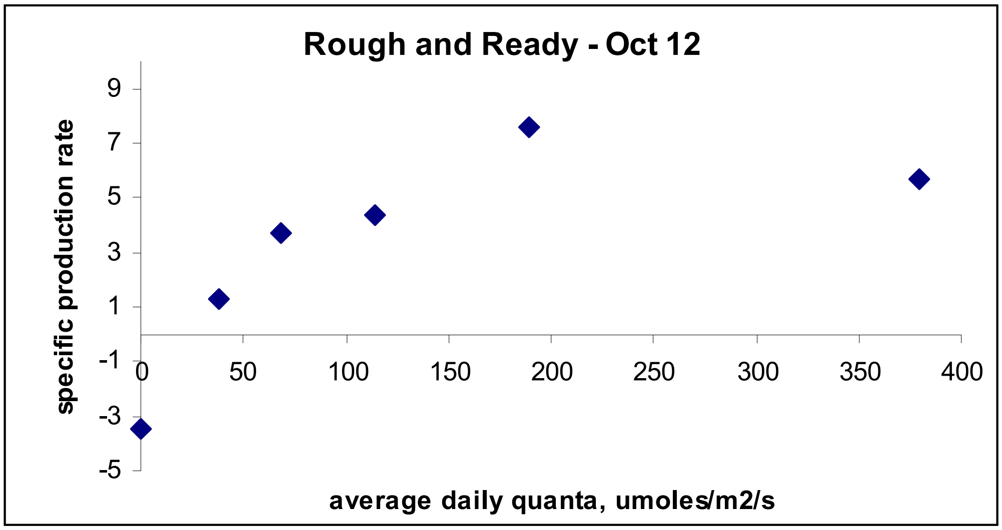


Fig. VI-4. Characteristic light extinction in the water column at station 43 at Rough and Ready Island measured on September 28, 2000.

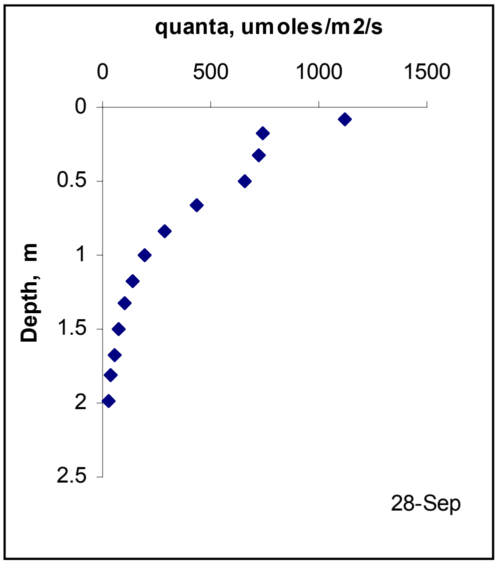


Fig. VI-5. Depth of euphotic zone or 1% surface light attenuation at station 24 near Turner Cut and station 43 near Rough and Ready Island.

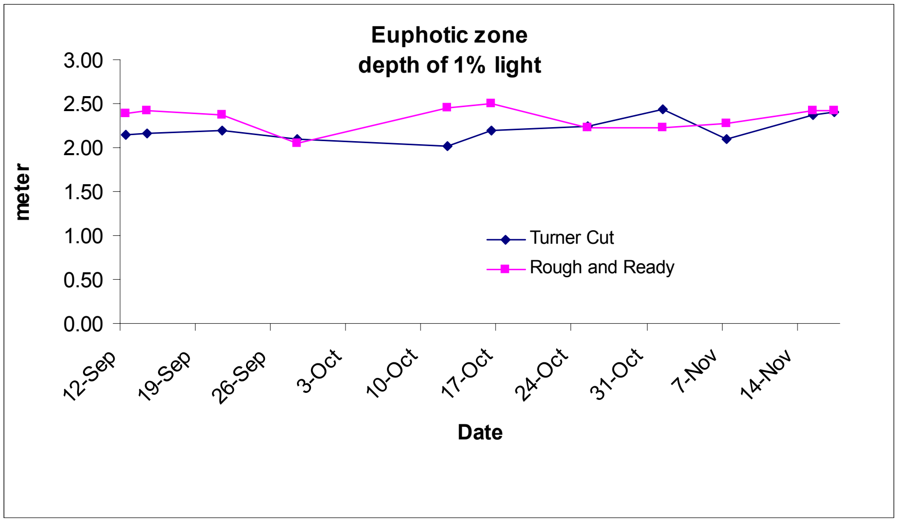


Fig. VI-6. Maximum specific production rate measured during light saturation experiments for Mossdale (MD), Channel Point (CP), Turner Cut (TC), Rough and Ready (RR) and Turning Basin (TB).

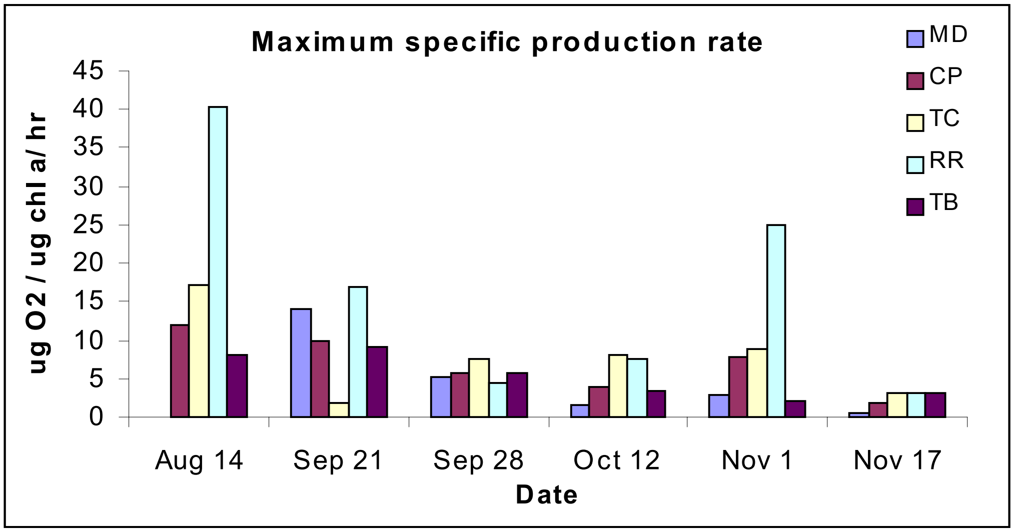


Fig. VI-7. Actual versus optimal percent surface irradiance for algal growth at station 43 near Rough and Ready Island.

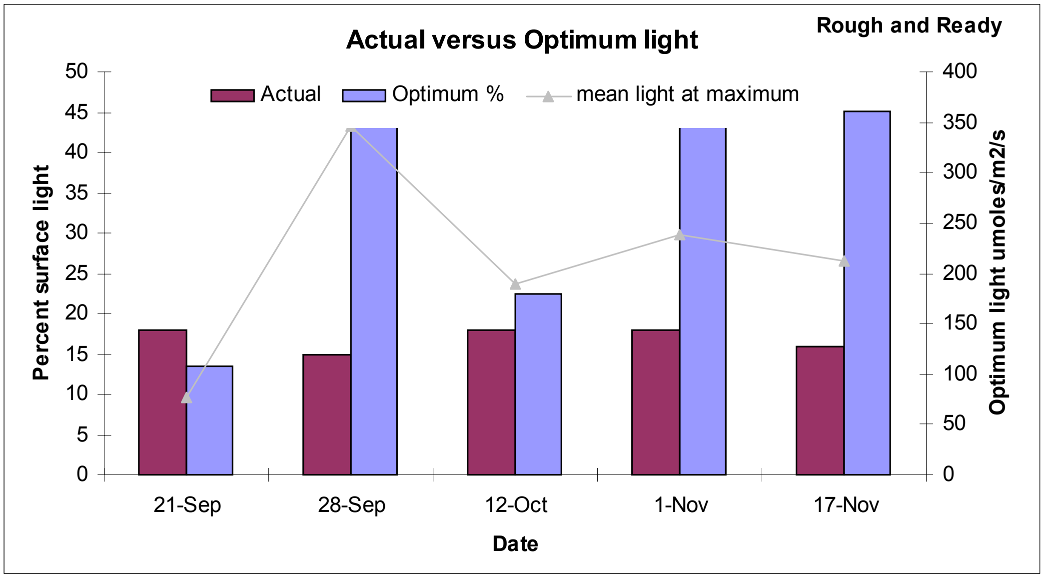
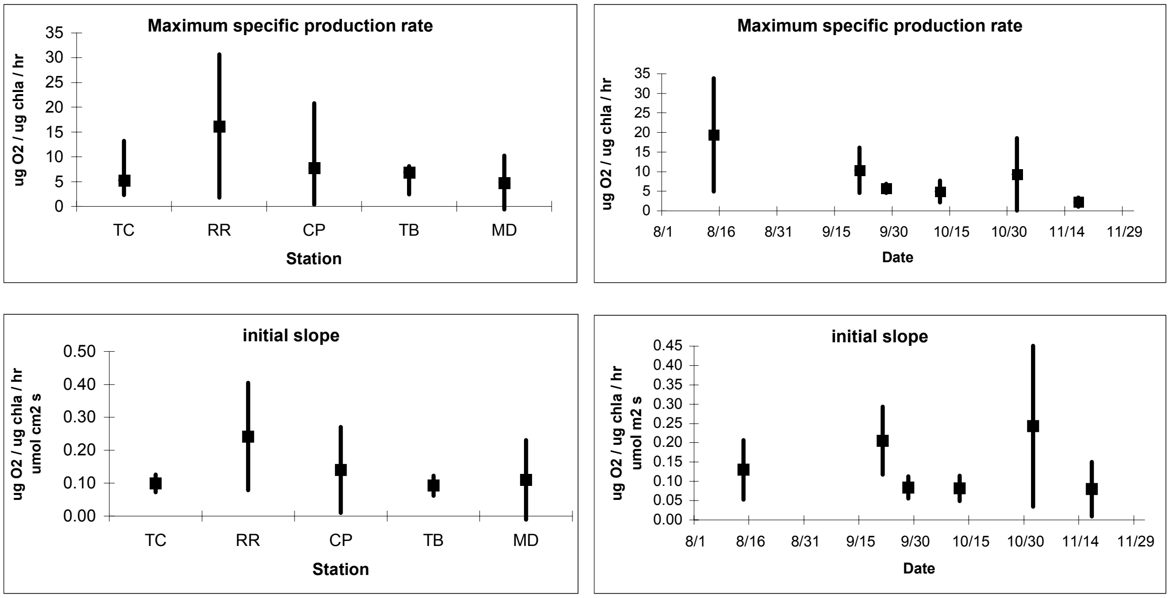


Fig. VI-8. Average maximum specific production rate and initial slopes measured during light saturation experiments for Mossdale (MD), Channel Point (CP), Turner Cut (TC), Rough and Ready (RR) and Turning Basin (TB).



Algal species composition

Spatial and temporal variation in algal species composition was used to assess whether algal species composition could be a significant factor in algal growth or oxygen demand. This study element addressed the basic question:

> **Question:** What mechanisms influence the impact of algal load and growth on oxygen demand?
> **Answer:** A highly mixed diatom community comprised the majority of algal biomass in the DWC and all adjoining stations. There was no indication that one input source controlled the algae in the DWC.

Methods

Water samples for algal species identification were collected by Van Dorn sampler and placed in a 50ml amber glass bottle with Lugol's preservative and stain. Species enumeration and identification were done using the Utermohl settling chamber technique (Utermohl 1958) and applied as described in Lehman (1996).

Results

Species composition within and outside of the DWC and was primarily composed of diatoms (Fig. VI-9). Bluegreen algae were sometimes abundant at Rough and Ready Island near station 43 in the DWC and high densities at Channel Point near station 51 suggested bluegreen algae often originated from the upper San Joaquin River. However, bluegreens contributed little to the total chlorophyll *a* biomass because their cell dimensions and associated biomass were small compared diatoms.

The species assemblage of the diatoms and bluegreens was highly mixed in the DWC and adjacent areas. High diversity occurred at Channel Point and the Turning Basin (Fig. VI-10). Common diatom species included *Achnanthes* spp., *Thalassiosira eccentrica*, *Cyclotella* spp., *Coscinodiscus* spp. and *Amphora coffaeiformis*. Abundant bluegreen species were *Anaebaena* spp., *Aphanizomenon flos-aquae*, *Agmenellum* spp. and *Oscillatoria* spp..

Species composition suggested the sources of algae in the DWC at Rough and Ready Island was highly variable. On August 14, the presence of the diatom *Aulacoseira(Melosira) granulata* at Rough and Ready Island suggested these algae were seeded from Channel Point, but the presence of the bluegreen *Agmenellum* spp. also indicated seeding from the Turning Basin at station 50 (Fig. VI-10). On August 24, the abundance of the diatoms *Achnanthes* spp. and *Amphora coffaeiformis* at all stations suggested the algae were well mixed throughout the region, but the presence of the diatom *Thalassiosira eccentrica* at Rough and Ready Island was probably caused by seeding from station 24 at Turner Cut where it was abundant (Fig. VI-11). On September 6, the diatoms *Achnanthes* spp., *Cyclotella* spp. and *Amphora coffaeiformis* were abundant at all stations, but the bluegreen algae*Oscillatoria* spp. at Rough and Ready could only have originated from Channel Point (Fig. VI-12).

Fig. VI-9. Representative percent composition by algal group among months for station 24 near Turner Cut (TC), station 43 near Rough and Ready Island (RR), station 50 near Turning Basin (TB), and station 51 upstream of Channel Point (CP).

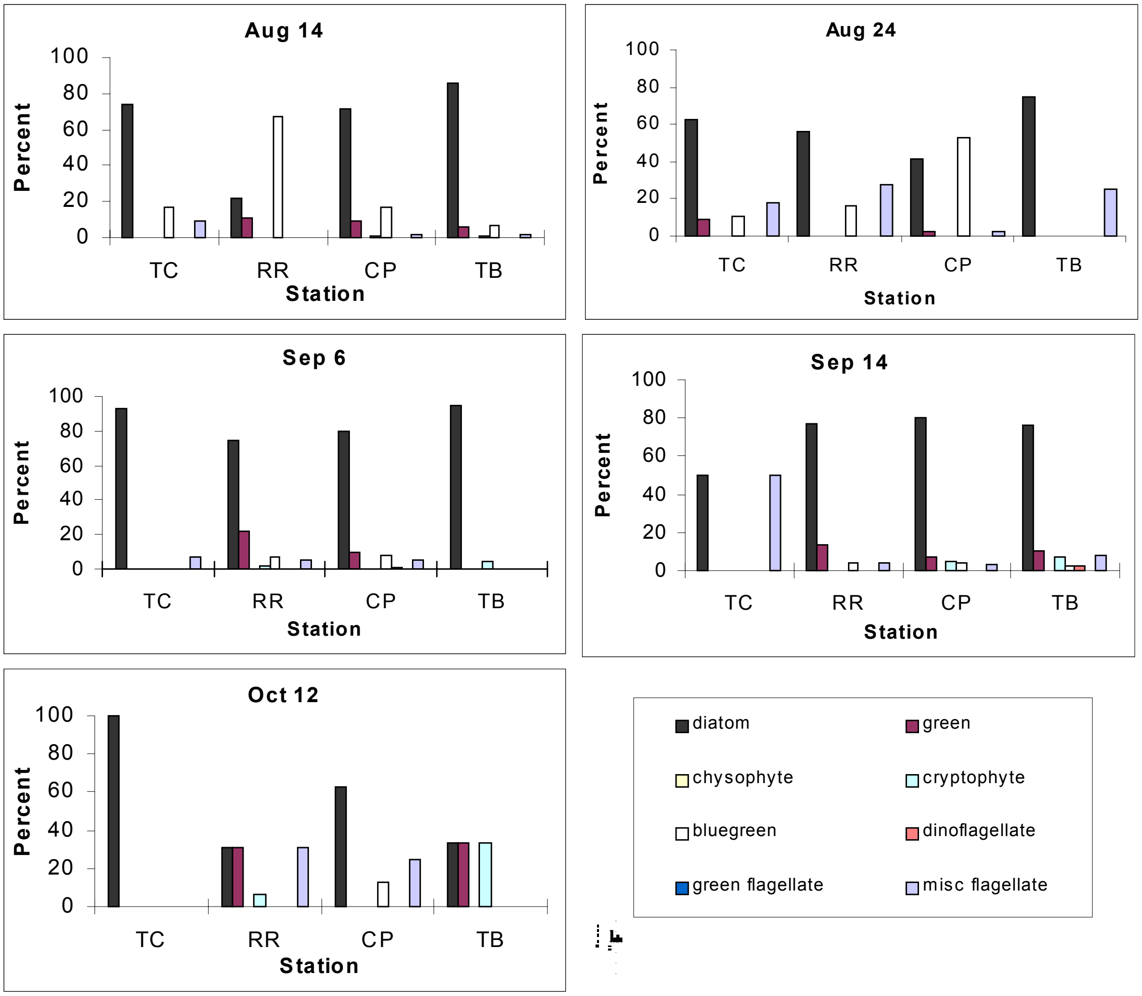


Fig. VI-10. Algal species composition measured in the DWC and adjoining stations on August 14, 2000.

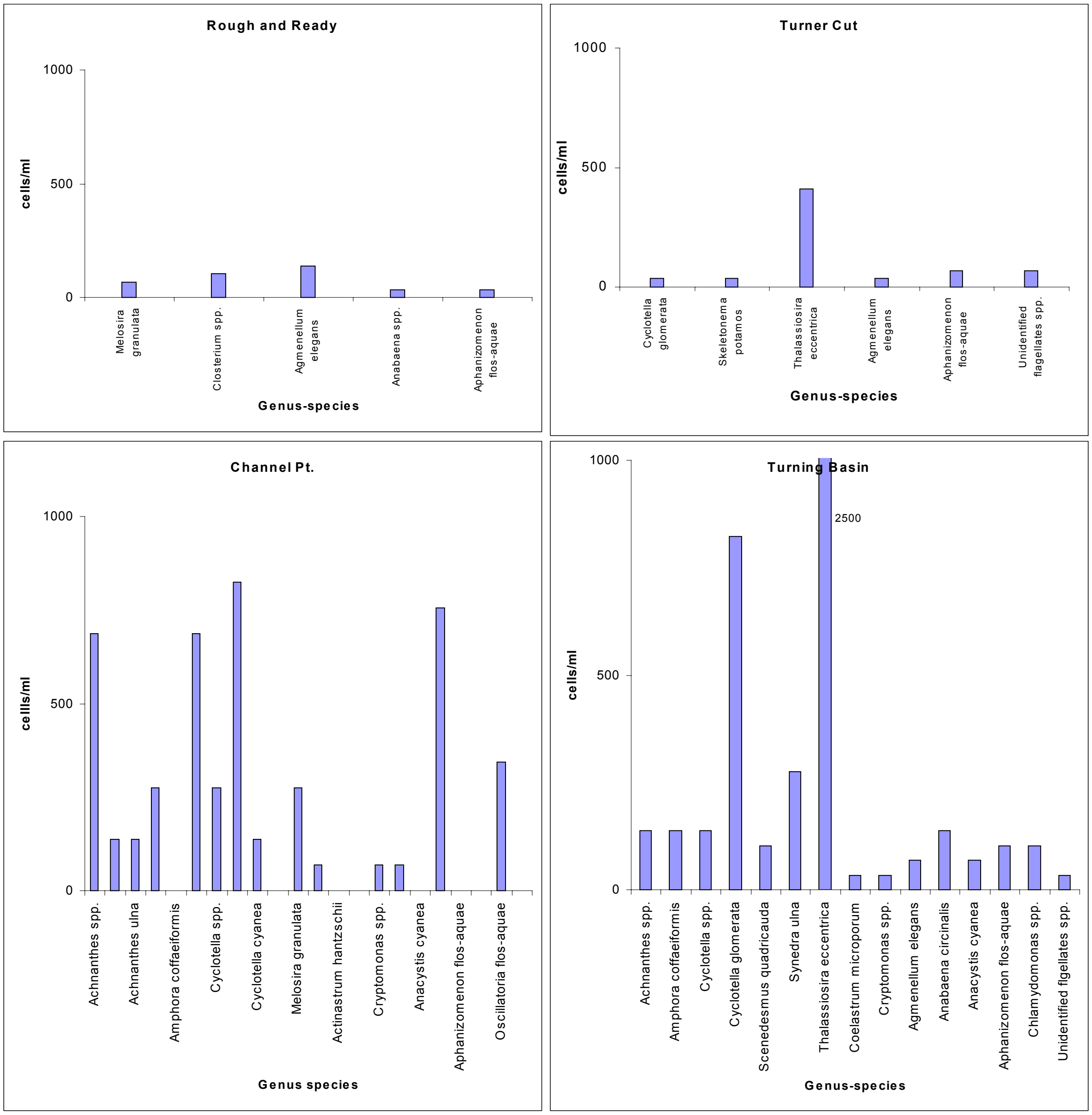


Fig. VI-11. Algal species composition and density in the DWC and input stations measured on August 24, 2000.

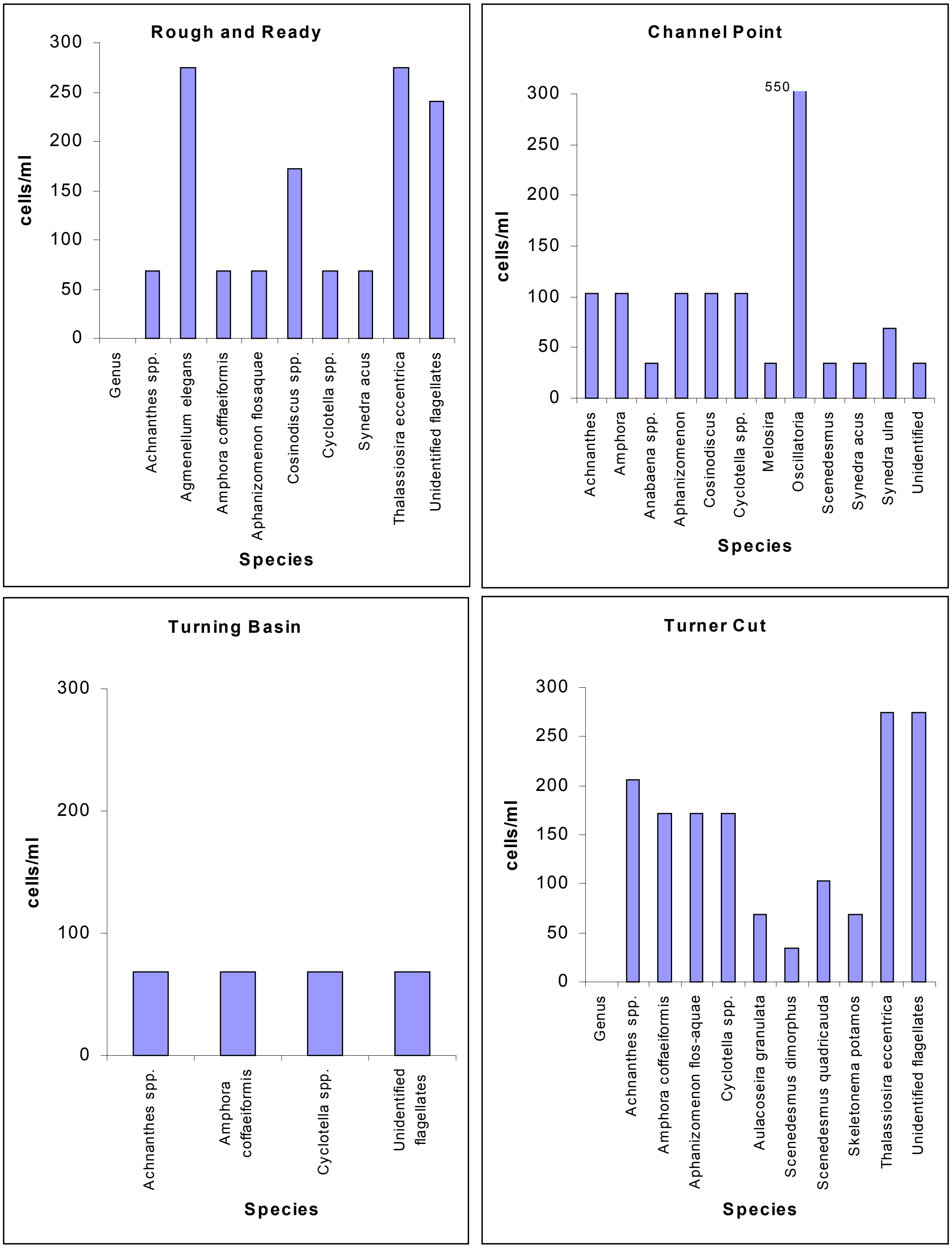
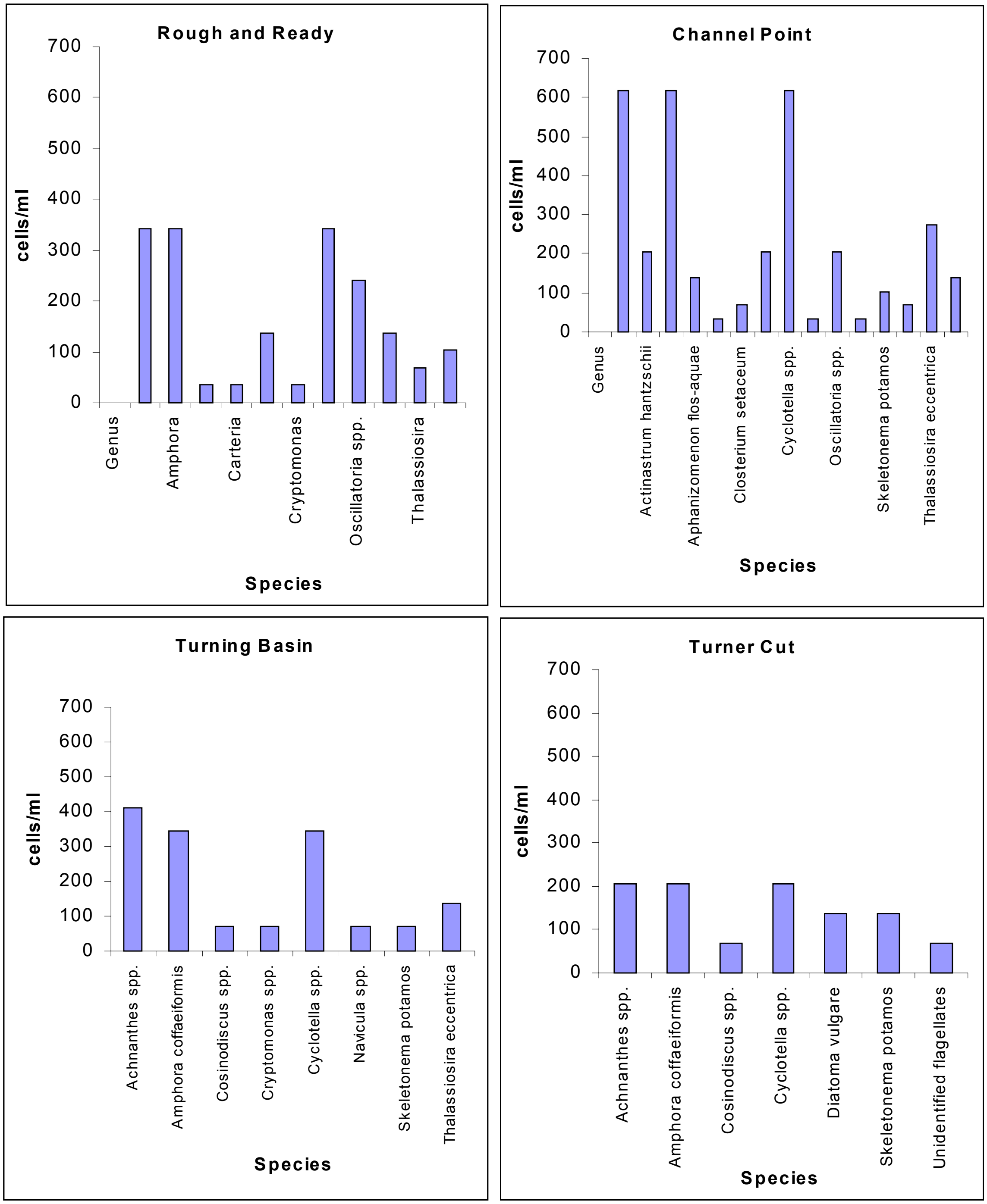


Fig. VI-12. Algal species density and composition in the DWC and nearby measured on September 6, 2000.



VII. Summary

1. New algal production was an important contributor to the oxygen demand in the DWC. Algal load from new production in the DWC could be 100 kg/day and was equivalent to the algal load from upstream during August and September.

2. Daily oxygen demand from algal biomass in the DWC was between 2 mg/L and 4 mg/L. The actual contribution of algal biomass to oxygen demand in the DWC cannot be measured accurately with the standard light/dark bottle productivity measurement because it measures a community response that includes both algal and bacterial respiration and bacterial respiration in the DWC is probably high. Calculated production rates using production and respiration equations developed for San Francisco Bay where nitrification is low suggest algal biomass contributed at most about 2 mg/L to the daily oxygen demand. This demand is small compared with the total deficit in the DWC, but may be significant when high water temperature drives saturation levels to 8 mg/L. A low oxygen demand from carbon sources was supported by carbonaceous BOD measurements that were consistently about 1-2 mg/L at all stations.

3. Nitrogenous BOD comprised most of the total 10 day BOD in the DWC. Carbonaceous BOD comprised about 30% of the total total BOD that reached 6 mg/L. The correlation coefficient between ammonia and either total BOD or nitrogenous BOD was 0.90 at Turner Cut and Rough and Ready Island in the DWC. In addition, total Kjeldahl nitrogen was significantly correlated with total BOD, but the correlation was lower than for ammonia except at Turner Cut. Total 10 day BOD was not significantly correlated with chlorophyll *a*, phaeophytin or volatile suspended solids. Even carbonaceous BOD was not significantly or poorly correlated with chlorophyll *a*, phaeophytin or volatile suspended solids. These patterns were not observed in the Turning Basin where algae comprise the majority of the organic matter and ammonia concentration is low.

   Direct application of the BOD test results to the in situ demand in the DWC requires consideration of ecosystem processes. The CBOD test is a 10 day incubation in the dark where all of the carbonaceous material is decomposed by bacteria. This is an overestimate of the carbonaceous demand in the river where algae produce oxygen through photosynthesis. In addition, all BOD tests are conducted at 20^{o}C that underestimated the oxygen demand in September when water temperature was near 25^{o}C and overestimated the oxygen demand in November when water temperature was near 15^{o}C. More effort is needed to quantify the relative importance of the carbon versus nitrogen components of the BOD at the ambient water temperature in the DWC.

4. Nitrogenous material that contributed to the nitrogenous BOD include the discharge of ammonia from the City of Stockton RWCF between September and November and non-ammonia Kjeldahl nitrogen load from upstream (the non-ammonia load does not include nitrate and nitrite). The non-ammonia nitrogenous load from upstream at Mossdale and Channel Point could be high and was sometimes many times higher than the ammonia load.

5. A potentially small contribution of algal biomass to the total oxygen demand in the DWC during 2000 was supported by historical data. Chlorophyll *a* concentration in the DWC and load from Vernalis upstream decreased by a factor of 4 over time. This suggests algal biomass may not be as important today as in the 1970s when chlorophyll *a* concentration in the DWC was over 100 ug/L.

6. The oxygen demand from algal growth was far less than maximum because the algae in the DWC and upstream are light limited by high suspended material concentration in the water column. Suspended material restricts the photic zone to the upper 2 m where algae receive only 18% of the surface irradiance and attain commomly 25 % of their maximum growth.

7. Algae from different input sources did not significantly alter the algal production rates in the DWC. The similarity of response was probably a function of the similarity of algal species composition, the presence of excess nutrient and the overriding effect of light limitation.

8. Upstream load into the DWC was poorly estimated by Vernalis or Mossdale load. Upstream algal load at station 51 near the entrance to the DWC was at times 100 kg/day to 300 kg/day lower than estimates made using Vernalis or Mossdale data. The loss of algal biomass was accompanied by loss of all suspended materials including TSS and VSS and total BOD when ammonia load was low. The cause of this material loss is unknown, but vertical settling, benthic and planktonic grazing and agricultural diversion are possible factors.

9. Seasonal average load suggest the DWC is a sink for total and volatile suspended solids and a source of algal detritus and BOD. Material in the DWC is imported on ebb tide from upstream and the retention of material despite tidal exchange may be due to high residence time and rapid settling.

10. Discrete and continuous monitoring systems demonstrated the relatively good dissolved oxygen conditions in the DWC during 2000 a cool-wet year compared with 1999 a warm-dry year. Dissolved oxygen concentration decreased to below the 5 mg/L and 6 mg/L standard only in August and September in a small section of the study reach and vertical stratification was weak. In contrast dissolved oxygen concentration was below 5 mg/L from Disappointment Slough to the Turning Basin and was characterized by a strong vertical gradient for most of fall 1999. The lower dissolved oxygen concentration in 1999 than 2000 was probably a function of a suite of factors. Algal biomass and ammonia concentration were

somewhat higher in 1999 and were accompanied by 2-3°C higher sustained water temperature that combined exerted a greater oxygen demand on the river.

11. The enhanced continuous monitoring program was a valuable tool for determining the spatial and temporal variation of dissolved oxygen and direct sources of oxygen demand. Continuous monitoring demonstrated a 4 mg/L diel variation in dissolved oxygen concentration that could affect compliance with standards and a higher frequency of dissolved oxygen depression than obtained by infrequent mid-day shipboard sampling by the DWR Channel Program. Continuous monitoring was also able to verify the absence of direct oxygen demand from upstream where dissolved oxygen concentrations were continually saturated despite high algal biomass. Bottom monitors verified that dissolved oxygen concentration could be below standard near the bottom but not at the surface but confirmed the absence of a severe oxygen depression during the night.

VIII. Recommendations

1. Considerable effort is needed in 2001 to quantify the sources, nature and contribution of nitrogenous sources to the oxygen demand in the DWC. BOD tests suggest at least half to two thirds of the total 10day BOD in the DWC during 2000 was nitrogenous BOD. BOD tests should include dissolved BOD in order to separate the dissolved from particulate nitrogen sources. Additional nitrogenous load measurements are needed at upstream stations in order to quantify upstream ammonia and non-ammonia Kjeldahl nitrogen load. In addition, the oxygen demand from algal growth versus nitrifying bacteria should be partitioned in light/dark bottle community growth rate studies using isotopes.

2. Below standard dissolved oxygen concentration also occurs early in June. Considerable effort is needed to determine the cause of this early season oxygen demand and if there is any carry over effect later in the fall. This will require starting the sampling program sometime in June.

3. Tidal studies in 2000 demonstrated the high variability of tidal day material load. More frequent discrete tidal day measurements are needed to produce more reliable estimates of mass balance for variables that cannot be measured with continuous monitors.

4. Considerable effort is needed to determine the magnitude and mechanisms associated with the load shift between Vernalis, a station used to represent upstream load, and the DWC. Additional information is needed on the loss of algal biomass and turbidity measured by the continuous monitors as well as new information on loss due to settling, grazing and local agricultural pumping between Vernalis, Mossdale and the DWC.

5. Information is needed on the influence of water-year type on sources and mechanisms that affect oxygen demand. The 2000 sampling program should at least be repeated in a dry or critically-dry year.

6. High daily variability in the material load and water quality conditions also suggest a year or two of measurements are inadequate to properly quantify material load and water column processes. A long-term program should be developed that will build such a data set.

7. The continuous monitoring network established in 2000 provided detailed information on the nature of the oxygen depletion and this network should be continued and perhaps enhanced in the future. The full use of the monitoring network could not be assessed in 2000 because the focus was on establishing the network grid and water conditions were fairly uniform during this wet year. The

network should be operated in future years, particularly during dry and critically-dry years.

IX. Citations

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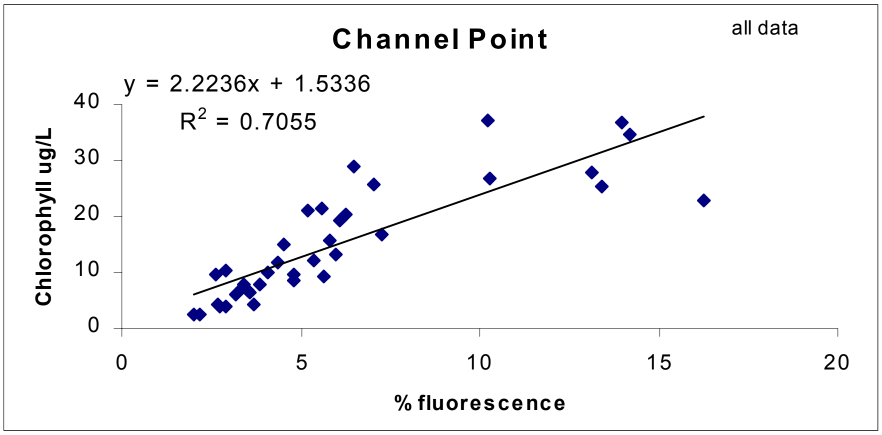
X. Appendix A

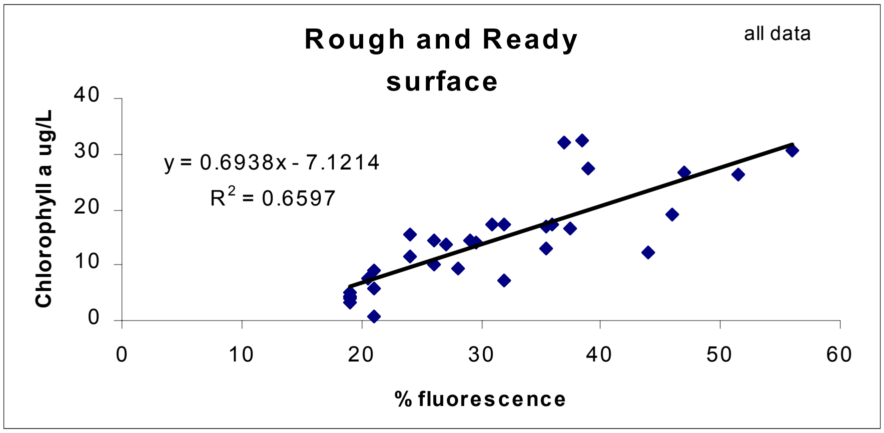
Methods used for water quality analyses

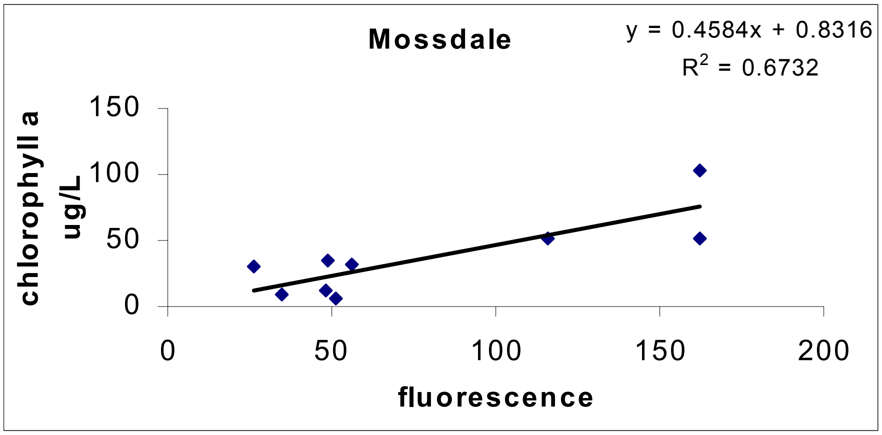
DWR San Joaquin Dissolved Oxygen Study Methods

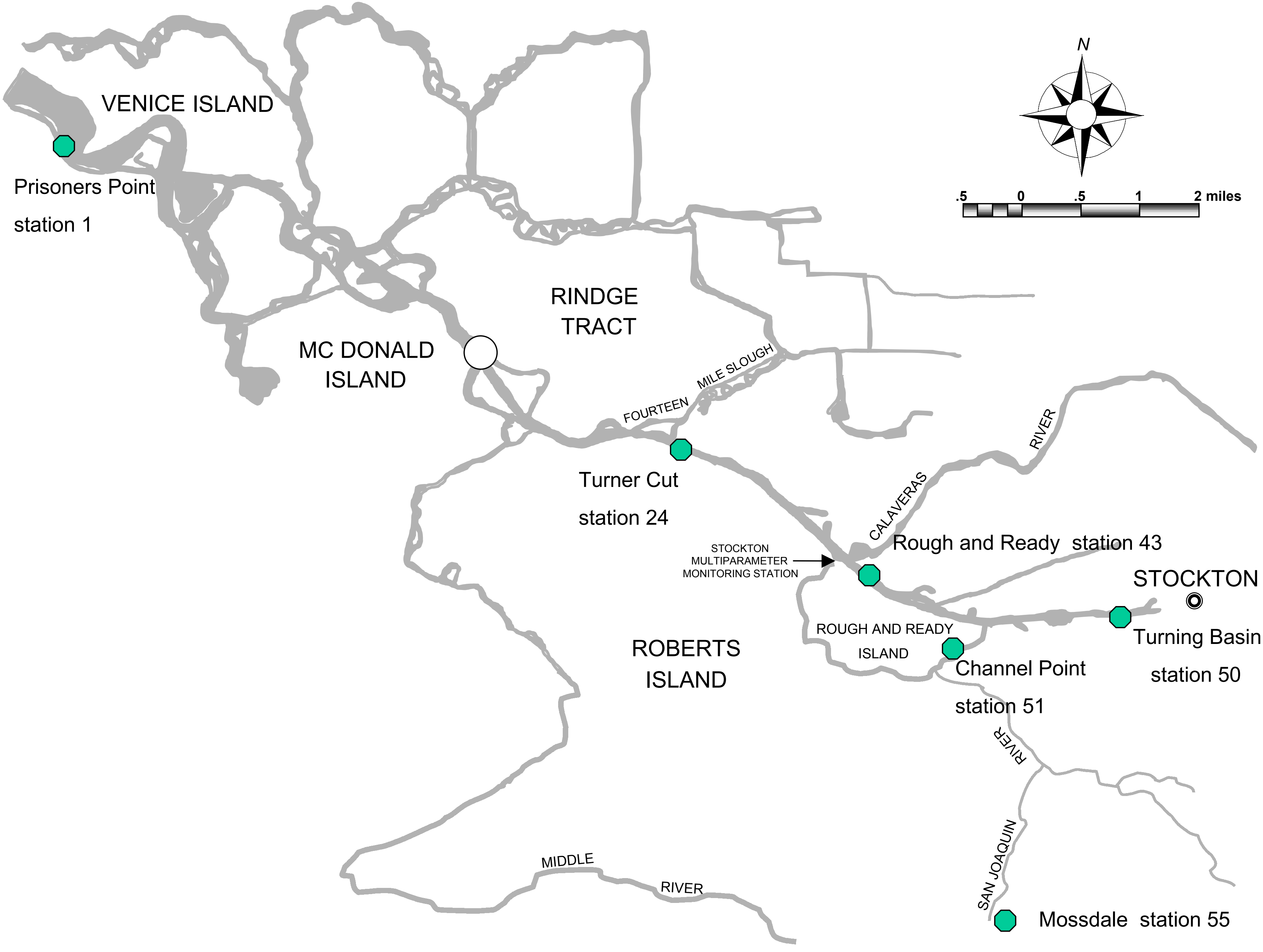
Label:	Method	Size	Preservative	Handling	Container Note:	Reporting Limit	Note
Dissolved Organic Carbon	EPA 415.1 (D), Organic Carbon (Dissolved)	40 ml Vial	H2PO4, pH <2	Ice, 4° C	Do Not Overfill. Vial Contains Acid.	0.10	
Total Organic Carbon	EPA 415.1 (T), Organic Carbon (Total)	40 ml Vial	H2PO4, pH <2	Ice, 4° C	Do Not Overfill. Vial Contains Acid.	0.10	
Chlorophyll a and Phaeophytin	Std Method 10200 H, Spectrometric Determination of Chlorophyll & Phaeophytin			Frozen, Dry Ice	Freeze Immediately	0.05	
Chloride	EPA 325.2, Chloride	1 Pint		Ice, 4° C		1.00	
Nitrate + Nitrite	Std Method 4500-NO3-F Modified, Nitrite, Nitrate (DWR Modified) (Dissolved)	1/2 Pint		Ice, 4° C	Freeze if held more than 24 Hrs.	0.01	
Total Kjeldahl Nitrogen	EPA 351.2, Kjeldahl Nitrogen	1/2 Pint		Ice, 4° C	Freeze if held more than 24 Hrs.	0.10	
Total Suspended Solids	EPA 160.2, Total Suspended Solids	1 Quart		Ice, 4° C	Freeze if held more than 24 Hrs.	1.00	
Volatile Suspended Solids	EPA 160.4, Volatile Suspended Solids	1 Quart		Ice, 4° C		1.00	
Total Phosphorus	EPA 365.4, Phosphorus (Total)	1/2 Pint		Ice, 4° C		0.01	
Ammonia	EPA 350.1, Ammonia, Nitrogen (Dissolved)	1/2 Pint		Ice, 4° C	Freeze if held more than 24 Hrs.	0.01	
Orthophosphate	EPA 365.1 (DWR Modified), DWR Othro-Phosphate (Dissolved)	1/2 Pint		Ice, 4° C	Freeze if held more than 24 Hrs.	0.01	
Biochemical Oxygen Demand	Std Method 5210B	1/2 gal		Ice, 4° C		1.00	
Carbonaceous Biochemical Oxygen Demand	Std Method 5210B	1/2 gal		Ice, 4° C		1.00	Hach Powder # 253; 0.16g/300ml (inhibitor)

Appendix B. Calibration curves for chlorophyll *a* measured by YSI 6600 fluorometers and DWR continuous monitors.





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MC DONALD
ISLAND
FOURTEEN MILE SLOUGH
Turner Cut
station 24
RIVER
CALAVERAS
Rough and Ready station 43
STOCKTON
MULTIPARAMETER
MONITORING STATION
STOCKTON
ROUGH AND READY
ISLAND
Turning Basin
station 50
Channel Point
station 51
ROBERTS
ISLAND
RIVER
SAN JOAQUIN
MIDDLE
RIVER
Mossdale station 55