Comparison of Nutrient Inputs, Water Column Concentrations, and Macroalgal Biomass in Upper Newport Bay, California

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ABSTRACT

A literature search focusing on synoptic nutrient water quality and macroalgal biomass data in estuaries was conducted to determine whether water quality objectives for total inorganic nitrogen (TIN) in San Diego Creek, which discharges to Upper Newport Bay (UNB), were similar to concentrations that induced macroalgal blooms in other estuaries. The goal was to assess (1) whether the TIN water quality objective was overly conservative, (2) whether the TIN water quality objective was not adequately stringent, or (3) whether insufficient data exists to assess the appropriateness of the TIN water quality objective. The literature review included data from estuaries around the world, data from estuaries in southern California, and mass emission and receiving water data measured in UNB.

A wide range of concentrations, loads, and algal biomass was found in the 14 studies that met the survey criteria. Nitrogen concentrations in the water column of estuaries throughout the world reached as high as 70 mg/L, but most of the estuaries were <5 mg/L including UNB. Loading rates of N ranged from 14 to ~10,000 kg/ha/y, and P ranged from 1 to ~1,000 kg/ha/y; UNB had the highest loading rates observed. Macroalgal blooms were associated with all of the estuaries referenced. However, water column concentrations were weakly correlated with macroalgal biomass, particularly for UNB.

Managers in UNB are not able to assess whether the current water quality objectives are appropriate for at least four reasons. First, an effects-based approach is inadequate because insufficient data has been collected on water quality and macroalgae from other estuaries. Second, a strong correlation has not been established between water column concentrations and macroalgal biomass in other estuaries. Moreover, southern California estuaries are distinctly different than most estuaries around the country, hindering attempts to extrapolate data from other locations. Third, significant secondary mechanisms could be operating in UNB that would affect water column concentration-macroalgal biomass relationships, such as the storage of nutrients in sediments or algal tissues. We recommend that additional studies be conducted to better understand local or regional nutrient-macroalgal relationships. Provided secondary mechanisms are significant, a load-based threshold as an alternative approach to establishing a water quality concentration threshold should be evaluated. Fourth, the critical habitat indicator that is being protected has not been clearly defined, making it difficult to evaluate water quality objectives. Once an indicator has been chosen (such as maximum algal biomass, restoring eelgrass beds, establishing the limits for the reduction of dissolved oxygen levels, or determining the minimum acceptable alterations in fish assemblages), mechanistic approaches to water quality thresholds can be evaluated.

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INTRODUCTION

Inputs of inorganic nutrients to coastal estuarine systems throughout the U.S. (Bricker *et al.* 1999) and abroad are increasing and are often associated with increases in algal growth and biomass. Sources of inorganic nutrients such as nitrogen (N) and phosphorous (P) include municipal wastewater, runoff from urban and agricultural activities, and combustion of fossil fuels (US EPA 1998).

Macroalgal species such as *Cladophora, Gracilaria, Ulva,* and *Enteromorpha* are natural components of estuarine systems. However, under nutrient enriched conditions, these algae often form large "nuisance" blooms that decrease the habitat quality of estuaries (Sfriso *et al.* 1992, Valiela *et al.* 1992, Duarte 1995, McComb 1995, Valiela *et al.* 1997, Flindt *et al.* 1999). Macroalgal blooms in temperate estuaries have been associated with seagrass decline (Valiela *et al.* 1992), which impacts organisms that rely on seagrass habitat. Macroalgal blooms can deplete oxygen in the water column (Sfriso *et al.* 1987) via cellular respiration when light is below the compensation point in the bottom layers of the mats. Reduced oxygen levels can result in fish and invertebrate mortality. In addition, algal blooms can affect recreational enjoyment of the aquatic systems by impeding boat progress or by producing toxins or noxious odors that keep visitors away.

The Upper Newport Bay (UNB) is a coastal estuary in southern California with high concentrations of nutrients both in the bay and in its largest tributary, San Diego Creek. High nutrient levels, combined with relatively warm water temperatures and high light levels in the summer season, have resulted in excessive macroalgal blooms including *Ulva* and *Enteromorpha* (AHA 1997). Because of the recurring algal blooms, and the fact that nutrient levels have exceeded the water quality objectives established for total inorganic nitrogen (TIN) for San Diego Creek, the Regional Water Quality Control Board (RWQCB) placed the creek and the bay on the State's list of impaired waterbodies.

Once a waterbody is placed on the State's list of impaired waterbodies, the RWQCB is required to develop a Total Maximum Daily Load (TMDL) in order to restore the beneficial uses lost by the impairment. In the case of San Diego Creek and UNB, a nutrient TMDL was developed and adopted by the RWQCB. The targeted endpoint for the TMDL was the TIN water quality objective for San Diego Creek established in the RWQCB Basin Plan (1995). For the upper portion of San Diego Creek (reach 2) the objective was 5 mg/L TIN and for the lower portion of the creek (reach 1) it was 13 mg/L TIN.   However, the TIN water quality objective was originally established with a limited amount of data and the adequacy of this objective in protecting both instream and downstream (i.e., the bay) water quality and beneficial uses was questioned. Therefore, the TMDL implementation plan includes, among other things, a commitment to evaluate the TIN water quality objective specified for San Diego Creek.

The goal of this project is to begin the process of evaluating the TIN water quality objective. The evaluation assumes an effects-based approach, which requires three steps.

The first step is to review studies from San Diego Creek and UNB. The UNB review includes four stages: (1) compiling historical monitoring data from San Diego Creek to determine what levels of nutrients are being contributed to the bay, (2) compiling historical monitoring data of nutrient levels in the bay, (3) reviewing algal surveys to assess biomass quantities, and (4) reviewing nutrient-algal interactions from UNB special studies. The second step is to review similar studies from other estuaries around the world, including southern California, to assess inputs, nutrient levels, and macroalgal biomass at these locations. The third step is to compare the inputs, water column concentrations, and biomass to determine whether these factors can be used to predict eutrophication in estuaries including UNB. This evaluation will result in one of the following conclusions: (1) the current water quality objective is overly conservative relative to the impacts in other estuaries; (2) the current water quality objective is not adequately stringent relative to impacts in other estuaries; or (3) insufficient data exists to evaluate whether the current water quality objective is appropriate.

MATERIALS AND METHODS

A literature search of peer-reviewed journals was conducted to determine the state of nutrient enrichment and algal biomass condition in estuaries throughout the world, estuaries in southern California, and UNB. The literature search was constrained by two variables. First, the studies were required to address macroalgal measurements, not plankton or water column chlorophyll measurements. Second, data sets from each estuary were required to have synoptic water quality measurements (either as water column concentrations or tributary loads) and biomass estimates.

Assessing inputs of N and P to UNB focused on concentrations and loads of N and P from San Diego Creek, the largest tributary to the bay. Historical data were obtained from the Orange County Public Facilities and Resources Department (COPFRD), whose monitoring site is located on San Diego Creek at Campus Drive just upstream of the Bay. The data included periodic measurements of nitrate and phosphate from the 1969/1970 to 1999/2000 water years, as well as directed storm event measurements from the same period.

Daily flow data from the 1983/1984 to 1999/2000 water years at the San Diego Creek site were also obtained from the COPFRD. This data set was divided into high and low flow, based upon the inflection point of flow duration curves derived from each year; the long-term average inflection point for the entire data set was approximately 50 cfs.

Loads were estimated according to Equation 1:

$$Load = \sum_{i=1}^{n}(C*V*k)$$

Equation (1)

where:

       $Load$ = Annual load
       C = Average concentration for stratum i
       V = Stream discharge volume for stratum i
       k = Conversion factor
       n = High- or low-flow strata

For the purpose of comparing UNB to other estuaries, loads were normalized to the estuary surface area. The surface area of UNB was estimated to be 784 ac based upon U.S. Army Corps of Engineers (USACE) and COPFRD data (2000).

Estimates of water column concentrations were derived from receiving water data collected by the Irvine Ranch Water District (IRWD) and by Kamer *et al.* (in press). Kamer *et al.*(in press) measured nitrate+nitrite, ammonia, total kjehdal nitrogen (TKN), total phosphate, and ortho-phosphate at 9 stations in UNB quarterly from December 1996 through December 1997. The IRWD also measured nitrate+nitrite, ammonia, total kjehdal nitrogen (TKN), total phosphate, and ortho-phosphate at three depths in the water

column (surface, mid-depth, and bottom) at five locations in UNB and in San Diego Creek above Campus Drive between February and November 1998. These data were averaged within and among sites for comparison. Measurements of general physical water parameters were also measured including salinity. Salinity was used as a conservative tracer of creek inputs to assess distribution of nutrient concentrations within the bay.

RESULTS

Eutrophication in Upper Newport Bay
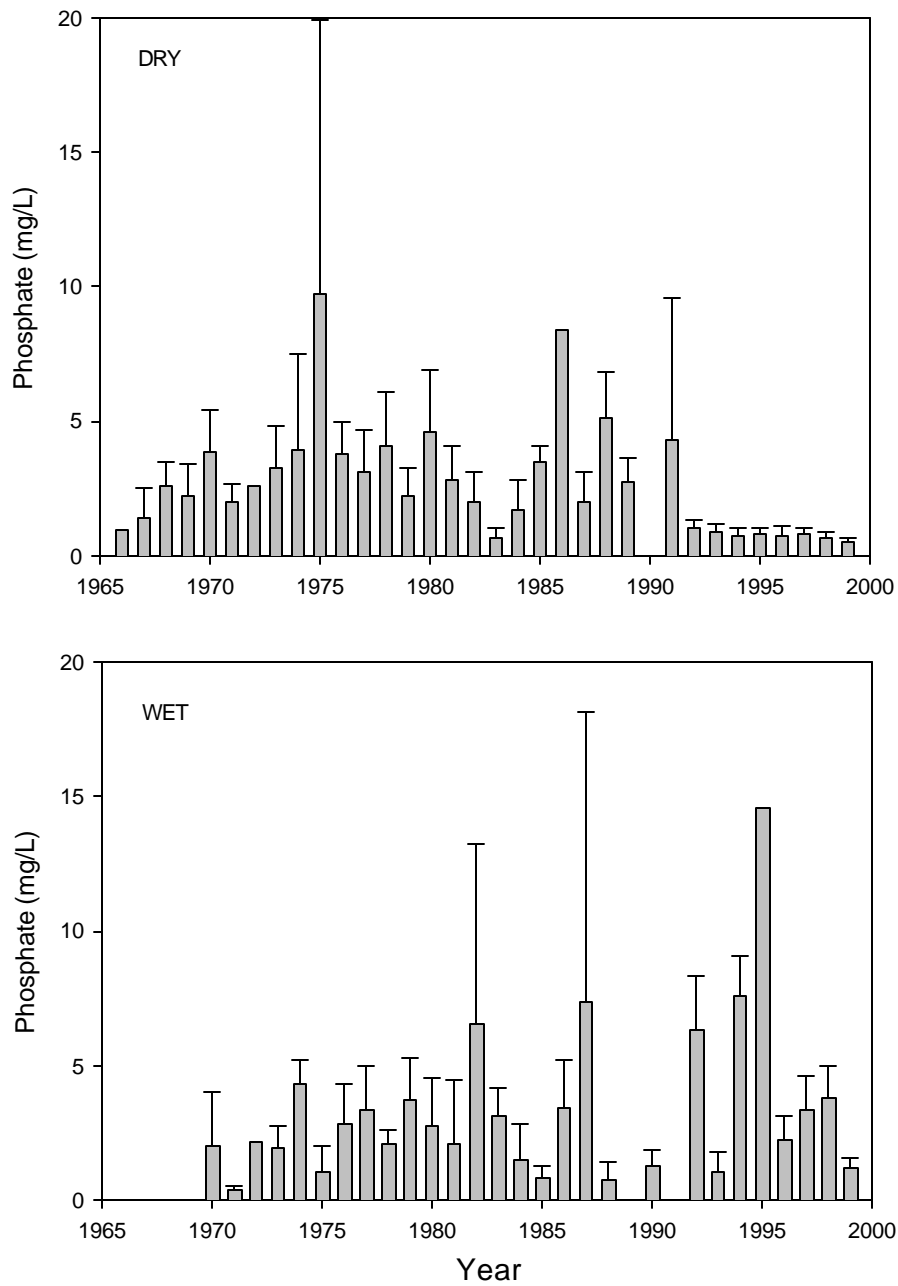
Inputs from San Diego Creek

There have been significant trends in concentrations of nitrate and phosphate from San Diego Creek over time (Figures 1 and 2). Concentrations of nitrate peaked in the mid-1980s, but have since decreased to levels observed prior to 1970. Similarly, concentrations of phosphates were highest from 1970 to 1990, but present day levels are lower than levels prior to 1970.

Examination of long-term trends in nitrate concentration from San Diego Creek indicates that higher concentrations occur during dry, low flow periods relative to inputs during wet, high flow periods (Figure 1). The annual dry weather average of 54 mg/L nitrate was 38% higher than the annual wet weather average of 39 mg/L during 1999. Between 1969 and 1999, dry weather nitrate concentrations averaged nearly four times higher than wet weather concentrations. The differences between dry and wet weather concentrations were greatest during the mid-1980s and again during the mid-1990s. However, the present-day differences between low and high flows are the smallest they have been in the 30-year historical record.
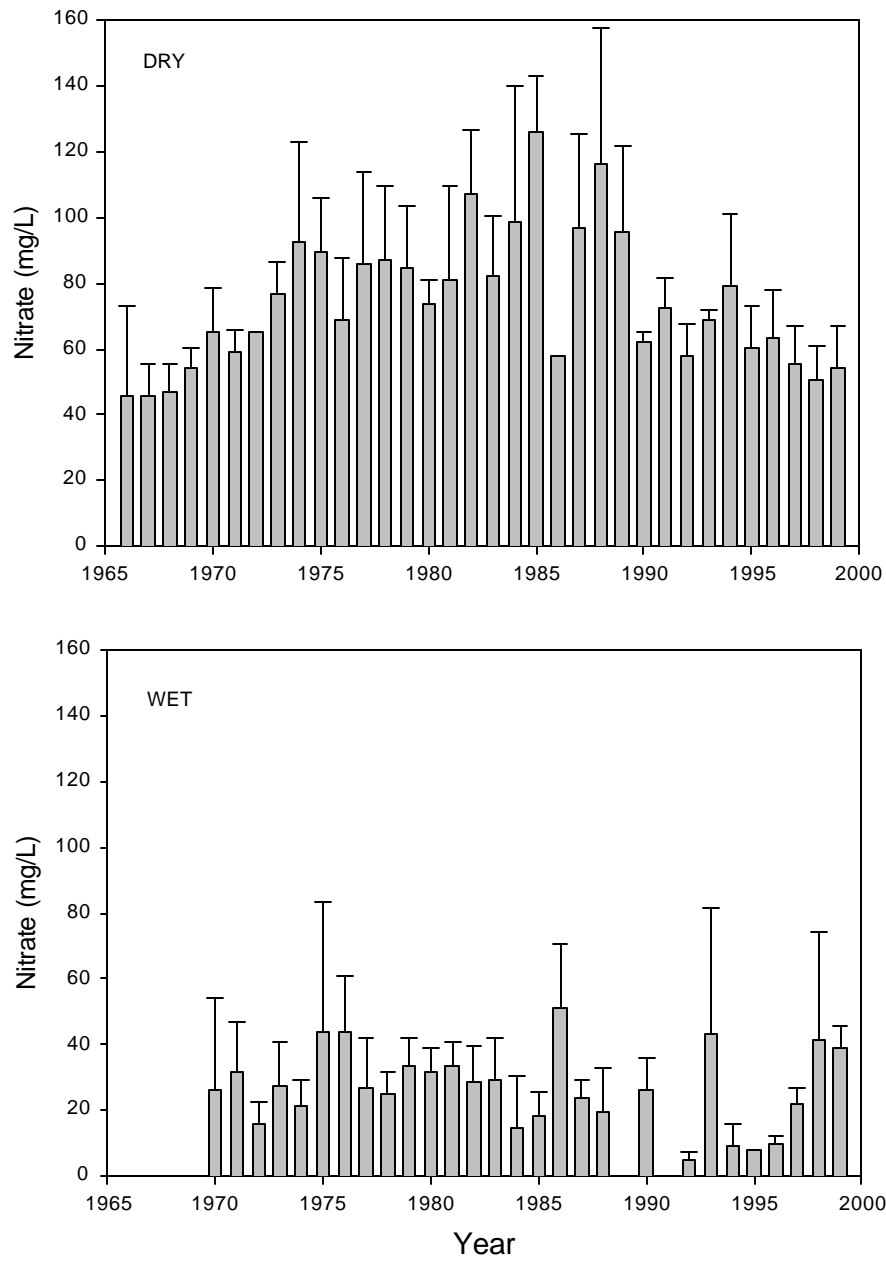
FIGURE 1. **Nitrate concentrations (±95% confidence intervals) in San Diego Creek discharges to Upper Newport Bay stratified by wet and dry flows from 1966 to 1999 (data from County of Orange Public Facilities and Resources Department).**

FIGURE 2. Phosphate concentrations (+95% confidence intervals) in San Diego Creek discharges to Upper Newport Bay stratified by wet and dry flows from 1969 to 1999 (data from County of Orange Public Facilities and Resources Department).

Unlike nitrate, phosphate concentrations are very similar among high and low flow conditions (Figure 2). On average, low flow concentrations have been 70% greater than high flow concentrations between 1969 and 1999. However, low flow concentrations have been 71% lower than high flow concentrations since 1992.

Although dry weather mass emissions of nitrate from San Diego Creek are typically greater than wet weather mass emissions, the wet weather mass emissions drive interannual variability in annual loadings (Figure 3). Rainfall accounted for 25 and 50% of the variation in annual mass emissions of nitrate and phosphate, respectively. This is because the interannual variability in dry weather mass emissions is less. However, some long-term trends have been observed in nitrate mass emissions that coincide with the trends observed in nitrate concentrations. The greatest loads and concentrations occurred in the early to mid-1980s. Dry weather loads have steadily decreased since 1985 and, in 1997, were at the lowest levels observed in 20 years of record.

The long-term trends in nitrate and phosphate concentrations and mass emissions are supported by earlier studies. Blodgett (1989) described annual loads of nitrate ranging from 1,000 to 3,000 metric tons (mt) between 1973 and 1989. Blodgett (1989) also described similar patterns in low flow and high flow contributions as described herein. Low flow typically had higher concentrations and contributed more mass emissions than high flow, but wet years produced extremely large discharge volumes and mass emissions during high flows. The COPFRD has conducted multiple upstream investigations into sources of nitrate and phosphate in the San Diego Creek watershed (COPFRD 2000). More than 80% of the load discharged from San Diego Creek came from Peters Canyon wash, a major tributary, during the September 1998 study period.
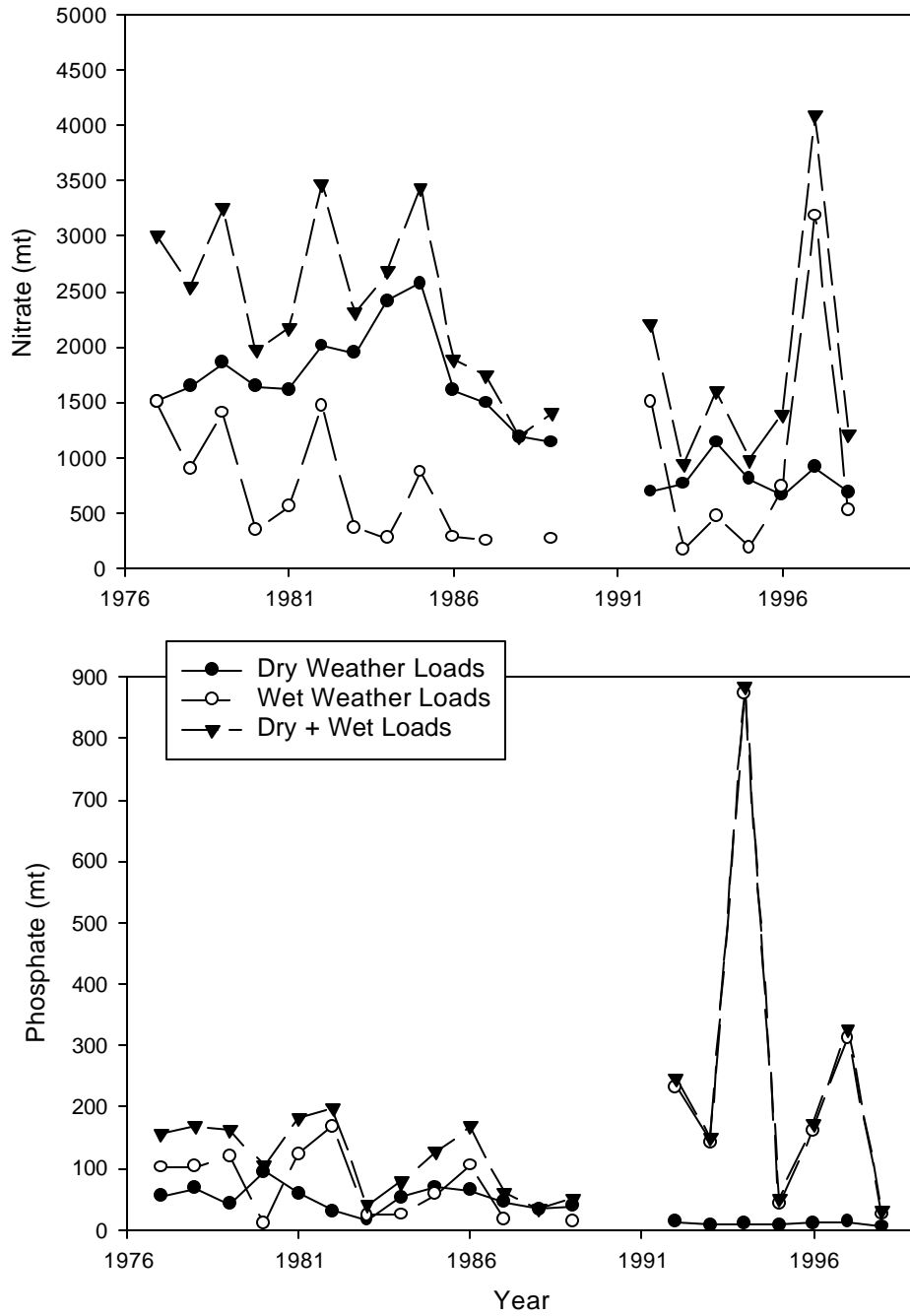
FIGURE 3. Mass emissions of nitrate and phosphate from San Diego Creek to Upper Newport Bay during wet weather flows, dry weather flows, and total annual loads (data from County of Orange Public Facilities and Resources Department). Flow data not available for 1991-1992.

Water Column

There was a gradient of concentrations in ammonia, nitrate+nitrite, TIN, TKN, phosphate, and ortho-phosphate that was highest near San Diego Creek and declined through UNB to its lowest point near the Pacific Coast Highway (PCH) Bridge (Table 1, Figure 4). For example, average TIN concentrations ranged from 13.5 mg/L in San Diego Creek at the head of UNB to 0.30 mg/L at the mouth of UNB near the PCH Bridge. During the monitoring period, the site near PCH Bridge was significantly lower in TIN than other sites ($p < 0.05$). There was no significant difference among sites for ammonia, total phosphate, or ortho-phosphate.

Surface water quality concentrations were significantly negatively correlated to salinity during the IRWD receiving water surveys (Figure 5). Assuming that salinity was a conservative tracer of freshwater inputs, freshwater inputs accounted for 67% of the variability in nitrate+nitrite and TIN concentrations. The co-correlation of these two constituents occurred because TIN was comprised primarily of nitrate+nitrite. In contrast, freshwater inputs only accounted for 18% of the variability in total phosphate concentrations. No salinity relationship was established with ammonia concentrations.

TABLE 1. Average concentrations (±95% confidence intervals) of nutrients for San Diego Creek (above Campus Drive) and in five locations in Upper Newport Bay (data from Irvine Ranch Water District). See Figure 4 for station locations.

| Station	NH3 Ave ± 95% CI		NO2+NO3 Ave ± 95% CI		TIN Ave ± 95% CI		TKN Ave ± 95% CI		TP Ave ± 95% CI		OrthoP Ave ± 95% CI	
Creek												
SDMF05	0.10	0.04	13.39	1.10	13.54	1.10	1.34	0.40	0.30	0.11	0.19	0.07
Bay												
UNBJAM	0.11	0.06	0.93	0.23	1.04	0.26	0.65	0.20	0.17	0.04	0.04	0.02
UNBSDC	0.12	0.03	1.03	0.43	1.15	0.43	0.69	0.26	0.22	0.06	0.05	0.02
UNBBCW	0.10	0.02	0.80	0.33	0.90	0.33	0.60	0.16	0.20	0.04	0.04	0.02
UNBNSB	0.08	0.02	0.65	0.28	0.74	0.28	0.57	0.10	0.19	0.03	0.05	0.03
UNBCHB	0.07	0.01	0.23	0.08	0.29	0.08	0.50	0.00	0.16	0.03	0.03	0.01
All UNB	0.09	0.01	0.69	0.14	0.78	0.15	0.59	0.07	0.19	0.02	0.04	0.01
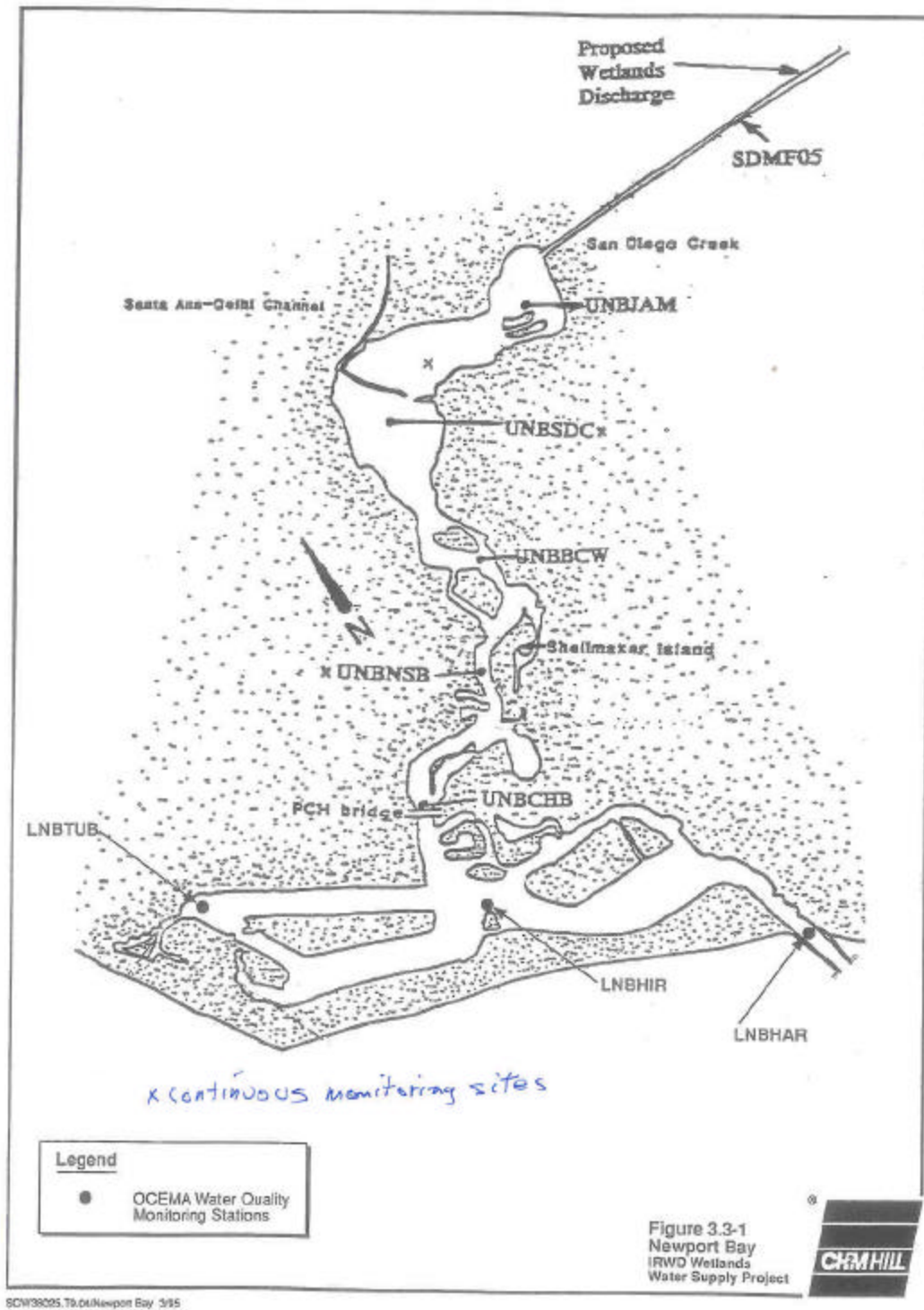
FIGURE 4. Map of sampling locations in Upper Newport Bay (image courtesy of Irvine Ranch Water District)
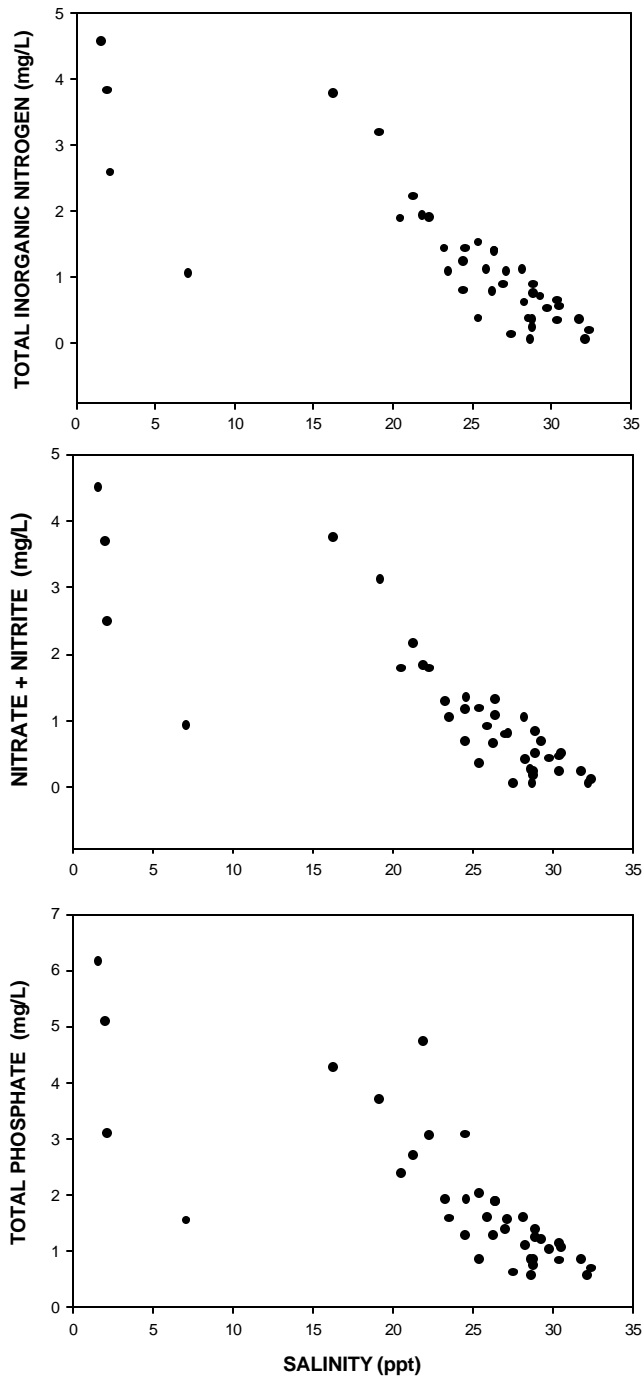
FIGURE 5. Relationship between total inorganic nitrogen, nitrate+nitrite nitrogen, or total phosphate and salinity in Upper Newport Bay during 1998 (data from the Irvine Ranch Water District).

Other investigators have identified similar concentrations and analogous distributions of nitrate and phosphate (Blodgett 1989, USACE and COPFRD 2000). These additional measurements, conducted by COPFRD, produced results similar to those observed in the IRWD data set; there was a nitrate+nitrite concentration gradient that was highest near San Diego Creek and decreased moving down UNB to the PCH Bridge. In addition, receiving water concentrations have been decreasing over time commensurate with reduced inputs from San Diego Creek and the deepening of UNB as a result of dredging, which has increased circulation and mixing.

Macroalgae

The macroalgal community of UNB has been studied by Kamer *et al.* (in press) and by Alex Horne Associates (AHA 1997). Both studies documented the seasonal occurrence of *Ulva expansa* and *Enteromorpha intestinalis*. AHA also found *Cladophora* and *Ectocarpus* while Kamer *et al.* found *Ceramium* spp. Algae were most abundant in summer months and generally declined in the fall season (AHA 1997, Kamer *et al.* in press). Biomass measurements ranged from 0.7 to 5.3 kg m^{-2} (mean 2.1 kg m^{-2}) in July 1996 and from 0.18 to 1.5 kg m^{-2} (mean 0.77 kg m^{-2}) in October 1996 for all species of macroalgae combined (AHA 1997). In October 1996, algal species were also weighed individually with the following results: 0.05-1.32 kg m^{-2} *Ulva*, 0-0.55 kg m^{-2} *Enteromorpha/Cladophora*, and 0-0.11 kg m^{-2} *Ectocarpus*. AHA also measured phytoplankton biomass in UNB and determined that it was low relative to the macroalgae. Residence time and grazing were identified as factors that may limit phytoplankton abundance. AHA has continued to survey UNB and in summer of 2000 reported that algal biomass was approximately half of the levels measured in previous summers. The reductions in nutrient inputs from San Diego Creek were cited as one factor responsible for the reduced algal biomass in the bay (A. Horne personal communication).

Kamer *et al.* (in press) also characterized the algal community of UNB from December 1996 through spring 1998. In the summer and fall of 1997, *Enteromorpha intestinalis* biomass ranged from 0 to 1.14 and 0.68 kg m^{-2}, respectively. *Ulva expansa* biomass in the summer and fall of 1997 ranged from 0 to ~0.80 kg m^{-2}. *Ceramium* spp. biomass was low in the summer of 1997 (0-0.14 kg m^{-2}), but reached up to 1.57 kg m^{-2} in the fall of 1997. In the winter and spring seasons, benthic diatoms with only sparse macroalgae dominated UNB, and it was not possible to quantify biomass with the methods used. To investigate the nutrient-algal dynamics of UNB, Kamer *et al.* (in press) also quantified the N and P content of algae collected from the estuary. In the summer and fall of 1997, tissue N of *Enteromorpha intestinalis, Ulva expansa*, and *Ceramium* spp. ranged from 1.31 to 4.49% dry weight, and tissue P ranged from 0.110 to 0.390% dry weight. N:P ratios for *E. intestinalis* and *U. expansa* were less than 31:1 (atom:atom). Other studies (Atkinson and Smith 1983, Duarte 1992, Larned 1998) have documented much higher N:P ratios in macroalgae, which indicate that algae in UNB may have the capacity to take up much more N. Additionally, tissue P values reported in the literature (Björnsäter and

Wheeler 1990, Wheeler and Björnsäter 1992) are well above those measured in UNB, suggesting that algae in UNB may have the ability to take up more P should it be added to the system. Even though algal biomass is high in UNB at certain times of the year, the algae may still be limited by nutrients and additional inputs of N and P to the system may worsen algal blooms.

Sediments

Estuarine sediments may be both sinks and sources of nutrients. Nutrients may enter the sediments either by diffusion if they are dissolved or by sedimentation if they are particle-bound (Sand-Jensen and Borum 1991). A 16-month study of UNB found seasonal patterns in sediment nutrient dynamics (Boyle *et al.* in preparation). Sediment N values were highest in the spring season following winter rainfall events for two years in a row (1997 and 1998). In 1997, sediment N decreased through the summer and fall seasons. High nutrient inputs that occurred during seasonal rainfall events were stored in the sediments and used by the macroalgal blooms that occurred in the summer and fall seasons. Nutrient inputs and algal blooms can be temporally decoupled through storage of nutrients in sediments.

Nutrients may enter sediments via the algal community (Owens and Stewart 1983). Pihl *et al.* (1999) compared sediment N values in areas with and without algal cover off the coast of Sweden. These investigators found that sediment N was higher when algae were present (0.15%) than in areas without algae (0.045%). Presumably, the bottom layers of the algae decomposed and became incorporated into the underlying sediments, releasing nutrients into the sediments. Through this process, which was also noted in Sfriso *et al.* (1987), nutrients entering a system are taken up by the algae, then transferred to the sediments as the algae decay. Organic matter in the sediments can then be re-mineralized and the nutrients released back into the water column where they may again enhance algal production (Pihl *et al.* 1999). These investigators suggested that the occurrence of algal mats is the result of gradual, long-term increases in nutrient loads to the system and that the nutrients are being retained in the system by the cycling that occurs between the water, the sediments, and the algae.

Nutrients may be returned from the sediment to the overlying communities in a variety of ways. Hydrologic conditions may re-suspend sediments and thereby transfer nutrients from the sediments to the water column (Schramm 1999). Nutrient release from the sediments may be stimulated under anoxic conditions, which may be promoted under algal mats (Lavery and McComb 1991). Thus, positive feedback occurs between the algae, which create anoxic conditions in sediments, and the sediments, which release nutrients that fuel algal growth. Additionally, Lavery and McComb (1991) and Boyle *et al.* (in review) showed that sediments could supply nutrients directly to macroalgae. Boyle *et al.* (in review) used data from the analysis of sediments, algae, and water from UNB, and found that sediment N and P values decreased significantly over time in the presence of *Enteromorpha intestinalis* and *Ulva expansa*. Benthic algae have the ability to intercept nutrients regenerated from sediments before they reach the water column (Valiela *et al.* 1997). Therefore, when water column nutrient levels are low, sediment nutrient pools can sustain macroalgal blooms (Lavery and McComb 1991).

Comparison of Eutrophication in Upper Newport Bay to Other Estuaries

Fourteen systems throughout the world met the synoptic water quality and macroalgal criteria we established as the basis for inclusion in our database. Two estuarine systems were in Australia, one in South Africa, five in Europe, and six in the U.S. (two from the east coast and four from southern California). We also included data on UNB from several independent studies, as well as from monitoring carried out by both the COPFRD and by IRWD. Data on water column N and P for 14 estuaries, including UNB, were available. Loading rates of N and P were available for 11 estuaries including UNB. Quantitative information on macroalgal biomass was only available from eight estuaries including UNB.
The loading rates of N and P were well correlated among the different systems ($r^2 = 0.874$, $P < 0.01$) (Figure 6). However, the loading rates of N and P into UNB were 1-2 orders of magnitude higher than the loading rates in other estuaries. The N:P loading ratio was also higher for UNB (39) relative to other estuaries (ranging from 5 to 38, with an average of 13 among all systems).

Unlike N and P loading, there was no relationship among water column NO_x and PO_4 concentrations (Figure 7). UNB had the second highest water column nitrate+nitrite (NO_x) concentration of the seven estuarine systems (5.28 mg/l). Water column NO_x concentrations for five estuaries were less than 2 mg/L. The Ythan River estuary (Scotland) had the highest NO_x concentration (8 mg/l). Water column nutrient concentrations were highly variable in virtually all of the estuaries, but particularly so in UNB. The variability is supported by other studies, such as Blodgett (1989), who reported concentrations of NO_3 in UNB as high as 26.5 mg/L. Although UNB had the highest P loading rates, it had the median PO_4 water column concentration. The PO_4 concentration in UNB was approximately 0.3 mg/L; the range of PO_4 concentrations was <0.01 to 0.5 mg/L among the seven estuarine systems.

Water column NO_x (r=0.41) and PO_4 (r=0.80) concentrations were weak predictors of macroalgal biomass for the estuaries with synoptic water quality and macroalgal biomass data (Figures 8 and 9). The UNB had the greatest NO_x concentration, but only intermediate biomass. The Lagoon of Venice had the greatest biomass and the second highest NO_x. Similarly, N loading among the different estuaries was not correlated with macroalgal biomass (Figure 10). Too few measurements of other nutrient enrichment indicators, including P loading, ammonia concentrations, or N:P ratios, existed to evaluate if significant relationships with macroalgal biomass existed (Table 2).
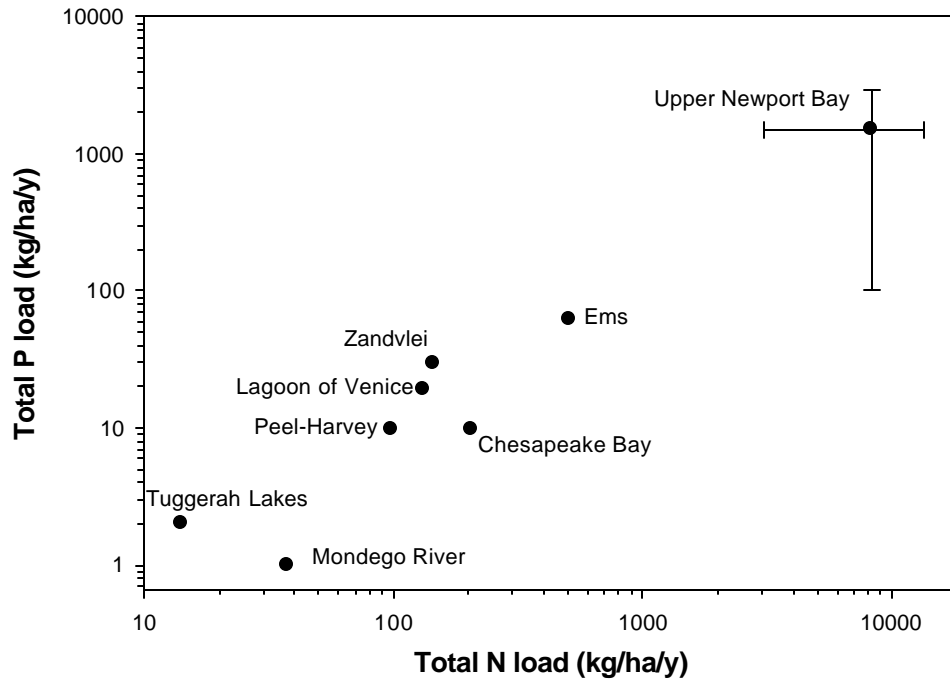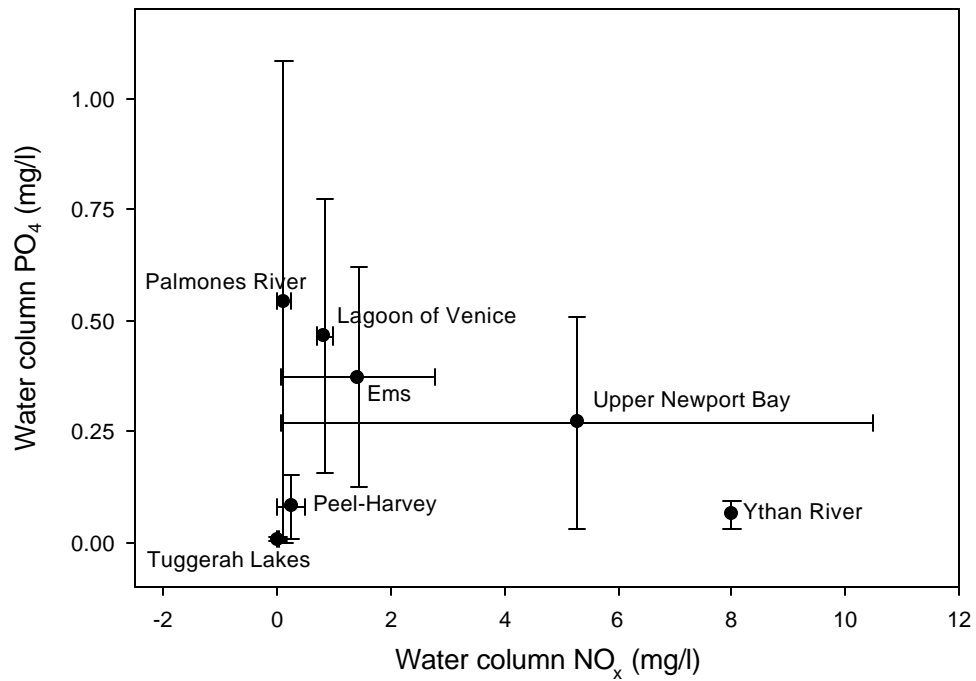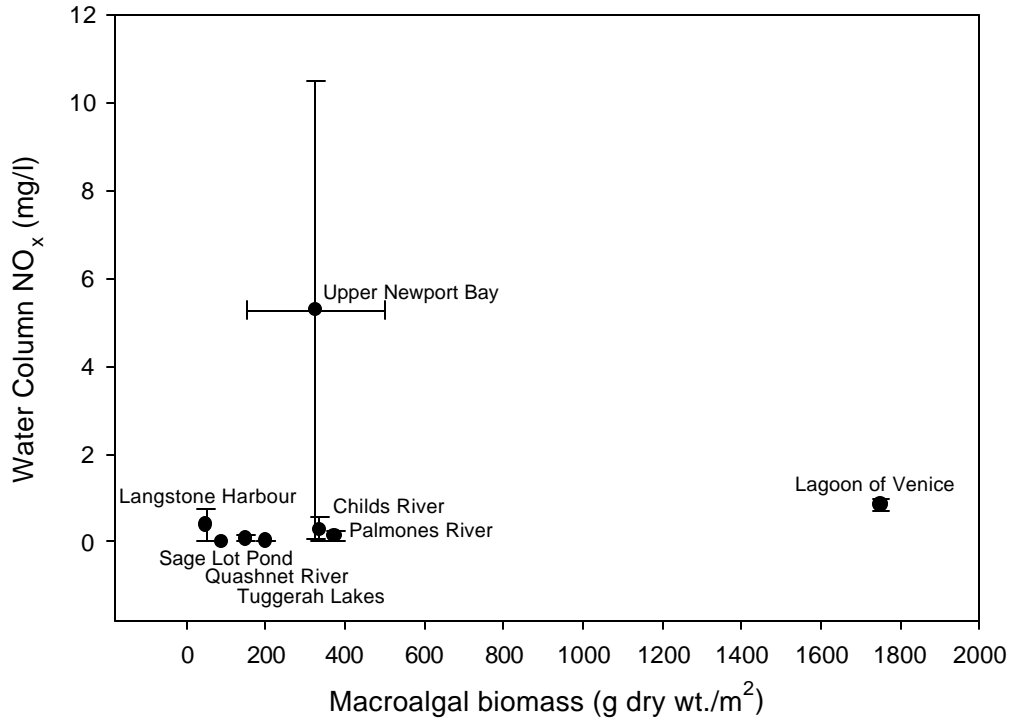
FIGURE 6. Nitrogen and phosphorus loading rates for various estuaries worldwide. Error bars around Upper Newport Bay represent ranges over the last 10 years.

FIGURE 7. Water column concentrations of nitrate or nitrate+nitrite (NO$_x$) and phosphate from various estuaries worldwide. Error bars represent ranges from each reported estuary.

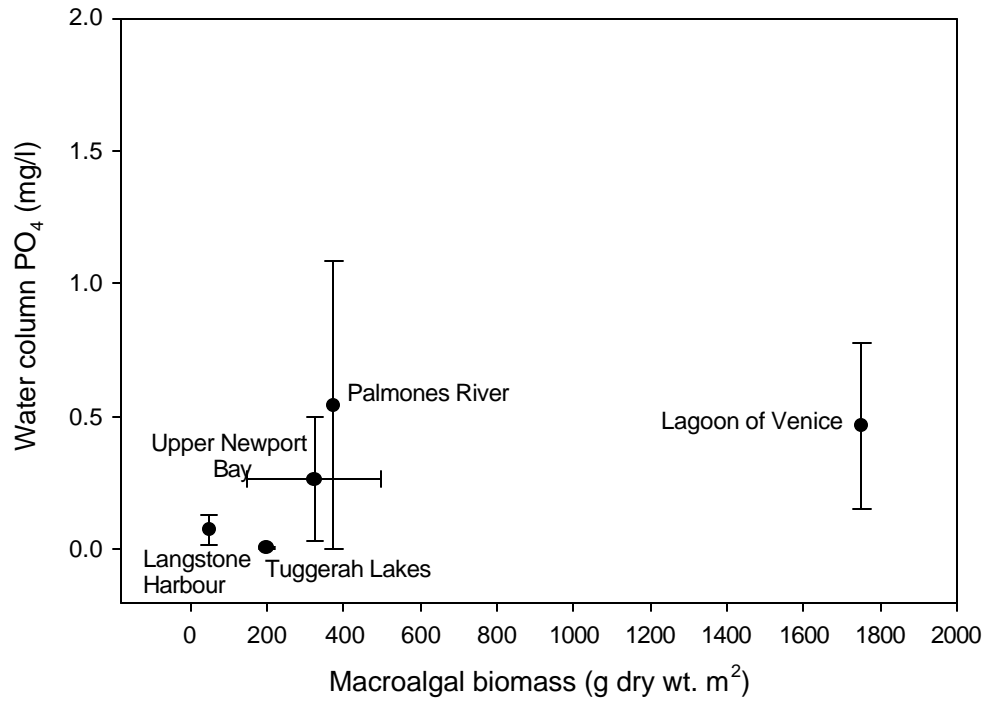**FIGURE 8. Comparison of macroalgal biomass to water column concentrations of nitrate or nitrate+nitrite (NO$_x$) from various estuaries worldwide. Error bars represent ranges from each reported estuary.**

FIGURE 9. Comparison of macroalgal biomass to water column concentrations of phosphate (PO_4) from various estuaries worldwide. Error bars represent ranges from each reported estuary.

FIGURE 10. Comparison of macroalgal biomass to nitrogen loads from various estuaries worldwide. Error bars for Upper Newport Bay represent ranges.
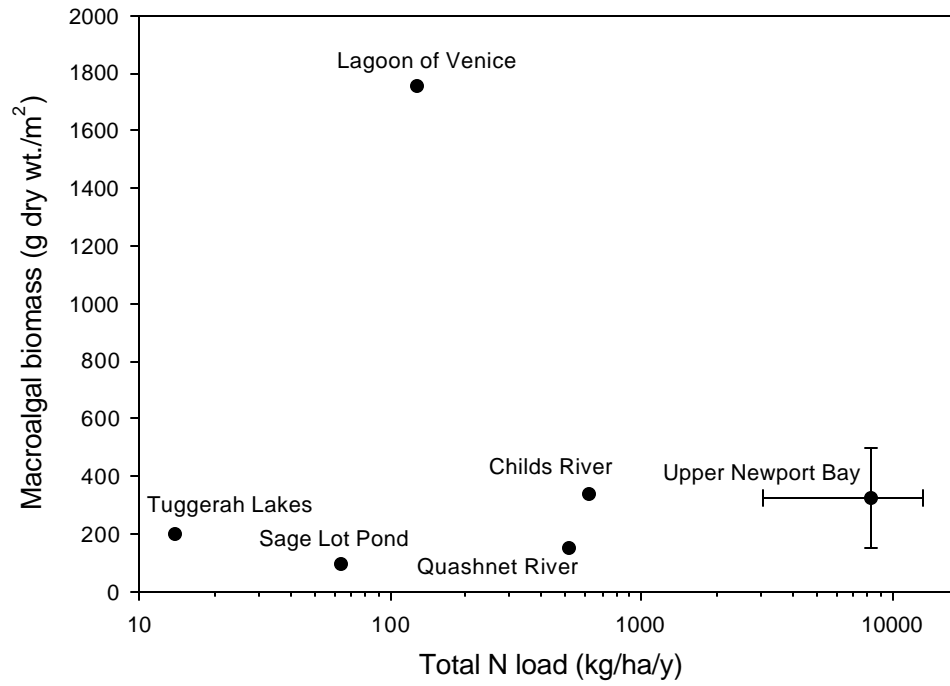
FIGURE 10. Comparison of macroalgal biomass to nitrogen loads from various estuaries worldwide. Error bars for Upper Newport Bay represent ranges.

Table 2. Macroalgal biomass, water column nitrogen and phosphorus values, and nitrogen and phosphorus loading rates for Upper Newport Bay and seven other estuaries worldwide.

Estuary	Macroalgal Biomass (g dry wt/m^2)	Water column (mg/l)				Load (kg/ha/y)	
		NO$_x$	NH$_x$	PO$_4$	N:P	N	P
Langstone Harbour	50	0.015-0.772	0.008-0.144	0.016-0.133	-	-	-
Sage Lot Pond	90	0	-	-	-	64	-
Quashnet River	150	0-0.14	-	-	-	520	-
Tuggerah Lakes	200	0.007-0.038	-	0.002-0.011	-	14	2
Upper Newport Bay	**325**	**0.06-10.50**	**0-0.19**	**0.03-0.50**	**<1-31**	**3068-13,413**	**101-2901**
Childs River	335	0-0.56	-	-	-	624	-
Palmones River	375	0-0.252	0-2.660	0-1.085	1-50	-	-
Lagoon of Venice	1750	0.70-0.98	0.001-0.014	0.155-0.775	1-78	130	19

Many of the estuaries in our review suffered from macroalgal or phytoplankton blooms, yet had low water column nutrient concentrations. While in some cases water column nutrients may be linked to macroalgal blooms (Rudnicki 1986), they more often do not correlate with primary producer abundance or productivity (e.g., Guildford and Hecky 2000, Sfriso and Marcomini 1997). Several factors can reduce water column nutrients to low or non-detectable levels even if the loading is high. For example, macroalgae with high uptake rates can deplete nutrients from the water column before being detected (Flindt *et al.* 1997, Fong *et al.* 1998). Additionally, water quality monitoring programs that sample periodically (i.e., monthly) may not detect episodic nutrient pulses. Therefore, some investigators have used total nutrient loads, rather than water column concentrations, to estimate primary productivity (Boynton *et al.* 1995, Staver *et al.* 1996).

The water column NO_x-macroalgal biomass relationship in UNB appears to be different than in other estuaries. The same algae that are found in UNB (*Enteromorpha* and *Ulva* spp.), were the same species that dominated most other estuaries evaluated for this study. However, not all estuaries compared in this study were comprised of similar macroalgae. The Childs River, Quashnet River and Sage Lot Pond, which are all sub-estuaries of Waquiot Bay, were dominated by two other opportunistic algae (*Cladophora vagabunda* and *Gracilaria tikvahiae*).

DISCUSSION

Our review found that insufficient data was available to assess whether the current water quality objectives for TIN are appropriate for UNB and San Diego Creek. This assessment is based upon four factors. First, only eight estuaries were identified in our literature review with synoptic water quality and quantitative macroalgal biomass data, which provided limited context for UNB. This result is in direct contrast to the multitude of synoptic water quality and plankton (or chlorophyll a) measurements that exist in estuaries nationwide (particularly on the east and gulf coasts) and abroad, where scientists have had sufficient data to establish effects-based relationships among these parameters. For example, Boynton *et al.* (1995) was able to collate large data sets to provide expected planktonic responses based upon tributary water quality and loads. Our collation of a limited data set impairs our ability to make reasonable extrapolations for macroalgae.

The second factor that limits our ability to assess the TIN water quality objective is the weak relationship that exists between water column concentrations and macroalgal biomass. Other investigators have observed this interaction and have found improved relationships with nutrient loading to an estuary and increases in productivity (Nixon *et al.* 1986). Human activities in coastal watersheds have led to increased loadings of N and P that have been correlated to increased primary production, including macroalgal biomass, in Waquoit Bay, Massachusetts (Valiela *et al.* 1992). An alternative approach for achieving the current water quality objective that might be considered in UNB is to evaluate load-based thresholds rather than concentration-based thresholds.

Not only was the effects-based relationship weak among all of the estuaries investigated, but UNB was furthest from the expected water column-macroalgal regression. This finding is due to the fact that southern California's coastal estuaries do not behave similarly to other estuaries around the country. Where estuaries around the world are typically found at the mouths of large watersheds with consistent flows, southern California estuaries are typically found at the mouths of small watersheds with episodic flows. Therefore, estuarine systems in southern California are predominantly marine embayments (Onuf 1987), as opposed to east coast systems that typically have long salinity gradients . In fact, algal mat production represents a very small percentage of total productivity in east coast estuaries, whereas algal mat production can represent 50% or more of the productivity in southern California estuaries (Zedler 1980). When assessing estuarine health nationwide, far fewer data were available in Pacific coast estuaries than for any other region of the U.S. (Bricker *et al.* 1999).

The third factor that limits our ability to assess the TIN water quality objective is the current lack of understanding about nutrient-macroalgal interactions. Several interactions can influence direct water column-biomass relationships including nutrient uptake and storage, or nutrient partitioning to sediments. Opportunistic macroalgae such as *Ulva* and *Enteromorpha* have high nutrient uptake rates (Rosenberg and Ramus 1984, Fujita 1985, Duarte 1995) and the ability to store nutrients (Fujita 1985, Duke *et al.* 1989, Lavery and McComb 1991, Fong *et al.* 1994). It is difficult to saturate these species as they grow

rapidly and consume internal pools of N and P. Nutrient storage complicates our ability to determine whether pulses of nutrient inputs or, alternatively, chronic low-level inputs are of most concern, which in turn limits our ability to assess the current water quality objective.

Sediment nutrient dynamics and their interaction with macroalgae also complicate our ability to assess the current water quality objective. Sediments can act as a sink for water column nutrients or as a repository for particle-bound nutrients that enter the estuary. Nutrient sorption/desorption from sediments may be a key secondary mechanism for nutrient inputs and control in UNB. Early evidence indicates that sediments can release nitrate for consumption by macroalgae (Valiela *et al.* 1997, Boyle *et al.* in preparation). Currently observed reductions in macroalgae in UNB have been partially attributed to reductions in sediment inputs and, *vice-versa*, sediment disruptions (i.e. dredging) may release nutrients to the estuary. At this point in time, the N or P saturation levels of UNB sediments are not known. In order to set appropriate water quality thresholds for UNB, sediment nutrient dynamics such as spatial and temporal concentrations and flux rates need to be well understood. This understanding will help managers cope with the spatial and temporal decoupling of nutrient inputs and increases in macroalgal biomass observed in UNB.

The fourth factor that limits our ability to assess whether current water quality objectives are appropriate is that UNB managers have not agreed upon a quantitative endpoint for assessing beneficial use impacts. Defining the maximum level of macroalgal impact on beneficial uses is a significant challenge and UNB managers have already made several positive steps in this direction. However, the endpoints selected thus far are still vague. Other estuaries that suffer from eutrophication have been able to target reduction goals and measure success by selecting quantifiable endpoints. In Chesapeake and Tampa Bays for example, submerged aquatic vegetation was identified as the beneficial use of management concern. In the case of Tampa Bay, managers wished to reclaim 20,000 acres of lost seagrass beds (TBEP 1998). In the case of UNB, no such endpoint exists, although several potential candidates exist. One endpoint might be tied to the restoration of eelgrass (*Zostera*) that has historically grown in UNB. A second endpoint might be tied to maintaining minimum dissolved oxygen levels for protection of aquatic organisms. A third endpoint might be tied to biomass-fish interactions, whereby limits are set in order to maintain acceptable fish assemblage characteristics.

RECOMMENDATIONS

Since insufficient data exists to evaluate the appropriateness of the TIN water quality objective in San Diego Creek, several actions need to be taken before such an evaluation can commence.

- *Use existing hydrodynamic models of Upper Newport Bay to help design nutrient-macroalgal dynamic studies. Use results from these studies to improve the macroalgal components of the model.*

    UNB has undergone substantial physical modification in the last several decades. The salt dikes that historically bisected the bay have been breached and periodic dredging has been conducted to maintain its use as a sediment retention basin. These changes affect water circulation in the bay dramatically and correlations between nutrient loads and concentrations that occurred in the past may no longer be applicable. Since the bay is very different now than it was 30 years ago, information on water quality and macroalgal abundance in the early 1970's may not be an appropriate reference point for the bay. Rather than begin with large surveys to assess extent and magnitude of water column nutrient concentrations, we suggest analysis of existing hydrodynamic models of UNB to estimate dilution and mixing of N and P inputs from San Diego Creek. Data generated from these analyses will aid in determining the range of expected water column N and P concentrations in UNB. The value of this exercise is two-fold. First, the results can be used to design relevant nutrient-macroalgal dynamic studies and to identify the proper locations in UNB to conduct such studies. Second, results of the nutrient-macroalgal dynamic studies can be incorporated back into models of UNB to incorporate parameters such as nutrient uptake and algal growth. The improved parameterization of the model will be useful for predicting the effect of different water quality objectives.

- *Conduct a series of laboratory studies to quantify nutrient-macroalgal dynamics and validate these studies in Upper Newport Bay.*

    An alternative to defining empirical water column concentration–macroalgal biomass relationships to set water quality objectives is to use a more mechanistic approach, which examines the factors that most influence algal growth and nutrient uptake. Unfortunately, these factors are not completely understood in southern California. We suggest that there are at least three studies necessary to assist in evaluating or establishing water quality objectives. The first study will identify the relative roles of N and P in limiting macroalgal growth. Based on the results of the first study, we will quantify uptake rates and storage in plant tissues of N or P, or both, under different light, temperature and flow regimes. These studies will help evaluate nutrient utilization in different seasons, the effect of chronic versus episodic dosing of nutrients, and the extent to which nitrogen and/or phosphorous need to be controlled. These studies are most efficiently conducted in the laboratory under controlled dosing and physical conditions, but are removed from the variability inherent in nature.

Therefore, additional field studies should be conducted in UNB that are designed to validate laboratory findings.

- *Conduct studies that identify the role of sediments in achieving water quality objectives.*

  Our ability to achieve any numerical water quality objective in the water column of San Diego Creek or UNB is confounded by sediments. Sediments have the ability to act as a sink for large pulses of nutrients, then slowly release nutrients back to the water column over time. Moreover, the extent to which sediment controls implemented as part of the sediment TMDL may aid in the nutrient TMDL are unknown. We recommend that two separate range-finding studies be conducted to assess the potential for sediment-macroalgal interactions. The first study will estimate the loading of N and P from sediments using historical sediment nutrient data and nutrient flux rates obtained from published scientific literature. These values, although rough, will help determine the potential importance of sediments as a significant nutrient source compared to other sources of nutrients in UNB. We also recommend that a sediment bioassay be conducted in which macroalgae will be used to estimate relative rates of nutrient flux from different locations in the bay. This study will provide direct evidence of sediment-macroalgal interactions and identify areas in the bay where sediments may be potentially important. If it is determined that sediments play an important role in the nutrient budget of UNB, we recommend additional studies to quantify the N and P saturation levels in sediments and to quantify the sediment flux rates of N and P .

  Each of these studies will help to determine if sediments are a significant hindrance to achieving water quality objectives set for the water column, as well as where and when these potential problems may arise.

- *Identify quantifiable endpoints for management of macroalgae in Upper Newport Bay.*

  Managers in estuaries from the east and gulf coasts, such as Chesapeake and Tampa Bays, have been successful in reducing nutrient loads and algal blooms because specific beneficial use endpoints have been targeted. For both of these estuaries, the endpoint has been the re-establishment of historic seagrass beds. No such endpoint currently exists in UNB, although several endpoints could be selected such as setting maximum extent or biomass of macroalgae, establishing minimum dissolved oxygen levels, alterations to fish communities, or the re-establishment of historic eelgrass beds, among others. A targeted endpoint not only improves management decision-making, but also provides the scientific guidance needed to establish water quality objectives that directly affect the attainment of that endpoint.

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