Sources of Oxygen demand in the San Joaquin River Deep Water Channel, fall 2001

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Report to

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Executive Summary

INTRODUCTION

This report describes the results of research conducted to determine the sources and causes of oxygen demand in the San Joaquin River Deep Water Channel (DWC) downstream of Stockton during the summer and fall of 2001. The research was funded by a CALFED Directed Action grant and was a continuation of CALFED Category III funding in 2000. The information from this research is needed by CALFED, the public, government agencies, and San Joaquin River stakeholders to determine the cause of oxygen depletion to below the US EPA water quality criteria of 5 mg/L in the river and develop management plans to eliminate the problem.

The research was designed to address the following questions:

- What was the spatial and temporal variation of dissolved oxygen and associated water quality variables in the DWC during 2001?
- What was the contribution of plankton production rate compared with other local and upstream sources to oxygen demand in the DWC?
- What mechanisms influenced oxygen demand in the DWC?

WATER QUALITY

Dissolved oxygen concentration frequently decreased to 3 mg/L and was commonly below the U. S. EPA water quality criteria of 5 mg/L throughout the summer and fall of 2001 in the DWC near Rough and Ready Island. Dissolved oxygen concentration was also frequently below the 6 mg/L standard for September through November set by the State of California Regional Water Quality Control Board Basin Protection Plan to protect fall run Chinook salmon. Dissolved oxygen concentration was lowest near the bottom and not usually associated with water temperature or salinity stratification. Dissolved oxygen concentration was relatively lower in the dry year 2001 than the wet year 2000 and demonstrated the high intraannual variability of this water quality problem that is produced by both diel and seasonal variation.

Oxygen demand in the DWC was strongly influenced by the net plankton production rate. Net plankton production rate measured the net growth of algae and bacteria and was sufficient to remove an average of 0.26 mg/L oxygen per day in the water column in the DWC between Turner Cut and Navigation Light 48 throughout the summer and fall. Most of this oxygen loss was caused by respiration of nitrifying bacteria. The loss of oxygen through plankton respiration was reduced by the production of oxygen by algal photosynthesis that often caused a small net gain of oxygen in the water column over the course of the day. The growth of algae and the resulting oxygen production was limited by high turbidity and a shallow mixing zone that restricted algal growth to the top 2 m of the water column where only 20% of the surface irradiance was available for photosynthesis. Algal growth in the photic zone increased the new algal biomass in the DWC by an average of 96 kg chlorophyll *a* /day. This was less than the average net chlorophyll *a* load at CP of 43 kg/d.

Nitrogenous biochemical oxygen demand (NBOD) was the primary cause of oxygen depletion in the DWC and produced from 50% to 80% of the total oxygen demand in the DWC. NBOD was strongly correlated with dissolved ammonia concentration (r = 0.78; 103 d.f.) that averaged 0.4 mg/L and reached as high as 1 mg/L. Dissolved ammonia concentration also accounted for 60% of the variation in biochemical oxygen demand (BOD) in stepwise multiple regression models. This was twice as much as the variation accounted for by carbonaceous BOD.

The Stockton Regional Water Treatment Control Facility (RWCF) discharge and upstream organic nitrogen load were two major sources of the dissolved ammonia in the DWC. Dissolved ammonia concentration was produced directly through dissolved ammonia load and indirectly through the oxidation of organic nitrogen. The strong correlation between the dissolved ammonia load from the RWCF and ammonia concentration and NBOD in the DWC compared with weak correlation for the organic nitrogen from upstream suggested the RWCF was a significant contributor to dissolved ammonia concentration in the DWC. Further evaluation of the source loads using a mass balance model indicated that the dissolved ammonia discharge from the RWCF could contribute a significant percentage of the dissolved ammonia in the DWC for residence times up to 25 days. This was true even though the total nitrogenous load from upstream was much higher than from the RWCF because the decay rate of the large upstream organic nitrogen load to dissolved ammonia was slow and most of the organic nitrogen was already highly decomposed. The relative contribution of the RWCF and upstream nonpoint load was a function of the total load, load composition, ammonification rate and residence time. Therefore either source could drive the oxygen demand on any given day.

ENVIRONMENTAL FACTORS

The magnitude of the oxygen demand in the DWC was influenced by many environmental factors. Light limitation in the DWC strongly reduced the influence of algal production rate on oxygen availability. High suspended sediment concentration restricted light penetration to the upper 2 m where only about 20% of the surface irradiance is available for photosynthesis. These low light levels reduced the photosynthetic potential of algae and restricted oxygenation from photosynthesis that attain maximum rates of photosynthesis near 50% of surface irradiance. Unlike many aquatic environments, algal growth was not limited by macronutrients such as dissolved inorganic nitrogen, orthophosphate and silicate that were an order of magnitude higher than limiting levels.

Net tidal transport was another major environmental factor that affected oxygen demand in the DWC. The retention time of the upstream organic and inorganic load into the DWC was often long because of rapid settling rate, slow downstream transport and slow net transport rate nearer the bottom than surface. High retention rate of both particulate and dissolved substances allowed oxidation of these substances in the DWC and the associated oxygen demand.

The oxygen demand potential of the upstream load was an important component of the oxygen demand in the DWC. A decrease in carbon to nitrogen molar ratios, increase in phaeophytin concentration, decrease in chlorophyll *a* concentration and change in algal species composition between upstream and downstream stations suggested the composition of the organic load between Mossdale and the DWC was often transformed to more oxidized material with less oxygen demand as it moved downstream. The magnitude and seasonal variability of this oxidation in relation to environmental factors is still unknown. Potential contributing factors include high respiration rate, settling, and zooplankton or benthic herbivory, turbidity, water temperature, salinity and algal species composition.

RECOMMENDATIONS

Additional research is needed to quantify the relative contribution of the dissolved ammonia discharge from the RWCF and other local and upstream loads of carbonaceous and nitrogenous substances to oxygen demand in the DWC. This will require additional measurements of the ammonification rate of the various organic nitrogen sources that enter the DWC and nitrification rates of ammonia in the DWC. Further information is also needed on the variation of ammonification and nitrification rate of these loads with ambient environmental conditions including water temperature, salinity and light. These oxidation processes need to be evaluated on a real-time basis and will require more intensive field measurements of the daily magnitude and composition of the upstream load. It may also require real-time testing of the influence of different oxygen demanding loads on dissolved oxygen concentration in the DWC through controlled field experiments that remove the load from selected sources for extended periods of time.

Quantification of the relative contribution of RWCF and upstream load will require accurate information on the net downstream transport of oxygen demanding material from upstream of the DWC. A primary goal should be to obtain accurate information on the downstream transport of oxygen demanding material between Mossdale and the DWC and the oxygen demand potential of this material compared with local sources. Local sources include the RWCF and Turning Basin. Accurate information is also needed on how much of the oxygen demanding material at Mossdale is transferred from sources farther upstream.

More information is needed to quantifying the potential contribution of in situ algal photosynthesis to oxygen availability in the DWC. This will require additional information on the relative contribution of algal and bacterial respiration to the net plankton production rate of oxygen and how this varies with environmental conditions such as day length, water temperature, turbidity, photic zone depth and vertical mixing. This information is vital to development of successful management alternatives that will not inhibit the positive contribution of algal growth rate processes to oxygen concentration in the DWC.

Dissolved oxygen concentration demonstrated high variability on diel, seasonal and interannual time scales. Understanding this variability in relation to causal factors including residence time, water temperature, turbidity, algal growth rate, algal species composition, load composition and tidal transport will be important to an evaluation the existing conceptual model and efficacy of management alternatives and management models. Additional continuous monitoring stations and more thorough analysis of existing continuous monitoring data are needed to fully characterize the dissolved oxygen problem and evaluate controlling mechanisms.

Three years of specialized data and a 30-year record of water quality monitoring data in the San Joaquin River provide a wealth of information from which to examine mechanisms and management alternatives. The accelerated schedule of the 1999 to 2001 research program provided little time to examine the new data in relation to historical data or to fully integrate the new data from the various research projects. More resources should be allocated to further analysis of the existing data before collection of new data begins.

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Table of Contents

II. Water quality conditions

III. Sources of oxygen demand

IV. Environmental factors

List of Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
aphotic zone	portion of water column where the percentage of the surface irradiance is less than 1%
BOD, BOD10	10-day biochemical oxygen demand
BOD5	5-day biochemical oxygen demand
CALFED	CALFED Bay Delta Program
CBOD5	5-day carbonaceous oxygen demand
CBOD, CBOD10	10-day carbonaceous BOD
CL	Crows Landing sampling station
chlorophyll *a*	photosynthetic pigment that estimates algal biomass
CP	Channel Point sampling station at Rough and Ready Island highway bridge
DOC	Dissolved organic carbon
DWC	Deep Water Ship Channel
L48	Navigation Light 48 sampling station
MD	Mossdale sampling station
NBOD	nitrogenous biochemical oxygen demand
organic nitrogen	total Kjeldahl nitrogen minus dissolved ammonia concentration
ortho-P	ortho-phosphate or soluble reactive phosphorus
photic zone	portion of water column where light exceeds 1% of the surface irradiance
RR	Rough and Ready sampling station
RWCF	Stockton Regional Waste Water Control Facility
TC	Turner Cut sampling station
TMDL	Total Maximum Daily Load
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
TSS	Total suspended solids
TB	Turning Basin sampling station
VN	Vernalis sampling station
VSS	Volatile suspended solids

List of Tables

List of Figures

Fig. III-3. Mean and standard deviation of net plankton production rate in the photic zone for stations in the San Joaquin River.

Fig. III-4. Mean and standard deviation of plankton respiration rate measured at stations in the San Joaquin River.

Fig. III-5. Mean and standard deviation of net plankton production rate normalized to chlorophyll *a* concentration at stations in the San Joaquin River. Stations as in Fig. III-3.

Fig. III-6 a. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Turner Cut.

Fig. III-6 b. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Rough and Ready Island.

Fig. III-6 c. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Navigation Light 48.

Fig. III-6 d. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Turning Basin.

Fig. III-6 e. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Channel Point.

Fig. III-6 f. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Mossdale.

Fig. III-6 g. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Vernalis.

Fig. III-6 h. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Crows Landing.

Fig. III-7. Comparison of ammonia load from the RWCF and ammonia concentration at Channel Point and Rough and Ready Island in 2001.

Fig. III-8. Comparison of ammonia load from the Regional Water Treatment Control Facility and NBOD at Rough and Ready Island.

Fig. III-9. Comparison of the potential oxygen demand from nitrification of ammonia and organic nitrogen concentration in the Deep Water Channel.

Fig. III-10. Comparison of ammonia concentration (a) and nitrogenous BOD (b) in the Deep Water Channel at Rough and Ready Island and organic nitrogen load from upstream at Channel Point.

Fig. III-11 a. Concentration of water quality variables measured at stations in the San Joaquin River on June 26, 2001.

Fig. III-11 b. Concentration of water quality variables measured at stations in the San Joaquin River on July 18, 2001.

Fig. III-11 c. Concentration of water quality variables measured at stations in the San Joaquin River on August 18, 2001.

Fig. III-11 d. Concentration of water quality variables measured at stations in the San Joaquin River on September 14, 2001.

Fig. III-11 e. Concentration of water quality variables measured at stations in the San Joaquin River on October 3, 2001.

Fig. III-12. Total organic carbon to total organic nitrogen molar ratios by station and date.

Fig. III-13. Percent contribution of algal biomass to total carbon and organic nitrogen measured in the Deep Water Channel.

Fig. IV-1. Laboratory measurements of the oxidation of chlorophyll *a* concentration and the associated increase in ammonia concentration measured at 5-day intervals for 30 days. Measurements were made at 20°C.

Fig. IV-2. Percentage of the organic nitrogen load from upstream at Mossdale comprised of chlorophyll *a* concentration in 2001.

Fig. IV-3. Average percent surface irradiance and depth of the photic zone at sampling stations in the San Joaquin River.

Fig. IV-4. Net plankton production rate measured at different daily average light intensity by station on September 5, 2001.

Fig. IV-5. Median plus 25 and 75 percent quartiles of dissolved inorganic nitrogen and orthophosphate concentration at each sampling station in the San Joaquin River.

Fig. IV-6. Water quality variables measured on ebb and flood tide near mid-depth at Channel Point.

Fig. IV-7 a. Water quality variables measured on ebb and flood tide at 1 m depth for Rough and Ready Island.

Fig. IV-7 b. Water quality variables measured on ebb and flood tide at 1 m from the bottom for Rough and Ready Island.

Fig. IV-8. Tidal day load measured at Channel Point near mid-depth in 2001.

Fig. IV-9. Net tidal day flow at Rough and Ready Island.

Fig. IV-10 a. Tidal day load of water quality variables at 1 m depth for Rough and Ready Island.

Fig. IV-10 b. Tidal day load of water quality variables at 1 m from the bottom for Rough and Ready Island.

Fig. IV- 11. Comparison of chlorophyll *a* concentration measured at Mossdale and Channel Point in 2001.

Fig. IV-12 a. Algal species carbon among stations on July 18 for Turner Cut (TC), Rough and Ready Is. (TC), Light 48 (L48), Turning Basin (TB), Channel Point (CP), Mossdale (MD), Vernalis (V) and Crows Landing (CL).

Fig. IV-12 b. Algal species carbon among stations on August 16. Stations are listed in IV-12 a.

Fig. IV-12 c. Algal species carbon among stations on August 29. Stations are listed in IV-12 a.

Fig. IV-12 d. Algal species carbon among stations on September 14. Stations are listed in IV-12 a.

I. Introduction

OVERVIEW

Dissolved oxygen concentration below 5 mg/L has occurred in the 10-mile reach of the San Joaquin River Deep Water Channel (DWC) below the city of Stockton from 20 to 60 percent of the time over the past 30 years during the summer and fall (Lehman and Ralston 2000). Because dissolved oxygen concentration below 5 mg/L violated the U. S. EPA national water quality criteria for ecosystem health, the DWC was placed on the Clean Water Act 303d list of impaired water bodies. In addition, research by the Department of Fish and Game in 1970 (Hallock et al. 1970) suggested dissolved oxygen concentration less than 6 mg/L may adversely impact upstream migration of fall run Chinook salmon, and endangered species. As a result, the California Central Valley Regional Water Quality Control Board set an additional dissolved oxygen standard of 6 mg/L between September and November for the protection of Chinook salmon.

In 1998, representatives of the environmental community served the U.S. EPA with an intent to sue because the dissolved oxygen condition in the DWC had not been eliminated despite the 303d listing. The U. S. EPA then set December 2002 as the deadline for completion of an allocation of responsibility or TMDL (total maximum daily load) and implementation plan by the California Central Valley Regional Water Quality Control Board. As a part of this process, San Joaquin River stakeholders decided it was in their best interest to develop the allocation of responsibility 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 DWC and assist development of management models and solution alternatives. These needs lead to locally funded research in 1999 and CALFED Bay-Delta Ecosystem Restoration Program funded research in 2000 and 2001.

This report summarizes research conducted in 2001 by the California Department of Water Resources to determine the sources of oxygen demand in the DWC between July and October 2001 and was an extension of similar research done in 1999 and 2000.

The research was designed to address the following questions:

- What was the spatial and temporal variation of dissolved oxygen and associated water quality variables in the DWC during 2001?
- What was the contribution of plankton production rate compared with other sources to oxygen demand in the DWC?
- What mechanisms influence oxygen demand in the DWC?

CONCEPTUAL MODEL

The low dissolved oxygen in the DWC was hypothesized to be caused by five factors including the small surface to volume ratio of the DWC, load of oxygen demanding substances from the Stockton RWCF, load of oxygen demanding substances from the upper San Joaquin River watershed, low streamflow and summertime environmental conditions (Bain and Pierce 1968; Brown and Caldwell 1970). Recent analyses suggested the causes have not changed since the 1960s (U. S. ACE 1988; Lee and Jones-Lee 2003).

However, a long-term decrease in algal biomass in the DWC and concurrent decrease in algal load from upstream suggested these hypotheses were not based on similar oxygen demand conditions. Average chlorophyll *a* concentration was 100 ug/L in the DWC (Lehman 1990; 1996a, b; Lehman et al. 2001) and two times 2 higher upstream in the 1970s (Lehman et al. 2001). This high algal biomass supported the early hypothesis that algal biomass was a significant factor controlling the long-term pattern of low dissolved oxygen concentration in the summer and fall in the 1970s. However, the factor of 4 decrease in chlorophyll *a* concentration in the DWC and upstream since 1970 (Lehman 1992) suggested algal biomass may be less important to oxygen demand today than historically.

A pilot study in 1999 indicated low dissolved oxygen concentration was common in the DWC and had a wider geographical range than previously measured. In addition, NBOD transport from upstream was identified as a larger source of oxygen demand in the DWC than CBOD from algal biomass (Lehman and Ralston 2000).

Research in 2000 again identified the primary source of oxygen demand in the DWC as nitrogenous (Lehman et al. 2001; Litton and Nikaido 2001) and a strong associated between BOD in the DWC and dissolved ammonia concentration (Lehman et al. 2001). Sources of dissolved ammonia included direct load of dissolved ammonia and the oxidation of organic nitrogen from both the RWCF and nonpoint sources upstream. However, the largest potential nitrogenous source was identified as the oxidation of organic nitrogen from nonpoint sources upstream.

This report describes research conducted in the summer and fall of 2001 to further quantify the source and cause of oxygen depletion in the lower San Joaquin River DWC. Continuous and discrete monitoring was used to characterize the dissolved oxygen concentration and associated water quality conditions in the DWC. Field and laboratory studies were conducted to determine the daily contribution of algal growth in the DWC to oxygen demand compared with the load of carbonaceous and nitrogenous oxygen demanding substances from local and upstream sources. Statistical and mass balance models were used to quantify the relative contribution of local and upstream sources to oxygen demand. This research provided a third year of information and second year of intensive field sampling needed to assess the relative contribution and variability of local and imported sources of organic and inorganic substances and environmental conditions on oxygen demand in the DWC.

This research was funded by a CALFED Bay-Delta Ecosystem Restoration Program research grant.

II. WATER QUALITY CONDITIONS

INTRODUCTION

Water quality conditions associated with the low dissolved oxygen concentration in the DWC and nearby locations were characterized by discrete and continuous water quality monitoring in the summer and fall of 2001. Sampling was conducted in the lower San Joaquin River downstream of the City of Stockton at four stations: Turner Cut near Navigation Light 24 (TC), Navigation Light 43 near Rough and Ready Island (RR), Navigation Light 48 near Channel Point (L48) and the Turning Basin (TB) (Fig. II-1). Upstream water quality conditions were monitored at four stations in the San Joaquin River upstream of the DWC: at the Rough and Ready Island highway bridge just upstream of Channel Point (CP), Mossdale (MD), Vernalis (VN) and Crows Landing (CL).

CONTINUOUS WATER QUALITY PROFILES

Introduction - Continuous monitors measured dissolved oxygen concentration and related water quality variables in the DWC and at upstream stations throughout the summer and fall. These data were used to describe the magnitude and variability of the dissolved oxygen problem and its relation to water quality variables.

Methods_- Continuous water quality monitoring was conducted at 1 m depth at stations TC, RR, TB, CP and MD (Fig. II-1). Water quality measurements were taken with two types of continuous monitoring systems. At stations RR and MD, measurements were made with a Schneider multi-parameter water quality monitoring system. This monitoring is part of the long-term continuous monitoring program operated by the California Department of Water Resources (DWR) and 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*.

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 at URL: http:// **iep.water.ca.gov** under DWR continuous water quality monitoring.

The permanent DWR continuous monitoring grid was enhanced with YSI 6600 continuous water quality monitors placed at the surface (1 m) of TC, TB and CP and 1 m from the bottom of RR and TB (Fig. II-1). The YSI 6600 water quality monitors measured turbidity (NTU), specific conductance (uS/cm), dissolved oxygen concentration (mg/L), water temperature (°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 and turbidity probes minimized the impact of low flow near the probe and environmental fouling. Accuracy of the YSI 6600 monitors was verified with either an YSI 85 or freshly calibrated YSI 6600 within one to two week intervals and each machine was calibrated monthly. The error associated with the YSI dissolved oxygen measurement was 0.2 mg/L.

Results - Daily average water temperature in the DWC at TC and RR reached a maximum of 28°C in June, but was about 25 °C most of the summer season until temperature dropped to 20 °C in October (Fig. II-2a,b,c). At the Turning Basin both surface and bottom water temperature were somewhat higher than in the DWC and average water temperature near 26 °C was common through August (Fig. II-2d,e). Again water temperature decreased to below 20°C in October. Similar water temperature was measured upstream of the at CP and MD (Fig. II-2 f,g).

The highest daily average dissolved oxygen concentration in the DWC occurred at TC, the downstream boundary of the DWC study reach (Fig. II-2a). Here daily average dissolved oxygen concentration was commonly 6 mg/L. Average daily dissolved oxygen concentration was 1 to 2 mg/L lower at the surface and commonly below 5 mg/L near the bottom just upstream at RR (Fig. II-2b) (Fig. II-2 c). Low dissolved oxygen concentration at night accompanied by high concentration during mid-day suggested the diel variability was associated with algal photosynthesis. The influence of photosynthesis on dissolved oxygen concentration was supported by the coincident daytime increase in both pH and chlorophyll *a* concentration.

Average dissolved oxygen concentration was consistently above 5 mg/L at the surface of the Turning Basin where chlorophyll *a* concentration was commonly the highest in the DWC (Fig. II-2d). In contrast, average dissolved oxygen concentration was consistently below 5 mg/L and often reached below 2 mg/L (Fig. II-2e). Again the coincident variation of dissolved oxygen concentration, pH and chlorophyll *a* concentration suggested photosynthesis was an important factor controlling dissolved oxygen concentration near the surface.

In the San Joaquin River upstream of the DWC at MD, high algal growth and strong vertical mixing kept dissolved oxygen concentration above 5 mg/L (Fig. II-

2 g). In contrast, dissolved oxygen concentration decreased to below 5 mg/L in September and October at CP just upstream of the DWC (Fig. II-2 f). Diel variation was large upstream of the DWC and dissolved oxygen concentration varied by up to 5 mg/L each day. Again, coincident diel variation of chlorophyll *a* concentration and pH suggested photosynthesis was an important factor controlling diel variation.

VERTICAL WATER QUALITY PROFILES

Introduction - Vertical profiles described the water quality conditions throughout the water column during discrete sampling at each station. These profiles provide information regarding the role of stratification in the formation of oxygen depletion and the spatial variability of water quality conditions.

Methods - Monthly vertical profiles of water quality conditions were made using a freshly calibrated YSI 6600 water quality monitor. Variables measured included dissolved oxygen (mg/L), specific conductance (uS/cm), pH (unit), turbidity (NTU) and chlorophyll fluorescence (volts).

Results - Dissolved oxygen concentration less than 5 or 6 mg/L often characterized the water column between TC and L48 in the summer and fall (Fig. II-3a,b,c). The lowest dissolved oxygen concentration occurred in September when values reached near 2 mg/L. The absence of a strong or persistent vertical gradient in water temperature, specific conductance or suggested the low dissolved oxygen near the bottom was not caused by a physical barrier to vertical mixing created by stratification. Instead, the higher water temperature, pH and chlorophyll *a* concentration near the surface suggest the dissolved oxygen gradient was a function of slow diffusion of oxygen produced by photosynthesis and surface aeration to the bottom and high respiration of organic and inorganic material near the bottom. A strong coincident vertical gradient in water temperature and dissolved oxygen concentration was measured on September 14 and suggests that stratification may be important on a short-term basis.

In contrast, a strong vertical gradient occurred at TB where dissolved oxygen concentration, pH, water temperature and chlorophyll *a* concentration decreased by a factor of 2 from top to bottom (Fig. II-3d) and dissolved oxygen concentration was often less than 3 mg l^{-1} near the bottom. The strong vertical gradient in these water quality variables suggested stratification restricted aeration from vertical mixing. However, the constant specific conductance with depth and relatively small gradient in water temperature suggested the vertical oxygen gradient was influenced by respiration near the bottom.

There was no vertical gradient in water quality conditions in the shallow water column of the San Joaquin River upstream of the DWC near CP where turbulent mixing was strong (Fig. II-3e). Yet, despite the strong turbulent mixing and high chlorophyll *a* concentration dissolved oxygen concentration was often below 5 mg/L in September and October.

III. Sources of Oxygen Demand

HISTORICAL OXYGEN DEMAND

Chlorophyll *a* concentration, a measure of algal biomass, was measured by the CA Department of Water Resources and U. S. Bureau of Reclamation in the San Joaquin River on a monthly or semi-monthly basis at 1 m depth since 1970 (Lehman 1996 b). These data indicate that chlorophyll *a* concentration is four times lower in the DWC currently than in the 1970s and suggests algal biomass may be less important to the current dissolved oxygen demand than historically (Fig. III-1). A reduced contribution of algal biomass to the oxygen demand in the San Joaquin River was supported by a factor of 2 decrease in the algal load at VN, the tidal head of the estuary (Fig. III-2).

PLANKTON PRODUCTION AND RESPIRATION RATE

Introduction - The plankton community consists of algae and bacteria that through growth and respiration affect the daily oxygen concentration in the water column. Daily plankton production and respiration rate measurements conducted between June and October 2001 in the DWC and San Joaquin River upstream of the DWC were used to determine the contribution of in situ photosynthesis and respiration by nitrifying bacteria to oxygen demand in the DWC.

Methods – Net plankton production and respiration rate was measured by dissolved oxygen light and dark bottle in situ incubation. Water samples were overflowed three times into replicate light and dark bottle glass-stoppered 300 ml BOD borosilicate bottles. Bottles were incubated in a 1.6 m X 1.3 m X 0.6 m Plexiglas open-air continuous flow through incubator that utilized ambient surface irradiance and river water to produce the natural diel pattern of light and water temperature at RR Island. Incubations were run for 24 hr (Vollenweider 1974) and continuous pumping of river water from the DWC through the chamber maintained water within 0.5 °C of the water temperature at 1-m depth. Diel changes in surface irradiance and chamber light were monitored with an Eppley pyroheliometer and LiCor quantum sensor.

Net plankton production rate was measured as the change in dissolved oxygen concentration in light bottles over the incubation period. Plankton respiration was measured as the change in dissolved oxygen concentration in dark bottles over the incubation period. Dissolved oxygen concentration was measured by a YSI 5000 dissolved oxygen meter fitted with a dissolved oxygen probe and stirrer. Dissolved oxygen concentration was verified with Winkler titration. Samples for Winkler titration were fixed in the field by addition of magnanous sulfate and bottles were kept cool and in the dark until titration within 24 hr. Addition of alkaline azide and sulfamic acid just before titration reduced the interference of organic material on the analysis (APHA et al. 1989; Carignan et al. 1998).

The oxygen demand in the DWC (kg/d) from plankton growth was estimated from net plankton production rate measured at TC, RR and L48. The percent contribution of nitrifying bacteria to plankton respiration was estimated by multiplying the NBOD/ BOD ratio from the laboratory BOD tests conducted for each sampling day times the in situ plankton respiration rate. Net oxygen production from algal growth (phytoplankton growth plus non-nitrifying bacteria) in the photic zone was estimated by the net plankton production rate plus the estimated respiration rate from nitrifying bacteria. Algal respiration in the water column was estimated as the difference between plankton respiration rate and the respiration rate of nitrifying bacteria. Total oxygen demand in the DWC (kg oxygen/day) was based on the volume of water between TC and L48.

Water samples for ancillary water quality measurements included dissolved ammonia (NH4-N), nitrate and nitrite, total phosphorus (TP), dissolved orthophosphate (ortho-P), chlorophyll *a*, phaeophytin, total and dissolved organic carbon (TOC and DOC), total Kjeldahl nitrogen concentration (TKN), biochemical oxygen demand (BOD), nitrogenous BOD (NBOD) and carbonaceous BOD (CBOD) and phytoplankton species composition. Non-ammonia TKN, commonly referred to as organic nitrogen, was calculated as the TKN minus dissolved ammonia. Water samples for all water quality analyses were collected using a Van Dorn water sampler. Water samples were processed immediately after collection and stored at 4°C or frozen until laboratory analysis. Laboratory methods for water quality variables are described in Appendix A. Phytoplankton species were preserved and stained with Lugol's solution and enumerated and identified using the inverted microscope technique (Utermohl 1958).

Ancillary field measurements at each sampling station included vertical profiles of light attenuance using a LiCor quantum sensor and specific conductance, chlorophyll *a* fluorescence, pH, water temperature and turbidity using an YSI 6600 water quality monitor.

Results - Average net plankton production rate in the photic zone ranged from 2 to 6 mg oxygen/L/day in the DWC and increased with distance upstream to 8 mg oxygen/L/day at CL (Fig. III-3). This increase was accompanied by an increase in the average plankton respiration rate from 1 mg oxygen /L/ day in the DWC to a little over 2 mg oxygen / L/day upstream (Fig. III-4). Although the net plankton production rate was higher upstream of the DWC, the net plankton production rate per unit algal biomass was lower (Fig. III-5).

Plankton production rate usually produced an average net gain of oxygen in the photic zone of the DWC where light in the water column enables photosynthesis to occur Table III-1. However, most of the water in the DWC is in the aphotic zone and does not receive sufficient light for photosynthesis. Here respiration dominates plankton production rate. As a result the combined daily photic and aphotic zone plankton production rate caused a net loss of oxygen from the water column of 4042 kg/d; an average oxygen demand of 0.26 mg/L. Most of this oxygen demand was produced by the respiration of nitrifying bacteria. The estimated loss of oxygen from bacteria in the DWC was 0.59 mg oxygen/L/day and contrasted with the gain of oxygen associated with the average net algal production rate of 0.33 mg/L/day (Table III-2).

NITROGENOUS OXYGEN DEMAND

Most of the plankton respiration in the DWC was caused by nitrification. Between 50% and 80% of the BOD in the study reach was associated with NBOD (Fig. III-6 a-h). The percentage contribution of NBOD to BOD increased with distance upstream between TC and CP.

The nitrogenous BOD in the DWC was most closely associated with dissolved ammonia concentration. Pearson correlation coefficients confirmed the high and significant correlation between dissolved ammonia concentration and both BOD and NBOD in the DWC (Table III-3). In contrast, the correlation between organic nitrogen and both NBOD and BOD was comparatively low.

In stepwise multiple regressions conducted with water quality variables, dissolved ammonia concentration and carbonaceous BOD accounted for 91% of the variation in BOD. Of these two independent variables, dissolved ammonia accounted for 60% of the variance compared with CBOD that accounted for a maximum of 30% (Table III-4).

The CBOD was probably produced by algal biomass because CBOD and total pigment concentration were strongly correlated (r = 0.81; 103 d.f). In addition, substitution of CBOD by total pigment concentration in the stepwise multiple regression models reduced the explained variance by only 5% (Table III-4). Similar results were obtained for 2000 data (Lehman et al. 2001).

Correlation analysis suggested RWCF load was the major factor controlling the variation in BOD. Dissolved ammonia load from the RWCF was correlated with dissolved ammonia concentration at both RR and CP just upstream of the DWC (Fig. III-7) and NBOD at RR (Figure III-8). This was surprising because the potential oxygen demand from oxidation of the organic nitrogen load from upstream was many times larger than the load from the RWCF (Fig. III-9). The subsequent ammonification and nitrification of this large upstream load should have masked the small dissolved ammonia load from the RWCF, but did not. The poor association between the organic nitrogen load from upstream and both dissolved ammonia concentration (r = 0.34, 103 d.f.) and NBOD (r = 0.34, 103 d.f.) was confirmed by correlation analysis (Table III-2) and trend plots (Fig. III-10).

The importance of local sources of nitrogenous oxygen demand to low dissolved oxygen in the DWC was supported by the decreased percentage contribution of nitrogenous BOD to the total with distance upstream. Nitrification accounted for 40-50% of the total BOD at MD and this percentage decreased to 10% to 20% near CL (Fig. III-6).

COMPOSTION AND OXYGEN DEMAND OF UPSTREAM MATERIAL

Introduction - The concentration of oxygen demanding substances measured at stations throughout the DWC and upper San Joaquin River were compared in order to determine the relative contribution of oxygen demanding substances from upstream and downstream sources.

Methods - Water samples for measurement of ammonia, nitrate and nitrite, total phosphorus, dissolved orthophosphate, chlorophyll *a*, phaeophytin, TOC, DOC, TKN, 5 day (BOD5) and 10 day (BOD10) total and dissolved BOD, 5 day (CBOD5) and 10 day (CBOD10) total and dissolved CBOD, and phytoplankton species composition were collected semi-monthly to monthly at 1 m depth using a Van Dorn water sampler. Water samples were processed immediately after collection and stored at 4°C or frozen until laboratory analysis described in Appendix A.

Concentration – The concentration of water quality variables and their associated oxygen demand varied seasonally and were highly variable among stations. BOD was higher upstream early in the season and downstream late in the season (Fig. III-1 a-e). However, the lowest BOD occurred consistently at TC near the downstream boundary of the study reach. High BOD at CP reflected the presence of high concentrations of carbonaceous and nitrogenous oxygen demanding substances including algal pigment, organic nitrogen, dissolved ammonia, DOC, TOC and VSS concentration. TOC concentration was similar among stations but DOC increased with distance upstream and comprised the largest fraction of the TOC at CL. VSS, a measure of organic carbon, was also consistently higher in the upper San Joaquin River. However, unlike other substances that described oxygen-demanding substances there was no consistent concentration pattern among stations or seasons. In addition, it did not appear to be a direct function of TSS. TKN concentration was a large potential source of NBOD and was fairly stable among stations and ranged from 1 to 2 mg/L. The variability in the TKN was primarily caused by the variability in dissolved ammonia concentration. CBOD was probably strongly influenced by the magnitude of chlorophyll *a* concentration that was consistently higher upstream than downstream (Fig. III 1 a-e).

Composition - The total organic carbon to total organic nitrogen molar ratio was used to provide insight into the nature of the organic substances upstream. If all of the organic material in the water column was derived from algae then the carbon to nitrogen molar ratio should be about 6.6 (Redfield 1958). The carbon to nitrogen ratio at the farthest upstream station near CL was near this idealized ratio (Fig. III-12). The decrease in these ratios with distance downstream suggested the organic material in the water column underwent change during downstream transport. However, they were still within the range of values for algal biomass. Most of this algal biomass was highly oxidized and could not be identified by algal pigment concentration. Live and detrital algae measured as chlorophyll *a* plus phaeophytin pigment concentration averaged only 20% to 40% of the organic carbon and 20% of the organic nitrogen among stations (Fig. III-13).

IV. Environmental factors

AMMONIFICATION RATE

Introduction - The rate at which organic nitrogen is oxidized to ammonia is called the ammonification rate. Quantification of the ammonification rate and its impact on the oxidation of organic nitrogen in the DWC was developed in order to gain an understanding of the relative contribution of upstream nonpoint versus the Stockton RWCF inorganic and organic nitrogen load to dissolved ammonia concentration in the DWC.

Method - A simple mass balance model was developed to estimate the relative contribution of dissolved ammonia and organic nitrogen load from upstream and the RWCF to the dissolved ammonia concentration in the DWC at residence times of 1 to 25 days. Nitrogenous loads were estimated from weekly to biweekly measurements of dissolved ammonia and organic nitrogen at MD by the Department of Water Resources and daily dissolved ammonia and biweekly organic nitrogen measurements at RWCF by the City of Stockton. The daily total dissolved ammonia load from each source was estimated by the sum of the dissolved ammonia load plus the dissolved ammonia load produced from ammonification of organic nitrogen. The ammonification rate was determined from laboratory measurements of the oxidation of chlorophyll *a* to dissolved ammonia at five day intervals over a period of 30 days and was approximately 0.15 mg N/ mg chlorophyll *a* /L/d at 20°C (Fig. IV-1). Oxidation of chlorophyll *a* should represent the fastest ammonification rate because most of the organic nitrogen in the river was of algal origin.

Two model scenarios were examined in order to set upper and lower bounds on the percent contribution of each source to the dissolved ammonia in the DWC. Model run 1 assumed all of the organic nitrogen oxidized at the maximum ammonification rate for chlorophyll *a* concentration and the ammonification rate was adjusted to ambient water temperature using a linear transformation. The combined dissolved ammonia load (AL) in kg/d from direct addition of dissolved ammonia and oxidation of organic nitrogen over a residence time of n days was computed as

$$\sum_{n} (AL_n) = DA_n + (r)(ON_n) + (r)(RON_{n-1})$$

where DA_n is the dissolved ammonia load (kg/d) on day n, $(r)(ON_n)$ was the dissolved ammonia load from the oxidation of organic nitrogen (ON_n kg/d) on day n based on the ammonification rate r (mg N/mg chlorophyll *a* /L/d), and $(r)(RON_{n-1})$ was the dissolved ammonia load (kg/d) from oxidation of the residual organic nitrogen (RON_{n-1} kg/d) from the preceding day, n-1.

Model run 2 assumed only the percentage of the organic nitrogen load composed of chlorophyll a (pchl) oxidized at the maximum ammonification rate of chlorophyll a and that this rate was a linear function of water temperature above 20°C. The ammonia load over n days was computed as:

$$\sum_{n} (AL_n) = DA_n + (r)(pchl)(ON_n) + (r)(pchl)(RON_{n-1})$$

Significant difference between the percentage of the accumulated dissolved ammonia in the DWC contributed by the RWCF and the upstream load at MD at each water residence time was identified using the Wilcoxon Man-Whitney nonparametric test.

Results - The relative contribution of the RWCF and upstream load to the dissolved ammonia concentration in the DWC was strongly influenced by the ammonification rate. When only the linear correction for water temperature was applied to the ammonification rate, the combined dissolved ammonia load from the direct addition of dissolved ammonia plus the decomposition of organic nitrogen was significantly higher ($p < 0.01$) for the RWCF than upstream at MD on a daily basis in the DWC (Table IV-1). This occurred even though the organic nitrogen load from upstream was significantly higher than the RWCF, because the ammonification rate was too slow on a daily basis to release as much dissolved ammonia as the direct dissolved ammonia input from the RWCF. This may partially explain why the weekly average RWCF load was significantly correlated with both the dissolved ammonia concentration ($r = 0.56$, $p < 0.01$, $n=32$) and NBOD ($r = 0.74$, $p < 0.01$, $n=32$) at RR, but the weekly average load at MD was not significantly correlated with either the dissolved ammonia concentration or NBOD.

However, as the water residence time increased in the DWC, the relative contribution of the upstream load to oxygen demand increased because there was more time for the accumulated organic nitrogen load in the DWC to be converted to dissolved ammonia by ammonification. In fact, it took a residence time of about 10 days for the percentage of the accumulated dissolved ammonia load from upstream to exceed the accumulated dissolved ammonia load from the RWCF (model run 1;Table IV-1).

The assumption in model run 1 was that all of the organic nitrogen was oxidized to dissolved ammonia at the maximum rate measured for the ammonification of chlorophyll *a* concentration. However, chlorophyll *a* concentration only contributed 21% to 62% of the organic nitrogen load at MD between July and October in 2001 (Fig IV-2). As a result, the conversion of organic nitrogen to dissolved ammonia in model run 1 represented an upper limit of the contribution of the upstream load to dissolved ammonia in the DWC.

The RWCF was the primary source of dissolved ammonia to the DWC for residence times of 1 to 25 days when the organic nitrogen load was adjusted to account for only the percent composition of chlorophyll *a* concentration (model run 2; Table IV-1). Model run 2 probably represented the lower limit of the impact of ammonification on the release of ammonia from organic nitrogen because there was probably some decomposition of algal detritus and non-algal material. However, this lower limit was probably closer to the actual influence of ammonification on the dissolved ammonia load because the organic nitrogen load primarily consisted of phytoplankton biomass that was already highly oxidized. The total organic carbon to organic nitrogen molar ratios from 4 to 6 at MD were near the range of 5 to 8 that characterize phytoplankton (Redfield 1958). Stable isotope analysis confirmed that the organic nitrogen load from upstream was primarily of phytoplankton origin (Kratzer et al. 2003).

Water temperature was probably not a significant source of daily variation in the nitrification rate in the DWC during most of the summer season. Water temperature hovered near 25°C most of the summer and usually varied by only one to two degrees each day. The largest change in water temperature occurred in October when water temperature shifted downward to 20°C.

LIGHT LIMITATION

Introduction - Algal growth rates were measured at different light intensities in order to determine the influence of light on plankton production rate in the DWC. This is important management information because algae are light limited in the San Joaquin River because of high suspended matter concentration. Management alternatives that affect light availability could impact algal production rate and the associated oxygen dynamics.

Method - Algal growth at varying light intensities was estimated by dissolved oxygen light/dark bottle incubation (Vollenweider 1974). Replicate water samples were overflowed three times into light and dark bottle 300 ml borosilicate BOD bottles and incubated in a 1.6 m X 1.3 m X 0.6 m plexiglass open-air flow through incubator. The incubator utilized ambient surface irradiance and pumped river water to reproduce 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 °C of ambient water temperature. Light intensity of replicate water samples was varied by a series of screens to achieve a light gradient. Diel change in surface irradiance and vertical light attenuance were measured with an Eppley pyroheliometer and LiCor quantum sensor, respectively.

Plankton production rate (mg oxygen /L/hr) and plankton production rate normalized to chlorophyll *a* concentration (ug oxygen /ug chla/hr) was used to generate plankton production rate versus light intensity curves that described the maximum potential plankton production rate at different light intensities among stations.

Results – Light limited plankton production rate in the DWC. Light extinction was rapid and surface irradiance decreased to 1% within a depth of about 2 m (Fig. IV-3). Algal photosynthesis only occurs in this portion of the water column called the photic zone that averaged about 20% of the surface irradiance. Both the maximum plankton production rate and the maximum production rate normalized to chlorophyll *a* occurred when daily light intensity averaged between 0.05 cal/ cm^2/min and 0.10 cal/cm^2/min (Fig. IV-4). The similarity of the maximum light intensity among stations suggested that light was a major limiting factor affecting plankton production rate throughout the region.

Maximum algal production rates were actually higher than those measured because the plankton production rate included respiration from nitrifying bacteria. This may account for the higher plankton production rate at CL where dissolved ammonia was low than in the DWC where dissolved ammonia was high. NBOD/total BOD ratios suggested bacterial respiration averaged 54% of the total (See Section III).

LIMITING NUTRIENTS

Both dissolved inorganic nitrogen (sum of the ammonia, nitrate and nitrite) and orthophosphate concentration were consistently an order of magnitude higher than limiting concentrations for the growth of algae at all stations (Fig. IV-5). Limiting concentrations are about 0.1 to 0.2 mg/L for inorganic nitrogen and 0.01 to 0.02 for orthophosphate.

DOWNSTREAM TRANSPORT

Introduction - Uncertainty in the contribution of the RWCF and upstream load to the oxygen demand in the DWC was associated with the influence of downstream transport processes on the import and export of oxygen demanding substances in the DWC. Both ebb and flood tide and spring and neap tidal cycles affected the net transport of oxygen demanding substances in the DWC. The largest uncertainty was associated with the net transport of oxygen demanding substances from MD 24 km upstream into the DWC and the net transport of material even from farther upstream to MD.

Methods - The concentration organic and inorganic water quality variables on ebb and flood tide was measured by discrete water samples by ISCO automatic water quality samplers at CP and RR. Samples were taken each month on both spring and neap tide. Water samples were analyzed for a suite of water quality and biological variables including dissolved ammonia, nitrate plus nitrite, orthophosphate, total phosphorus, TOC, DOC, TSS, VSS, chlorophyll *a* and phaeophytin concentration, BOD, CBOD and algal species composition, cell dimension and density. Algal cell dimensions were used to calculate cell carbon (Strathmann 1967). Methods for these analyses are listed in Appendix A.

The net downstream transport of organic and inorganic material between CP and RR was calculated as the product of each 15-min flow value (cfs) and the concentration (mg/L) of the desired constituent during that time summed over the day; units were converted to kg/day.

Results – The concentration of water quality variables measured on ebb and flood tide often differed by many times at CP and RR and was an important factor for the transport of organic material downstream (Fig. IV-6; Fig. IV-7 a,-b). Organic constituents such as VSS, chlorophyll *a* concentration and both BOD and CBOD were usually higher on ebb tide and contrasted with non-organic constituents such as chloride, nitrate plus nitrite and orthophosphate concentration that were similar among tides. In addition, bottom concentration varied less with tide near the bottom than at the surface at RR (Fig. IV-7 a-b).

The net transport of material into the DWC from upstream at CP was positive and was high for suspended materials like TSS that added 80,000 to 140,000 kg/day to the DWC (Fig. IV-8). Very little of this TSS load was organic matter and only a small fraction was live or detrital algae measured as chlorophyll *a* or phaeophytin pigment concentration. Nitrogenous material load described by TKN was high and 25-50% of this material was dissolved ammonia. These organic and inorganic materials produced a BOD load from 10,000 to 20,000 kg/day.

The net transport of oxygen demanding substances, inorganic nutrients and suspended sediment was usually downstream at RR and was a function of the net downstream streamflow during the summer (Fig IV-9). The BOD exported near the surface was at least 5000 kg/day and about a quarter to a half of this was CBOD (Fig. IV-10 a). Downstream export of oxygen demand from algal blooms was apparent at the beginning of July and October when CBOD was about 60% of the BOD and coincided with downstream export of chlorophyll *a,* VSS, TOC and DOC. TSS export was poorly associated with VSS or chlorophyll *a* concentration. TKN export was fairly stable throughout the season and dissolved ammonia concentration comprised 25% to 50% of the total.

Net downstream material transport was lower near the bottom than the surface (Fig. IV-10 b). Oxygen demanding substances may be trapped near the bottom where horizontal velocities are slower than near the surface. This may be an important mechanism by which oxygen-demanding substances are retained near the bottom until their oxygen demand is fully expressed. The retention of material near the bottom was demonstrated in July when chlorophyll *a* was exported near the surface, but retained near the bottom.

Net transport between CP and RR confirmed the daily retention of oxygen demanding substances in the DWC needed to facilitate the release of ammonia through oxidation of organic material. On average, 61% of the chlorophyll a̲ was retained in the study reach. The average percentage retention of organic nitrogen, BOD and dissolved ammonia was lower at 35-39% and more variable than chlorophyll a̲ (Table IV-2). The similar and short retention time of BOD and dissolved ammonia reinforced the potential influence of ammonia load on daily oxygen demand. Similarly, the relatively short average retention time of organic nitrogen reinforced the importance of chlorophyll *a* concentration oxygen demand.

The largest uncertainty in net transport was associated with the transport of inorganic and organic material into the DWC from MD, 24 km upstream of the DWC. The significantly ($p < 0.05$) higher chlorophyll a̲ concentration at MD than CP suggested there was a loss of live phytoplankton with transport downstream (Fig. IV-11). In addition, the higher ($p < 0.05$) average phaeophytin concentration at CP of 36.9 ± 24.5 ug/L than MD of 17.6 ± 4.6 ug/L suggested decomposition of organic matter occurred during downstream transport. As a result, the upstream organic nitrogen load calculated for MD probably represented the maximum potential load from upstream.

Differences in algal species carbon between successive sampling stations also suggested algal biomass was altered during transport downstream. Diatoms comprised a large percentage of the algal species carbon composition at the farthest upstream station CL (Fig. IV-12 a-d). The algal species carbon shifted from diatoms at CL to green and bluegreen species or different diatoms at VN and MD downstream. This suggested algal species changed, decomposed or were replaced as they moved downstream toward the DWC. In contrast, the source of algal species carbon in the DWC was clearly from stations near the DWC. Algal species at RR matched diatom and green species at CP, the bluegreen and green flagellate species at TB and the miscellaneous flagellate and freshwater species at TC.

V. Summary/Discussion

WATER QUALITY CONDITIONS

Dissolved oxygen concentration in the DWC was relatively low in 2001 as would be expected in this warm-dry year. Both the daily average and daily minimum dissolved oxygen concentration near RR was below 5 mg/L or 6 mg/L most of the season between June and October and frequently decreased to less than 3 mg/L. The magnitude and duration of dissolved oxygen concentration episodes below 5 mg/L was greater than in 2000 (Lehman et al. 2001) and more similar to those measured in the dry year 1999 (Lehman and Ralston 2000). Historically, dissolved oxygen concentration below 5 mg/L occurred more frequently during low flow years (Lehman and Ralston 2000).

The lowest dissolved oxygen concentration occurred near the bottom. This bottom minimum was not produced by persistent stratification near the surface that prevented aeration through vertical mixing that is common in Chesapeake Bay (Officer et al. 1984) and the Gulf of Mexico (Rabalais and Turner 2001). Instead, water temperature usually decreased by only 1°C and specific conductance was stable between the surface and bottom. A well-mixed water column was also observed in 1999 (Lehman and Ralston 2000) and 2000 (Litton and Nikaido 2001; Lehman et al. 2001). The vertical gradient in water temperature measured on September 14 near the surface suggested vertical stratification can occur. However, comparison of diel vertical profiles suggested stratification near the surface in the late afternoon was gone by morning (Litton 2002).

OXYGEN DEMAND

NBOD was the major source of oxygen demand in the DWC and was most closely associated with dissolved ammonia concentration that accounted for 60% of the variation in BOD within stepwise multiple regression analysis. Similar results were obtained for 2000 (Lehman et al. 2001). The large contribution of NBOD to oxygen demand in the DWC was identified as early as the late 1960s (McCarty 1969). Nitrification can directly control oxygen demand in the water column when ammonia concentration is high (Berounsky and Nixon 1993; Brion et al. 2000). This appeared to be the case in the DWC where dissolved ammonia concentration averaged 0.4 mg/L and reached 1.0 mg/L.

RWCF was a major contributor to the NBOD produced by dissolved ammonia in the DWC. This finding differed from the results of previous mass balance calculations (Lee and Jones-Lee 2003). The importance of the RWCF load was surprising because the organic nitrogen load from the upper San Joaquin River was many times higher than the ammonia load from the RWCF. Ammonification and nitrification of this upstream nitrogen load should have created both the high ammonia concentration and NBOD in the DWC and masked the influence of the comparatively small ammonia load from the RWCF. However, both correlation analyses and mass balance calculations computed for daily intervals suggested the RWCF was a major contributor to the dissolved ammonia in the DWC.

CBOD accounted for 30% of the variation in BOD and was the second water quality variable most closely associated with the variation of BOD in stepwise multiple regression analysis. This finding conflicts with current (Jones and Stokes Associates 1998) and historical (Bain and Pierce 1968) hypotheses that suggest the decomposition of algal biomass from upstream was the primary cause of BOD in the DWC. This hypothesis was not surprising because historically algal biomass upstream at Vernalis often reached 200 ug/L and coincided with algal biomass in the DWC of up to 100 ug/L in the summer. However, a factor of 4 decrease in algal biomass since the 1970s coupled with only a 20% decrease in the frequency of dissolved oxygen concentration below 5 mg/L in the 1990s suggested the importance of algal biomass may have changed (Lehman et al. 2001).

Respiration of organic matter from upstream was the primary cause of CBOD in the DWC. This differed from estuaries in the Chesapeake Bay and the Gulf of Mexico where the oxidation of algal biomass from in situ algal growth was sufficient to cause heterotrophy (Kemp et al. 1997; Rabalais and Turner 2001). The difference was partly a function of the low algal biomass and growth rate in DWC. In the Susquehanna River estuary, chlorophyll *a* concentration ranged from 1000 to 2000 mg/m^2 and was associated with primary productivity from 15 to 427 mg C/m^2 /hr (Malone 1992). This was at least two times higher than the chlorophyll *a* concentration of 33 to 698 mg/m^2 and algal growth rate of 65 to146 mg C/m^2/hr in the DWC. Algal growth rate in the DWC is limited by high concentrations of inorganic suspended solids that create light limiting conditions for phytoplankton growth year-round (Jassby et al. 2002).

Most of the carbonaceous oxygen demand in the DWC came from algal growth upstream. The daily flux of live algal biomass measured as chlorophyll a from upstream ranged from 20 to 180 kg/d. This load was larger than the chlorophyll a load from daily algal growth in the photic zone of 16 to 59 kg/d. In addition, the live algal load from upstream was accompanied by a larger load of oxidized algal biomass. The oxidized algal load included detrital algal biomass measured as phaeophytin and an even larger load of highly decomposed organic material that could not be identified as algal biomass by pigment concentration. Yet, both carbon to nitrogen molar ratios and stable isotope analysis indicated the suspended material was of algal origin (Kratzer et al. 2003) and regression analysis suggested it was the primary source of BOD at upstream stations (Foe et al. 2002; Stringfellow and Quinn 2002; Dahlgren 2001). Most of this upstream phytoplankton material was retained within the DWC because a high settling rate at the junction of the San Joaquin River and the DWC caused the upstream load to settle immediately upon entry into the DWC (Litton 2003). Full oxidation of this phytoplankton biomass load was supported by high retention time in the DWC.

CONTROLLING FACTORS

Light availability for algal growth was an important controlling factor for algal production in the DWC. Algal production rate was light limited in the DWC where surface irradiance penetrated to only 2 m depth and only about 20% of the surface irradiance was available for algal growth (Lehman et al. 2001). Light limitation is a well-known limiting factor for algal productivity in SFB (Cloern 1987) and for long-term chlorophyll *a* production in the San Joaquin River (Lehman 1992) and is caused by large quantities of inorganic suspended particles in the water column. This suspended material is imported from upstream and settles to the bottom of the DWC where resuspension keeps turbidity high (Litton 2002).

Net transport between upstream stations was uncertain and added substantial uncertainly to estimates of the upstream load into the DWC. Current estimates of upstream load into the DWC (Foe et al. 2002) rely on the assumption that material from the San Joaquin River watershed upstream of the DWC reached the DWC intact and concentrations of suspended material increased with distance downstream as each new source was added. The assumption was supported short transport times measured between Merced and the DWC (Kratzer et al. 2003). However, concentrations and loads of suspended material usually decreased between MD and CP in 2001 or previous years (Lehman and Ralston 2000; Lehman et al. 2001). Further, a decrease in carbon to nitrogen molar ratio, decrease in chlorophyll *a* concentration, increase in phaeophytin concentration and change in carbon distribution among algal species groups suggested the characteristics of the upstream load changed with distance downstream in 2001. A decrease in the oxygen demand potential of riverine organic material with distance downstream was also measured for Chesapeake Bay (Kemp et al. 1997).

Residence time was an important factor influencing the expression of oxygen demand in the DWC. Sediment and oxygen demanding substances from upstream entered the DWC on ebb tide. This material was often retained in the DWC because of rapid settling or long residence time. The amount of organic matter that settled to the bottom increased with the amount of TSS (Litton 2002) and facilitated concentration of oxygen demanding substances near the bottom. Here resuspension of bottom sediments by tidal action facilitated the full expression of the oxygen demand in the sediment. Low sediment oxygen demand was confirmed in sediment core studies (Litton 2002).

VI. Recommendations

1. Further information is needed on the relative contribution of nitrifying bacteria and algae on oxygen demand in the DWC and upstream in

response to environmental conditions on a daily basis. This information will assist development of an accurate conceptual model and critical analysis of the impact of management alternatives on oxygen dynamics associated with both algal growth in the DWC and upstream. This information will also assist evaluation of predictive management models.

2. Further effort is needed in analysis of existing data. Substantial quantities of data were collected between 1999 and 2001 by a many researchers but relatively little of this information has been fully analyzed or integrated because of the aggressive project schedule. Additional resources are also needed to evaluate the data findings over the past three years with long-term data sets. Existing data should also be used to critically evaluate the accuracy and reliability of the existing models.

3. Quantification is needed on the contribution of oxygen demanding substances from the San Joaquin River upstream of the DWC to oxygen demand in the DWC. This verification will require quantification of the load of oxygen demanding materials from upstream into the DWC as well as the net transport of oxygen demanding materials between locations upstream. One potential approach would be to utilize a Lagrangian sampling regime whereby the net change in materials in the water column such as algal biomass and species composition are measured as they move downstream with streamflow.

4. Information is needed on the environmental factors that influence the net transport of oxygen demanding substances from downstream. These environmental factors include water temperature, removal by grazing, oxidation by light, suspended sediment concentration, agricultural diversion, reservoir release, export flow and channel barrier operation.

5. Diel, seasonal and interannual variability of oxygen demand was high. A long-term monitoring is needed to quantify this variability and determine how environmental conditions and oxygen demanding loads interact to create oxygen demand.

6. Monitoring has revealed spatially and temporally variable dissolved oxygen concentration and high ammonia concentration in the DWC. Both of these may adversely impact fisheries resources. More directed studies are needed to assess the acute and chronic impact of these conditions on fisheries resources.

7. BOD tests were a useful tool for assessment of the potential oxygen demand but these laboratory tests are conducted below ambient water temperature. Information is needed on the oxidation rates of the various organic materials and ammonia under varying environmental conditions including water temperature and light.

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VIII. Appendix

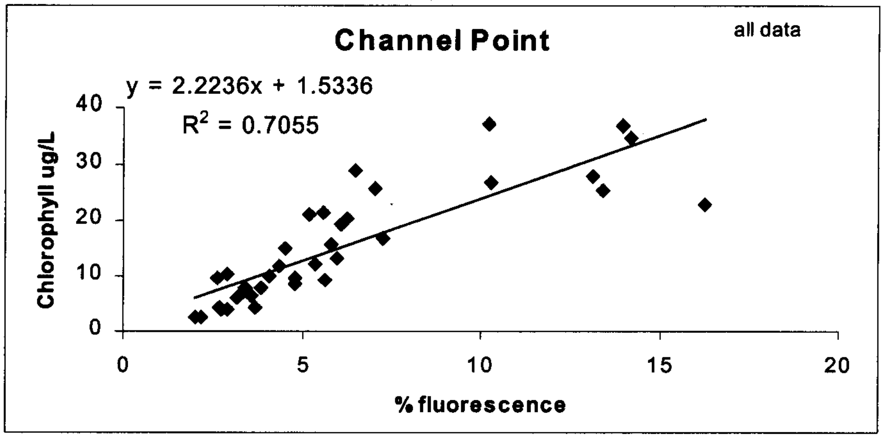
Appendix A

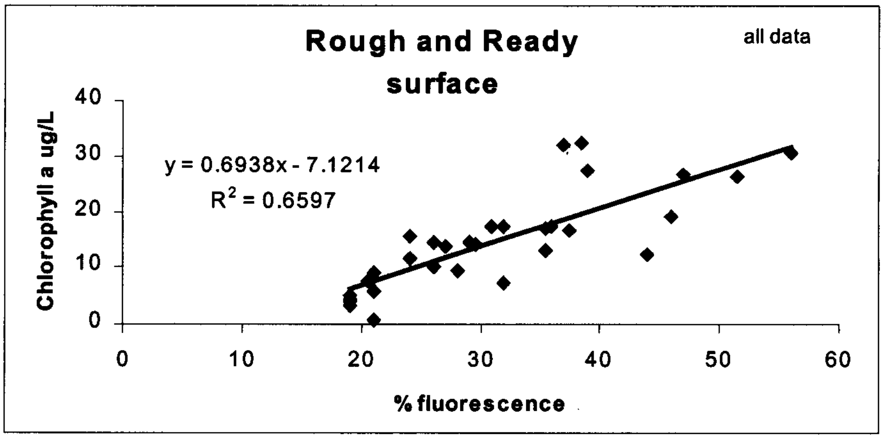
Methods used for water quality analyses

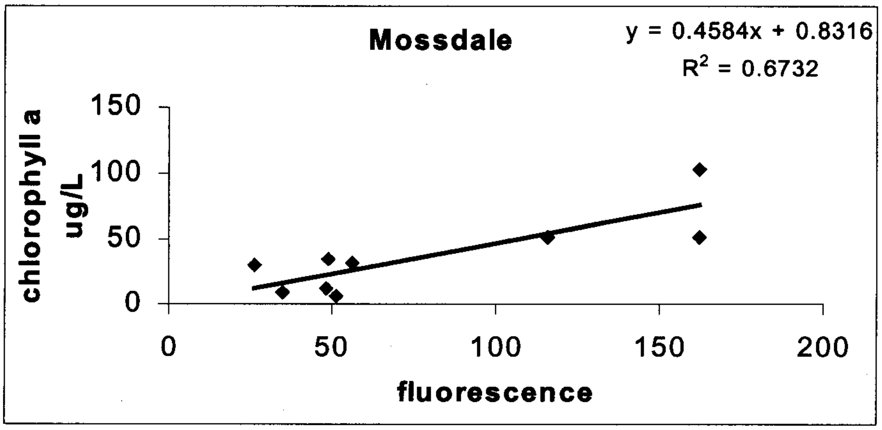
DWR San Joaquin Dissolved Oxygen Study Methods

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.







Appendix C: Tables and Figures

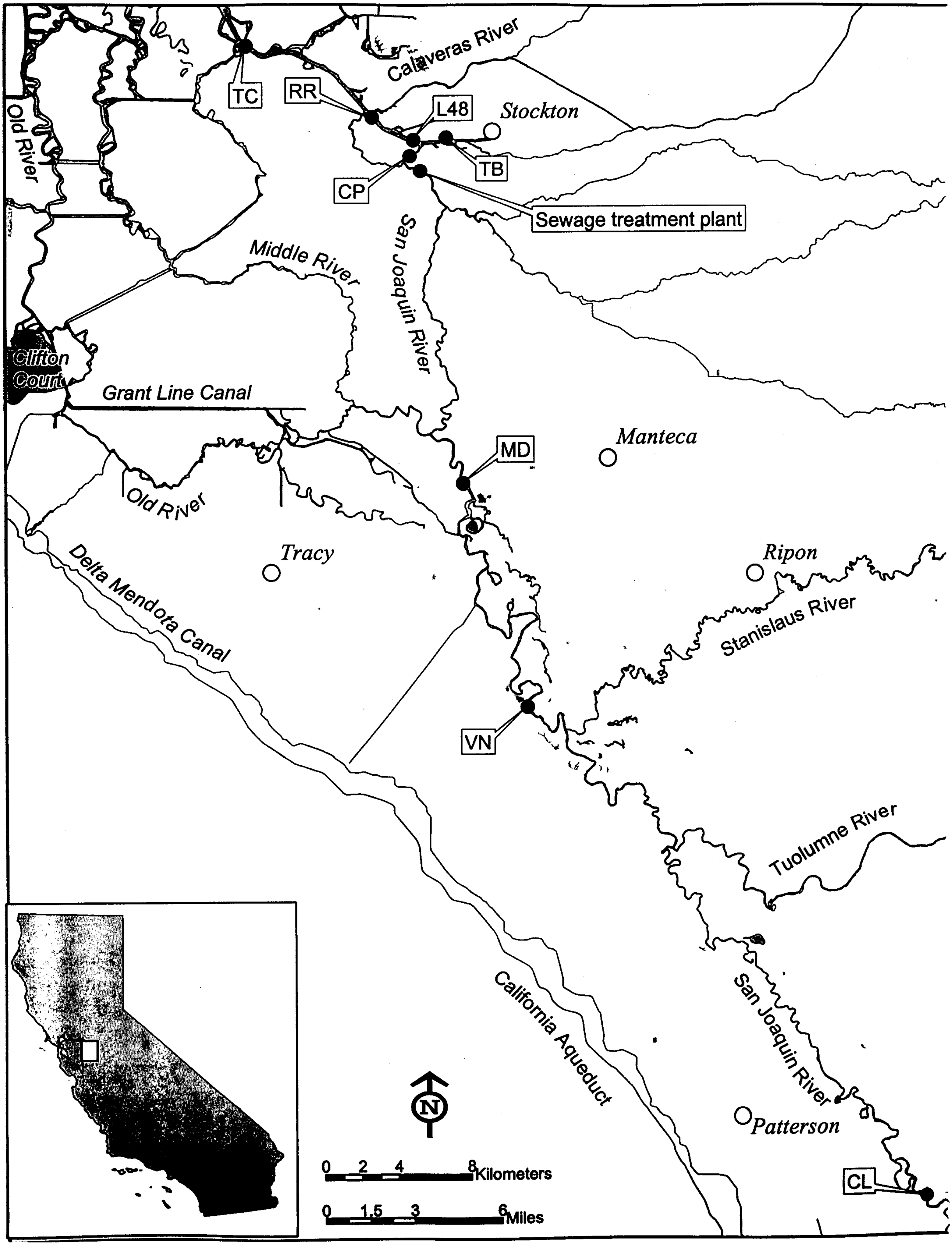

Calaveras River
TC
RR
L48
Stockton
TB
CP
Sewage treatment plant
Old River
Middle River
San Joaquin River
Clifton Court
Grant Line Canal
MD
Manteca
Old River
Tracy
Ripon
Delta Mendota Canal
Stanislaus River
VN
Tuolumne River
California Aqueduct
San Joaquin River
N
Patterson
0 2 4 8 Kilometers
0 1.5 3 6 Miles
CL

Fig. II-2a. Daily average, minimum and maximum water quality measurements collected using a YSI monitor at Turner Cut.

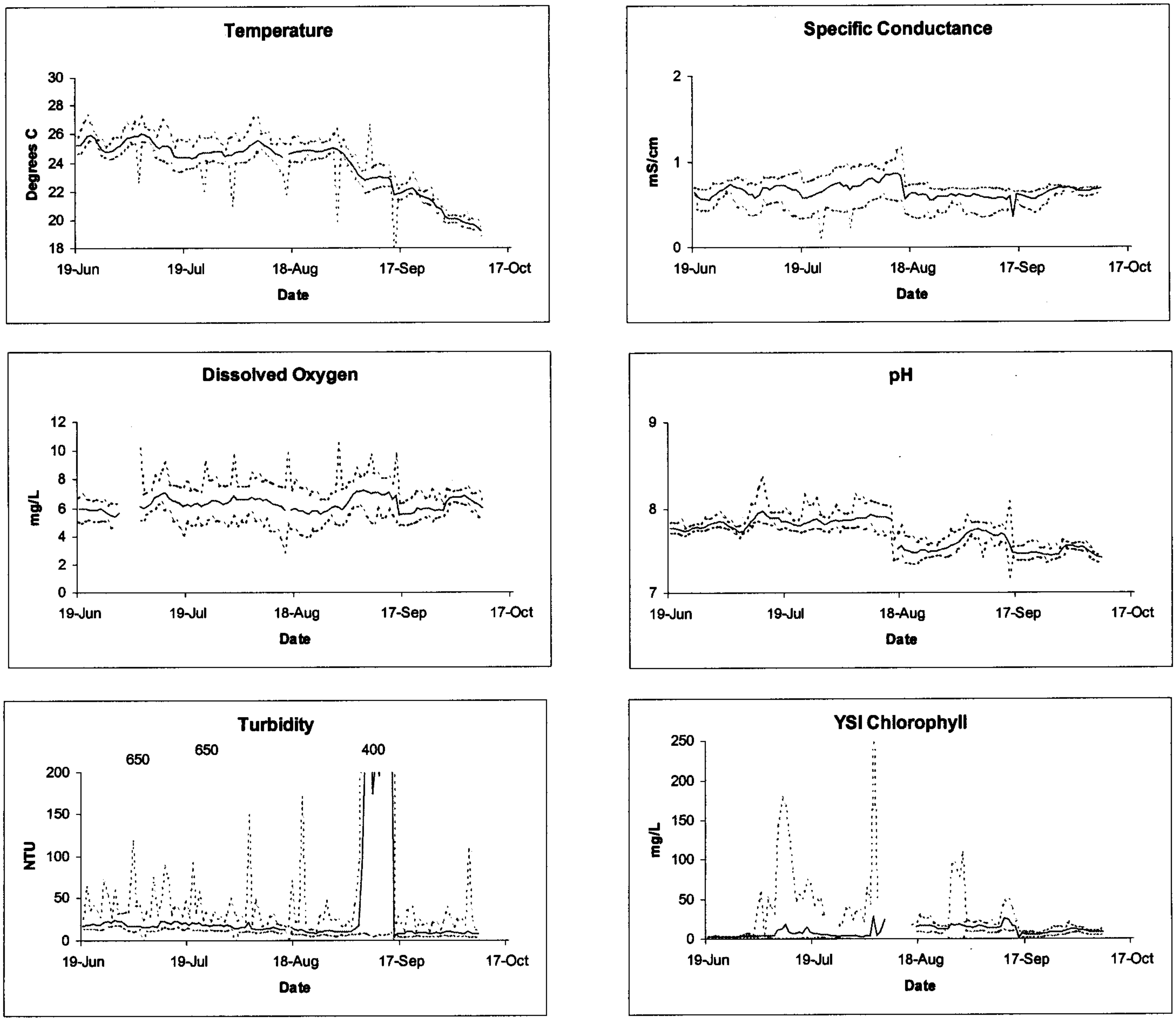


Fig. II-2b. Daily average, minimum and maximum water quality measurements collected using a Schneider water quality monitor at 1 m depth for Rough and Ready Island.

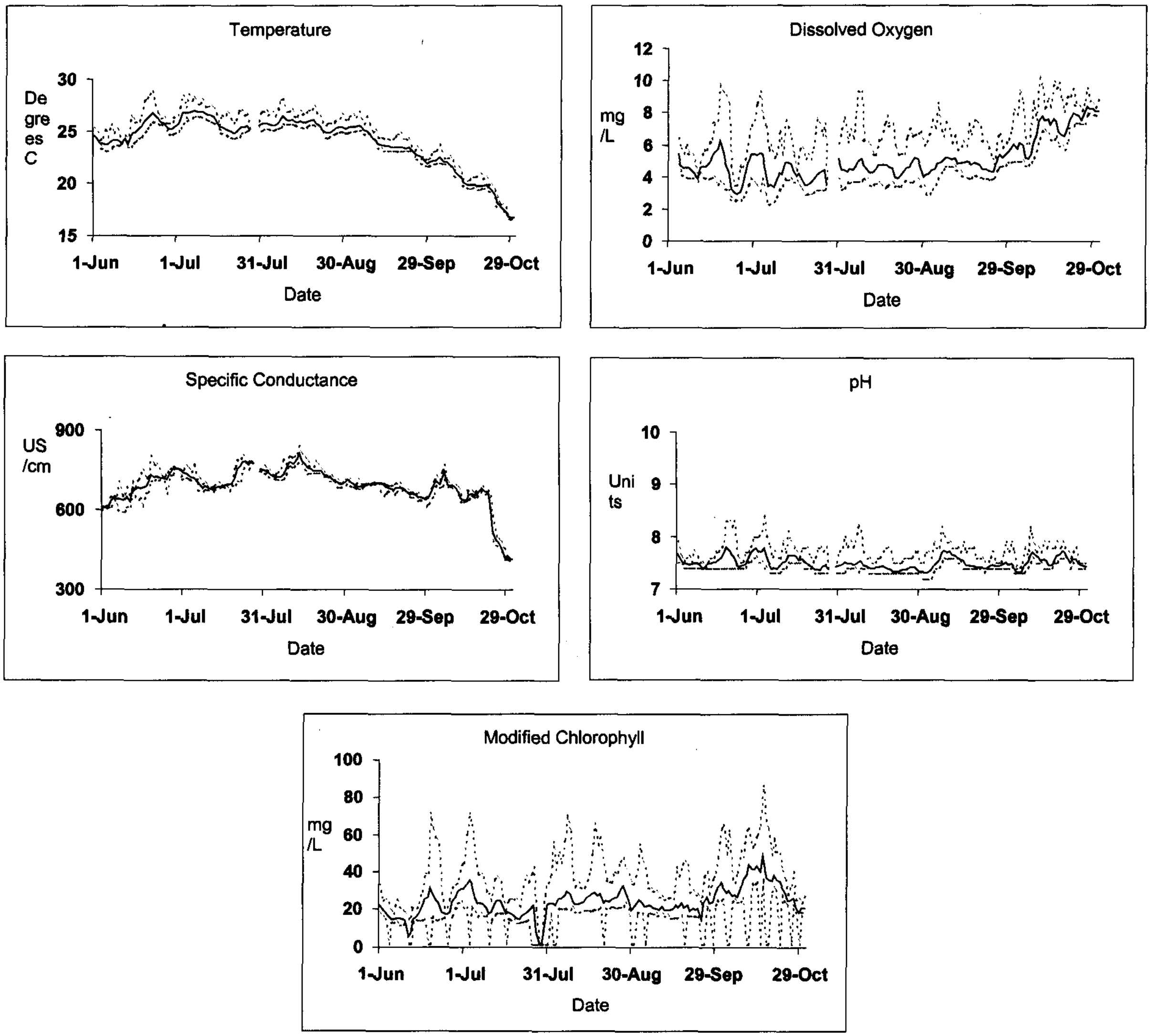


Fig. II-2c. Daily average, minimum and maximum water quality measurements collected using a YSI monitor at 1 m from the bottom for Rough and Ready Island.

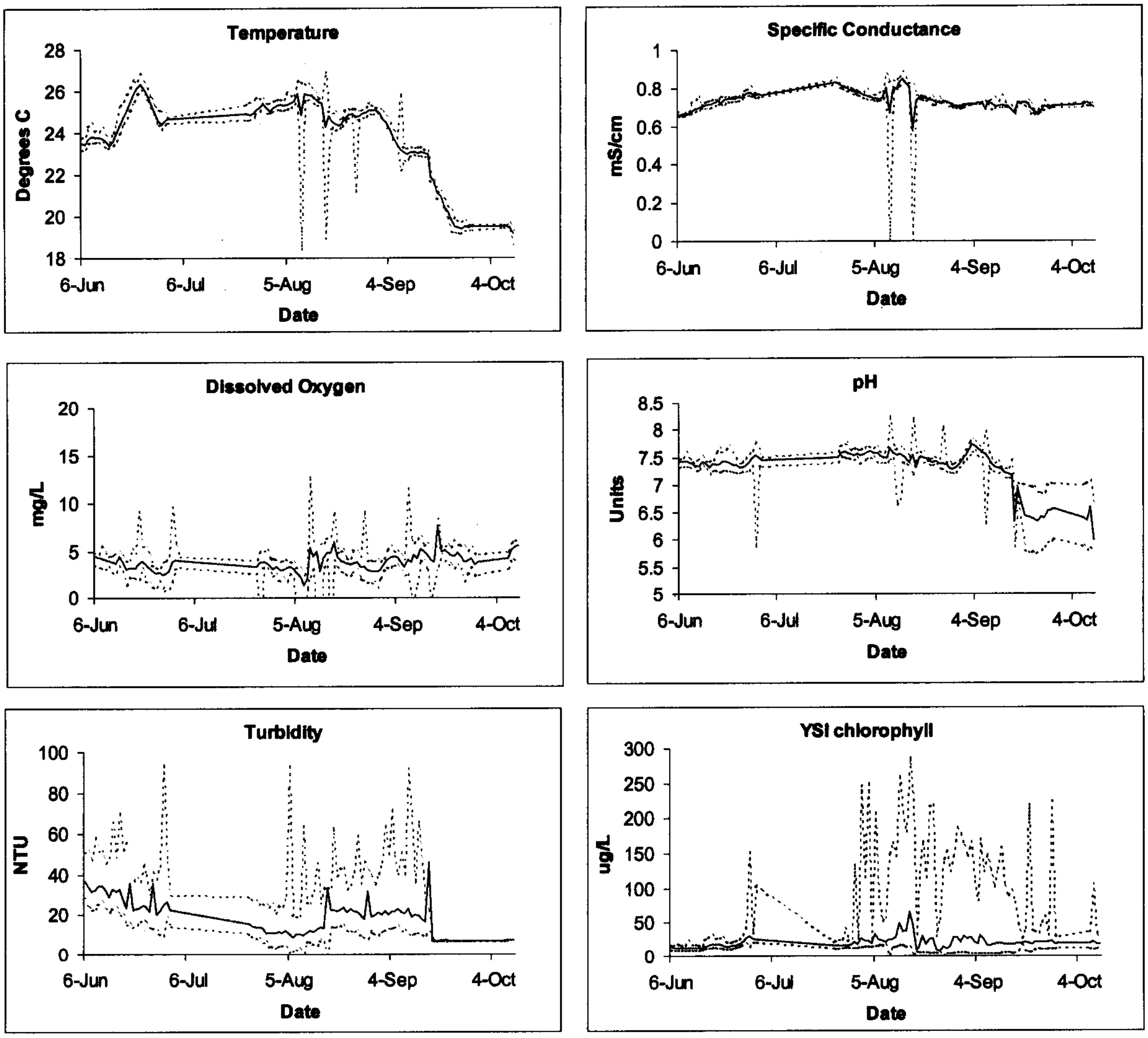


Fig. II-2d. Daily average, minimum and maximum water quality measurements collected using a YSI monitor at 1 m depth in the Turning Basin.

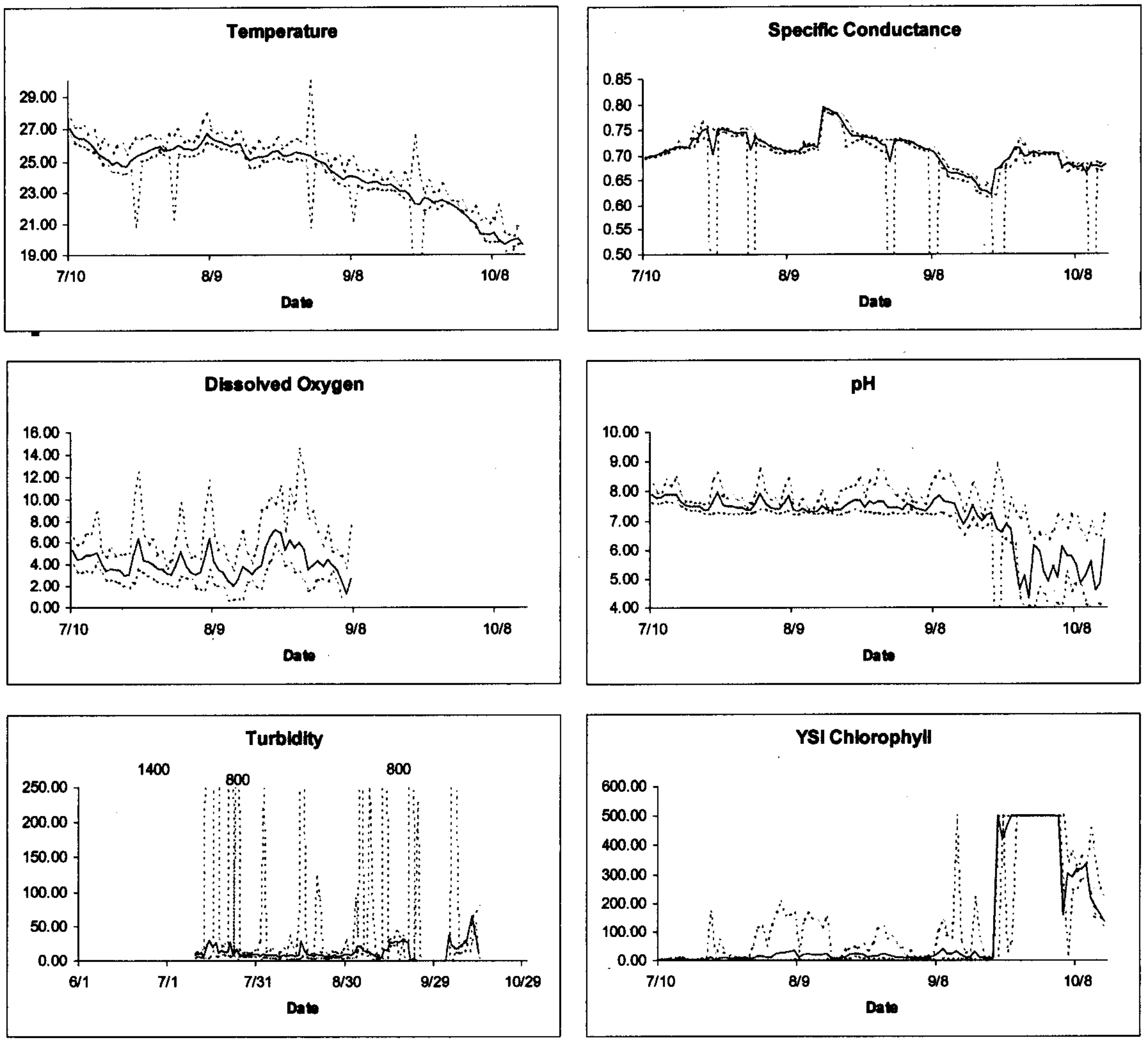
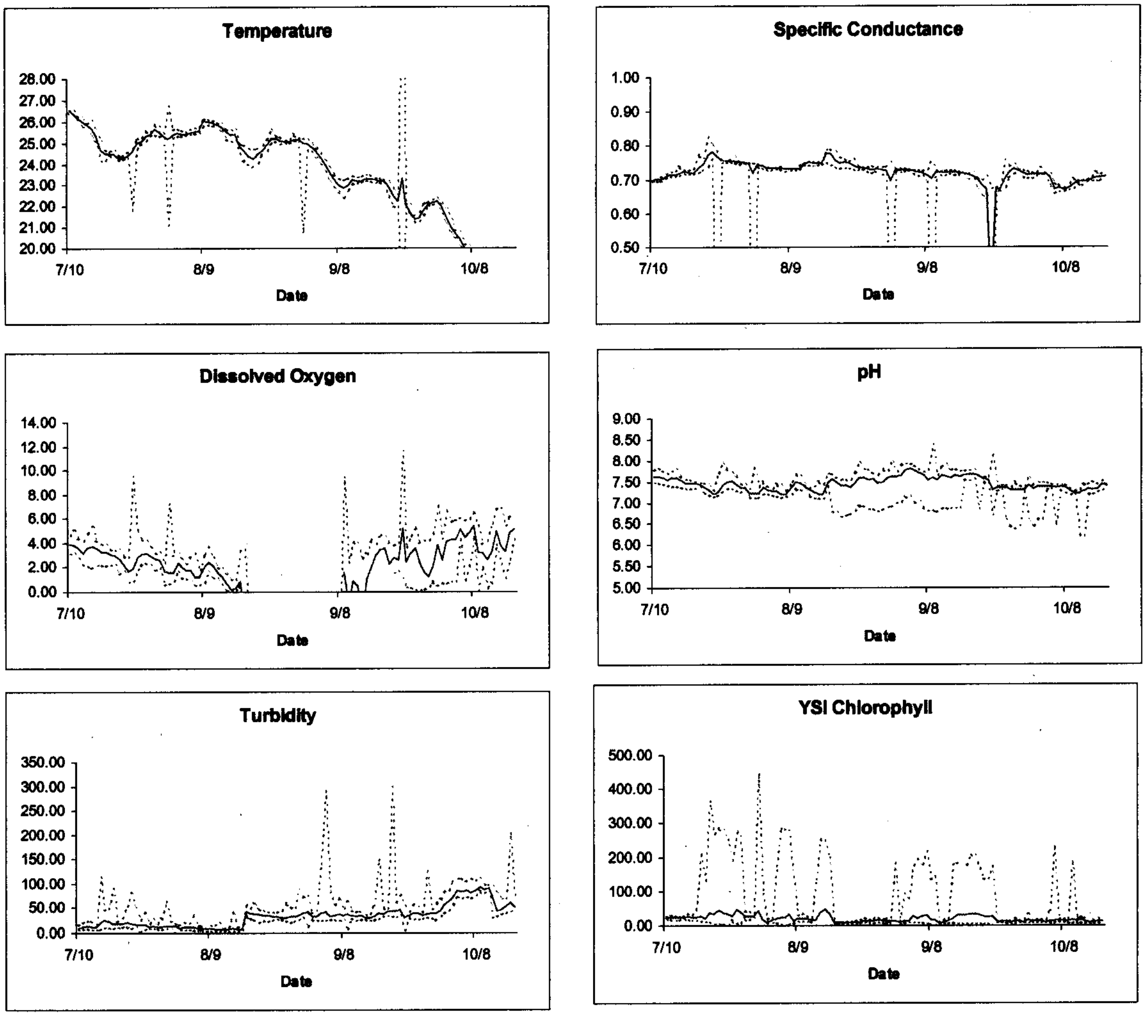


Fig. II-2e. Daily average, minimum and maximum water quality measurements collected using a YSI monitor at 1 m above the bottom in the Turning Basin.



Lehman 4-19-02 Oxygen demand Figures and Tables

Fig. II-2f. Daily average, minimum and maximum water quality measurements collected using a YSI monitor at Channel Point.

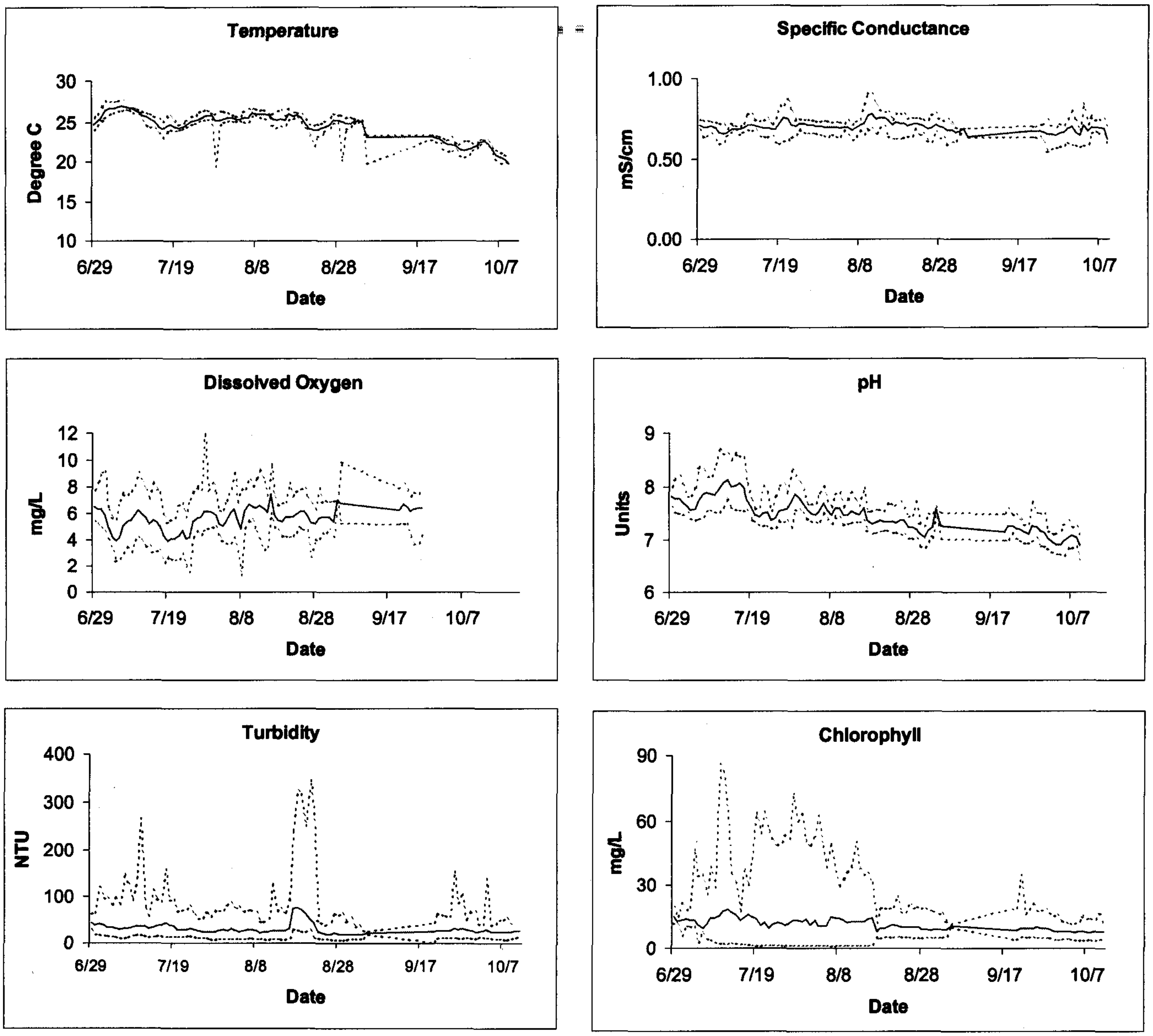


Fig. II-2g. Daily average, minimum and maximum water quality measurements collected using a Schneider water quality monitor at Mossdale.

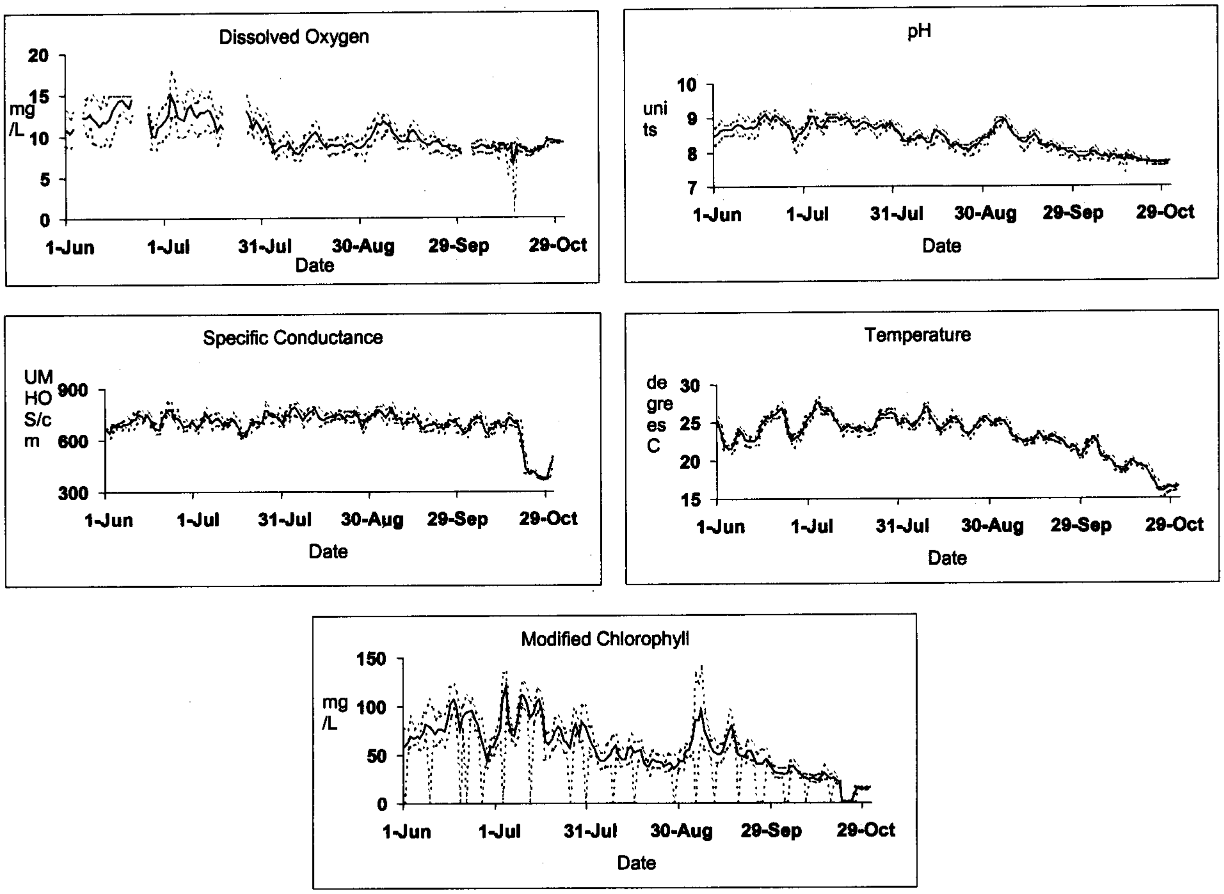


Fig. II-3a. Vertical profiles of water quality variables near Turner Cut

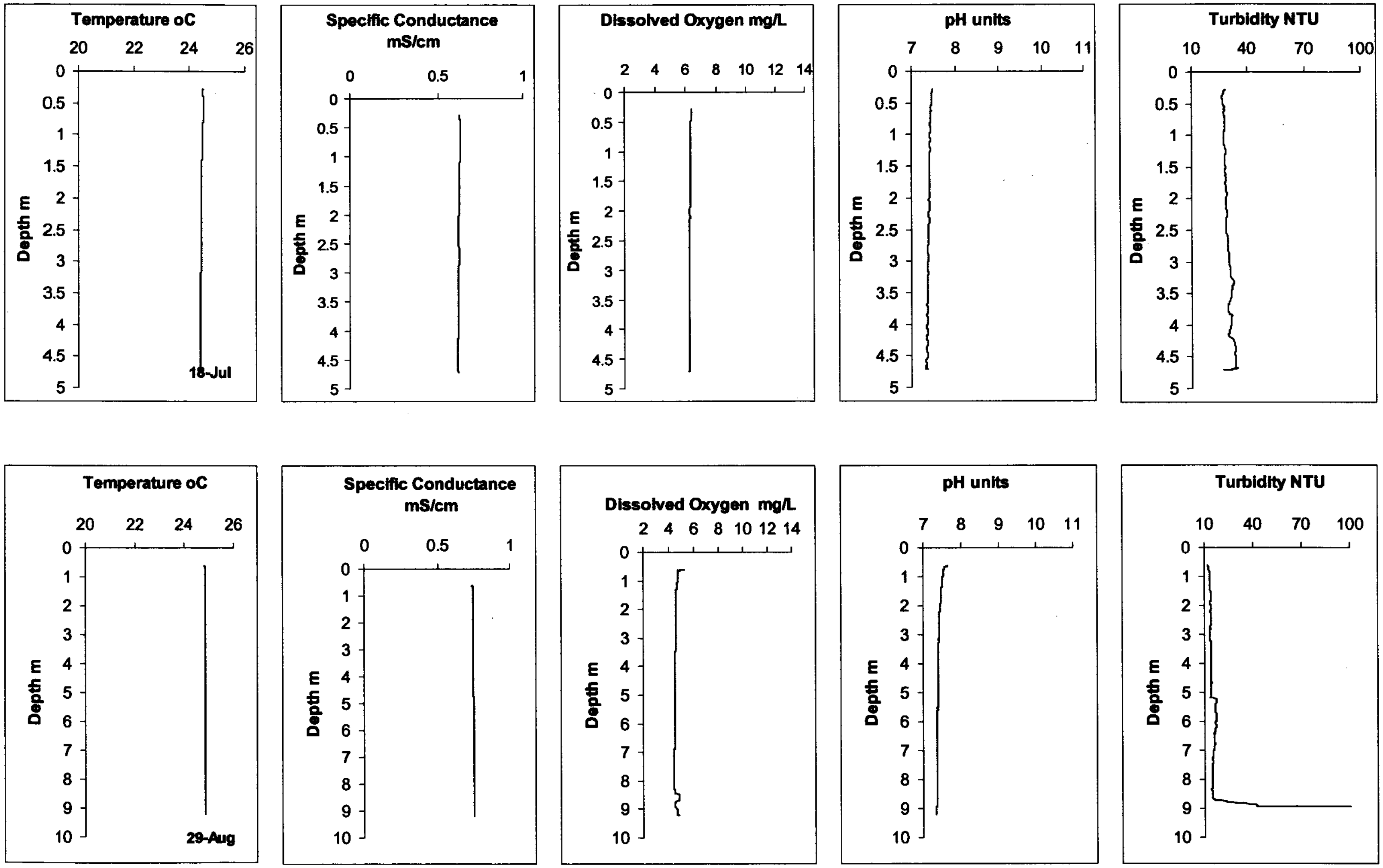


Fig. II-3a. Vertical profiles of water quality variables near Turner Cut.

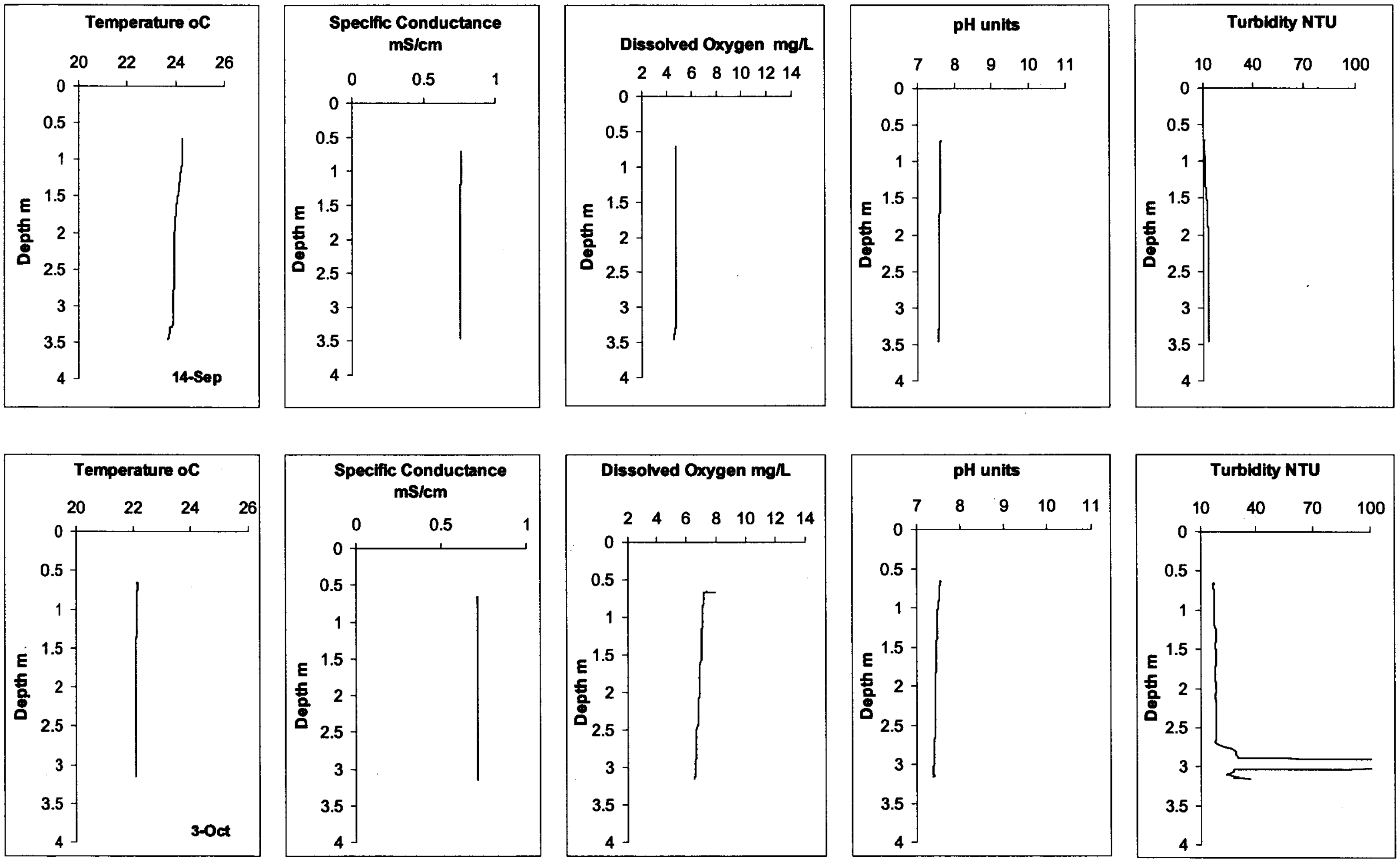


Fig. II-3b. Vertical Profiles of water quality variable near Rough and Ready Island.

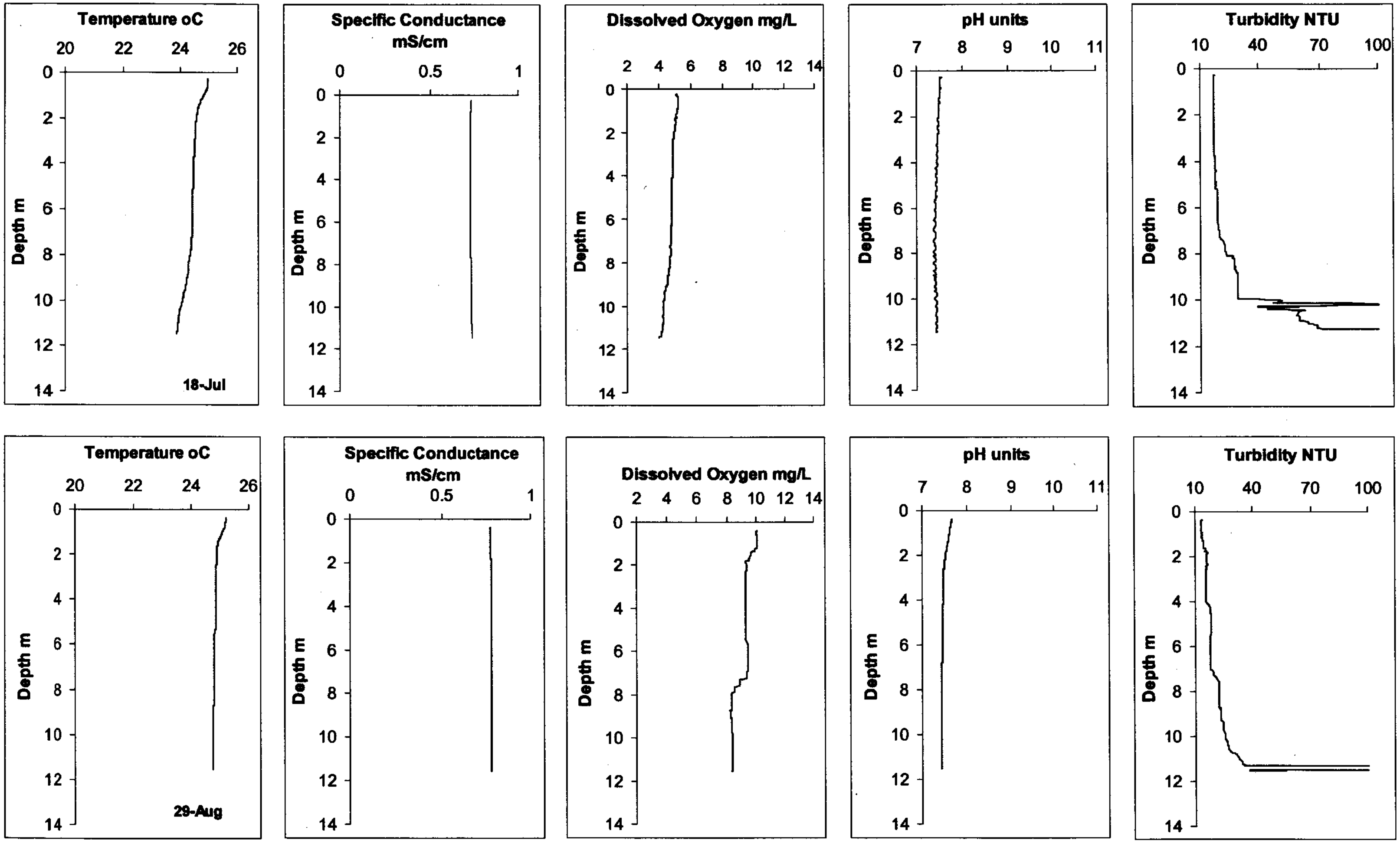


Fig. II-3b. Vertical Profiles of water quality variable near Rough and Ready Island.

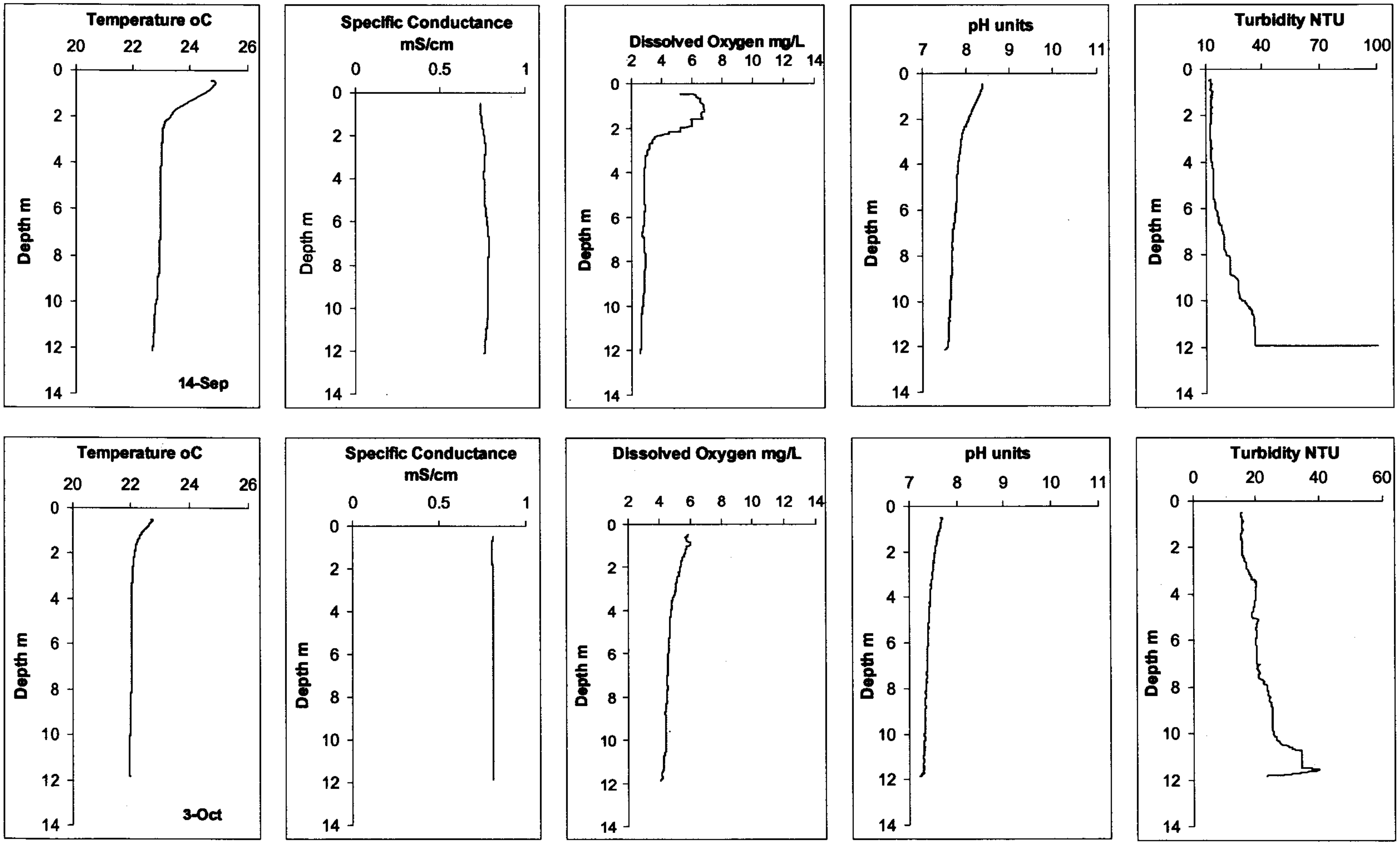


Fig. II-3c. Vertical Profiles of water quality variable near Navigation Light 48.

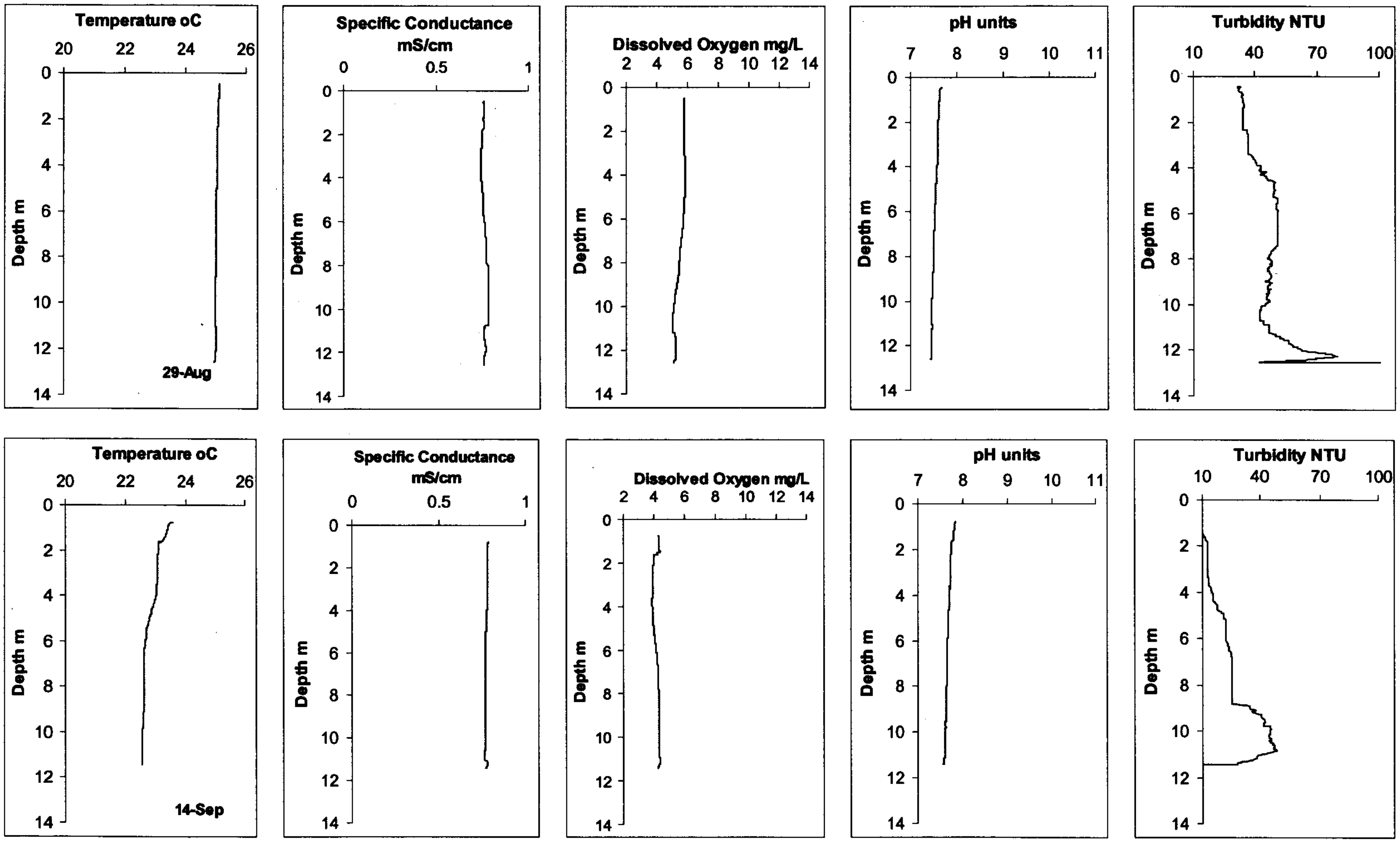


Fig. II-3c. Vertical Profiles of water quality variable near Navigation Light 48.

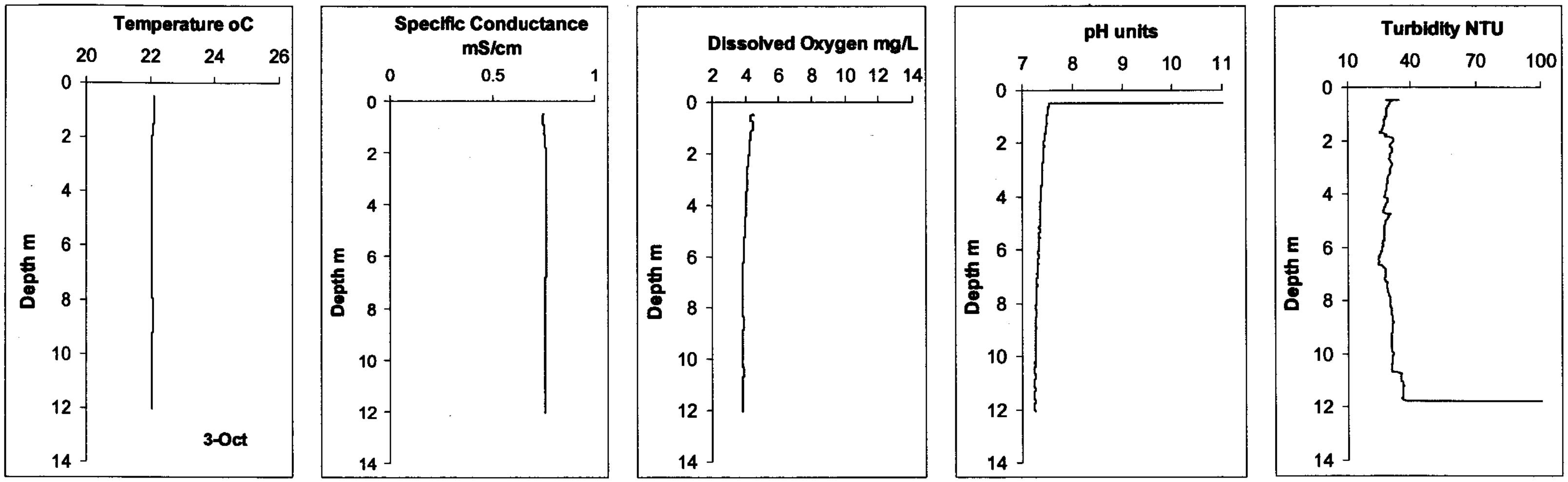


Fig. II-3d. Vertical Profiles of water quality variables near Turning Basin.

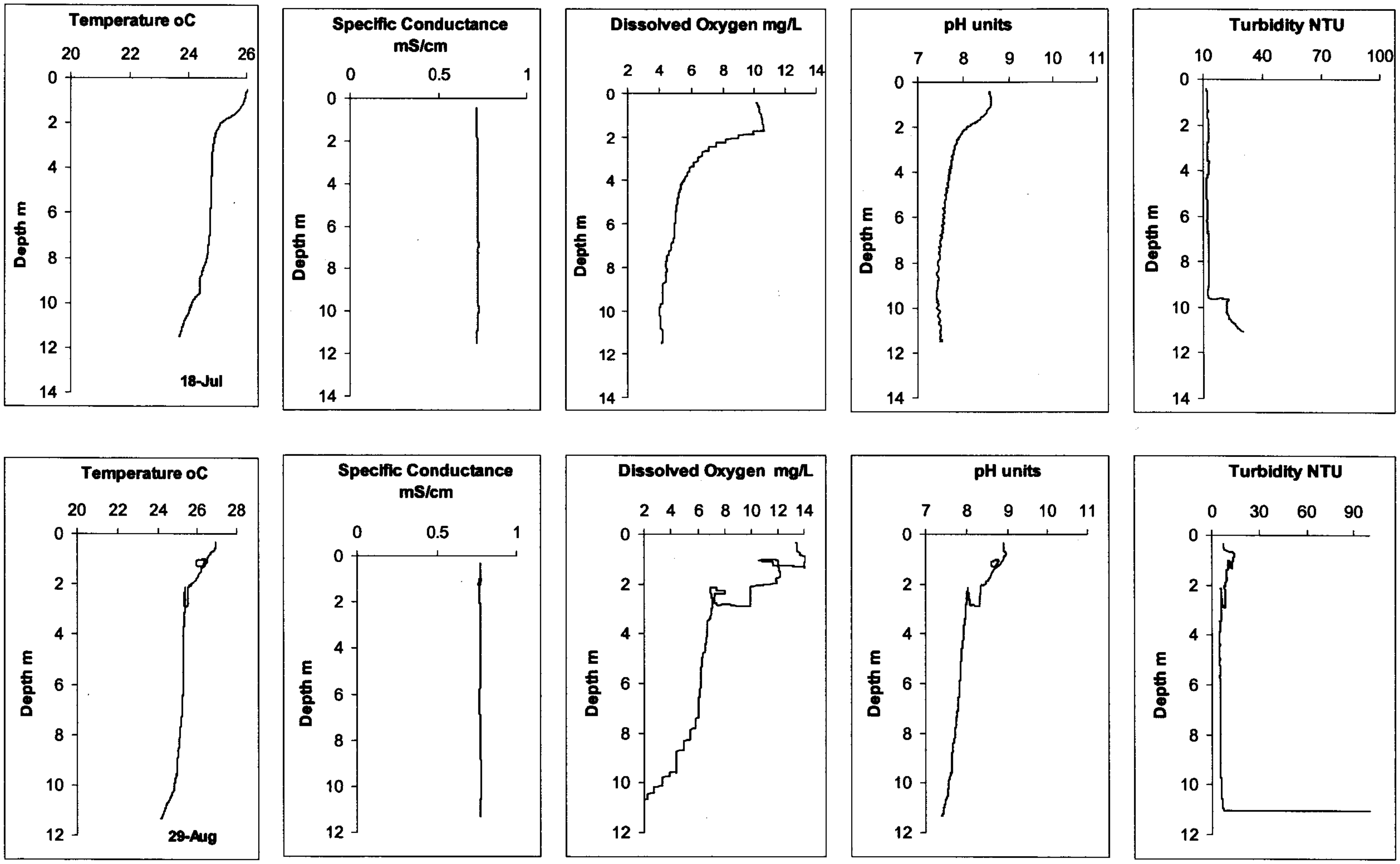


Fig. II-3d. Vertical Profiles of water quality variable near Turning Basin.

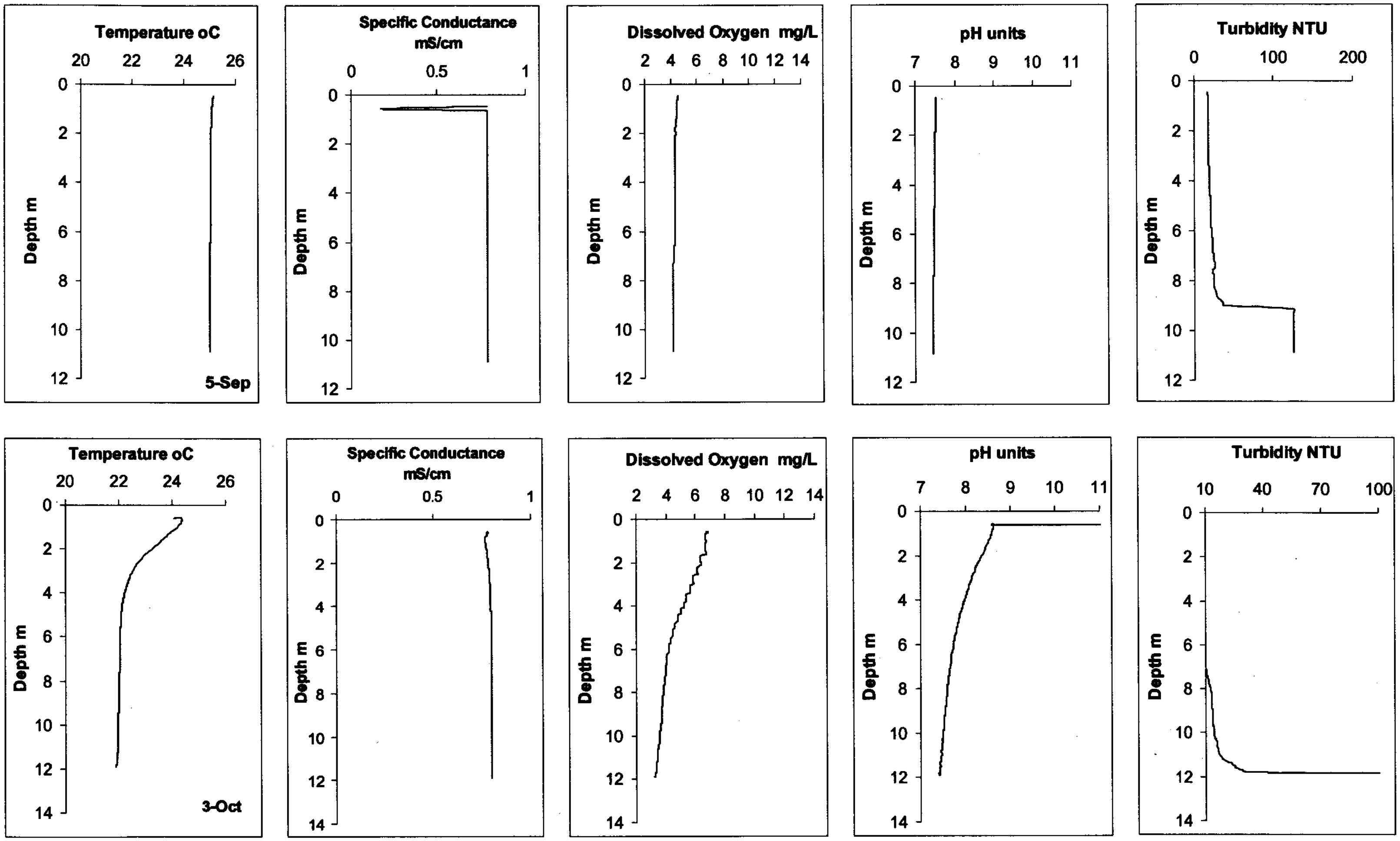


Fig. II-3d. Vertical Profiles of water quality variable near Turning Basin.

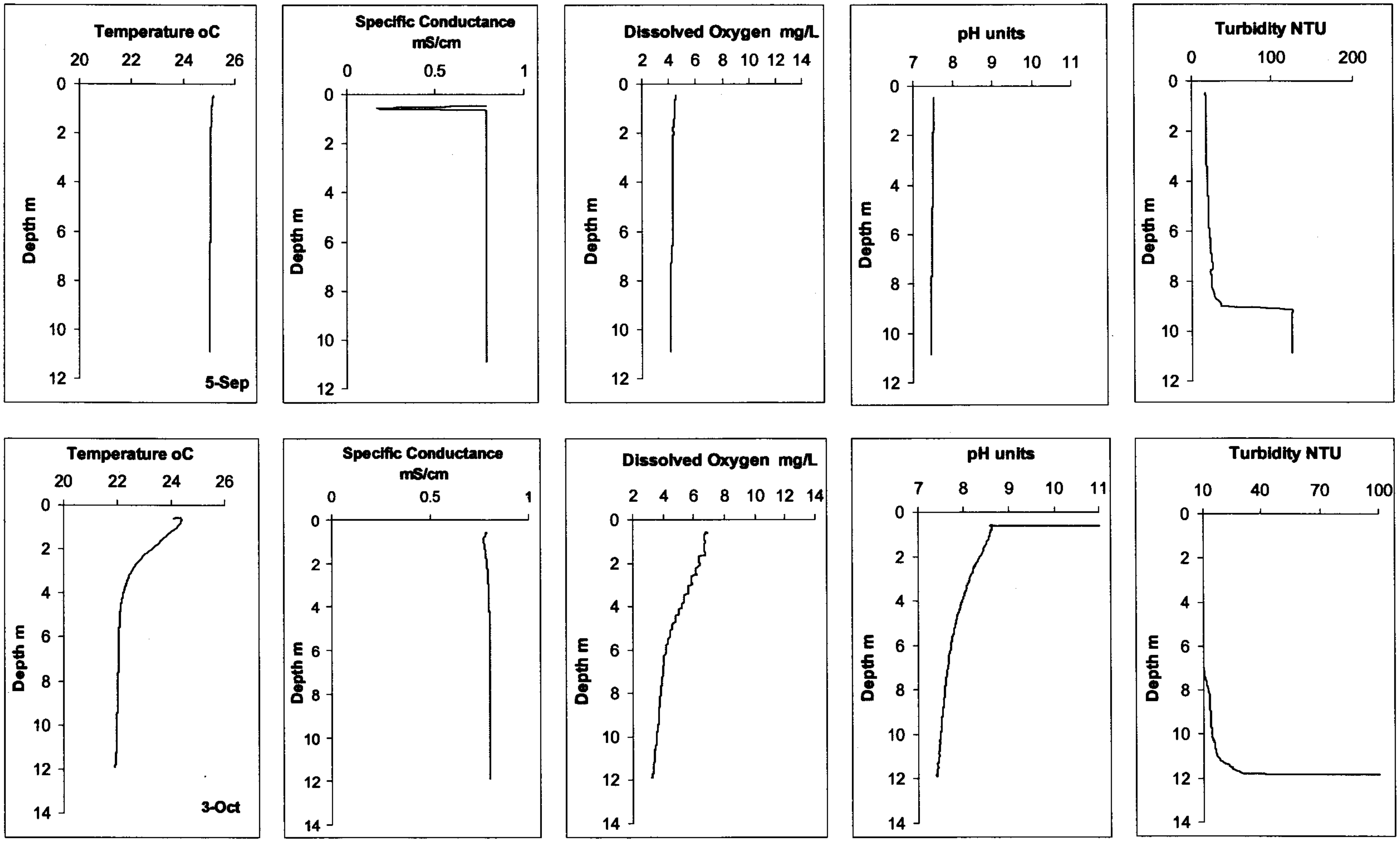


Fig. II-3e. Vertical profiles of water quality variables near Channel Point.

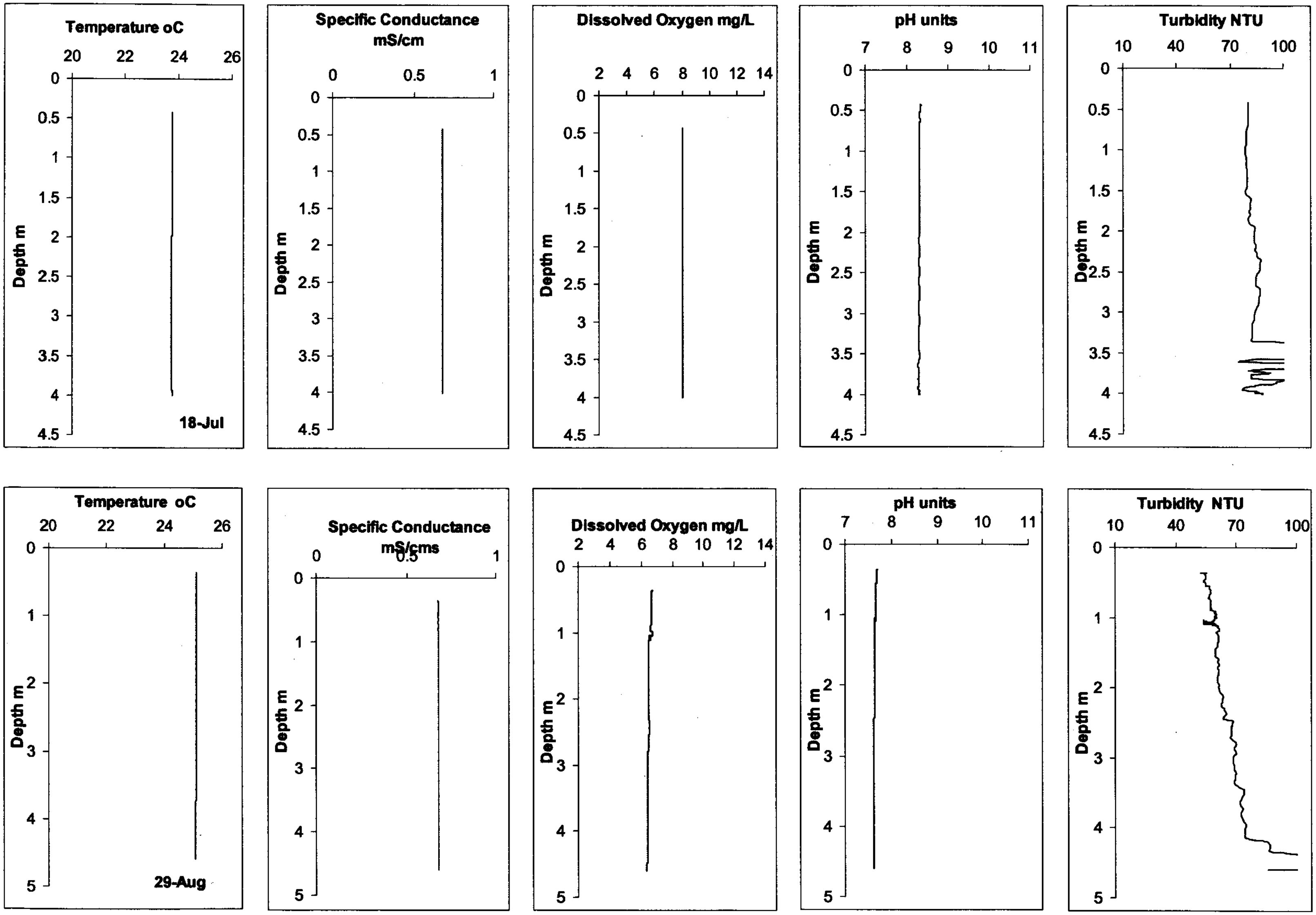


Fig. II-3e. Vertical profiles of water quality variables near Channel Point.

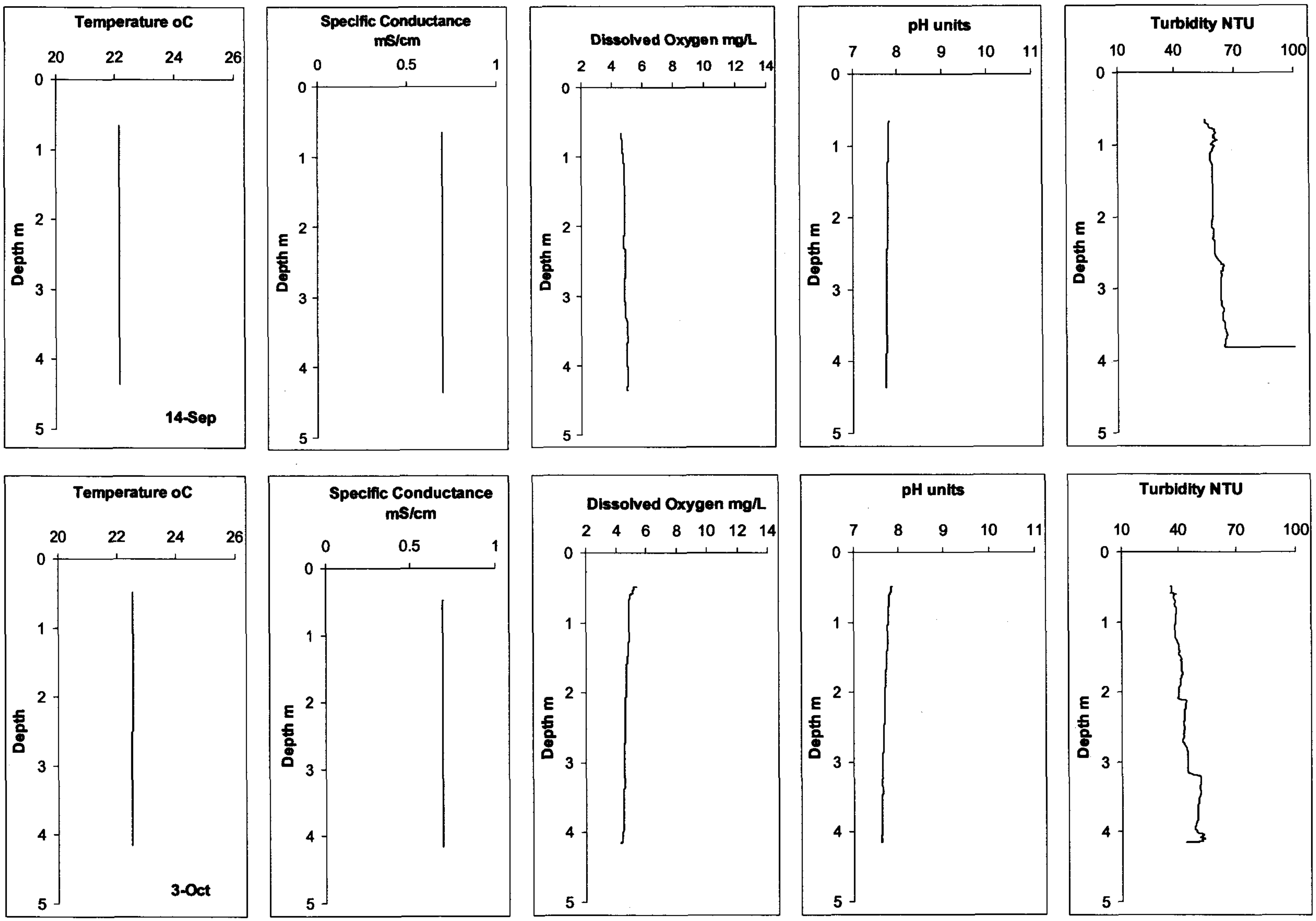


Fig. III-1. Monthly average chlorophyll *a* concentration measured at Rough and Ready Island between 1970 and 2000.

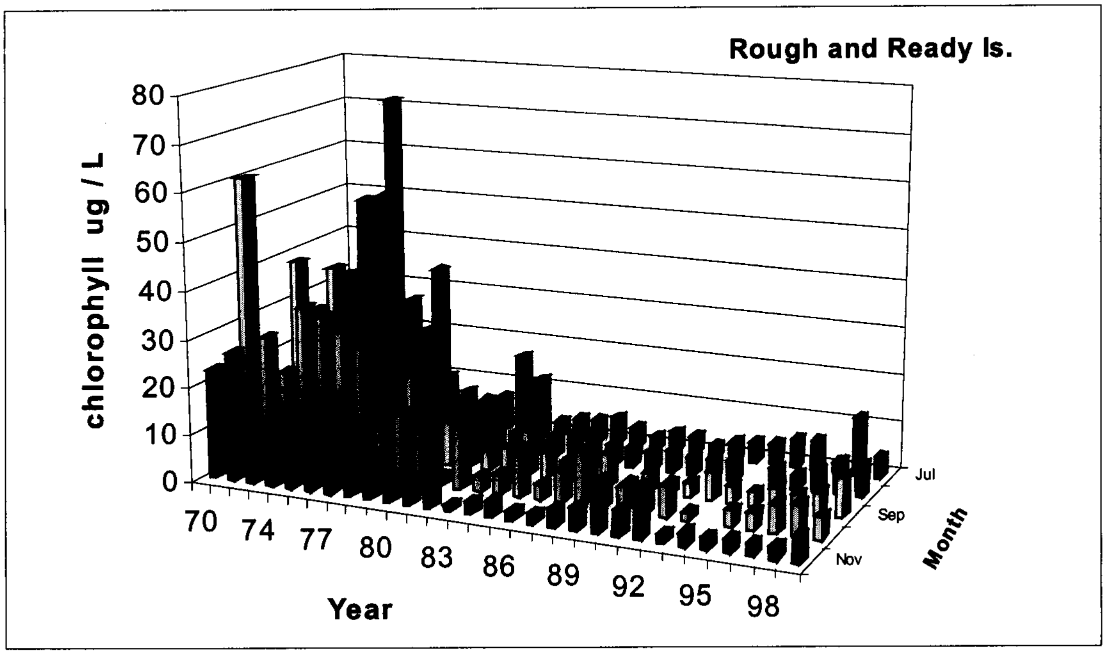


Fig. III-2. Chlorophyll *a* load at Vernalis between 1970 and 2000.

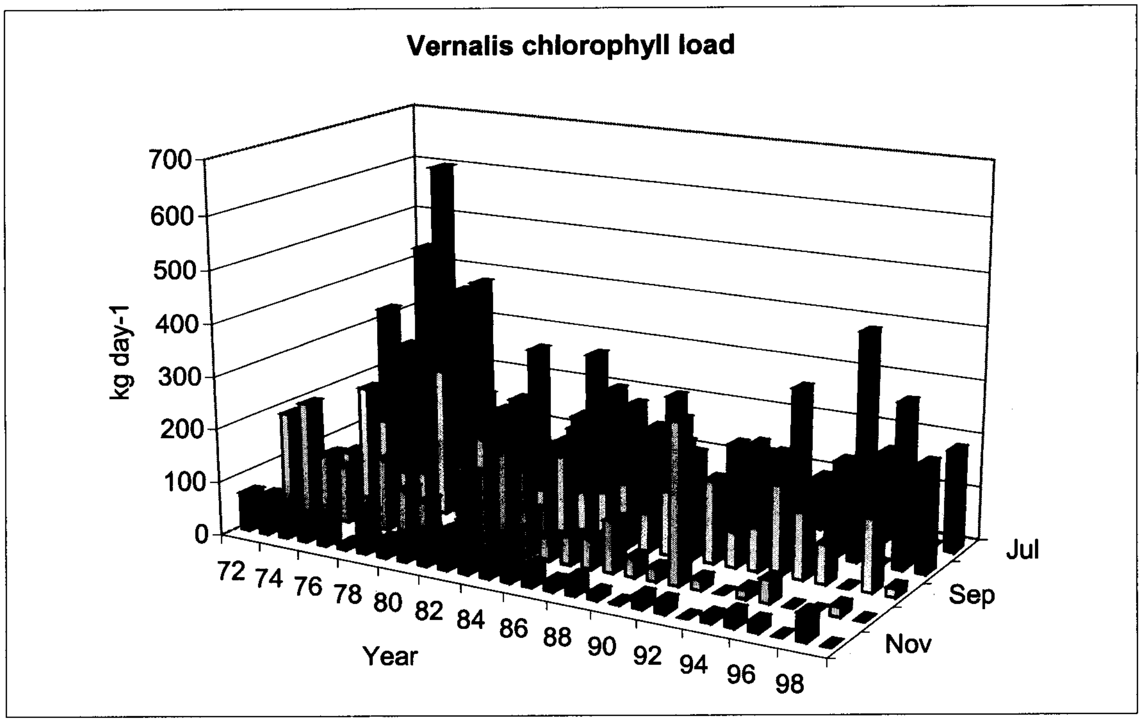


Fig. III-3. Mean and standard deviation of net plankton production rate in the photic zone for stations in the San Joaquin River. Turner Cut (TC), Rough and Ready (RR), Light 48 (L48), Turning Basin (TB), Channel Point (CP), Mossdale (MD), Vernalis (V), Crows Landing (CL).

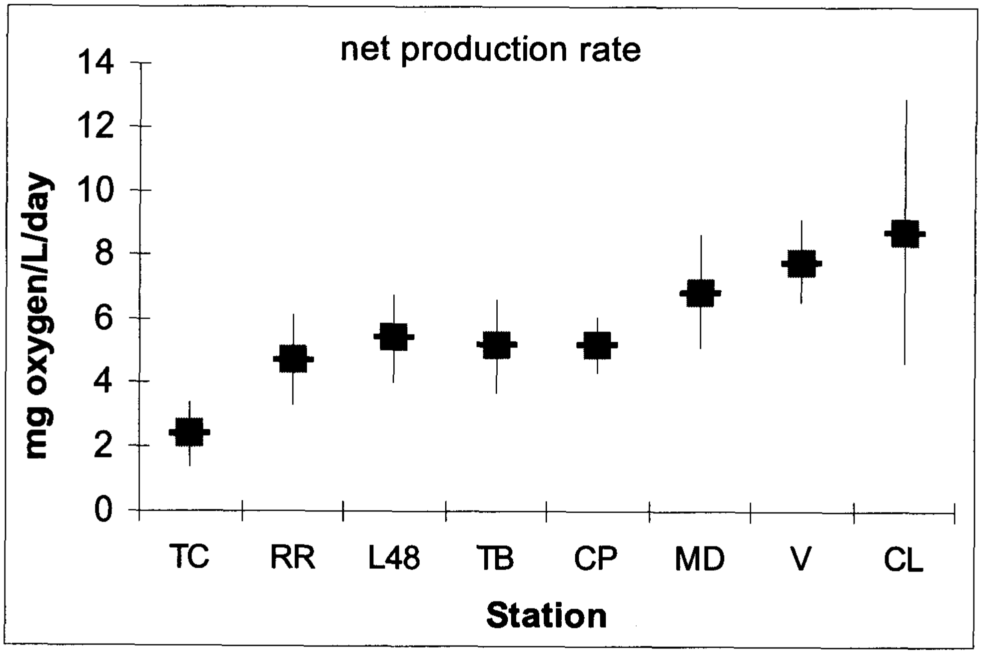


Fig. III-4. Mean and standard deviation of plankton respiration rate measured at stations in the San Joaquin River. Stations as in Fig. III-3.

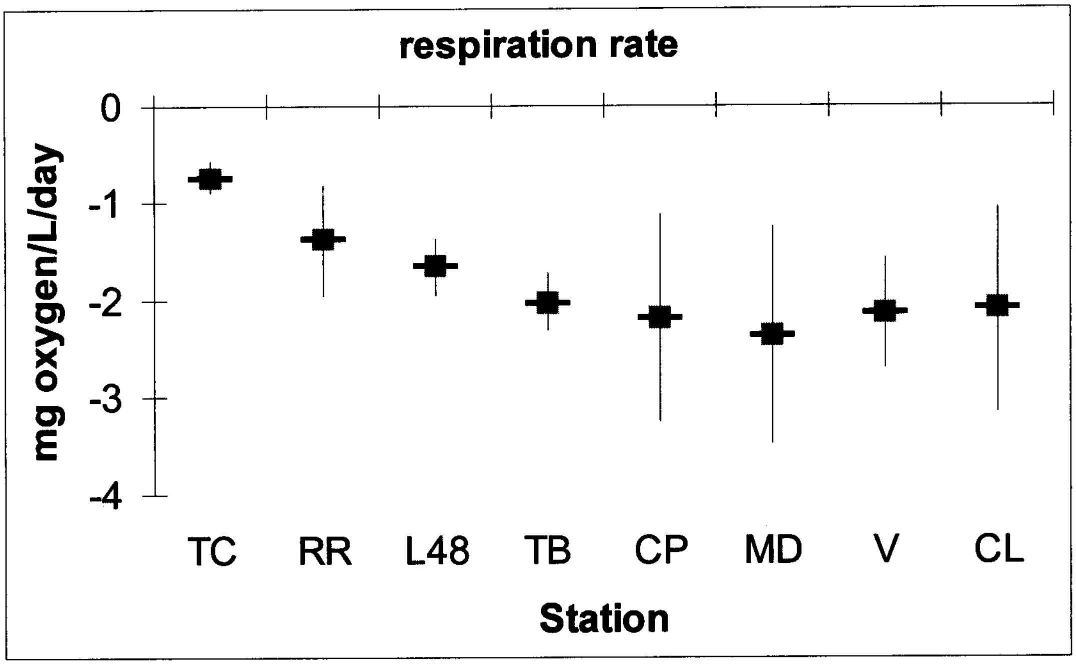


Fig. III-5. Mean and standard deviation of net plankton production rate normalized to chlorophyll *a* concentration at stations in the San Joaquin River. Stations as in Fig. III-3.

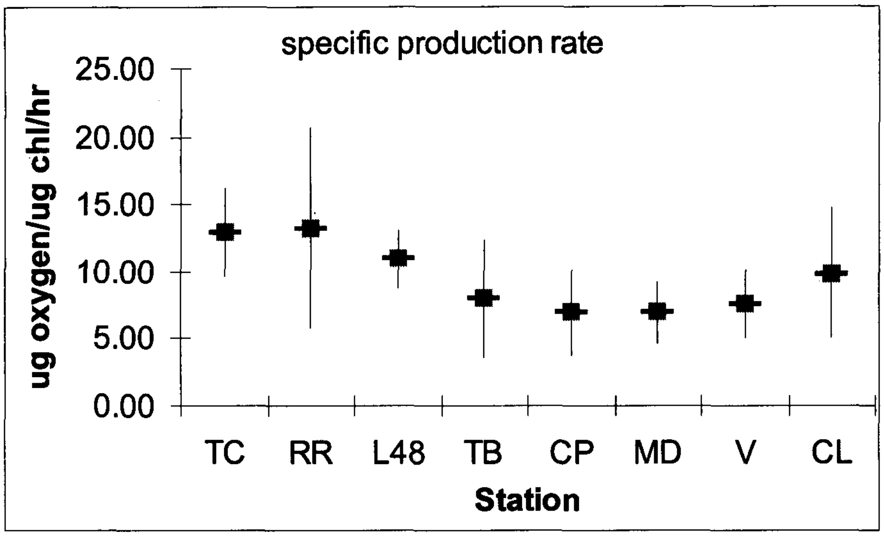


Fig. III-6 a. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Turner Cut.

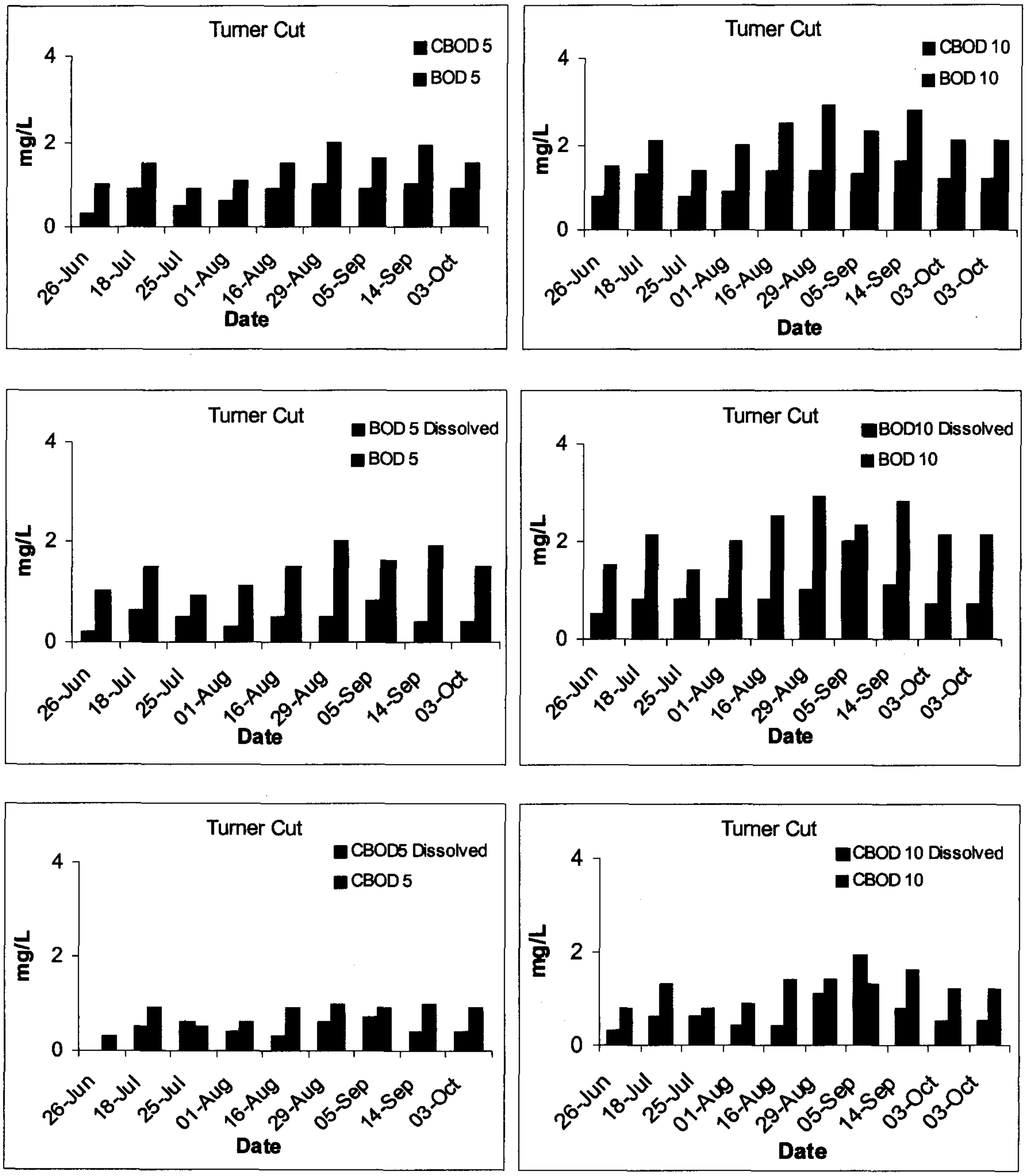


Fig. III-6 b. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Rough and Ready Island.

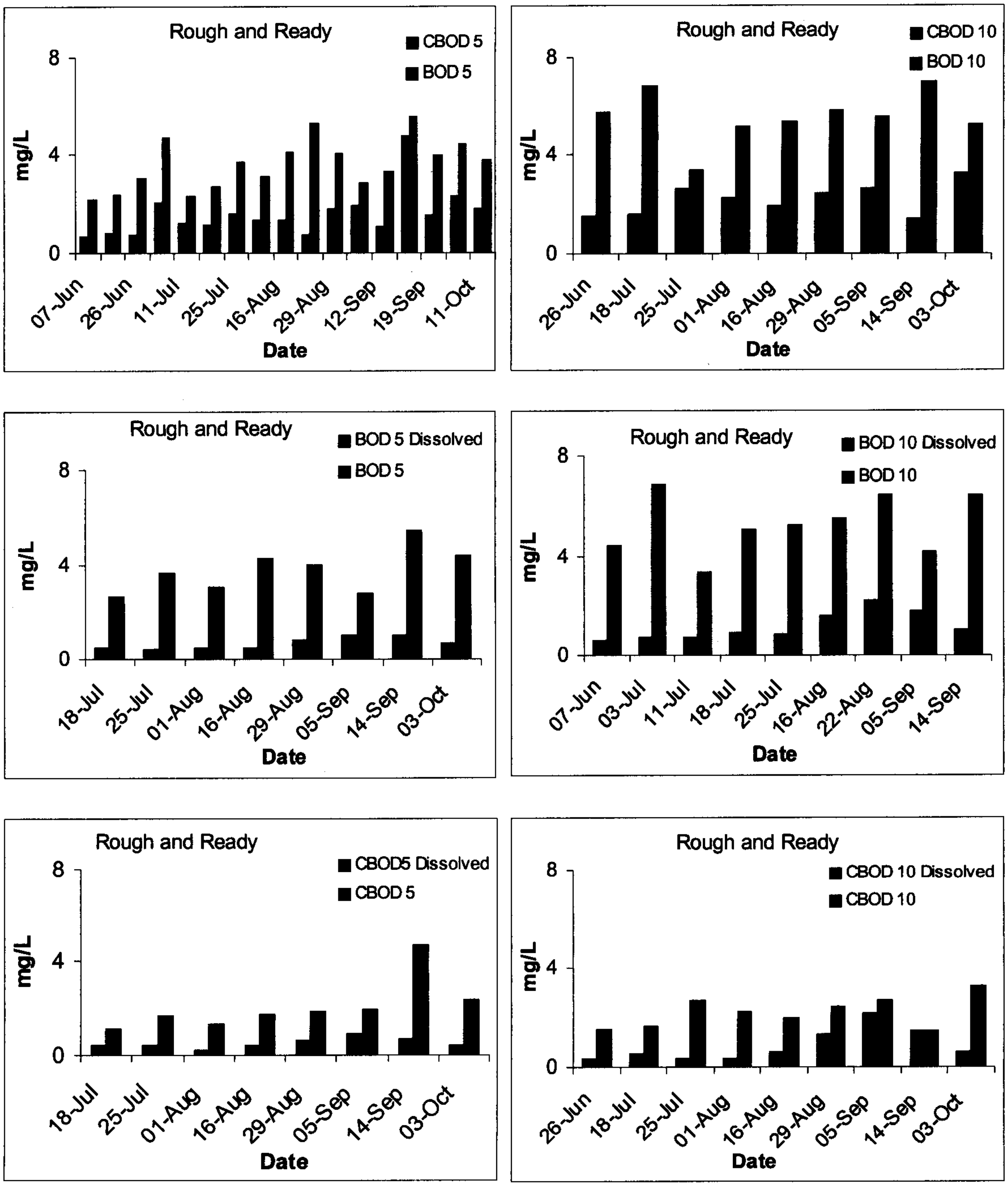


Fig. III-6 c. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Navigation Light 48.

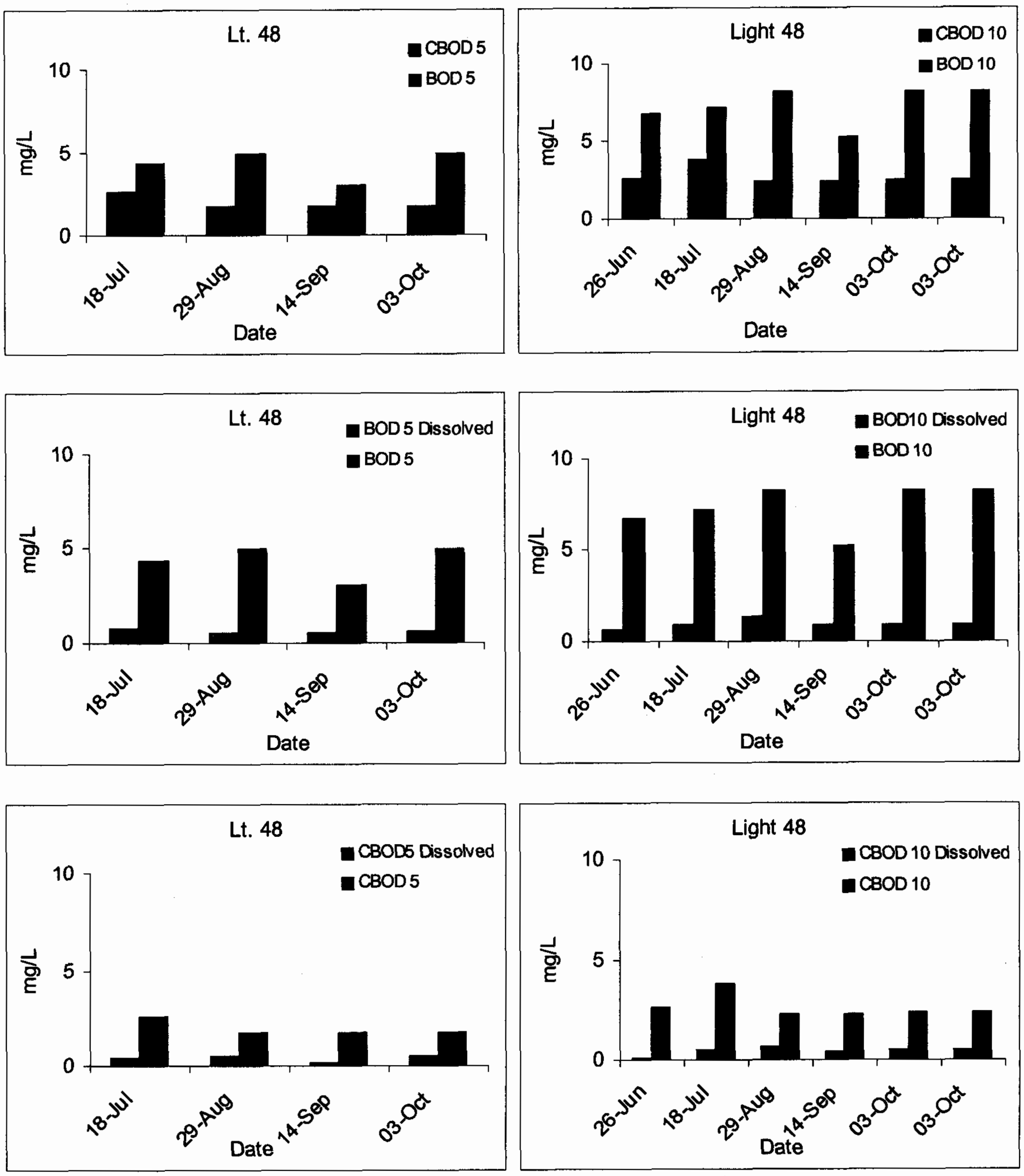


Fig. III-6 d. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Turning Basin.

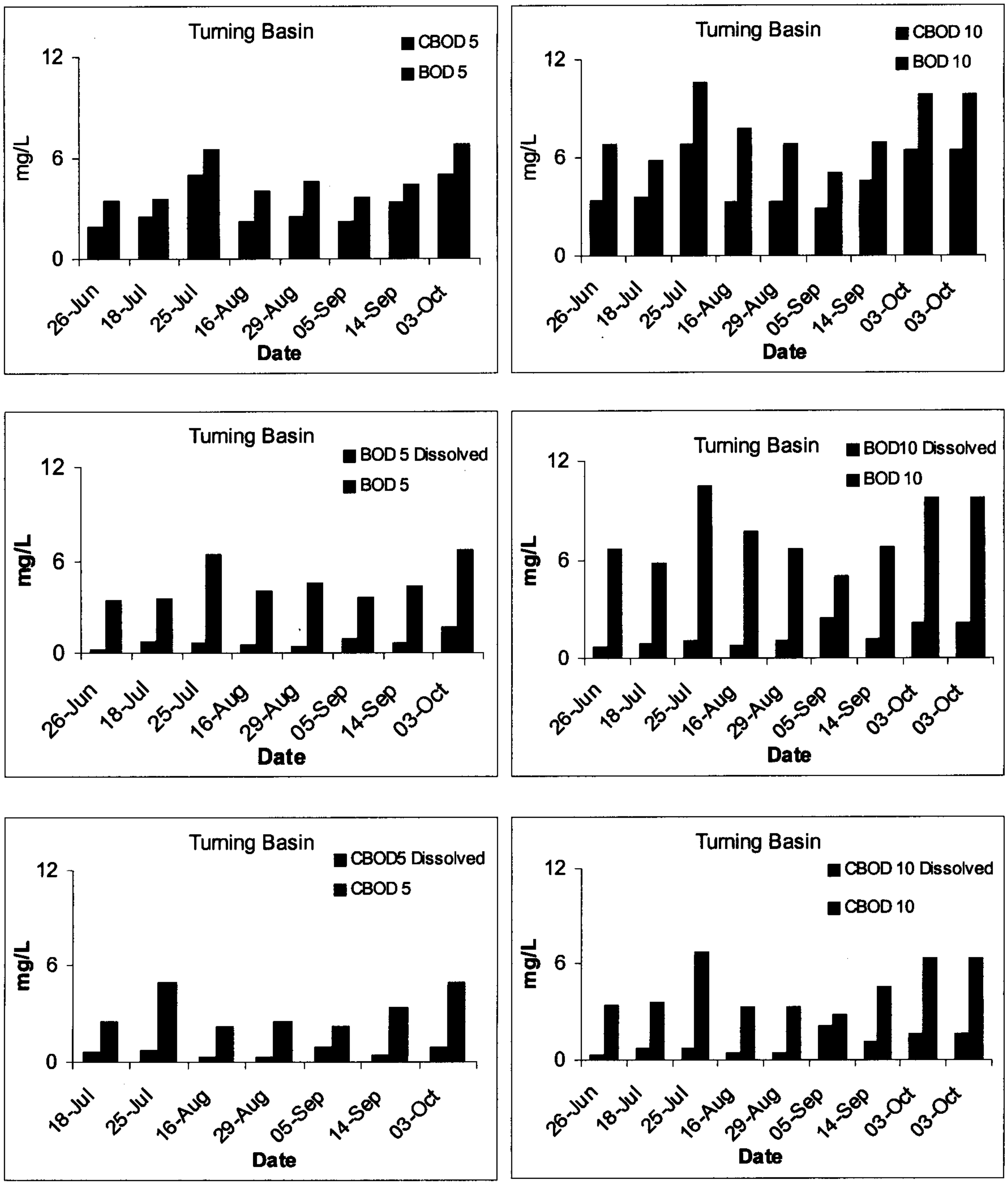


Fig. III-6 e. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Channel Point.

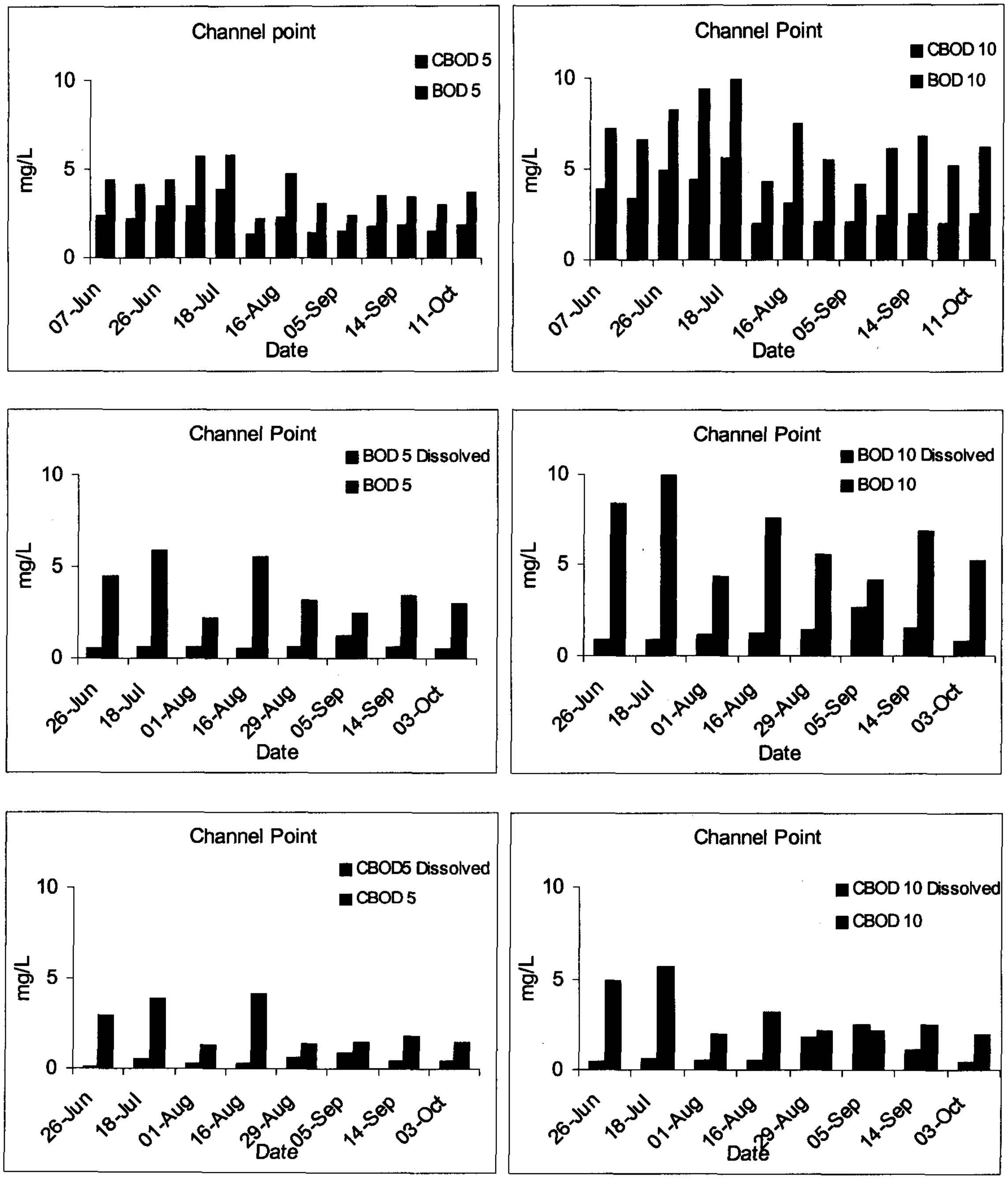


Fig. III-6 f. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Mossdale.

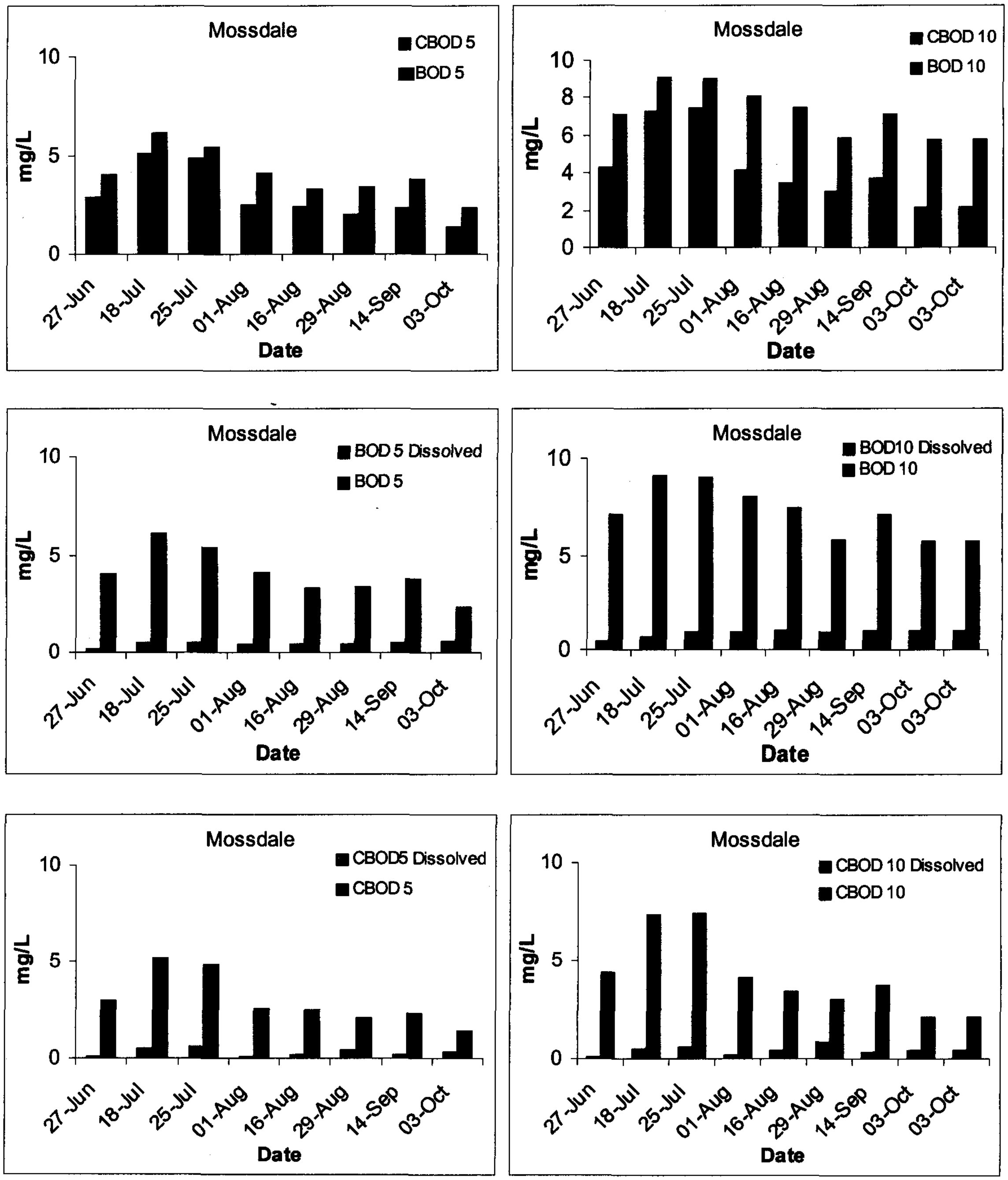


Fig. III-6 g. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Vernalis.

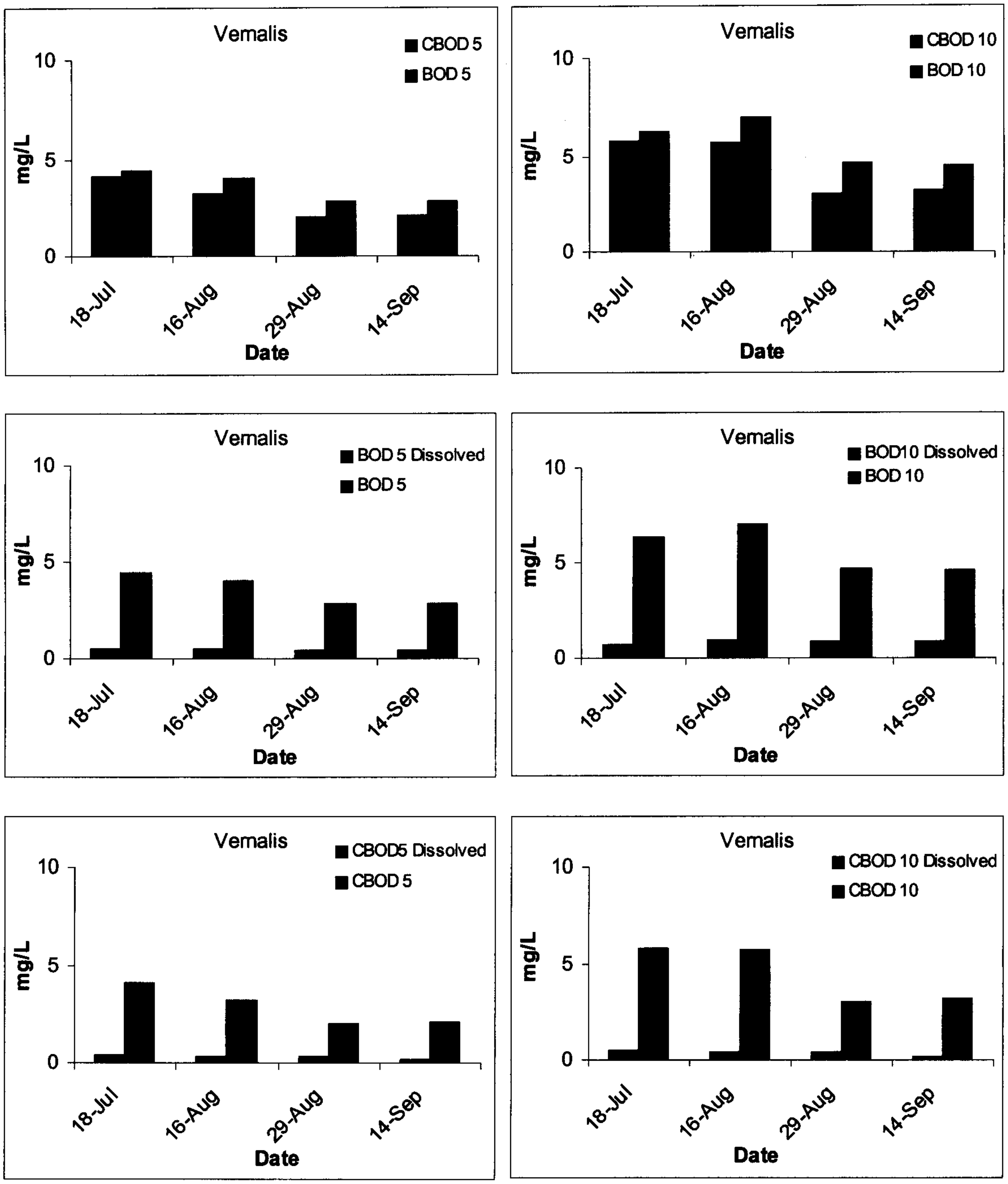


Fig. III-6 h. Comparison of total and dissolved BOD5 and BOD10 and total and dissolved carbonaceous BOD5 and BOD10 at Crows Landing.

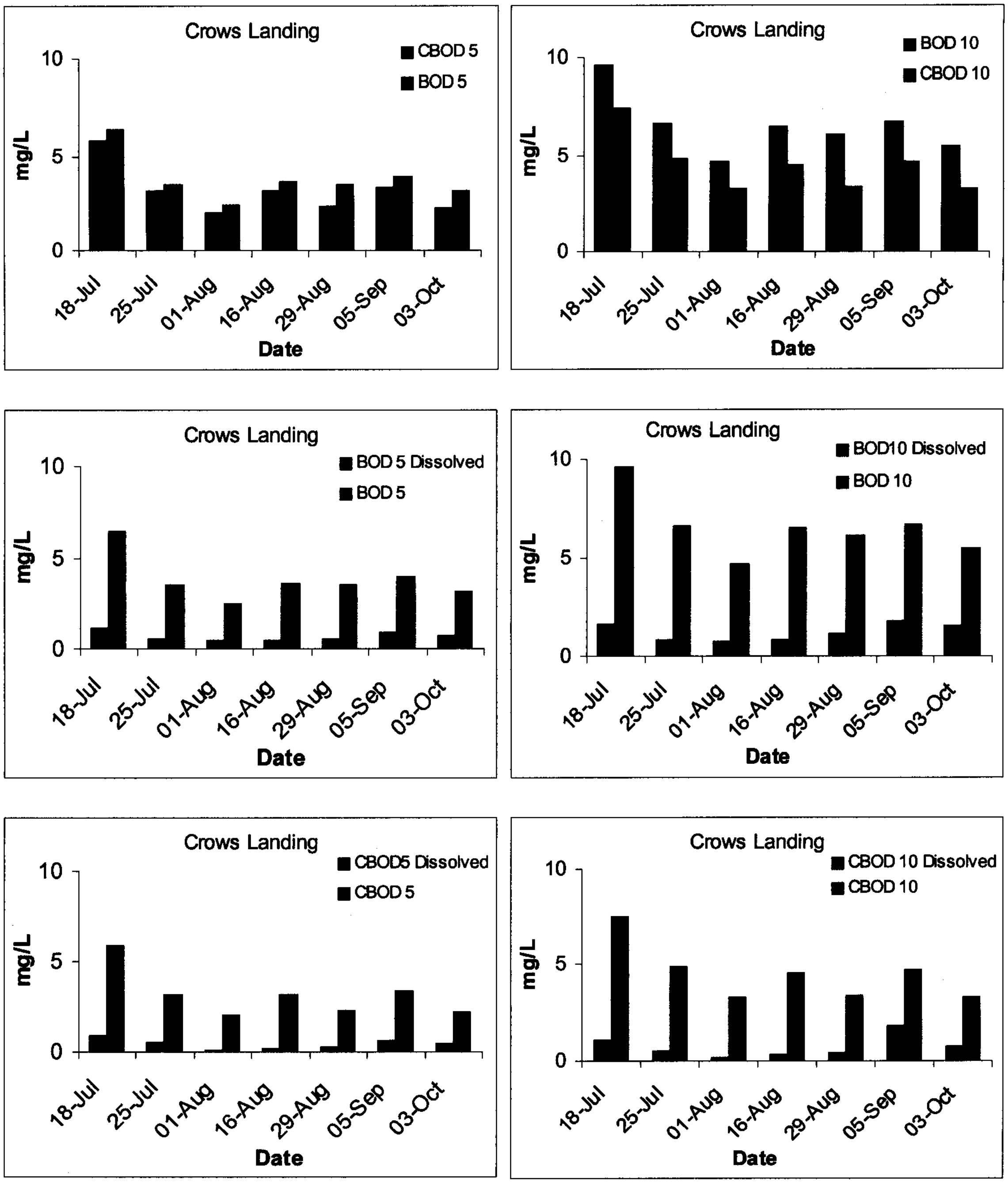
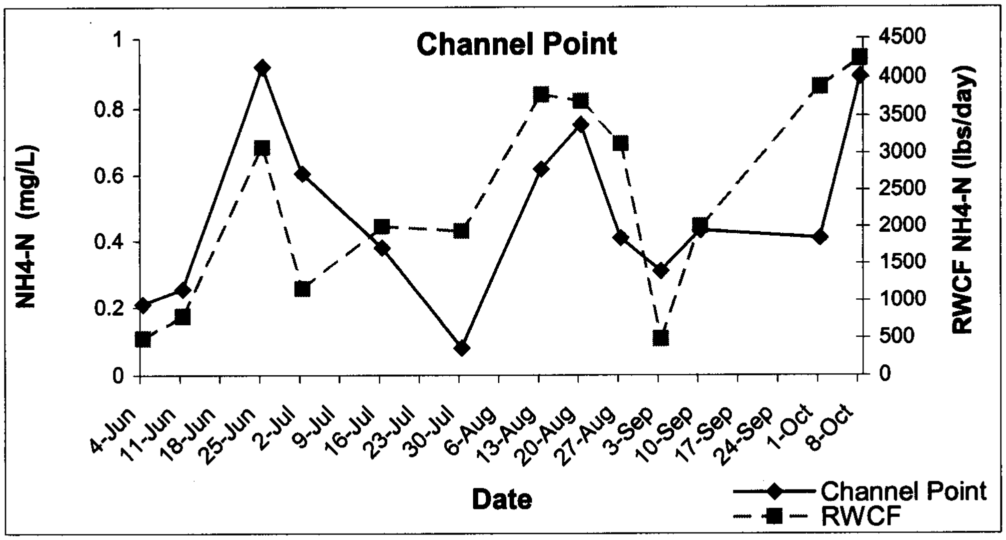


Fig. III-7. Comparison of ammonia load from the RWCF and ammonia concentration at Channel Point and Rough and Ready Island in 2001.



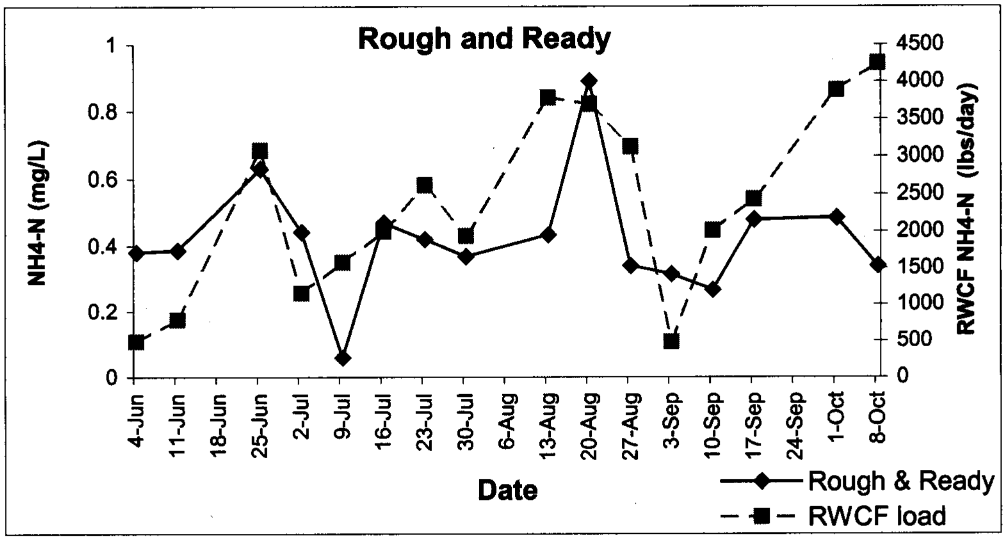


Fig. III-8. Comparison of ammonia load from the Regional Water Treatment Control Facility and NBOD at Rough and Ready Island.

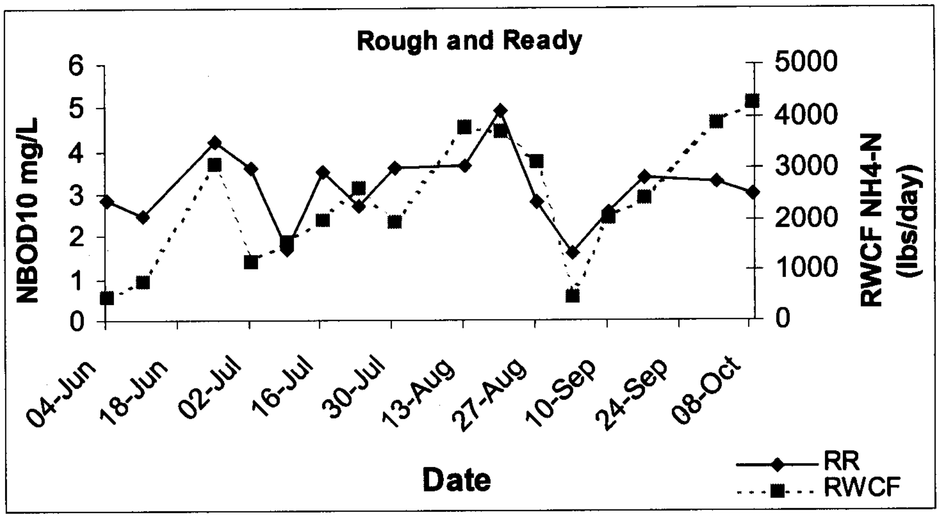
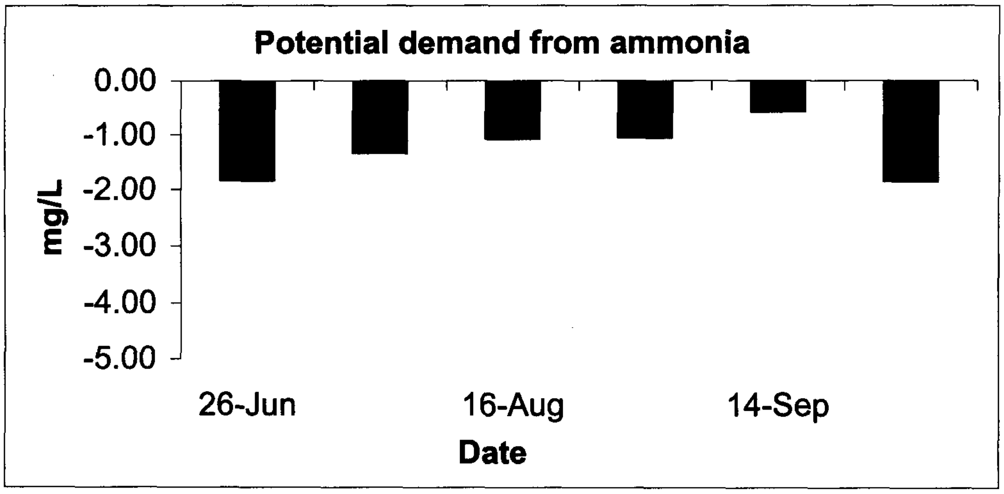


Fig. III-9. Comparison of the potential oxygen demand from nitrification of ammonia and organic nitrogen concentration in the Deep Water Channel.



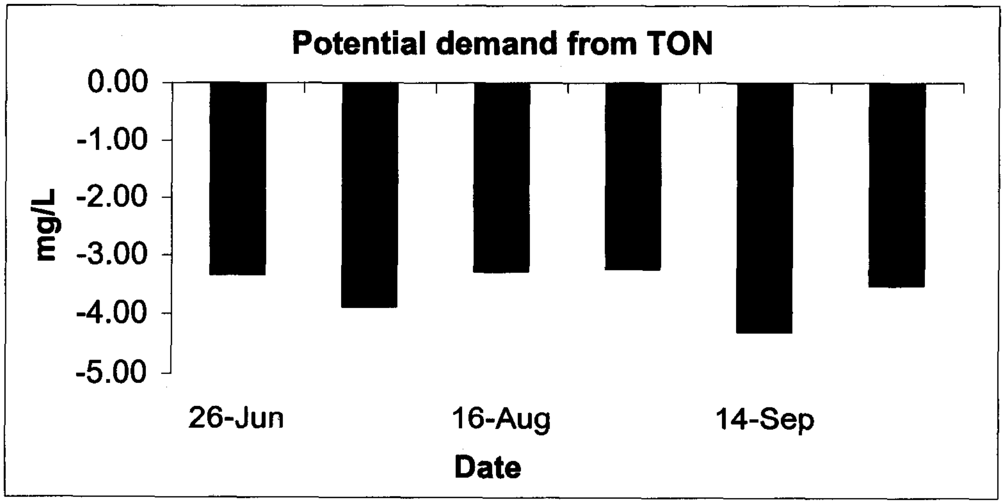
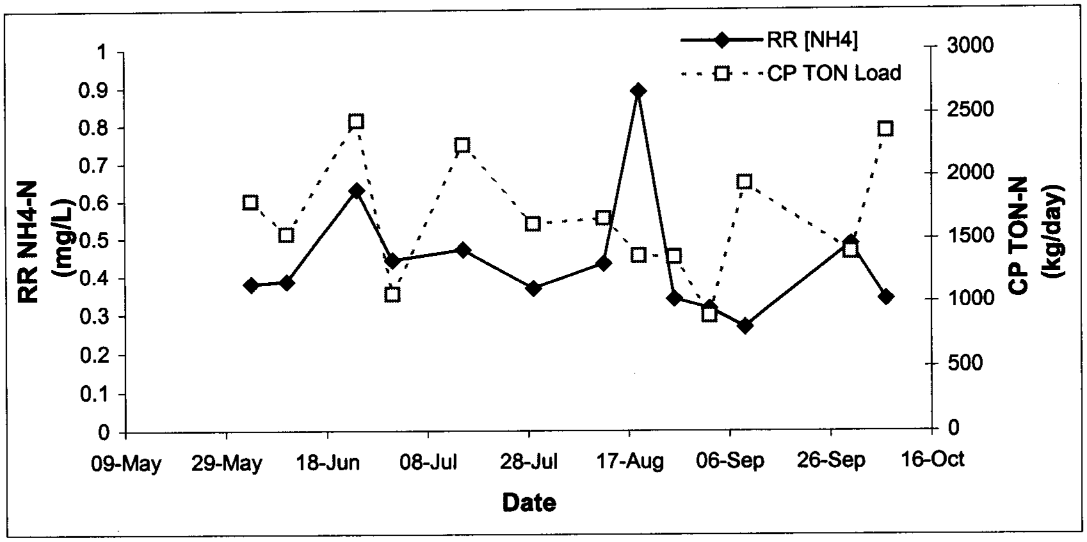


Fig. III-10. Comparison of ammonia concentration (a) and nitrogenous BOD (b) in the Deep Water Channel at Rough and Ready Island with organic nitrogen load from upstream at Channel Point.

a)



b)

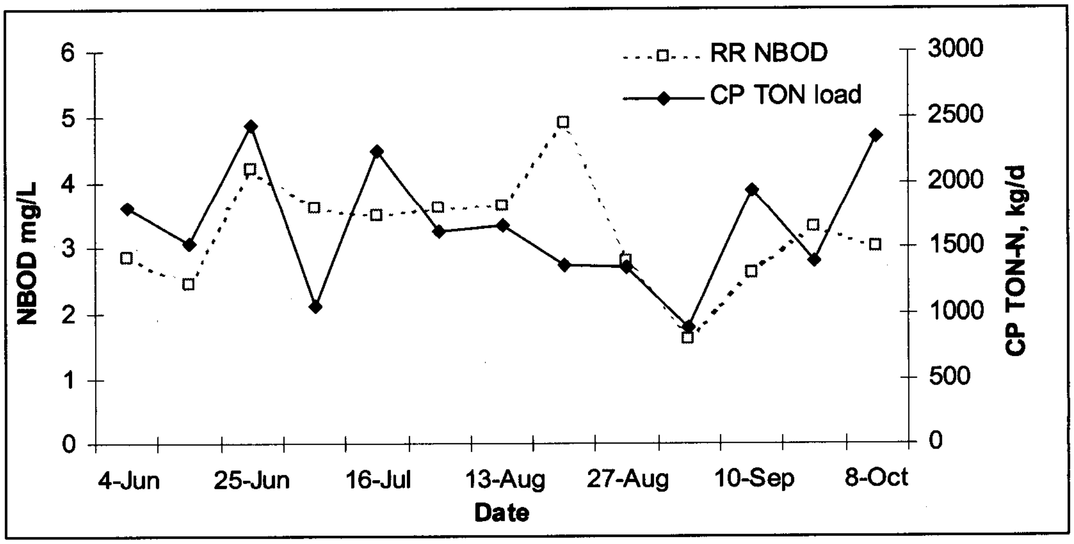
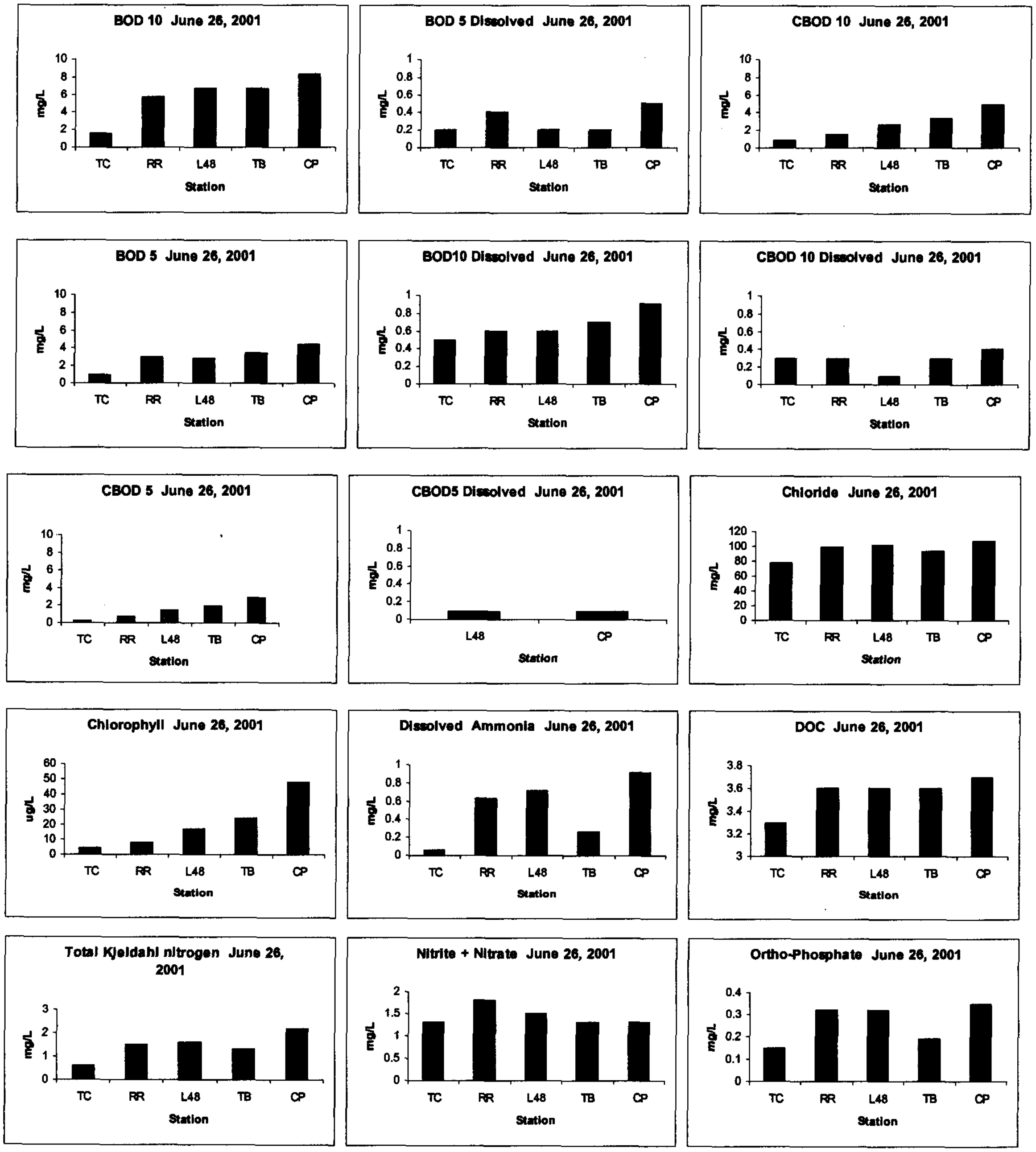
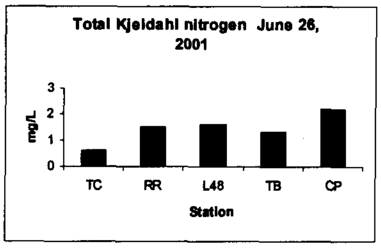
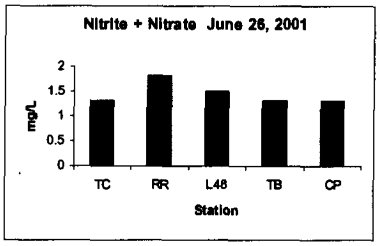


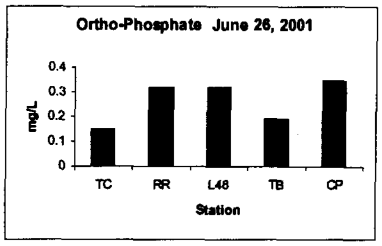
Fig. III-11 a. Concentration of water quality variables measured at stations in the San Joaquin River on June 26, 2001. Turner Cut (TC), Rough and Ready Island (RR), Light 48 (L48), Turning Basin (TB) and Channel Point (CP).

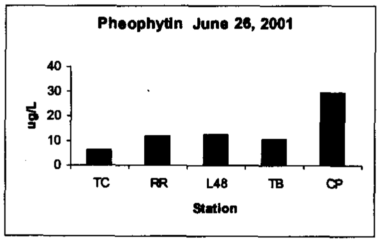


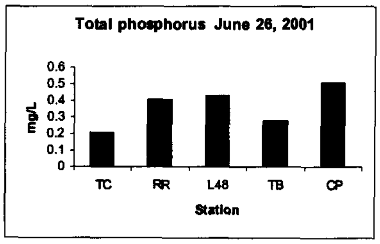
Lehman 4-19-02 Oxygen demand Figures and Tables

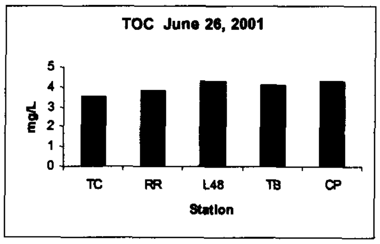

Total Kjeldahl nitrogen June 26, 2001

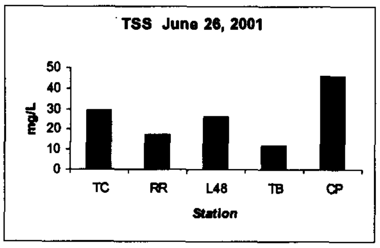

Nitrite + Nitrate June 26, 2001


Ortho-Phosphate June 26, 2001


Pheophytin June 26, 2001


Total phosphorus June 26, 2001


TOC June 26, 2001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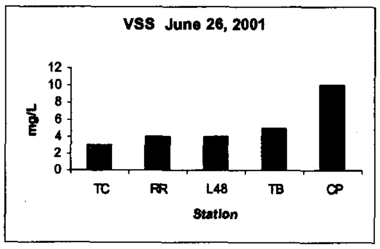
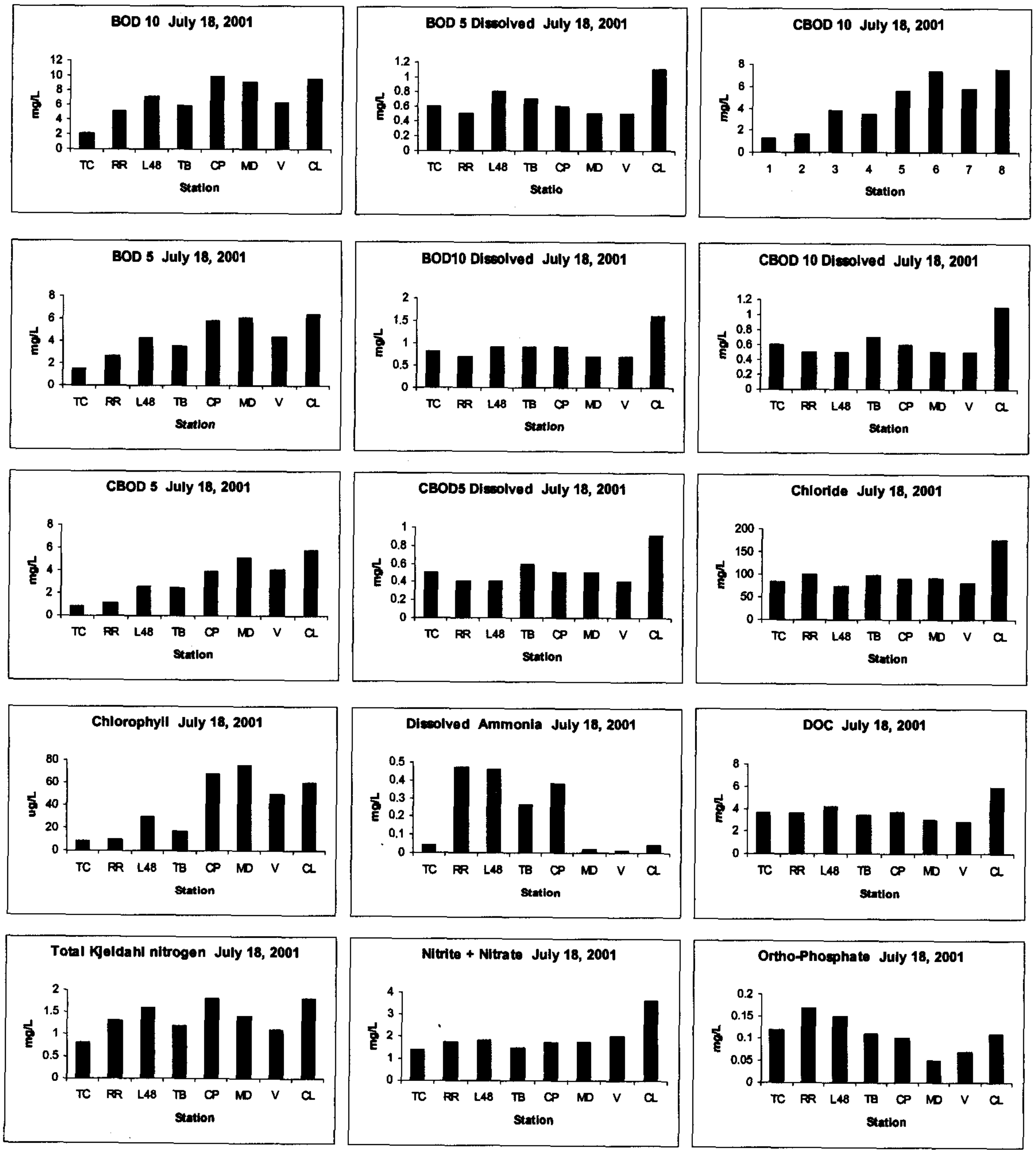
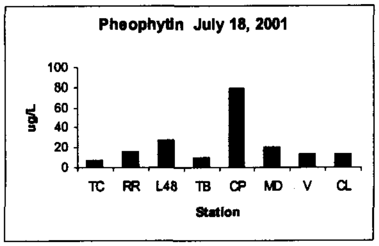
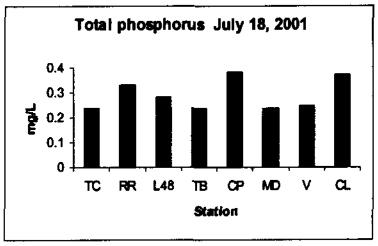

VSS June 26, 2001

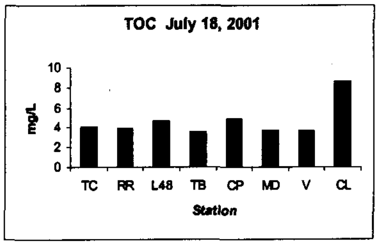
Fig. III-11 b. Concentration of water quality variables measured at stations in the San Joaquin River on July 18, 2001.

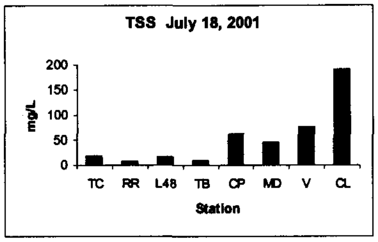


Lehman 4-19-02 Oxygen demand Figures and Tables


Pheophytin July 18, 2001


Total phosphorus July 18, 2001


TOC July 18, 2001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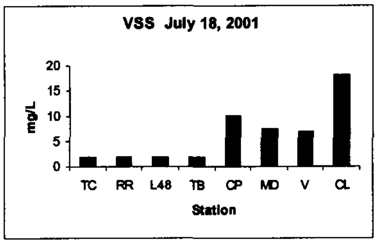
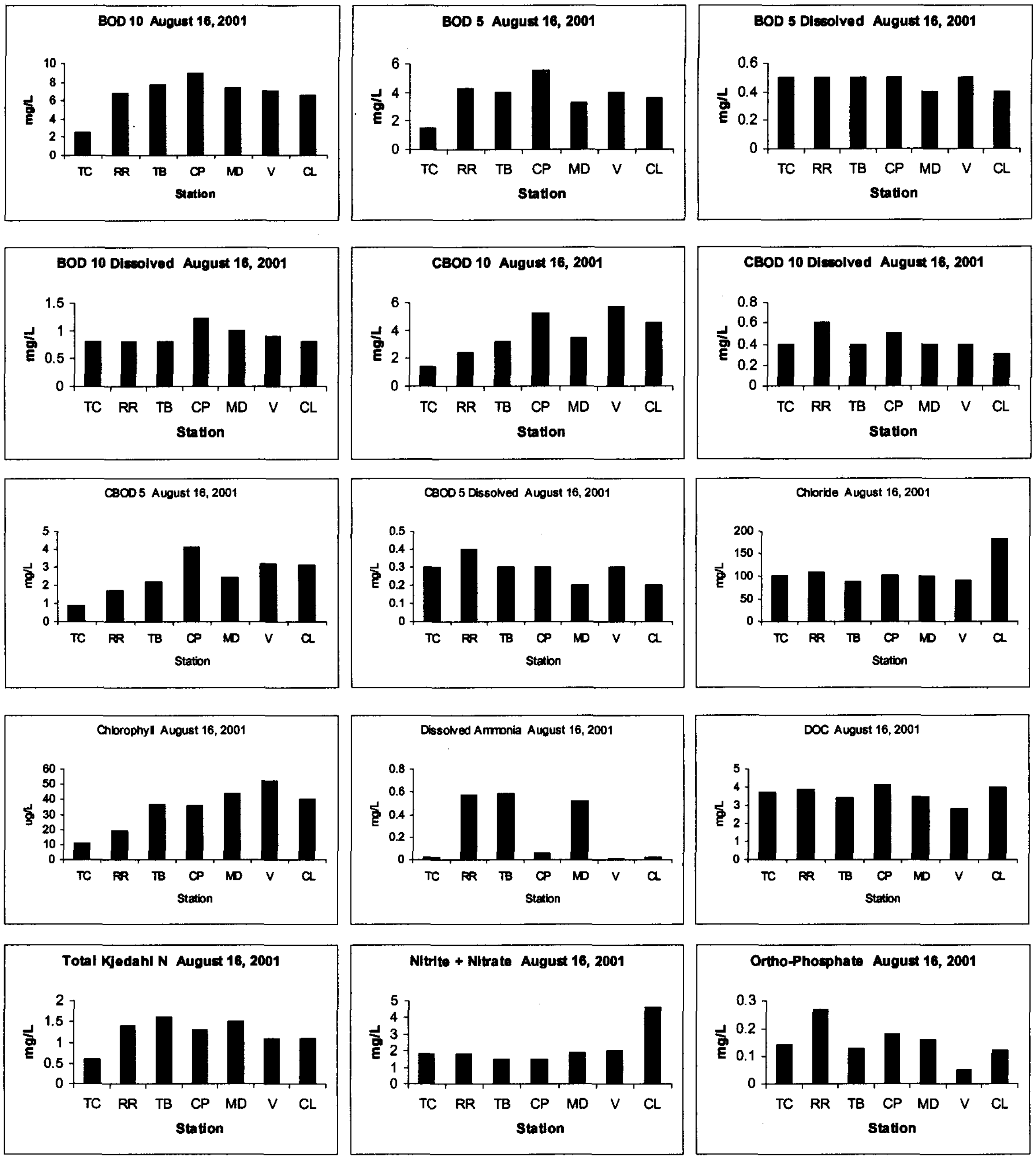
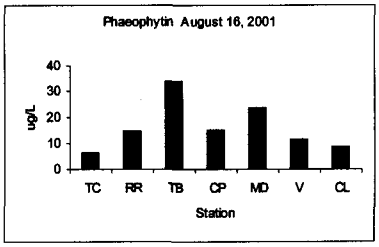

VSS July 18, 2001

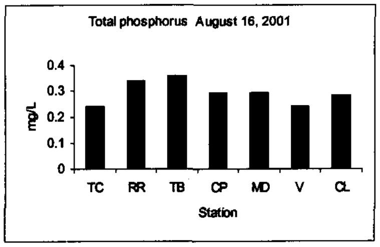
Fig. III-11 c. Concentration of water quality variables measured at stations in the San Joaquin River on August 18, 2001.



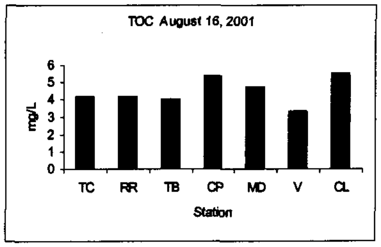
Lehman 4-19-02 Oxygen demand Figures and Tables



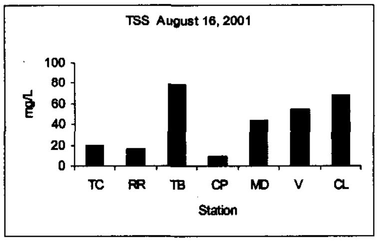
Phaeophytin August 16, 2001



Total phosphorus August 16, 2001



TOC August 16, 2001



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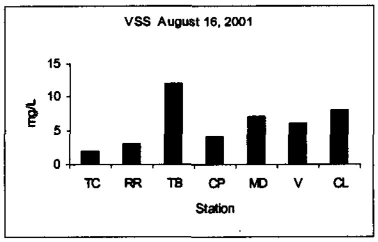
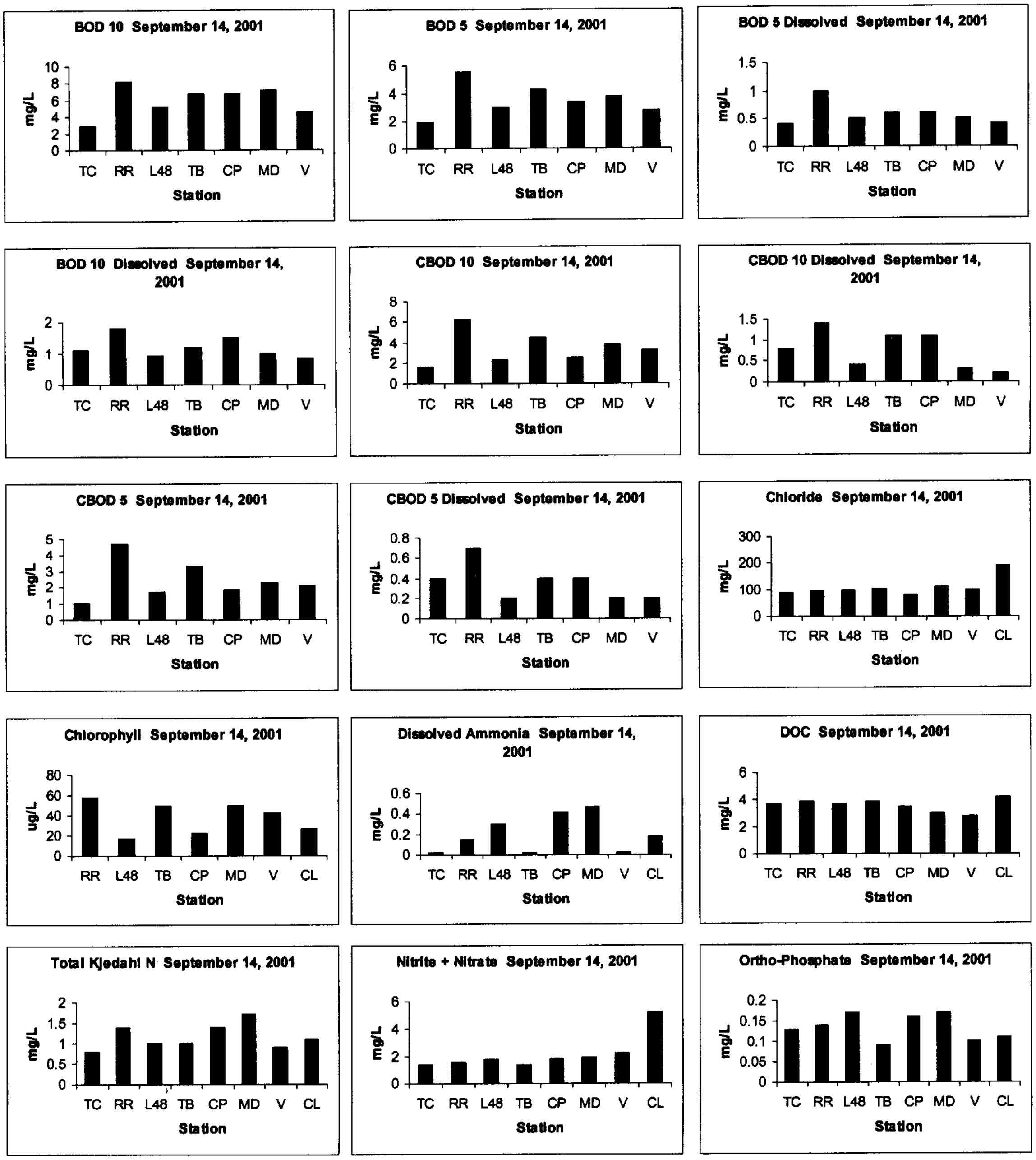
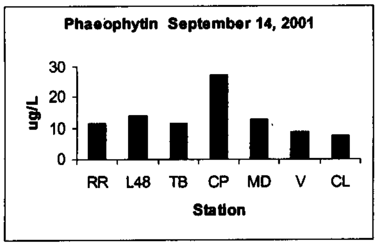


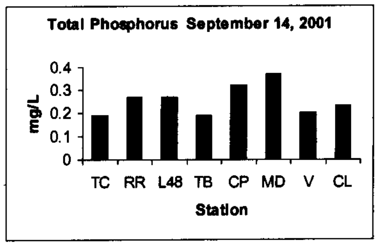
VSS August 16, 2001

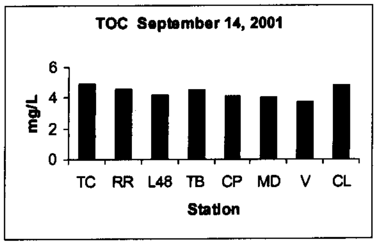
Fig. III-11 d. Concentration of water quality variables measured at stations in the San Joaquin River on September 14, 2001.

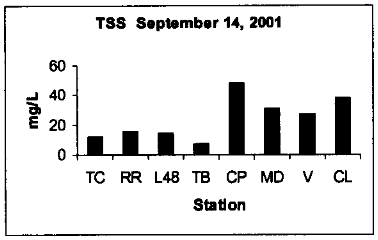


Lehman 4-19-02 Oxygen demand Figures and Tables









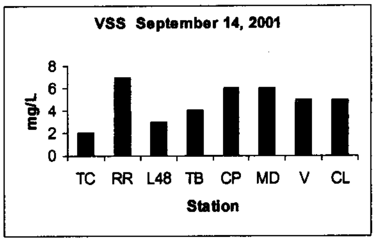
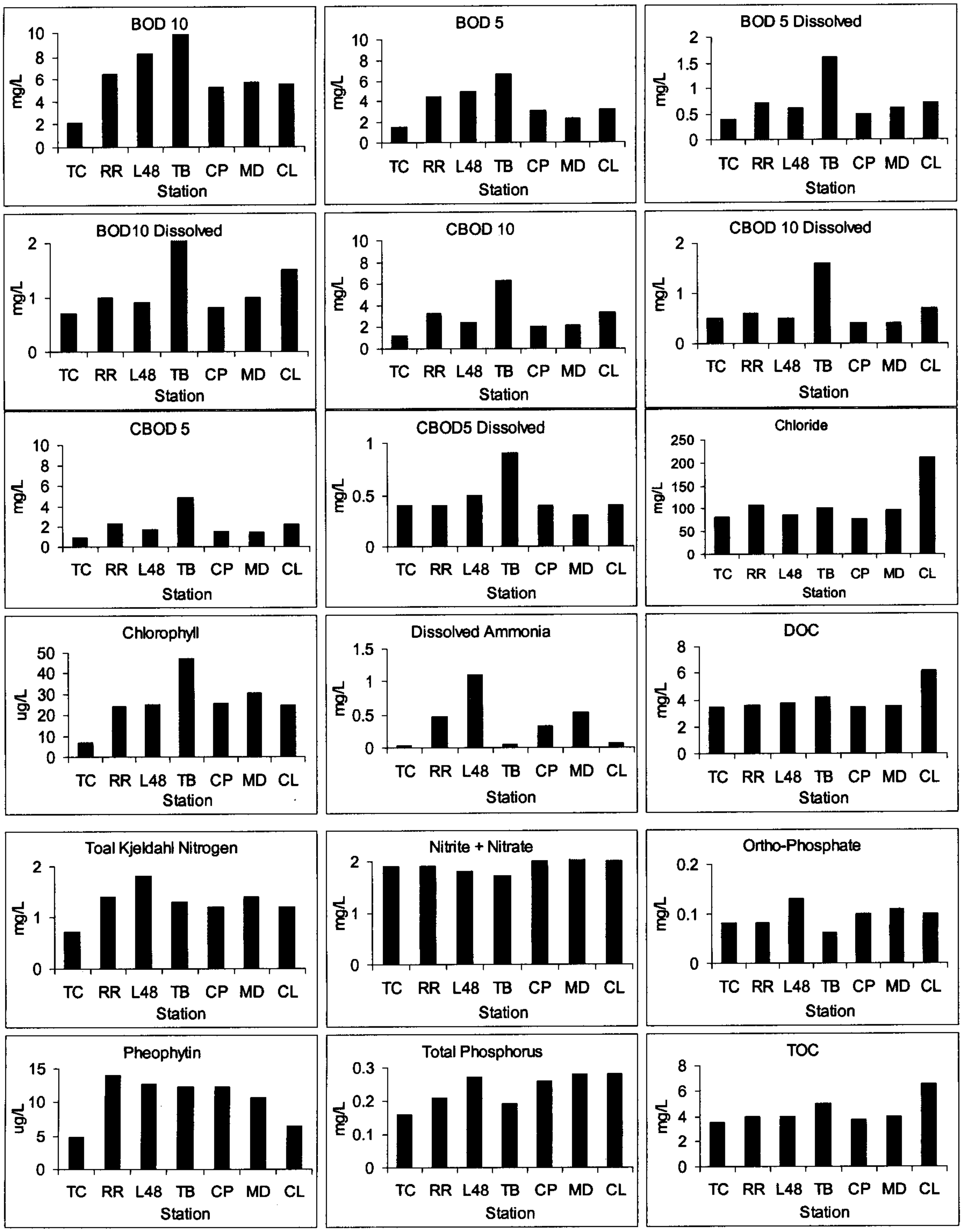
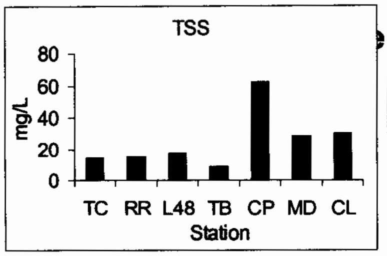
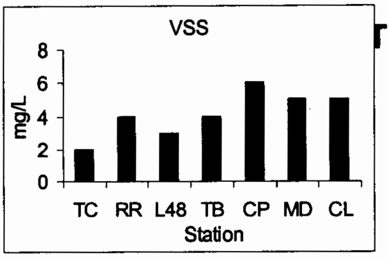


Fig. III-11 e. Concentration of water quality variables measured at stations in the San Joaquin River on October 3, 2001.




TSS
80
60
40
20
0
mg/L
TC
RR
L48
TB
CP
MD
CL
Station


VSS
8
6
4
2
0
mg/L
TC
RR
L48
TB
CP
MD
CL
Station

Tables

Fig. III-12. Total organic carbon to total organic nitrogen molar ratios by station and date.

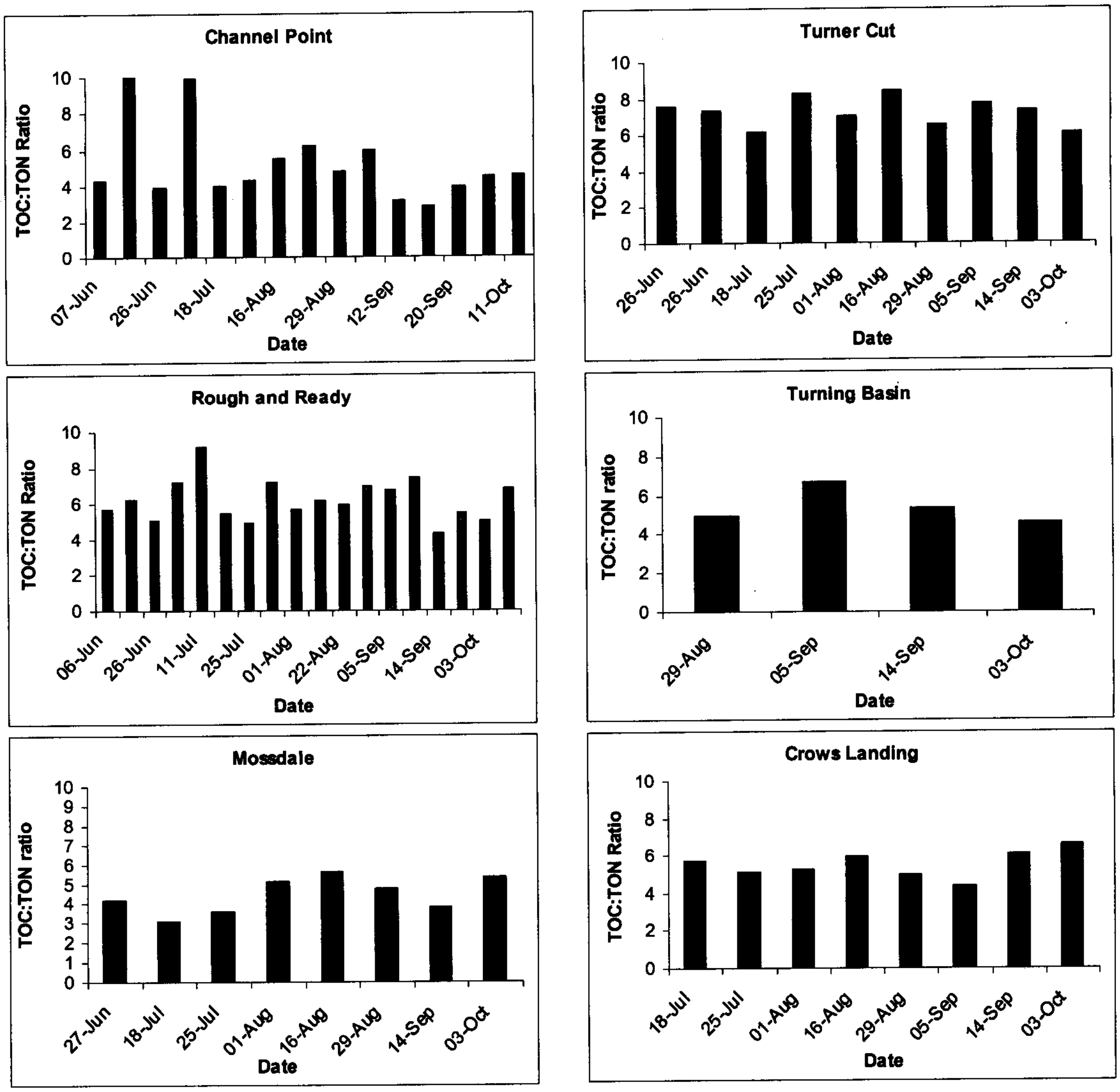


Fig. III-13. Percent contribution of algal biomass to total carbon and organic nitrogen measured in the Deep Water Channel.

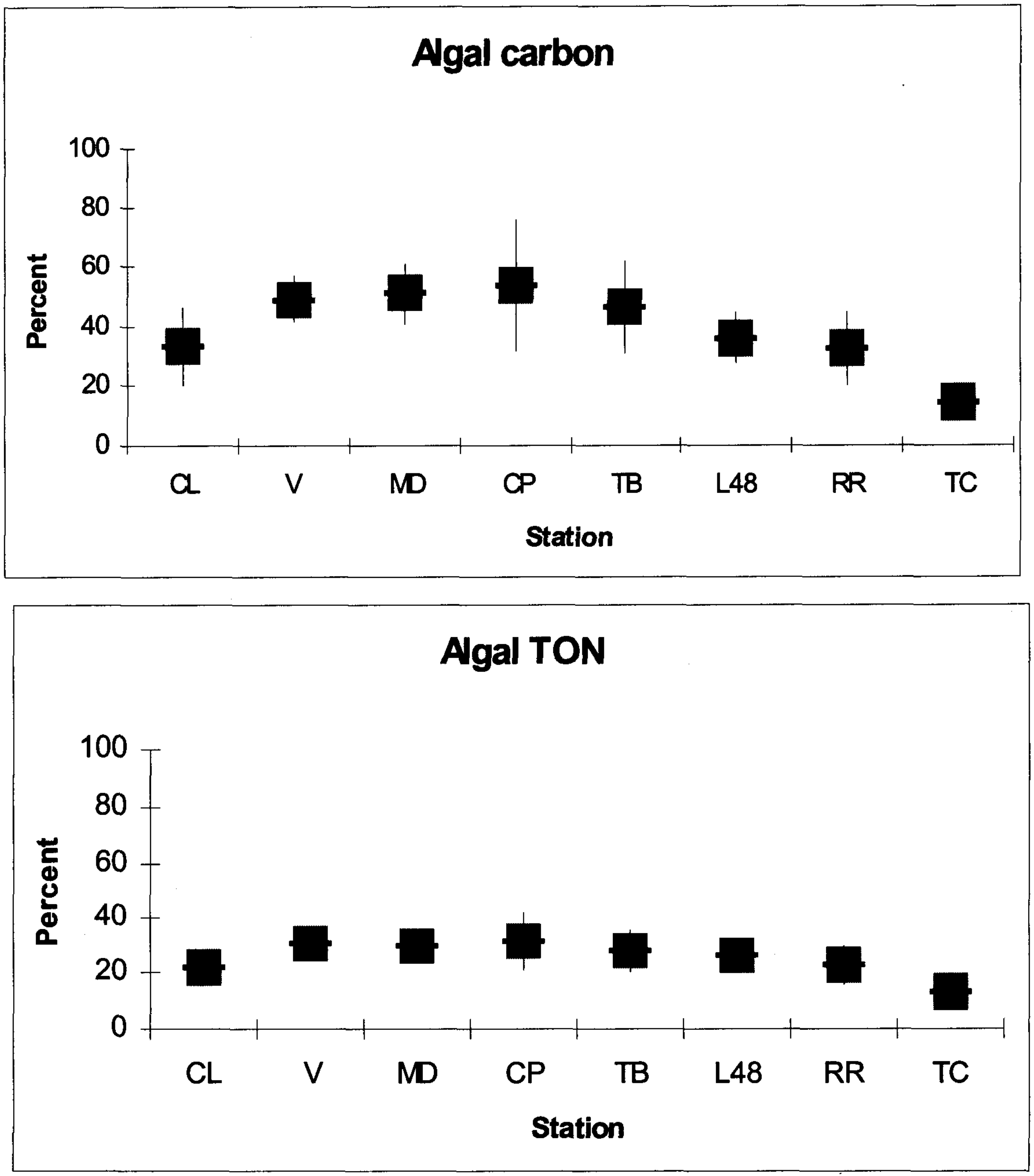


Fig. IV-1. Oxidation of chlorophyll *a* concentration and the associated increase in ammonia concentration measured at 5-day intervals for 30 days. Measurements were made at 20°C.

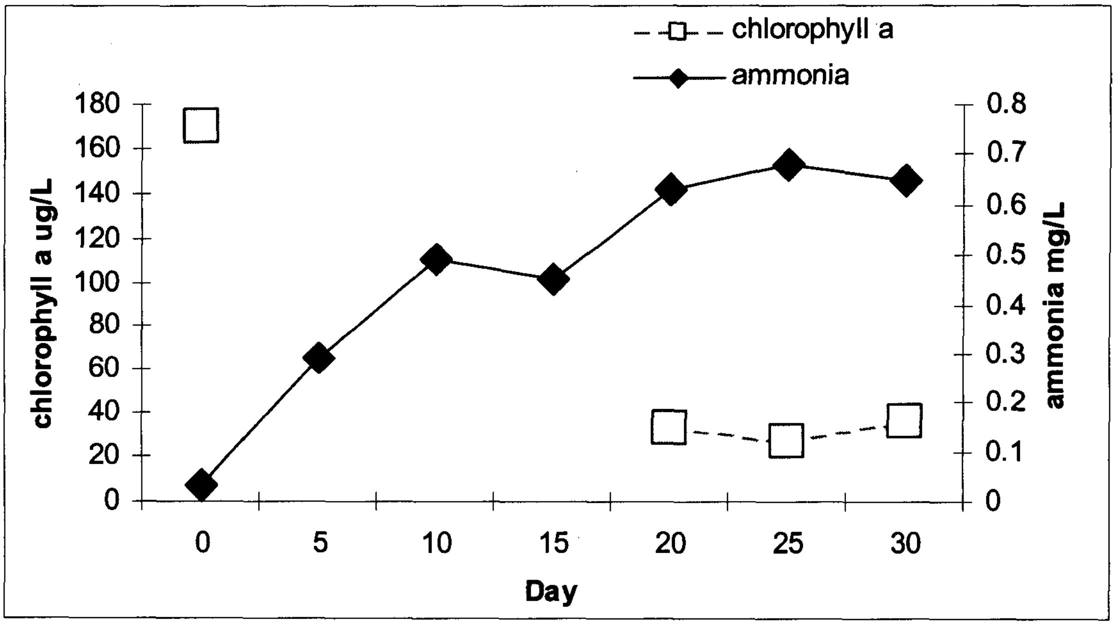


Fig. IV-2. Percentage of the organic nitrogen load from upstream at Mossdale comprised of chlorophyll *a* concentration in 2001.

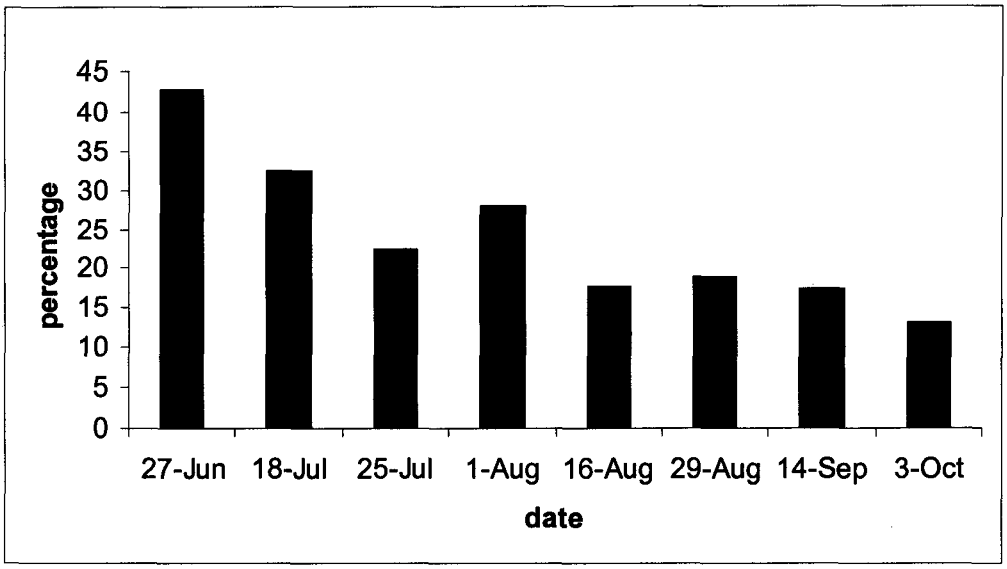


Fig. IV-3. Average percent surface irradiance and depth of the photic zone at sampling stations in the San Joaquin River.

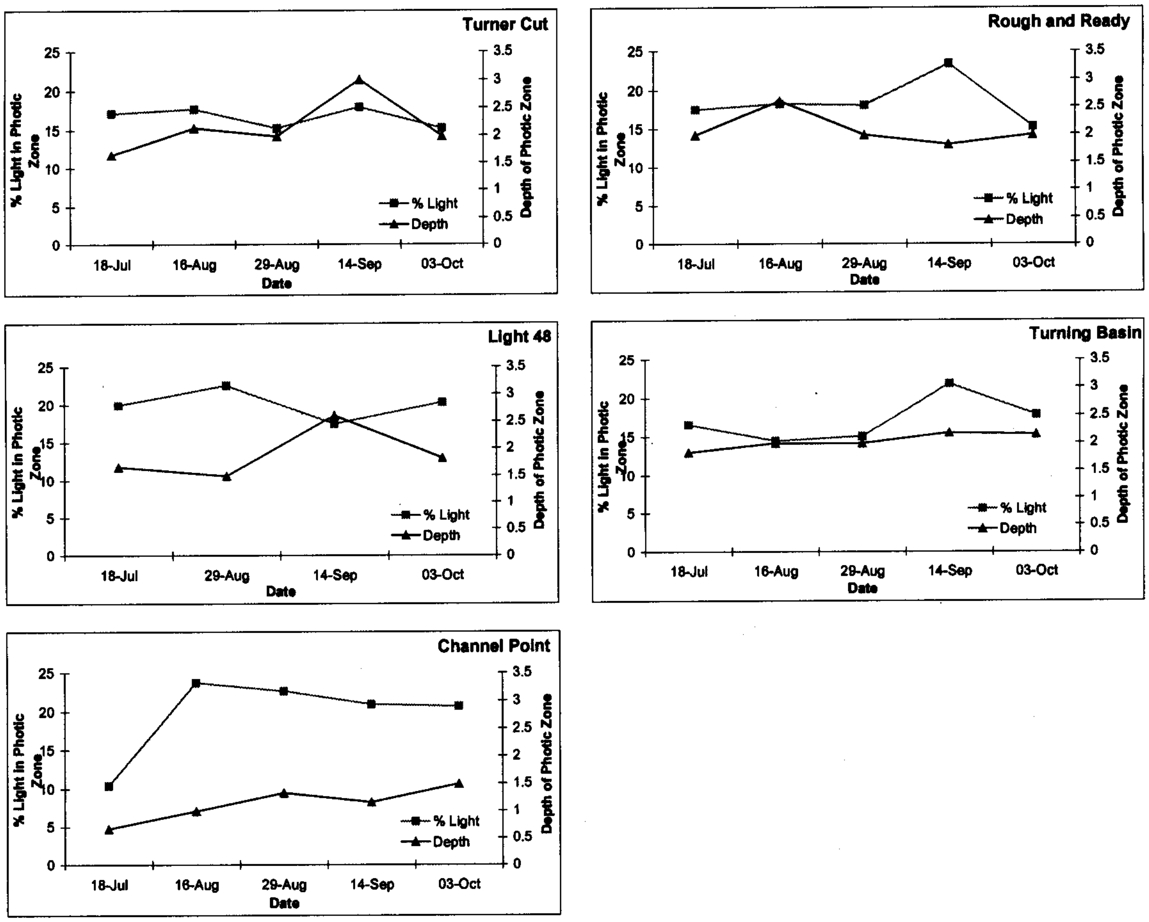


Fig. IV-4. Net plankton production rate measured at different daily average light intensity by station on September 5, 2001.

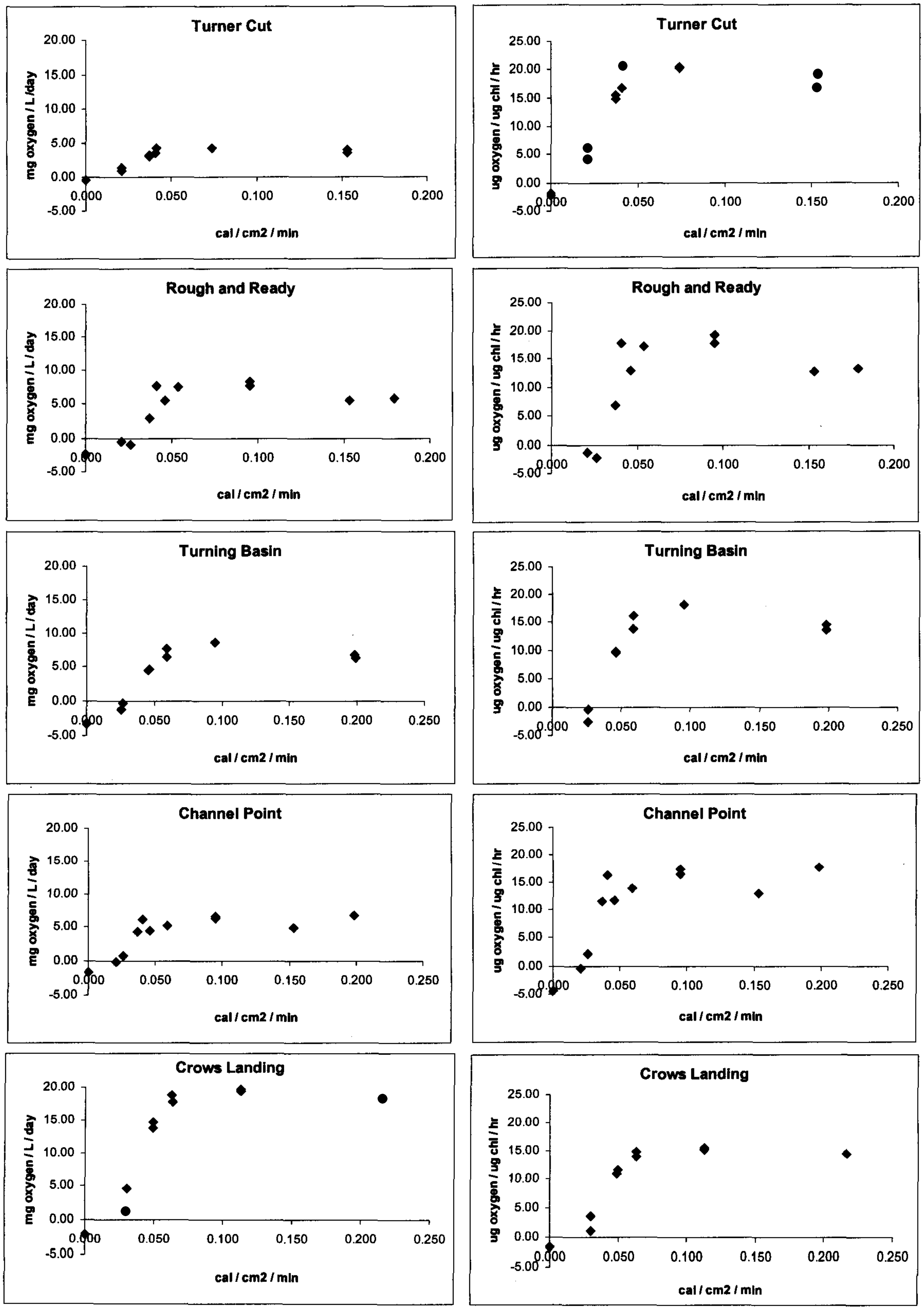


Fig. IV-5. Median plus 25 and 75 percent quartiles of dissolved inorganic nitrogen and orthophosphate concentration at each sampling station in the San Joaquin River.

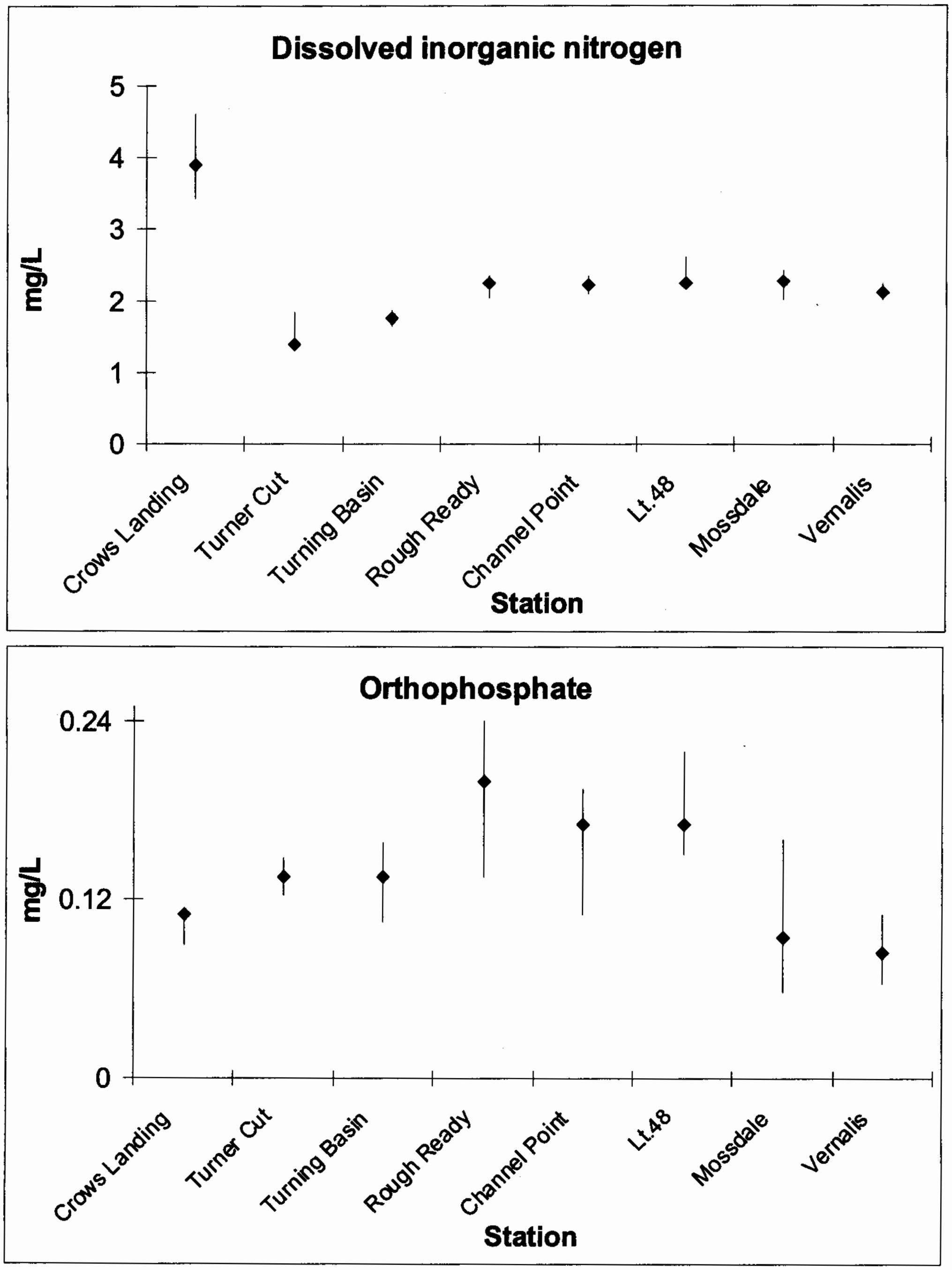
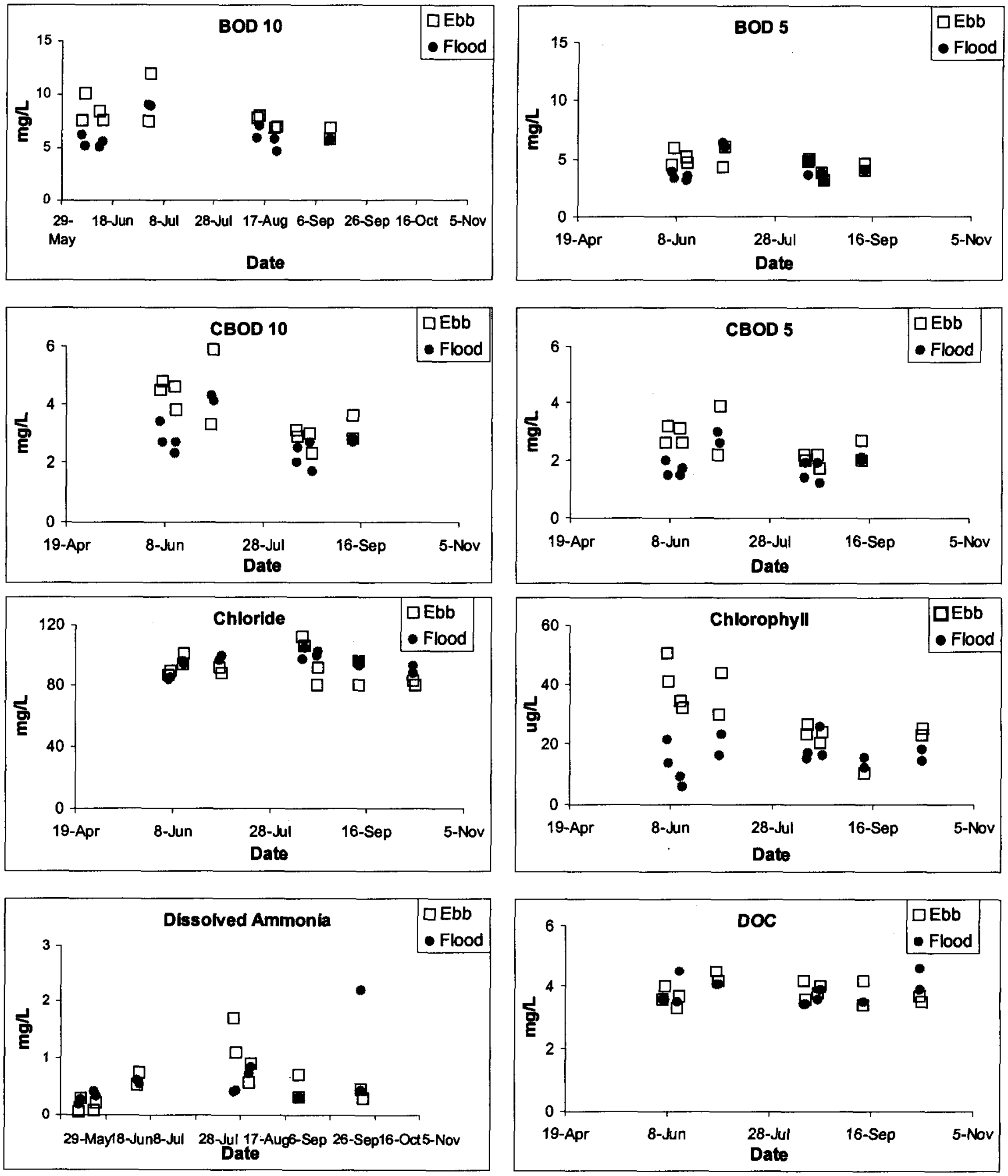
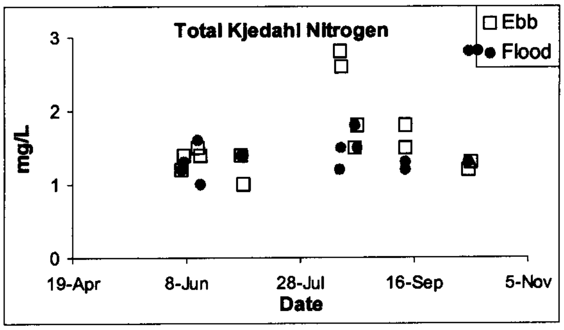
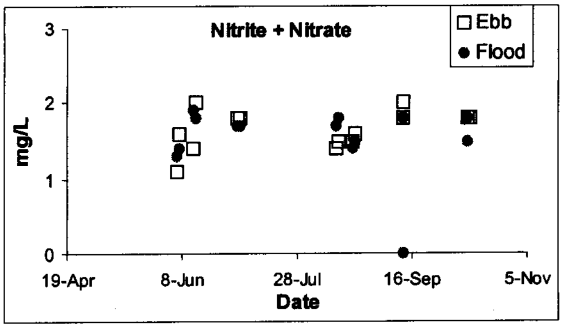


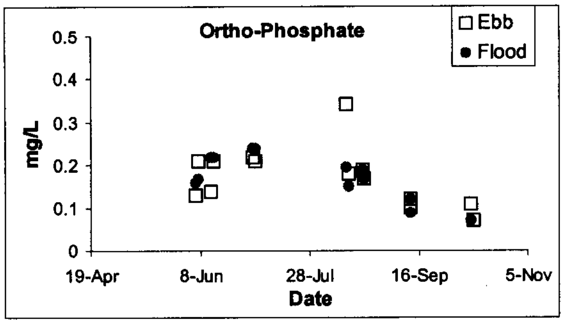
Fig. IV-6. Water quality variables measured on ebb and flood tide near mid-depth at Channel Point.

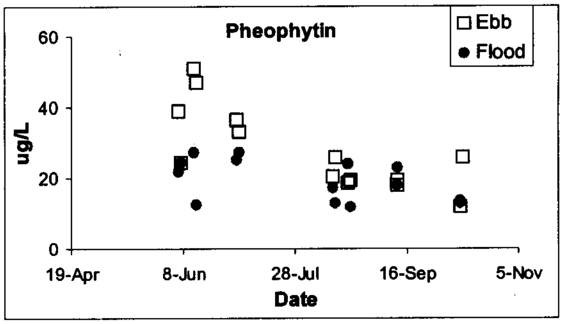


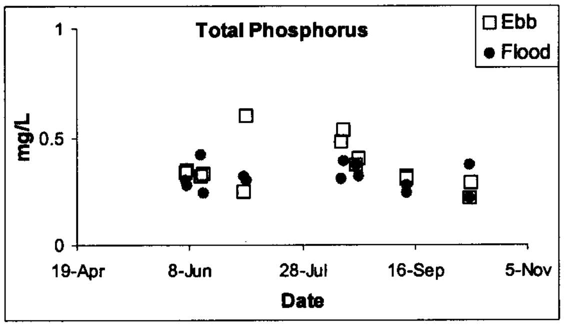
Lehman 4-19-02 Oxygen demand Figures and Tables

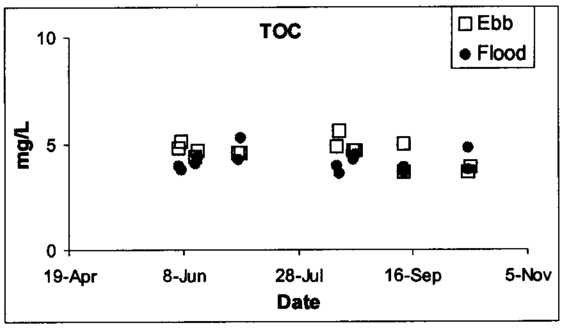


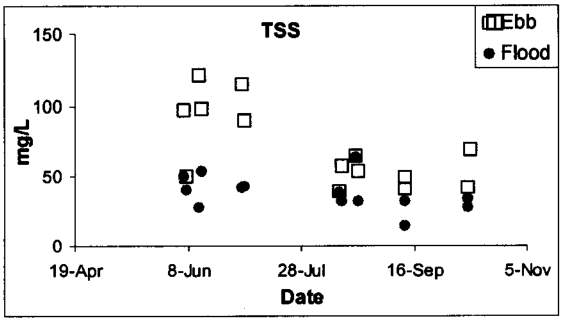


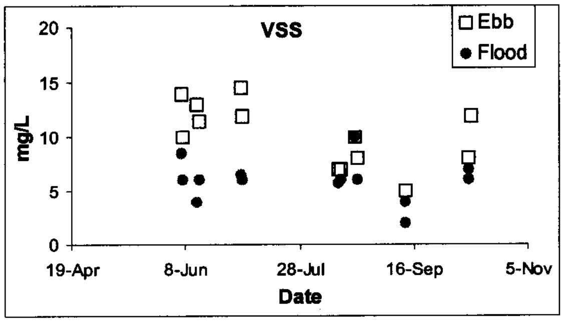






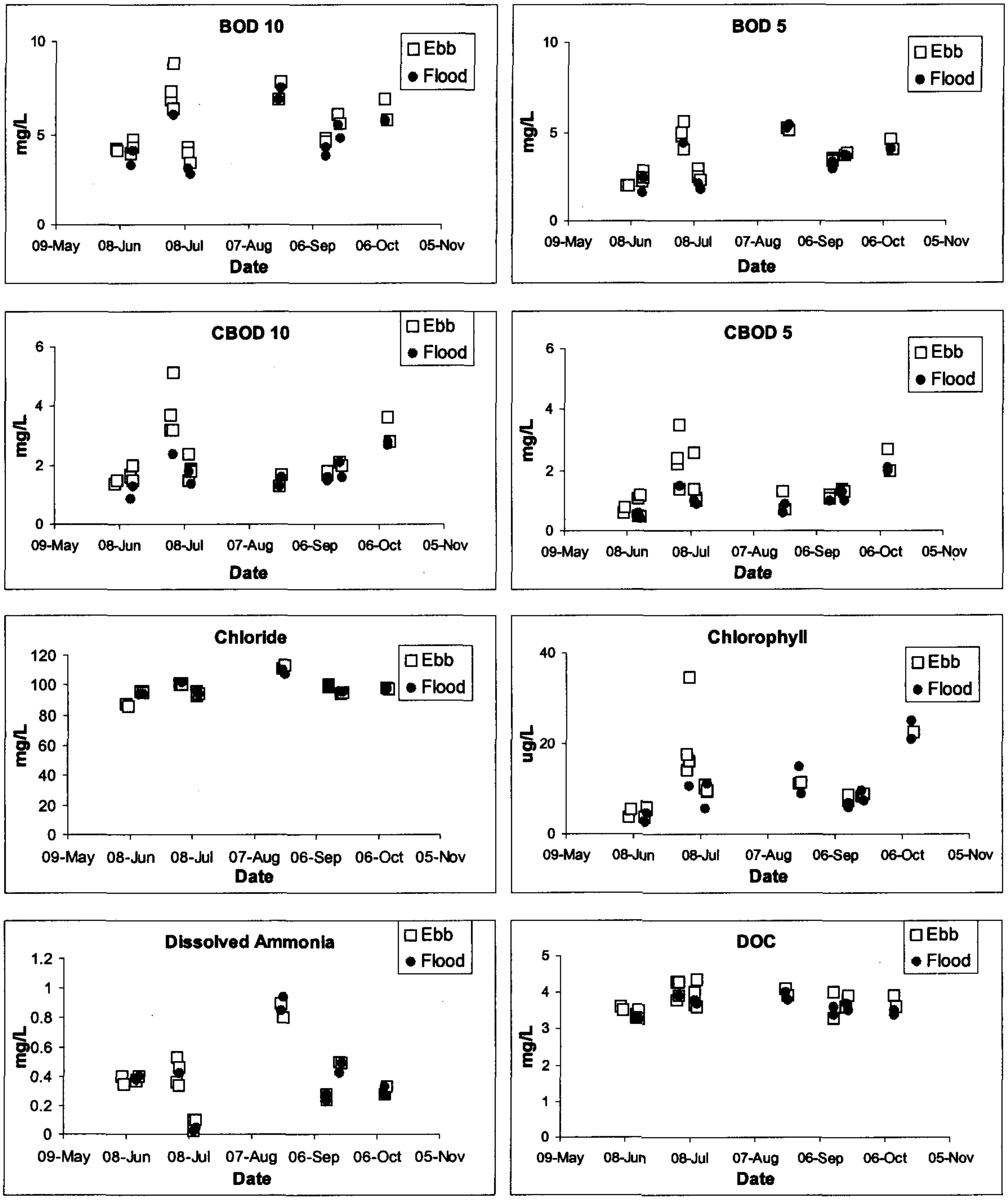




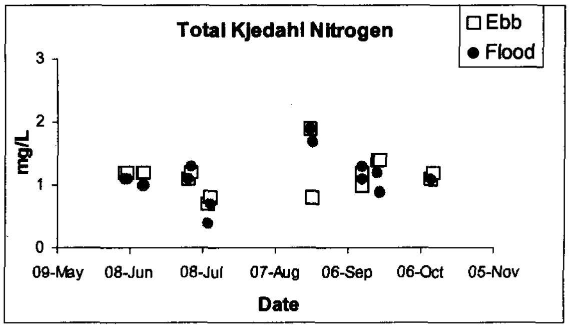


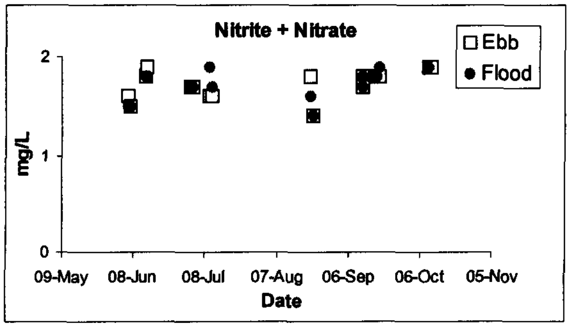
Lehman 4-19-02 Oxygen demand Figures and Tables

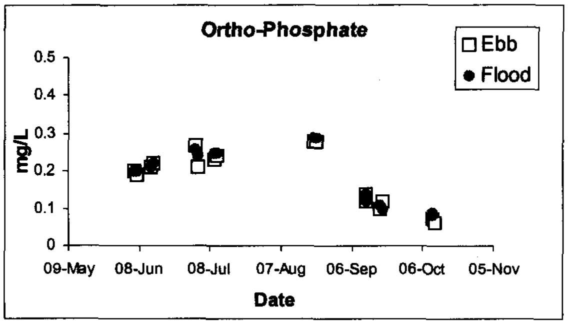
Fig. IV-7 a. Water quality variables measured on ebb and flood tide at 1 m depth for Rough and Ready Island.

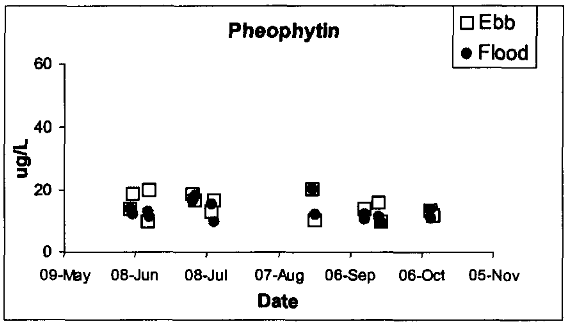


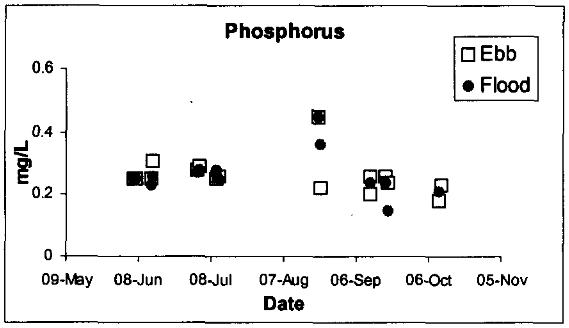
Lehman 4-19-02 Oxygen demand Figures and Tables

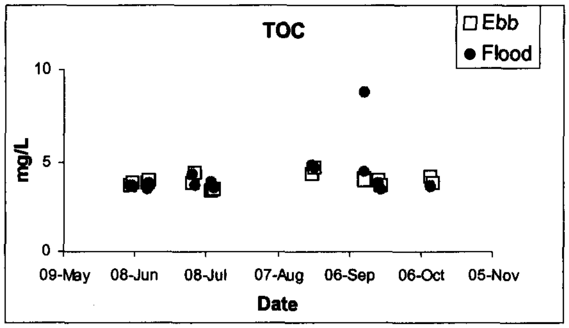


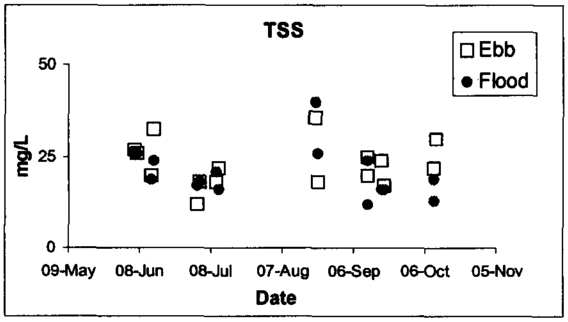












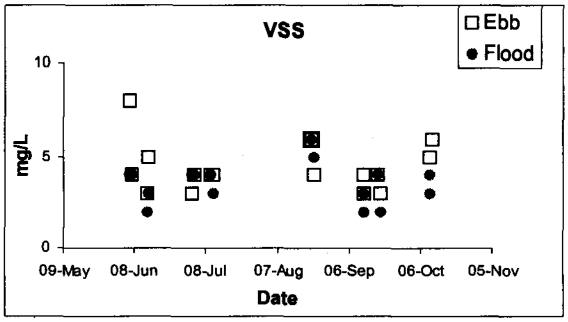
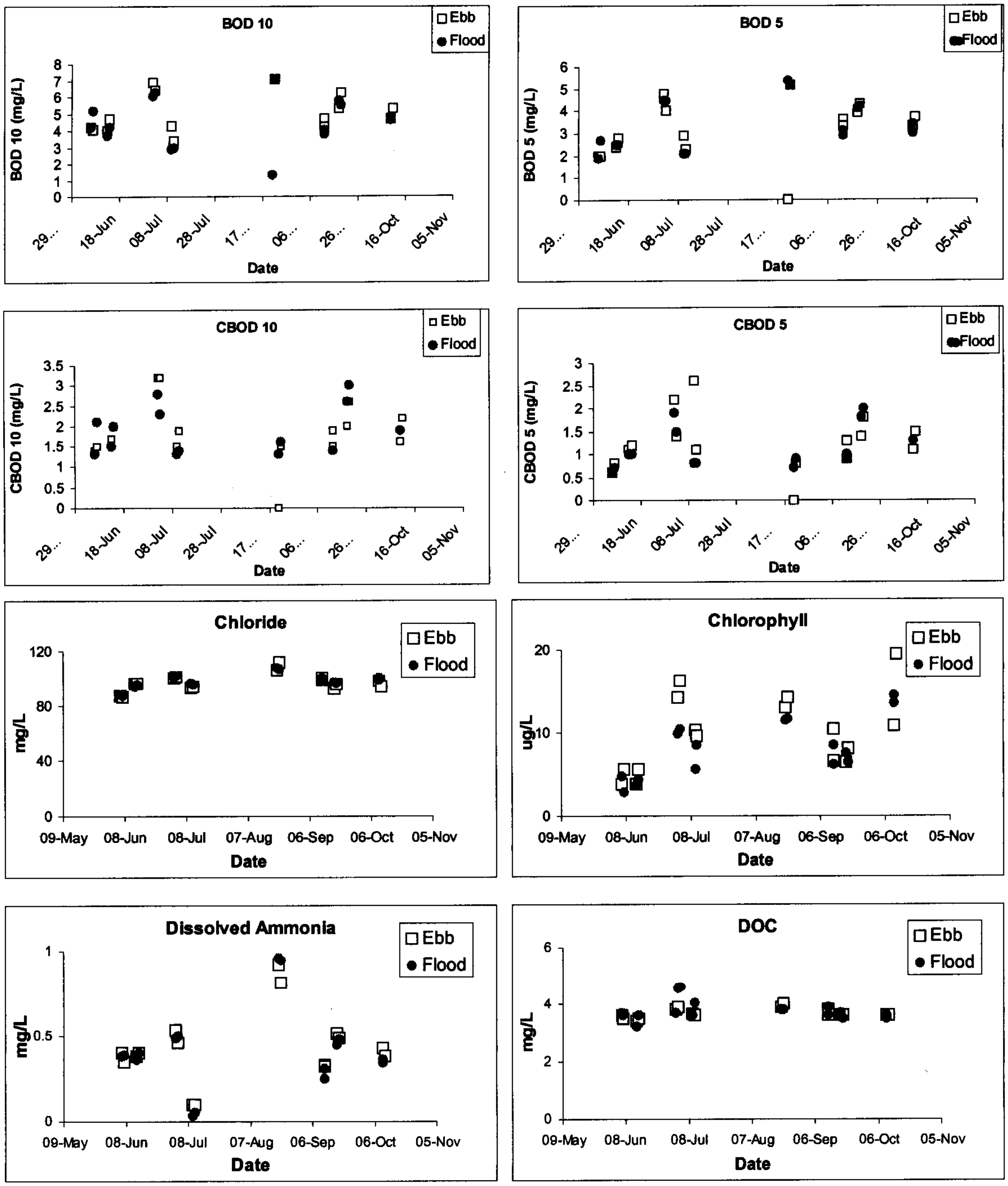
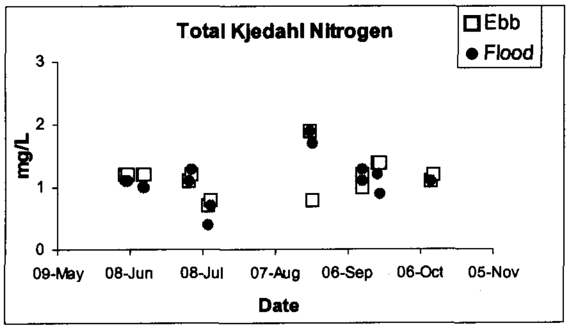
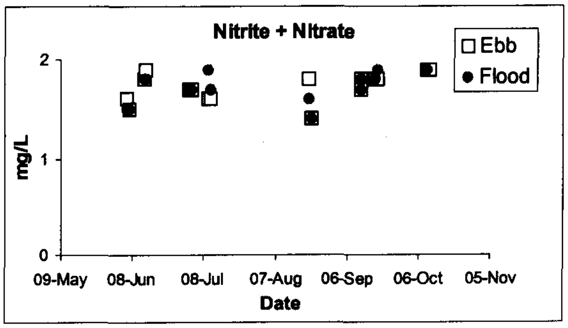


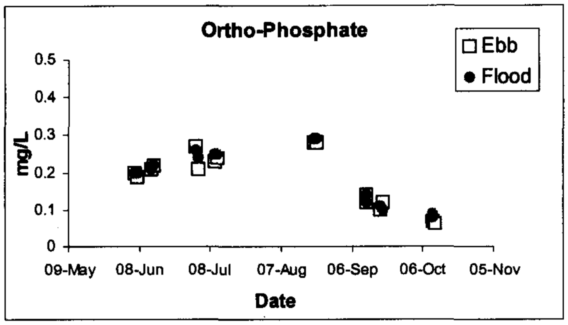
Fig. IV-7 b. Water quality variables measured on ebb and flood tide at 1 m from the bottom for Rough and Ready Island.

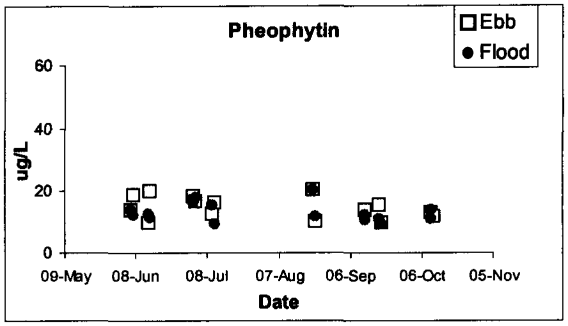


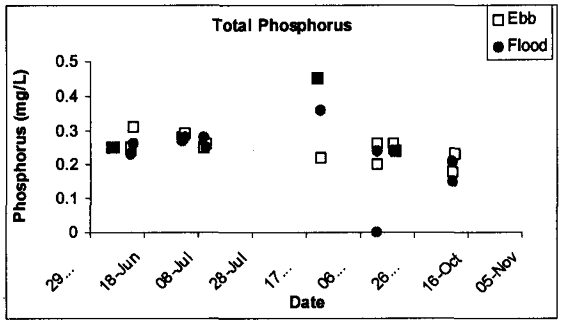
Lehman 4-19-02 Oxygen demand Figures and Tables

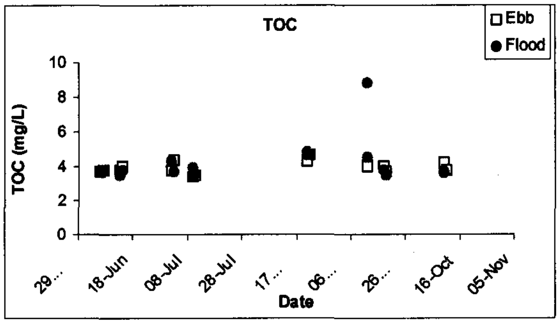


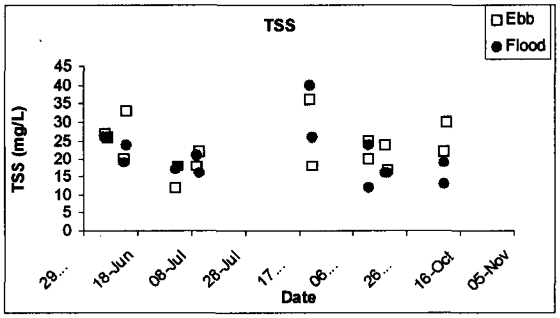












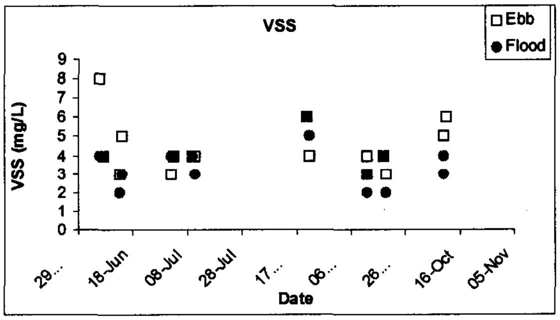
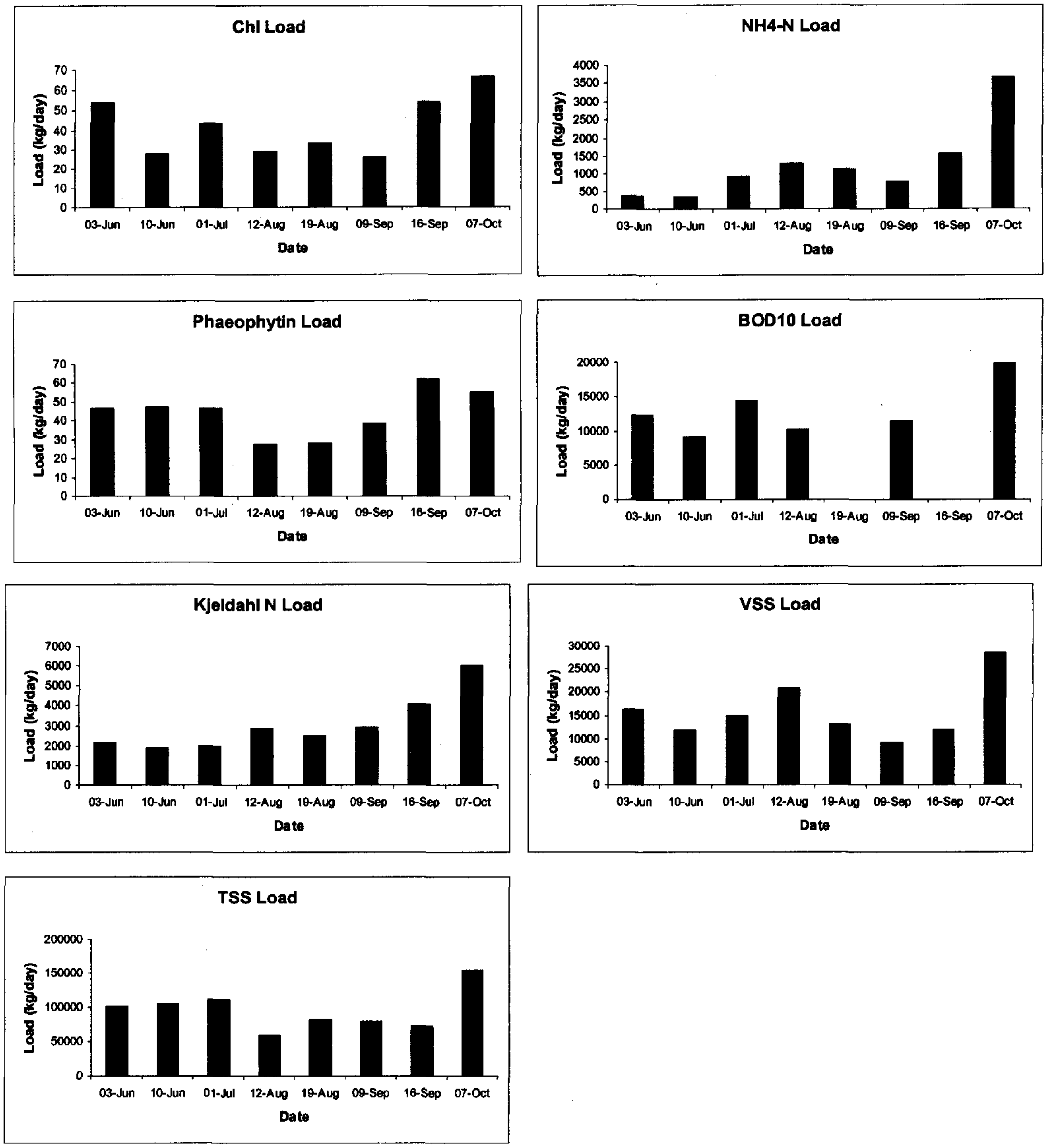
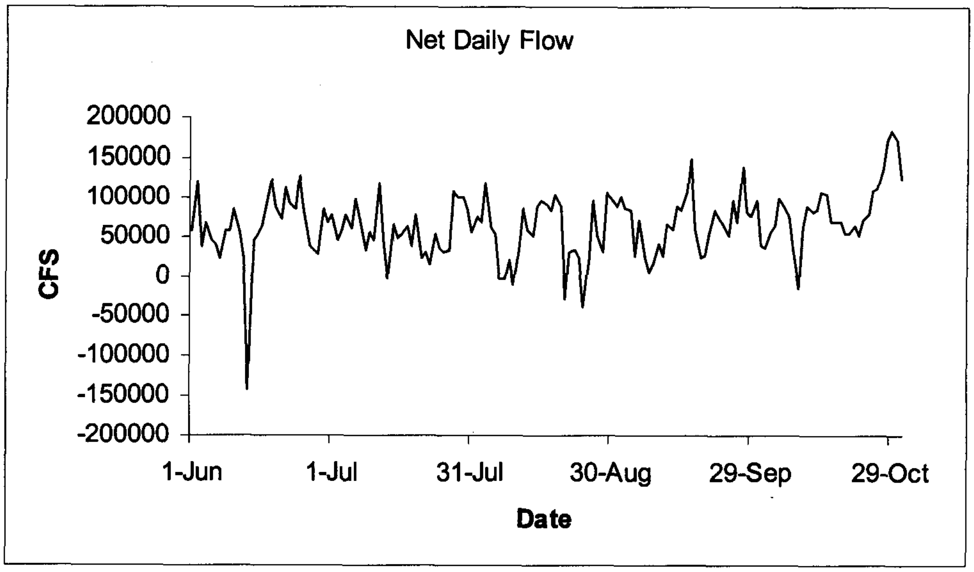


Fig. IV-8. Tidal day load measured at Channel Point near mid-depth by date.



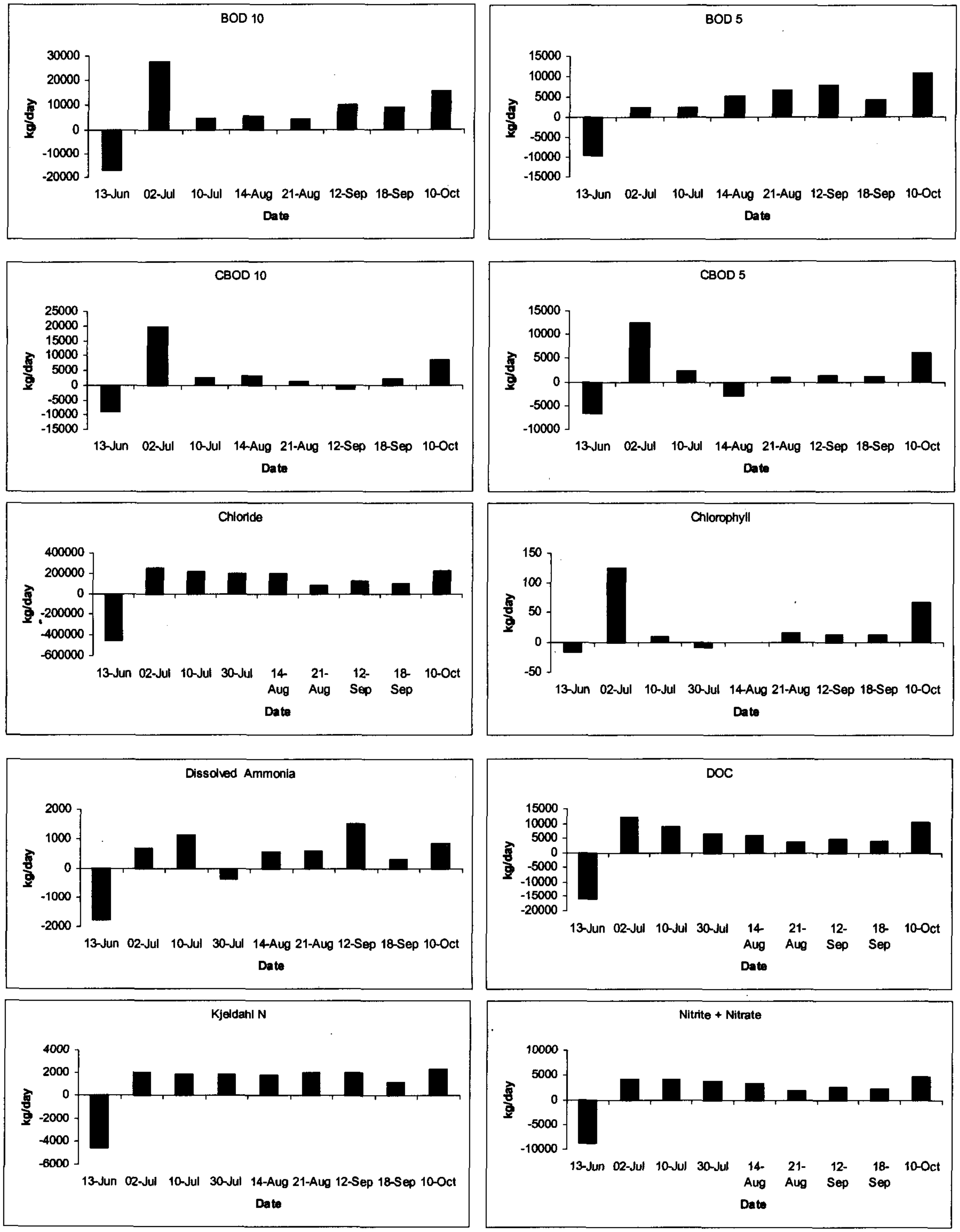
Lehman 4-19-02 Oxygen demand Figures and Tables

Fig. IV-9. Net tidal day flow at Rough and Ready Island.

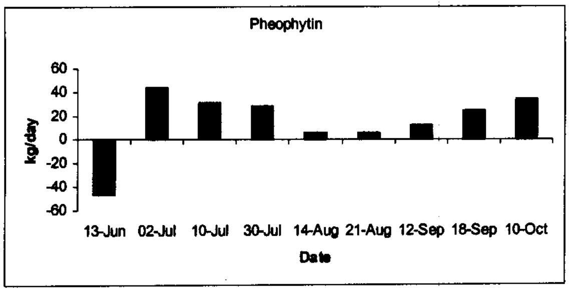


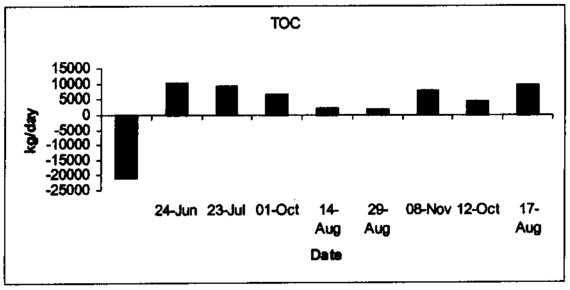
Lehman 4-19-02 Oxygen demand Figures and Tables

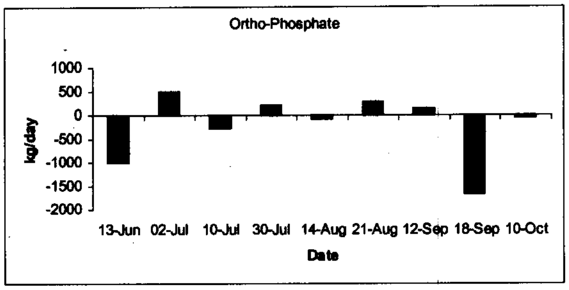
Fig. IV-10 a. Tidal day load of water quality variables at 1 m depth for Rough and Ready Island.

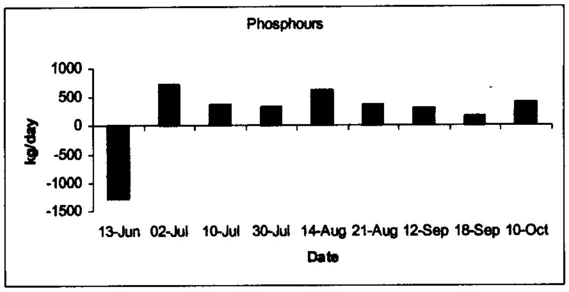


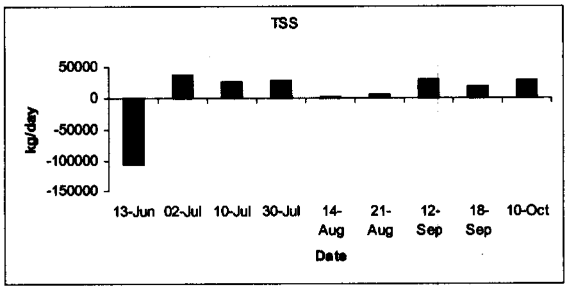
Lehman 4-19-02 Oxygen demand Figures and Tables


Pheophytin


TOC


Ortho-Phosphate


Phosphours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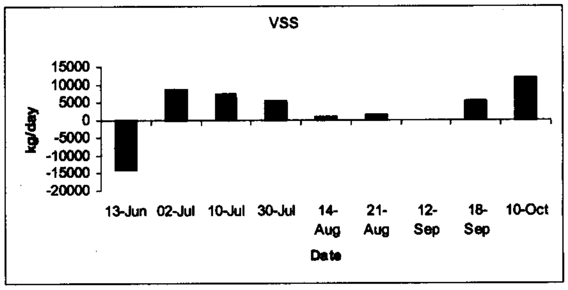
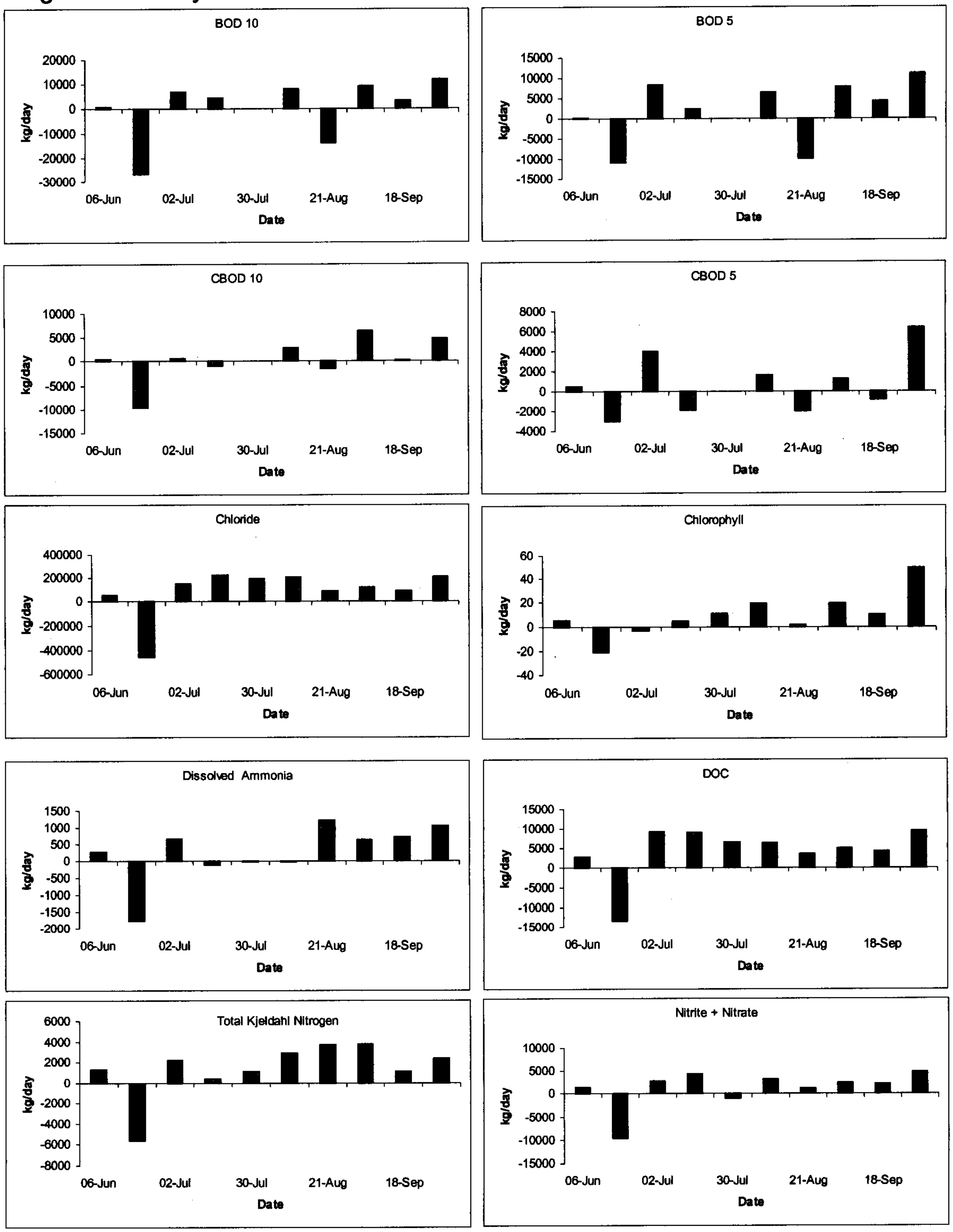
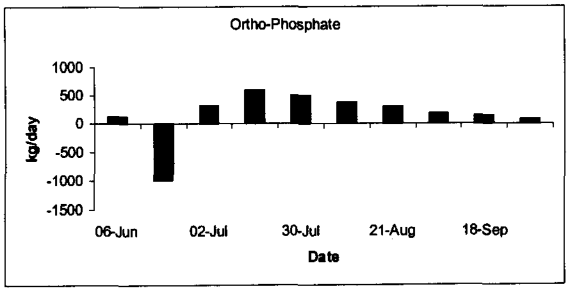
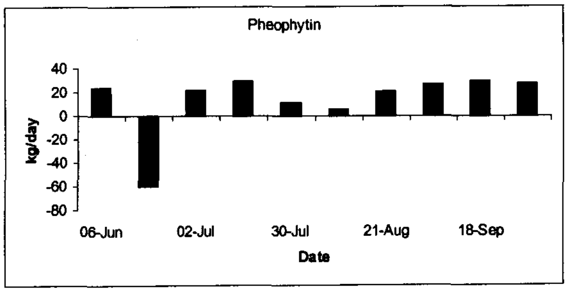

VSS

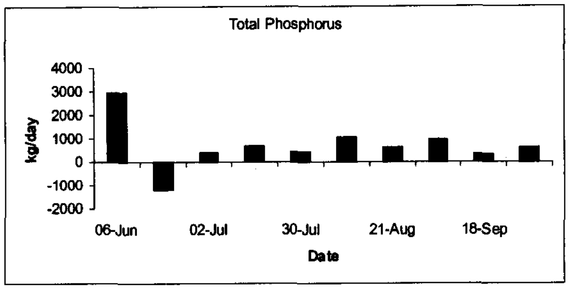
Fig. IV-10 b. Tidal day load of water quality variables at 1 m from the bottom for Rough and Ready Island.

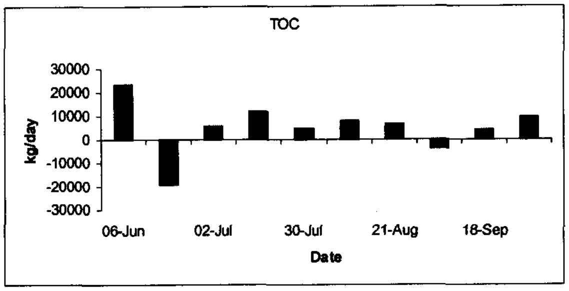


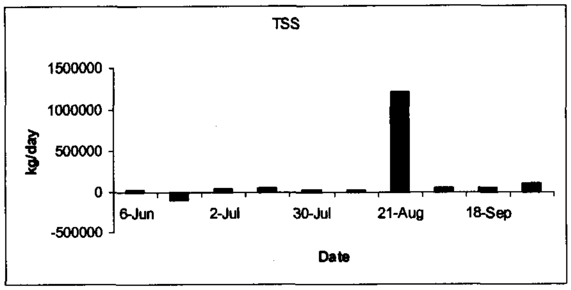
Lehman 4-19-02 Oxygen demand Figures and Tables











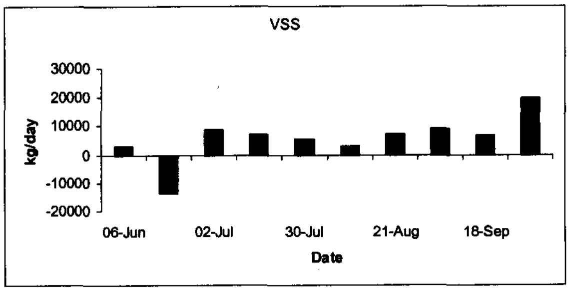


Fig. IV-11. Comparison of chlorophyll *a* concentration measured at Mossdale and Channel Point in 2001.

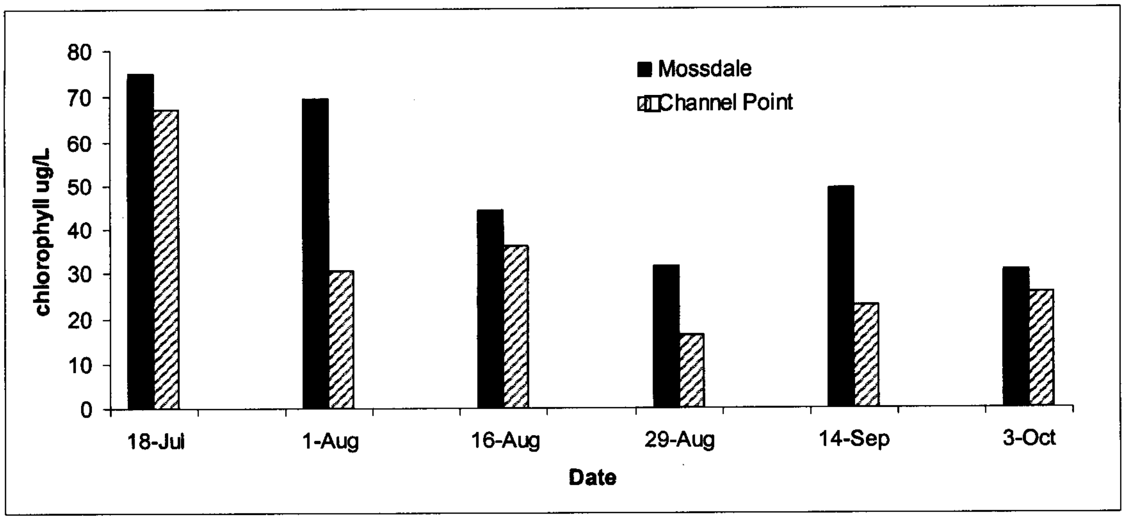


Fig. IV-12 a. Algal species carbon among stations on July 18 for Turner Cut (TC), Rough and Ready Is. (TC), Light 48 (L48), Turning Basin (TB), Channel Point (CP), Mossdale (MD), Vernalis (V) and Crows Landing (CL).

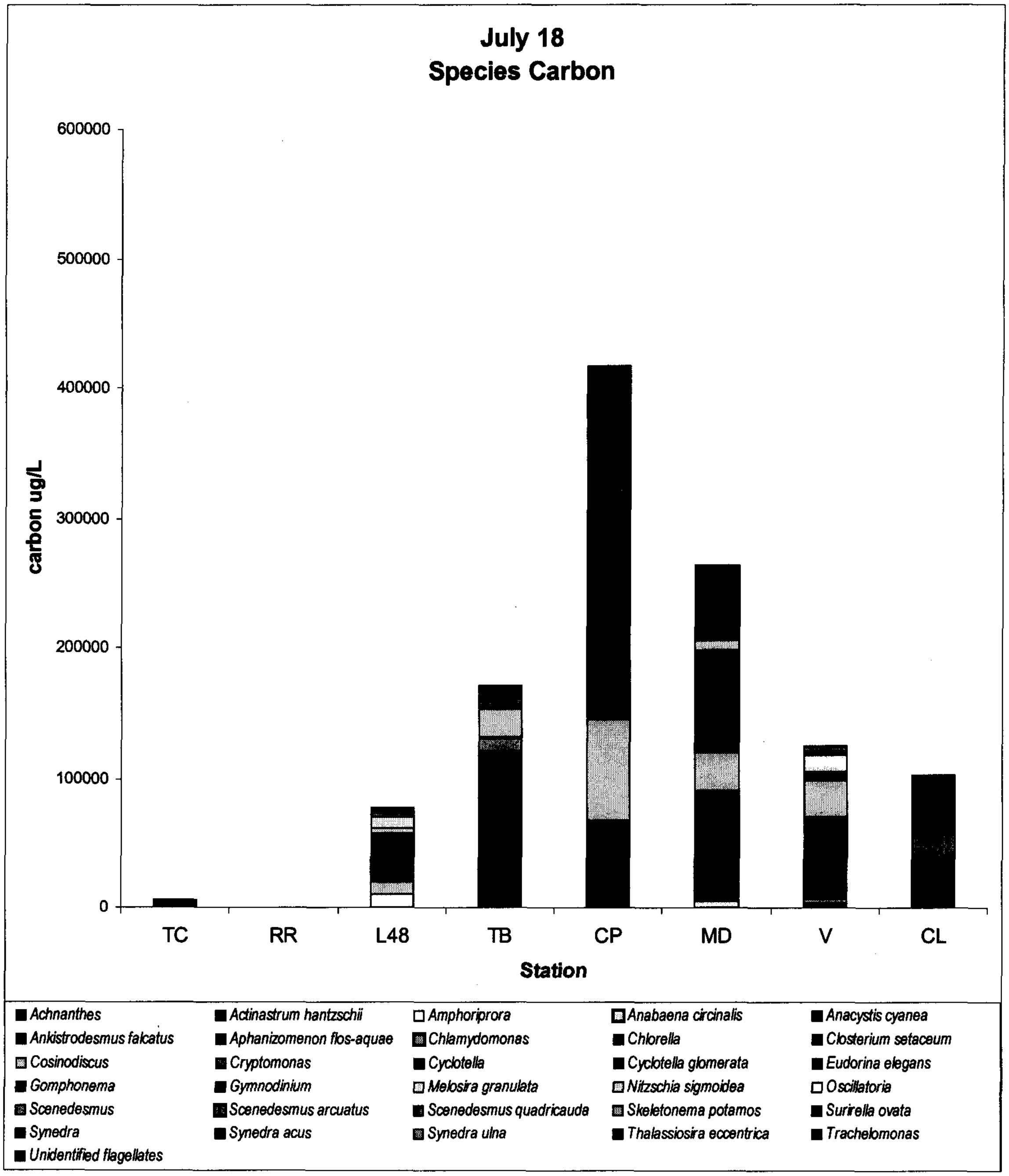


Fig. IV-12 b. Algal species carbon among stations on August 16. Stations are listed in IV-12 a.

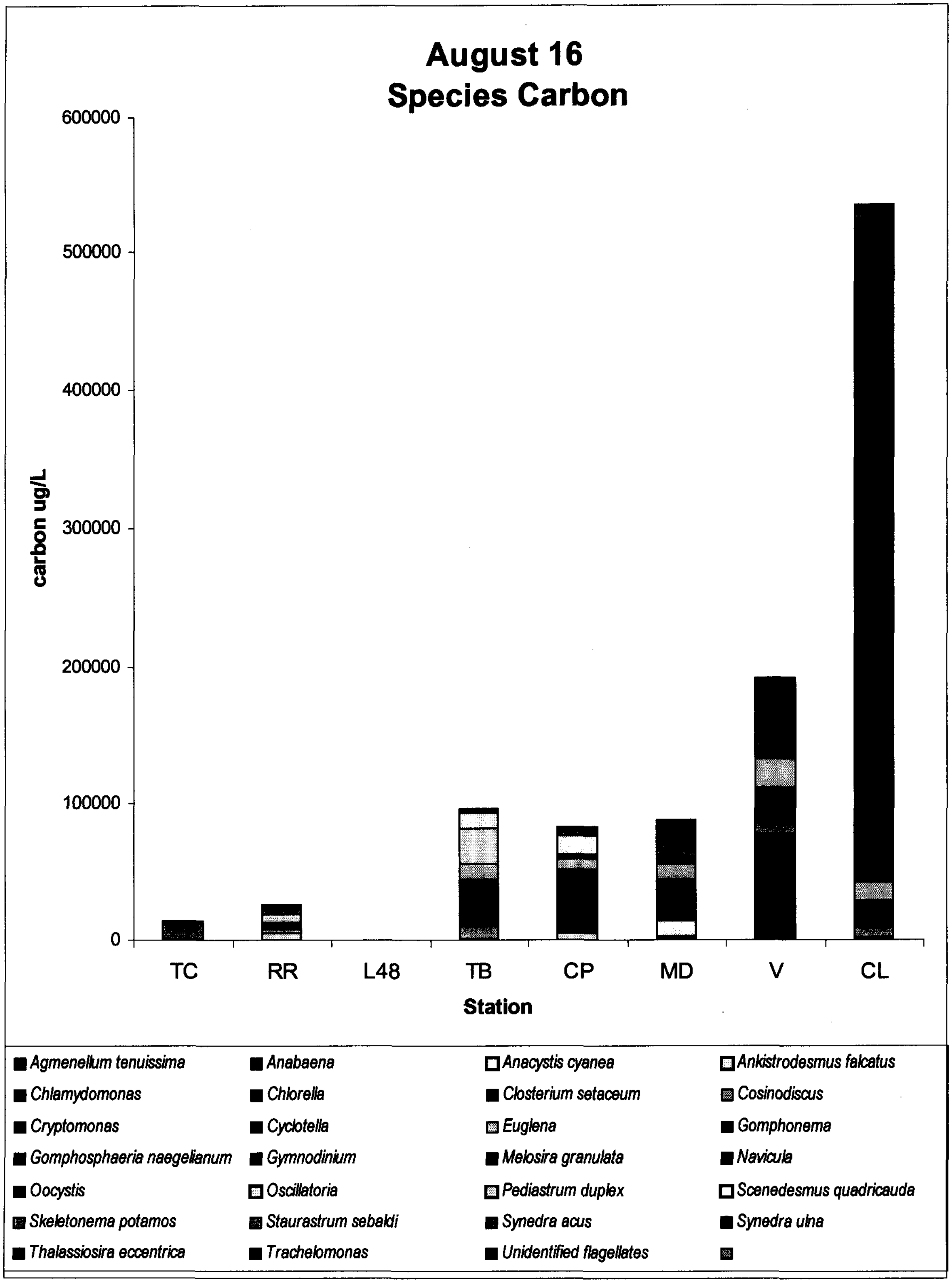


Fig. IV-12 c. Algal species carbon among stations on August 29. Stations are listed in IV-12 a.

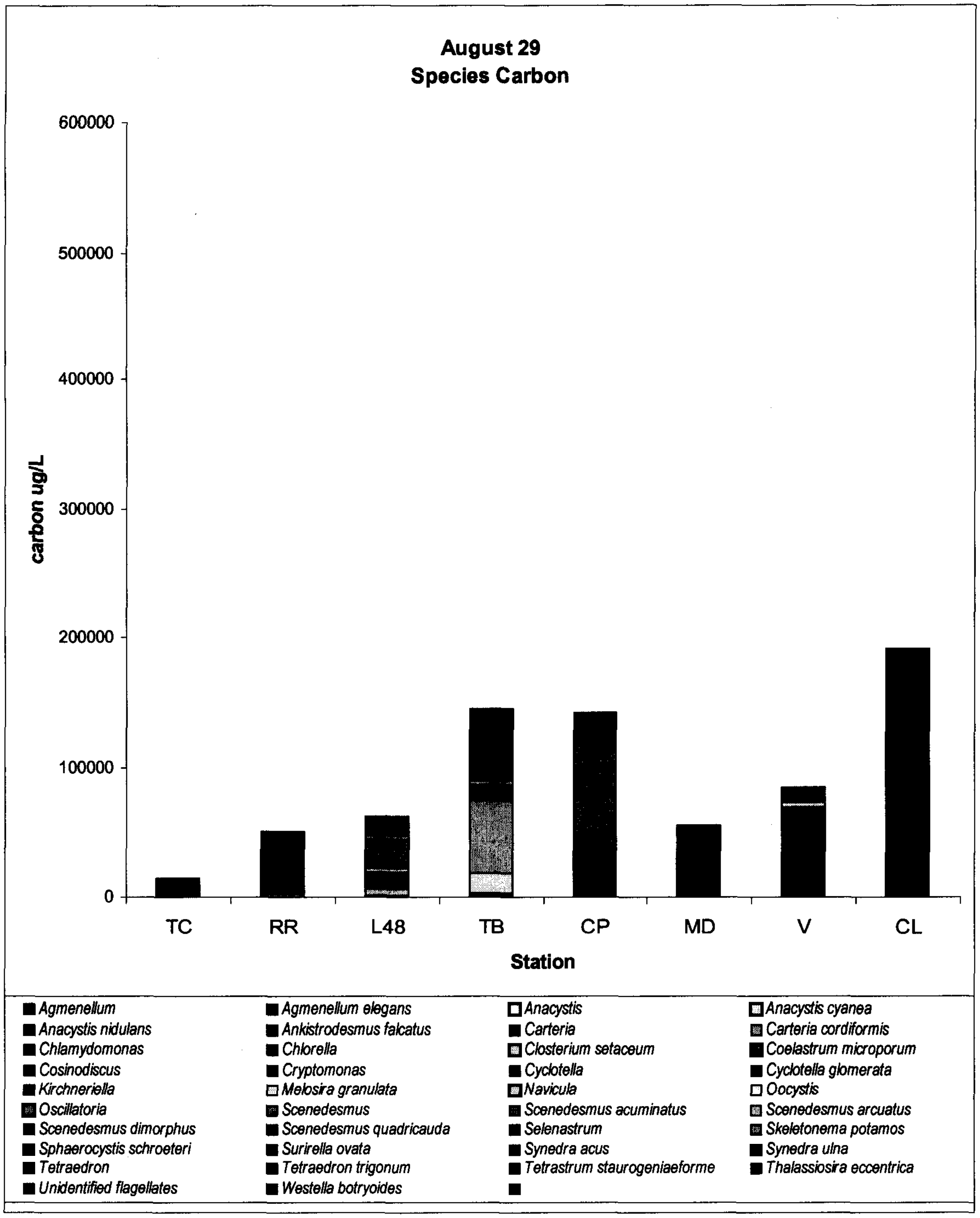
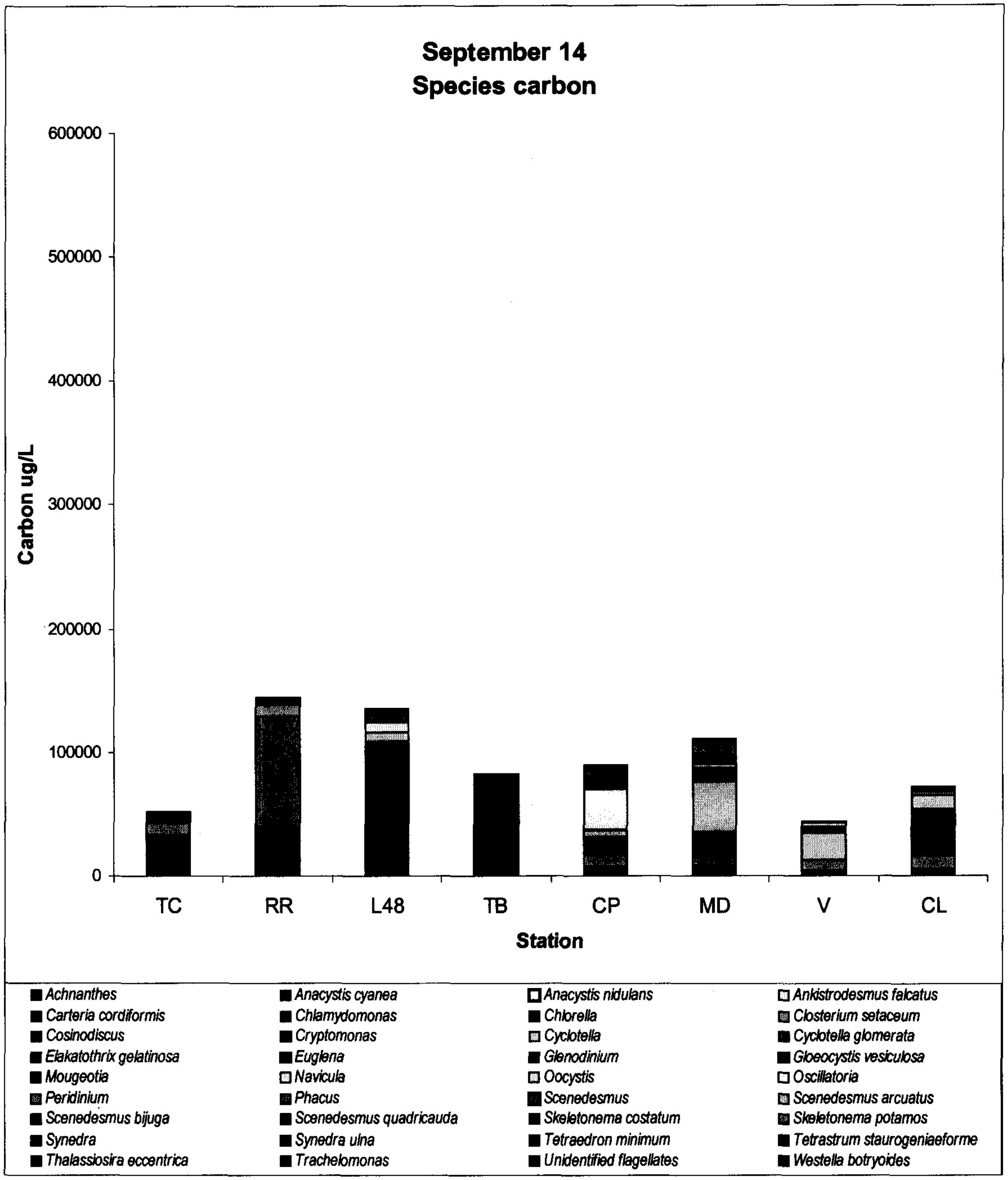


Fig. IV-12 d. Algal species carbon among stations on September 14. Stations are listed in IV-12 a.



Lehman 4-19-02 Oxygen demand Figures and Tables

Table III-1. Average plankton production rate measured for the Deep Water Channel between Turner Cut and Navigation Light 48.

Date	net production rate in photic zone	gross productioin rate in photic zone	respiration rate in aphotic zone	net production rate of water column kg/day	total oxygen demand in study reach	increase chl *a* in photic zone
	kg O2/ day	kg O2/ day	kg O2/ day	kg O2/ day	mg O2 / L	kg / day
26-Jun	7158	9415	-11309	-4151	-0.27	56
18-Jul	10149	12812	-14681	-4532	-0.29	79
16-Aug	13928	17536	-13699	229	0.01	109
29-Aug	15041	18736	-17329	-2287	-0.15	117
14-Sep	11274	16156	-20142	-8869	-0.57	88
03-Oct	6083	8198	-10725	-4643	-0.30	47
mean	10605	13809	-14648	-4042	-0.26	83

Lehman 4-19-02 Oxygen demand Figures and Tables

Table III-2. Estimated production and respiration rate of algae and bacteria in photic and aphotic zones between Turner Cut and Navigation Light 48 in the Deep Water Channel in 2001.

Date	average percent respiration by algae	algal net production rate in photic zone	gross productioin rate in photic zone	algal respiration rate in aphotic zone	algal net production rate in water column	algal oxygen production in study reach	chl *a* produced in photic zone	bacterial respiration in photic zone	bacterial respiration in aphotic zone	bacterial oxygen demand
	percent	kg O2/ day	kg O2/ day	kg O2/ day	g O2/ da	mg / L	kg / day	kg O2/ day	kg O2/ day	mg/L
26-Jun	39	8545	9415	4166	4379	0.28	67	1468	7143	-0.55
18-Jul	49	11564	12812	7021	4542	0.29	90	1415	7659	-0.58
16-Aug	42	16078	17536	5680	10398	0.67	125	2151	8019	-0.65
29-Aug	41	17124	18736	7318	9805	0.63	134	2082	10011	-0.78
14-Sep	59	13001	16156	13499	-498	-0.03	101	1727	6643	-0.54
03-Oct	45	7200	8198	5020	2180	0.14	56	1117	5706	-0.44
mean	46	12252	13809	7117	5134	0.33	96	1660	7530	-0.59

Table III-3. Pearson correlation coefficients calculated among variables measured in the Deep Water Channel at Turner Cut, Rough and Ready Island and Navigation Light 48. n=103.

	BOD10	CBOD10	NBOD10	Ammonia	TKN	non-ammonia TKN	Total pigment	Chloride	Chlorophyll	Dissolved organic carabon	Nitrate	Ortho-phosphate	Phaeophytin	Total phosphorus	Total organic carbon	Total suspended solids
BOD10																
CBOD10	0.62															
NBOD10	0.86	0.13														
Ammonia	0.78	0.09	0.93													
TKN	0.75	0.20	0.82	0.87												
non-ammonia TKN	0.41	0.28	0.34	0.34	0.76											
Total pigment	0.66	0.81	0.30	0.22	0.30	0.28										
chloride	0.44	0.10	0.49	0.40	0.41	0.25	0.03									
Chlorophyll	0.59	0.81	0.21	0.10	0.20	0.24	0.91	0.05								
Dissolved organic carabon	0.46	0.29	.40.40	0.23	0.27	0.20	0.29	0.56	0.24							
Nitrate	0.23	0.13	0.20	0.10	0.22	0.28	0.00	0.49	0.02	0.26						
Orthophosphate	0.27	-0.07	0.40	0.39	0.30	0.05	-0.03	0.43	-0.11	0.36	0.06					
Phaeophytin	0.44	0.36	0.32	0.33	0.34	0.21	0.61	-0.02	0.24	0.23	-0.04	0.16				
Total phosphorus	0.46	0.08	0.58	0.60	0.64	0.44	0.08	0.54	-0.02	0.47	0.22	0.72	0.23			
Total organic carbon	0.24	0.12	0.23	0.20	0.24	0.19	0.18	0.33	0.15	0.36	0.09	0.14	0.13	0.30		
Total suspended solids	-0.12	-0.26	0.01	0.26	0.24	0.11	0.07	0.06	-0.04	0.01	-0.08	0.17	0.25	0.29	0.11	
Volatile suspended solids	0.43	0.33	0.32	0.29	0.31	0.20	0.42	0.14	0.32	0.22	0.07	0.19	0.38	0.24	0.05	0.26

Table III-4. Comparison of stepwise multiple regressions developed to describe the variation in BOD for 2000 and 2001.

Independent variables: Ammonia and CBOD

Year	n	Variable	Parameter estimate	t value	probability	F value	Adj. R-square
2001	85	intercept	1.0	6.5	<.01	446	0.91
		ammonia	5.0	22.6	<.01		
		CBOD	1.1	17.8	<.01		
2000	100	intercept	1.1	4.5	<.01	137	0.73
		ammonia	3.9	15.6	<.01		
		CBOD	1.0	7.8	<.01		
2000 & 2001	186	intercept	0.8	5.8	<.01	458	0.83
		ammonia	4.4	24.0	<.01		
		CBOD	1.2	19.0	<.01		

Independent variables: Ammonia and total pigment

Year	n	Variable	Parameter estimate	t value	probability	F value	Adj. R-square
2001	85	intercept	1.3	6.7	<.01	254	0.86
		ammonia	4.5	15.7	<.01		
		total pigment	0.1	12.6	<.01		
2000	100	intercept	2.2	10.6	<.01	76	0.60
		ammonia	0.0	3.0	<.01		
		total pigment	4.0	12.3	<.01		
2000 & 2001	186	intercept	2.0	10.7	<.01	133	0.59
		ammonia	0.0	6.2	<.01		
		total pigment	4.7	16.0	<.01		

Lehman 4-19-02 Oxygen demand Figures and Tables

Table IV-1. Comparison of the dissolved ammonia load contributed by Mossdale (MD) and the Stockton Wastewater Treatment Control Facility (RWCF at residence times from 1 to 25 days. Percentages were based on mass balance model runs. Model run 1 included only a seasonal adjustment for water temperature on oxidation rate of organic nitrogen. Model 2 included the water temperature adjustment plus an adjustment for the percentage chlorophyll a concentration in the organic nitrogen load.

Model	residence time day	MD median percent	10th percentile	90th percentile	WTCF median percent	10th percentile	90th percentile	Significant difference level	sample size n
Run 1									
	1	38	16	52	62	0	72	< 0.01	102
	5	49	40	56	51	18	56	ns	20
	10	55	42	57	45	29	49	< 0.02	10
	15	61	45	61	39	35	46	< 0.04	7
	20	58	50	62	42	33	46	< 0.04	5
	25	58	56	59	42	38	43	ns	4
Run 2									
	1	34	6	47	66	0	83	< 0.01	102
	5	38	15	47	62	35	70	< 0.01	20
	10	43	26	45	57	46	69	< 0.01	10
	15	42	31	46	58	46	64	< 0.02	7
	20	38	35	45	62	48	63	< 0.05	5
	25	41	34	44	59	49	61	ns	4

Table IV-2. Net tidal day transport between Channel Point and Rough and Ready Island measured in 2001.

	chlorophyll a		organic nitrogen		ammonia		total BOD	
	Net transport kg d -1	Percent retention %	Net transport kg d -1	Percent retention %	Net transport kg d -1	Percent retention %	Net transport kg d -1	Percent retention %
Week								
03-Jun	49	91	903	50	-61	-17	7489	61
10-Jun	25	89	988	64	72	20	6287	69
01-Jul	8	19	-389	-37	8	1	-206	-1
12-Aug	8	27	-181	-11	418	32	-1166	-11
19-Aug	28	85	1054	77	787	69	8025	73
09-Sep	13	51	791	37	333	44	4166	37
16-Sep	41	77	1226	49	782	50	4638	34
07-Oct	32	47	1112	47	3056	84	10186	52
median	27	64	946	48	375	38	5462	44
10th percentile	8	19	-389	-37	-61	-17	-1166	-11
90th percentile	34	86	1068	54	783	55	7623	63

Dr. P. W. Lehman
Division of Environmental Services
Department of Water Resources

April 2, 2003

Response to 2002 peer review comments

Appendix A.

No response needed.

Appendix B.

Mass balance calculations can be useful, but have to be applied carefully to this problem because of the importance of oxidation rate to the daily oxygen demand contributed from upstream load. Most of the upstream organic matter is highly decomposed phytoplankton (Kratzer et al. 2003) and only about 40% of the organic nitrogen in the upstream load is live phytoplankton that oxidizes to dissolved ammonia at the measured rate of 0.15 mg N / mg chlorophyll *a* / day (20° C). Because of the relatively low rate of oxidation and small percentage of chlorophyll *a* in the upstream load, the dissolved ammonia load from the RWCF was higher on a daily basis than the dissolved ammonia load produced by oxidation of nitrogenous organic matter from upstream. The relative contribution of both sources to the dissolved ammonia concentration in the DWC varied with residence time, but was strongly influenced by the percentage of chlorophyll *a* in the upstream load. A mass balance model that takes the oxidation rate of the organic matter into consideration was included in the revised report.

I agree with the reviewer that reduction of the dissolved ammonia load from the treatment plant alone would not eliminate the low dissolved oxygen in the DWSC because of the oxygen demand from upstream sources. High chlorophyll *a* concentration at Mossdale in June and October and are probably the primary cause of low dissolved oxygen concentration in the DWSC about 20 days later. In addition, 30% of the variation in total BOD was associated with carbonaceous demand throughout the season. Management alternatives that do not address the decomposition of high phytoplankton biomass in the DWSC will not be adequate.

Appendix C. – David Beasley

No comment necessary.

Appendix D. – Alex Horne

No comment necessary

Appendix E. – Alan Jassby

Item 1.

Chlorophyll *a* load from in situ growth was estimated based on net oxygen production from light and dark bottle incubations in the photic zone. In this technique, net growth rate is estimated from a change in oxygen concentration and is a direct estimate of new carbon production in the photic zone.

It is true that the net carbon produced in the total DWSC water column (photic plus aphotic zone) is far less than that produced in the photic zone alone because of respiration processes in the aphotic zone. However, the purpose of this calculation was to determine the relative amount of new organic matter than would be respired in the aphotic zone. This quantity was the best value for comparison with the upstream load because both sources of chlorophyll *a* caused respiration in the aphotic zone of the DWSC. Additions were made to the text for clarity.

Item 2.

There was no intention to indicate the upstream load was unimportant and changes were made in the text in order to clarify that point. However, the correlation analysis cannot be discounted and is very important. The upstream load of organic nitrogen and TBOD or NBOD in the DWSC were poorly correlated and contrasted sharply with the strong correlation between the RWCF dissolved ammonia load and both TBOD and NBOD in the DWSC. I agree with the reviewer that this correlation is probably not spurious because of the variable nature of the RWCF load.

It is true, there was often a large load of dissolved ammonia from upstream based on Mossdale water quality data. Dissolved ammonia concentration reached as high as 0.42 mg/L at Mossdale in 2001 in our data set. How much of this reached the DWSC is unclear. It is hard to imagine that oxidation processes were not operating in the 12-mile journey to the DWSC between Mossdale and Channel Point.

A simple mass balance model was developed to assess the relative contribution of upstream and RWCF dissolved ammonia load from both direct addition of dissolved ammonia and indirect addition of dissolved ammonia through the oxidation of organic nitrogen. The load calculations assumed there was no loss for each source during transport into the DWSC. The range of potential contributions was developed based on the measured ammonification rate of chlorophyll *a* concentration of 0.19 mg N/ mg chlorophyll *a* /d at 25 °C. If all of the organic nitrogen oxidized at the maximum rate then it took 10 days for the accumulated load of dissolved ammonia plus dissolved ammonia from the oxidation of organic nitrogen from upstream at MD to exceed that from the RWCF dissolved ammonia discharge. In contrast, if only the most reactive organic material, chlorophyll *a*, was oxidized at the measured rate then the RWCF consistently contributed the majority of the ammonia in the DWSC at all residence times from 1 to 25 days. Clearly the RWCF is a major contributor to oxygen demand in the DWSC but as expected the magnitude of its impact varies with a suite of conditions.

I agree that the importance of the RWCF ammonia load does not eliminate the importance of oxygen demand from phytoplankton blooms. The carbonaceous BOD comprised up to 50% of the total BOD and accounted for 30% of the variation in the daily total BOD for both years. This was a significant percentage of the total BOD. In fact, this percentage might have been higher if the impact of the June phytoplankton bloom on low dissolved oxygen concentration in July was included.

A check of the Mossdale NBOD in 2001 indicated NBOD comprised an average of 42%. Most of the total BOD was not NBOD as indicated by the reviewer. This was the result of an inappropriate graphical format. All graphs were revised.

A plot of non-ammonia TKN against NBOD was added for clarity.

Fig. III-10 was revised.

Yes, there was very little correspondence between NBOD and non-ammonia TKN. A graph was added to demonstrate this fact. See above.

Item 3.

There was no evaluation of the algal production rate or environmental variables on the BOD in the correlation analysis. The correlation analysis only explored the potential impact of the concentration of oxygen demanding substances on the variation in oxygen demand. As it turned out, these variables accounted for most of the variance so the analyses didn't go further.

Environmental variables such as water temperature and mechanistic processes are logically important, but were not needed to explain most of the variance. This may be due to the relatively stable water temperature, surface irradiance and turbidity during the study period and the near zero net oxygen production of the phytoplankton. This is a good point and was included in the revised report.

Item 4.

Upstream load is an important contributing factor to oxygen demand in the DWSC. The relative contribution of the upstream load and the RWCF was addressed by development of the mass balance model for ammonia concentration. Both were important and their relative importance was strongly influenced by the oxidation rate of the upstream load. See item 2.

Appendix F.

No responses needed.