# Sources, sinks, and fluxes of nutrients (N + P)in a small highly modified urban estuary in southern California

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**Abstract.** Our objective was to begin to investigate sources, sinks, and flux rates of nitrogen (N) and phosphorus (P) in Famosa Slough, a small (12 ha) highly modified urban estuary in San Diego, California, U.S.A. The hydrology of Famosa Slough has been modified by culverts that dampen tidal influence and seasonal runoff from two urban watersheds, each of which has been implicated as a nutrient source that generates nuisance algal blooms. In 1995 and 1996, the ranges of nutrients measured in the water column were extremely wide; upper values exceeded those in other estuaries identified as eutrophic. Average dissolved inorganic nitrogen ranged from 2 to 250  $\mu$ M, while dissolved inorganic phosphorus ranged from <1 to 15  $\mu$ M. Nutrient content of the water changed rapidly both spatially and temporally depending on the tides and rainfall. While tidal water dominated this system, especially in the dry season, our results indicate that Famosa Slough's small watershed, not the larger watershed of the San Diego River, was the major source of nutrients during rainfall. Sediment nutrients were also high (~3 mg N g dry wt<sup>-1</sup> 1 and 0.6 mg P g dry wt<sup>-1</sup>). Short-term flux studies suggest that the large accumulations of opportunistic green macroalgae commonly found in this estuary, and possibly the sediments, may act as a large and rapid sink for nutrients during times of high nutrient supply. We suggest that small, shallow estuaries in urban settings may have more complex and rapid nutrient dynamics than those found in larger systems.

Keywords: nitrogen, phosphorus, macroalgae, estuary, anthropogenic

#### Introduction

Nutrient processes in estuaries have been extensively studied in many parts of the world, including the East and Gulf Coasts of the U.S. (e.g., Boynton *et al.*, 1980, 1995; Day *et al.*, 1989; Nixon *et al.*, 1995; Staver *et al.*, 1996; Pinckney *et al.*, 1998), Australia (McComb *et al.*, 1981; Cambridge and McComb, 1984; McComb and Davis, 1993; Eyre, 1993; Eyre and Twigg, 1997), Europe (Sfriso, 1995; Sfriso *et al.*, 1993, 1995; Castel *et al.*, 1996; Flindt *et al.*, 1997; Sfriso and Marcomini, 1997; Rigollet *et al.*, 1998), and South Africa (for a review see Day, 1981; Watt, 1998). Nutrient cycling is complex and often poorly understood, even where many studies have been done; this may be especially true in highly modified systems in urban settings. One long-term, multidisciplinary study of an East Coast

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(U.S.) estuary found that nutrient cycling was very dynamic, depending on nutrient loading rates, water residence time, presence of a fringing marsh, and composition of the biotic community (Valiela *et al.*, 1997).

Nutrient processes in estuaries and lagoons of southern California have received little attention (Williams and Zedler, 1992), and three studies (Winfield, 1980; Page *et al.*, 1995; Fong *et al.*, 1998) gave conflicting results. At the ecosystem scale, Winfield (1980) found that Tijuana Estuary was a net sink of N, importing N from the ocean on inflowing tides. In contrast, Page *et al.* (1995) found that Carpinteria Marsh exported N, acting as a conduit of N from the watershed to the ocean. In Carpinteria Marsh, net export of N, as  $NH_4^+$ , occurred even in the dry season when loading from the watershed was minimal. Thus some of the nutrients entering the system in the rainy season were retained, recycled, and then flushed to the ocean. However, in Sweetwater Estuary, San Diego County, the salt marsh and tidal creeks retained nutrients during the dry season even when nutrient addition rates were high (Fong *et al.*, 1998). Both Carpenteria and Sweetwater Estuaries are small, while Tijuana Estuary is relatively large; hydrologists that work in these systems suggest that water flow and therefore nutrient dynamics in the small systems may be more variable than those in large, well-buffered estuaries (J. Haltiner, personal communication).

In southern California estuaries, N supply is critical to several primary producers. In the field, nuisance species of macroalgae commonly bloom following nitrogen influxes (Rudnicki, 1986; Fong, 1986; Peters *et al.*, 1985). Microcosm experiments suggest that phytoplankton and macroalgal communities are limited by the supply of nitrogen to the water column (Fong *et al.*, 1993a,b, 1994a,b). However, there is some evidence that P is also important to primary productivity. In Tijuana Estuary (southern California), N : P ratios in the water column were usually low (Fong, 1986), suggesting that N is in short supply compared to P. The exception was during spring, when N-rich runoff entered the estuary, and P or other factors became limiting. Many other studies have found that both N and P may be important in controlling primary productivity of estuaries (e.g., McComb *et al.*, 1981; Flint, 1985; D'Elia *et al.*, 1986; Lapointe, 1987; Kimmerer *et al.*, 1993); thus, recent studies have included both N and P dynamics in estuaries (Eyre, 1993; Boynton *et al.*, 1995; Nixon *et al.*, 1995).

One important source of N and P in estuaries is inflowing rivers. In many estuarine systems, N supply and availability to primary producers is largely controlled by rates of freshwater discharge from rivers (McComb *et al.*, 1981; Cambridge and McComb, 1984; McComb and Davis, 1993; Castel *et al.*, 1996; Staver *et al.*, 1996; Mackas and Harrison, 1997); these rates may vary seasonally and from year to year. In southern California, river flow is extremely seasonal because it is tightly coupled to winter rainfall events (Zedler, 1982). Thus allochthonous nutrients enter coastal bays and estuaries as distinct pulses associated with individual storms within the rainy season (Rudnicki, 1986; Fong, 1986; Peters *et al.*, 1985; Page *et al.*, 1995).

Estuarine sediments may play an important role in the cycling of N and P by acting as either sources or sinks for primary producers. Some measures of sediment/water fluxes of nutrients show that estuarine sediments are a source of  $NH_4^+$  (Rizzo and Christian, 1996; Trimmer *et al.*, 1998) and a sink of  $NO_3^-$  (Trimmer *et al.*, 1998). Others found that, although hourly  $NO_3^-$  fluxes are large, they are extremely variable, resulting in no net flux over a

year (Rizzo and Christian, 1996). There may also be a seasonal component to nutrient flux. Boderie *et al.* (1993) found that sediments release  $NO_3^-$  in winter and take it up in summer. Fluxes of  $PO_4^{3-}$  are measured less often; Rizzo and Christian (1996) found that the sediments generally release  $PO_4^{3-}$ .

In estuaries subject to large accumulations of macroalgal biomass, this biomass may play an important role in the nitrogen cycle by sequestering large pools of nutrients. Many shallow estuaries have developed massive blooms of macroalgae in response to increased nutrient loading (Waite and Mitchell, 1972; Peters *et al.*, 1985; Rudnicki, 1986; Lapointe and O'Connell, 1989; Sfriso *et al.*, 1993; Peckol *et al.*, 1994; Valiela *et al.*, 1997). Peckol *et al.* (1994) found that two bloom species of macroalgae in Waquoit Bay (MA) removed substantial amounts of N from the water column, reducing water column concentrations to very low levels in the summer.

We explored N and P dynamics in Famosa Slough, a small, highly modified estuary in San Diego, CA, U.S.A. (figure 1), for which algal blooms are a common nuisance. Suggestions for controlling algal blooms differed, as some considered the nutrient source to be the large San Diego River watershed, which provides freshwater that is pushed into the estuary along with tidal water, while others attributed the problem to the local, but much smaller, watershed (J. Haltiner). Our objective was to investigate the relative importance of these sources of nutrients. We also hypothesized that storage in the sediments or macroalgae was an important mechanism of retaining nutrients within the slough. To accomplish these objectives, we measured water column nutrients in sites from the head of the estuary to the mouth. Samples were taken under three tidal conditions (inflowing, slack high, and outflowing), and under the same tidal conditions during a rain event. We used estimates of water inflow from the tides, the regional watershed, and the local watershed to investigate the relative importance of these sources of nutrients. Our second approach was to measure N and P fluxes between the water column, the sediment, and macroalgae both during and after a rain event.

#### Methods

### Study site

Famosa Slough is located in San Diego County, California, U.S.A. (figure 1). It is a small (15.1 ha) remnant of a much larger estuarine system originally called False Bay (Pacific Southwest Biological Services, 1993). In the 1950s, False Bay underwent extensive dredging and was renamed Mission Bay (figure 1, upper right panel). At the same time, the San Diego River was channelized and diverted from Mission Bay to empty directly into the Pacific Ocean. Famosa Slough is the only portion of the expansive False Bay Estuary that remains connected to the San Diego River Flood Control Channel (SDR). Famosa Slough consists of a long (460 m) and narrow (12 m) channel bounded by a fringe of vegetated marsh plain (80–150 m) that connects to the SDR. The creek opens into a broader, triangular lagoon of relatively uniform depth (-30 to +30 cm National Geodetic Vertical Datum), with a gentle slope from north to south. This slopes away from the channel and prevents the slough from ever draining completely. The lagoon region is about 450 m north to south



*Figure 1.* Map of Famosa Slough with sampling stations identified. Stations are (1) mouth of Famosa Slough; (2) transition between lagoon and channel; (3) mid lagoon; (4) upper lagoon; (5) east drainage ditch; (6) west drainage ditch.

and 170 m east to west. Much of the slough is unvegetated, due to poor drainage; the tidal culverts are higher than the minimum low tide.

Famosa Slough has three hydrologic systems. The tidal circulation of seawater carried by the SDR is the primary force that created and maintains the system (Pacific Southwest Biological Services, 1993). The creek is connected to the SDR by three tide gates that are from 0.20 m to 0.27 m National Geodetic Vertical Datum (NGVD). Thus the slough never drains completely. In addition, although the tide gates are 1.52 m diameter culverts, the flap gates are propped open only 30 cm, resulting in very damped tidal flows. A 1992 study established that the maximum tidal range in the slough was 30–60 cm (Pacific Southwest Biological Services, 1993). However, this maximum is rarely reached. In general, the tidal amplitude is less than 30 cm in the lagoon.

The second hydrologic influence is runoff from the local 81 ha watershed. Winter rainfall runoff and small volumes of summer runoff drain to city streets and enter the slough, creating areas of freshwater ponds and brackish marsh around the edges of the slough. These areas are often isolated from direct contact with the slough by earthen berms. On the eastern and southern edge of the slough, freshwater is collected and conveyed through subsurface storm drains and enters the slough through culverts (figure 1). On the west side, the water is surface flow and enters the slough directly from the ends of the streets. Although freshwater influence from the watershed is year-round, a large majority of the water enters during the winter rainy season.

The final hydrologic influence is episodic freshwater flow from the SDR. This river has a watershed of about 111,400 ha that begins in the nearby Cuyamaca Mountains and includes a substantial portion of the City of San Diego. High flows in the SDR are extremely rare but have the potential to cause the highest water in the slough. The relative importance of these three potential sources of nutrients is unknown.

If the watershed of the SDR was a significant source of nutrients for Famosa Slough during the sampling times, we expected to see a gradient of nutrients from mouth to the head of the slough that changed with the tidal status. On the inflowing tide, we would predict higher concentrations at the mouth of the slough. This gradient of high to lower concentration should diminish as the slack tide approaches and become even less pronounced as the tide reversed and flowed out. Alternatively, if the major nutrient source was Famosa Slough's 81 ha watershed, then we would predict that nutrient concentration would be highest near the freshwater drainage ditches. When these are isolated from tidal influence by earthen berms, we expected no dilution and no enrichment of the lagoon stations. If ditches had subsurface connections to the slough, we would predict that high tides would influence nutrient content. Inflowing tides should push tidal water through the berm, diluting the water in the ditches; maximum dilution should occur at slack high tide. This pattern should change during rainfall, when flood waters flow over the berms and enter the slough.

## Water column nutrients

Water samples were collected on 8 December 1995 and 22 Jan 1996. December 8 preceded the rainy season, and the January sampling occurred during the first rainfall of the wet season. Samples were taken from stations on a gradient from the mouth to the head of

the slough (figure 1). One station (#1) was at the mouth of the slough just south of the tide gates to SDR. The next station (#2) was located where the main creek widens into the lagoon; we call this the transition station. We sampled the lagoon portion of the slough in two places. The first (#3) was in the mid lagoon, the other (#4) in the upper reaches near the historic head of the slough. The latter station was sampled only in December. Two earthen drainage ditches were sampled. One (#5) was on the eastern side of the slough and receives freshwater from a subsurface storm drain system. The other (#6) was on the western side and collects surface runoff. During the December sampling period, the high tide did not overtop the berms. However, in January, rainfall and runoff resulted in water flowing over the berms and entering the slough. On each sampling date, samples were taken 1 hour before high tide, at slack high tide, and 1 hour after high tide. Both were relatively high-amplitude morning tides. The predicted high tides for the Pacific Ocean were similar on both days; 8 December was 1.92 m and 22 Jan was 2.07 m NGVD.

During each sampling interval, 6 replicate samples were taken at each station. Samples were placed in a cooler and returned to the Pacific Estuarine Research Laboratory within 2 hours of the final collection. Three of the replicate samples per station were filtered with Whatman GF/C microfiber filters, while three remained unfiltered; all were frozen until the time of analysis, and analyses were completed within 30 days. Unfiltered water was analyzed for total Kjeldahl nitrogen (TKN) and total phosphorus (TP); this provided an estimate of the total amount of nutrients in both particulate (PN and PP) and dissolved (DN and DP) forms in the water column. Filtered water was analyzed (TKN, TP) to estimate the total amount of dissolved N and P. Inorganic dissolved nutrients ( $NO_3^- + NO_2^-$ ,  $NH_4^+$ ,  $PO_4^{3-}$ ) were quantified in filtered water in order to estimate the nutrients available for uptake by primary producers. Nutrient analyses were conducted on a Lachat AutoAnalyzer, model #2100-000, using Quik Chem standard methods.

Two-factor ANOVA (Super ANOVA for the Macintosh) was used to determine the effect of station and tidal condition on the concentration of water column nutrients. Data were tested for normality and homogeneity of variances. In cases where ANOVA revealed significant differences due to only one of the factors, the data were reanalyzed using a one-factor model; then a Fishers' Protected Least Significant Difference (PLSD) test was performed.

#### Estimating water inflow from tides, and the local and regional watersheds

We estimated the volume of water flowing into Famosa Slough from each of the three hydrologic systems on an annual and wet season basis. These estimates were based on two studies using hydrological modeling of flood risks and a short-term (4 day) field measure of water elevation (State Coastal Conservancy and California Department of Fish and Game, 1986; Pacific Southwest Biological Services, 1993). Influx of tidal water was calculated from measured changes in water elevation in the slough during an average tidal cycle (Pacific Southwest Biological Services, 1993) and an elevation vs. volume curve developed for the slough by the State Coastal Conservancy and California Department of Fish and Game (1986). This volume for an average day was multiplied to get wet season (3 month) and yearly volumes.

Influx of water from the local watershed was calculated from predictions of a rainfall/runoff model presented in the report by the State Coastal Conservancy and California Department of Fish and Game (1986). Volume of runoff from the watershed after rainfall was calculated based on land use. Runoff into the slough was rapid (within 30 minutes) and a large percentage of total rainfall (80–90%) due to extensive coverage by impervious surfaces in the local watershed. In our estimate, we calculated inflow based on an average year with 20 inches of rain (Zedler, 1982).

Calculation of volumes of inflow from the regional watershed were based on changes in water elevation measured with gauges during a 4 day sampling period (Pacific Southwest Biological Services, 1993) covering a set of average tides. During this period, a "moderately intense" rain event ( $\sim$ 1 inch over most of the watershed) occurred in the regional watershed. Changes in water elevation within the slough due to the elevated water in the SDR were used to calculated changes in volume and thus volume of influx from the SDR. This 1 inch rain event was then multiplied by 20 to estimate volume during an average year with 20 inches of rain. This calculation is likely to overestimate the contribution of the regional watershed because to use these data we must assume that each of the times there is high water in the SDR there is also a high tide.

# Sediment and algal nutrient pools and fluxes

The next objective was to quantify the magnitude and variance of the nutrient pools in the sediments and to measure fluxes between sediments, algae, and water. We selected the water sampling site in the upper reaches of the lagoon for the flux study (figure 1) and conducted incubations in the morning at slack high tide during a rainfall and again in the afternoon during a slack low tide after the rain had stopped. The predicted morning high tide in the ocean was +1.55 m NGVD and the afternoon low was +0.10 m NGVD in the SDR. However, the difference in water depth in the slough between slack low and high tides was only 10 cm.

Ten chambers were constructed from 5-gallon buckets and used to measure fluxes between the sediment and the water column. The bottoms of the buckets were removed and the edges sharpened to facilitate insertion into the sediment in a broad and level area of the lagoon. We used a canoe to reach the sampling site to minimize sediment disruption. To measure nutrient fluxes, buckets were gently inserted 10 cm into the sediment 1 hour before slack high and low tides on 17 April 1996. Buckets enclosed a known surface area of sediment and a known volume of lagoon water, but left the upper end open to the air. To investigate the role of the large accumulation of macroalgae on nutrient dynamics, we placed 150 g wet wt of the macroalga *Enteromorpha* spp. into five chambers, and left five without macroalgae.

The sediment and water within the buckets were left undisturbed for 30 minutes, and then the water was gently mixed and an initial water sample taken. Except for  $NH_4^+$ , initial water column nutrients were significantly higher in the A.M. (high tide) flux incubations than in the P.M. (low tide; Table 1); initial  $NO_3^-$  concentration was an order of magnitude higher in the A.M. Thus incubations were labeled as "high" vs. "low" initial water column nutrients. At the same time as nutrient samples were taken, dissolved oxygen concentration and salinity were measured. No significant differences occurred among initial samples for

#### FONG AND ZEDLER

*Table 1.* Mean initial water column nutrient concentation in the two flux measurement incubation periods. The A.M. incubation was conducted during a rain at slack high tide while the P.M. incubation was conducted after the rain ended at slack low tide. Due to the low amplitide tide and the complexity of the tide gate, low and high tide were only 10 cm different. T-tests.

	Water columnn nutrient concentration (SE		
Nutrient	A.M.	P.M.	
TKN***	67.86 (3.54)	53.21 (0.74)	
TP*	3.51 (0.50)	2.27 (0.08)	
$\rm NH_4^+$	5.86 (0.73)	7.43 (0.50)	
$NO_{3}^{-***}$	10.21 (1.06)	0.82 (0.48)	
$PO_{4}^{3-*}$	1.18 (0.14)	0.75 (0.15)	

p < 0.05. p < 0.01. p < 0.01. p < 0.001.

either incubation period. However, temperature was lower in the A.M. than in the P.M. incubation. After 1 hour, water samples and measurements were taken again. Per area nutrient fluxes were calculated based on changes in N and P concentration in a known water volume. At the end of each incubation, three sediment cores (2.5 cm diameter, 10 cm depth) were taken from randomly chosen locations within the area enclosed by each chamber. Sediments from the three cores were pooled, homogenized, dried, ground, and analyzed for N and P content.

Data were tested for normality and homogeneity of variances. Two-factor ANOVA was used to determine the effect of sampling time (A.M. high tide vs. P.M.low tide) and the presence or absence of macroalgae on the flux of water column nutrients as well as sediment nutrient content. Simple linear regression was used to relate the flux of nutrients to temperature, dissolved oxygen content, initial concentration of nutrients in the water, and sediment nutrient content.

# Results

## Comparing nutrient concentrations with and without rain

There was a significant effect of both station (p < 0.001) and tidal condition (p < 0.0001) on the concentration of particulate nitrogen (PN) plus dissolved nitrogen (DN) in the water column during both sampling periods (figures 2a and b). In the absence of rain, PN + DN in unfiltered water in the west drainage ditches was elevated compared to other stations. During rainfall, both drainage ditches had elevated concentrations of PN + DN. In addition, there was a decrease in PN + DN concentration as the tide changed from inflowing to outflowing in the west ditch without rain and in the east ditch with rain. Nitrogen concentration in the west ditch during the rainfall was lower than without rain; it is possible that N was washed out of this reservoir with the rain.



*Figure 2.* Water column concentrations of different forms of N in sampling stations of Famosa Slough (bars represent SE).

In both sampling periods (with and without rain), there was a significant effect of both station (p < 0.001) and tidal state (p < 0.05) on DN (figures 2c and d). The distribution of DN was similar to the pattern found with the PN + DN together; the west ditch had significantly higher N concentration in both sampling periods, while the east ditch was only enriched during the rains. In all but one case, the dissolved portion of the nitrogen averaged  $\sim 60\%$  of the PN + DN. The exception was the samples taken during rainfall in the east drainage ditch on the outflowing tide. During this period, 100% of the nitrogen was in the dissolved form.

During both sampling periods (figures 2e and f), there were significant differences in the ammonium concentration among stations (p < 0.001) and tidal stage (p < 0.05). Like PN and DN, there was elevated NH<sub>4</sub><sup>+</sup> concentration in the west ditch without rain, but in both

ditches with rain. In addition, each of the enriched ditches decreased in  $NH_4^+$  concentration as the tide progressed from inflowing through outflowing.

Nitrate concentrations were low and variable in the slough during the sampling period with no rain (figure 2g). There was a significant effect of both station and tidal stage (p < 0.05 for both tests) on the concentration of NO<sub>3</sub><sup>-</sup>. The effect of station can be attributed to the higher yet variable concentrations of NO<sub>3</sub><sup>-</sup> in the transition and west ditch stations during incoming tide. In both of these stations, nitrate concentrations decreased as the tide progressed from inflowing to outflowing.

Rainfall and runoff were an important source of nitrate ( $NO_3^-$ ) from the 81 ha local watershed.  $NO_3^-$  concentration in the ditches was higher than in the other stations during rainfall (figure 2h); nitrate levels exceeded 200  $\mu$ M during ebb tide in the west ditch. In addition, the concentration of  $NO_3^-$  increased in the ditch stations as the tide turned to ebb, further suggesting enrichment from the local watershed. There was also higher  $NO_3^-$  concentration in the lagoon than in the creek stations during the rain event. However, the  $NO_3^-$  concentration in the lagoon was much lower than that washing in from the ditches, suggesting dilution and removal of  $NO_3^-$  as the water passes through the broad lagoon area.

There was a significant effect of station (p < 0.001) and tidal state (p < 0.05) on the concentration of particulate phosphorus (PP) + dissolved phosphorus (DP) during both sampling times (figures 3a and b). This pattern was reflected in both the DP and PO<sub>4</sub><sup>3-</sup> concentrations (figures 3c–f), suggesting there was little particulate or organic P in the water during either sampling time. In contrast to nitrogen, the highest concentration of phosphorus was consistently found in the east ditch, followed by the west ditch. In addition, there was always less phosphorus during rainfall.

There was a significant effect of station (p = 0.0001), but not tidal condition on N : P ratio in both sampling times (figures 3g and h). During rainfall, there was a significant interaction (p = 0.0144). The N : P ratio in the east ditch was always lower than the other stations (PLSD, p < 0.05) due to the large concentration of PO<sub>4</sub><sup>3-</sup>. In contrast, the west ditch had very high N : P ratios during the rainfall due to the high NO<sub>3</sub><sup>-</sup> concentration. Although there is high variability, there is an overall pattern of higher N : P ratios during the rain, suggesting that proportionally more N than P enters this system from the local watershed during rains.

#### Estimating water inflow from tides, and the local and regional watersheds

Results of our calculations of water volumes entering the slough should only be considered estimates. There has been little work on the hydrology of Famosa Slough (State Coastal Conservancy and California Department of Fish and Game, 1986; Pacific Southwest Biological Services, 1993), and the primary objective of these studies has been to determine the risk of flooding. In addition, Southern California is subject to droughts and floods, and calculations based on average conditions are therefore only of comparative value (Zedler, 1982).

On an annual basis, tidal water is the most important source of water to the slough (Table 2). In an average year, 83.5% of the water entering the slough is tidal water. In contrast, in an average year, Famosa Slough receives about 10% of its water from the local



*Figure 3.* Water column concentrations of different forms of P and the inorganic N : P ratio in sampling stations of Famosa Slough (bars represent SE).

watershed and 6.5% from the regional watershed via the SDR. When comparing water inflow during the rainy season, tidal influence, while still important, is a lesser proportion of the total water budget. In the rainy season, the contribution from the local watershed increases to 26.8% and from the SDR to 17.5%. On both an annual and a seasonal basis the local watershed contributes more water than the SDR.

# Pools and fluxes of N and P

Flux of TKN between the water and sediment of the flux chambers varied greatly after the hour-long incubations (figure 4a). Change ranged from a loss of 3550 to a gain of 760  $\mu$ M

#### FONG AND ZEDLER

*Table 2.* Estimated volumes of water inflow to Famosa Slough from various sources. Annual as well as rainy season estimates are given.

Water source	$m^3 vr^{-1}$	$% \mathrm{vr}^{-1}$	% rainy season <sup>-1</sup>
water source	ili yi	70 yı	70 ranny season
Local watershed	378,879	10.0	26.8
Regional watershed	246,696	6.5	17.5
Tides	3,152,779	83.5	55.7



*Figure 4.* Flux of N into or out of the water during flux incubations (bars represent SE). Incubations are labeled high and low based on initial water column concentrations of nutrients presented in Table 1.

N .  $m^{-2} \cdot h^{-1}$ . With such high variability, there were no significant differences in mean flux of TKN due to either initial water column nutrient concentration or presence of algae. Though not significant, the means suggest that TKN might have fluxed out of the water column when macroalgae were present and nutrients in the water column were initially high.

Fluxes of inorganic nutrients in the flux chambers were also dynamic during the incubations. Mean fluxes of  $NH_4^+$  ranged from -250 to  $380 \ \mu M \ N \cdot m^{-2} \cdot h^{-1}$  (figure 4b). There were no differences in mean  $NH_4^+$  flux due to either presence of macroalgae or between incubations (p = 0.090). Ammonium accumulated in the water in the presence of macroalgae during the incubation when nutrients in the water were initially higher. In contrast, in this same treatment  $NO_3^-$  was lost from the water (figure 4c). There was a significant difference in flux of  $NO_3^-$  due to initial nutrient content (p = 0.016) but not the presence of algae (p = 0.084). Overall there was a net flux of inorganic N into the sediment or macroalgal tissue (figure 4d), except for the incubations where nutrients were initially low and macroalgae absent.

Fluxes of both TP and  $PO_4^{3-}$  varied greatly over the incubations (figure 5). There were no significant differences in the fluxes due to either factor.

Mean nitrogen content in the sediments enclosed by the flux chambers ranged from 2.773 to 3.360 mg N  $\cdot$  g sediment dry wt<sup>-1</sup> (figure 6) after the incubation period. Phosphorus content ranged from 0.057 to 0.064 mg P  $\cdot$  g sediment dry wt<sup>-1</sup>. Sediment N and P content did not differ significantly among the areas randomly selected for the morning and afternoon flux studies (p = 0.59 and 0.45 for N and P, respectively). These areas were within 50 m of each other in a relatively homogeneous portion of the benthos. However, both N and P content of the sediment after the incubation period were significantly lower in the presence



*Figure 5.* Changes in the concentration of different forms of P in the water during flux incubations (bars represent SE). Incubations are labeled high and low based on initial water column concentrations of nutrients presented in Table 1.



Figure 6. Mean N and P content in the sediment contained within the incubation chambers. Bars represent SE.

of macroalgae (p < 0.05 for both tests) than in its absence after the 1 hour incubation period (figure 6).

The N : P ratio in the sediment ranged from 4.3 to 5.9. These ratios are significantly lower than the ratios found in the water column under most of the sampling conditions; the exception is the water from the east drainage ditch.

# Physical chemical factors correlated with fluxes: temperature and initial water column nutrients

There was a positive linear relationship between water temperature within the flux chambers and the flux of  $NO_3^-$  from the water column (figure 7); however, temperature and initial  $NO_3^-$  content covaried between the sampling times, potentially confounding the relationship between temperature and flux. Variability in flux of  $NO_3^-$  was greater in the A.M. high-nutrient incubation than in the P.M. No other flux rate was related to water temperature, dissolved oxygen content, or sediment N or P content.

There were significant negative linear relationships between the initial concentration of TKN,  $NH_4^+$ ,  $NO_3^-$ , and  $PO_4^{3-}$  in the water and the flux rate of that nutrient (figure 8), suggesting that flux rate into and from the sediment and algae is dependent on water column nutrient concentration. In each case, when water column concentrations were initially low, nutrients fluxed into the water column from the sediment or macroalgae. In contrast, when water column concentration that corresponds to the change from net influx into the water column to efflux from the water column was different for each form of nutrient; for the inorganic forms it was lowest for  $PO_4^{3-}$  (1.3  $\mu$ M),



Figure 7. Relationship between temperature and changes in water column nitrate.



Figure 8. Relationships between initial water column nutrients and changes in nutrient content in the water during incubations.

intermediate for NO<sub>3</sub><sup>-</sup> (2  $\mu$ M), and highest for NH<sub>4</sub><sup>+</sup> (6.5  $\mu$ M). The very low water column concentration where the net flux of PO<sub>4</sub><sup>3-</sup> goes into the sediment may explain the lower N : P ratio in the sediment than the water column; sediments may have a greater affinity for or ability to adsorb P than N.

## Discussion

Nutrient processes in Famosa Slough were very complex and dynamic. Water column nutrient concentrations in the slough changed rapidly both temporally and spatially. As water flow changed from inflowing to outflowing (a 2 h period), water column concentrations

of DIN were reduced by as much as 50% in some areas. Similarly, nutrients were rapidly diluted or removed from the inflowing runoff as the water traveled through the slough toward the mouth during rains. Both the small size and the complex hydrodynamics of Famosa Slough may be responsible for these rapid changes in water column nutrients. Either the daily tidal influence or episodic runoff events can rapidly dilute water retained in the shallow lagoon and channel. All of these controlling factors were modified through time as a result of the urban setting of this system.

The range in water column nutrient concentrations in Famosa Slough is wider than that found in many larger estuarine systems categorized as eutrophic. Dissolved inorganic nutrients in Famosa Slough were comparable to and often exceeded those measured in other eutrophic systems, especially during times of rainfall and subsequent runoff. High concentrations of NO<sub>3</sub><sup>-</sup> in the head of Famosa Slough were comparable to concentrations in another small estuary in southern California, Carpinteria Marsh (Page *et al.*, 1995). In contrast, during times of high river flow, NO<sub>3</sub><sup>-</sup> in the upper reaches of the larger Choptank only reached 130  $\mu$ M (Staver *et al.*, 1996). In other large estuaries considered eutrophic or even hypereutrophic, DIN levels were never as high as those found in the ditches at the "head" of Famosa Slough. Rizzo and Christian (1996) found that DIN in the Neuse River Estuary, North Carolina, ranged from 1.0 to 44  $\mu$ M over a 3 yr sampling period. Similarly, Kress and Herut (1998) reported DIN of up to 70  $\mu$ M in Haifa Bay, Israel, and Bartoli *et al.* (1996) measured maximum concntrations of DIN  $\sim 80 \ \mu$ M in enriched coastal lagoons in Italy and France.

Orthophosphate concentrations similar to Famosa Sough were found in the Neuse River estuary (Rizzo and Christian, 1996), the Choptank (Staver *et al.*, 1996), and three estuaries of various eutrophic status in the Mediterranean (Bartoli *et al.*, 1996). However, peak values comparable to Famosa Sough were only found in Haifa Bay (Kress and Herut, 1998). N : P ratios in Famosa Slough were usually  $\leq 25$  without rain. However, during the rain these ratios became either very low or very high depending on which site was measured, suggesting that one side is a source of N, the other a source of P. Similarly, Staver *et al.* (1996) found that N : P ratios increased during times of high river discharge in the Choptank, while ratios were always low, 0.4 to 3.8, in Haifa Bay (Kress and Herut, 1998). This suggests that inflows may be differentially enriched in other systems.

The sediments of Famosa Slough also suggest that the slough is highly eutrophic; TKN averaged 3 mg N g dry wt<sup>-1</sup> and TP was 0.6 mg P g dry wt<sup>-1</sup>. This is enriched compared to deeper water estuaries on the East Coast such as Narragansett Bay where Nixon *et al.* (1976) report values of 0.10–1.00 mg N  $\cdot$  g<sup>-1</sup>. Hansen and Kristensen (1997) found that the average sediment N content was 1.0 mg-N g dry wt<sup>-1</sup> in Kertinger Nor, Denmark, lower than that of Famosa Slough. However, the maximum sediment N content found in Kertinger Nor was 5.4 mg-N g dry wt-1, exceeding the maximum for Famosa Slough.

The results of our study suggest that the local 81 ha watershed, not the SDR, is an important source of nutrients for Famosa Slough. According to our estimates, on both an annual and a seasonal basis more water enters Famosa Slough from the local watershed than the SDR. In addition, the water that enters the slough through the drainage ditches is highly enriched. Less water carrying fewer nutrients enters from the SDR. However, nutrients enter the slough from the local watershed in pulses because the Slough is isolated from

direct connection to the local watershed except during rains and associated runoff. When there is no rainfall, nutrients accumulate in various forms in the ditches, often reaching very high concentrations. Interestingly, one pond has a very large reservoir of N and the other a large reservoir of P, suggesting different sources of water for these two ditches. Even when there is no rain and no surface connection between the ditches and the slough, there must be subsurface connectivity; the concentration of nutrients in the ditches changes with the tides, decreasing as the tides come in and then flush out. When it rains, the berms isolating the ponds from the lagoon are overtopped, and nutrients are washed into the lagoon. For the first rain of the season, at least, the N and P disappear from the water column quickly, suggesting a nutrient sink somewhere within the system.

Both the large biomass of algae and the sediments in Famosa Slough may act as sinks for nutrients during times of high supply associated with rainfall. Rizzo and Christian (1996) found that sediments are generally a source of  $NH_4^+$  in the Neuse Estuary; measured fluxes ranged from 200 to 500  $\mu$ M  $NH_4^+$  m<sup>-2</sup> h<sup>-1</sup>. Similarly, Hansen and Kristensen (1997) found that sediments were almost always a source of  $NH_4^+$ . Average supplies to the water column were  $\sim 200 \,\mu$ M  $NH_4^+$  m<sup>-2</sup> h<sup>-1</sup> with maximum fluxes of 800  $\mu$ M  $NH_4^+$  m<sup>-2</sup> h<sup>-1</sup>. In contrast to these studies, in Famosa Slough it appears that algae may be a source of  $NH_4^+$  to the water. Other studies have suggested that *Enteromorpha intestinalis* often leaks N into the water, even when N supplies are limited (Fong *et al.*, 1996; Kamer and Fong, in prep.).

Our results suggest that in Famosa Slough macroalgae rapidly respond to influxes of nitrogen from the water and the sediments. Although  $NO_3^-$  disappeared from the water column in treatments with algae, the sediments also lost N. Thus the algae must be sequestering N from both sources. E. intestinalis is capable of extremely rapid uptake and sequestering of DIN (Fugita, 1985; Bjornsater and Wheeler, 1990; Fong et al., 1994a, 1996, 1998). In most estuaries with macroalgal blooms, the blooms consist of opportunistic green macroalgae such as *E. intestinalis* with very fast nutrient uptake and growth rates, and large internal storage capacities for nutrients (Waite and Mitchell, 1972; Birch et al., 1981; Gordon et al., 1981; Lapointe and Tenore, 1981; Duke et al., 1987, 1989). Peckol et al. (1994) found that large masses of macroalgae in Waquoit Bay were an important sink of inorganic N, serving to deplete water column concentrations and retain N in the estuary that would have been removed in the absence of algae. Correlations of N flux with temperature and initial nutrient concentration support the work of others that measured sediment/water fluxes (Boynton et al., 1980; Rizzo and Christian, 1996). However, these correlations are also consistent with loss of nutrients to algal biomass. Up to a certain point, E. intestinalis takes up nutrients and grows more quickly as temperature increases (Fong and Zedler, 1993). Similarly, nutrient uptake rate is concentration dependent (Fong et al., 1994b).

In summary, Famosa Slough is an eutrophic estuary with enriched water and sediments. Eutrophication is a result of increased anthropogenic supplies of N and P, and the effects are exacerbated by modifications of the hydrology as a result of urbanization of the watershed. Nutrient dynamics are complex and change rapidly both spatially and temporally. Our results suggest that the small, local watershed, not the larger one, is an important source of nutrients. Large accumulations of opportunistic green macroalgae readily bloom following pulsed influxes of nutrients, sequestering and retaining within the estuary large amounts of N in times of high nutrient supply. This estuary is highly dynamic, both because it is small

in size relative to the volume of inflowing water from tides and runoff, and because nutrient supplies are sufficiently high to generate algal blooms.

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#### FONG AND ZEDLER

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