Restoring Water Quality in Greenwich Bay: A Whitepaper Series

Paper 1: An Assessment of Eutrophication in Greenwich Bay

This whitepaper series is the result of a collaborative research effort among Rhode Island Sea Grant, the City of Warwick, and the R.I. Department of Environmental Management to determine specific means to restore water quality in Greenwich Bay.

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Sea Grant
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GREENWICH BAY INITIATIVE WARWICK, R.I.
Bring Back The Bay

An Assessment of Eutrophication in Greenwich Bay

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Introduction

The photographs from Greenwich Bay surprised us. We first saw them in 1992, but they had been taken four years earlier by researchers from Science Applications International Corporation (SAIC) with a special underwater camera designed to capture images of the sediment-water interface and the organisms living there (Valente et al., 1992). Based on the color of the sediment and the kinds and numbers of animals present, the SAIC scientists concluded that dissolved oxygen concentrations in water near the bottom were very low, and that relatively large amounts of organic matter were reaching the bottom from sewage inputs or from nutrient-stimulated algal growth in the overlying water. If the SAIC scientists were right, the situation in Greenwich Bay was not good. We had initially expected that some of the shallow areas around the bay, especially Greenwich Cove—which receives effluent from the East Greenwich sewage treatment plant—might experience low oxygen concentrations, but we assumed that the open waters of Greenwich Bay proper would contain enough oxygen to sustain a healthy bottom community. The camera survey suggested that we were wrong—a sampling station in mid bay as well as three stations in each of Warwick, Apponaug, and Greenwich coves all showed signs of bottom life exposed to high levels of organic deposition and low concentrations of dissolved oxygen.

The potential threat of hypoxic (2 mg/liter of dissolved oxygen, O_2,or less) and even anoxic (no dissolved oxygen) bottom waters in Greenwich Bay was soon overshadowed by the closure of the bay to shellfishing because of high bacterial counts in the water. In the long run, however, the images of the bay bottom may have been an early warning of a much more serious problem for the health and fisheries of Greenwich Bay. Our efforts as part of the Rhode Island Sea Grant Greenwich Bay Collaborative Study involved obtaining actual measurements of dissolved oxygen, temperature, and salinity at various depths throughout the bay during a complete annual cycle. Temperature and salinity were included because they regulate how much oxygen can dissolve in the water and because the way in which they vary with depth reflects how well the water is mixed vertically. Such mixing by wind and tidal currents is an important factor influencing oxygen concentrations in the near-bottom water. We also measured the amount of plant material growing in the bay and compared the various sources of nutrients (nitrogen, N, and phosphorus, P) that were stimulating and supporting the plant growth. We focused on the plants and nutrients because increases in the amount of N and P entering the bay from human activities may have fertilized the water to such an extent that the growth of larger algae (seaweeds) and phytoplankton (microscopic plants that give the water a green or brownish color) has increased markedly. An increase in the rate of growth of the plants is called eutrophication, a process that may have major impacts on the ecology of the bay (Nixon 1995).

As more organic matter is produced through plant growth in the sunlit surface water, more oxygen will be consumed in the deeper water when that organic matter eventually falls to the bottom and decomposes. Without sufficient oxygen, the bottom organisms that are harvested, as well as those that serve as food for finfish, will die. If large amounts of seaweed accumulate, they may clog beaches and boating areas and cause odor problems when they decompose. If the abundance of phytoplankton increases markedly, their green pigment, chlorophyll *a*, may shade out eelgrass beds and bottom-living microalgae. It is also possible that the addition of large amounts of N and P to Greenwich Bay might change the species composition of the phytoplankton and alter food chains dependent on the plankton. There is even a possibility that overfertilization of the bay could lead to blooms of phytoplankton that are toxic.

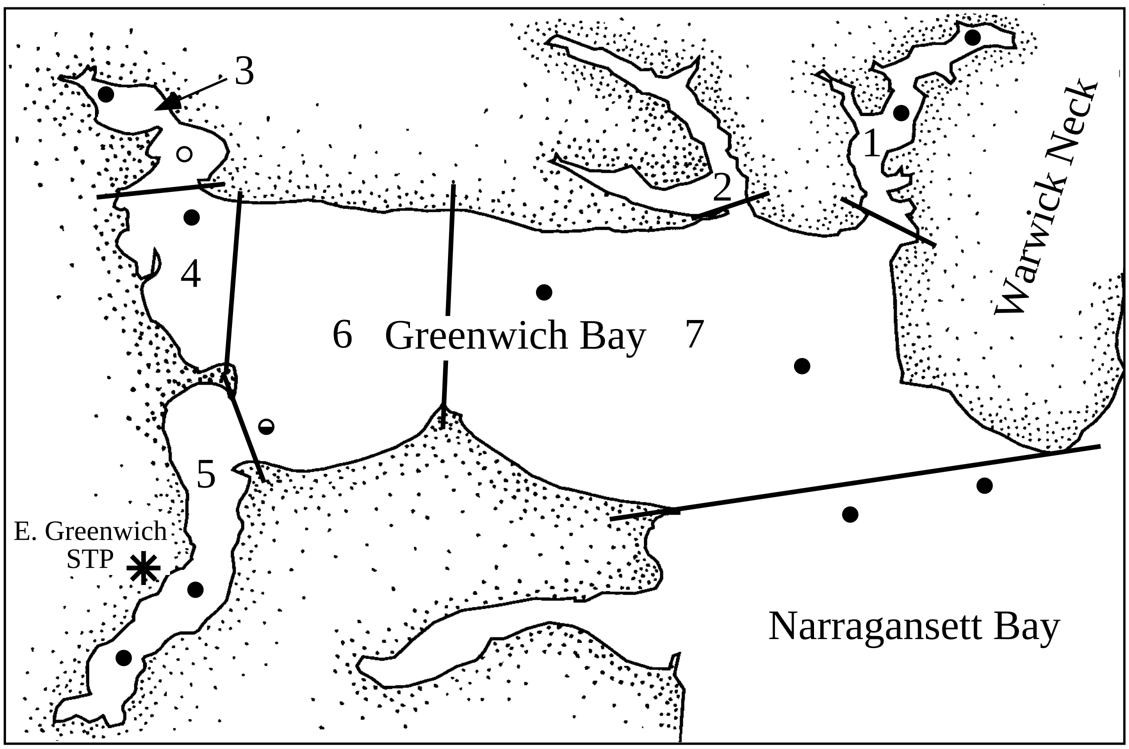

Figure 1. *Major elements or areas of Greenwich Bay: Warwick Cove (1), Brushneck Cove (2), Apponaug Cove (3), Inner Bay (4), Greenwich Cove (5), Mid Bay (6), Outer Bay (7). Dots show the locations of stations where regular measurements of dissolved oxygen, light, temperature, salinity, chlorophyll, and nutrients were made during 1995–1997. No measurements were made in Brushneck Cove because it was too shallow for our boat.*

Dissolved Oxygen

We began our study by dividing Greenwich Bay into seven areas or elements based on the shape and depth of the bay, anticipated differences in biology, and our assumptions about potential water quality problems (Fig. 1). The physical characteristics of the elements are summarized in Table 1. With the exception of very shallow Brushneck Cove, one or two sampling stations were established in each element and in the upper West Passage of Narragansett Bay (Fig. 1), and measurements of dissolved oxygen, salinity, and temperature were made at 0.5 to 1 m depth intervals every few weeks from August 1995 to May 1997 using a YSI Model 600XL rapid pulse polargraphic probe. Thirty surveys were carried out with most taking place during the warmer months. We began all of our sampling runs early in the morning, when oxygen concentrations were lowest. Our analysis of a continuous record of oxygen measurements obtained by M. Spaulding and colleagues of the University of Rhode Island (URI) ocean engineering department in Greenwich Cove between June 1 and September 31, 1997, showed a mean daily range of 4.6 mg O_2/liter, with a mean daily maximum of 6.6 mg/liter ± 2.8 (S.D.) and a mean daily minimum of 2.1 mg/liter ± 1.5. Daily variations in the open waters of the bay are certainly much smaller.

Out of over 1,900 measurements of dissolved oxygen in all parts of Greenwich Bay, less than 5 percent showed concentrations less than 2 mg/liter, the level at which many marine organisms begin to evidence physiological stress. Low oxygen concentrations were only found during the summer months and only in near-bottom water when there was significant vertical density stratification (e.g., Fig. 2). Low oxygen concentrations were most common in the inner bay (Element 4), in Greenwich Cove, and in Apponaug Cove (Table 2). While oxygen concentrations in the outer bay proper and in Warwick Cove were virtually always above 2 mg/liter, concentrations below 2 mg/liter were common in near-bottom water in the inner bay proper and in Greenwich Cove (Table 2).

Our sampling program documented three occasions (June 2 and 16 and July 18, 1997) when very low-oxygen bottom water covered Apponaug and Greenwich coves as well as the inner and mid regions of the bay proper (Fig. 3). During sampling on July 18, 1997, it was evident that over 40 percent of the bay bottom was exposed to oxygen concentrations of 3 mg/liter or less and that 25 percent was exposed to water containing 2 mg/liter or less (Fig. 3). The extensive hypoxia may have been the result of a phytoplankton bloom that was evident throughout Greenwich Bay during sampling in June (see Fig. 6) combined with moderate but widespread vertical density stratification in the water column. In any case, oxygen concentrations were largely restored to values above 2 mg/liter by the time we resampled on July 23.

Oxygen Uptake Rates

In order to assess the potential for low oxygen conditions in various parts of Greenwich Bay, we measured the rate at which oxygen was consumed by unfiltered water samples held in the dark at common summer water temperatures of 22 to 24°C. We also measured the rate at which the bottom sediments and associated organisms consumed oxygen in darkened chambers placed over the bottom and in cores collected from the bay and incubated in the dark in the laboratory at temperatures of 16 to 20°C.

We then compared rates of oxygen consumption to the amount of oxygen contained in the bottom water. Bottom water is found below the pycnocline or depth at which the density of the water changes most rapidly when the water column is stratified—an example is shown in Figure 2. We assumed a high initial concentration of dissolved oxygen in the bottom water of 7.5 mg/liter, the most commonly observed overall value in surface and bottom water during our survey.

It was evident even from a preliminary assessment such as this that the biological activity in the sediments and water of all parts of Greenwich Bay is sufficiently great that the oxygen in the bottom waters can be depleted very quickly at summer temperatures (Table 3). Because of the shallowness of the bay, bottom communities appear to account for most of the oxygen demand (about 60 to 95 percent of the total). The major reasons hypoxia and anoxia are not much more common are that relatively little fresh water flows into the bay (which minimizes density stratification), and the shallow depths of the bay allow frequent vertical mixing by wind. It is also important that the average residence time of water in the bay and its coves is short, though it appears that the rate of water exchange during August to October may be two to three times slower than the annual average shown in Table 1.

Plant Growth

At times, the most conspicuous plants in the bay are the macroalgae or seaweeds found along parts of the shoreline, especially in the shallower coves. Unfortunately, it is extremely difficult to measure the rate at which the algae grow because their distribution is so patchy and the plants are often carried from place to place with wind and tidal currents. We did, however, quantify the amount or biomass of the macroalgae at various times during the summer so that we could gain a rough appreciation for how much oxygen

Table 1. *Physical characteristics of various parts of Greenwich Bay[1].*

Element No.	Name	Area (10^3 m^2)	Volume (10^3 m^3)	Mean Depth (m)	Residence Time (days)
1	Warwick Cove	391	395	1.0	4.2
2	Brushneck Cove	207	55	0.3	0.3
3	Apponaug Cove	350	290	0.8	0.7
4	Inner Bay	813	1,420	1.7	1.5
5	Greenwich Cove	1,029	1,668	1.6	3.9
6	Mid Bay	2,577	6,508	2.5	2.1
7	Outer Bay	6,395	18,070	2.8	3.2
	Total Bay	11,762	28,406	2.4	7

[1]Estimates in the table were developed in collaboration with Li Erikson, URI ocean engineering department. Areas, depths, and volumes are based on mean low water. The mean tidal range is 0.5 m (Spaulding et al., in press). Residence time is defined as the time required for a well-mixed conservative substance in an element to be diluted to one-third of its initial concentration through mixing with adjacent elements.

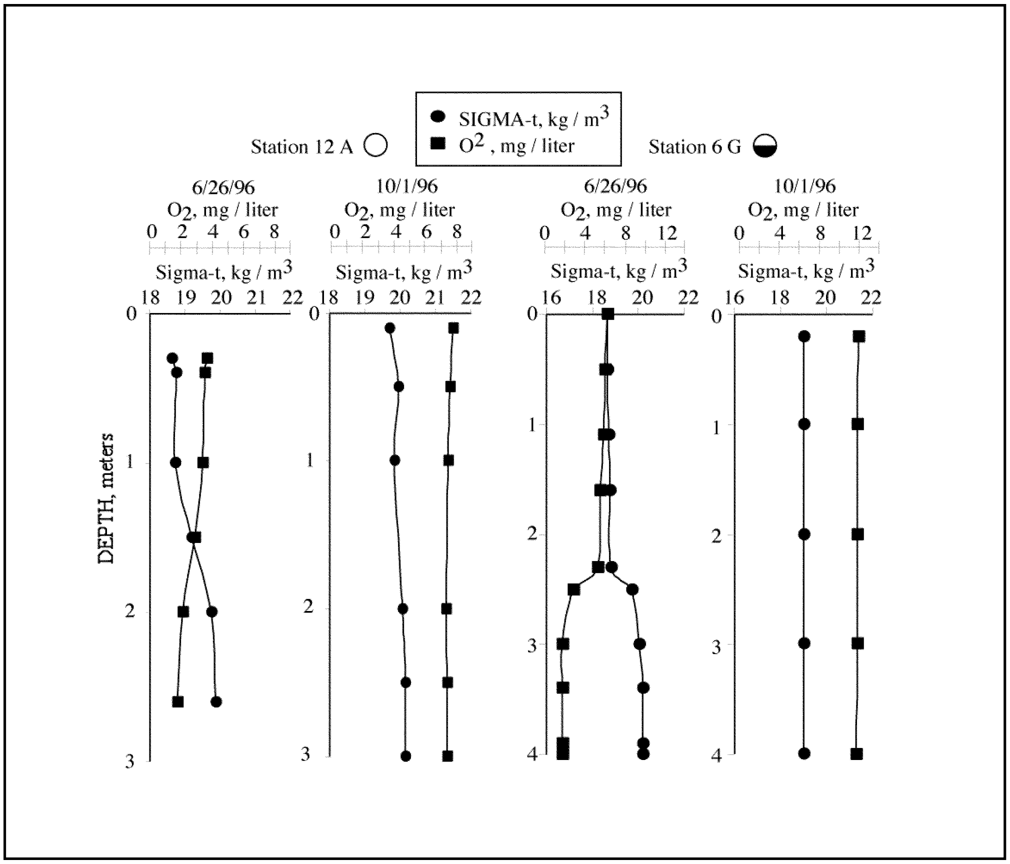

Figure 2. *Variation in water density (sigma-t) and the concentration of dissolved oxygen with depth at two sampling stations in Greenwich Bay on two days in 1996. Location of the stations is shown in Fig. 1. When the water is well mixed and there is little or no change in density with depth (as on 10/1/96), oxygen concentrations are high and uniform through the water column. When the lighter surface water overlays denser bottom water (as on 6/26/96), oxygen becomes depleted in the bottom layers.*

Table 2. *Summary of measurements of dissolved oxygen in near-bottom[1] water in various parts of Greenwich Bay based on 30 surveys at 12 stations between August 1995 and May 1997.*

Area	Number of Measurements	% below 4 mg/liter	% below 2 mg/liter	% below 1 mg/liter
Brushneck Cove	37	16	5	0
Apponaug Cove	45	27	13	7
Greenwich Cove	48	42	25	10
Inner Bay	47	43	30	11
Mid Bay	48	31	10	2
Outer Bay	38	10	0	0
Total	263			

[1]~0.2 m above the sediment. Measurements made in surface waters are not included.

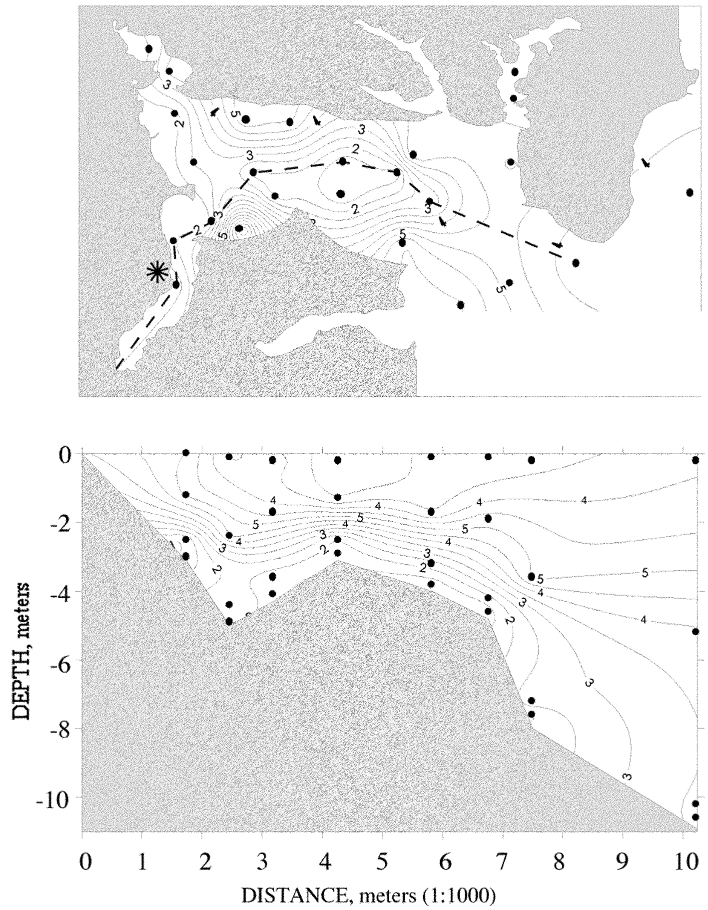

Figure 3. *Top: Concentrations of dissolved oxygen in the near-bottom water of Greenwich Bay during the morning of July 18, 1997. Bottom: Vertical distribution of dissolved oxygen concentrations along the transect shown with a broken line in the top figure. Sampling points are shown with dots; ✳ = East Greenwich sewage treatment plant; contour interval = 0.5 mg/liter.*

Table 3. *Estimates of the approximate time[1] required for water column respiration and benthic oxygen uptake to lower bottom water oxygen concentrations from 7.5 mg/liter to 2 mg/liter and 0 mg/liter in various parts of Greenwich Bay at summer temperatures.*

Element Name	Time to reach 2 mg/liter	Time to reach 0 mg/liter
Apponaug Cove[2]	5.8 hrs	8 hrs
Greenwich Cove[3]	1.1 days	1.5 days
Mid Bay[4]	2.9 days	4.0 days
Outer Bay[5]	3.4 days	4.7 days

[1]Assuming darkness, constant rates of respiration, and no oxygen input from surface waters or adjacent areas

[2]Stratification at 1 m, sediment O_2 uptake = 70 mg m^{-2} h^{-1}, water column respiration = 40 mg m^{-3} h^{-1}. Benthic consumption = 96 percent of total

[3]Stratification at 1.5 m, sediment O_2 uptake = 100 mg m^{-2} h^{-1}, water column respiration = 45 mg m^{-3} h^{-1}. Benthic consumption = 77 percent of total

[4]Stratification at 2 m, sediment O_2 uptake = 35 mg m^{-2} h^{-1}, water column respiration = 30 mg m^{-3} h^{-1}. Benthic consumption = 62 percent of total

[5]Stratification at 2.5 m, sediment O_2 uptake = 35 mg m^{-2} h^{-1}, water column respiration = 25 mg m^{-3} h^{-1}. Benthic consumption = 63 percent of total

consumption might occur when the seaweeds died and decomposed in the bottom water.

The plants which produce the vast majority of the organic matter in Greenwich Bay as a whole are inconspicuous microscopic phytoplankton that may amount to millions of cells per liter and add a greenish-brown color to the water. Because they are mixed with the water, the phytoplankton are more uniformly distributed and it is somewhat easier to estimate the amount of organic matter they may contribute to the bay each year.

Macroalgae

During the summer of 1996, we worked with volunteers from Save The Bay, who regularly raked sampling strips through the intertidal zone perpendicular to the shore at low tide. The algae thus collected were identified, dried, and weighed in the laboratory. The volunteers tended to sample areas where the algae were particularly conspicuous, and their results best serve to quantify maximum abundances at a few points around the shoreline. The major species were always the common green and red seaweeds, *Ulva lactuca* and *Gracilaria tikvahiae*, respectively, with lesser amounts of *Enteromorpha linza*, another green alga.

The surveys showed that macroalgae could be found along the shoreline in great abundance (100–400 g dry weight/m^2) in all of the coves, though the periods when drift-line algae were really abundant only lasted one or two weeks. Of the eight stations sampled, most showed peak biomass in late June, with a second period of abundance in late August to early September.

During the summer of 1997, we changed our sampling strategy to map subtidal macroalgal biomass in the major coves and to quantify the average standing crop over the bottom. We used a small boat to collect between 20 and 170 cores (100 cm^2 each) over the whole area of each cove. The core results showed clearly that while both *Ulva* and *Gracilaria* could be found in dense patches of up to 1,000 g dry weight/m^2, only a small area of the bottom had dry weights exceeding 100 g/m^2 of either major species. Standing crops of *Ulva* of 50 g dry weight/m^2 or more were only found in areas less than 1 m deep, while 50 g/m^2 samples of *Gracilaria* were found as deep as 2.5 m. When the data on macroalgal standing crops were mapped and contoured (Fig. 4), the area-weighted average biomass of seaweeds was not very great at any time in any of the coves in spite of the impressive accumulations of plants in local areas (Table 4). It is also evident that macroalgae biomass is greater in the inner bay coves (Apponaug and Greenwich) and that *Gracilaria* is much less abundant in Brushneck and Buttonwoods coves, perhaps because of their very shallow depths.

Even though our sampling for macroalgae was confined to the coves, parts of Greenwich Bay proper are also shallow enough to be seaweed habitat. We estimated the total area of seaweed habitat by assuming that *Ulva* growth was confined to areas with an average water depth of 2 m or less, and that *Gracilaria* was confined to areas with an average depth of 2.5 m or less based on hundreds of observations in the coves. A hypsographic analysis of the bay (Erikson, URI ocean engineering department), corrected for one-half the mean tide range of 0.5 m (Spaulding et al., in press), showed that approximately 32 percent of the total bay area (including coves) was suitable for *Ulva* and that 45 percent was available for *Gracilaria*. If we assume that average growing season biomass over these areas is 5 g dry weight/m^2 of *Ulva* and 10 g/m^2 of *Gracilaria*, that 40 percent of the dry weight is organic carbon, and that the annual growth of macroalgae is three to five times the average biomass, then the seaweeds provide about 5 to 15 g carbon/m^2/year to the overall productivity of Greenwich Bay as a whole. While this is not large, the macroalgae in the coves may have some impact on dissolved oxygen concentrations in the bottom waters if the coves become stratified.

It is unlikely that this impact is significant for two reasons. First, the respiration rate of the macroalgae is relatively slow, even with abundant oxygen in the water, and it slows even further as oxygen concentrations decline (Fig. 5). Second, while consumption of the macroalgal biomass during decomposition would require a considerable amount of oxygen, such decomposition is relatively slow compared to the water (and oxygen) renewal rates in the coves (Table 1) (Enriquez et al., 1993).

Phytoplankton

We measured the abundance of phytoplankton from May 1996 through May 1997 at each of our 12 regular sampling stations (Fig. 1) by filtering samples of near-surface and near-bottom water through 0.7 µm pore–size filters and extracting the major photosynthetic pigment, chlorophyll *a*, with acetone (Holm-Hanson et al., 1965). During the year of our study, phytoplankton were least abundant during late winter and early spring,

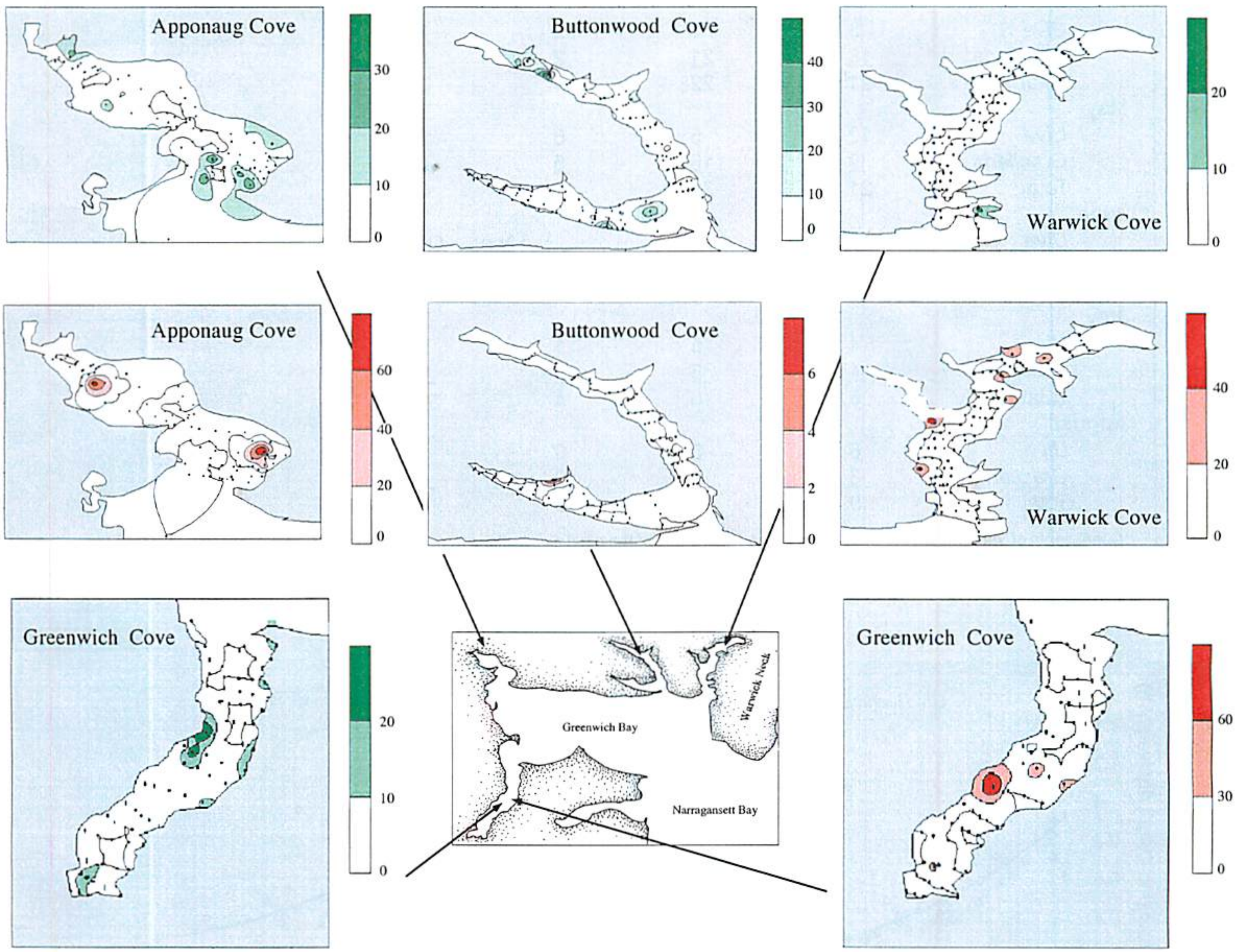

Figure 4. *Biomass of* Ulva *(a green algae) and* Gracilaria *(a red algae) in the major coves of Greenwich Bay in July 1997. Units are in grams dry weight/m^2. Dots show sampling locations.*

Table 4. *Area-weighted average[1] standing crop of dominant macroalgae in Greenwich Bay coves during summer 1997. June to August surveys are more reliable because greater numbers of stations were sampled.*

	Grams dry weight/m²				
	Apponaug	Greenwich	Warwick	Brushneck	Buttonwoods
April					
Ulva	3	1	2	3	1
Gracilaria	18	21	2	0	1
Total	21	22	4	3	2
May					
Ulva	12	5	6	3	5
Gracilaria	9	16	5	0	0
Total	21	21	11	3	5
June					
Ulva	16	9	No Data		
Gracilaria	6	13			
Total	22	22			
July					
Ulva	4	5	1	5	3
Gracilaria	4	5	3	0	0
Total	8	10	4	5	3
August					
Ulva	6	5	0	3	0
Gracilaria	3	9	10	0	0
Total	9	14	10	3	0

[1]Coefficients of variance on the means are large. Patchiness of the algal distributions in each cove is evident in Figure 4.

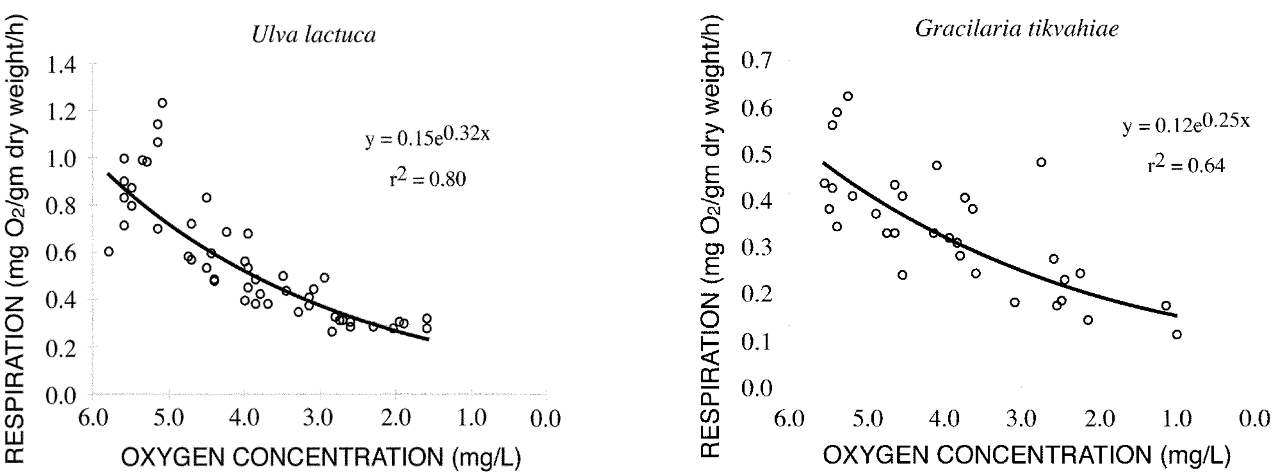

Figure 5. *The rate of oxygen consumption by the two most common species of macroalgae in Greenwich Bay. The respiration rate slows as the average oxygen concentration in the water declines.*

with a bay-wide bloom during June (Fig. 6). Phytoplankton remained abundant in Greenwich Cove and the inner portion of the bay proper throughout the summer, while their abundance was more variable in Apponaug and Warwick coves. The entire bay and its coves experienced a very intense and uncommon bloom in late October (Fig. 6). There was surprisingly little variation around the bay in annual mean concentrations of chlorophyll, though Greenwich Cove was consistently greener (Table 5).

At the same time we collected water samples for chlorophyll analyses we also measured the rate at which sunlight was attenuated with depth in the water column at each station. We did this by lowering a submarine photometer through the water and comparing the amount of photosynthetically active radiation (PAR) at each depth with that at the surface. In general, the more abundant the phytoplankton, the greener the water, and the more rapidly light is attenuated with depth. The attenuation takes the form of an approximately exponential decay (the percent reduction is constant for equal increments of increase in depth) with a slope denoted by $-k$ per m. The greater the value of k, the more rapidly light is attenuated.

We found such a pattern, but it was evident that the waters of Greenwich Bay and its coves are also made turbid by materials other than chlorophyll (Fig. 7). The intercepts of the regressions of k as a function of chlorophyll indicate that about 80 percent of the light extinction in the open bay (with an annual mean chlorophyll concentration of 10 mg/m^3) is due to background turbidity rather than to the phytoplankton. In the coves with 15 mg chlorophyll/m^3, the figure is similar. We were not able to relate the level of background turbidity to season or to the wind experienced shortly before or during sampling, though a more thorough analysis of the latter might prove instructive.

One reason for our interest in light attenuation is that the amount of light reaching the bottom is a critical factor in determining which areas could support growth of the seagrass, *Zostera marina* or eelgrass. While eelgrass is now virtually absent from Greenwich Bay, it was probably abundant in the past (Kopp et al., 1995). We wanted to see how important an increase in water column chlorophyll concentrations might have been in reducing the area covered by eelgrass. A rough guideline is that 20 percent of surface illumination must reach the bottom for eelgrass to thrive (Kenworthy and Haunert, 1991). The regressions relating extinction coefficient to chlorophyll *a* (Fig. 7) suggest that with no chlorophyll, the water of Greenwich Bay proper has a $-k$ value of 0.73 m^{-1} and that the coves have a

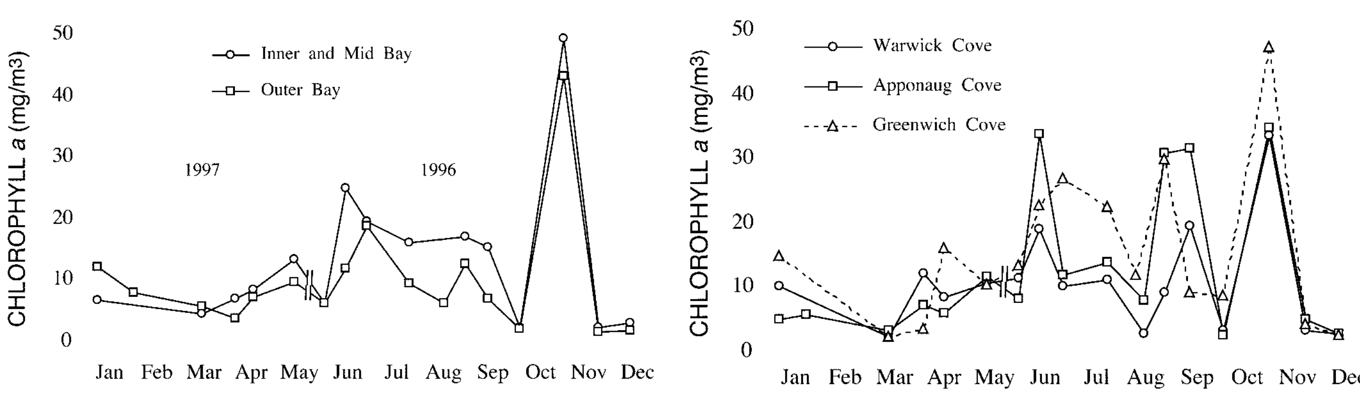

Figure 6. *The abundance of phytoplankton measured as chlorophyll* a *in various parts of Greenwich Bay from May 1996 to May 1997. Values plotted are the mean of near-surface and near-bottom samples at each station in each area of the bay (see Figure 1 and Table 5).*

Table 5. *Concentrations of chlorophyll* a *in the waters of Greenwich Bay measured during 1996. Values are the means of near-surface and near-bottom samples at two or more stations in each element. Units are mg/m³.*

Element Name	Annual Mean	May-September Mean	June-August Mean
Warwick Cove	9.9	10.7	10.0
Apponaug Cove	11.6	16.2	16.6
Greenwich Cove	14.0	17.7	21.7
Inner and Mid Bay	11.7	13.7	15.9
Outer Bay	9.7	9.5	11.1
Total Bay	10.5	11.2	13.1

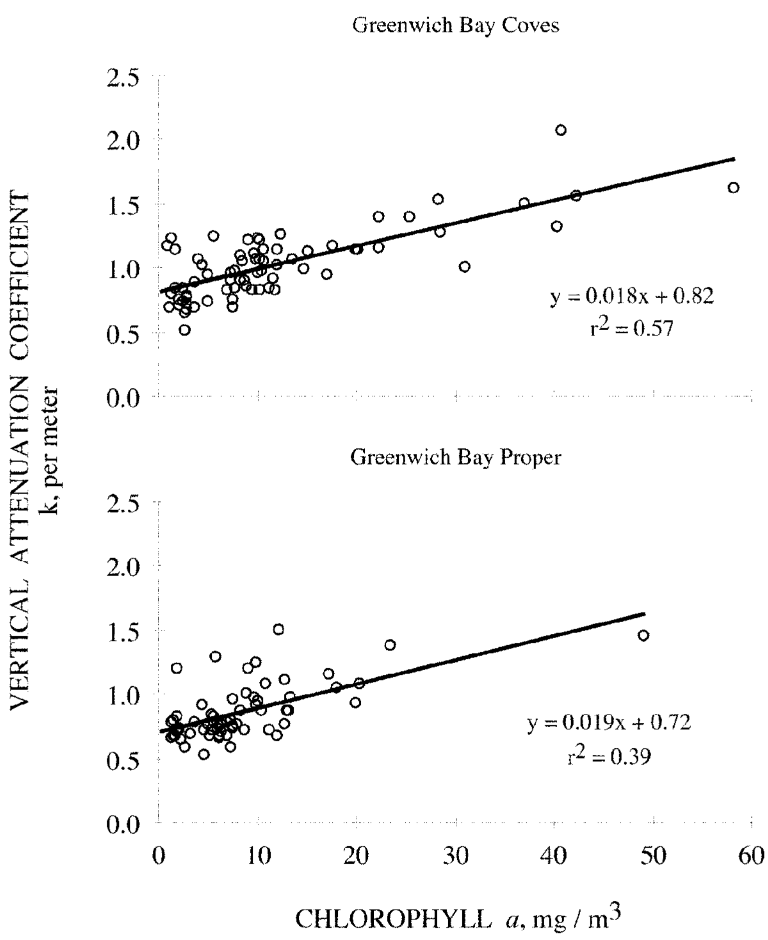

Figure 7. *The relationship between water turbidity measured as the attenuation of photosynthetically available light (PAR) and mean near-surface and near-bottom chlorophyll* a *concentrations in the waters of Greenwich Bay.*

$-k$ of 0.89 m^{-1}. With these extinction coefficients, light is reduced to 20 percent of the surface value at 2.20 and 1.79 m, respectively. After allowing for half of the mean tide range of 0.5 m (Spaulding et al., in press), Erikson's hypsographic analysis of the bay and coves suggests that approximately 3.7 km^2 of the open bay and 1.3 km^2 of the coves would receive enough light to support eelgrass. This is about 43 percent of the total bay area. The same analysis using the mean chlorophyll values observed during May to September of our survey suggests that about 2.4 km^2 of the open bay and 1.2 km^2 of the coves are currently potential eelgrass habitat (based on light availability only). This is just over 30 percent of the total bay area. Since there were phytoplankton in the bay even under prehistoric conditions (Nixon, 1997), this admittedly rough comparison suggests that the maximum loss of eelgrass habitat due to shading by phytoplankton is about 1.4 km^2 in Greenwich Bay proper, or some 25 to 30 percent of the area that might once have been available to the plants.

Fortunately, we now also know roughly how much organic matter the phytoplankton in Greenwich Bay produce during a complete annual cycle. In a recently completed Sea Grant study of the rate at which phytoplankton in Narragansett Bay convert inorganic carbon (C) into organic matter, C. A. Oviatt and colleagues at the URI Graduate School of Oceanography found that phytoplankton photosynthesis in the open waters of Greenwich Bay proper amounted to 210 to 250 g C/m^2/year. This compares to 5 to 15 g C/m^2/year we estimated earlier for the macroalgae. In other words, in spite of their often impressive accumulation of biomass, the organic matter produced by the seaweeds is only 2 to 7 percent of that produced by the phytoplankton. And because the respiration and decomposition of the plankton is also much more rapid than that of the larger algae (Enriquez et al., 1993), their impact on dissolved oxygen levels is much greater.

Nutrient Inputs

Nitrogen (N) and phosphorus (P) enter Greenwich Bay by three paths—in deposition directly on the surface of the bay from the atmosphere, in freshwater discharged from the watershed, and in water from the upper West Passage of Narragansett Bay that flows into Greenwich Bay as a result of wind and tidal currents and gravitational or estuarine circulation.

Direct Deposition

The atmospheric pathway is important for N (but not for P), and detailed measurements of wet and dry N deposition have been made over at least one annual cycle on nearby Prudence Island (Fraher, 1991; Nixon and Buckley, unpublished) (Table 6). The major source of the reactive N carried by the atmosphere is the

Table 6. *Total N inputs to Greenwich Bay and its watershed.*

		Metric tons per year
WATERSHED[1]	Atmospheric deposition on watershed[2]	67
	Unsewered human population[3]	130
	Total Input	197
	Estimated Export to Bay[4]	41–60
GREENWICH BAY	Atmospheric deposition on bay[2]	15
	Streams and groundwater[4]	41–60
	East Greenwich sewage treatment facility[5]	29
	Narragansett Bay (DIN only)[6]	50–130
	Total Input	135–234

[1]Area = 53.6 km^2 (20.7 square miles)
[2]Fraher (1991), Nixon et al. (1995)
[3]26,635 persons (R. Wright, personal communication) and 13.4 g N/person/day (mean of the ranges for consumption by adolescent and adult males and females (National Research Council, 1989))
[4]Calculated assuming the loss of N per unit land area from the watershed of Greenwich Bay is equal to the mean annual loss from the watersheds of the Woonasquatucket, Moshassuck, and Taunton rivers (765 kg dissolved inorganic N/km^2/year ± 51 S.D. and 1,125 kg total N/km^2/year ± 51 S.D.) measured by Nixon et al. (1995). Lower value is DIN export, upper is total N export.
[5]From Nixon et al. (1995). DIN recently accounted for 13,000 kg according to monitoring carried out by the treatment plant.
[6]Authors' estimates based on box model calculations and DIN concentrations in the upper West Passage of Narragansett Bay.

combustion of fossil fuels (coal, oil, natural gas) in electric power generation and transportation in the upper Midwest and in the Northeast.

The Watershed

The atmosphere is also an important path by which N enters the watershed of Greenwich Bay, though the largest source of N and P in the watershed is human metabolic waste (Tables 6 and 7). We have not included sewage N and P from the roughly 1,900 persons served by the East Greenwich sewage treatment plant as an input to the watershed because their waste is discharged directly into Greenwich Cove. The treatment plant also receives waste water from 180 nonresidential connections (J. McCarey, East Greenwich sewage treatment plant, personal communication). Both N and P are essential components of animal nutrition, and significant amounts of P are also contained in some detergents. Livestock and domestic pets release N and P in the watershed, but their contribution to the total input in this area is almost certainly small enough to be neglected. We have also neglected fertilizer inputs to the watershed because less than 5 percent of the land area is in agriculture, and much of that is pasture (Table 8). In the absence of overwatering, it also appears that nutrient losses from the fertilization of home lawns are negligible (Morton et al., 1988; Gold et al., 1989).

Natural biological fixation of N must take place in the watershed, but we have no reliable estimates of rates for a largely urban/suburban watershed such as this one. Our assumption is that this source is small relative to atmospheric deposition and human waste.

Our conservative estimate of N input to the Greenwich Bay watershed of about 200,000 kg/year amounts to an average of just over 3,700 kg/km^2, a value approximately equal to the anthropogenic N input averaged over the Northeast (Howarth et al., 1996). The important question for us, however, is how much of that N leaves the watershed and enters Greenwich Bay.

In an analysis of the major watersheds of the North Atlantic, Howarth et al. (1996) found a strong linear correlation between the amount of N leaving a unit area of watershed and the input of anthropogenic N to the watershed. Their regression suggests an export from the Greenwich Bay drainage area of about 840 kg N/km^2. Fortunately, we can compare this estimate based on a large-scale regional analysis with measurements made in nearby rivers and streams. Annual measurements of dissolved inorganic nitrogen (DIN) and total N export from the Woonasquatucket, Moshassuck, and Taunton rivers show a remarkably similar export of N per unit area of watershed amounting to an average of 765 and 1,125 kg N/km^2/year, respectively (Nixon et al., 1995).

Table 7. *Total P inputs to Greenwich Bay and its watershed.*

		Metric tons per year
WATERSHED[1]	Atmospheric deposition on watershed[2]	0.9–4.9
	Unsewered human population[3]	22.3
	Total Input	23.2–27.2
	Estimated Export to Bay[4]	2.5–5.6
GREENWICH BAY	Atmospheric deposition on bay[2]	0.2–1.1
	Streams and groundwater[4]	2.5–5.6
	East Greenwich sewage treatment facility[5]	17.6
	Narragansett Bay (DIP only)[6]	14.7–38.3
	Total Input	35–63

[1]Area = 53.6 km^2 (20.7 square miles)
[2]Graham (1977) plus authors' estimates for inorganic and dissolved organic P.
[3]26,635 persons (R. Wright, personal communication) and 2.3 g P/person/day (mean for adult male and female consumption (Bunch, 1987) plus detergent (Booman et al., 1987))
[4]Calculated assuming the loss of P per unit land area from the watershed of Greenwich Bay is equal to the mean annual loss from the watersheds of the Woonasquatucket, Moshassuck, and Taunton rivers (45.3 kg dissolved inorganic P/km^2/year ± 22.6 S.D. and 102 kg total P/km^2/year ± 11.3 S.D.) measured by Nixon et al. (1995). Lower value is DIP export, upper is total P export.
[5]Treatment plant monitoring
[6]Authors' estimates based on box model calculations and DIP concentrations in the upper West Passage of Narragansett Bay.

Table 8. *Distribution of land cover in the Greenwich Bay watershed[1].*

	Area, km^2	% of Total
Residential	24.4	44.5
Other Developed	11.5	21.0
Forest	9.7	17.7
Wetlands	4.3	7.8
Agriculture	1.8	3.3
Brush	0.8	1.5
Open Water	0.5	0.9
Other[2]	1.8	3.3

[1]Based on analysis of RIGIS data by M. Brush
[2]Largely transitional or "urban open" areas

These rates of N loss are very much in line with the Howarth et al. (1996) regression. Total N export from the Blackstone and Pawtuxet rivers is somewhat higher at about 1,480 kg/km^2/year, but each of these rivers receives discharge from major sewage treatment plants and they are less useful as a model of the drainage into Greenwich Bay. If we apply the average N export per unit area from the watersheds of the Woonasquatucket, Moshassuck, and Taunton rivers to the Greenwich Bay drainage area, it suggests that some 60,000 kg N/year enter the bay from land drainage. This amounts to about 30 percent of the N we estimated as input to the watershed (Table 6). The remaining 70 percent of the N must be denitrified within the watershed and returned to the atmosphere as N_2 gas or be stored in the watershed in plant biomass, in litter, and in soils and sediments. This is a common finding in watershed nitrogen balance studies (Howarth et al., 1996).

The total N added to Greenwich Bay from land must also include the N discharged from the sewage treatment plant or about 29,000 kg/year (Table 6). The importance of processes within the watershed in reducing the potential amount of N entering the bay is clear—the N entering the bay from only 1,900 persons connected to the treatment plant (plus 180 nonresidential connections) is about half of the total N entering the bay from the 26,600 persons served by individual on-site sewage treatment systems plus the N deposited on the entire watershed from the atmosphere (Table 6).

If we use the same approach to estimate phosphorus export from the watershed, it appears that some 5,600 kg P/year enter the bay from land drainage (Table 7). This represents 20 to 25 percent of our calculated input to the watershed. Since P is retained in soils more efficiently than N, it seems surprising that so much P is being lost. This may be an indication that point sources play a more important role in the loading of P to the measured rivers than they do in the Greenwich Bay watershed. To the extent that this is true, we may be overestimating the runoff of P in land drainage.

Consideration of the amount of P released from the East Greenwich sewage treatment plant indicates that there is a major source of P to the bay in addition to human metabolic waste and detergents. There are 720 residential and 180 "other" connections to the treatment plant (J. McCarey, personal communication). The residential population served is thus about 1,900 persons. Human consumption of P in food amounts to about 1.5 g/person/day (Bunch, 1987) and use of detergents may release another 0.8 g (Booman et al., 1987) for a daily total of 2.3 g/person/day. On an annual basis, the residential population might therefore provide some 1,600 kg P to the treatment plant, some of which must certainly be removed from the wastewater as sludge before the treated wastewater is discharged to the bay. But the measured discharge of P from the plant is over 10 times larger at 17,600 kg/year (Table 7). The release of N from the plant is about three times larger than our estimate of the N produced by the residential population. Each of the 180 "other" connections to the treatment plant must be releasing, on average, as much N as a home with 9.4 people and as much P as a home with 106 people. It seems clear that there is at least one very large industrial source of P being discharged to Greenwich Cove.

The Upper West Passage

The water in the upper West Passage of Narragansett Bay often contains significant concentrations of DIN and dissolved inorganic phosphorus (DIP) (and organic forms of N and P). Mixing and circulation processes carry this water into Greenwich Bay where the nutrients can be taken up by phytoplankton and macroalgae. The Narragansett Bay water also contains salt that can be used as a conservative tracer to follow the mixing of Narragansett Bay water with the fresher water in Greenwich Bay and its coves (Officer, 1980). In collaboration with Erikson and Spaulding, we used our salinity measurements to develop a "box model" to calculate the mixing of West Passage water into Greenwich Bay with varying rates of freshwater flow from land. The daily flow of freshwater into each element of the bay (Fig. 1) was estimated by R. Wright and D. Urish of the URI civil and environmental engineering department. We multiplied daily estimates of the volume of upper West Passage bottom water entering Greenwich Bay by daily estimates of DIN and DIP concentrations in near-surface and near-bottom water in the West Passage that we interpolated from our nutrient measurements in the area (Figs. 1 and 8) to arrive at daily nutrient fluxes across the mouth of Greenwich Bay. The results suggest that the input of N and P to Greenwich Bay from Narragansett Bay may be equal to or as much as twice the amount added to the bay from land (Tables 6 and 7). The input from the watershed is greater during late winter and spring, while the flux from the upper West Passage dominates most of the rest of the year (Fig. 9). Since there is often a marked gradient in N and P concentrations in Narragansett Bay from high values in the Providence River to low at the mouth of the West Passage (Kremer and Nixon, 1978), it seems clear that some fraction of the very large anthropogenic N and P loads to the Providence River enter Greenwich Bay (Nixon et al., 1995). We also obtained preliminary data during February 1997 showing very high concentrations of chlorophyll *a* and associated organic matter in the bottom water potentially entering Greenwich Bay in the deep channel off Warwick Neck. This organic matter was derived from the sinking of a portion of the

DISSOLVED INORGANIC NITROGEN

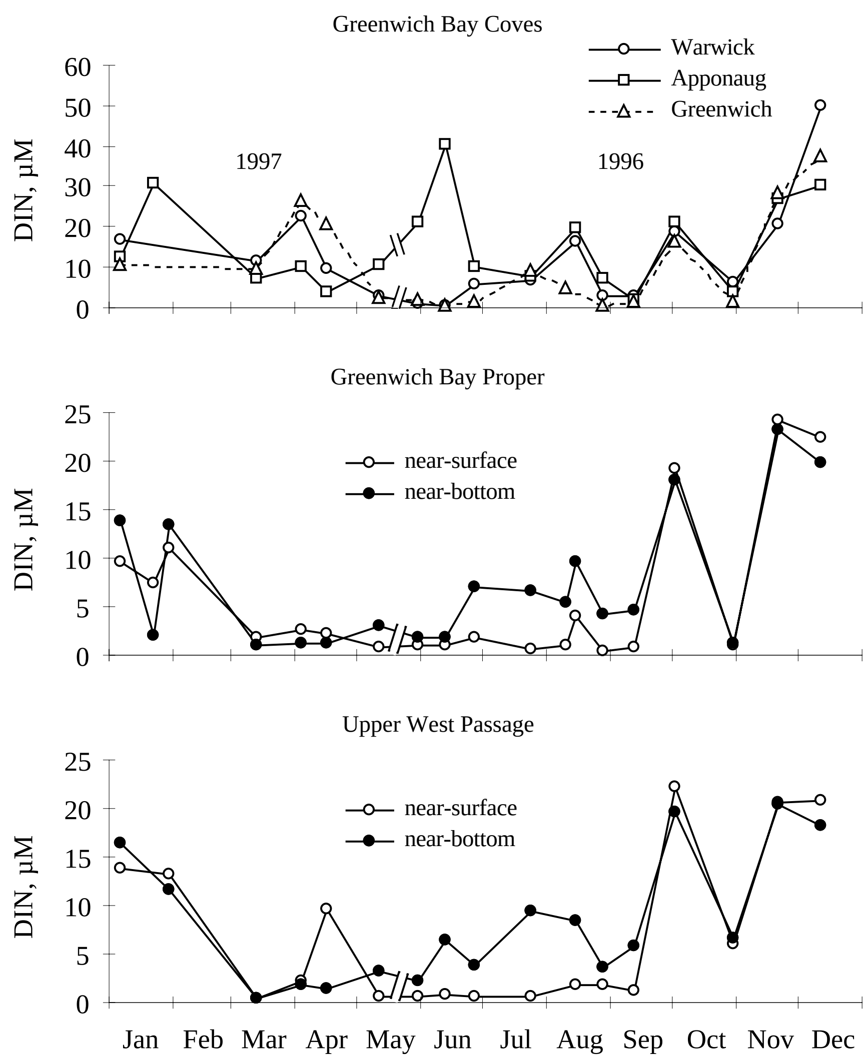

Figure 8a. *Concentrations of DIN (ammonia, nitrite, nitrate) in near-surface and near-bottom water in Greenwich Bay from May 1996 to May 1997. Stations in each cove were averaged. Bay proper is the mean of stations in elements 4, 6, and 7 (see Fig. 1).*

winter-spring phytoplankton bloom in upper Narragansett Bay and it may contribute to the overall oxygen demand in Greenwich Bay as water temperatures increase in early summer. The importance of this flux between bays deserves further evaluation.

EUTROPHICATION

Previous sections of this report have shown that the SAIC scientists were essentially correct in their interpretation of the photographs of sediments in Greenwich Bay. There is no question that during summer, Apponaug Cove, Greenwich Cove, and the inner and mid regions of Greenwich Bay proper experience recurring periods when the near-bottom water contains very little or no dissolved oxygen (Table 2). Current nutrient inputs are clearly sufficient to stimulate rates of organic matter production and consumption that can deplete bottom water oxygen supplies in only a few days if the water is not mixed or exchanged.

It is more difficult to know how the input of nutrients to the bay has changed over time and how our fertilization of the bay may have altered the primary production of the system. In the absence of any human impact on the watershed, the flow of DIN from land into Greenwich Bay may have been about 70 kg/km^2/year (Nixon, 1997) or 10 percent of our estimate under

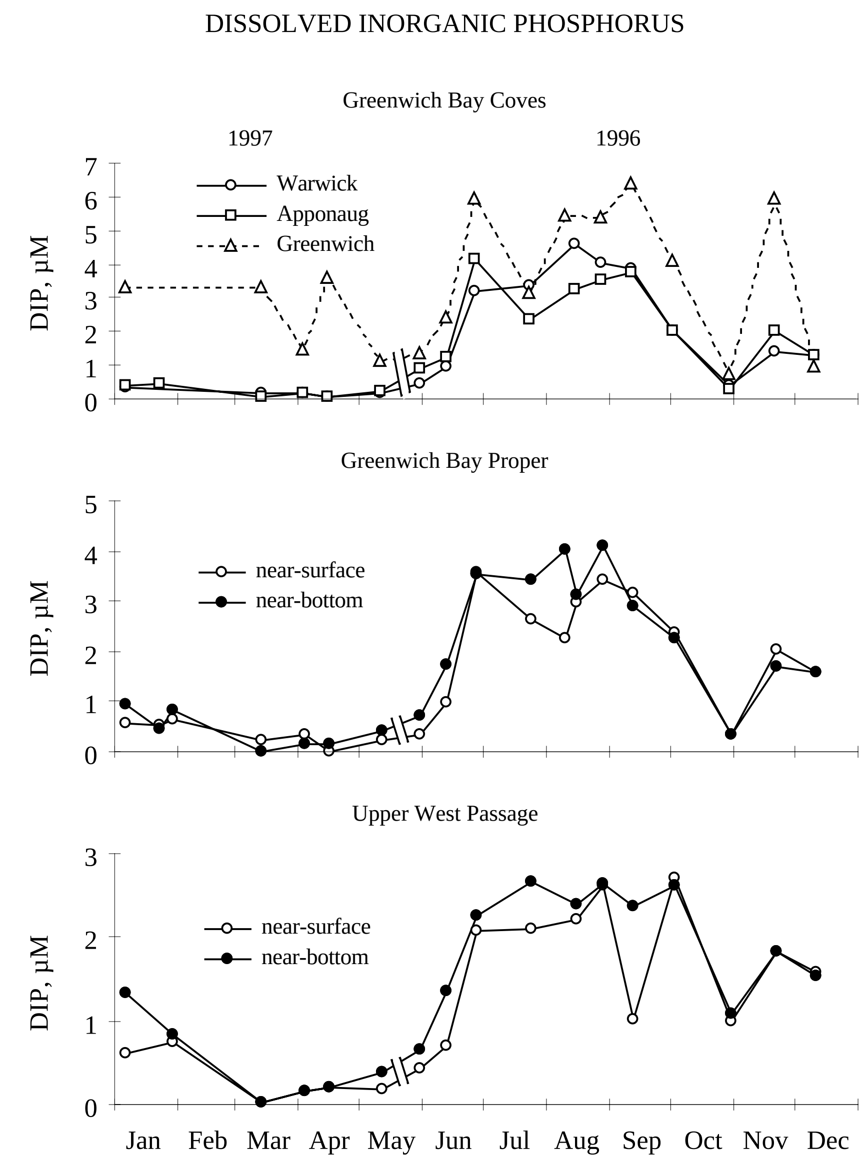

Figure 8b. *Concentrations of DIP in near-surface and near-bottom water in Greenwich Bay from May 1996 to May 1997. Stations in each cove were averaged. Bay proper is the mean of stations in elements 4, 6, and 7 (see Fig. 1).*

SEASONALITY OF DIN INPUTS FROM THE WATERSHED AND UPPER WEST PASSAGE

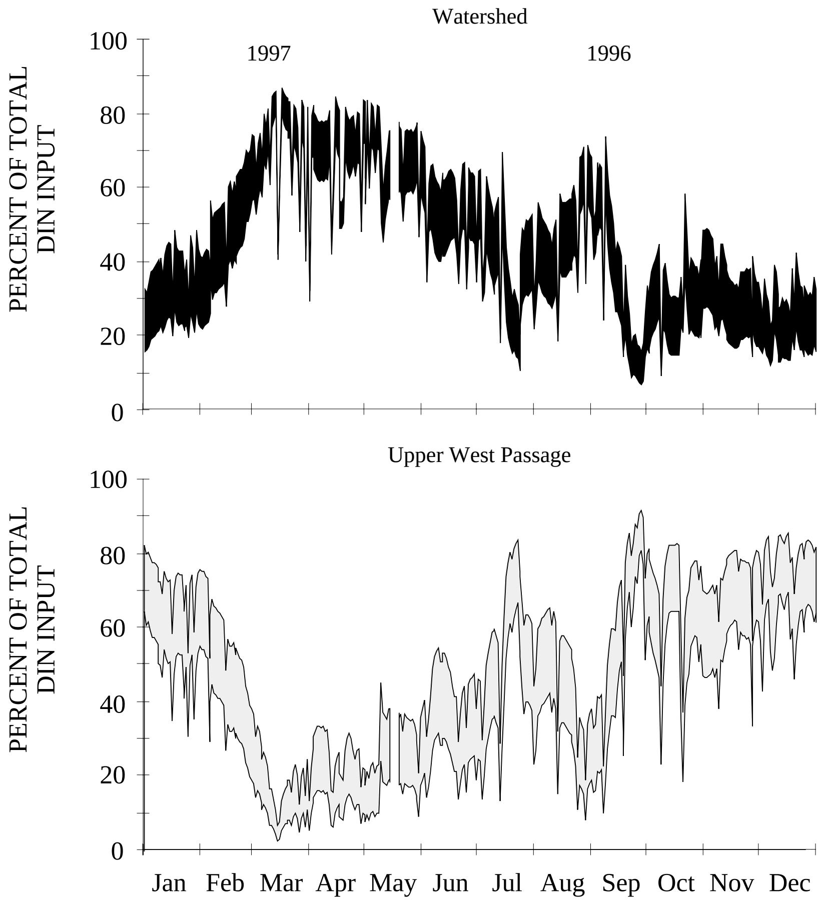

Figure 9. *Relative importance of DIN inputs to Greenwich Bay from the watershed and from the upper West Passage of Narragansett Bay from May 1996 to May 1997. The total annual DIN flux from the watershed (including the East Greenwich sewage treatment plant (see Table 7)) was divided into daily increments in proportion to the daily stream flow as a fraction of the total annual freshwater input according to estimates provided by R. Wright and colleagues. The ranges result from uncertainties in the exchange of water between Greenwich Bay and Narragansett Bay.*

current conditions. We have no way of knowing the concentrations of DIN in the upper West Passage of Narragansett Bay under prehistoric conditions, but it is reasonable to assume that concentrations at the mouth of the West Passage have changed much less. With little enrichment from land, we make a working assumption that there was a small DIN gradient along the bay under prehistoric conditions, and that concentrations in the upper bay in the distant past may have been similar to those presently found near the mouth. At present, the concentrations of DIN are roughly two to three times greater in the upper West Passage than they are at the mouth during the time of year when the flux of DIN into Greenwich Bay from the West Passage is greatest (Kremer and Nixon, 1978). Considering that present day DIN concentrations at the mouth of the bay have almost certainly been increased somewhat by anthropogenic activities, we estimate that the DIN flux from the upper West Passage into Greenwich Bay might have been about one-third or less of the current value, or 15 to 40 metric tons of DIN per year. The total DIN input to Greenwich Bay under prehistoric conditions, including direct atmospheric deposition of 70 kg/km^2/year (see discussion in Nixon, 1997) may thus have been about 20 to 45 metric tons per year, or 15 to 20 percent of our estimated current loading (Table 6).

It is possible to estimate the amount of phytoplankton primary production this low level of N input might have supported by using an empirical regression relating these two parameters in a wide variety of temperate marine ecosystems (Nixon et al., 1996). With present rates of N input (Table 7), the regression predicts phytoplankton production of 200 to 250 g C/m^2/year, a range consistent with the 220 to 250 g C/m^2/year measured by C. A. Oviatt and colleagues using ^{14}C uptake. With our estimated prehistoric N loading, the regression suggests that phytoplankton production may have been only 85 to 120 g C/m^2/year or 40 to 50 percent of the current rate. One caveat regarding the estimate is that while the correlation between primary production and N input is very strong for the systems included in the regression ($r^2 = 0.93$, $n = 19$), our estimate of prehistoric N inputs to Greenwich Bay is lower than that reported for any of the systems included in the regression. It is always risky to extrapolate beyond the data, but if the calculated lower rate of organic production is anywhere near correct, it would almost certainly have been accompanied by lower rates of summer respiration and fewer and much less extensive episodes of low oxygen bottom water. On the other hand, reduced phytoplankton populations would have meant clearer water and, perhaps, more extensive eelgrass meadows. It is difficult to know if greater eelgrass production would have had much of an impact on oxygen consumption. A significant amount of dead eelgrass would have washed up on beaches where it would have decomposed slowly in the air and another portion floating on the surface would have been washed out into Narragansett Bay. The eelgrass that did get consumed within Greenwich Bay would have decomposed much more slowly than dead phytoplankton (Enriquez et al., 1993) and thus placed a smaller demand on the bottom water oxygen supply at any given time.

A core of sediment collected near mid-Greenwich Bay and dated using ^{210}Pb and specific chemical horizons (Corbin, 1989) showed concentrations of organic carbon that increased markedly from background levels of about 1.5 percent in the 1870s to 3.9 percent at present. Similar analyses of a core from Apponaug Cove showed organic carbon increasing from the early 1800s (Corbin, 1989). While the latter may reflect local enrichment from agriculture and the textile industry, we interpret the mid-bay core as a record of eutrophication largely due to the overall fertilization of the Providence River and upper Narragansett Bay region as a consequence of the construction of the Providence sewer system beginning in 1871 (Nixon 1989 and 1995). Worcester, Mass., also began to develop its public water and sewer systems in the early 1870s (Rafter and Baker, 1900), and it is reasonable to assume that the flux of nutrients carried into Narragansett Bay by the Blackstone River increased markedly during this period. It seems unlikely that the early eutrophication of Greenwich Bay was caused by local sources of nutrients. The population of East Greenwich remained small and relatively constant between 1850 and 1950, and construction of a public sewer system there did not begin until 1897 (Gage, 1922). The population of the area now defined as Warwick was still less than 10,000 at the turn of the century, before it began a period of rapid growth that resulted in a peak of almost 90,000 persons in 1980. In the absence of a public water supply or electric pumps, domestic water consumption was low and the retention of N and P from human waste placed in dry privies must have been very high.

Because of plans to expand the public sewer system in Warwick, it may be useful to explore the potential impact of this action on future N inputs to Greenwich Bay. The roughly 26,600 persons not presently connected to public sewers release approximately 130 metric tons of N/year (Table 6). However, we estimate that only 30 percent of the total N added to the watershed as human waste and atmospheric deposition is exported from the watershed to the bay. If both major sources of N are retained in the watershed with equal efficiency, eliminating all of the human waste through sewers will divert 39 metric tons of N each year away from Greenwich Bay. This would reduce the total input of N to the bay by 17 to 29 percent (Table 6). Unfortunately, the regression model suggests that this would only reduce phytoplankton production in the bay as a whole by about 10 percent. However, the impact of nitrogen diversion on some of the coves might well be more dramatic and result in less macroalgae and fewer episodes of hypoxia and anoxia.

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