EUTROPHICATION AND NUTRIENT CYCLING IN FAMOSA SLOUGH: A SUMMARY OF BASELINE STUDIES FOR MONITORING ORDER R9-2006-0076

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Executive Summary

The purpose of this report is to summarize the findings of the SCCWRP study conducted in Famosa Slough in support of the SDRWQCB Monitoring Order (R9-2006-0076). The Monitoring Order required stakeholders to collect data necessary to develop models to establish TMDLs for nutrients and other contaminants (e.g., bacteria). SCCWRP, LSU and UCLA, supported by a Prop 50 grant from the State Water Resources Control Board (SWRCB), conducted studies in support of model development including monitoring of primary producer biomass, measurement of sediment and particulate nitrogen and phosphorus deposition, measurement of benthic dissolved oxygen and nutrient fluxes, and sediment bulk and porewater nutrients.

The purpose of this report is two-fold:

- Provide a summary of SCCWRP study data that will be used to develop and calibrate the water quality model for Famosa Slough.
- Synthesize study data to inform management actions to address eutrophication and improve the efficiency of nutrient cycling in Famosa Slough.

The following are the major findings of this study:

1. The combination of high biomass/cover of macroalgae, chronic hypoxia, and accumulated sediment organic matter indicate that Famosa Slough is highly eutrophic.
    - Primary producers in Famosa Slough were dominated by macroalgae and cyanobacteria mats, with peak biomass of 150 g dry weight m^{-2} and 100% areal cover occurring during the summertime.
    - Chronic nighttime hypoxia (DO < 2 mg L^{-1}) occurred throughout the summer and fall, when primary producer biomass was greatest. Chronic hypoxia is a consequence of the accumulation and decomposition of live and dead algal biomass upon and within sediments.
    - Study data indicates that the slough has accumulated high organic matter content in the sediments, a symptom of eutrophication. Limited data on benthic in fauna show declines in abundance during the summer and fall periods, coincident with periods of prolonged hypoxia. Because benthic infauna play an important role in nutrient cycling, additional studies should be undertaken to investigate causes of stress to benthic infauna (contaminants) in order to understand how to improve benthic habitat quality.

2. Preliminary nutrient budgets for Famosa Slough illustrate that benthic nitrogen flux has a more important role than terrestrial runoff from San Diego River and the local catchment in supporting primary producers during peak periods of productivity. Data suggest that productivity in the Slough is limited by nitrogen rather than phosphorus. Inputs of groundwater into the Slough are unquantified.
    - Annually, the contribution of benthic flux was about 50% of the terrestrial runoff from local catchment. Contributions from atmospheric deposition and benthic nitrogen fixation were negligible, as were losses from denitrification.

- During the summer peak in primary producer biomass (May-July), benthic TN efflux (223 kg TN and 112 kg DIN) is twice the amount of terrestrial runoff from the local watershed (110 kg TN and 20 kg DIN) .Exchange with San Diego River, estimated to be 70 kg TN and 20 kg DIN during the May-July period, appears to provide a minor source of DIN.
- Macroalgae are known to prefer dissolved inorganic forms of nitrogen for growth. The amount of dissolved inorganic nitrogen from all sources (162 kg DIN) is slightly less than what is required to support the peak primary producer biomass during the summer index period, estimated as 223 kg. Benthic flux supplies 68% of the DIN to macroalgae during peak growth. In contrast, terrestrial runoff represents approximately 13% of DIN sources. Some recycling of organic forms of nitrogen may be occurring to supply additional DIN.
- Because benthic flux is the major source of nitrogen to the Slough, recycling of this organic matter to biologically available forms of nutrients will likely continue to cause problems with algal blooms and hypoxia, even with nutrient reductions, unless restoration is undertaken to flush the Slough of the fine-grained sediments and improve circulation.

3. Terrestrial loads appear to be the major source of phosphorus (P) to the Slough and provide sufficient quantities to support peak primary producer biomass. Direct atmospheric deposition to the Slough is negligible.
    - Terrestrial loads, estimated from the mass emission site, provided an annual total phosphorus (TP) load of 213 kg (Table 4.5), 70% of which was ortho-phosphate (inorganic P).
    - The sediments appear to be a sink for total and dissolved inorganic P for most index periods, except summer when it is a minor source. Annually, benthic exchange was a sink of 45 kg P.
    - During the peak in primary productivity, terrestrial loads from the local catchment and San Diego River were estimated to provide 90 kg of TP and 56 kg of SRP. In contrast, benthic flux provided 16 kg TP and only 2 kg of this amount is SRP. Thus, 58 kg of SRP is readily available for biological uptake which is roughly equivalent to that required to support the 62 kg P stored in primary producer biomass. Terrestrial sources provide 60% of available TP and 90% of available SRP to support primary productivity.

Options for management of eutrophication in Famosa Slough are as follows:

- Increase flushing and circulation within Famosa Slough to decrease detention of fine-grain sediments and decrease water residence time. The City of San Diego, in concert with Friends of Famosa Slough, has already undertaken some restoration actions and is considering additional options to further these goals.
- Reduce terrestrial loads from the Famosa Slough catchment and/or San Diego River. Installation of the Valleta Street Treatment wetlands has already reduced loads from the Famosa Slough catchment. Loads from the catchment are likely an overestimate because the effect of the treatment wetlands is not accounted for in mass loads. Some additional reductions of nutrients could be considered; emphasis should be placed on detention of suspended matter before it reaches the Slough.

- Harvest algal biomass. This option could help to alleviate algal blooms and associated problems. However, is not likely to solve problems with eutrophication in the short-term because of the importance of sediments in driving hypoxia and eutrophication in Famosa Slough. Therefore, the cost-effectiveness of harvesting as a management tool must be carefully considered.

Disclosure

Funding for this project has been provided in full or in part through an agreement with the State Water Resources Control Board. The contents of this document do not necessarily reflect the views and policies of the State Water Resources Control Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use (Gov. Code 7550, 40 CFR 31.20).

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1 Introduction

1.1 Background and Purpose of Report

The Famosa Slough is a 15-hectare estuarine wetland that serves as refuge, foraging area, and breeding grounds for a number of terrestrial and aquatic species. Land use changes in the San Diego River watershed resulted in the Slough becoming greatly reduced in size and hydrologically muted by installation of a series of tide gates and culverts. Increased urbanization also led to increased amounts of nutrients and other contaminants to the Slough.

Increased nutrient loads are known to fuel the productivity of macroalgal communities in the Slough, in a process known as *eutrophication*. Eutrophication is defined as the increase in the rate of supply and/or *in situ* production of organic matter (from aquatic plants) in a water body. While these primary producers are important in estuarine nutrient cycling and food web dynamics (Mayer 1967, Pregnall and Rudy 1985, Kwak and Zedler 1997, McGlathery 2001, Boyer et al. 2004), their excessive abundance can reduce the habitat quality of a system. Increased primary production can lead to depletion of oxygen (O_2) from the water column causing hypoxia (low O_2) or anoxia (no O_2); (Valiela et al. 2002, Camargo and Alonso 2006, Diaz and Rosenberg 2008), which can be extremely stressful to resident organisms.

As a result of increased macroalgal blooms, the San Diego Regional Water Quality Control Board (SDRWQCB) placed Famosa Slough on the federal 303(d) list of impaired water bodies for eutrophication. The SDRWQCB issued a Monitoring Order (R9-2006-0076) requiring stakeholders to collect data necessary to develop watershed loading and estuarine water quality models. The Southern California Coastal Water Research Project (SCCWRP), Louisiana State University (LSU) and University of California Los Angeles (UCLA), supported by a Prop 50 grant from the State Water Resources Control Board (SWRCB), conducted studies to aid model development including monitoring of primary producer biomass, measurement of sediment and particulate nitrogen (N) and phosphorus (P) deposition, measurement of benthic dissolved oxygen and nutrient fluxes, and sediment bulk and porewater nutrients. During October 2007 through October 2008, SCCWRP and Weston Solutions, subcontract to the City of San Diego conducted monitoring to address the requirements of Investigation Order R9-2006-0076.

The purpose of this report is two-fold:

- Provide a summary of SCCWRP study data that will be used to develop and calibrate the water quality model for Famosa Slough.
- Synthesize study data to inform management actions to address eutrophication and improve the efficiency of nutrient cycling in Famosa Slough.

Studies were conducted in conjunction with Weston Solutions, Inc. to address the following research objectives:

- Characterize the seasonal trends in surface water ambient nutrient concentrations, sediment solid phase and porewater nutrients, and primary producer communities.
- Estimate the seasonal and long-term annual deposition of sediments and particulate nutrients to Famosa Slough.

- Characterize the seasonal trends in N and P exchange between the Slough sediments and surface waters (benthic nutrient flux).
- Assess the efficiency of nutrient cycling in Famosa Slough by estimating, to the extent possible, N and P budgets.

1.2 Report Organization

This report is organized into an executive summary and four chapters:

Executive Summary
Chapter 1: Introduction, purpose, and organization of report, site description, and general study design
Chapter 2: Seasonal trends in Loma Alta Slough surface water and sediment nutrients and primary producer communities
Chapter 3: Seasonal trends in exchange of nutrients between surface waters and sediments
Chapter 4: Famosa Slough Nitrogen and Phosphorus Budgets

A summary of quality assurance results is provided in Appendix 1. Appendix 2 provides the data tables for summarized SCCWRP study data (as a complement to graphs used to present the data in Chapters 2-5) to facilitate use of data for modeling.

1.3 Site Description

Famosa Slough was originally a part of the Mission Bay wetland complex known as False Bay, which received freshwater and sediments from the San Diego River and local watersheds. Over time, Famosa Slough was gradually isolated from Mission Bay due to infrastructure development and the channelization of the San Diego River. The Slough now drains a more isolated watershed area of approximately 1.5 km^2. The construction of Interstate 8 ultimately separated the Slough from the San Diego River and currently, the only connection to the river during tidal exchange is through a culvert, consisting of three circular 5-ft diameter concrete pipes, with tide gates. The gates are usually closed during storm events to prevent water from entering the Slough from the river channel (SDRWQCB, 2006), but during the monitoring period, these flap gates were never closed. The combination of culverts and gates restrict tidal exchange in and out of the Slough, resulting in tidal muting within the Slough. Muting also occurs as a result of culverts under the West Point Loma Boulevard Bridge.

In its present configuration, Famosa Slough consists of a 4.8 hectare channel portion to the north, directly adjacent to the San Diego River, which is separated from the 10.2 hectare southern basin by West Point Loma Boulevard, with water exchange occurring via a box culvert in the north-west corner of the southern basin. Total estuarine subtidal area is approximately one-third (5.5 hectares) of the 15 hectare area. The two main inputs into the Slough are the San Diego River and the surrounding watershed, which enter through a series of storm drains throughout the Slough. The Slough is subject to muted tidal cycles through its connection to the San Diego River. Freshwater enters the Slough both from the watershed and as a small fraction of the San Diego River flow. Several enhancements have been added to the Slough in recent years to improve water quality: water treatment ponds on the south and southeast sides of the Slough which collect dry weather urban runoff, trash and sediment prior to discharge into the Slough. Most recently, a second 24-inch concrete pipe between the channel and the Slough under West Point Loma Boulevard was added to increase tidal flushing.

1.4 General Study Design

The general study design for all monitoring conducted to support TMDL modeling is based on a basic conceptual model developed to describe the sources, losses, and transformations of targeted constituents within Famosa Slough (McLaughlin et al. 2007). The three principal types of monitoring were conducted:

1. Continuous monitoring of hydrodynamic and core water quality parameters (salinity, temperature, etc.);
2. Wet weather monitoring, which was conducted during and immediately following a specified number of storm events at the mass emission (ME) site in the main tributary, targeted locations in the lagoon, and at the ocean inlet; and
3. Dry weather monitoring, which was conducted during "index" periods that were meant to capture representative seasonal cycles of physical forcing and biological activity in the lagoon. During each index period, sampling was conducted at the ME and ocean inlet sites, as well as at the segment site within the Slough. In Famosa Slough, the Ocean Inlet site represents the bottom portion of the Slough, while the Segment site represents the upper estuary of the Slough.

In general, stakeholder monitoring was intended to cover: 1) continuous monitoring of hydrodynamic and core water quality parameters, 2) all wet weather monitoring, and 3) dry weather ambient monitoring of surface water nutrient concentrations within the lagoon and at points of exchange between the lagoon and the ocean inlet and watershed freshwater flows (ME site).

SCCWRP studies collected three types of data: 1) estimates of inventories of nutrients within certain pools in Famosa Slough (e.g., sediments, primary producer biomass) to complement stakeholder sampling during dry weather index periods, 2) measurements of key rates of exchange or transformation within or among sediments and surface waters, and 3) rates of net sediment and particulate N and P deposition to support sediment transport modeling and lagoon water quality modeling.

Sampling to develop the dataset occurred during four index periods in one year (Table 1.1). Each index period represents seasonal variations in each lagoon: Storm season (January 2008), post-storm/pre-algal bloom (March 2008), high algal bloom (July 2008), and post-algal bloom/pre-storm (September 2008). This sampling design aimed to provide a means to examine annual variability in lagoon processes affecting nutrient availability and cycling. SCCWRP sampling was coordinated to coincide with stakeholder monitoring of dry weather ambient water quality (WestonSolutions 2009). Figure 1.1 summarizes the sampling locations for each of the different types of monitoring studies in Famosa Slough.

Table 1.1. Summary of the different sampling activities in Famosa Slough by time period, types of sampling event, organization and actual dates sampling occurred.

Period	Event	Organization	Date
Background	Sediment Deposition	LSU	11/15/07
Wet Weather Monitoring	Storm Sampling (3 storm events)	Weston Solutions	11/30/07 12/7/07 2/3/07
Wet Weather Monitoring	Post Storm Sediment Sampling	Weston Solutions	2/12/08
Continuous Monitoring	Water Quality Monitoring	Weston Solutions	10/10/07 - 10/7/08
Index Period 1	Ambient Sampling	Weston Solutions	1/14-1/16/08 1/21-1/23/08
	Transect Sampling	Weston Solutions	1/17/08
	Benthic Chamber Study	SCCWRP	1/11/08
	Porewater Peeper Deployment	SCCWRP	1/7-1/17/08
	Sediment Core	SCCWRP	1/17/08
	Macroalgae Monitoring	UCLA	1/22/08
	Sediment Deposition	LSU	1/21/08
	Sediment Deposition	LSU	2/28/08
Index Period 2	Ambient Sampling	Weston Solutions	3/17-3/20/08 3/24-3/26/08
	Transect Sampling	Weston Solutions	3/20/08
	Benthic Chamber Study	SCCWRP	3/18/08
	Porewater Peeper Deployment	SCCWRP	3/18-4/3/08
	Sediment Core	SCCWRP	4/3/08
	Macroalgae Monitoring	UCLA	4/11/08
	Sediment Deposition	LSU	4/3/08
	Sediment Deposition	LSU	5/15/08
Index Period 3	Ambient Sampling	Weston Solutions	7/14-7/16/08 7/21-7/23/08
	Transect Sampling	Weston Solutions	7/17/08
	Benthic Chamber Study	SCCWRP	7/15/08
	Porewater Peeper Deployment	SCCWRP	7/3-7/23/08
	Sediment Core	SCCWRP	7/23/08
	Macroalgae Monitoring	UCLA	7/21/08
	Sediment Deposition	LSU	7/23/08
	Sediment Deposition	LSU	8/20/08
Index Period 4	Ambient Sampling	Weston Solutions	9/15-9/17/08 9/22-9/24/08
	Transect Sampling	Weston Solutions	9/18/08
	Benthic Chamber Study	SCCWRP	9/16/08
	Porewater Peeper Deployment	SCCWRP	9/12-9/30/08
	Sediment Core	SCCWRP	9/30/08
	Macroalgae Monitoring	UCLA	9/29/08
	Sediment Deposition	LSU	9/29/08

Figure 1.1. Location of sampling activities in Famosa Slough.

2 Seasonal Trends in Surface Water and Sediment Nutrients and Primary Producer Communities in Famosa Slough

2.1 Introduction

All estuaries exhibit distinct temporal and spatial patterns in hydrology, water quality and biology that are integral to the ecological services and beneficial uses they provide (Day et al. 1989, Loneragan and Bunn 1999, Caffrey 2004, Rountree and Able 2007, Shervette and Gelwick 2008, Granek et al. 2010). Characterization of seasonal and spatial patterns in surface water and sediment nutrient concentrations and aquatic primary producer communities provides valuable information about the sources, dominant transport mechanisms, and fate of nutrients in Famosa Slough and helps to generate hypotheses regarding the controls on biological response to nutrients.

The purpose of this chapter is to present a baseline characterization of the patterns in surface water and sediment nutrients and aquatic primary producers in Famosa Slough. This work forms the foundation for interpretation of benthic fluxes (Chapter 3) and characterizing the efficiency of nutrient cycling through N and P budgets for the Slough (Chapter 4).

2.2 Methods

The following types of field data were collected and methods are explained in detail in this section:

- Longitudinal and seasonal trends in surface water ambient nutrient concentrations, conducted in conjunction with Weston Solutions Inc.
- Seasonal trends in aquatic primary producer biomass and/or percent cover and tissue nutrient content.
- Seasonal variation in sediment bulk characteristics (grain size, solid phase N and P content).

A detailed presentation of the intent and field, analytical, and data analysis methods associated with each of these data types follows below.

When appropriate, ambient water quality data collected and analyzed by Weston Solutions are incorporated into the results and discussion. These data are cited when used and for a detailed explanation of methods, see Weston Solutions (2009).

2.2.1 Field Methods

2.2.1.1 Surface Water Nitrogen and Phosphorus along a Longitudinal Gradient

Longitudinal transects of surface water nutrient concentrations provide valuable spatial information about how concentrations vary along a gradient from the freshwater source to the ocean (or in this case river) end-member.

Surface water samples were collected by Weston Solutions at 14 sites along a longitudinal gradient from the southern basin to the northern arm of Famosa Slough (Figure 1.1; Weston Solutions 2009). Longitudinal transect sampling occurred on the fourth day of the first week of each index period.

Transect sampling was performed using kayaks and grab-sampling techniques. Sampling occurred in the tidal channels and samples were collected once at ebb tide and once at flood tide.

The sample bottle was triple rinsed before filling completely. Sample bottles were open and closed under water to avoid contamination with surface films or stratified water masses. One-liter sample bottles were returned to the shore for immediate filtering where appropriate. Ambient water samples were subsampled for a suite of analytes using a clean, 60 ml syringe. Each syringe was triple rinsed with sample water. Mixed cellulose ester (MCE) filters were used for nutrient analysis and polyethersulfone (PES) filters were used for dissolved organic carbon and metals analysis. Each filter was rinsed with ~20 ml of sample water (discarded) before collection into vials.

2.2.1.2 Inventory of Aquatic Primary Producer Cover and Tissue Content

Aquatic primary producer communities include macroalgal and cyanobacteria mats, benthic algal mats, suspended phytoplankton, and submerged aquatic vegetation. The purpose of this study element was to characterize seasonal variation in the standing biomass, cover, and the tissue nutrient content of these communities. This information will be used to calibrate the component of the eutrophication water quality model that accounts for the storage and transformation of nutrients in primary producer community biomass.

Aquatic primary producer biomass was measured during the four index periods at the within Slough segment site. At the site, intertidal macroalgae were sampled along a 30 m transect parallel to the waterline and one meter down-slope from the vascular vegetation. Macroalgal abundance was determined by measuring percent cover and algal biomass; we included both attached and detached mats. At five randomly chosen points along each transect, a 0.25 m^2 quadrat with 36 evenly spaced intercepts (forming a 6 x 6 grid) was placed on the benthos. The presence or absence of each macroalgal species in the top layer under each intercept was recorded. When present, algae were collected from a 530.9 cm^2 area circumscribed by a plastic cylinder placed on the benthos in the center of each quadrat. Each sample was placed in an individual ziploc bag in a cooler, transported to the laboratory and refrigerated. Algal samples were transferred to low nutrient seawater where they were cleaned of macroscopic debris, mud and animals. For each sample, algae were placed in a nylon mesh bag, spun in a salad spinner for one minute, wet weighed, rinsed briefly in deinonized water to remove salts, and dried at 60° C to a constant weight. Macroalgal biomass was normalized to area (g wet wt m^{-2}). Fine macroalgal filaments that grow within the sediment may be visible but biomass cannot be collected quantitatively at this early growth stage, making percent cover in this case a more sensitive measurement. In addition, when there is 100% cover, and mats are different thicknesses, biomass will be a more useful measure to make distinctions between sites (Sfriso et al. 1987). Thus it is important to use both methods to estimate abundance. Samples were cleaned and weighed to determine wet and dry weights. Dried samples were analyzed for percent organic carbon (OC), percent organic N and percent P.

2.2.1.3 Sediment Bulk Characteristics and Solid Phase and Porewater Nutrients

All sediment loads carry nutrients, either as organic matter or, in the case of P, associated with particles. When deposited in the estuary, these particulate nutrients may break down to biologically available forms and may build up in high concentrations in sediment porewaters. Sediment bulk characteristics control nutrient content; finer particle size fractions are associated with higher organic carbon, nitrogen and phosphorus content. Temporal trends in sediment solid phase and porewater nutrients provide information about the load and fate of nutrients associated with sediments in Loma Alta Slough.

The purpose of this study element was to better characterize the load and fate of nutrients associated with sediments. Specifically, this involved two types of activities:

1. Measurement of the sediment solid phase bulk characteristics (grain size, porosity, etc.) and sediment N and P concentrations.
2. Measurement of porewater N and P concentrations.

Sediment bulk characteristics and solid phase nutrient concentrations were estimated for a vertical profile in one sediment core taken from the segment site. For each sampling period, one sediment core was taken and vertically sectioned on site into 1 cm intervals from the sediment water interface until 6 cm depth and then sectioned every 2 cm down to 12 cm. Sediments were placed in plastic storage bags and stored on ice in the dark until they reached the laboratory. In the lab, sections were wet weighed, dried at 50 °C to a constant weight, and reweighed to determine percent solids and wet bulk density. A subsample of each section (~10 grams dry weight) was removed and ground to a fine powder for percent organic carbon, percent total nitrogen (TN) and percent total phosphorus (TP) analysis. The remainder of the section was utilized for grain size analysis (percent fines).

Sediment porewaters were sampled from the subtidal area of the southern basin using porewater equilibrators (peepers: (Hesslein 1976)) during each index period (Figure 2.1). When the peepers are placed into the sediment, solutes from the porewaters come into contact with the filter and a concentration gradient is established between the cell water (no solute) and the porewaters. This causes solutes to diffuse into the cells and, over time, equilibrium is established between the peeper cells and the porewaters whereby the concentrations on both sides of the filter paper are equal. Each peeper was constructed from a 50 x 18 cm solid plexiglass frame into which cells (0.5 x 3.0 x 13 cm) were milled in at a spacing of approximately 1 cm, which are used to sample a depth profile of the sediment porewaters. Each cell is filled with distilled, deionized water that had been bubbled with N gas for 24 hours to remove the oxygen and covered with a 0.45 μm polycarbonate filter paper. The filter is held in place by an outer plexiglass frame secured with Teflon screws. Peepers are kept under a N atmosphere until deployment. Peepers were pushed by hand into the subtidal sediment, making sure that the peeper is vertical and the top of the sediment surface was flush with the top well of the peeper. Peepers were secured with a 30 m cable attached to a stake driven into the upper intertidal zone to facilitate recovery and the location was recorded using GPS coordinates. After a two-week equilibration period (Hesslein 1976, Brandl and Hanselmann 1991), the peepers were retrieved. Peeper recovery was coordinated with the collection of the sediment core and a collection of ambient bottom water. Sediment cores for bulk characteristics and nutrients, described above, were collected within 2 feet of the peeper location.

Immediately following retrieval, the peepers are placed inside large format ziploc bags that were purged with N gas to minimize artifacts from oxidation of porewater fluids. Porewater samples were extracted from each well using a repeater pipette, dispensed into vials and immediately frozen for analysis. Wells sampled represent porewater depths of: 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, 7-8, 10-11, 13-14 cm. Each peeper is processed within 15 minutes of recovery. Following sub-sampling of the peeper, ambient bottom water samples were also filtered, collected into vials and frozen for analysis. All water samples were analyzed for the following: sulfide (S^{-2}), ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), soluble reactive phosphate (SRP), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), dissolved iron (Fe), dissolved manganese (Mn), total carbon dioxide (TCO_2), and dissolved organic carbon (DOC). Before freezing sulfide samples were preserved with zinc acetate. One field blank was collected for each porewater analyte; a field blank and a duplicate were collected for each ambient sample. Surface water samples were collected at the time of peeper retrieval.

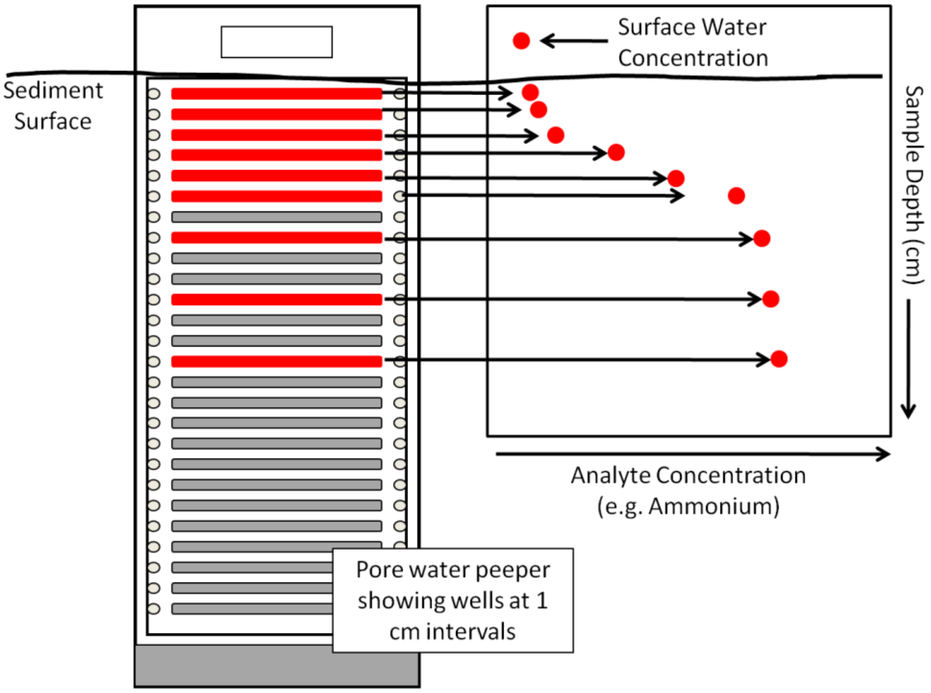


Figure 2.1. Graphic depicting how porewater profiles are generated from porewater peepers.

2.2.1.4 Sediment Berylium-7 Radioisotope Seasonal Inventory

Berylium-7 activity in sediments was measured during the four index periods and three additional periods at the segment site in Loma Alta Slough. One sediment core was taken per segment per site and vertically sectioned down to 12 cm (this was the same core that is used for bulk sediment characteristics – see above). Radioisotope levels were measured in the core, starting from the top of the core and proceeding down core until no radioisotopes were detected. Sediments were placed in plastic storage bags and stored on ice in the dark until they reached the laboratory. In the lab, sections were wet weighed, dried at 50 °C to a constant weight, and reweighed to determine percent solids and wet bulk density. A subsample of each section (~10 grams dry weight) was removed and ground to a fine powder for Beryllium-7 (^{7}Be) radioisotope analysis and % OC, % TN, and % TP analysis. The remainder of the section was utilized for grain size analysis (percent sand).

2.2.2 Analytical Methods

All water samples were assayed by flow injection analysis for dissolved inorganic nutrients using a Lachat Instruments QuikChem 8000 autoanalyzer for the analysis of NH_4, NO_3, NO_2, and SRP. Dissolved Fe and Mn were measured by atomic adsorption spectrophotometry on a Varian Instruments AA400. Water samples were assessed for TDN, TDP, TN and TP via two-step process: first water samples undergo a persulfate digest to convert all N from all N compartments into NO_3 and the P from all P compartments into orthophosphate; then the resulting digests are analyzed by automated colorimetry (Alpkem or Technicon) for nitrate-N and orthophosphate-P (Koroleff 1985). Water DOC was analyzed on a Shimadzu TOC-5000A Total Organic Carbon Analyzer with ASI-5000A Auto Sampler. Water TCO_2 was analyzed on a UIC instruments carbon dioxide coulometer. Sulfide samples were allowed to react with N,N-dimethyl-p-phenylenediamine and ferric chloride under acidic conditions to yield the product methylene blue, and the concentration of methylene blue was determined spectrophotometrically at 668 nm. Concentration of sulfide in the sample was calculated by reference to a standard curve (absorbance vs. sulfide concentration). Inorganic nutrients and trace metals were run by the Marine Science Institute at the University of California, Santa Barbara and total dissolved and total nitrogen and phosphorus and DOC were run at the University of Georgia Analytical Chemistry Laboratory. Sulfide and TCO_2 were measured by SCCWRP.

Dried sediment samples were subsampled and ground for analysis of %OC, %TN, and %TP. Samples for %OC were acidified to remove carbonates; %OC and %TN were measured by high temperature combustion on a Control Equipment Corp CEC 440HA elemental analyzer at the Marine Science Institute, Santa Barbara. Sediment %TP were prepared using and acid persulfate digest to convert all P to orthophosphate, which was then analyzed by automated colorimetry (Technicon) at the University of Georgia Analytical Chemistry Laboratory.

To determine percent fines, a portion of sediment from each interval was weighed dry (total dry weight), then wet sieved through a 63 µm sieve, dried at 50 °C to a constant weight, and reweighed as sand dry weight. Percent sand was calculated as a function of the sand dry weight divided by the total dry weight of the sample. Percent fines were calculated as the total weight minus the percent sand.

Seasonal sedimentation rates were determined using radioactive isotopes of ^{7}Be. The ^{7}Be activity (53-day half-life) was used to document the short term sediment deposition rate. This activity was determined by gamma spectrometry using a low-energy Germanium (LeGe) planar detector coupled with a low background cryostat and shielding. Samples were counted for 24 hours on an intrinsic germanium detector, and the ^{7}Be radioisotope was measured at the photon peak 477.1 keV.

The analytical methods for grain size, % OC and TN, and TP are given in Section 2.24.

2.2.3 Data Analysis

Analysis of variance (ANOVA) tests were used to test for differences in concentration data by index period and, where relevant, by ebb and flood tide (SAS Proc GLM, 2008). Data were transformed to correct for unequal variance and mean and standard errors were generated from Tukey's pairwise comparisons.

Standing biomass of aquatic primary producers groups (phytoplankton, macroalgae, microphytobenthos, and cyanobacteria mats) were converted to carbon per meter squared in order to make comparisons among the groups. The following assumptions were used in this conversion:

- Phytoplankton- Average 1.5 m depth of water, Chl a: C ratio of 30 (Cloern et al. 1995)
- MPB – Chl a: C ratio of 30:1 (Sundbäck and McGlathery 2005)
- Cyanobacteria: 50% C by dry wt (study data)
- Macroalgae: 22% C by dry wt (study data)

Porosity, fractions of water and sediment, and wet bulk density were used to estimate seasonal and annual sediment deposition rates and to evaluate changes in sediment nutrient and radioisotope inventories. These values are calculated from parameters measured in the laboratory.

The difference between wet and dry weights was used to calculate the fraction water (f_{wet}) and fraction sediment (f_{dry}):

$$f_{wet} = \frac{W_{wet} - W_{dry}}{W_{wet}}$$

Eq. 2.1, 2.2

$$f_{dry} = 1 - f_{wet}$$

where W_{wet} and W_{dry} are the wet and dry sediment weights, respectively. Subsequently, when enough sample was available, a small known fraction of the initial dried sample was weighed, and dry grain density was determined gravimetrically using Archimedes principle, i.e., by volume displacement. The weighed sediment divided by the displaced volume yielded the dry grain density of each sediment core sample section. The dry grain density and fractions wet and dry were used in turn to calculate the porosity and bulk density. Often the shallowest sections of the cores did not contain enough material for a complete sediment physical properties analysis. We took extra cores near the end of the project to complete any missing sediment physical property data needed for future calculations. Porosity is a measure of the amount of "empty space" in the sediment, defined by the ratio of the volume of voids to the total volume of a rock or unconsolidated material. Porosity was calculated using the following equation:

$$\phi = \frac{\frac{f_{wet}}{\rho_{water}}}{\frac{f_{wet}}{\rho_{water}} - \frac{f_{dry}}{\rho_{drygrain}}}$$ **Eq. 2.3**

where ϕ is the porosity; ρ_{water} and $\rho_{drygrain}$ are the density of ambient water and dry sediment grains, respectively. Bulk density, $\rho_{wetbulk}$ or $\rho_{drybulk}$, was calculated based on the total mass of each core section divided by the core section interval volume. Thus both a wet and a dry bulk sediment density could be determined on deeper samples more often when a larger mass of sample was available for the different analyses. Wet bulk density (ρ in g cm^{-3}) is given by the Equation 2.4:

$$\rho = \frac{\mathrm{W_{SEDwet\,(i)}}}{\mathrm{V_i}}$$ **Eq. 2.4**

where $W_{SEDwet\ (i)}$ is the wet weight of each sediment core section interval, and V_i is the volume of the sediment core section interval.

Samples were prepared for ^{7}Be analysis by homogenizing about 5 g of dry sediment in a mortar and pestle until the sediment is finely ground. This step ensures the sediment can be densely packed in the sample container to maximize the content being counted and increase the efficiency of the detector. Once the sample was ground, small aliquots were transferred to 1-ml test tube shaped vials and tapped gently for about two to three minutes per transfer to pack the sample down as we filled the vial. When each pre-weighed vial was filled to 33 mm height, the sample and vial were weighed. Each sediment sample was analyzed on a Canberra well germanium detector for 12 hours by measuring the peak gamma ray energy at 477 keV to obtain the ^{7}Be activity. Efficiencies were calculated using an International Atomic Energy Agency (IAEA) reference standard. Net peak area was recorded for each nuclide of interest (^{7}Be), and activities (A; dpm g^{-1}) were calculated using the following equation:

$$A = \frac{cpm_{sample} - cpm_{background}}{f_{inensity} * f_{eff} * W_{sediment}}$$ **Eq. 2.5**

where *cpm* is count rate per minute of sample or background, $W_{sediment}$ is sample mass in the vial, $f_{intensity}$ is γ-ray intensity, and f_{eff} is system efficiency for a particular photon energy. Activities below detection were reported as zero, and the average background count rate was 0.02 cpm.

From these ^{7}Be activities, down core sediment inventories were quantified using the equation:

$$I_{total} = \sum_{z=0}^{n}(A_z * \rho_z * h_z) \qquad \textbf{Eq. 2.6}$$

where I_{total} is total ^{7}Be inventory (dpm cm^{-2}), A_z is the activity at depth z, ρ is sample bulk density, and h is sample interval thickness (cm). Total ^{7}Be inventories at each site for each sampling event were corrected for the residual activities remaining from previous events. This residual inventory was estimated by correcting the previous month's total inventory for radioactive decay by the elapsed time between sampling events using the following equation:

$$I_R = I_T e^{-\lambda t} \qquad \textbf{Eq. 2.7}$$

where I_R is the residual inventory (dpm cm^{-2}), I_T is the total inventory from Eq. 2.6, λ is the decay constant for ^{7}Be (0.0130046 d^{-1}), and t is the time elapsed between sampling periods (days). New inventory (I_N) for the current sample month was then calculated by subtracting the calculated residual inventory remaining from a previous month from the total inventory via the following:

$$I_N = I_T - I_R \qquad \textbf{Eq. 2.8}$$

New inventory physically represents the portion of the total inventory associated with recent sediment deposition or resuspension events. A positive new inventory represents a deposition event while a negative inventory indicates a removal event. Net ^{7}Be flux (dpm cm^{-2} d^{-1}) into or out of the sediments between sampling periods was calculated by dividing the new inventory by the time interval between sampling.

The time-dependent ^{7}Be flux, used here to determine short-term sediment mass accumulation or removal rates, was estimated as:

$$\psi = \frac{I_N}{A_{new}} \qquad \textbf{Eq. 2.9}$$

where ψ is the short-term sediment deposition or removal rate (g cm^{-2} d^{-1}), and A_{new} is the average activity in the sample after subtracting the decay-corrected activity that existed from the previous sampling period.

Temporal variability in short-term (seasonal) sediment deposition and remobilization was evaluated using the general conceptual model in which the first sediment sampling event (November 2007, before the index periods) sets a baseline of low ^{7}Be activity because of a four-month dry season. Subsequent sampling trips (during wet season and throughout dry season) revealed possible changes occurring at the site in the intervening time period, including: (1) an inventory reflecting recent deposition and/or residual inventory reflecting older deposition events; (2) a small residual inventory associated with decay or partial sediment removal when no recent deposition events had occurred; and (3) no inventory, indicating complete removal of the uppermost sediment layer or complete decay when the sampling interval was sufficiently long (i.e., during the dry season; see (Giffin and Corbett 2003) for in depth discussion on interpretation of ^{7}Be profiles). These time-series inventory comparisons can be used to evaluate the short-term sediment deposition rate, discern whether or not a site is a focal point for sediment deposition or a net-loss site over time, and observe reworking of sediments that may have been caused by bioturbation (birds, burrowing organisms, etc.).

The use of ^{7}Be radioisotope tracers to calculate N and P associated with new sediment deposition during the wet season requires the establishment of a pre-wet season baseline of ^{7}Be inventory in the sediments (November 2007) and subsequent sampling approximately once per month for the duration of the period of interest. Intensive temporal sampling of ^{7}Be inventories in sediment from November 2007 – October 2008 yielded the estimated weight of new sediment deposited over the interval between sampling periods “t” and “t+1” (M_{SED} in g wet weight cm^{-2}). This deposition rate, when divided by the average wet-bulk density of the first 0-6 cm of the sediment in the core, yielded the approximate depth of mass accumulation (D) during that time period (Equation 2.10):.

$$\boldsymbol{D_{MA} = \frac{M_{SED}}{\rho}} \qquad \textbf{Eq. 2.10}$$

The mean sediment N and P concentration ($SN_{0\text{-}D}$ and $SP_{0\text{-}D}$, expressed in % of dry weight sediment) and average fraction of solids in the sediment interval (X_{SED}) was calculated the over the depth of mass accumulation (D) for the “t+1” sampling period for each core. Calculation of the mass of SN or SP deposition (M_{SN} or M_{SP}) during this sampling, interval is given by Equation 2.11.

$$\boldsymbol{M_{SN} = M_{SED} * X_{SED} * SN_{0-D} * 100} \qquad \textbf{Eq. 2.11}$$

M_{SN} or M_{SP} was then divided by the total number of days in the interval to yield a daily SN or SP.

2.3 Results

2.3.1 Seasonal and spatial trends in physiochemical parameters and nutrients

Water quality and primary producer biomass would be expected to change as a function of freshwater flow, salinity, and temperature. During the winter and spring index periods, freshwater flow into the Slough impacts caused declines in temperatures and higher variability in salinity (Figure 2.2).

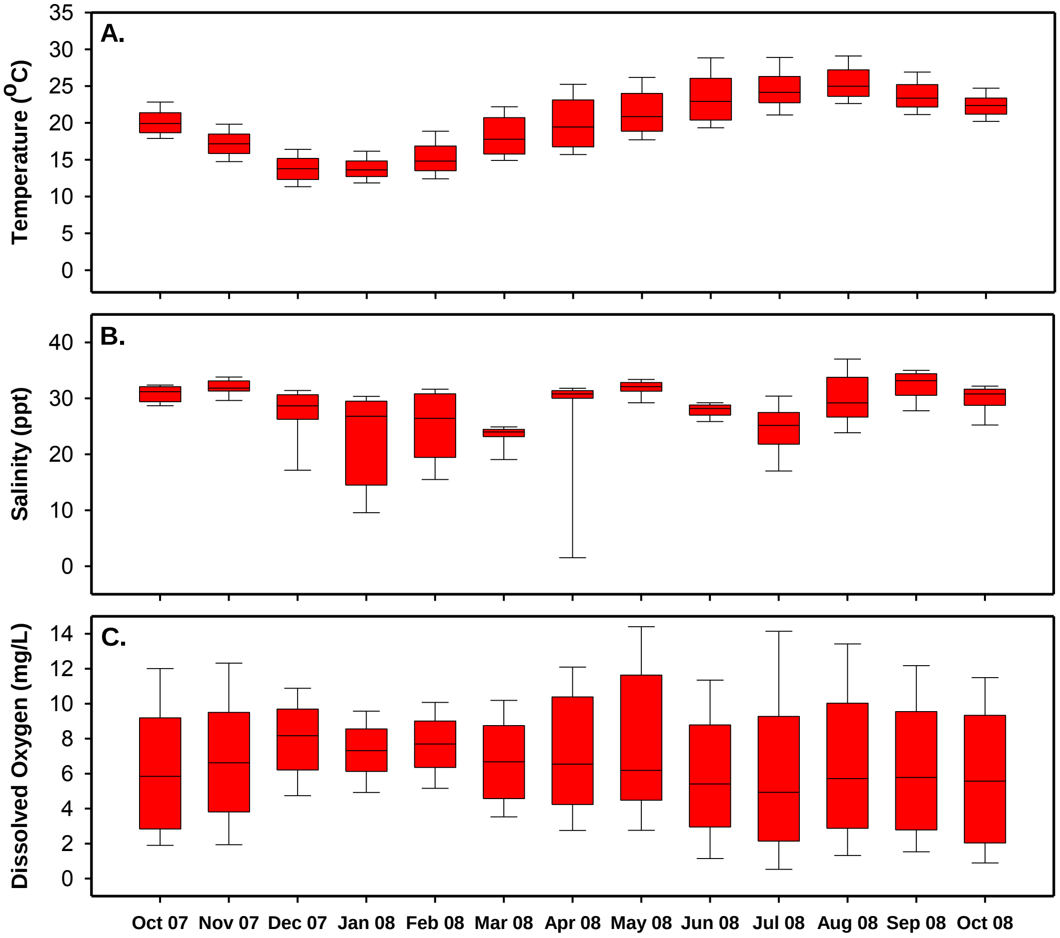


Figure 2.2. Seasonal Variation in temperature (A), salinity (B), and dissolved oxygen (C) at the Famosa Slough continuous monitoring site (WestonSolutions 2009).

Seasonally, the highest surface water nutrient concentrations were observed in both the freshwater discharge and ambient slough waters during wet weather events when TN concentrations averaged 99.8 μM and TP concentrations averaged 10 μM, which was 70 μM and 8 μM higher than average dry weather conditions for TN and TP respectively (Figures 2.3 and 2.4; (WestonSolutions 2009). Freshwater nutrients (TN, TP, NH_4, NO_3, and SRP) were routinely higher than ambient slough concentrations at the segment site. During wet weather approximately half of the TN and TP was dissolved inorganic nutrients (NH_4, NO_3, SRP).

During dry weather, dissolved inorganic forms of nutrients were typically low relative to organic forms, both in incoming freshwater and ambient slough water, particularly during the summer and fall index periods (Table 2.1). Peak TN and TP concentrations occurred during the summer index period, and the bulk of these totals were in the organic form. Average SRP values showed no variation among sampling periods and were consistently low. (Figure 2.4; Table 2.1; (WestonSolutions 2009).

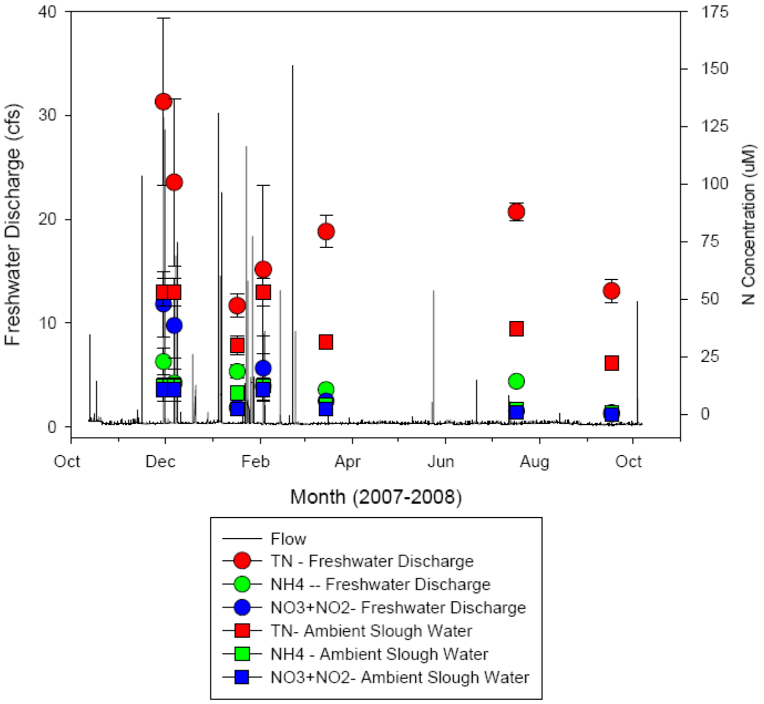


Figure 2.3. Dry weather concentrations of TN, ammonium and nitrate in freshwater discharge and ambient slough water as a function of freshwater flow into Famosa Slough. Data from Weston Solutions (2009).

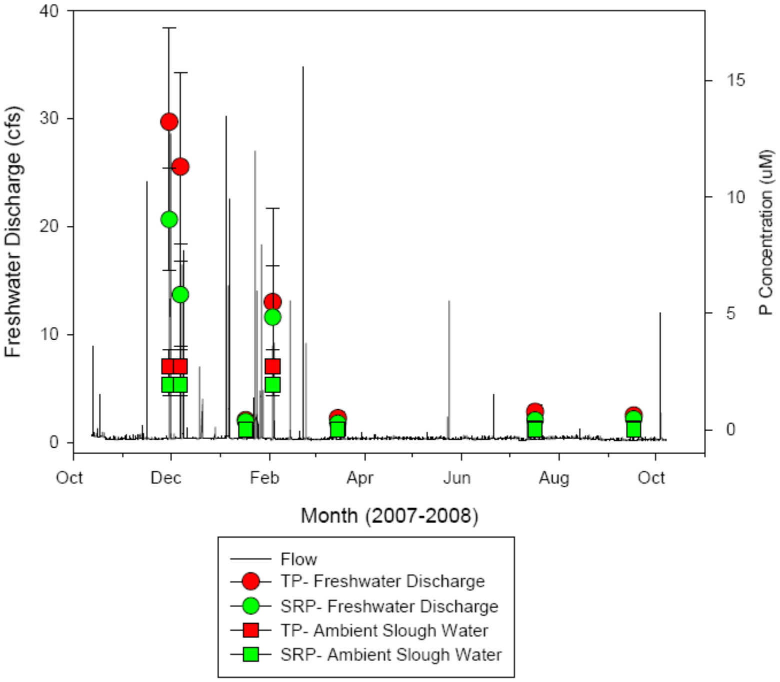


Figure 2.4. Dry weather concentrations of TP, and SRP in freshwater discharge and ambient slough water as a function of freshwater flow into Famosa Slough. Data from Weston Solutions (2009).

Table 2.1. Mean Concentrations of nutrients and TSS at segment site of Famosa Slough (WestonSolutions 2009).

Constituent	Wet Weather Average	Index Period 1 Winter	Index Period 2 Spring	Index Period 3 Summer	Index Period 4 Fall
TSS (mg L^{-1})	31.5 ± 19.8	9.8 ± 4.8	7.1 ± 2.7	10.7 ± 9.3	8.2 ±3.2
TN (µM)	99.8 ± 36.4	29.7 ± 13.8	31.6 ± 7.6	37.3 ± 8.8	22.0 ± 11.7
TDN (µM)	--	29.0 ± 11.8	29.3 ± 11.5	34.6 ± 11.6	16.8 ± 12.4
NH_4 (µM)	16.2 ± 5.8	10.3 ± 7.9	4.5 ± 1.2	2.0 ± 0.5	1.0 ± 1.0
NO_3 + NO_2 (µM)	35.5 ± 14.1	3.2 ± 2.6	1.9 ± 0.8	0.8 ± 0.3	0.5 ± 0.5
TP (µM)	10.0 ± 4.0	0.9 ± 0.4	1.3 ± 0.4	2.3 ± 0.7	1.9 ± 3.2
TDP (µM)	9.2 ± 3.8	1.3 ± 1.9	1.3 ± 0.5	1.7 ± 0.9	0.4 ± 0.4
SRP (µM)	6.6 ± 2.2	0.8 ± 0.2	0.6 ± 0.1	0.8 ± 0.2	0.5 ± 0.4

Spatially, some trends were visible along a longitudinal gradient in Famosa Slough (Figures 2.5 and 2.6). With respect to TN and TP, concentrations were higher in the southern basin relative to the northern channel during both ebb and flood tides in the summer and fall index periods and during the spring index period on the flood tide. TN and TP concentrations at the ocean inlet site during ebb and flood tides were highly variable, but it appears that San Diego River may be a source of TN and TP during the winter and summer index periods (Table 2.2).

Longitudinal trends were more variable with respect to dissolved inorganic nutrients. Ammonium and SRP were higher in the northern channel than the southern basin during both ebb and flood tides in the summer index period. Ammonium concentrations also followed this same trend during the fall index period, but only on the ebb tide. The San Diego River may be acting as a minor source of NH_4 and SRP to the Famosa Slough, as average flood tide concentrations were slightly higher than those of ebb tide (Table 2.2).

Nitrate numbers were low and no obvious spatial trends were observed within the longitudinal transects. Flood tide NO_3 concentrations were significantly higher than ebb tides for the winter index period, but the differences were slight (Table 2.2).

On average a greater fraction of the TN was DIN in the channel sites compared to the southern basin sites in both the summer (2% basin compared to 9% channel) and fall (4% basin and 21% channel), and a greater fraction of the TP was SRP was greater in the channel compared to the basin during the summer (2% basin compared to 50% channel). TP values for the fall were often below the detection limit in the channel so no clear determination can be made for this period.

Table 2.2. Mean concentrations of nutrients at "ocean inlet" site during ebb and flood tides in Famosa Slough (WestonSolutions 2009). All concentrations are in µM.

Nutrient Form	Tidal Direction	Index 1	Index 2	Index 3	Index 4
SRP	Flood	1.6±0.2	0.7±0.2	1.3±0.5	0.8±0.3
	Ebb	0.5±0.1	0.9±0.2	0.9±0.1	0.9±0.3
TP	Flood	2.2±0.4	1.1±0.1	3.1±1.3	0.8±0.3
	Ebb	1.3±0.3	1.6±0.3	2.1±0.5	0.9±0.3
Ammonium	Flood	11.5±5.8	3.7±1.6	3.1±1.1	2.8±1.6
	Ebb	9.7±5.9	6.2±1.5	2.7±0.4	2.2±0.9
Nitrate + Nitrite	Flood	3.3±1.5	3.4±0.6	1.3±0.4	0.3±0.5
	Ebb	1.0±0.2	3.2±1.2	0.6±0.2	0.6±0.3
TN	Flood	64.9±12.3	26.4±4.7	46.2±9.2	19.7±6.5
	Ebb	35.2±4.6	39.1±8.8	29.8±4.1	16.6±3.2

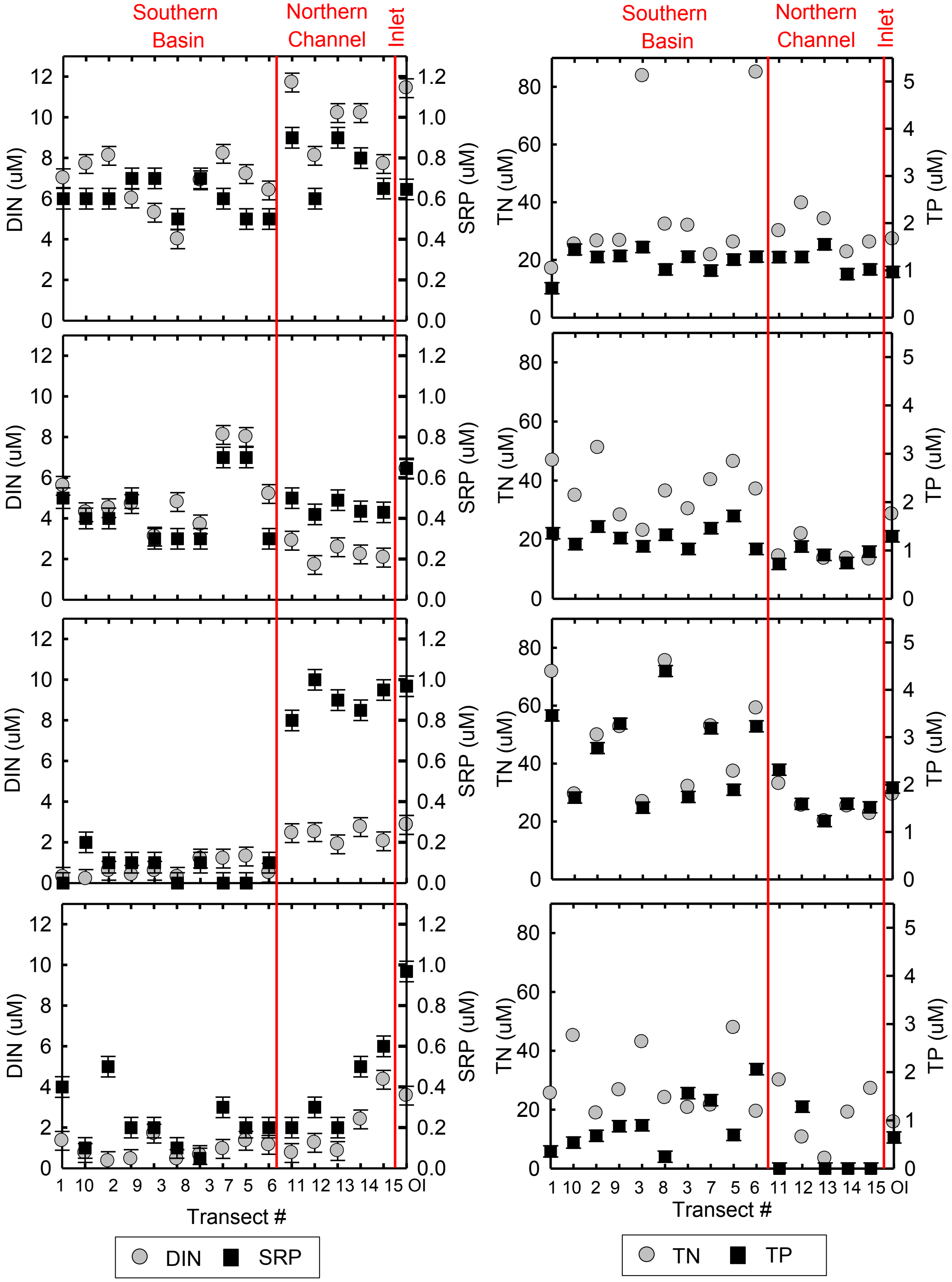


Figure 2.5. Transect data for each index period during ebb tide.

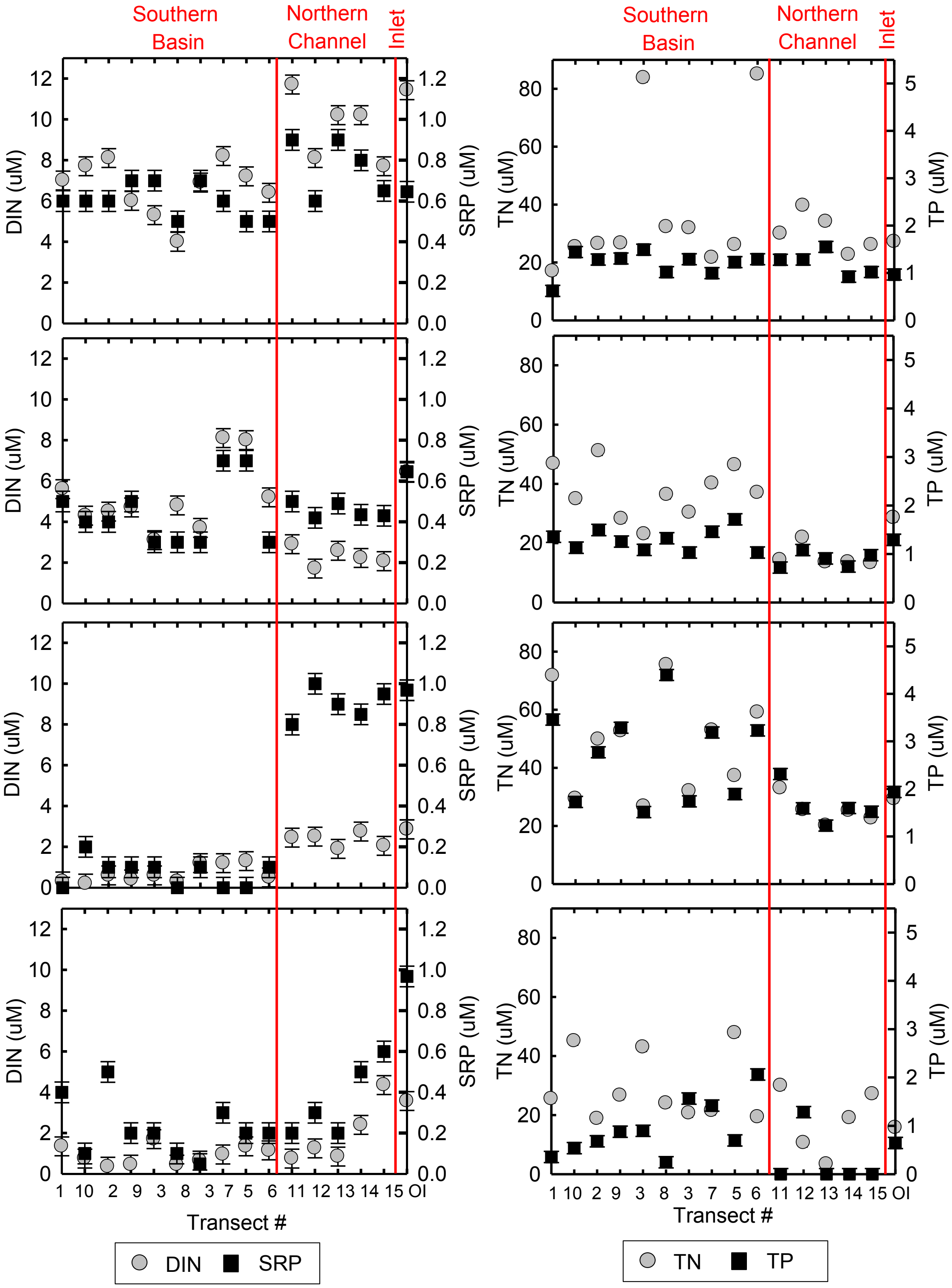


Figure 2.6. Transect data for each index period during flood tide.

2.3.2 Seasonal Trends in Primary Producers

This study assessed seasonal trends in biomass and or percent cover of three aquatic primary communities:

- phytoplankton (measured as suspended chlorophyll a)
- macroalgae (biomass and percent cover)
- microphytobenthos (measured as benthic chlorophyll a)

A fourth community, submerged aquatic vegetation, was observed in small quantities in Famosa Slough but was not quantitatively assessed.

Figure 2.7 shows the comparative biomass of phytoplankton, macroalgae and microphytobenthos, standardized to mass of carbon (C) per unit area relative to benthic infauna abundance by sampling period. During the winter index period, no biomass or cover of macroalgae was observed. By the spring index period, microphytobenthos dominated the aquatic primary producers. Macroalgal biomass (*Ulva sp.* and cyanobacteria mats) dominated the aquatic primary producers during summer and fall index periods (Figures 2.9), with 100% cover in the summer and high biomass (33 g C m^{-2}) during the summer. In terms of species composition, *Ulva intestinalis* dominated during spring and summer, while more diverse community during the fall (*Ulva intestinalis*, *Ulva expansa* and cyanobacterial mats) but lower cover and biomass during the fall.

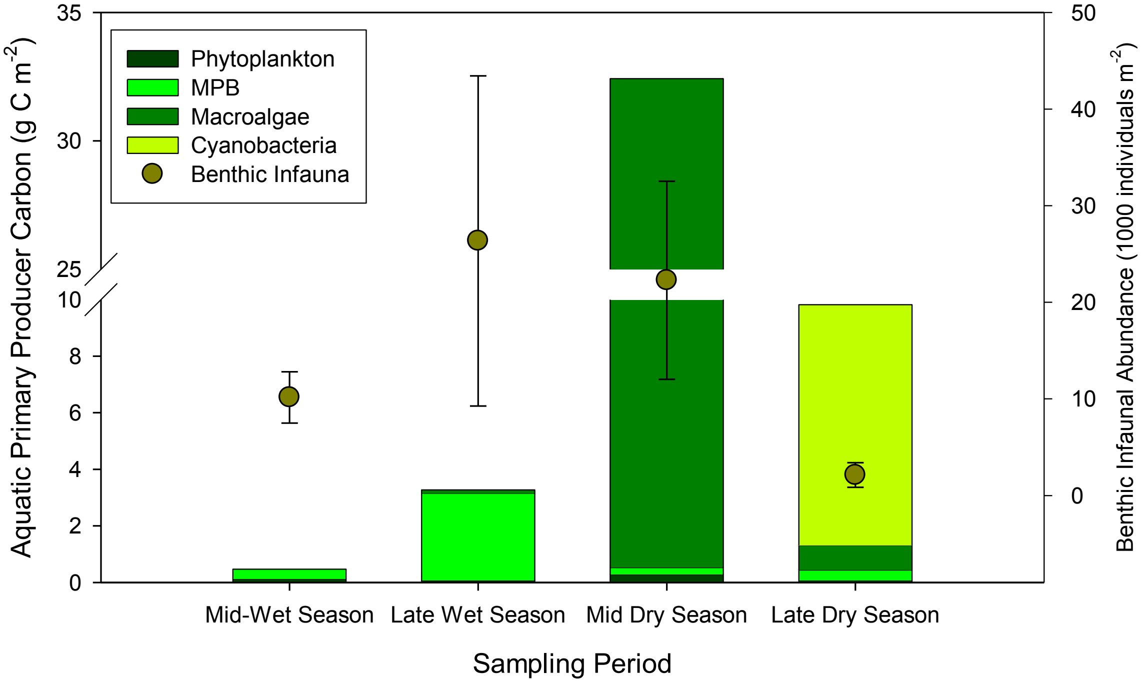


Figure 2.7 Mass of carbon associated with the four types of primary producers observed in Famosa Slough, relative to benthic infaunal abundance (measured in benthic chambers—see Section 3.3.2).

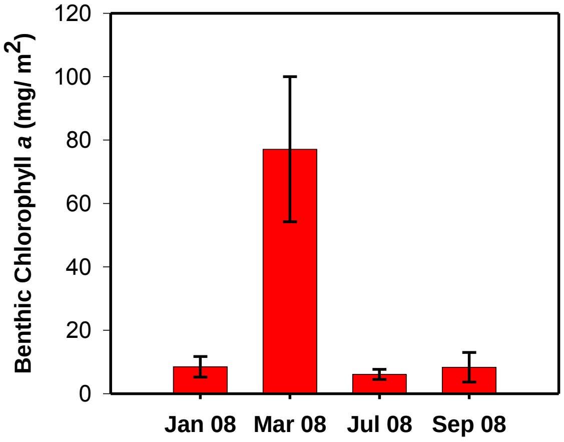


Figure 2.8. Benthic chlorophyll a concentrations (microphytobenthos biomass) for each index period.

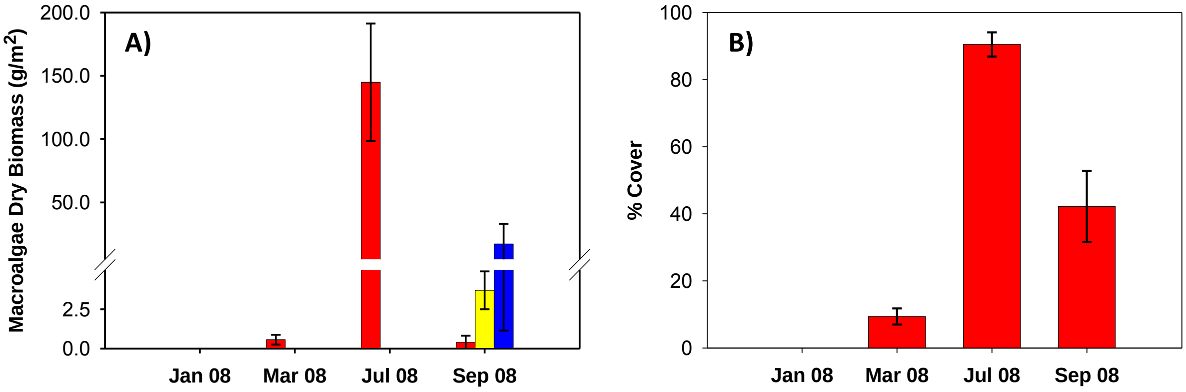


Figure 2.9. Macroalgae dry biomass by species (A) and total macroalgae percent cover (B) for each index period in Famosa Slough.

Phytoplankton chlorophyll a biomass was moderately high (30-49 mg m^3), but relative to other primary producers was insignificant portion of total biomass (Table 2.3). There was a seasonal pattern observed in the suspended chl a measurements with the greatest concentrations occurring during the summer and fall index periods, whereas the winter and spring index periods were an order of magnitude lower and not significantly different from one another. Distinct differences in suspended chl a concentration between the southern basin and northern channel were present in the summer and fall index periods. Chlorophyll a concentrations during the summer and fall index periods were significantly higher in the southern basin verses the northern channel (p-value <0.0001).

Table 2.3 Mean and standard deviation of chlorophyll a concentrations for southern basin and northern channel during each index period. Chlorophyll a concentrations are in mg m^{-3}.

Index Period	Southern Basin		Northern Channel	
	ebb	flood	ebb	flood
index 1	6±2	6±2	6±2	9±4
index 2	5±1	5±1	4±1	4±1
index 3	49±12	33±15	3±1	3±1
index 4	30±15	38±32	4±2	4±1

2.3.3 Seasonal Variation in Sediment Grain Size and Total Organic Carbon, Nitrogen and Phosphorus Characteristics by Index Period

Seasonal trends in sediment bulk characteristics were moderate (Figure 2.10). Percent of fine sediments increased from the winter and spring to the fall and the summer. During the winter, surface sediments have the lowest recorded percent fine sediments indicating possible scour of fine sediments during storm events. During the spring, fine sediments are more prevalent at the surface than during the winter; however mid-sediment column still showed a large percentage of sandy-grained sediments. By the summer and fall, the entire sediment column was chiefly comprised of fine-grained sediments (>75%).

Calculation of molar organic carbon to nitrogen (OC:N) and organic carbon to phosphorus (OC:P) are useful to control for the effects of grain size on sediment N and P content and allow for an estimation of the extent to which the sediment is enriched in N or P. OC:N molar ratios in sediments were typically lower in the surface sediments and increased with depth (Figure 2.10). This increase was most dramatic in the fall time periods (Nov 2007 and Oct 2008) and suggests a relative loss of N with depth. Organic carbon to total phosphorus (OC:P) molar ratios were fairly consistent with depth for all sampling periods with the exception of the January 2008 index period when there was wide variability and no obvious trend with depth.

Seasonal trends in sediment nutrient concentrations are not as clear as grain-size distributions. The OC:N ratios are relatively consistent from winter to summer, but are highest in the fall suggesting a loss of sediment N between summer and fall. OC:P ratios do not seem to show any significant temporal trends.

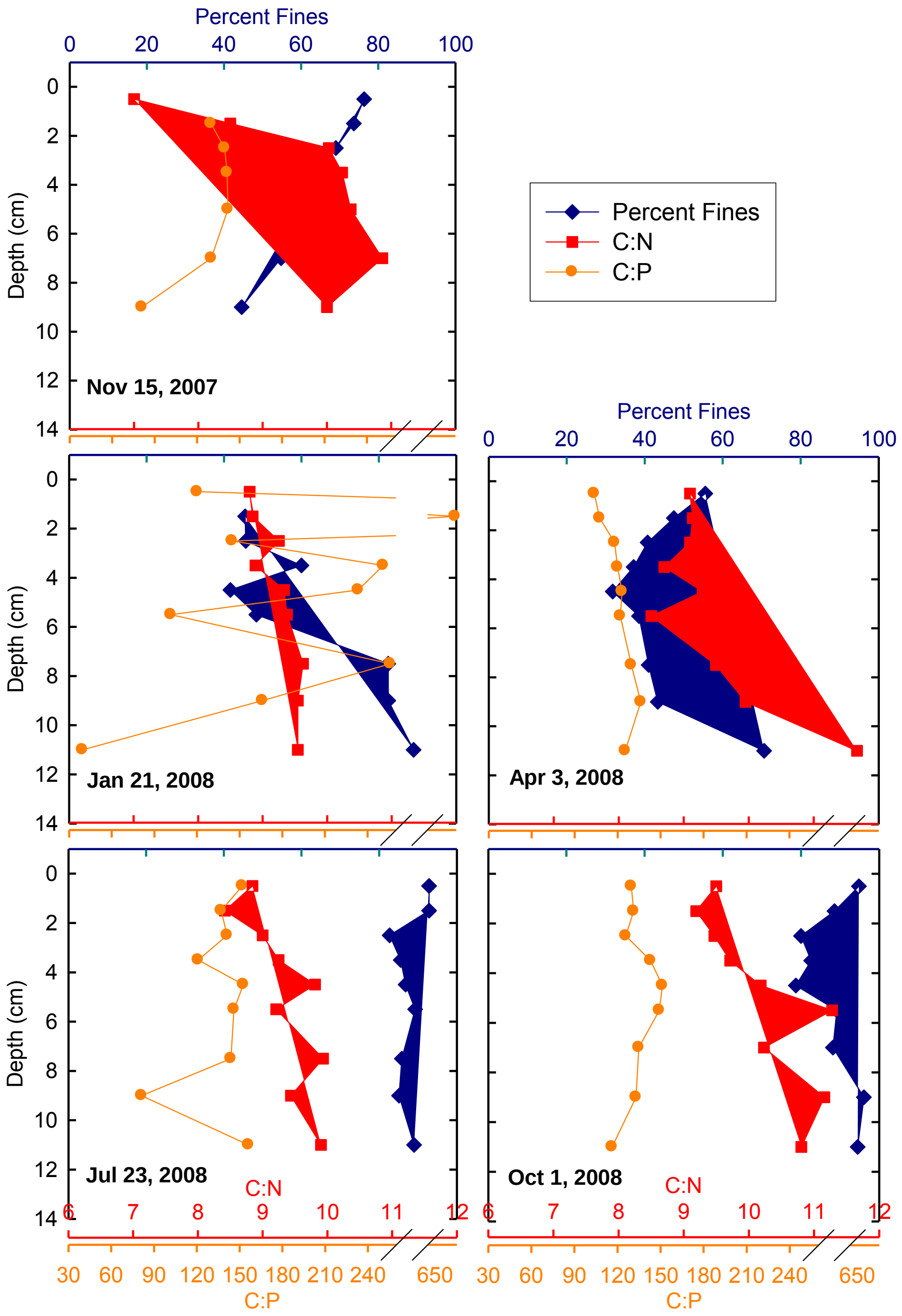


Figure 2.10. Sediment grain size (as percent fines, ♦), carbon: nitrogen (C:N, ■), and carbon: phosphorus (C:P, ●) ratios of cores taken in the southern basin of Famosa Slough during each index period.

2.3.4 Seasonal Trends in Sediment Deposition

Sediment deposition and removal events were measured using the particle tracer, ^{7}Be. This cosmogenic radionuclide is produced in the upper atmosphere by spallation of O_2 and N atoms. Because ^{7}Be is particle reactive, it will adsorb to any aerosols or dust present in the atmosphere at the time of formation. These particles are scrubbed from the atmosphere during rain events or fall out slowly as dry deposition. The ^{7}Be particles can then act as particle tracer proxies for all internal sediment movement, and track the downstream flow of sediment in streams and calculate the mass accumulation of sediment in the system.

Sediment mass fluxes can be compared to discharge and precipitation events to identify important events. Mass fluxes are presented as a material inventory (g cm^{-2}; Fig. 2.11) and indicate Famosa Slough is primarily a depositional environment throughout the year. While transport during rainfall events is possible, the fact that deposition is recorded throughout the year may be due to the resuspension of surface sediments in the Slough. Alternatively or in addition to resuspension, primary producer biomass can incorporate ^{7}Be particles into their biomass and consequently, when they senesce and are deposited onto the sediments, surface sediments will show a "new" inventory of ^{7}Be.

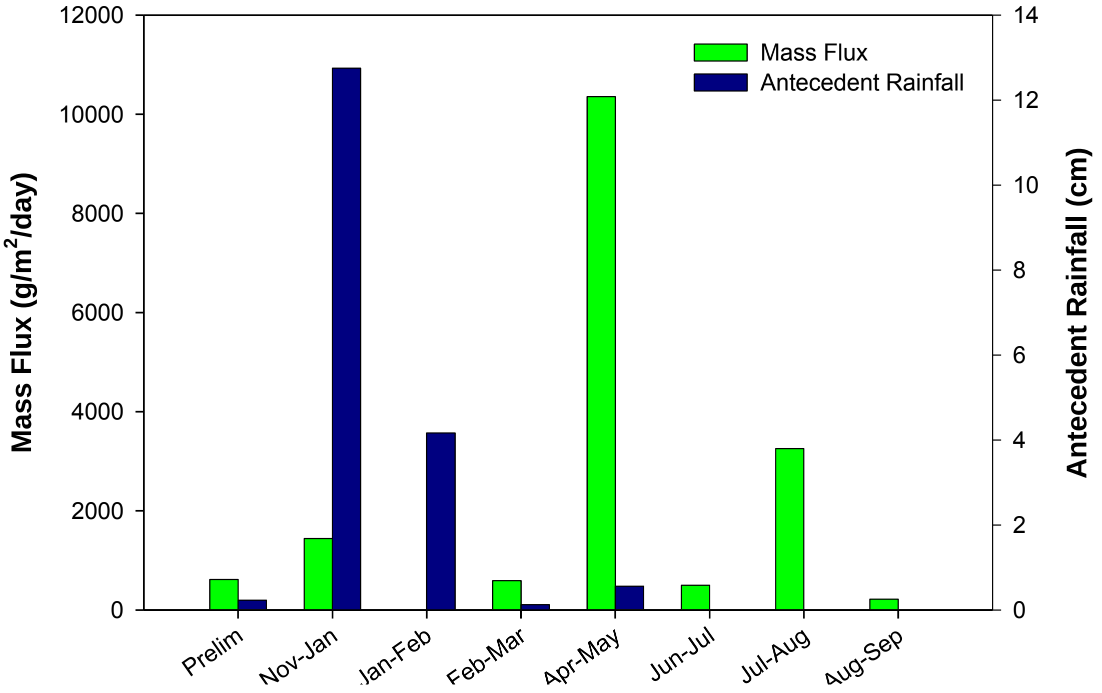


Figure 2.11. Mass flux is given as an inventory of material deposited (+) or removed (-) through time (red bars) and accumulated monthly rainfall (blue bars).

Sediment deposition of particulate organic carbon, N and P can be estimated based on the mass accumulation rates determined from the ^{7}Be data and sediment bulk %OC, N and P values respectively

(Figure 2.12). Deposition of OC, N, and P were related throughout the year with greatest recorded deposition during the summer; though as noted above, this may be due to resuspension or incorporation of decaying algal matter into the sediments, rather than deposition of new sediment from the watershed.

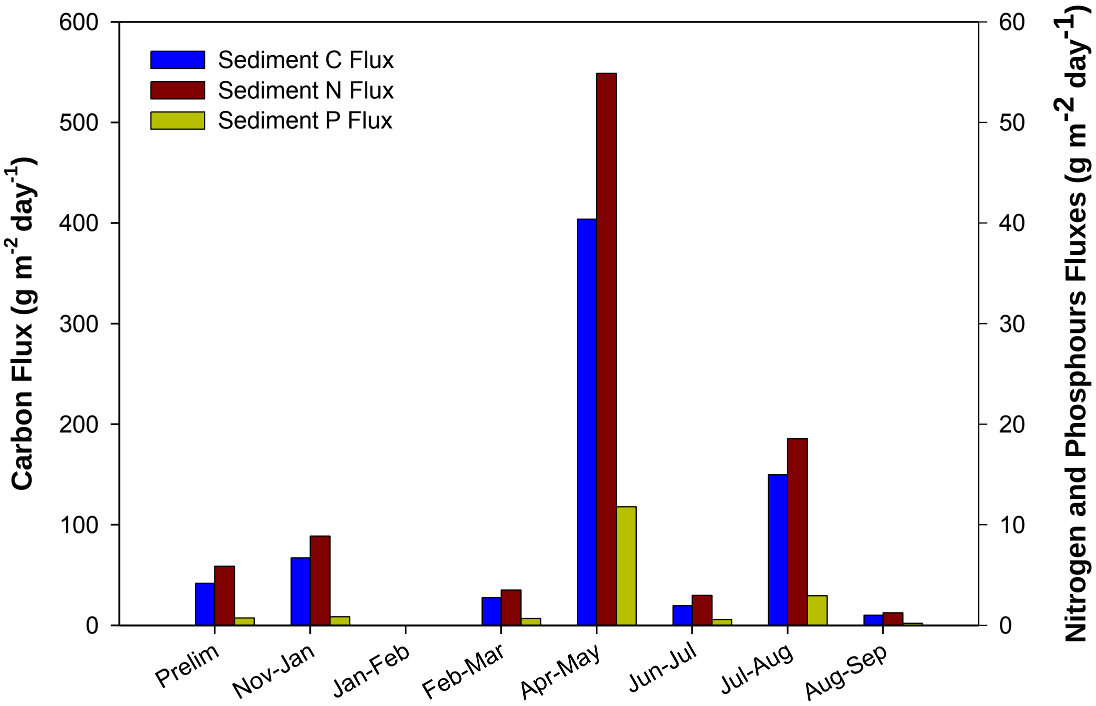


Figure 2.12. Particulate organic carbon, nitrogen and phosphorus deposition in Famosa Slough.

2.3.5 Seasonal Trends in Sediment Porewater Concentrations

Porewater Nitrogen and Phosphorus. In all index periods, TDN in porewaters is chiefly comprised of ammonium with only a minor fraction composed of NO_3, and little or no NO_2 (Figure 2.13). Porewater ammonium typically increases with depth from low concentration near the surface and increasing by three to four orders of magnitude with depth. Porewater ammonium concentrations were highest at depth during the summer.

Total dissolved phosphate in porewaters is primarily composed of soluble reactive phosphate (SRP) and follows a similar depth profile and seasonal trend as TDN and ammonium, where peaks in ammonium and TDN correspond directly with peaks in TDP and SRP.

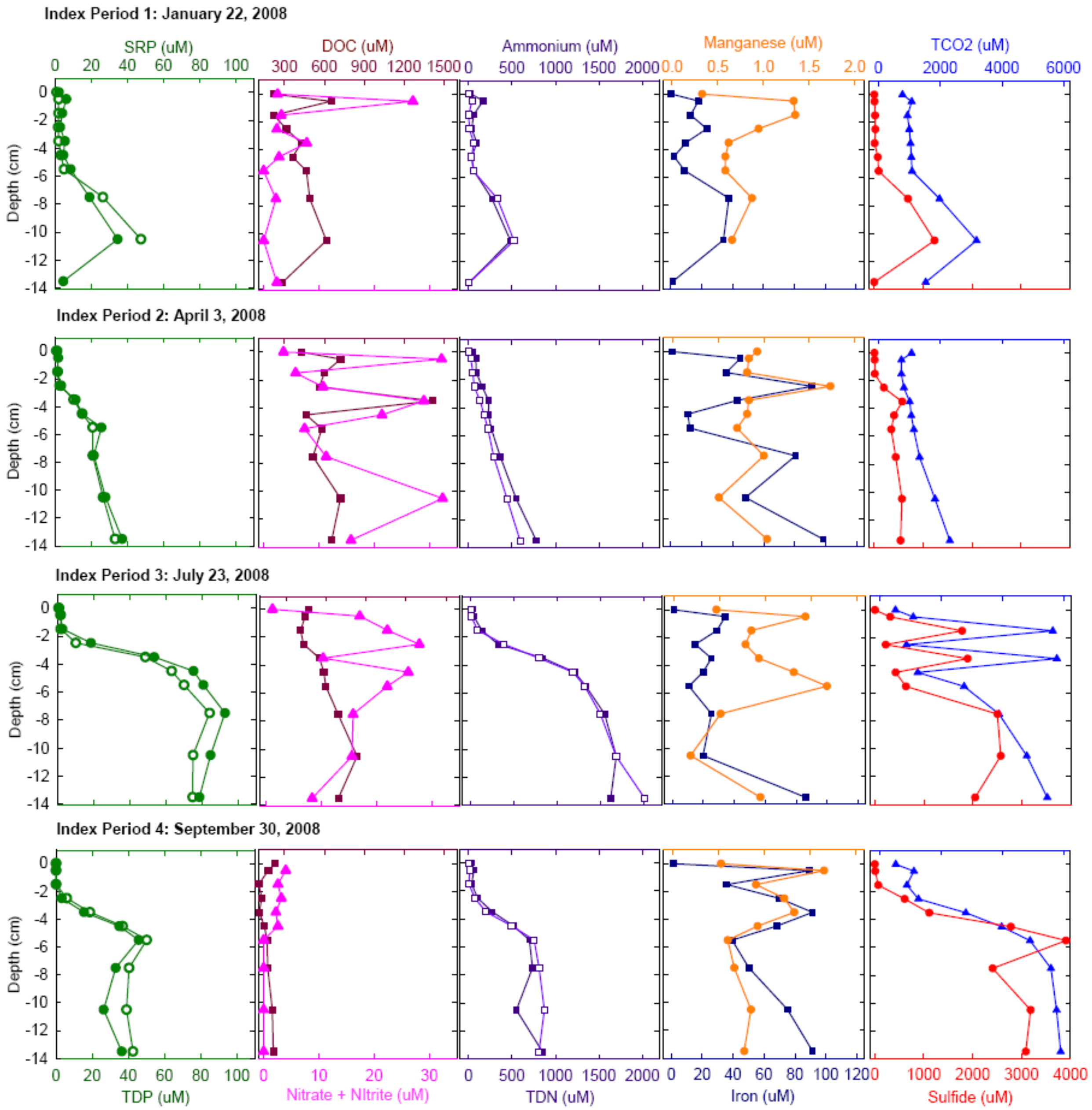
Porewater NO_3 values, though low throughout all sampling periods compared to ammonium, were highest in the spring and summer in the near-surface depths, though profiles in the spring and summer were variable. Thus nitrate tends to follow a pattern opposite to NH_4, SRP, sulfide (concentrations are high when concentrations of these constituents are low). Peaks in nitrate coincided with peaks in manganese and, at times, iron concentrations.

Dissolved organic carbon concentrations in the porewaters were similar in the winter, spring and summer, but declined in the fall.

Sulfide and Total Carbon Dioxide. Porewater total carbon dioxide concentrations are indicative of respiration/decomposition of organic matter in the sediments (Figure 2.13). Sulfide concentrations are indicative of the microbially-mediated reduction of sulfate to sulfide in very anoxic sediments. Sulfate reduction results in the decomposition of organic matter and the production of TCO_2. For this reason, these two indicators of decomposition showed similar depth and seasonal trends.

Near surface sediments had low concentrations of TCO_2 and S^{-2}, and concentrations typically increased with depth. During winter TCO_2 and S^{-2} concentrations remained low until 7 cm depth when concentrations rose sharply by two orders of magnitude. During the spring, S^{-2} concentrations rose after 3 cm and remained fairly steady with depth, whereas TCO_2 concentrations rose more steadily. Deep sediments had the highest S^{-2} concentrations during summer and fall rising from near detection at the surface to over 1000 µM starting around 2-3 cm to concentrations between 3000 and 4000 µM. TCO_2 concentrations showed a similar pattern with bottom water concentrations near 500 µM and surface sediment concentrations near 1000 µM rising to highs near 6000 µM at depth. The increase in TCO_2 and S^{-2} concentrations with depth correspond with the increase in concentrations of ammonium, TDN, SRP and TDP for each index period.

Iron and Manganese. Porewater Fe and Mn are indicative of iron and manganese redox reactions in which solid-phase oxidized forms are converted via a microbially-mediated reaction to the reduced, soluble forms (Figure 2.13). Iron and manganese reduction and denitrification reactions occur in mildly anoxic sediment, so increases in the concentrations of these constituents indicate redox status of the sediments. In Famosa Slough, porewater concentrations of Fe and Mn typically highest in surface sediments before the peaks in of ammonium, TDN, SRP, TDP, TCO_2 and S^{-2} concentrations. There was no clear seasonal variation in the Mn or Fe profiles.



Index Period 1: January 22, 2008

Index Period 2: April 3, 2008

Index Period 3: July 23, 2008

Index Period 4: September 30, 2008

Figure 2.13. Results of sediment porewater sampling in Famosa Slough during each index period; each row represents an index period, first column is total dissolved phosphorus (●) and soluble reactive phosphate (○), second column is nitrate + nitrite (▲) and dissolved organic carbon (■), third column is total dissolved nitrogen (■) and ammonium (□), fourth column is iron (■) and manganese (●), fifth column is sulfide (▲) and total carbon dioxide (●). The same scale applies to each column.

2.4 Discussion

Summary of Findings. Increased eutrophication in estuaries often results in a shift in primary producer communities (McGlathery et al. 2007), most notably the proliferation of macroalgae within shallow coastal estuaries. In Famosa Slough, macroalgae dominated aquatic primary production and, together with the Valeta Street Treatment marsh, was the mechanism likely responsible for maintaining low dissolved inorganic nutrient concentrations (particularly NO_3) throughout the year. Area-weighted nutrient loads to the Slough were small relative to other well studied eutrophic estuaries such as Newport Bay (Chapter 4, (Sutula et al. 2006)) and wet and dry weather concentrations of dissolved inorganic nutrients are low. Despite this, macroalgal cover was over 90% during the summer index period, suggesting that the internal recycling of organic matter, coupled with long residence times from a muted tidal regime, may be a major factor supporting primary productivity and driving chronic hypoxia in the winter and fall.

Significance of Macroalgae in Famosa Slough. Opportunistic macroalgae are highly successful in nutrient–rich freshwater and estuarine systems. These algae typically have filamentous or sheet-like growth forms (e.g., *Ulva* spp.) that can accumulate in extensive, thick mats over the seagrass or sediment surface. Although macroalgae are a natural component of these systems, their proliferation due to nutrient enrichment reduces habitat quality in four ways: 1) increased respiration at night and large oxygen demand from decomposing organic matter, 2) shading and out-competing submerged aquatic vegetation, 3) impacts on the density of benthic infauna, which are a principle food source for birds and fish, and 4) development of poor aesthetics and/or odor (Fong et al. 1998, Kamer et al. 2001, Kennison et al. 2003).

In Famosa Slough, the relative biomass of benthic primary producers followed a seasonal trend typical of eutrophic coastal lagoons (Kamer et al. 2001). During the winter index period (January 2008), aquatic primary producers were largely absent at the segment site. Despite the fact that water column NH_4 and NO_3 were the highest during this period, low temperatures, low light levels, and flushing during storm events act together to inhibit growth of macroalgae. Microphytobenthos (MPB; e.g., benthic diatoms) biomass peaked in the spring and showed a higher relative percent cover than macroalgae during this period. MPB has been found to efficiently control the availability of sediment-derived nutrients to ephemeral macroalgae during critical periods for the onset of blooms, competing for N flux from the sediments (Sundbäck and Miles 2002). By the summer index period, however, microphytobenthos appear to be out competed by macroalgae (*Ulva intestinalis* in spring and summer and *Ulva expansa* in fall), which dominated the primary producer community both in terms of total biomass and cover.

The presence of macroalgae in estuarine environments can alter dissolved oxygen (DO) concentrations significantly on a diurnal scale. High rates of respiration from elevated biomass may reduce DO content of estuarine waters at night (e.g., Peckol and Rivers (1995)), while decomposition of accumulated organic matter may cause a large microbial O_2 demand both day and night (Sfriso et al. 1987). This effect is evident in Famosa Slough, where nighttime hypoxia was common in during the summer and fall (WestonSolutions 2009).

Macroalgal mats can rapidly deplete dissolved inorganic nutrients from the water column (Pedersen and Borum 1997). This depletion of nutrients in the water column increases the rate of benthic flux of nutrients from the sediments, thus diverting N loss from denitrification and providing a mechanism for N retention and recycling within the estuary (Krause-Jensen et al. 1999, Fong and Zedler 2000). In Famosa Slough, the peak in macroalgae productivity is also coincident with a depletion in sediment N relative to OC, suggesting remobilization of sediment N is being at least partially retained within the system as macroalgal biomass (Boyle et al. 2004).

While dissolved inorganic nutrients were lowest during periods of peak macroalgal biomass, TN and TP were at their highest, indicating higher dissolved organic nutrients. Ambient water column nutrients are often only temporarily retained in the dissolved organic pool in eutrophic systems during bloom periods. For macroalgae, tissue turnover times are on time scales of days to weeks (McGlathery et al. 2007).

Benthic microalgae (microphytobenthos) can act to decouple nutrient turnover in the sediments from the overlying water column by acting as a “filter” for nutrient efflux from the sediments. Researchers have shown that during particularly active times of year this “filter” can completely intercept nutrient fluxes across the sediment-water interface, thereby reducing availability for phytoplankton, bacteria and macroalgae in a range of shallow coastal estuaries (McGlathery et al. 2004).

Significance of Famosa Slough Sediment Deposition and Bulk Characteristics. A common problem in tracking the fate and transport of nutrient sources to estuaries and coastal lagoons is the lack of consideration of particulate load from the watershed and its effects on eutrophication (Sutula et al. 2004, Sutula et al. 2006). Thus nutrient load can be underestimated if calculated from surface water nutrient concentrations and flow alone (data which was collected during the stakeholder monitoring). Watershed-derived sediments deposited in estuaries during the wet season carry an associated particulate nutrient load. When deposited in the estuary, these particulate nutrients may break down to biologically available forms and may build up in high concentrations in sediment porewaters. Thus use of sediment and particulate nutrient data and seasonal data on the fate of sediment solid phase and porewater provide a means to model the load and ecological response of these inputs in Famosa Slough.

Throughout the year at the site sampled, Famosa Slough was a net depositional environment with mass fluxes observed during almost every sampling event with the sole exception of the February sampling. Sediment grain size as measured in sediment cores decreased with depth during the winter from sandy sediment near the surface to finer sediments at depth. The spring through fall sediment cores indicated that the entire sediment column was comprised chiefly of fine grained sediments. These fine grained sediments appear to serve as a continuous source of remineralized N and P due to the prevalence of organic carbon and production of NH_4 and PO_4 in the porewaters as well as the high concentrations of TCO_2. It should be noted however, that because the fine grain size of the surface sediments, the deposition recorded during the spring and summer may be due to internal resuspension of these fine particles and redeposition in the Slough, rather than accumulation from the watershed, or alternatively, the incorporation of algal biomass into the sediments. Furthermore, the sediment core on which these data are based was taken at only one location, the eastern side of the southern basin, which would be more likely to be a depositional environment, compared to the western end of the southern basin and the northern channel, which might be expected to be erosional. Hydrodynamic and sediment transport modeling for the purposes of restoration planning indicated that the site selected is depositional, while the other side of the central basin may be net erosional (N. Garrity, PWA Assoc.). Thus, the estimates of mass accumulation should not be extrapolated to the entire basin.

Significance of Famosa Slough Surface Water and Porewater Nutrient Concentrations. Ambient nutrient concentrations within an estuary are the integration of various pathways of sources, sinks and transformations, including both uptake and release (Valiela et al. 1992, Valiela et al. 1997, Dalsgaard 2003, Bergamasco et al. 2004, Paerl 2009). The relative ratios of the different species can provide some insight into the dominant processes controlling nutrient availability within the estuary. Seasonally, Famosa Slough exhibited typical trends in the ratio of dissolved inorganic to total nutrients. During wet weather and winter index periods, ambient dissolved inorganic nutrients were slightly elevated, suggesting an urban wet weather source. During summer and fall index periods, dissolved inorganic nutrients were low and organic nutrients were elevated, suggesting the importance of internal recycling.

The ambient concentrations of NO_3 in the Slough during the wet weather and winter index periods were surprisingly low and atypical of estuaries with heavily urbanized water sources (Kamer et al. 2001, Sutula et al. 2006). It is likely that the Valeta Street Treatment Wetland, which captures wet weather flows from the main freshwater source to the Slough, is aiding in reducing NO_3 concentrations (Kadlec and Knight 2006).

Denitrification, the microbially-mediated conversion of NO_3 to N gas, is typically a major pathway through which ambient NO_3 concentrations can be reduced (Figures 2.14 and 2.15). Measurements of denitrification in Famosa Slough during the study were exceedingly small (0.01 - 0.1 μmol m^{-2} hr^{-1}, T. Kane, UCLA Department of Biology Doctoral Dissertation), three orders of magnitude below the range of published rates in eutrophic estuaries (50 -250 μmol m^{-2} hr^{-1}, Seitzinger 1988). Both NO_3 uptake associated with primary production (microphytobenthos or macroalgae) may have limited denitrification through competition for NO_3 (Dalsgaard 2003, McGlathery et al. 2007). Denitrification is thought to be an unimportant sink for N in shallow coastal lagoons because primary producers typically outcompete bacteria for available NO_3 (McGlathery et al. 2007). Interestingly, porewater nitrate concentrations were relatively high during the spring and summer index periods. Peaks were observed in the vertical profiles of nitrate and coincided with elevated manganese and iron porewater concentrations and low sulfide, TCO_2, NH_4 and SRP concentrations (Figure 2.13), suggesting that the shallow surface sediments were perched at higher redox levels (Figure 2.15)(Roden and Edmonds 1997). It is likely that nitrification, a process that occurs in relatively aerobic environments and converts NH_4 to NO_3, is occurring at these depths. With depth, NH_4increases, with a corresponding decrease in NO_3, signaling the dissimilatory NO_3 reduction (conversion of $NO_3$to NH_4) may be a dominant process (An and Gardner 2002, Brock 2006, Porubsky et al. 2009).

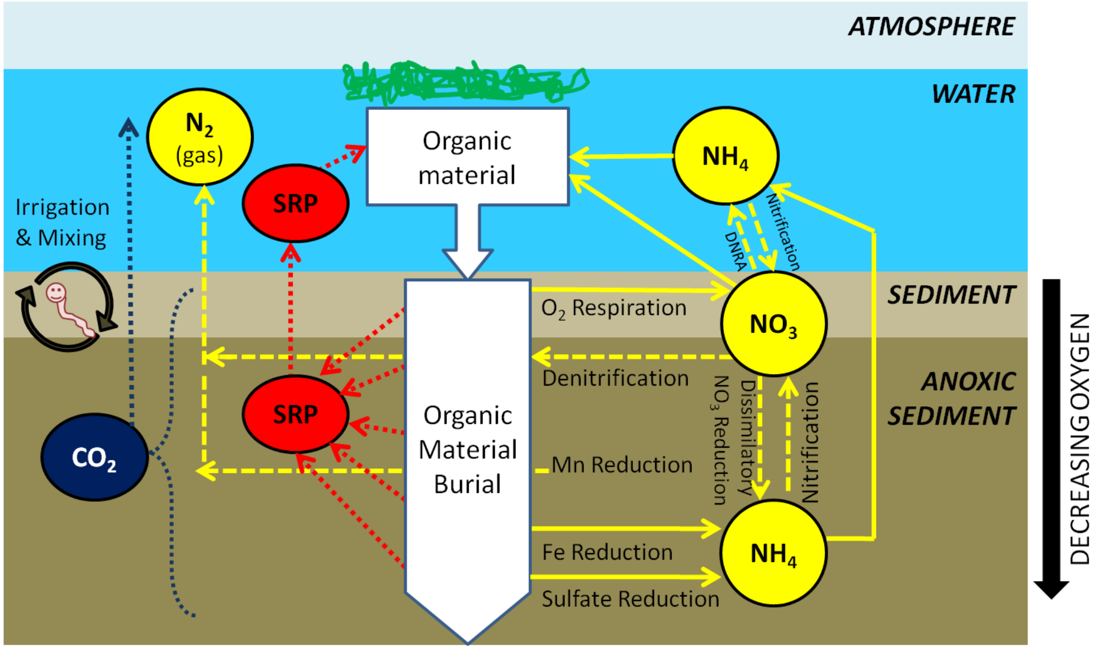


Figure 2.14. Pathways for nutrient cycling and decomposition of organic matter in the sediments.

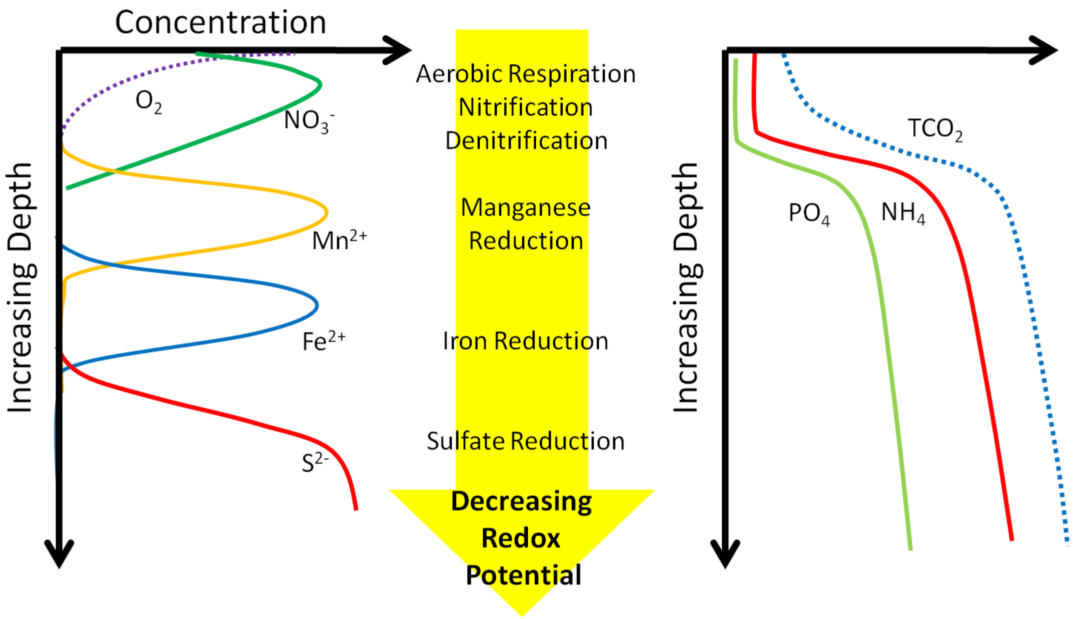


Figure 2.15. Sediment porewater profiles reflect redox status of the sediment.

The fact that porewater concentrations indicative of mildly negative redox conditions (N, Mn) are in relatively high concentrations in the top 4 cm of the sediment during the summer index period was somewhat surprising, given the occurrence of low nighttime dissolved oxygen values during this time (Figure 3.6; Weston 2009). This indicates that low nighttime DO during these periods may to a greater extent due algal respiration and long residence time, rather than a very high sediment oxygen demand. As primary production peaks and standing biomass of macroalgae degrade, as represented in the fall index period, peak concentrations of sulfide and NH_4 approach surface sediments and abundance of benthic infauna decline indicating more a more anaerobic environment.

3 Seasonal Trends in Sediment Oxygen Demand and Benthic Nutrient Flux

3.1 Introduction

Sediments are a potentially significant internal source of N and P to surface waters in estuarine systems. Watershed-derived sediments, deposited in estuaries during the wet season, carry an associated particulate N and P load (Sutula et al. 2004, Sutula et al. 2006). When deposited in the estuary, particulate nutrients can be mineralized to biologically-available forms and may build up in high concentrations in sediment porewaters. These porewaters can diffuse into the overlying water column or be released through advective processes such as bioturbation by benthic infauna, forced flow of water through sediments by bioirrigation or tidal pumping, or physical resuspension of sediments through scouring or resuspension during strong tidal currents or storm flows (Boynton et al. 1980, Grenz et al. 2000, Jahnke et al. 2003). Once released to the water column, these particulate-derived nutrients are available for uptake by primary producers, including macroalgae, microphytobenthos, and submerged aquatic vegetation.

Primary producer abundance is often limited by availability of nutrients (Howarth 1988, Valiela et al. 1997, Kamer et al. 2004, Paerl 2009). Macroalgae generally obtain nutrients directly from the water column, though studies have shown that algae may intercept nutrients fluxing out of sediments (Lavery and McComb 1991, McGlathery et al. 2007). In Southern California, wet-season particulate-nutrient loads deposited in lagoons where shown to provide a significant source of nutrients that fueled excessive growth of submerged aquatic vegetation and macroalgae during the dry season (Boyle et al. 2004, Sutula et al. 2004, Sutula et al. 2006). Thus, sediment-derived nutrients may cause algal blooms to persist even when nutrient loading from the watershed is reduced to levels calculated to limit macroalgal biomass (Sutula et al. 2004, Neto et al. 2008).

The principal methods of estimating sediment contribution of nutrients (benthic flux) include benthic chambers (Hammond et al. 1985, Clavero et al. 2000, Berelson et al. 2003), sediment-core incubations (Risgaard-Petersen and Ottosen 2000, Welsh et al. 2000) and porewater profiles (Hammond et al. 1999, Qu et al. 2005). Vertical fluxes of solutes diffusing between the sediment and overlying waters can be calculated from Fick's law of diffusion (i.e., porewater diffusive fluxes). The major controls on diffusive fluxes are sediment porosity and the diffusive boundary layer (DBL). Benthic chambers and sediment-core incubations are direct measurements and may integrate diffusive and advective transport of porewater by means of bioturbation/or bioirrigation processes (Berelson et al. 1999). Additionally, the comparison of computed (diffusive) fluxes with measured (*in situ*) fluxes can provide information about the relation between fluxes at the sediment–water interface and nutrient cycling within sediment column (Clavero et al. 2000, Qu et al. 2005).

In addition to nutrients, the fluxes of oxygen and total inorganic carbon (TCO2) and trace metals provide valuable information the biogeochemical functioning of the sediments. In particular, O2 and TCO2 fluxes provide insight on the rates and dominant pathways of organic matter mineralization and benthic community metabolism, which are of primary interest in understanding ecosystem functioning and disturbances caused by eutrophication (Ferguson et al. 2003, Ferguson et al. 2004, Qu et al. 2005). The production of total inorganic C, measured as the release of TCO2 from the sediment to the overlying water, has been used to interpret the balance between aerobic and anaerobic mineralization since both yield CO_2 as the ultimate oxidation product of carbon (Berelson et al. 1998, Hammond et al. 1999). Measurement of dissolved iron and manganese fluxes provide valuable information about the redox chemistry of the benthic boundary layer, since these constituents are only released if the environment has a sufficiently low redox potential (hypoxic).

The goal of the benthic flux studies in Famosa Slough was to estimate the *in situ* flux of nutrients, dissolved oxygen (DO), TCO2, Fe and Mn between sediments and surface waters during four index periods (see Section 1.3 for study design). A combination of techniques was used to estimate these fluxes including: 1) direct *in situ* measurements of nutrient flux and sediment oxygen demand using benthic flux chambers and 2) calculation of diffusive fluxes based on concentration gradient between surface waters and porewaters. Data were also collected on some of the key factors (sediment characteristics and nutrient content, primary producer biomass) known to control fluxes in order to understand key drivers on the magnitude and direction of flux.

3.2 Methods

Benthic flux chambers were the primary method used to measure the fluxes *in situ* during each of the four index periods. Because the flux of nutrients from the sediments is controlled by a suite of physical, chemical, and biological factors which vary substantially over the course of the year, the sediment grain size, C:N and C:P ratio, the taxa and abundance of benthic infauna, and the biomass of microphytobenthos (benthic chl a) and macroalgae were also measured within each chamber.

3.2.1 Field Methods

3.2.1.1 Measurement of In Situ Benthic Fluxes

In situ sediment nutrient, trace metal, and dissolved organic carbon (DOC) fluxes and sediment oxygen demand were measured using benthic flux chambers (Burdige et al. 1999, Berelson et al. 2003, Elrod et al. 2004). A minimum of two replicate chamber deployments were conducted in the southern basin of Famosa Slough per index period and were incubated for three to five hours during a neap tidal cycle. Water samples were periodically drawn from the chamber as oxygen levels within the chamber decline (Figure 3.1). These samples, when analyzed, yield the change in concentration of the targeted analyte over time. The surface area of the chamber is known and the volume of water contained with the chamber can be calculated, therefore, a flux rate can be derived.

Four identical benthic flux chambers were built based on a modified design from Webb and Eyre (Webb and Eyre 2004). The chamber is made of clear acrylic measuring 25 cm x 25 cm x 26 cm (l x w x h) mounted to an aluminum frame and is designed such that 10 cm of the chamber height is submerged in the sediment (leaving a height of 16 cm above the sediments) (Figures 3.2 and 3.3). The chamber frame is placed on top of an acrylic “skirt”, a thin sheet of acrylic measuring 24 in x 36 in with a hole cut in the center. This “skirt” allowed for the acrylic chamber to sink into the sediments but prevented the frame from also sinking into the sediments and thus changing the chamber height over the deployment time.

When properly deployed the total chamber volume is 10 liters. Two of the chambers were left clear and open to variations in ambient light throughout the deployment (light chambers; Figure 3.4); the other two chambers were covered in aluminum foil to prevent ambient light from penetrating the chambers (dark chambers).

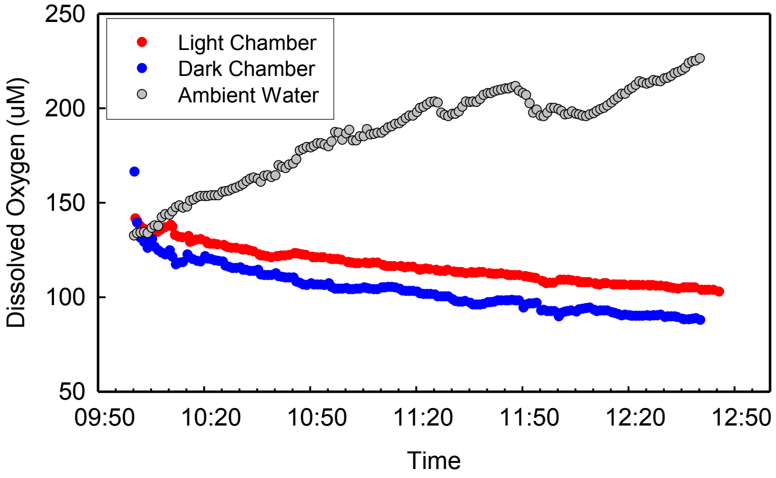


Figure 3.1. Typical chamber time series of dissolved oxygen concentration within the light and dark chambers relative to ambient surface water (September 2008). Oxygen concentrations in both the light and dark chambers steadily decreased over the incubation. Flux calculations were made during the most linear part of the curve.

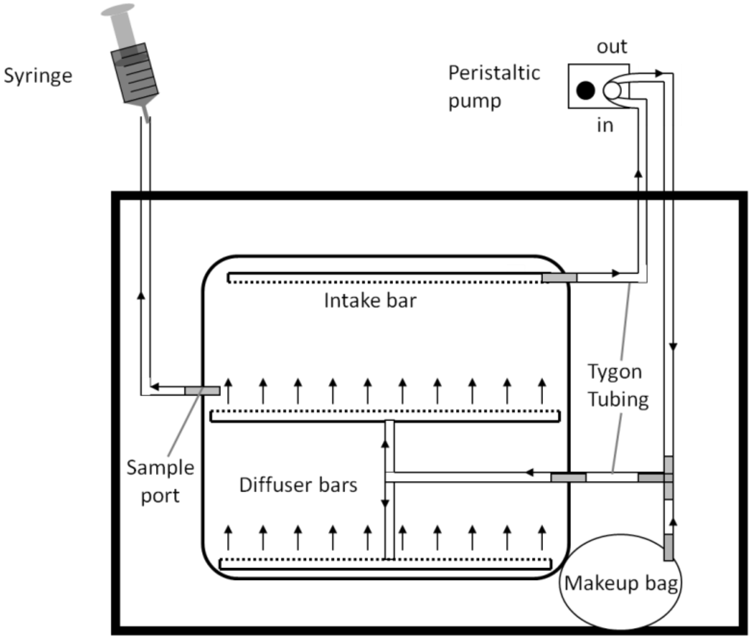


Figure 3.2. Schematic of benthic chamber design as viewed from above.

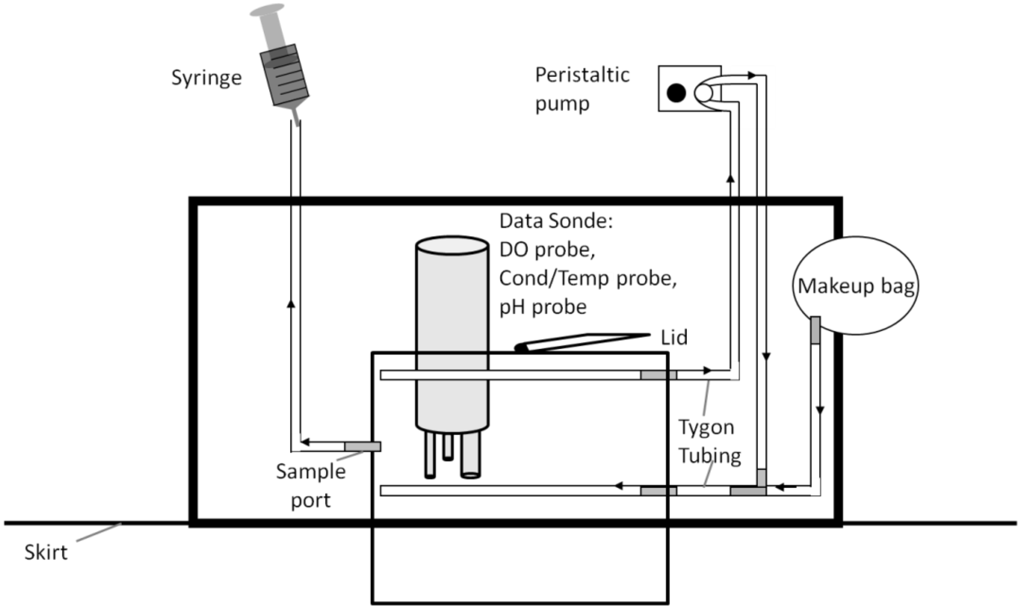


Figure 3.3. Schematic of benthic chamber design as viewed from side.

Figure 3.4. Flux chambers during deployment in Famosa Slough.

Each chamber is equipped with a YSI 6920 data sonde containing a temperature/conductivity probe, optical dissolved oxygen probe, and pH probe allowing for continuous measurements within each chamber and of ambient water every minute. All probes were calibrated in the laboratory before deployment. Two of the chamber probes were connected to a YSI 650 hand-held data display unit allowing for real-time monitoring of dissolved oxygen levels within each chamber. Such a set up allowed the field team to set the timing of chamber samplings to insure that all five samplings were evenly spaced in time and that no sampling would occur after the chamber DO levels fell below 2 mg L^{-1}.

The chamber is “plumbed” with tubing from the chamber to a peristaltic pump which keeps water circulating through the chamber, preventing the development of a benthic boundary layer which would alter the benthic-flux rate (Webb and Eyre 2004). An additional tube is connected to a clean 60 ml syringe which is used to pull water samples from the chamber at the designated intervals. There were five sample draws from each chamber and each sample draw removed approximately 130 ml of water from the chamber (two syringes plus 10 ml of rinse). In order to maintain consistent chamber volume, water from a “make-up” bag is drawn into the chamber as the sample water is withdrawn. The two syringes used to draw chamber water at each sampling port are immediately taken to the shoreline for processing.

Sediments were mildly disturbed during deployment, so chambers were allowed to equilibrate with surroundings before the tops were closed. Chambers were closed when the turbidity measurement in Chamber 1 returned to baseline. Dissolved oxygen, temperature, salinity and pH were measured continuously in each chamber and the surface water directly adjacent to the chambers with data sondes. Dissolved oxygen concentrations in the chambers were monitored during the incubation and observed to steadily decline in both the light and dark chambers over the course of the experiment relative the ambient DO concentration (Figure 3.1). Samples were pulled from the chamber at evenly spaced intervals to measure the change in concentration within the chambers as a function of time; these data were used to calculate the flux from the sediments. The interval between samplings was determined based on the rate at which the real-time measurements of DO decreased; the aim of the experiments was to collect five distinct samplings before the DO levels fell below 2 mg L^{-1} (62 µM).

Chamber water and ambient surface water samples were analyzed for TDN, TDP, NH_4, SRP, NO_3, NO_2, DOC, iron, manganese, and TCO_2. One unfiltered split was collected for TN and TP, and then the syringe was fitted with an MCE filter, which was rinsed with 10 ml of sample water, and splits were collected for dissolved nutrients (NO_2, NO_3, NH_4, and SRP), and TDN/TDP. The second syringe was fitted with a PES filter, which was rinsed with 10ml of sample water, and splits collected for DOC, dissolved metals (iron and manganese), and TCO_2. All samples were placed in the dark on ice while in the field. Total carbon dioxide samples were analyzed in the laboratory within 6 hours of collection. The remaining samples were frozen upon return to the laboratory until analysis within their respective holding times.

After the deployment was completed, surface sediment samples were collected and analyzed for grain size, OC, organic N, and TP content, and sediment chlorophyll a. Algal biomass and SAV biomass were comprehensively harvested from the chamber whenever applicable, sorted, cleaned and weighed.

Ambient water samples were collected by SCCWRP during both the benthic chamber deployment (surface waters) and the porewater peeper extraction (bottom waters). The protocol for sampling and processing was the same as given above for the transect sampling (Section 2.3.1).

3.2.1.2 Benthic Infauna

Benthic infauna cores (5 cm diameter, 10 cm deep) were collected from each benthic flux chamber following deployment in each index period. Individuals were identified and counted by genus and extrapolated to estimate the number of infauna of each genus in the top 10 cm of each square meter of subtidal sediment.

3.2.2 Analytical Methods

Analytical methods for nutrients, TCO_2, trace metals, and chlorophyll a are identical to those given in Section 2.2.2.

3.2.3 Data Analysis

3.2.3.1 In Situ *Benthic Flux*

Flux rates (F) for each constituent (dissolved nutrients, metals, TCO_2, and O_2) are calculated from the chamber height (h) and the change in constituent concentration within the chamber over time (dC/dt):

$$\mathbf{F} = \mathbf{h} * \left(\frac{dC}{dt}\right) \qquad \textbf{Eq. 3.1}$$

Concentration versus time was platted as a linear gradient using all data that passed a quality assurance check. Use of the linear portion of the incubation curve assumes that the flux of a constituent is constant during the incubation interval (Figure 3.1).

3.2.3.2 Diffusive Flux

Instantaneous diffusive-flux rates were calculated for each species of nutrient using Fick's law given in Equation 3.2.

$$J = -\phi * D_{aq} * \theta^{-2} * \left(\frac{dC}{dz}\right) \qquad \textbf{Eq. 3.2}$$

where J is the rate of flux of species (mol m^{-2} s^{-1}), Φ is the porosity (dimensionless), D_{aq} is the aqueous diffusion coefficient, ϑ is the tortuosity, and dC/dz is the change in porewater concentration (dC) over the distance from the overlying water to the sediments (dz). ϑ^{-2} was estimated from Boudreau's law (Boudreau 1997) given in Equation 3.3.

$$\theta^{-2} = \frac{1}{(1-\ln(\phi^2))} \qquad \textbf{Eq. 3.3}$$

D_{aq} for each nutrient species were obtained from Boudreau (1997) and are given in Table 3.1 below. The constant selected was that closest to the ambient water temperature at time of field sampling.

Table 3.1. Aqueous diffusion coefficients (D_{aq}) for each nutrient species by temperature.

Species	10 °C	15 °C	20 °C	25 °C
NO_3^-	1.26 E -09	1.44 E -09	1.62 E -09	1.79 E -09
NH_4^+	1.45 E -09	1.68 E -09	1.90 E -09	2.12 E -09
HPO_4^{-2}	4.75 E -10	5.56 E -10	6.37 E -10	7.16 E -10
Lactate (proxy for DON and DOP)	6.44 E -10	7.54 E -10	8.64 E -10	9.72 E -10

Diffusive flux rates were predicted using the following assumptions:

- Exchange between the sediments and surface waters occur at steady state;
- Advective transport processes in Loma Alta Slough (groundwater, pumping from tidal currents, and bioturbation) are minor relative to diffusive transport; and
- Chemical or biological processes that can modify chemical fluxes at the sediment water interface (O_2 content, benthic diatoms, sediment redox chemistry, etc.) have a negligible impact relative to diffusion on exchange rates.

3.3 Results

3.3.1 Seasonal Trends and Factors Influencing Dissolved Oxygen and Carbon Dioxide Fluxes

The sediments in the southern basin showed a consistent net release of TCO_2 during the spring through the fall, indicating that the sediments were net heterotrophic (respiration exceeds primary production). Net TCO2 flux, which is an integrated estimate of flux during light and dark periods throughout a 24-hr day, also peaked in the spring and summer. Net fluxes among replicate chambers were variable, particularly in the spring and summer index period. Ratios of TCO2:O2 were 5:1 during the spring index period, 2.6:1 during the summer, and <0.5 during the fall and winter index periods. Ratios greater than 1.3:1 indicate that more CO2 is being produced than can be respired by aerobic decomposition indicating that the Slough is net heterotrophic during spring and summer.

Productivity at the sediment/water interface can be estimated from the fluxes of TCO2 and O2 as carbon fixation and gross primary productivity (GPP) respectively. Carbon fixation is a measure of the amount of inorganic carbon (carbon dioxide) converted to autotrophic biomass and is calculated from the difference between light (with photosynthesis) and dark (without photosynthesis) TCO2 fluxes:

$$\text{Carbon Fixation} = \text{Flux TCO2}_{light} - \text{Flux TCO2}_{dark} \qquad \textbf{Eq. 3.4}$$

Gross Primary Productivity is the rate at which primary producers capture and store chemical energy as biomass and can be calculated from the difference between light (with photosynthesis) and dark (without photosynthesis) O2 fluxes:

$$\text{GPP} = \text{Flux O2}_{light} - \text{Flux O2}_{dark} \qquad \textbf{Eq. 3.5}$$

Carbon fixation was highly variable, but estimated to be the highest during the summer, the period of peak macroalgal biomass (Table 3.2). A number of factors, such as total infaunal abundance, % fines, and benthic chl a biomass within the chamber, were found to have significant, positive correlations with TCO_2 flux (Table 3.3).

Net sediment DO flux was consistently negative among all index periods, with little difference between light and dark chambers, indicating highly heterotrophic benthos (Figure 3.5, bottom panel). Overall, significant differences in DO flux were found by index period and chamber light regime as well as an index period by regime interaction (p-value <0.05; Figure 3.5, bottom panel). Across all index periods and light regimes, sediment oxygen demand was the lowest in the winter and fall (p-value <0.05).

Of the factors measured within the benthic chambers, benthic chl a had a significant, positive correlation, while both temperature and macroalgal biomass had significant, negative correlations with DO flux (Table 3.2).

Table 3.2 Spearman's Rank Correlation Between DO, TCO2 and factors known to influence flux (Temperature – Temp, Salinity (Sal), pH, sediment C:N Ratio, total infaunal abundance, sediment % fines, benthic chl a and macroalgal biomass within chambers). Table gives correlation (r) and p-value for α=0.05).

Variable	DO	TCO_2	Temp	Sal	pH	C:N Ratio	Total Infauna Abundance	% Fines	Benthic Chl a	Macroalgae
DO Corr. (r)	1	0.26	**-0.58**	0.18	-0.39	0.16	0.44	-0.30	**0.66**	**-0.65**
DO (p-val)		0.39	**0.036**	0.55	0.18	0.62	0.15	0.35	**0.01**	**0.015**
TCO2 Corr.(r)	0.26	1	0.12	0.16	-0.37	0.39	**0.71**	**0.59**	**0.59**	0.32
TCO2 (p-val)	0.38		0.66	0.54	0.16	0.14	**0.0033**	**0.022**	**0.015**	0.23

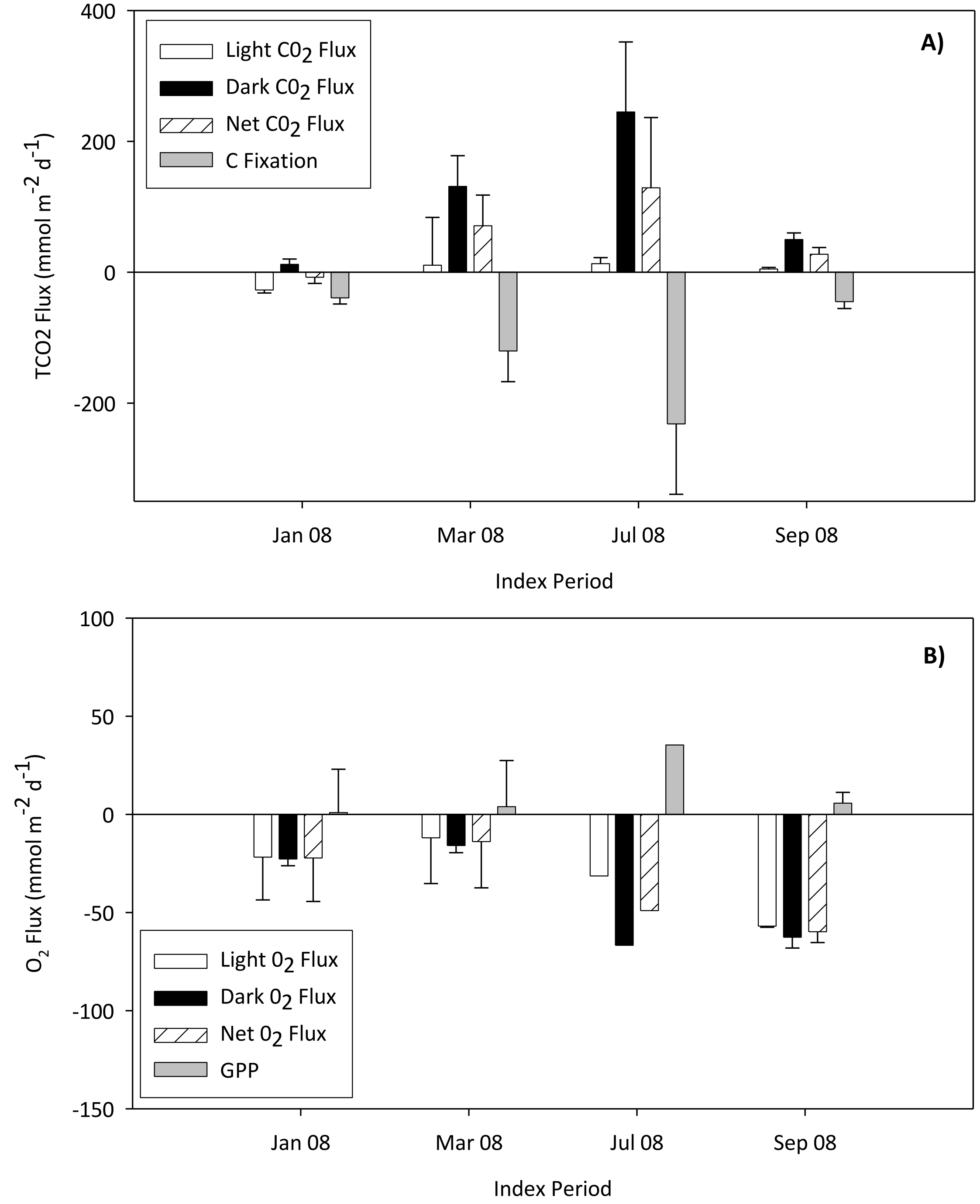


Figure 3.5. Light , dark , net (24-hour average of light and dark), TCO_2 fluxes, and estimated C fixation (A); and O_2 fluxes and Gross Primary Productivity (GPP; B). Error bars represent the standard deviation between replicates.

Continuous DO measured via sonde in the water column (WestonSolutions 2009) showed strong diurnal variability in dissolved oxygen concentration beginning in the late spring. Night-time DO concentrations dropped below 5 mg L^{-1} and remained low during the night until the fall (November). Furthermore, during summer months (July- October) DO concentrations fell below the 2.0 mg L^{-1} during the early morning hours between 03:00 and 07:00 (Figure 3.6). These chronically low DO levels, suggest that Famosa Slough is most affected by hypoxia during the summer and fall.

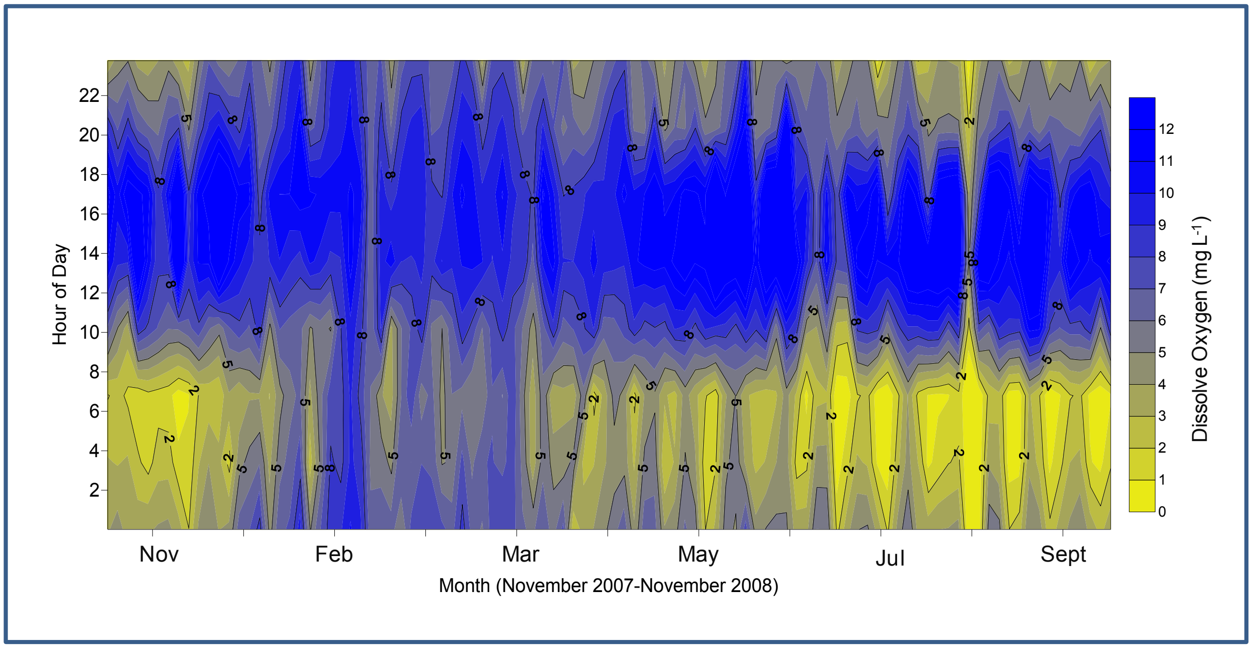


Figure 3.6. Dissolved oxygen in Famosa Slough as a function of time of year and time of day. The 2 and 5 mg L^{-1} contour lines are shown.

3.3.1.1 Nitrogen Fluxes

Nitrogen fluxes (NO_3, NO_2, NH_4, and TDN) exhibited high variability, with no significant differences by index period or chamber light regime for any of the three forms (p-value<0.05; Figure 3.7, top two panels). Variability among replicate chambers was high and mean fluxes among chamber replicates were not significantly different from zero (p-value >0.05) during most index periods and chamber light regimes. Of the TDN flux only a small fraction was comprised of dissolved inorganic N species (NO_3, NO_2,NH_4). Nitrite was typically non-detectable.

Nitrate fluxes were small during all index periods, ranging from a small positive flux during the summer (~1 mmol m^{-2} d^{-1}) to a small negative flux during the fall (~2.2 mmol m^{-2} d^{-1}). Nitrate fluxes in dark chambers were into the sediment, with the exception of the winter index period. Nitrate fluxes from light chambers were generally positive (out of the sediments) during the winter, spring and summer index periods; during fall there was a small flux into the sediments in both the light and dark chambers.

Of the factors that could affect N flux, only macroalgae was significantly correlated (r = ±0.47, p-value<0.05). The simple linear regression model regressing macroalgal biomass in the chamber versus nitrate flux was significant (R^2 = 0.28, p-value = 0.03; Table 3.2).

Ammonium fluxes had a slightly wider range compared to NO_3 ranging from a high of 6.8 mmol m^{-2} d^{-1} during the summer to a low of -3.5 mmol m^{-2} d^{-1} measured in one chamber during the winter. During the winter index period, average ammonium fluxes were typically positive (out of the sediments) in both light and dark chambers. Ammonium fluxes were small and slightly negative (into the sediments) during the spring. Summer fluxes of ammonium were the largest observed and positive (out of the sediments), though highly variable. Fall fluxes were small and slightly positive in the dark chamber and slightly negative in the light chamber.

On average, TDN fluxes were 95% dissolved organic nitrogen (DON). Fluxes for DON ranged from highly positive (40 mmol m^{-2} d^{-1} measured in one chamber during both the winter and spring) to highly negative (-49 mmol m^{-2} d^{-1} measured in one chamber during the spring). Light DON fluxes were positive in the winter, summer and fall, with lowest variability between replicate chambers in summer and fall and in opposite direction from DOC fluxes. During these periods, dark DON fluxes were negative, but with greater variability and consistent with the direction of DOC fluxes. Spring dark and light DON fluxes were highly variable, and always in the direction of DOC fluxes. None of the factors examined were significantly correlated with TDN flux.

3.3.1.2 Phosphorus Fluxes

Dissolved organic phosphorus and SRP fluxes were highly variable and not significantly different by index period or chamber light regime (p-value <0.05, Figure 4.7, third panel). On average, 68% of TDP fluxes were DOP. As with N, variability among replicate chambers were high and mean DOP and SRP fluxes among chamber replicates were not significantly different from zero (p-value >0.05) during most period and chamber light regimes. DOP fluxes ranged from a high of 1.9 mmol m^{-2} d^{-1} measured in one chamber during the spring to -2.0 mmol m^{-2} d^{-1} also measured during the spring. SRP ranged from 0.3 mmol m^{-2} d^{-1} measured in the summer to -0.4 mmol m^{-2} d^{-1} measured in both the winter and spring, with many below detection measurements in the spring and summer. During the winter and fall, both light and dark DOP and SRP fluxes were negative. During spring and summer, light DOP and SRP fluxes were positive, while dark fluxes were negative.

Of those factors measured, DOP flux was significantly correlated with Fe flux (r=0.57, p-value = 0.02), while SRP flux was significantly correlated with macroalgal biomass (r=+0.60, p-value <0.05) and % fines (r=0.56, p-value<0.05).

3.3.1.3 Organic Carbon Fluxes

As with N and P species, DOC fluxes were highly variable among the benthic chambers during each index period and mean fluxes among replicate chambers were generally not significantly different from zero, with the exception of the spring sampling period (Figure 4.7, second panel). DOC values ranged from a high of 440 mmol m^{-2} d^{-1} measured during the spring to a low of -700 mmol m^{-2} d^{-1} measured fall. There were no significant differences by index period nor by chamber light regime (p-value>0.05).

Of those factors measured which could impact DOC flux, total infaunal abundance was significantly positively correlated to DOC flux (r=+0.66, p-value<0.05).

3.3.1.4 Trace Metal Fluxes

Trace metal fluxes (dissolved iron and manganese) were also highly variable (Figure 3.7, bottom panel), with mean fluxes among replicate chambers typically not significantly different from zero (p-value<0.05), with the exception of Mn in the summer and fall index periods. Trace metal fluxes were typically negative (into the sediments) in the winter, spring and summer and typically positive during the fall (out of the sediments). Neither Fe nor Mn were significantly different by chamber light regime (p=value>0.05). Iron fluxes ranged from a high of 2.9 mmol m^{-2} d^{-1} measured during the spring to -2 mmol m^{-2} d^{-1} measured during the winter, but mean values were not significantly different by index period. Only Mn fluxes were significantly different by index period (p-value<0.05), with the winter flux (-1.6 mmol m^{-2} d^{-1}) significantly different from the spring index period flux (0.15 mmol m^{-2} d^{-1}). Many measurements of trace metals were near the detection limit, particularly for Mn.

Of those factors measured which could impact trace metal flux, no significant correlations were found for Fe. Both sediment C:N ratio (r=+0.84) and percent fines (r=+0.54) were significantly positively correlated to Mn flux.

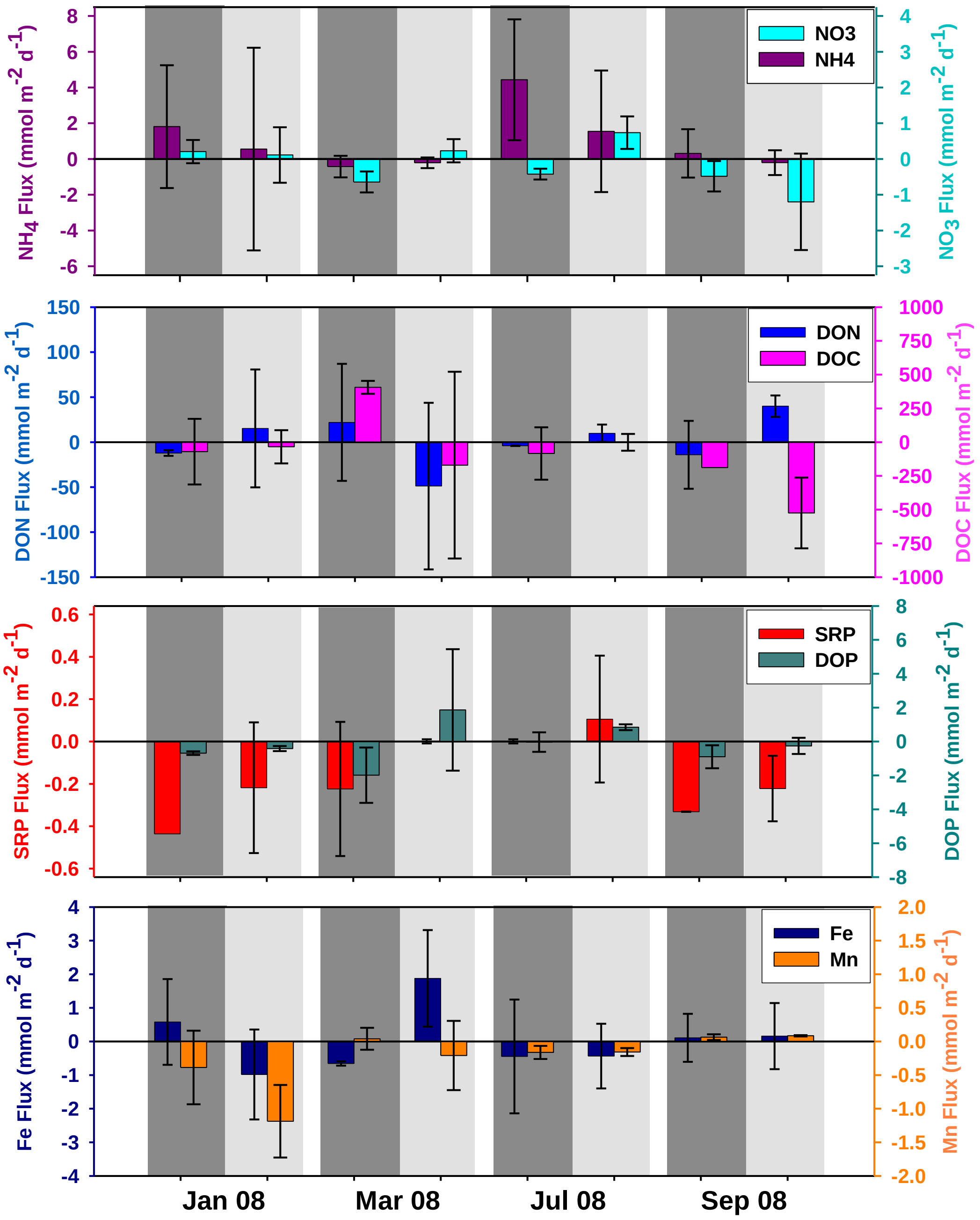


Figure 3.7. Benthic fluxes for dark (dark grey bands) and light (light grey bands) for each of the index periods. Error bars represent the standard deviation between replicate chambers.

3.3.2 Benthic Infaunal Diversity and Abundance

In Famosa Slough, the benthic infauna community appears to be dominated by polychaetes and capitelids at densities exceeding 15,000 individuals m^{-2}, indicative of organically enriched sediments (Figure 3.8). Few large burrowing infauna were present, suggesting that the depth of bioturbation in this system is limited. These findings are compatible observations of extremely high sulfide concentrations in the porewaters. Abundances peak in March, but crash in July and September, coincident with peak macroalgal biomass and chronic nighttime hypoxia.

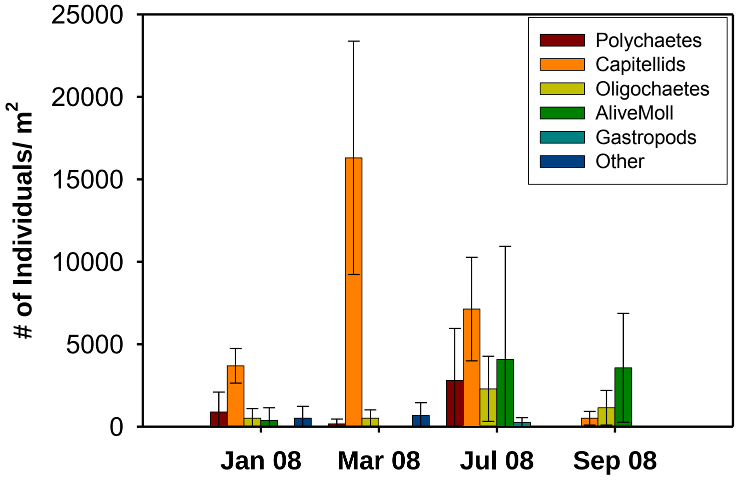


Figure 3.8. Mean and standard deviation of the abundance of benthic infauna taxa in Famosa Slough in benthic chambers by index period.

3.3.3 Relationship Between In Situ and Diffusive Fluxes

Of the constituents modeled, ammonium diffusive fluxes are the most predictive of *in situ* chamber fluxes (Tables 3.4 and 3.5). Fluxes were within the same order of magnitude and direction, though diffusive fluxes slightly under predicted *in situ* fluxes. With NO_3, this relationship was not as strong as with ammonium, but predicted diffusive fluxes were within a factor of 3 of measured *in situ* fluxes. SRP predicted diffusive fluxes, while showing a reasonable regression relationship with *in situ* fluxes, under predicted the *in situ* flux by a factor of 20. For the dissolved organic constituents (DOP, DON and DOC), the regression relationship between diffusive and *in situ* fluxes was poor (highly non-significant) and fluxes differed by one to two orders of magnitude.

Table 3.4. Diffusive fluxes calculated from porewater concentrations by index period for each constituent of interest.

Index Period	Predicted Diffusive Fluxes (mmol m^{-2} d^{-1})					
	NH4	NO3	DON	SRP	DOP	DOC
Winter	0.45	0.41	-2.97E-02	8.38E-03	2.34E-02	-1.87E+00
Spring	0.36	0.52	-6.39E-02	2.32E-03	7.31E-03	2.28E-01
Summer	1.70	0.33	-1.80E-01	1.23E-02	-5.10E-03	-5.69E+00
Fall	0.28	0.08	1.28E-01	-2.03E-03	-3.41E-03	-6.02E+00

Table 3.5. Summary of linear regression relationship between calculated diffusive fluxes and *in situ* chamber flux data.

Constituent	In Situ Flux Data Used For Regression	Regression Equation	R^2 and Pr>F
NH4	Dark Chambers	$NH4_{IS} = 2.51*NH4_{DF}$	**R^2 = 0.86, Pr>F : 0.01**
	Light Chambers	$NH4_{IS} = 0.83*NH4_{DF}$	**R^2 = 0.76 Pr>F : 0.03**
	All	$NH4_{IS} = 1.66*NH4_{DF}$	**R^2 = 0.84, Pr>F : 0.02**
NO3	Dark Chambers	$NO3_{IS} = -0.68 + 1.63*NO3_{DF}$	R^2 = 0.08, Pr>F : 0.47
	Light Chambers	$NO3_{IS} = -1.42 + 3.38*NO3_{DF}$	**R^2 = 0.94, Pr>F : 0.10**
	All	$NO3_{IS} = -1.05 + 3.234*NO3_{DF}$	**R^2 = 0.90, Pr>F : 0.14**
DON	Dark Chambers	$DON_{IS} = -3.909 - 49.72*DON_{DF}$	R^2 = 0.14, Pr>F : 0.61
	Light Chambers	$DON_{IS} = 24.3 + 98.26*DON_{DF}$	R^2 = 0.78, Pr>F : 0.22
	All	$DON_{IS} = 6.67 + 33.01*DON_{DF}$	R^2 = 0.33, Pr>F : 0.39
SRP	Dark Chambers	$SRP_{IS} = -0.28 + 22.90*SRP_{DF}$	**R^2 = 0.99, Pr>F : 0.01**
	Light Chambers	$SRP_{IS} = -0.12 + 20.52 * SRP_{DF}$	**R^2 = 0.66, Pr>F : 0.28**
	All	$SRP_{IS} = -0.20 + 21.71* SRP_{DF}$	**R^2 = 0.95, Pr>F : 0.13**
DOP	Dark Chambers	$DOP_{IS} = -1.35 + 31.04*DOP_{DF}$	R^2 = 0.22, Pr>F : 0.68
	Light Chambers	$DOP_{IS} = 0.87 + 123.2*DOP_{DF}$	R^2 = 0.21, Pr>F : 0.42
	All	$DOP_{IS} = -0.39 + 11.60*DOP_{DF}$	R^2 = 0.34, Pr>F : 0.60
DOC	Dark Chambers	$DOC_{IS} = 263.4 + 74.23*DOC_{DF}$	R^2 = 0.58, Pr>F : 0.15
	Light Chambers	$DOC_{IS} = -91.839 + 27.22*DOC_{DF}$	R^2 = 0.11, Pr>F : 0.65
	All	$DOC_{IS} = 89.9 + 56.20*DOC_{DF}$	R^2 = 0.36, Pr>F : 0.26

3.4 Discussion

Estuaries, at the terminus of watersheds, are typically subject to eutrophication due to high inputs of anthropogenic nutrient loads and hydromodification. Shallow coastal lagoons with natural or anthropogenic muting of the tidal regime are particularly susceptible, because restricted exchange increases the residence time of water and thus the amount of time nutrients are available for uptake by primary producers (Sundbäck and McGlathery 2005). Primary production in these tidally restricted estuaries can be fueled by either "new" nutrients entering the system from the watershed or from "recycled" nutrients from the remineralization of particulate and dissolved organic matter.

One of the key factors that determine the trophic state of an estuary is the balance between carbon production (productivity) and respiration. The more organic matter present in the system, the greater the respiration rates are in absolute terms (benthic carbon dioxide flux), and the greater the respiration compared to the productivity, yielding a lower ratio of productivity to respiration (p:r ratio). Excessive nutrient input disrupts the balance between primary productivity (carbon production) and respiration in coastal systems; therefore, management indicators of eutrophication are most soundly based on carbon loading and respiration rather than nutrient loading (Nixon 1995, Eyre and Ferguson 2002a). In shallow coastal lagoon, such as Famosa Slough, nutrient and carbon cycling in the water column and sediments are tightly coupled, with much of the organic matter production taking place in the water column and sediment-water interface and much of the respiration within the sediments. Consequently, the sediments and benthic communities tend to be a sensitive to nutrient enrichment and rates of biogeochemical cycling in the sediments make ideal indicators for eutrophication in these systems (Jorgensen and Richardson 1996).

3.4.1 Significance of Rates of Benthic O_2 and TCO_2 in Famosa Slough

Eutrophication produces excess organic matter that fuels the development of hypoxia (i.e., low surface water DO concentration) as the organic matter is respired (Diaz 2001). When the consumption of oxygen exceeds the rate of resupply (decomposition of excessive amounts of organic matter exceeds diffusion/mixing of oxygen to bottom waters), oxygen concentrations can decline below the limit for survival and reproduction of organisms (Stanley and Nixon 1992, Borsuk et al. 2001, Diaz 2001). The consequence of this is often a cascade of effects including loss of habitat and biological diversity, development of foul odors and taste, and altered food webs (Sutula et al. 2007). Dissolved oxygen levels that fall below 5 mg L^{-1} can be a stressor to aquatic life and levels below 1 to 2 mg/L for more than a few hours can be lethal to both fish and benthic invertebrates (USEPA 2000, 2003). The basin plan water quality objective for Famosa Slough states that DO shall be greater than or equal to 5 mg/L.

Data on the benthic fluxes of oxygen, TCO2, nutrients and continuous water column DO show that Famosa Slough is in a eutrophic state. Comparison of oxygen and TCO2 fluxes to *in situ* measurements in other systems indicate that Famosa Slough is of equal magnitude to most well-documented eutrophic estuaries (Table 3.6). The net O2 and TCO2 fluxes during most seasons were net respiratory, indicating that the Slough is decomposing more organic matter than producing it at the time of sampling (Berelson et al. 1998, Eyre and Ferguson 2005, McGlathery et al. 2007). O2 fluxes measured in benthic flux chambers were in agreement with expected patterns in continuously monitored DO flux, which showed chronic nighttime hypoxia during the summer and late fall.

Table 3.6. Comparison of fluxes from Famosa Sough to other estuarine environments.

Site	O_2	TCO_2	SRP	NH_4	NO_3
Santa Margarita (this study)					
Segment One	4.5±66.5	-4.2±14.7	0.5±1.3	8.5±11.2	-13.9±14.3
Segment Two	-6.5±33.1	-3.1±23.8	0.1±0.4	0.2±0.9	-6.4±10.4
Loma Alta Slough (this study)	46.0±63.8	-6.7±58.0	0.1±0.2	1.8±4.9	-0.6±2.9
San Elijo Lagoon (this study)					
Segment One	-12.3±17.9	28.6±21.7	0.4±0.3	0.9±0.3	-8.1±8.5
Segment Two	-51.5±26.8	98.1±36.4	0.8±0.3	11.8±2.3	-4.4±2.8
Buena Vista Lagoon (this study)					
East Basin	-4.6±28.5	13.4±14.8	-0.3±0.6	0.3±2.2	-5.9±13.0
Central Basin	-145.02±48.0	50.9±26.0	0.9±2.4	2.0±18.0	-1.2±4.3
Famosa Slough (this study)	-43.8±17.7	58.9±46.4	-0.2±0.2	1.0±1.4	-0.2±0.5
Shallow SE Australian Lagoons (Eyre and Ferguson 2002)	-50 to 0	10 to 100		-3.4 to 0.3	0 to -60
Hog Island Bay (Tyler et al. 2003)	-0.003 to +0.012			-0.33 to + 0.42	-0.12 to +0.009
Shallow NE Australian Lagoons (Ferguson et al 2004)				-0.2±0.3	-0.4 ± 0.3
Newport Bay (Sutula *et al.* 2006)	-43 ± 20	107 ± 81	0.36 ± 0.52	5.7 ± 2.7	-3.0 ± 5.3
Los Angeles Harbor (Berelson unpublished)	-18.9 ± 6.3	39 ± 29	0.33 ± 0.40	3.9 ± 2.9	-0.19 ± 0.18
San Francisco Bay (Hammond *et al.* 1985)	-30 ± 7	24 ± 8	0.10 ± 0.50	1.1 ± 0.1	-0.5 ± 0.6
Monterey Bay (Berelson *et al.* 2003)	-9.1 ± 2.4	9.9 ± 2.7	0.11 ± 0.07	0.56 ± 0.24	-0.57 ± 0.48
Chesapeake Bay (Callender and Hammond 1982, Cowan and Boynton 1996)	-49		0.8	10.2	-2.9 – 0.2
San Quentin Bay, Baja CA (Ibarra-Obando *et al.* 2004)	-23.4 ± 10.7	31 ± 22.9	0.114 ± 0.140	2.15 ± 1.39	
Tomales Bay (Dollar *et al.* 1991)	-9.37 ± 9.56	20.7 ± 24.4	0.24 ± 0.40	1.96 ± 2.39	-0.01 ± 0.17
Plum Island Sound (Hopkinson *et al.* 1999)	-33 – -170	23 – 167	-0.25 – 1.5	4.8 – 21.2	

3.4.2 Seasonal Patterns of Nutrient Fluxes and Benthic Metabolism in Famosa Slough

In shallow coastal lagoons such as Famosa Slough, the seasonal trends in benthic metabolism and nutrient flux are typically regulated by temporal changes in the primary producer community (Sundbäck and McGlathery 2005). In Famosa Slough, macroalgae and benthic diatoms (microphytobenthos, MPB) were a major factor driving the magnitude and direction of benthic fluxes observed in this system. The dominant pathways of benthic nutrient cycling shifted seasonally during the four index periods, as described below.

The winter index period was characterized by frequent storm events. Peak flows during storm events in the winter index period would be expected to provide a subsidy of nutrients and particle-bound nutrients as well as an environment dominated by physical mixing of the surface waters and sediments (Smith et al. 1996, Correll et al. 1999, Paerl 2006). As evidence of this, surface sediments during this period contained the lowest percent fines of any of the four index periods (Chapter 2). Mean water temperatures were relatively low (15^{o} C), limiting microbially-mediated decomposition of organic matter during this time period, as indicated by low NH_4 and DOC. Sediment oxygen demand was moderate, and negative fluxes of Mn and SRP as well as porewater profiles of these constituents and sulfide indicate only mildly reduced sediments (Froelich et al. 1979). As a result, primary producer biomass was low and fluxes may have been controlled to a greater extent by advective processes (Sutula et al. 2004, Sutula et al. 2006).

During the spring sampling period, oxygen demand was low but TCO2 efflux was high. Gross primary productivity (3.86 mmol m^{-2} d^{-1} 02) and TCO2 uptake rates were both high during this index period (i.e., net CO2 production exceeds oxygen production, -120 mmol m^{-2} d^{-1} TCO2; (Eyre and Ferguson 2002b, 2005)). Furthermore, both MPB biomass and infaunal diversity and abundance peak in the spring, suggesting that the MPB has a positive feedback effect on benthic infauna (Sundbäck and McGlathery 2005). The combined effect of peak infaunal abundance and MPB biomass appear to have increased the depth of oxygen penetration into the sediments. Porewater NO_3values peak, surface water $NO_3$is low, and porewater NH_4 concentrations are low, suggesting that nitrification (an aerobic pathway in which NH_4 is converted to NO_3) may be occurring (An and Joye 2001, Anderson et al. 2003). Interestingly, TCO2:O2 ratios are 2 to 3 times that expected under aerobic conditions, suggesting that other processes, such as anaerobic decomposition or sulfate reduction may be contributing to the excess TCO2 flux. Since porewater sulfide values are extremely low during this period, it may be possible that bioirrigation by benthic infauna has greatly enhanced the anaerobic decomposition of organic matter, fueling large TCO2 fluxes.

Organic matter decomposition results in the liberation of dissolved inorganic nutrients (remineralization). Interestingly, $NO_3$and NH_4 efflux from the sediments was the lowest during the spring. MPB can act to decouple nutrient turnover in the sediments from the overlying water column by acting as a “filter” for nutrient efflux from the sediments, at times completely intercepting nutrient fluxes across the sediment-water interface (McGlathery et al. 2004, McGlathery et al. 2007). Low fluxes of dissolved inorganic N compared to other eutrophic systems (Table 3.4), coupled with peak MPB biomass and high gross primary productivity rates, are an indication that this phenomenon may be occurring.

Measured rates of denitrification during the spring and summer index periods were either extremely low or non-detectable (T. Kane, Doctoral Dissertation, UCLA Dept. of Biology). Nitrate uptake associated with MPB or macroalgae may have also limited denitrification through competition for NO_3. Denitrification is thought to be an unimportant sink for N in shallow coastal lagoons because these primary producers can typically outcompete bacteria for available N (Dalsgaard 2003, McGlathery et al. 2007).

During the summer index period, macroalgae replaced MPB as the dominant primary producer. Macraolgae have been shown to control the biomass of other primary producer communities, including benthic microalgae. Macroalgae have been shown to control the biomass of other primary producer communities, including benthic microalgae, because of a competitive advantage in nutrient uptake rate (Fong et al. 1993, Fong et al. 2003). Net TCO2 efflux, C-fixation and GPP peaked during this period.

While MPB has been shown to enhance the oxygen penetration of sediments, macroalgal biomass was significantly negatively correlated with DO flux (increasing sediment oxygen demand with increasing macroalgal biomass; Table 3.2). As a result of increased sediment oxygen demand, gross benthic productivity and net O2 production were lowest during the summer index period, coinciding with time periods of chronic nighttime hypoxia in the Slough. Sulfide reached peak concentrations surficial sediments. TCO2:O2 ratios during this time period were 2.6:1 and were likely driven by the increased importance of sulfate reduction. Benthic infaunal abundance and diversity declined from springtime levels, possibly due to chronic nighttime hypoxia and elevated sulfide concentrations. This decline would result in reduced bioirrigation of the sediments and less oxygen penetration, further exacerbating sediment oxygen demand. Macroalgal biomass was also positively correlated with SRP and NO3 flux. Previous studies have suggested that macroalgae can drive an increased efflux of dissolved inorganic nutrients from sediments by drawing down surface water concentration, thereby increasing the concentration gradient (Tyler et al. 2003, Sutula et al. 2006). As these nutrients are trapped as biomass, macroalgae become an effective mechanism to retain and recycle nutrients within an estuary, diverting loss from denitrification or tidal outflow. This concept is supported by non-detectable rates of denitrification in the Slough during this index period.

During the fall, the dominant primary producer community shifted from macroalgae to cyanobacteria mats. Net sediment oxygen demand remained high, but light and dark O2 fluxes were roughly equivalent, suggesting that gross benthic productivity was a minor component relative to respiration for this time period (Eyre and Ferguson 2002b). TCO2 fluxes were lower, with a TCO2:O2 ratio of 0.4, which is more reflective of aerobic decomposition and, to some extent, other non-metabolic processes that may be consuming O2 (e.g., oxidation of reduced metals, sulfide, etc.: (Froelich et al. 1979)). Surface water hypoxia is the most chronic during this period and benthic infaunal abundance and diversity is at its lowest point. In shallow systems, water column stratification does not typically develop and thus, hypoxia occurs as seasonally episodic events driven by the collapse or senescence of primary producer communities (McGlathery et al. 2007). The decrease in sediment oxygen demand from the summer index period is counterintuitive when paired with surface water DO data showing chronic hypoxia. One suspected reason for this lower than expected TCO2 efflux and low sediment oxygen demand could be that the rates of bioirrigation would decline due to low abundances of infauna (Rabouille et al. 2003).

4 Famosa Slough Nitrogen and Phosphorus Budgets

4.1 Introduction

Nutrient cycling is one of the critical functions of estuaries (Day et al. 1989). The net balance of nutrient sources, transformations and losses from the estuary dictate the biomass and community structure of primary producers and bacteria, which forms the foundation for the estuarine food webs and dictates the habitat quality for benthic and pelagic fauna. One means of evaluating the efficiency of nutrient cycling within an estuary is to estimate its N and P budgets (Sutula et al. 2001). Budgets are a useful method to assess the relative importance of allochthonous inputs (“new” nutrients) versus internal recycling (“recycled” nutrients) on primary productivity (Mitsch and Gosselink 1993) – the main symptom of eutrophication.

The purpose of this section is to estimate Famosa Slough N and P sources, losses, and change in storage for those terms which are readily estimated, to use this information to discuss efficiency of nutrient cycling and potential management options. The estuarine hydrodynamic and water quality models will be used in the future to develop refined nutrient budgets for Famosa Slough. However, in the interim, coarse estimates of nutrient budgets can be derived. This information, in conjunction with data estimating the change in storage, can shed light on the efficiency of nutrient cycling and inform potential management actions in Famosa Slough.

4.2 Methods

Budgets are estimated by determining the sum of source and loss terms from an estuary during the time period of interest (Figure 4.1). The sum of the source and loss terms, plus the change in “storage” of nutrients within specific compartments within the estuary (e.g., sediments, surface water, primary producers), should be equal to zero (equation 4.1). Table 4.1 gives a summary of all the possible nutrient source, loss, and change in storage terms for an estuary and which of these were measured in Famosa Slough.

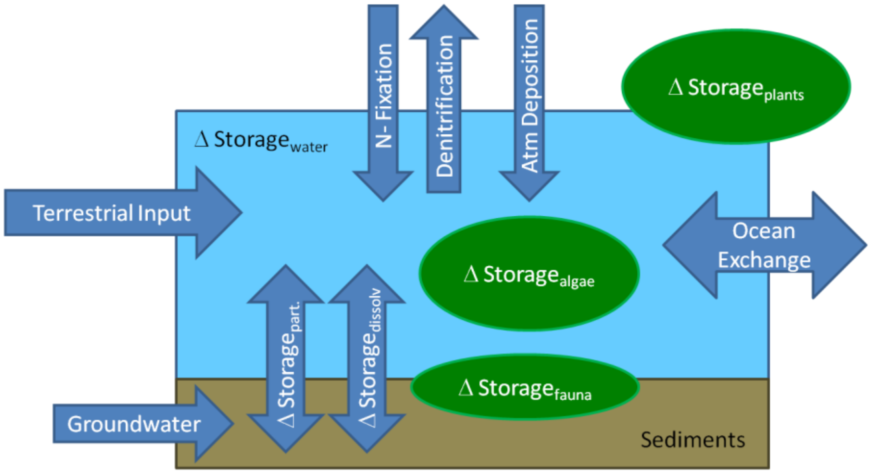


Figure 4.1. Conceptual model for development of budget estimates.

Nutrient sources to Famosa Slough include: terrestrial runoff (wet and dry weather from creeks and storm drains), groundwater efflux, atmospheric deposition, tidal surface water inflow, and benthic N fixation (Table 4.1). Nutrient losses to include: groundwater recharge, tidal surface water outflow, sediment burial, and benthic denitrification. Change in storage includes benthic exchange with surface waters, aquatic primary producer biomass (positive during the growing season, negative during when they senesce), sediment mass accumulation or loss, and faunal uptake and release. If the sum of source, loss and change of storage terms are not equal to zero, we have nominally assigned this quantity to a "residual" term. Because groundwater, tidal exchange with San Diego River, exchange with emergent macrophytes (salt marsh) and faunal uptake and release are not estimated, quantities associated with these terms are assigned to this residual.

$$\text{Load}_{\text{watershed}} + \text{Load}_{\text{ocean}} + \text{Load}_{\text{groundwater}} + \text{Atmospheric Deposition} - \text{Denitrification} + \text{N fixation} - \Delta\text{Storage}_{\text{algae}} - \Delta\text{Storage}_{\text{plants}} - \Delta\text{Storage}_{\text{fauna}} + \Delta\text{Storage}_{\text{particulate}} + \Delta\text{Storage}_{\text{dissolved}} - \Delta\,\text{Storage}_{\text{water column}} = 0 \qquad \textbf{Eq. 4.1}$$

Table 4.1. Summary of nutrient budget terms: sources, losses and change in storage.

Budget Term	Nitrogen	Phosphorus
Sources		
Terrestrial runoff (wet and dry weather)	Weston	Weston
Groundwater efflux	Assumed negligible	Assumed negligible
Atmospheric deposition	Literature values	Literature values
Tidal surface water inflow (with San Diego R.)	Weston[1]; included in residual term	Weston, included in residual term
Benthic nitrogen fixation	UCLA Study	N/A
Losses		
Tidal surface water outflow	Weston; included in residual term	Weston; included in residual term
Denitrification	UCLA Study	N/A
Change in Storage		

---

[1] Tidal surface water inflow and outflow were measured by Weston, but must be modeled to be accurately estimated. This report presents a coarse estimate of this net exchange for May – July and August - 2009.

Benthic exchange of dissolved nutrients with surface waters	SCCWRP	SCCWRP
Plant/algal uptake/ release	Residual of Sum of Sources, Losses and Change in Storage Terms	
deposition/resuspension of particulate nutrients	LSU	LSU
Faunal uptake and release	Assumed negligible	Assumed negligible

Terrestrial runoff was estimated from wet and dry weather runoff monitoring conducted by Weston Solutions, Inc. (2009). Benthic N fixation and denitrification were measured during each of the index periods at the segment site (personal communication, T. Kane, UCLA Department of Biological Sciences Doctoral Dissertation). Atmospheric deposition rates are estimated from a National Atmospheric Deposition Program site in the San Bernardino Mountains during 2007. Dry deposition for NH_4 and NO_3 for this site was 2.6 kg ha^{-1} $year^{-1}$ while wet deposition was 1.5 kg ha^{-1} $year^{-1}$. Fewer data are available for atmospheric deposition of phosphorus; data from south Florida indicate total (wet+dry) P fluxes ranging from 0.1 to 0.4 kg ha^{-1} $year^{-1}$, with an average of 0.3 kg ha^{-1} $year^{-1}$ (Redfield 2000, Ahn and James 2001). Typically ratios of dry:wet P deposition are 3:1. These numbers were used to estimate annual atmospheric loads for Loma Alta Slough. These terms were estimated from monitoring data or from literature values for the period of November 1, 2007- October 31, 2008.

Groundwater interactions and faunal contributions were assumed negligible. Tidal surface water exchange with San Diego River was not included in the budget, as water inflow and outflow and net loads should be estimated by modeling changes in concentration and flow over neap and spring tidal cycles. This term would therefore be included in the "residual" of the net sum of sources, loss, and change in storage. We did, however, make an attempt to develop a coarse estimate of tidal surface water exchange for the May-July period in order to determine whether tidal exchange could account for any budget residual. To do this, mean ocean inlet concentrations of total and dissolved inorganic nutrients were used in conjunction with PWA hydrodynamic modeling output to estimate the magnitude and direction of exchange of Famosa Slough with San Diego River. Modeling output was available for a one month period during August 2007 and these data were extrapolated over three months to estimate net exchange.

Sediment mass accumulation and loss was estimated from long-term annual deposition rates measured by Louisiana State University but were confounded by internal processes (see Chapter 2). These numbers are not tabulated in the budget but are discussed below. The following literature values and assumptions were used to convert primary producer biomass to N and P (Table 4.2).

Table 4.2. Literature values for Chl a:C and C:N:P ratios of primary producer communities and assumptions to convert biomass to areal estimates of N and P associated with biomass.

Community	Stoichiometry (C:N:P)	Reference
Phytoplankton (assumed 1.5 m water depth)	Chl a: C Ratio of 30:1 C:N:P = 106:16:1	Cloern 1995 Redfield Ratio (Redfield 1958, Anderson and Sarmiento 1994)
Cyanobacteria Mats	50% C by dry wt	Study Data

	C:N:P = 550:30:1	(Atkinson and Smith 1983)
Macroalgae	22% C by dry wt C:N:P = 80:5:1	Study Data (Eyre and McKee 2002)
Benthic Microalgae	Chl a: C ratio of 30:1 C:N:P = 90:15:1	Sundeback and McGlathery 2005 (Eyre and McKee 2002)

4.3 Results and Discussion

Coarse estimates of seasonal N and P budgets for Famosa Slough provide order of magnitude estimates of nutrients available for primary productivity and help interpret the importance of external loads versus internal biological recycling in supporting this productivity. Our expectation is that dynamic simulation models of water quality and sediment transport will provide a greatly improved and more precise nutrient budget and thus these estimates should be considered preliminary.

4.3.1 Nitrogen Budget for Famosa Slough

Table 4.3 provides of source and loss terms for N for all terms except exchange with San Diego River. It also provides estimates of the amount of N that changed from the sediment porewaters to surface waters (benthic flux) and from surface waters to primary producer biomass for these periods within the Slough.

Overall, without accounting for net exchange with San Diego River or net sediment deposition, budget estimates show a net annual TN export (as the residual) from the Slough of 660 kg (Table 4.3). The pattern of net export is consistent for all index periods except the spring, where high benthic TN influx into sediments would require an “input” of N into Slough. Since this high TDN influx is driven mostly by DON, it is not clear how credible this number is; DON fluxes were highly variable throughout the study period. Wet weather events were not as important as dry weather loading; wet weather periods represented 25% of annual terrestrial loads from the local catchment. Although, estimates of terrestrial runoff from local catchment are likely to be an overestimate, as there is expected to be some treatment and detention of loads occurring within the Valeta Street treatment wetland.

The contribution of benthic flux was a major driver in the overall N budget of Famosa Slough, representing annually about 50% of the terrestrial runoff from local catchment (Table 4.4). During the summer peak in primary producer biomass (May-July), benthic TN efflux (223 kg TN and 112 kg DIN) is twice the amount of terrestrial runoff from the local watershed (110 kg TN and 20 kg DIN). Exchange with San Diego River, estimated to be 60 kg TN and 20 kg DIN during the May-July period, appears to provide a minor source of DIN.

Macroalgae are known to prefer dissolved inorganic forms of N for growth. The amount of dissolved inorganic nitrogen from all sources during the three month period (May-July; 162 kg DIN) is slightly less than what is required to support the peak primary producer biomass during the summer index period, estimated as 223 kg. Thus benthic flux supplies 68% of the DIN to macroalgae during peak growth. Some recycling of organic forms of nitrogen may be occurring to supply additional DIN. Furthermore, estimates of benthic flux may be an underestimate because macroalgae has been shown to intercept benthic nutrient effluxes and can even increase the net flux by increasing the concentration gradient between sediments and surface waters (Tyler et al. 2001, Tyler et al. 2003, Sutula et al. 2006).Thus, during peak algal growing season, the majority of bio-available N is coming out of the sediments rather than from the catchment.

Table 4.3. Comparison of estimated nitrogen source, loss and change in storage terms in Famosa Slough during dry weather periods (kg N). Positive and negative under "source and loss" terms indicates source and loss to Slough respectively. Positive and negative numbers in change of storage terms indicate gain and loss from compartment respectively. Residual is the sum of source and loss terms, minus the change in storage.

Budget Term	Wet Weather	Dry Weather Nov-Jan	Dry Weather Feb-Apr	Dry Weather May-Jul	Dry Weather Aug-Oct	Annual (Wet +Dry)
Source and Loss Terms						
Terrestrial Runoff	86	60	93	110	53	316
N - Fixation	--	23.9	13.8	17.6	0.3	55.6
Atmos. Deposition	9	4	4	4	4	25
Denitrification	--	-0.31	-0.01	0.00	-0.32	-0.64
Source + Loss Terms	95	75	103	122	59	454
Change in Storage						
Benthic N Flux	--	19	-488	223	433	187
1^0 Producer N	--	0	1	139	-120	19
Residual	95	94	-384	484	372	660

Table 4.4. Comparison of loads from watershed versus benthic nutrient flux (kg).

kg	Wet Weather	Index Period 1		Index Period 2		Index Period 3		Index Period 4		Annual (Wet+ Dry)	
		Water-shed	Benthic Flux	Water-shed	Benthic Flux	Water -shed	Benthic Flux	Water -shed	Benthic Flux	Water -shed	Benthic Flux
TN	86	60	--	93		110		53		316	--
TDN	--	--	19	--	-488	--	223	--	433	--	187
NH_4	14	24	42	13	-11	18	106	11	2	80	139
NO_3	28	4	6	7	-7	2	6	0	-30	40	-26
TP	19	38	--	42	--	70	--	44	--	213	--
TDP	18	37	-20	39	-14	64	16	42	-28	201	-45
SRP	12	33	-26	24	-4	45	2	33	-10	147	-38

Nitrogen fixation and atmospheric deposition together contribute a small but significant amount of TN to Famosa Slough. Collectively, they represent 10 to 40% of the terrestrial runoff during any index period. Atmospheric deposition is a very minor source of N to the Slough and N fixation can incorporate new organic N to the system to support cyanobacterial growth. Since the estimates of atmospheric deposition directly deposited to the are based on the literature, improved numbers needed to characterize this source, though it is anticipated that the magnitude of the estimate would not likely change substantially. Atmospheric deposition the local and San Diego River watershed may be a more important source.

Denitrification was negligible as a loss term for N. Denitrification is thought to be an unimportant sink for N in shallow coastal lagoons because primary producers typically outcompete bacteria for available N, and partitioning of NO_3 reduction will shift to dissimilatory NO_3 reduction to NH_4 in later stages of eutrophication (Risgaard-Petersen and Ottosen 2000, An and Gardner 2002, Dalsgaard 2003, McGlathery et al. 2007). Net heterotrophic sediments, such as those in Famosa Slough typically have lower rates of coupled nitrification-denitrification than net autotrophic sediments (An and Joye 2001, An and Gardner 2002). Furthermore the high free sulfide concentrations in organic rich sediments underlying macroalgae accumulations may inhibit nitrification (Joye and Hollibaugh 1995). Primary producers in Famosa Slough are somewhat N-limited (Figure 4.1), which favors organisms (*e.g.,* cyanobacteria) that are able to convert N from the atmosphere to NH_4 to meet their N requirements. Loads from N-fixation are slightly variable, but represent a small but significant addition to the N budget of Famosa Slough.

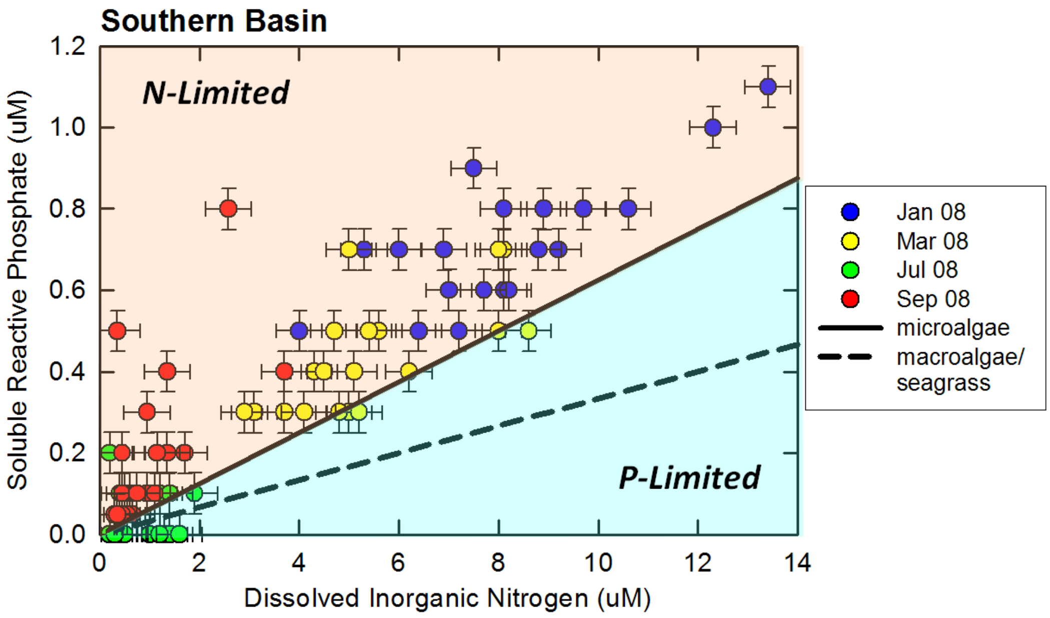


Figure 4.2. Ambient soluble reactive phosphorus versus dissolved inorganic nitrogen (nitrate, nitrite, and ammonium) from transect data taken in the northern channel (transect station # 11- 15) and the southern basin (transect station # 1-10). The solid black line indicates the N and P requirements for both phytoplankton and benthic microalgae (N:P = 16:1), and the dotted black line indicates the N:P ratio for macroalgae and seagrasses (N:P = 30:1). If ambient values fall above these lines the communities are N limited. If values fall below, the communities are P limited.

4.3.2 Phosphorus Budget for Famosa Slough

Table 4.5 provides of source and loss terms for phosphorus for all terms except exchange with San Diego River. It also provides estimates of the change in storage of P within sediment, primary producer biomass, and sediment storage compartments within the Slough.

Overall, without accounting for net exchange with San Diego River, budget estimates show a net annual TP export from the Slough of 205 kg (Table 4.5). This annual export is driven predominantly by terrestrial runoff, as atmospheric deposition is negligible and benthic flux of P is typically into the sediment rather than out. During the winter, spring, and fall benthic TP influx into sediments would require an "input" of P into Slough. Wet weather loads of TP were relatively unimportant compared to dry weather terrestrial loads; wet weather periods represented only 10% of annual terrestrial loads. Although, estimates of terrestrial runoff from the local catchment are likely to be an overestimate, as there is expected to be some treatment and detention of loads occurring within the Valeta Street treatment wetland.

In contrast to N, benthic exchange is either not a source of total and dissolved inorganic P or a very small source. Terrestrial loads, estimated from the mass emission site, provided an annual load of 213 kg (Table 4.5), 70% of which was SRP. In contrast, benthic exchange represented a net sink for TP and SRP annually, a loss of approximately 20% of the terrestrial load. Atmospheric deposition appears to be an insignificant contribution of phosphorus, but as with N, local data are needed to make these estimates more realistic.

Table 4.5. Comparison of estimated phosphorus source and loss terms in Famosa Slough during dry weather periods (kg P). Positive and negative under "source and loss" terms indicates source and loss to Slough respectively. Positive and negative numbers in change of storage terms indicate gain and loss from compartment respectively. Residual is the sum of source and loss terms, minus the change in storage.

P Budget Term	Wet Weather	Dry Weather Nov-Jan	Dry Weather Feb-Apr	Dry Weather May-Jul	Dry Weather Aug-Oct	Annual
Source and Loss Terms						
Terrestrial runoff	19	38	42	70	44	213
Atmos. Deposition	0.5	0.3	0.3	0.3	0.3	1.7
Source + Loss Terms	20	38	42	70	44	215
Change in Storage						
Benthic P Flux	--	-20	-14	16	-28	-45
1^0 Producer P	--	0	0	62	-27	35
Residual	20	18	28	148	-11	205

During the May – July period, the peak in primary productivity, terrestrial loads from the local catchment and San Diego River were estimated to provide 90 kg of TP and 56 kg of SRP. In contrast, benthic flux provided 16 kg TP; however only 2 kg of this amount is SRP. Thus, 58 kg of SRP is readily available for biological uptake which is roughly equivalent to that required to support the 62±19 kg P stored in primary producer biomass, but relatively little of this SRP is derived from the sediments. Terrestrial sources provide 60% of available TP and 90% of available SRP to support primary productivity.

At first glance, the direction of the predicted residuals are not entirely consistent with differences in mean TN and TP concentrations between ebb and flood waters during these periods (Table 2.2); however dynamic simulation model of water quality should greatly clarify and provide finer resolution of Slough budgets. Observations of mass balance made here should be regarded as preliminary. Notably, modeling the exchange with San Diego Creek will be hampered by lack of available TN and TP concentration data for San Diego River, since this is likely to be critical in achieving a mass balance for Famosa Slough. Another unknown is the effect of the treatment wetlands, which intercepts freshwater flow as it enters the Slough. It would be expected that this decreases nutrient loads to Famosa, but treatment occurring has not been quantified.

4.4 Options for Reducing Eutrophication in Famosa Slough

These preliminary nutrient budgets for Famosa Slough illustrate that internal recycling of N and P have a more important role than terrestrial runoff during peak periods of productivity. While the inputs of nutrients from San Diego River are not well quantified here, the relative magnitude of these inputs is not likely to change this conclusion. Sediment data indicate that the Slough has accumulated a large amount of organic matter in the sediments. Limited data on benthic infauna show declines in abundance during summer and fall periods, which coincides with peak macroalgal abundance and prolonged hypoxia. Because benthic flux is the major source of N to the Slough, recycling of this organic matter to biologically available forms of nutrients will likely continue to cause problems with algal blooms and hypoxia, even with nutrient reductions, unless restoration is undertaken to flush the Slough of the fine-grained sediments and improve circulation. Because benthic infauna plays an important role in nutrient cycling and denitrification, additional studies should be undertaken to investigate causes of stress to benthic infauna (contaminants) in order to understand how to improve benthic habitat quality.

Given the findings of this study, the following options for management of eutrophication in Famosa Slough should be considered:

1. Increase flushing and circulation within Famosa Slough to decrease detention of fine-grain sediments and decrease water residence time. The City of San Diego, in concert with Friends of Famosa Slough, has already undertaken some restoration actions and are considering additional options to further these goals.
2. Reduce terrestrial loads from the Famosa Slough catchment and/or San Diego River. Installation of the Valleta Street Treatment wetlands has already reduced loads from the Famosa Slough catchment. Estimated loads from the catchment are likely an overestimate because the effect of the treatment wetlands is not accounted for in the estimate of mass loads. Some additional reductions of nutrient could be considered; emphasis should be placed on detention of suspended matter before it reaches the Slough.

3. Harvest algal biomass. This option could help to alleviate algal blooms and associated problems. However, is not likely to solve problems with eutrophication in the short-term because of the importance of sediments in driving hypoxia and eutrophication in Famosa Slough. Therefore, the cost-effectiveness of harvesting as a management tool must be carefully considered.

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Appendix 1 - Quality Assurance Documentation

This section presents the results of the QA/QC procedures conducted throughout the sampling period at Famosa Slough.

Sampling Equipment Maintenance:

Benthic chambers, porewater peepers and sediment cores were inspected prior to each deployment for cracks and/or deformities. Chambers were "re-plumbed" with new tubing and make-up bags during each index period and the diffuser bars were scrubbed internally and flushed with distilled water to make sure they were not clogged with sediment. Dark chambers were further inspected to make sure they were completely covered and no light was transmitted to the chamber. Peepers were cleaned and scrubbed with ethyl alcohol (to kill algae and microbial growth), rinsed in a 5% hydrochloric acid bath, then rinsed three times with distilled water prior to assembly to minimize contamination.

Data Sondes: Calibration, Drift, and Logging

Data sondes deployed in each benthic chamber and in the ambient surface water were calibrated not more than four days prior to deployment and a drift check was completed after deployment. No calibration problems or drift were apparent in any of the sonde maintenance events. During index period 1 sondes in chambers 3 and 4 failed to log data and during index period 3 the sonde in chamber 1 failed to log data. Reason for the lost data was due to a failure of the power supply.

Holding Times Violations

All water and sediment samples met the required holding times for benthic flux study in Famosa Slough SCCWRP special studies. Porewater samples had holding times violations for dissolved inorganic nutrients (NH4, NO3, NO2, and SRP) by UCSB for two periods: samples collected on 4/3/08 were not analyzed until 5/5/08 and exceeded the holding times by four days, and samples collected on 7/23/08 were run on 8/27/08 and exceeded the holding time by six days. These were considered minor violations and the data were used in calculations.

Laboratory Blanks

All of the laboratory blanks were reported to be below the level of detection, suggesting no bias from analytical techniques.

Field Blanks

One field blank was collected for each analyte during each benthic flux study and during each porewater peeper study. Field blank samples were collected using the same sample handling and collection equipment as field samples, except distilled- deinonized water was processed instead of sample water to assess possible contamination issues. Field blanks for total dissolved nitrogen, ammonium, total carbon dioxide and iron had a small percentage of samples fall outside the acceptable range. All other field blanks were below the minimum detection limit.

Laboratory Control Standards

All of the laboratory control standards were met acceptance criteria for percent recovery.

Laboratory Duplicates

Laboratory duplicates were processed by all analytical laboratories. A subset of samples (~5%) was randomly selected by the technician, split in the laboratory, and run separately to assess the comparability of the sample analysis process. All laboratory duplicates were within the analytical reporting limits for each analyte.

Field Duplicates

One field duplicate was collected for each analyte during each benthic flux study and during each porewater peeper study. Ammonium, nitrate + nitrite, and total dissolved phosphorus had a small percentage of samples fail to meet the acceptance criteria. Field duplicates for all other analytes fell within the acceptance criteria.

Laboratory Matrix Spikes

Matrix spike samples were processed in the laboratory by adding a known concentration of a specific analyte to a field sample. The sample was analyzed prior to addition of the spike and again after addition. The calculated analyte concentration was prepared and compared to the analytical concentration. Matrix spike results are acceptable when the percent recovery is between 80 and 120%. All of the matrix spike results were within the acceptable range for the Famosa Slough special studies.

Table A1.1. QA/QC analysis for Famosa Slough data set.

Constituent	Percentage Lab Blanks >MDL	Percentage Field Blanks >MDL	Percentage Lab Duplicates >25% RPD	Percentage Field Duplicates >25% RPD	Percentage Holding Times Violation
Water Analyses					
TN	0%	0%	0%	0%	0%
TDN	0%	12%	0%	0%	0%
NH_4	0%	12%	0%	12%	15%
NO_3 + NO_3	0%	0%	0%	12%	15%
NO_3	0%	0%	0%	0%	15%
TP	0%	0%	0%	0%	0%
TDP	0%	0%	0%	12%	0%
SRP	0%	0%	0%	0%	15%
TCO_2	0%	12%	0%	0%	0%
Fe	0%	12%	0%	0%	0%
Mn	0%	0%	0%	0%	0%
S^{-2}	0%	0%	0%	0%	0%
Suspended CHL a	0%	0%	0%		0%
Sediment Analyses					
%OC	0%	NA	0%	0%	0%
%TN	0%	NA	0%	0%	0%
%TP	0%	NA	0%	0%	0%
Grain Size	NA	NA	NA	0%	0%
Benthic CHL a	0%	NA	0%		0%

Appendix 2 - Summary of Data to Support Modeling Studies

This appendix provides SCCWRP data in tabular format to facilitate use of the data for the development and calibration of the water quality model for Famosa Slough.

MASS EMMISIONS

Table A2.1. Summary of mass emission site data by analyte for all storm events.

All Storms	TSS (mg/L)	TN (mg/L)	TDN (mg/L)	NH_4 (mg/L)	$NO_3 + NO_2$ (mg/L)	TP (mg/L)	TDP (mg/L)	SRP (mg/L)	$CBOD_5$ (mg/L)
Mean	30.04	1.54	0.26	0.55	0.03	0.35	0.31	0.22	6.79
Minimum	7	0.66	0.11	0.2	0.01	0.15	0.13	0.12	1.1
Maximum	109	5.27	0.64	1.86	0.06	0.98	0.82	0.68	32.6

SEDIMENT DEPOSITION

Table A2.2. Mass flux of sediment organic carbon, total nitrogen, and total phosphorus.

Index Period	Date	Deposition (g/cm^2)	Mass Flux $g/m^2/day$	Flux C ($g/m^2/day$)	Flux of N ($g/m^2/day$)	Flux of P ($g/m^2/day$)
preliminary	1-Nov-07	1.84	614	41.8	5.86	0.721
1	21-Jan-08	11.8	1440	67.1	8.87	0.843
	28-Feb-08	0	0	0	0	0
2	3-Apr-08	4.19	590	27.4	3.51	0.671
	15-May-08	43.5	10,400	404	54.9	11.8
3	23-Jul-08	3.45	500	19.5	2.98	0.569
	20-Aug-08	9.11	3300	150	18.6	2.94
4	30-Sep-08	0.921	219	10.1	1.24	0.198
Summary			**17,000**	**719**	**95.9**	**17.7**

SEDIMENT BULK CHARACTERISTICS BY INDEX PERIOD: C, N, P

Table A2.3. Sediment bulk characteristics for each index period.

Index Period	Sample Depth	% Organic C	% Total N	% Total P	OC:N (molar)	OC:P (molar)	N:P (molar)	% Fines
Preliminary Sampling	0 – 1 cm	7.7	1.10	NR	7.00	NR	NR	76.4
	1 – 2 cm	5.9	0.81	0.1175	8.49	129.72	6.89	73.7
	2 – 3 cm	4.9	0.57	0.0908	10.03	139.41	6.28	69.0
	3 – 4 cm	4.3	0.49	0.0787	10.24	141.15	6.23	64.8
	4 – 6 cm	4.0	0.45	0.0729	10.37	141.75	6.17	66.5
	6 – 8 cm	2.7	0.29	0.0537	10.86	130.01	5.41	54.8
	8 – 10 cm	1.2	0.14	0.0383	10.00	80.94	3.66	44.6
Index Period 1 - Winter	0 – 1 cm	4.6	0.61	0.0990	8.80	120.03	13.64	--
	1 – 2 cm	4.7	0.62	0.0179	8.84	678.31	76.70	45.5
	2 – 3 cm	4.6	0.58	0.0821	9.25	144.74	15.64	45.7
	3 – 4 cm	4.8	0.63	0.0494	8.89	251.01	28.24	60.0
	4 – 5 cm	4.4	0.55	0.0487	9.33	233.40	25.01	41.7
	5 – 6 cm	4.1	0.51	0.1043	9.38	101.55	10.83	48.4
	6 – 8 cm	3.3	0.40	0.0333	9.63	256.01	26.60	--
	8 – 10 cm	1.8	0.22	0.028	9.55	166.07	17.40	82.5
	10 – 12 cm	0.90	0.11	0.059	9.55	39.41	4.13	89.0
Index Period 2 - Spring	0 – 1 cm	4.6	0.59	0.1146	9.10	103.70	11.40	55.6
	1 – 2 cm	4.7	0.60	0.1129	9.14	107.51	11.76	47.5
	2 – 3 cm	4.6	0.59	0.1008	9.10	117.91	12.96	40.7
	3 – 4 cm	4.4	0.59	0.0948	8.70	119.90	13.78	37.1
	4 – 5 cm	4.3	0.54	0.0902	9.29	123.15	13.26	31.8
	5 – 6 cm	4.3	0.59	0.0912	8.50	121.85	14.33	38.5
	6 – 8 cm	3.5	0.43	0.0698	9.50	129.56	13.64	41.0
	8 – 10 cm	2.9	0.34	0.0550	9.95	136.19	13.69	43.3
	10 – 12 cm	2.3	0.23	0.0474	11.67	125.26	10.74	70.6
Index Period 3 - Summer	0 – 1 cm	3.8	0.50	0.0645	8.84	151.86	17.17	--
	1 – 2 cm	4.0	0.56	0.0761	8.42	137.12	16.29	92.9
	2 – 3 cm	4.3	0.56	0.0790	9.00	141.25	15.69	82.7
	3 – 4 cm	4.3	0.54	0.0914	9.25	120.97	13.08	85.5
	4 – 5 cm	4.1	0.49	0.0697	9.81	152.65	15.56	86.8
	5 – 6 cm	3.7	0.47	0.0656	9.21	146.11	15.87	89.3
	6 – 8 cm	3.3	0.39	0.0596	9.93	143.88	14.49	85.8
	8 – 10 cm	3.2	0.40	0.1016	9.44	81.25	8.61	85.1
	10 – 12 cm	3.5	0.41	0.0575	9.90	156.22	15.78	89.0
Index Period 4 - Fall	0 – 1 cm	4.6	0.56	0.0909	9.50	129.61	13.64	94.8
	1 – 2 cm	4.6	0.58	0.0899	9.19	131.26	14.28	88.6
	2 – 3 cm	4.1	0.51	0.0850	9.47	125.78	13.28	80.0
	3 – 4 cm	3.8	0.46	0.0692	9.71	143.03	14.72	82.6
	4 – 5 cm	2.9	0.33	0.0492	10.18	151.27	14.86	78.7
	5 – 6 cm	2.9	0.30	0.0502	11.28	149.19	13.23	89.2
	6 – 8 cm	2.3	0.26	0.0437	10.23	134.88	13.18	88.2
	8 – 10 cm	2.2	0.23	0.0427	11.16	132.96	11.91	96.1
	10 – 12 cm	2.1	0.23	0.0473	10.80	116.23	10.76	94.5

-- Depths where no percent fines value is recorded had insufficient sample for analysis.

SEDIMENT POREWATER CONCENTRATIONS

Table A2.4. Porewater constituent analysis for each index period.

Sample Period	Depth	TDN (μM)	NH_4 (μM)	NO_3 + NO_2 (μM)	NO_2 (μM)	TDP (μM)	SRP (μM)	TCO_2 (μM)	S^{-2} (μM)	DOC (μM)	Fe (μM)	Mn (μM)
Index Period 1 – Winter 1/22/2008	Bottom water	19.2	3.75	2.55	0.00	1.97	0.75	773	0.63	217.5	0.35	0.33
	0–1 cm	168	39.4	27.00	0.00	6.14	1.80	1070	6.56	650.0	17.9	1.33
	1–2 cm	57.1	1.80	3.20	0.00	3.90	1.80	935	16.3	220.0	12.9	1.35
	2–3 cm	36.5	7.40	2.40	0.00	2.67	1.60	994	21.9	312.5	23.3	0.95
	3–4 cm	94.2	58.4	7.80	0.00	5.34	1.80	1030	8.75	425.0	9.67	0.62
	4–5 cm	36.5	35.6	2.80	0.00	4.46	3.20	1060	70.6	360.0	2.15	0.58
	5–6 cm	60.8	51.8	0.00	0.00	8.44	4.80	1080	88.4	465.0	8.95	0.58
	7–8 cm	270.6	332	2.20	2.90	18.9	26.4	1970	6878	490.0	37.6	0.87
	10–11 cm	483.6	522	0.00	3.20	34.5	47.4	3170	1230	615.0	34.0	0.66
	13–14 cm	3.14	2.00	2.40	0.00	4.44	NR	1530	NR	285.0	1.24	NR
Index Period 2 – Spring 4/3/2008	Bottom water	42.4	6.45	3.60	0.00	0.31	0.90	1060	0	424.8	0.78	0.93
	0–1 cm	83.3	24.6	32.20	0.00	1.51	NR	733	5.94	723.0	44.8	0.84
	1–2 cm	90.6	48.2	5.80	0.00	1.17	1.20	731	6.87	600.3	35.8	0.82
	2–3 cm	155	65.2	10.80	0.00	2.13	3.00	817	193	562.3	91.3	1.73
	3–4 cm	234	131	29.00	0.00	11.2	10.0	1000	568	1418	43.0	0.84
	4–5 cm	229	177	21.40	0.00	14.6	14.8	1050	400	463.0	10.9	0.82
	5–6 cm	262	222	7.40	0.00	25.4	20.6	1130	343	580.8	12.4	0.71
	7–8 cm	364	290	11.30	0.00	21.3	20.7	1320	434	513.7	80.6	1.00
	10–11 cm	546	442	32.40	0.00	27.7	26.4	1820	562	721.5	48.4	0.51
	13–14 cm	781	594	15.80	0.00	36.9	33.0	2300	534	654.1	98.5	1.04
Index Period 3 – Summer 7/23/2008	Bottom water	27.4	1.60	1.20	0.00	1.04	0.65	524	0.313	462.9	0.82	0.46
	0–1 cm	32.2	4.60	17.00	0.00	1.64	1.8	1100	311	440.0	34.0	1.44
	1–2 cm	127	79.4	22.00	0.00	2.79	1.8	5620	1780	405.0	28.7	0.85
	2–3 cm	314	382.0	27.80	0.00	18.6	10.2	877	220	425.0	14.7	0.78
	3–4 cm	833	788.0	10.40	5.40	53.5	48.6	5750	1890	547.5	25.1	0.93
	4–5 cm	1200	1180	25.80	5.00	75.3	63.2	1240	422	580.0	19.7	1.31
	5–6 cm	1330	1310	22.00	0.00	80.8	70.0	2750	631	595.0	10.6	1.67
	7–8 cm	1540	1490	15.80	0.00	92.7	84.2	3880	2500	687.5	25.1	0.51
	10–11 cm	1680	1680	15.60	0.00	84.7	75.0	4780	2570	830.0	19.7	0.18
	13–14 cm	1610	2000	8.40	0.00	78.5	74.8	5440	2050	690.0	85.9	0.95
Index Period 4 – Fall 9/30/2008	Bottom water	26.3	1.50	0.00	0.00	0.00	0.00	536	0	229.6	1.23	0.53
	0–1 cm	60.6	12.8	4.00	0.00	0.00	0.00	1120	7.81	177.5	89.5	1.66
	1–2 cm	36.1	3.40	2.60	0.00	0.00	0.00	897	69.7	105.0	35.8	0.91
	2–3 cm	103	70.8	3.20	0.00	3.20	6.00	1270	609	127.5	69.8	1.22
	3–4 cm	276	199	2.20	0.00	15.5	18.8	2810	1110	107.0	91.3	1.33
	4–5 cm	515	494	2.60	0.00	35.0	36.8	3970	2780	147.5	68.0	0.93
	5–6 cm	700	754	0.00	0.00	45.8	50.2	4890	3910	167.5	39.4	0.60
	7–8 cm	736	812	0.00	0.00	33.0	40.4	5570	2410	172.5	50.1	0.67
	10–11 cm	550	872	0.00	0.00	26.4	39.0	5750	3180	206.7	75.2	0.86
	13–14 cm	852	810	0.00	0.00	36.4	42.6	5880	3080	215.0	91.3	0.78

WATER COLUMN TRANSECT DATA

Table A2.5. Transect data for each index period during ebb tide (constituents are in mmol/L, except for chlorophyll a, which is in µg/l).

Index Period	Site #	TN	TDN	NH_4	NO_3 + NO_2	NO_2	TP	TDP	SRP	TSS	Chl a
Index Period 1 Winter	1	24.08	15.26	7.40	1.50	0.30	1.54	0.74	0.80	6.70	6.70
	2	25.67	23.70	7.20	0.90	0.50	1.34	1.09	0.80	7.10	2.70
	3	68.68	16.54	6.40	1.10	0.50	1.21	0.90	0.90	6.70	5.30
	4	30.34	37.72	9.70	2.60	0.50	1.77	1.12	1.00	7.30	4.50
	5	23.70	33.79	7.00	2.20	0.40	1.46	0.69	0.70	7.30	9.80
	6	32.47	27.58	6.90	1.10	0.50	1.27	0.47	0.70	11.70	6.20
	7	33.56	28.06	11.81	1.60	0.30	1.10	1.12	1.10	11.30	4.50
	8	31.78	28.86	7.40	1.40	0.50	1.26	0.88	0.70	7.00	3.90
	9	32.04	29.76	8.00	1.70	0.60	1.52	0.72	0.80	6.70	6.00
	10	23.81	13.67	8.00	2.60	0.40	0.85	0.51	0.80	12.30	6.20
	11	21.47	28.01	8.20	2.60	0.40	0.81	0.97	0.80	18.30	8.90
	12	27.42	28.86	8.50	2.10	0.50	0.81	0.95	0.80	6.70	4.50
	13	26.94	27.90	5.60	1.00	0.70	0.95	0.73	0.60	6.30	7.10
	14	24.23	34.73	7.40	1.45	0.50	1.33	0.91	0.75	8.15	6.20
	15	46.99	28.09	7.50	2.00	0.50	1.24	1.03	0.80	10.65	5.30
Index Period 2 Spring	1	42.22	22.12	3.80	1.20	0.00	1.59	0.79	0.30	9.70	5.30
	2	51.23	29.92	4.80	0.00	0.00	0.66	0.91	0.30	8.30	5.30
	3	26.86	21.49	6.20	1.80	0.00	1.25	0.70	0.50	9.25	6.90
	4	35.64	24.20	4.40	1.00	0.00	0.99	0.61	0.50	6.00	6.60
	5	39.22	22.18	6.60	2.00	0.00	1.64	0.52	0.50	12.00	4.50
	6	18.37	19.58	2.90	0.00	0.00	0.55	0.38	0.30	8.70	5.30
	7	43.78	15.65	4.60	1.60	0.00	1.39	0.36	0.40	7.30	4.00
	8	21.66	24.14	3.30	1.80	0.00	0.51	0.42	0.40	24.20	6.90
	9	30.15	20.79	3.00	1.10	0.00	1.02	1.89	0.30	7.40	4.90
	10	34.19	17.62	3.80	1.20	0.00	1.29	0.66	0.70	10.40	4.90
	11	41.41	25.13	3.70	0.70	0.00	1.36	0.41	0.60	4.40	3.10
	12	25.24	11.21	3.91	1.28	0.00	1.03	0.47	0.55	4.40	4.00
	13	19.81	43.26	2.90	0.63	0.00	0.70	1.07	0.56	4.70	5.30
	14	21.34	25.10	3.13	0.91	0.00	0.77	0.61	0.43	4.70	4.10
	15	20.88	16.84	3.72	1.16	0.00	1.19	0.57	0.56	8.20	4.90
Index Period 3 Summer	1	84.98	28.43	1.00	0.90	0.10	3.83	0.33	0.10	-0.50	63.80
	2	83.16	43.62	0.20	0.00	0.00	3.84	0.51	0.00	23.70	61.40
	3	33.60	22.76	0.30	0.00	0.00	1.52	0.47	0.00	14.30	27.60
	4	48.10	29.96	0.40	0.00	0.00	2.70	0.22	0.00	21.70	51.40
	5	36.47	41.85	0.20	0.80	0.00	1.65	0.55	0.00	28.70	51.90
	6	52.90	26.40	0.40	1.00	0.10	2.13	0.25	0.00	21.00	51.80
	7	79.45	38.29	0.50	0.00	0.00	4.25	0.44	0.00	10.30	32.60
	8	56.85	30.12	0.80	0.80	0.10	2.92	0.31	0.00	47.30	50.60
	9	70.40	34.31	0.50	0.00	0.00	4.01	0.32	0.10	25.70	61.00
	10	43.49	19.49	0.60	0.80	0.00	2.44	0.34	0.10	25.00	37.40
	11	33.36	25.03	3.15	1.15	0.20	1.82	0.97	0.65	14.00	4.30

Table A2.5. Continued

Index Period	Site #	TN	TDN	NH_4	NO_3 + NO_2	NO_2	TP	TDP	SRP	TSS	Chl a
Index Period 3 Summer	12	32.83	23.89	2.40	0.80	0.00	1.94	1.13	0.80	20.00	2.20
	13	30.75	22.26	1.50	0.00	0.10	1.81	1.04	0.70	13.00	1.80
	14	29.76	35.10	2.30	0.00	0.05	1.77	1.20	0.95	17.15	3.45
	15	30.26	24.82	2.30	0.90	0.15	1.88	1.34	0.90	13.00	3.15
Index Period 4 Fall	1	65.56	18.84	--	0.25	0.04	4.24	0.28		8.70	46.30
	2	19.76	25.40	0.70	0.25	0.04	1.11	0.00	0.10	12.30	24.00
	3	38.47	10.90	0.20	0.25	0.04	1.50	0.00	0.05	7.70	17.60
	4	35.33	17.34	0.04	0.25	0.04	1.11	0.01	0.05	28.70	27.80
	5	33.21	14.92	0.30	0.25	0.04	1.06	0.00	0.05	16.00	25.60
	6	32.21	17.34	0.04	0.25	0.04	1.75	0.00	0.05	11.00	67.60
	7	28.19	14.60	0.20	0.25	0.04	1.37	0.00	0.05	10.00	23.00
	8	62.64	12.91	0.60	0.50	0.04	0.69	0.00	0.10	11.40	25.60
	9	21.39	6.73	0.10	0.25	0.04	1.15	0.00	0.05	11.50	17.10
	10	14.74	17.58	2.60	1.10	0.10	0.09	0.00	0.40	11.80	25.60
	11	53.66	9.98	1.20	0.25	0.04	0.76	0.00	0.40	6.00	2.20
	12	7.38	6.52	1.10	0.50	0.04	0.00	0.00	0.30	7.50	2.70
	13	1.12	3.08	0.80	0.25	0.04	0.00	0.00	0.40	5.50	2.20
	14	17.76	24.80	1.60	0.50	0.07	0.00	0.00	0.50	16.50	8.50
	15	16.24	33.31	1.70	0.50	0.07	0.00	0.00	0.80	19.00	5.50

Table A2.6. Transect data for each index period during flood tide.

Index Period	site #	TN	TDN	NH_4	NO_3 + NO_2	NO_2	TP	TDP	SRP	TSS	Chl *a*
Index Period 1 Winter	1	16.94	19.38	5.90	1.10	0.50	0.62	0.62	0.60	17.30	5.30
	2	26.45	25.30	6.60	1.50	0.50	1.28	0.90	0.60	13.70	9.30
	3	83.72	22.17	4.50	0.80	0.40	1.49	0.59	0.70	7.00	2.70
	4	31.88	22.91	6.20	0.70	0.40	1.29	0.97	0.70	11.30	8.00
	5	26.07	25.62	6.10	1.10	0.60	1.23	0.95	0.50	10.00	5.30
	6	84.98	24.98	5.70	0.70	0.50	1.29	0.88	0.50	13.00	8.00
	7	21.65	15.92	6.50	1.70	0.50	1.00	0.74	0.60	15.70	5.30
	8	32.28	26.56	3.50	0.50	0.50	1.02	0.76	0.50	12.70	5.00
	9	26.64	19.43	6.00	0.00	0.30	1.31	0.66	0.70	5.70	4.80
	10	25.33	25.96	7.20	0.50	0.40	1.44	0.69	0.60	18.70	5.30
	11	29.98	33.56	9.90	1.80	0.30	1.28	0.72	0.90	8.00	6.20
	12	39.63	27.83	7.10	1.00	0.60	1.28	0.90	0.60	17.00	16.00
	13	34.09	23.16	8.70	1.50	0.40	1.55	0.91	0.90	13.70	7.10
	14	22.64	76.11	7.95	2.25	0.55	0.92	1.57	0.80	7.80	7.50
	15	26.08	40.70	6.40	1.30	0.70	1.02	1.20	0.65	8.70	7.10
Index Period 2 Spring	1	46.78	20.97	4.20	1.40	0.00	1.35	0.83	0.50	10.30	4.30
	2	34.89	25.24	4.30	0.00	0.00	1.13	0.44	0.40	16.70	6.90
	3	51.06	28.82	4.50	0.00	0.00	1.49	0.50	0.40	8.00	4.90
	4	28.24	22.82	3.90	0.80	0.00	1.25	0.62	0.50	8.00	4.90
	5	23.05	43.89	3.10	0.00	0.00	1.08	1.03	0.30	6.70	4.50
	6	36.33	42.57	4.20	0.60	0.00	1.32	0.47	0.30	10.00	2.70

Table A2.6. Continued

Index Period	site #	TN	TDN	NH_4	NO_3 + NO_2	NO_2	TP	TDP	SRP	TSS	Chl *a*
Index Period 2 Spring	7	30.32	23.74	3.70	0.00	0.00	1.03	0.34	0.30	12.00	4.70
	8	40.14	39.91	6.60	1.50	0.10	1.46	0.98	0.70	6.70	4.00
	9	46.32	22.12	6.80	1.20	0.00	1.71	0.64	0.70	6.00	5.80
	10	37.02	27.03	4.50	0.70	0.00	1.03	0.70	0.30	7.00	5.30
	11	14.33	20.16	1.60	1.30	0.00	0.72	0.45	0.50	7.00	2.70
	12	21.89	15.37	1.71	0.00	0.00	1.08	0.56	0.42	8.00	2.20
	13	13.58	10.23	1.43	1.15	0.00	0.91	0.29	0.49	7.70	4.00
	14	13.58	9.33	1.59	0.64	0.00	0.74	0.43	0.43	12.60	2.90
	15	13.32	11.64	1.52	0.56	0.00	0.97	0.72	0.43	11.70	11.00
Index Period 3 Summer	1	71.67	29.19	0.30	0.00	0.00	3.46	0.39	0.00	10.50	55.50
	2	49.76	30.43	0.60	0.00	0.00	2.77	0.26	0.10	13.70	46.60
	3	26.71	21.89	0.60	0.00	0.00	1.51	0.18	0.10	6.70	22.30
	4	31.96	19.99	0.50	0.70	0.00	1.74	0.45	0.10	11.00	35.60
	5	37.24	13.95	0.40	0.90	0.00	1.89	0.25	0.00	8.70	25.60
	6	59.07	31.41	0.50	0.00	0.00	3.23	0.40	0.10	8.00	24.40
	7	52.87	26.05	0.40	0.80	0.00	3.19	0.48	0.00	7.70	11.10
	8	75.41	42.96	0.30	0.00	0.00	4.40	0.42	0.00	9.30	61.40
	9	52.64	32.44	0.40	0.00	0.00	3.29	0.41	0.10	22.00	32.80
	10	29.35	31.88	0.20	0.00	0.00	1.73	0.30	0.20	17.00	22.30
	11	32.99	28.32	1.95	0.50	0.20	2.31	1.21	0.80	8.70	5.80
	12	25.55	24.16	1.90	0.60	0.10	1.59	1.24	1.00	7.00	3.60
	13	20.10	22.68	1.40	0.50	0.00	1.23	0.97	0.90	7.70	2.20
	14	25.25	19.30	1.80	0.95	0.00	1.60	1.20	0.85	20.00	2.55
	15	22.61	33.67	2.05	0.00	0.00	1.52	1.46	0.95	9.85	1.80
Index Period 4 Fall	1	25.48	45.72	1.10	0.25	0.04	0.35	2.05	0.40	62.30	122.8
	2	18.74	18.98	0.10	0.25	0.04	0.68	0.45	0.50	19.30	12.80
	3	42.98	33.85	1.10	0.60	0.10	0.90	0.02	0.20	54.00	67.60
	4	20.62	24.59	0.40	0.25	0.04	1.56	0.00	0.05	17.00	25.80
	5	47.81	25.85	1.10	0.25	0.04	0.70	0.00	0.20	26.70	30.70
	6	19.33	34.74	0.90	0.25	0.04	2.06	0.47	0.20	15.70	48.10
	7	21.47	17.50	0.70	0.25	0.04	1.42	0.00	0.30	11.00	20.80
	8	24.00	20.00	0.20	0.25	0.04	0.25	0.08	0.10	16.70	21.40
	9	--	24.70	0.20	0.25	0.04	0.88	0.00	0.20	10.30	12.80
	10	45.08	43.25	0.50	0.25	0.04	0.54	--	0.10	12.70	21.90
	11	--	6.33	0.50	0.25	0.04	0.00	0.00	0.20	8.30	2.70
	12	10.60	6.76	1.00	0.25	0.04	--	0.00	0.30	12.00	6.10
	13	3.37	7.06	0.60	0.25	0.04	0.00	0.00	0.20	6.00	2.20
	14	19.00	32.07	1.90	0.50	0.07	0.00	0.01	0.50	15.00	4.90
	15	27.09	17.25	2.90	1.45	0.14	0.00	0.00	0.60	10.30	4.30

PRIMARY PRODUCER BIOMASS AND/OR PERCENT COVER

Table A2.7. Mean suspended chlorophyll *a* and benthic chlorophyll *a* concentrations during each index period.

Index Period	Mean Suspended Chlorophyll a (mg m^{-3})	Benthic Chlorophyll a (mg m^{-2})
Index Period 1 Winter	5.42	8.48
Index Period 2 Spring	5.57	77.1
Index Period 3 Summer	4.04	6.08
Index Period 4 Fall	11.08	8.30

Table A2.8. Macroalgae total percent cover and biomass by species during each index period.

Index Period	Total Percent Cover	*Ulva intestinalis* Mean Biomass (g m^{-2})	*Ulva expansa* Mean Biomass (g m^{-2})	Cyanobacteria Mean Biomass (g m^{-2})
Index Period 1 Winter	0.0	0.0	0.0	0.0
Index Period 2 Spring	9.5 ± 2.4	14.7 ± 7.1	0.0	0.0
Index Period 3 Summer	90.6 ± 3.6	1169.4 ± 331.7	0.0	0.0
Index Period 4 Fall	42.2 ± 10.6	2.5 ± 2.0	29.8 ± 11.1	80.8 ± 71.0

RATES OF EXCHANGE BETWEEN SURFACE WATERS AND SEDIMENTS – BENTHIC FLUX

Table A2.9. Benthic Fluxes for all index periods in Loma Alta Slough.

Index Period	Light/ Dark	Benthic Flux (mmol m^{-2} d^{-1})												
		DO	TCO_2	TDN	DON	DOP	TDP	DOC	NH_4	NO_3	DIN	SRP	Fe	Mn
Index Period 1 Winter	dark	-45.45	82.35	-10.55	-9.94	0	-0.61	101.1	-0.62	0.44	-0.18	-0.44	-0.32	-0.77
	dark	NR	20.22	-9.25	-14.33	0	-0.76	-242.4	4.24	-0.02	4.22	-0.44	1.48	0.00
	dark avg	-45.45	51.29	-9.90	-12.13	0	-0.69	-70.65	1.81	0.21	2.02	-0.44	0.58	-0.39
	dark stdev	--	43.93	0.92	3.11	0	0.11	242.9	3.44	0.33	3.11	0.00	1.27	0.54
	light	-108.6	18.07	66.55	61.54	0	-0.31	52.57	4.56	0.66	5.22	0.00	-1.93	-1.57
	light	NR	57.00	-44.62	-31.09	0	-0.52	-121.6	-3.46	-0.44	-3.89	-0.44	-0.04	-0.80
	light avg	-108.6	37.54	10.97	15.23	0	-0.42	-34.52	0.55	0.11	0.67	-0.22	-0.99	-1.19
	light stdev	--	27.53	78.61	65.50	0	0.15	123.2	5.67	0.78	6.44	0.31	1.34	0.54

Table A2.9. Continued

Index Period	Light/ Dark	Benthic Flux (mmol m^{-2} d^{-1})												
		DO	TCO$_2$	TDN	DON	DOP	TDP	DOC	NH$_4$	NO$_3$	DIN	SRP	Fe	Mn
Index Period 2 Spring	dark	-19.56	182.3	-24.51	-24.08	-0.83	-1.49	372.4	0.00	-0.44	-0.44	-0.45	-0.70	-0.08
	dark	-12.16	207.1	66.19	67.89	-3.14	-3.57	439.5	-0.85	-0.85	-1.70	0.00	-0.61	0.15
	dark avg	-15.86	194.7	20.84	21.90	-1.99	-2.53	405.9	-0.43	-0.65	-1.07	-0.23	-0.66	0.04
	dark stdev	5.23	17.54	64.13	65.03	1.63	1.47	47.45	0.60	0.29	0.89	0.32	0.06	0.16
	light	11.24	90.46	-114.3	-114.32	-0.67	-0.96	318.5	-0.42	0.46	0.04	0.00	0.86	-0.57
	light	-35.23	215.4	16.64	16.64	4.40	4.40	-659.3	0.00	0.00	0.00	0.00	2.89	0.15
	light avg	-12.00	152.9	-48.83	-48.84	1.87	1.72	-170.4	-0.21	0.23	0.02	0.00	1.88	-0.21
	light stdev	32.86	88.35	92.59	92.61	3.59	3.79	691.4	0.30	0.33	0.03	0.00	1.44	0.51
Index Period 3 Summer	dark	NR	184.1	3.02	-3.89	0.38	0.38	53.06	6.82	-0.53	6.29	0.00	0.75	-0.09
	dark	-49.39	137.9	-2.27	-4.30	-0.44	-0.44	-221.0	2.04	-0.32	1.72	0.00	-1.64	-0.23
	dark avg	-49.39	161.0	0.38	-4.10	-0.03	-0.03	-83.97	4.43	-0.43	4.01	0.00	-0.45	-0.16
	dark stdev	--	32.67	3.74	0.29	0.58	0.58	193.8	3.38	0.15	3.23	0.00	1.69	0.10
	light	-124.1	172.3	8.29	2.97	0.73	1.04	-45.00	3.96	1.06	5.02	0.32	-1.11	-0.20
	light	-129.3	102.9	16.21	16.65	0.97	0.86	42.99	-0.86	0.41	-0.44	-0.11	0.24	-0.12
	light avg	-126.7	137.6	12.25	9.81	0.85	0.95	-1.01	1.55	0.74	2.29	0.11	-0.44	-0.16
	light stdev	3.68	49.07	5.60	9.67	0.17	0.13	62.22	3.41	0.46	3.86	0.30	0.95	0.06
Index Period 4 Fall	dark	-57.12	5.71	11.78	12.61	-0.42	-0.75	--	-0.65	-0.18	-0.83	-0.33	0.62	0.03
	dark	-68.13	60.10	-40.29	-40.77	-1.38	-1.84	-188.7	1.27	-0.79	0.49	-0.33	-0.40	0.09
	dark avg	-62.63	32.91	-14.26	-14.08	-0.90	-1.30	-188.7	0.31	-0.49	-0.17	-0.33	0.11	0.06
	dark stdev	7.79	38.46	36.82	37.75	0.68	0.77	--	1.36	0.43	0.93	0.00	0.72	0.04
	light	-57.52	13.84	28.64	31.49	0.08	0.41	-339.7	-0.70	-2.15	-2.85	-0.33	0.85	0.09
	light	-56.40	119.9	48.43	48.39	-0.60	-0.91	-709.9	0.29	-0.25	0.04	-0.11	-0.53	0.08
	light avg	-56.96	66.87	38.54	39.94	-0.26	-0.25	-524.8	-0.21	-1.20	-1.41	-0.22	0.16	0.09
	light stdev	0.79	75.00	13.99	11.95	0.48	0.93	261.8	0.70	1.34	2.04	0.16	0.98	0.01

Table A2.10. Predicted Diffusive Fluxes by index period for each constituent of interest.

Index Period	Predicted Diffusive Fluxes (mmol m^{-2} d^{-1})					
	NH4	NO3	DON	SRP	DOP	DOC
Winter	0.45	0.41	-2.97E-02	8.38E-03	2.34E-02	-1.87E+00
Spring	0.36	0.52	-6.39E-02	2.32E-03	7.31E-03	2.28E-01
Summer	1.70	0.33	-1.80E-01	1.23E-02	-5.10E-03	-5.69E+00
Fall	0.28	0.08	1.28E-01	-2.03E-03	-3.41E-03	-6.02E+00

Table A2.11. Summary of linear regression relationship between predicted diffusive fluxes and in situ chamber flux data.

Constituent	In Situ Flux Data Used For Regression	Regression Equation	R^2 and Pr>F
NH4	Dark Chambers	$NH4_{IS} = 2.51*NH4_{DF}$	**R^2 = 0.86, Pr>F : 0.01**
	Light Chambers	$NH4_{IS} = 0.83*NH4_{DF}$	**R^2 = 0.76 Pr>F : 0.03**
	All	$NH4_{IS} = 1.66*NH4_{DF}$	**R^2 = 0.84, Pr>F : 0.02**
NO3	Dark Chambers	$NO3_{IS} = -0.68 + 1.63*NO3_{DF}$	R^2 = 0.08, Pr>F : 0.47
	Light Chambers	$NO3_{IS} = -1.42 + 3.38*NO3_{DF}$	**R^2 = 0.94, Pr>F : 0.10**
	All	$NO3_{IS} = -1.05 + 3.234*NO3_{DF}$	**R^2 = 0.90, Pr>F : 0.14**
DON	Dark Chambers	$DON_{IS} = -3.909 - 49.72*DON_{DF}$	R^2 = 0.14, Pr>F : 0.61
	Light Chambers	$DON_{IS} = 24.3 + 98.26*DON_{DF}$	R^2 = 0.78, Pr>F : 0.22
	All	$DON_{IS} = 6.67 + 33.01*DON_{DF}$	R^2 = 0.33, Pr>F : 0.39
SRP	Dark Chambers	$SRP_{IS} = - 0.28 + 22.90*SRP_{DF}$	**R^2 = 0.99, Pr>F : 0.01**
	Light Chambers	$SRP_{IS} = -0.12 + 20.52 * SRP_{DF}$	**R^2 = 0.66, Pr>F : 0.28**
	All	$SRP_{IS} = -0.20 + 21.71* SRP_{DF}$	**R^2 = 0.95, Pr>F : 0.13**
DOP	Dark Chambers	$DOP_{IS} = -1.35 + 31.04*DOP_{DF}$	R^2 = 0.22, Pr>F : 0.68
	Light Chambers	$DOP_{IS} = 0.87 + 123.2*DOP_{DF}$	R^2 = 0.21, Pr>F : 0.42
	All	$DOP_{IS} = -0.39 + 11.60*DOP_{DF}$	R^2 = 0.34, Pr>F : 0.60
DOC	Dark Chambers	$DOC_{IS} = 263.4 + 74.23*DOC_{DF}$	R^2 = 0.58, Pr>F : 0.15
	Light Chambers	$DOC_{IS} = -91.839 + 27.22*DOC_{DF}$	R^2 = 0.11, Pr>F : 0.65
	All	$DOC_{IS} = 89.9 + 56.20*DOC_{DF}$	R^2 = 0.36, Pr>F : 0.26

DATA ON ADDITIONAL FACTORS CONTROLLING BENTHIC FLUX

Table A2.12. Number of benthic infauna in each chamber and slough average.

Index Period	Chamber	Polychaetes (individuals/ m^2)	Capitellids (individuals/ m^2)	Oligochaetes (individuals/ m^2)	Mollusks (individuals/ m^2)	Crustaceans (individuals/ m^2)	Other (individuals/ m^2)	Total Polychaetes (individuals/ m^2)	Total Infauna (individuals/ m^2)
Index Period 1 Winter	Chamber 1 (light)	1000	2500	1000	0	0	500	3600	5100
	Chamber 2 (dark)	0	3100	0	1500	0	1500	3000	6100
	Chamber 3 (light)	0	4600	0	0	0	0	4600	4600
	Chamber 4 (dark)	2500	4600	1000	0	0	0	7100	8100
	Average	**900**	**3700**	**500**	**400**	**0**	**500**	**4600**	**6000**
	Standard Deviation	**1200**	**1100**	**600**	**800**	**0**	**700**	**1800**	**1600**

Table A2.12. Continued

Index Period	Chamber	Polychaetes (individuals/ m^2)	Capitellids (individuals/ m^2)	Oligochaetes (individuals/ m^2)	Mollusks (individuals/ m^2)	Crustaceans (individuals/ m^2)	Other (individuals/ m^2)	Total Polychaetes (individuals/ m^2)	Total Infauna (individuals/ m^2)
Index Period 2 Spring	Chamber 1 (light)	0	12,700	500	0	0	0	13,000	13,000
	Chamber 2 (dark)	500	24,000	1000	0	0	1500	25,000	28,000
	Chamber 3 (light)	--	--	--	--	--	--	--	--
	Chamber 4 (dark)	0	12,000	0	0	0	500	12,000	12,000
	Average	**200**	**16,000**	**500**	**0**	**0**	**700**	**16,000**	**18,000**
	Standard Deviation	**300**	**7100**	**500**	**0**	**0**	**800**	**7400**	**8500**
Index Period 3 Summer	Chamber 1 (light)	3100	6600	4600	2000	500	0	9700	17,000
	Chamber 2 (dark)	7100	11,000	3100	0	0	0	18,000	21,000
	Chamber 3 (light)	0	3600	0	14,000	500	0	3600	18,000
	Chamber 4 (dark)	1000	7100	1500	0	0	0	8100	9700
	Average	**2800**	**7100**	**2300**	**4100**	**300**	**0**	**9900**	**17,000**
	Standard Deviation	**3200**	**3100**	**2000**	**6900**	**300**	**0**	**6200**	**5000**
Index Period 4 Fall	Chamber 1 (light)	0	0	500	2000	0	0	0	2500
	Chamber 2 (dark)	0	1000	2000	0	0	0	1000	3100
	Chamber 3 (light)	0	500	0	4600	0	0	500	5100
	Chamber 4 (dark)	0	500	2000	7600	0	0	500	10,000
	Average	**0**	**500**	**1100**	**3600**	**0**	**0**	**500**	**5200**
	Standard Deviation	**0**	**400**	**1100**	**3300**	**0**	**0**	**400**	**3500**