EUTROPHICATION AND NUTRIENT LOADING IN BARNEGAT BAY: INITIAL STUDIES OF THE IMPORTANCE OF SEDIMENT-WATER NUTRIENT INTERACTIONS

FINAL REPORT

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EXECUTIVE SUMMARY

Nutrient (nitrogen and phosphorus) inputs from non-point and point sources are a potential source of pollution in Barnegat Bay and other back bay estuaries along the coast of New Jersey. Excess nutrient inputs can lead to numerous problems including eutrophication, decline of seagrass beds, anoxia and, if associated with sewage inputs, high coliform levels. Effective management decisions regarding nutrient control strategies require a clear understanding of the relationship between nutrient inputs, nutrient recycling and removal, and eutrophication in the Bay.

The current study (initiated in 1988) is phase I of a longer-term project designed to address several information needs of the New Jersey Department of Environmental Protection. These needs include understanding: the role of the sediments in controlling algal and seagrass production and possibly the occurrence of nuisance algal blooms, the ability of different areas of the Bay to assimilate nutrient loading, the factors controlling which nutrient, nitrogen or phosphorus, limits algal production in the Bay, the role that marinas play in nutrient loading to the Bay, and the importance of pulsed inputs of nutrients, such as from storm drains, to nutrient loading and eutrophication in the Bay. Sediments were chosen to study first because they are a major factor in controlling the availability and assimilation of nutrients in the Bay.

Sediments can be important in controlling nutrient recycling and removal within the Bay, and thus the fate and effects of external nutrient inputs to the Bay, in a number of ways. Nitrogen and phosphorus can be recycled from the sediments for algal production; pulsed inputs of nutrients can be stored in the sediments and later released to fuel summer algal blooms; nutrients can be removed from the estuary by burial in the sediments or via denitrification; and processes in the sediments can control which nutrient, nitrogen or phosphorus, is most limiting to algal production.

The major purpose of the first year of study (actually a 2.5-month field season) was to adapt and develop methods to investigate the importance of the sediments in Barnegat Bay as an internal source of and/or sink (removal site) for the nutrients nitrogen (N) and phosphorus (P). To that end, *in situ* benthic flux chambers were designed and constructed for measuring sediment-water nutrient fluxes. Measurements of sediment-water fluxes of ammonia, nitrate plus nitrite, phosphate, and oxygen under different light conditions were made in September 1988 at four locations in Barnegat Bay: two locations with vegetated (*Zostera* and macroalgae), sandy sediments, an unvegetated fine grained silt-clay sediment (referred to as mud site in the figures), and a silty-sand location in Long Quay Marina. Light conditions included full light (clear chambers), 50% ambient light, and dark

incubations. All study sites, except the marina location, were located in the northern, more developed portion of Barnegat Bay north of the state route 37 bridge near Toms River. The development of methods to measure the deposition of particulate N and P to the sediments was also started and preliminary measurements of organic N and P deposition at one of the vegetated study areas in the Bay were made. In addition, phytoplankton primary production measurements were made at each of the sediment-water nutrient flux sites to compare with the organic matter decomposition rates in the sediments and with benthic primary production rates. The measurements made in the present study are the first in a series of measurements to be made over an annual cycle in the upper Bay.

Primary production rates in the upper Bay measured on five separate days between 31 August and 29 September 1988 ranged from 250 to 500 mg O_2 $m^{-3}h^{-1}$ at mid-day. Oxygen consumption rates in the dark chambers demonstrated that the sediments at all four study sites were active sites for decomposition of organic matter. The average oxygen consumption rates in the dark were: vegetated site 1, -3660 ug-at $m^{-2}h^{-1}$; vegetated site 2, -2270 ug-at $m^{-2}h^{-1}$; marina, -1015 ug-at $m^{-2}h^{-1}$; and unvegetated silt-clay location, -740 to -1230 ug-at $m^{-2}h^{-1}$. Benthic photosynthesis was active at both the vegetated site 1 and marina study site, with photosynthesis exceeding respiration in the light. Benthic gross photosynthesis rates were approximately 75 mg O $m^{-2}h^{-1}$ and 30 mg O $m^{-2}h^{-1}$ at the vegetated site 1 and marina study site, respectively, which is considerably less than the measured planktonic primary production rates. There was no measurable benthic photosynthesis at the silt-clay site or the vegetated site 2.

While considerable amounts of organic matter were metabolized in Barnegat Bay sediments in September, essentially none of the nitrogen or phosphorus predicted to be released as a result of that decomposition was returned to the overlying water. This suggests that at this time of year, at the locations studied, the sediments in Barnegat Bay are a sink for both nitrogen and phosphorus. The sediments are thus retaining/removing nutrients which would otherwise be released back to the water for phytoplankton production.

Ammonia, nitrate and phosphate concentrations in the water were low at all locations studied. Concentrations of ammonia and nitrate plus nitrite were less than or equal to 1 uM at all locations and phosphate concentrations were less than or equal to 0.5 uM except at the marina where the concentration was 1 uM. The N:P ratio was approximately 3 or less at all four locations, suggesting that nitrogen is the most limiting nutrient for phytoplankton production in these portions of the Bay.

The measurements made during the present study encompass a limited time period (September 1988) and thus caution is advised in extrapolating these results to other locations or times (e.g. summer). Studies are currently in progress over an annual cycle at the two sites to delineate possible seasonal differences.

ACKNOWLEDGMENTS

The efforts of many people made the first year of this study possible. Pulling together crews of already very busy people was no easy task and that we were able to do a full field season in two months is a credit to their levels of cooperation and flexibility. The New Jersey DEP Division of Science and Research provided us with two boat operators: Bruce Ruppel and Craig Ruggeri. DEP Division of Science and Research also allowed us to use their boats for work on the benthic fluxes and water column enclosures. Fredrika Moser and Bob Scro were instrumental in making the project possible. The New Jersey Marine Sciences Consortium provided a boat on a number of occasions. Tom Thomson and Jim Nickels were very helpful. Staff members at the Academy of Natural Sciences who helped with our field work were: Suzanne Faurot, Anne Spratt, Dan Brennan, Drew Palavage and Ron Kijewski. We would like to thank them for their humor and their endurance. The vast majority of our field work was done out of the town of Mantoloking. The Mantoloking Yacht Club graciously opened their kitchen for use as a makeshift laboratory for filtering samples and made available their ramps and parking lots as a base camp. Special thanks go to John and Connie Pilling who opened up their house to the field crew, night and day. They also provided us with use of their boat when our regular boat failed.

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INTRODUCTION

Eutrophication is a potential threat to Barnegat Bay and other shallow bays behind barrier islands (back bays) that line the coast of New Jersey. These shallow bays are currently receiving inputs of nutrients from a variety of sources, including storm drains, marinas,, runoff, groundwater, septic systems and direct discharge. In the future, nutrient inputs are expected to increase due to continued population growth in the watershed surrounding Barnegat Bay, as well as from increased recreational use of the Bay by boaters. Barnegat Bay has already shown signs of eutrophication such as summer algal blooms and reported localized areas of anoxia in marinas. High coliform counts, which are indicative of nutrient inputs from sewage, result in approximately 20% of Barnegat Bay being closed to shellfishing (W. Eisele, Division of Water Resources, Bureau of Marine Water Classification and Analysis, pers. comm.). Eutrophication can also decrease seagrass (Zostera and Ruppia) areas, which provide important habitat for blue crabs and various finfish. All of these effects of excess nutrients can ultimately lead to a decrease in both the commercial and recreational uses of Barnegat Bay and eventually to a decrease in property values.

Gauging the effects of increased development on eutrophication in Barnegat Bay is difficult, however, because there is little information on historic or current conditions in Barnegat Bay, as well as a lack of information on nutrient concentrations or nutrient inputs. In addition, little is known about the nutrient dynamics (including the relationship between nutrient inputs and eutrophication) in Barnegat Bay or any of these shallow, highly productive bays. Previous studies of eutrophication and nutrient dynamics in estuaries have focused on relatively deep estuaries such as Delaware Bay, Narragansett Bay, and Chesapeake Bay (reviews by Boynton et al. 1982; Nixon 1981), and it is not clear to what extent results from studies of deeper estuaries can be used to predict the effects of nutrient inputs to shallow bays such as Barnegat Bay.

Once nutrients enter an estuary, internal cycling of those nutrients within the plankton and between the water column and sediments can influence the overall effect of the external nutrient inputs on the system. In particular, processes occurring within the sediments can modify the supply of nitrogen (N) and phosphorus (P) for algal production within the estuary.

The release of nutrients from sediments following decomposition of organic matter has been shown to be a major source of nutrients to phytoplankton in estuaries. Studies in deeper estuaries have demonstrated that external inputs of nutrients are often not sufficient to supply the needs of phytoplankton. The sediments are a major source of nutrients, providing 2 to 10 times as much N and P to the phytoplankton (b

continual recycling) as the external inputs to the estuary (Nixon 1981; Boynton et al. 1982). In Barnegat Bay and other back bays, sediment-water exchanges of nutrients may be particularly important as a source of recycled nutrients for algal growth due to the shallowness of the water column. In addition, the sediments can act as a short-term storage site for pulsed inputs of nutrients that enter the Bay from storm drains or during spring runoff. Those nutrients can be recycled back to the water column later to fuel summer algal blooms.

On the other hand, the sediments may play an important role in nutrient removal, either through burial or nitrogen removal through denitrification. Denitrification (reduction of NO_3^- to N_2 gas by bacteria) is a major removal process for N in deeper estuaries; approximately 50% of the external N inputs from natural and anthropogenic sources in deeper estuaries is removed by denitrification in the sediments (Seitzinger et al. 1984; Seitzinger 1988). Denitrification in Barnegat Bay, and back bays in general, may be an even more important removal process for N because of the greater interaction between the sediments and water column. Many studies in estuaries have shown that N is more limiting to algal production than P (Durand 1984 for Great Bay, NJ; Boynton et al. 1982; D'Elia et al. 1986; and others). Thus the permanent removal of a major portion of N inputs by denitrification may be an important factor controlling the degree of eutrophication of shallow back bay estuaries like Barnegat Bay.

The sediments may also play a major role in controlling which nutrient, nitrogen or phosphorus, is most limiting to algal production. Differential removal of N or P in the sediments (by burial or denitrification) can markedly affect the N:P ratio of nutrients recycled for algal growth (Seitzinger et al. 1984) thereby influencing which nutrient, N or P, is more limiting to algal production regardless of the relative amounts of N and P coming into the Bay from external sources.

Sediment-water nutrient interactions, therefore, are likely a major factor controlling the response of Barnegat Bay to a given rate of nutrient loading, as outlined above, by: greatly amplifying the magnitude of the external nutrient inputs by recycling processes, storing pulsed inputs of nutrients to fuel summer algal blooms, permanently removing nutrient inputs by burial in the sediments or via denitrification, and/or controlling the ratio of N:P available for algal production. Unfortunately, few studies of sediment-water nutrient interactions in shallow back bay estuaries (Durand 1984; Nowicki and Nixon 1985a) like Barnegat Bay exist. The development of cost-effective management decisions regarding control of present nutrient inputs and continued future development and use of Barnegat Bay depends on a clear understanding of the coupling between external nutrient inputs, nutrient supply or removal by the sediments, and eutrophication of the Bay.

The multi-year study, as laid out in our original proposal, was designed to address several informational needs of NJDEP.

Algal Blooms: Are the sediments an important source of nutrients fueling nuisance algal blooms in Barnegat Bay? Are sediments in some areas of the Bay more important than others as a source of nutrients?

Regulating Development: Are certain areas of the Bay inherently better able to assimilate increased nutrient loading from future development because of such environmental factors as their degree of vegetation (Zostera) or the composition (grain size) of their sediments (which can influence the amount of nutrients removed or released from the sediments)?

Nutrient Control Strategy: Does the N:P ratio of nutrients in the Bay differ from the N:P ratio of nutrients entering the Bay from external sources? If so, what are the most important factors controlling the N:P ratio of nutrients in the Bay and how does this affect which nutrient (N or P) should be targeted for reduction in a nutrient control strategy for the Bay?

Marina Siting and Operations: Do marinas contribute significantly to overall nutrient loading to Barnegat Bay? Does nutrient release and oxygen consumption by marina sediments contribute significantly to poor water quality and intermittent anoxia in the marinas?

Storm Drains: Would allocation of resources to mitigate impacts from storm drain effluent reduce nutrient loading enough to result in measurable improvement in Bay water quality?

To address these issues our complete multi-year research program, is designed to provide quantitative data on the magnitude of external (including marinas, storm drains, groundwater, etc.) and internal (sediments) sources of nutrients to the Bay, the importance of short-term storage of nutrients in the sediments which can be released later to fuel algal blooms, long-term removal of nutrients in the sediments by burial or nitrogen removal by denitrification, and factors controlling the N:P ratio of nutrients available for algal production.

That program will span a number of years and will encompass several phases. The first phase focuses on the importance of the sediments in Barnegat Bay as a source or sink for nutrients. The major objectives of the first year of study (which was limited to a two-month field season) were as follows:

(1) Adapt a method for using *in situ* domes to measure sediment-water nutrient (NH_4^+, NO_3^-, PO_4^{3-}) fluxes in Barnegat Bay.

(2) Use the *in situ* dome method to measure sediment-water nutrient fluxes in the late summer/early fall at four locations in the Bay including vegetated (*Zostera* and macroalgae) and unvegetated sediments, as well as in sediments within a marina. Based on the results of those measurements, an assessment was started of the magnitude of N and P release from the sediments and the relative importance of various sediment types.

(3) Begin development of methods to measure deposition of organic matter to the sediments and make initial organic N and P deposition measurements.

This program is also linked to a multi-investigator, multi-institutional NOAA/Sea Grant funded project that is using coastal lagoon mesocosms at the University of Rhode Island to study the effects of nutrient loading rates on eutrophication in coastal lagoons. The results of those studies, as available, will be used to help further understand eutrophication processes in Barnegat Bay. In addition, methods development for measurement of denitrification in seagrass sediments will be of direct use in later stages of the Barnegat Bay project.

Basic Theory of Sediment-Water Flux Measurements

In estuaries and other shallow marine systems, a considerable amount of the organic matter produced by phytoplankton or by benthic photosynthesis is decomposed (consumed, oxidized) in the bottom sediments by benthic organisms and bacteria. During the oxidation of organic matter in the presence of free oxygen, oxygen is consumed and carbon dioxide, ammonia or nitrate, and phosphate are released. According to Richards (1965) the decomposition of typical organic matter (carbohydrate) can be described stoichiometrically by the following equation:

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 106O_2 = 106CO_2 + 16NH_3 + H_3PO_4 + 106H_2O \quad \text{(Eq. 1)}$$

According to this equation, 106 moles (212) atoms of oxygen are consumed and 16 moles of nitrogen and 1 mole of phosphate are released for every mole of organic matter consumed. This ratio of C:O:N:P of 106:212:16:1 is referred to as the Redfield ratio for the decomposition of organic matter (Redfield 1934). From measurements of the rate of oxygen consumption by benthic sediments, the rate of organic carbon decomposition can be estimated as well as the expected rate of release of ammonia and phosphate to the water column from the sediments due to organic matter decomposition.

The equation for photosynthesis is essentially the reverse of the one for decomposition:

$$106CO_2 + 16NH_3 + H_3PO_4 + 106H_2O = (CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 106O_2 \quad \text{(Eq. 2)}$$

Thus, for every 106 moles of carbon dioxide that phytoplankton fix into organic matter during photosynthesis, 16 moles of ammonia and 1 mole of phosphate are consumed and 106 moles (212 atoms) of oxygen are produced. This equation can be used to estimate the amount of ammonia and phosphate required to support measured rates of photosynthesis (rates of oxygen production). The importance of benthic processes in supplying phytoplankton nutrient requirements can be examined from a comparison of measured benthic N and P effluxes and calculated phytoplankton N and P requirements.

METHODS

Study Areas

During late July and early August 1988 a preliminary survey of sediment type and extent of vegetated sediments was carried out in Barnegat Bay. Grab samples were taken at 15 locations throughout the Bay ranging from near the Mantoloking Bridge in northern Barnegat Bay to south of Barnegat Inlet. Samples were visually inspected for sediment grain size and presence/absence of vascular and non-vascular vegetation. Based on the results of this survey we chose two sandy vegetated and one silt-clay unvegetated study sites north and west of NW Point in the northern end of the Bay (Fig. 1a). Long Quay was chosen as the marina study site to coordinate with additional studies planned by NJDEP DSR and Dr. Ken Able of Rutgers University. Benthic flux measurements were made at a location near the mouth of the marina (Fig. 1b), near the location used for clam/bacteria studies carried out by NJDEP DSR during 1988.

Field Measurements

Sediment-Water Nutrient Fluxes

Measurements of the net flux of ammonia, nitrate plus nitrite, phosphate, and oxygen between sediments and overlying water were made during 20-29 September at each of the four study sites. A series of six chambers (Fig. 2), including two light, two dark, and two single-screened (approximately 50% light transmittance) were placed over the bottom sediments for approximately 6 h at each location. Chambers were carefully deployed by divers using SCUBA gear at the three Bay locations and from an inflatable boat at the marina so that bottom sediments remained as undisturbed as possible. Incubation times ranged from approximately 5 to 7.5 h, and were determined based on the rate of oxygen consumption by the sediments. Oxygen levels were monitored using a YSI field oxygen meter and probe. Incubation and sampling times were chosen to prevent oxygen levels within the chambers from dropping below 4 mg O_2 per liter. An expansion glove inside the chamber allowed samples to be withdrawn from the sealed chambers without admitting surrounding Bay water or sediment pore waters. The water in the chambers was carefully and thoroughly stirred manually with a small paddle stirrer located inside each chamber before each sample was taken.

In addition to chamber incubations, a series of light, dark, and single-screened glass bottles was filled with Bay water from the site of chamber deployment. These bottles were incubated on the bottom near the chambers and served as controls for assessing changes in nutrient and oxygen concentrations in the chamber water

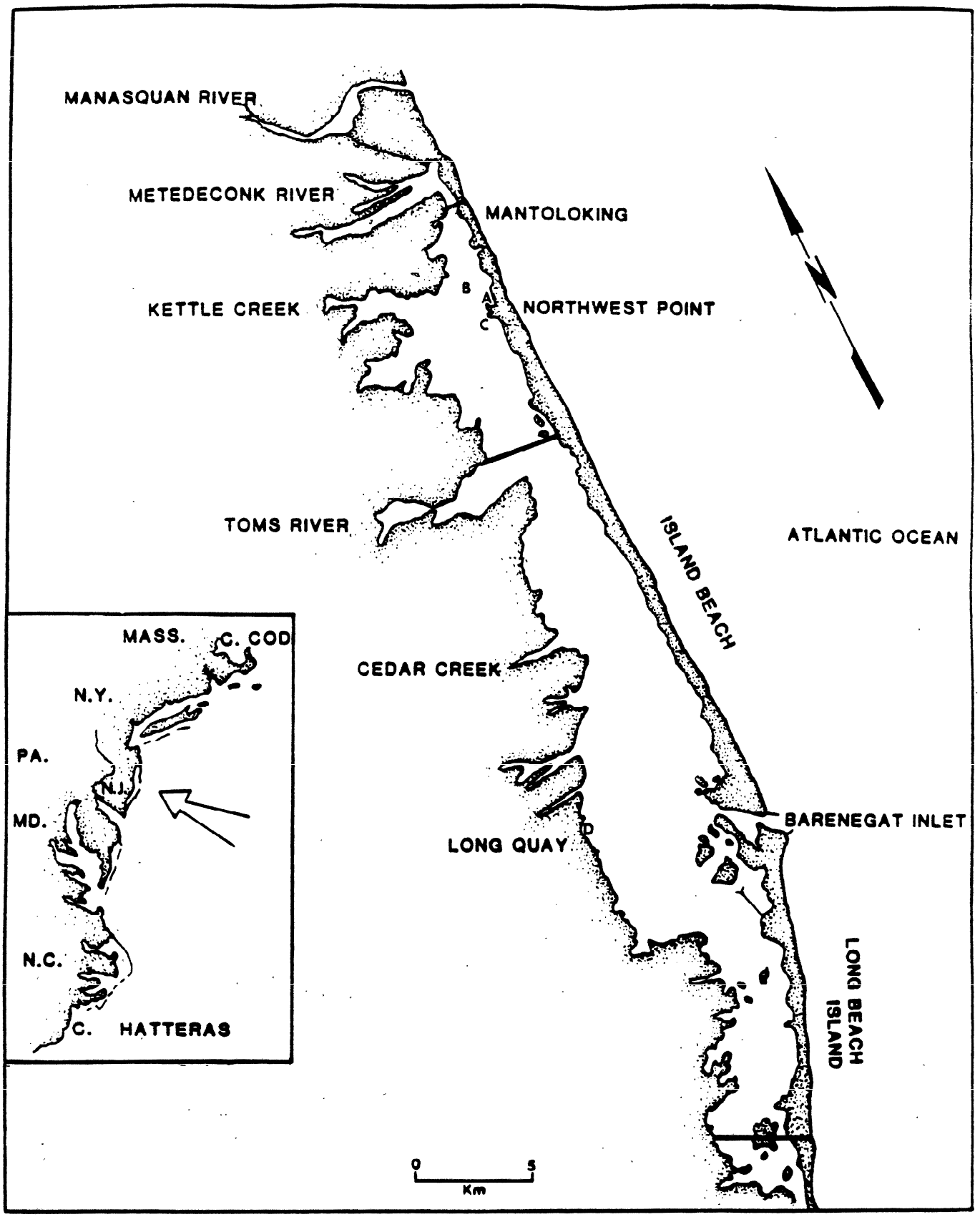

Figure 1a. Locations of sediment-water nutrient flux study sites in Barnegat Bay. A = vegetated site 1; B = silt-clay (mud) site; C = vegetated site 2; D = marina site. Map adapted from Kennish and Lutz (1984).

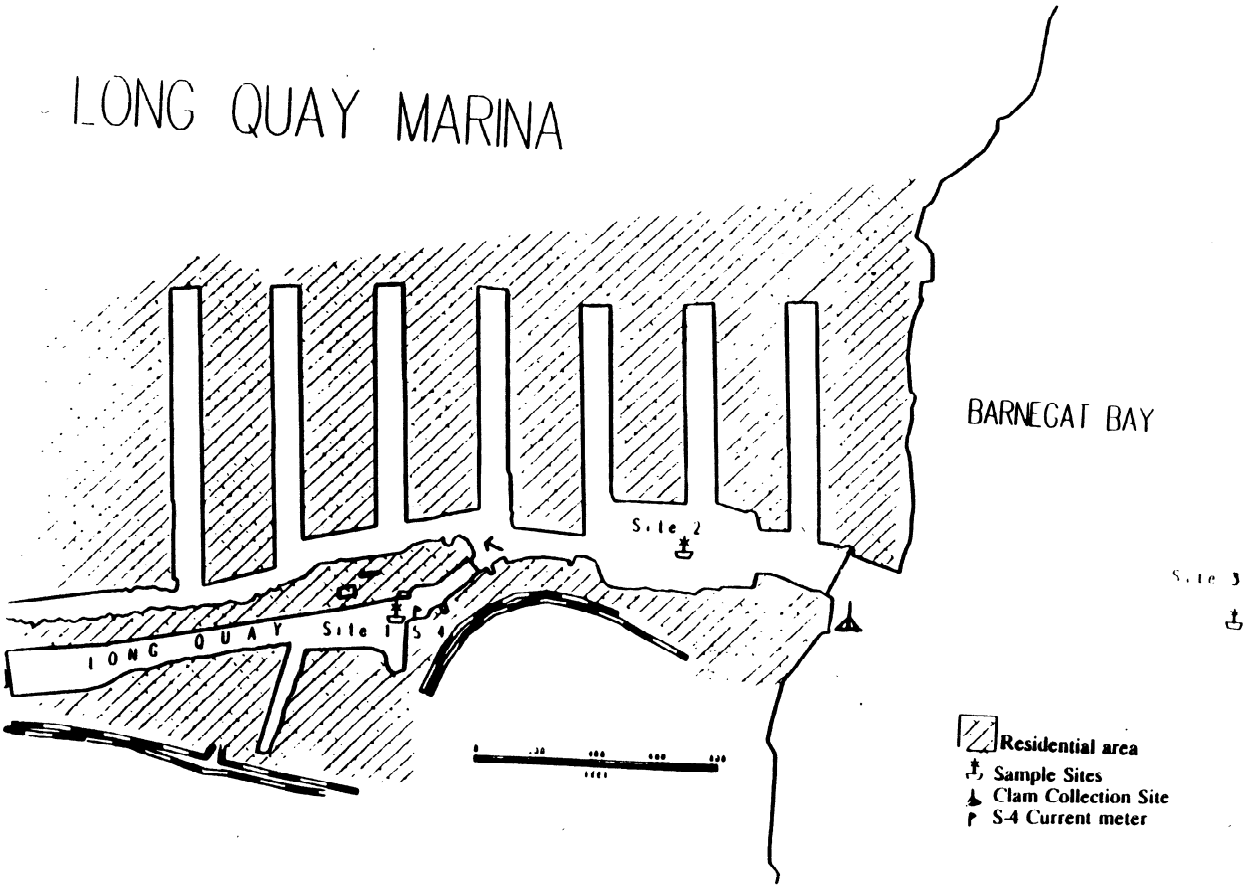

Figure 1b. Approximate location (indicated by arrow) of sediment-water nutrient flux study sites near Long Quay Marina.

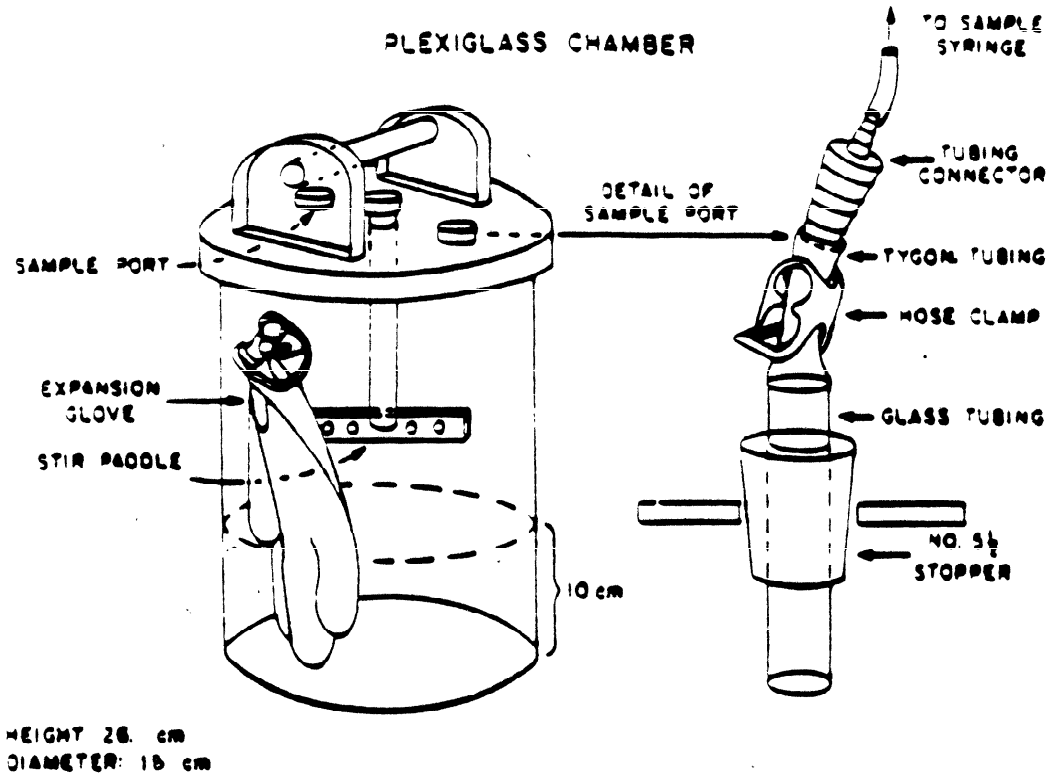

Figure 2. Schematic of benthic chambers used for <u>in</u> <u>situ</u> sediment-water flux measurements (modified from Nowicki and Nixon 1985a).

due to water column processes. The control bottles allow isolation of near bottom planktonic production and sediment organic matter decomposition (benthic respiration), as discussed below.

Time series samples for nutrient analyses were taken from the chambers and control bottles with 60-ml plastic syringes fitted with 4-mm diameter tygon tubing. An oxygen probe was inserted into each chamber through a special port at each sampling time to determine oxygen concentration in the water inside the chambers. Samples were taken approximately 1, 3 and 6 h after chamber deployment. While chambers were deployed as carefully as possible, some sediment disturbance was unavoidable. Therefore, initial samples were taken approximately one hour after chamber deployment to allow any sediment resuspended during chamber deployment to settle and disturbed organisms to acclimate. All samples were kept in the dark on ice. Ammonia samples (unfiltered) were analyzed immediately upon return to the laboratory. Samples for nitrite plus nitrate and phosphate were filtered immediately upon return to the Nutrient Laboratory at the Academy of Natural Sciences (vegetated site 1) or filtered on shore in a temporary lab set-up immediately after collection (all other sites). The filtered samples were frozen and later analyzed by the NJDEP Bureau of Marine Water Classification and Analysis laboratory at Leeds Point.

During an incubation, light meter measurements were made throughout the water column. Temperature and salinity of near surface waters were also recorded.

Sediment-water nutrient and oxygen fluxes were calculated based on the time rate of change in concentration of nutrients or oxygen inside the chambers after correcting for concentration changes in control bottles, the volume of water inside the chamber, and the surface area of sediment as follows:

$$\text{Flux (umole } m^{-2}h^{-1}) = \frac{(\Delta C - \Delta c) \times V}{A}$$

where C and c are the time rates of change in concentration in the chamber water (C) or control (c) bottles calculated from linear regression analysis of the data in units of umole/L/h, V equals chamber water volume in liters, A equals cross-sectional area of chamber in m^2.

Based on these calculations, rates of oxygen consumption in the dark chambers are a measure of benthic organic matter decomposition (benthic respiration). Rates of oxygen production in the light chambers are a measure of net photosynthesis by benthic algae and macrophytes (e.g., Zostera). The sum of oxygen

fluxes in the dark and in the light is a measure of gross benthic photosynthesis.

Sediment Trap Collections

The quantity of particulate N and P deposited in the sediments was measured using sediment traps. Sediment traps have been used extensively to measure the vertical flux of particulate matter. The major problem in the past with the use of sediment traps in estuaries is that they collect not only newly deposited material but also resuspended material. Resuspension often greatly exceeds the newly deposited material.

In order to overcome the resuspension problem, we isolated columns of water from resuspension of bottom sediments for short periods of time. The sedimenting material was collected in a series of sediment traps deployed for 24-h periods over a period of approximately 3 to 5 days. The objective of the enclosures was to isolate a column of water from further resuspension of bottom sediments long enough to measure new deposition of organic P and N, and briefly enough to avoid measurably altering the natural rate of organic sedimentation. The assumption was that the rate of sedimentation of newly deposited (not resuspended) organic matter inside the enclosures is the same as that outside the enclosures, if the primary production rates are similar in both. These sediment traps and enclosures underwent considerable development in Barnegat Bay during August and September.

Experiments with various construction materials, methods for ensuring adequate surface floatation to prevent waves from breaking over the top, procedures for filling the enclosures with a column of water, methods for anchoring the enclosure, methods of deploying and retrieving the sediment traps, measurements of the turbulence regime, and measurements of primary production rates, light regimes and dissolved oxygen were carried out. The enclosures are cylindrical (1.0-m diameter) and made of clear, 6-mil plastic sheeting with hoop supports at approximately 0.5-m intervals (Fig. 3). The tubes are anchored at the bottom with a flexible ring filled with sand, open to the air at the top, and float at the surface. A collar extends approximately 20 cm above the flotation at the surface of the water to prevent outside water from entering. The enclosures were filled by vertically collapsing the enclosure, floating it at the surface and then slowly allowing the bottom to sink to the sediments. Inside the enclosure, near the bottom, a single layer of fiberglass screening was used to further prevent bottom materials from being resuspended during storm events while allowing nutrients to diffuse from the sediments to the water column. Cylindrical traps with a height-to-diameter ratio of 3 were used to minimize resuspension in the traps. The traps were located away from the walls of the enclosure in approximately the center of the

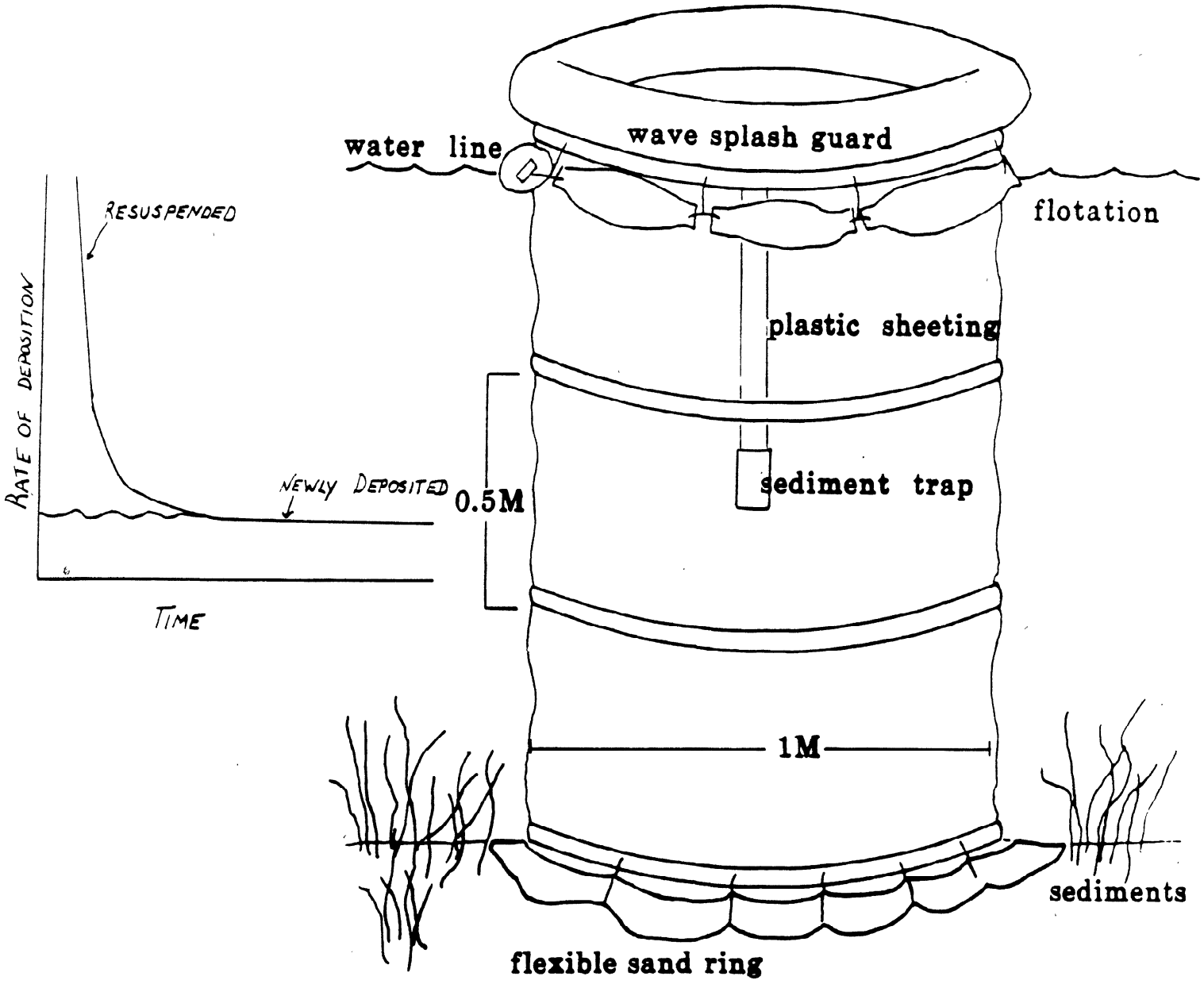

Figure 3. Water column enclosure developed and used to isolate a section of the water column from resuspended material and collect newly deposited organic matter. See text for a more complete description of construction and use.

enclosure. Traps were also deployed outside the enclosure for comparison.

Repeated measurements of the primary production rates (light-dark bottle O_2 measurements), light intensities, and oxygen profiles inside and outside the enclosures were made during August and September. These parameters were tested for enclosure deployment periods of up to 10 days. Visual observations of the rate of dye dispersion inside and outside the enclosures were made and indicated that the turbulence inside and outside the enclosures was similar.

Measurements of sediment deposition rates were made during September at the vegetated study site using the water column enclosures with sediment traps as described above. We also constructed and deployed (22 September) a water column enclosure at the silt-clay study site where the water is approximately 2.5-m deep compared to 1.5-m deep at the vegetated site. However, the strong wind conditions and stormy weather in late September damaged the enclosure and thus we were not able to obtain deposition measurements at that or additional locations. The shortness of the field season this year (basically two months) resulted in deposition being measured at only one location.

Planktonic Primary Production

Phytoplankton primary production and plankton respiration rates were calculated based on measured oxygen changes in duplicate 300-ml BOD bottles incubated *in situ* (two initial bottles, two final dark bottles, two final light bottles). Samples were incubated at 30-cm depth from approximately 1000 h to 1400 h. Oxygen concentrations were determined by Winkler titration (Carritt and Carpenter 1966) with 0.025 N thiosulfate. All samples were titrated in duplicate. Rates of gross planktonic primary production were calculated as the sum of oxygen concentration increases in light bottles plus oxygen consumption in dark bottles.

Sample Analysis

Soluble reactive phosphate (hereafter referred to as phosphate) and nitrate plus nitrite (hereafter referred to as nitrate) concentrations in water samples collected from the benthic flux chambers were analyzed by the NJDEP Leeds Point Laboratory. Phosphate concentrations were measured by the molybdenum blue method (Leeds Point Method #300) and nitrate concentrations by cadmium reduction (Leeds Point Method #201), both on an auto-analyzer. Sample turbidity blanks were not analyzed for nitrate or phosphate by the Leeds Point Laboratory. Turbidity blanks for Barnegat Bay samples taken during Year II of

this study were analyzed by the Academy of Natural Sciences Nutrient Laboratory. We found that turbidity blanks were insignificant for nitrate, but were a significant fraction of sample absorbance for phosphate. Thus, the phosphate concentrations reported in Year I are likely overestimates of the absolute phosphate concentrations. However, this should not affect calculated concentration changes from the benthic flux chambers and thus would not affect calculated PO_4 flux rates or conclusions drawn from the benthic flux data. Distilled water blanks, standards, and spikes were analyzed with each set of samples. Standard concentrations ranged from 0.16 uM to 1.6 uM for phosphate and 0.36 uM to 2.14 uM for nitrate.

Ammonia, particulate N and particulate P samples were analyzed in the Nutrient Laboratory at the Academy of Natural Sciences. Analysis of all samples was carried out according to our standard laboratory protocols. Ammonia concentrations in water samples collected from the benthic flux chambers were determined by the phenol hypochlorite method of Solorzano (1969). Turbidity blanks were analyzed for each sample. Sediment trap material was filtered through precombusted (500^{o}C) glass fiber filters and analyzed for particulate N and P. Particulate P was determined by persulfate digestion according to Martin and Knauer (1973) and colorimetric analysis using the method of Murphy and Riley (1962). Particulate N was determined by persulfate digestion followed by colorimetric analysis of nitrate using the cadmium reduction method (Technicon 1977). All samples analyzed for ammonia, total N and total P were analyzed in duplicate. Sample turbidity blanks were analyzed for each NH_4^+ sample. Turbidity blanks for ammonia were significant. Distilled water blanks (reagent blanks) and standards (at least four different concentrations) were analyzed in triplicate with each set of samples. Reagent blanks for ammonia, total N and total P were small compared to sample absorbances. Standard concentrations covered the range of concentrations found in the samples.

Changes in Original Study Design

The proposed study as outlined in the Schedule of Project Tasks was scheduled to begin with methods development in May with actual measurements beginning in July and continuing through August. However, because the funding did not begin until mid-July the entire methods development and field measurements for sediment-water nutrient fluxes and sediment deposition measurements was compressed into essentially two months. This resulted in the following changes in the study design.

During our survey of bottom types in Barnegat Bay we located areas in the northern Bay with silt-clay unvegetated sediments, sandy vegetated and sandy unvegetated sediments for the sediment-water nutrient flux measurements. The sandy unvegetated areas

were difficult to locate as the seagrasses covered a much more extensive area of the Bay than we had anticipated. When we returned in September to the area previously located as an unvegetated sandy area we could no longer find an area that was not vegetated or covered by dense mats of decomposing vegetation. Because of the rapidly deteriorating weather conditions at the end of September and the difficulty of coordinating boats and SCUBA divers, we made the decision to proceed with sediment-water nutrient flux measurements at that location, which was now a vegetated site.

The second change in the study related to the sediment deposition measurements. Analysis of the data to date suggests that we have successfully developed a method to measure, for the first time, organic matter deposition rates in shallow estuaries. As outlined above, this method uses water column enclosures (or resuspended sediment exclosures). As part of the methods development phase we had originally planned to make measurements of primary production rates, phytoplankton composition and nutrient concentrations inside and outside the enclosures to check for differences in organic matter production rates. We also had planned to test variability between replicate traps. However, again because of time constraints we had to cut back on some of the analyses. We chose to concentrate on comparing measurements of primary production rates inside and outside the enclosures as the best measure of organic matter production rates in both areas. We also made some measurements of N and P concentrations inside and outside the enclosures. We were preparing to add measurements of phytoplankton composition, more extensive nutrient concentration measurements, and to compare variability between traps when the weather conditions forced an end to the field season. We plan to include these in next year's program.

RESULTS

The sediments at all four sites examined during the late summer/early fall in Barnegat Bay are active sites for decomposition of organic matter as shown by the oxygen consumption rates under dark conditions (Table 1; Figs. 4a, 5a, 6a, 7a; at the end of this section). Highest rates of oxygen consumption in the dark were measured at the vegetated site 1 (average -3660 ug-at $m^{-2}h^{-1}$). Average oxygen consumption rates in the dark at the other sites were -2270 ug-at $m^{-2}h^{-1}$ (vegetated site 2), -1015 ug-at $m^{-2}h^{-1}$ (marina), and -740 ug-at $m^{-2}h^{-1}$ (silt-clay site).

The average calculated rate of oxygen consumption at the silt-clay site may be an underestimate as one of the two dark chambers (D1) showed a dramatic drop in oxygen at the second sampling interval and then an increase in concentration for the third sample (Fig. 6a) resulting in a calculated oxygen consumption rate of approximately -250 ug-at $m^{-2}h^{-1}$. (The low concentration measured at the second sample interval was likely due to the expansion glove inside the chamber covering the O_2 probe. Nitrate, phosphate and ammonia concentrations measured at the second sample interval do not show unusual behavior, which is as expected if the oxygen value is erroneous due to glove obstruction of the oxygen probe.) The O_2 rate in chamber D2 (-1230 ug-at $m^{-2}h^{-1}$) is likely a better estimate of the true rate.

There was net photosynthesis in the daytime by benthic algae and/or sea grasses at both the vegetated site 1 and the marina location, as demonstrated by the net increases in oxygen concentration in the full light chambers at those locations. At the vegetated site 1, the water in one of the light chambers (L1) was very turbid, likely due to the stirrer mixing up sediment/detritus or due to animal activity. The decreased light level inside that chamber probably accounts for the net oxygen consumption in that chamber (-520 ug-at $m^{-2}h^{-1}$) compared to the other light chamber with a relatively large net oxygen production rate (+1060 ug-at O $m^{-2}h^{-1}$). At the silt-clay site and vegetated site 2, there was no benthic photosynthesis as oxygen consumption rates were similar in the light, intermediate and dark incubated chambers (Figs. 5a, 7a; Table 1).

It should be noted that the marina site was not in the deeper channel area of the marina, but on a shallow sandy-silt bar at the mouth of the marina, and thus may not be typical of the deeper sediments in the marina. The location for the benthic flux studies in the marina was chosen to be near the location used for clam/bacteria studies carried out by NJDEP DSR during 1988.

There were only a few systematic increases or decreases in the concentrations of ammonia, nitrate or phosphate inside the benthic flux chambers at any of the four locations in the light, intermediate, or dark incubations (Figs. 4b-d, 5b-d, 6b-d, 7b-d).

Linear regression analysis of the nutrient concentration data demonstrated that in only a few cases were the changes in concentration versus time significantly different from zero (at alpha = 0.10) (Table 2, at the end of this section). If the slope of the regression line was significantly different from zero, sediment-water fluxes were calculated (Table 2). Minimum levels of detection of sediment-water fluxes were estimated to be approximately 4 ug-at NH_4 $m^{-2}h^{-1}$, 2 ug-at NO_3 $m^{-2}h^{-1}$, and 2 ug-at PO_4 $m^{-2}h^{-1}$ based on minimum detectable concentration changes, water volume in chambers, and incubation times. In a number of cases (e.g., silt-clay site nitrate fluxes in L1 and M2 and phosphate fluxes in D1 and D2), the calculated sediment-water fluxes were less than the estimated minimum detectable fluxes and are therefore reported as greater than zero but less than the minimum detectable flux.

Phytoplankton net primary production rates measured between 31 August and 16 September 1988 at the vegetated site 1 ranged from 250 to 500 mg O_2 $m^{-3}h^{-1}$ (Table 3). Phytoplankton net primary production rates measured during the benthic fluxes at the silt-clay, marina and vegetated site 2 locations were 250, 400 and 250 mg O_2 $m^{-3}h^{-1}$, respectively (Table 3).

Planktonic primary production rates measured inside the water column enclosures at vegetated site 1 were not significantly different (P=0.01; paired t-test) from those measured outside the enclosures at that site.

Particulate organic nitrogen deposition rates measured using sediment traps inside the enclosures ranged from 2.3 to 9.2 mmol N $m^{-2}d^{-1}$ (Table 4). Particulate phosphorus deposition rates ranged from 0.1 to 0.48 mmol P $m^{-2}d^{-1}$ (Table 4). The N:P ratio of particulate material inside the sediments traps ranged from 12 to 32.

Table 1. Sediment-water dissolved oxygen fluxes at four locations in Barnegat Bay, September 1988. Measurements made *in situ* with clear benthic chambers (L1, L2), chambers with 50% light transmittance (M1, M2) or with dark chambers (D1, D2). A negative flux represents a net uptake of oxygen by the sediments (i.e., net respiration); a positive flux represents a net release of oxygen from the sediments (i.e., net photosynthesis).

Site/Treatment	Date	Water Depth (m)	Near-Bottom Mid-Day Light Levels (uE $m^{-2}sec^{-1}$)	O_2 Flux (ug-at $m^{-2}h^{-1}$)	Comments
Vegetated Site 1					
L1	20 Sept.	1.5	4	-520	turbid water in chamber
L2				+1060	
M1				-980	
M2				-2200	
D1				-3530	
D2				-3790	
Silt-Clay Site					
L1	22 Sept.	2.3	10	-950	
L2				-500	
M1				-915	
M2				260	
D1				-250	only two points
D2				-1230	
Marina					
L1	26 Sept.	0.8	30	+840	
L2				-770	turbid water in chamber
M1				160	
M2				450	
D1				-1310	
D2				-720	
Vegetated Site 2					
L1	29 Sept.	1.2	5	-2670	
L2				-1570	expansion glove fell off
M1				-2690	
M2				-2830	
D1				-1890	only two points
D2				-2650	

OXYGEN CONCENTRATION vs TIME BENTHIC CHAMBERS AT VEGETATED SITE 1

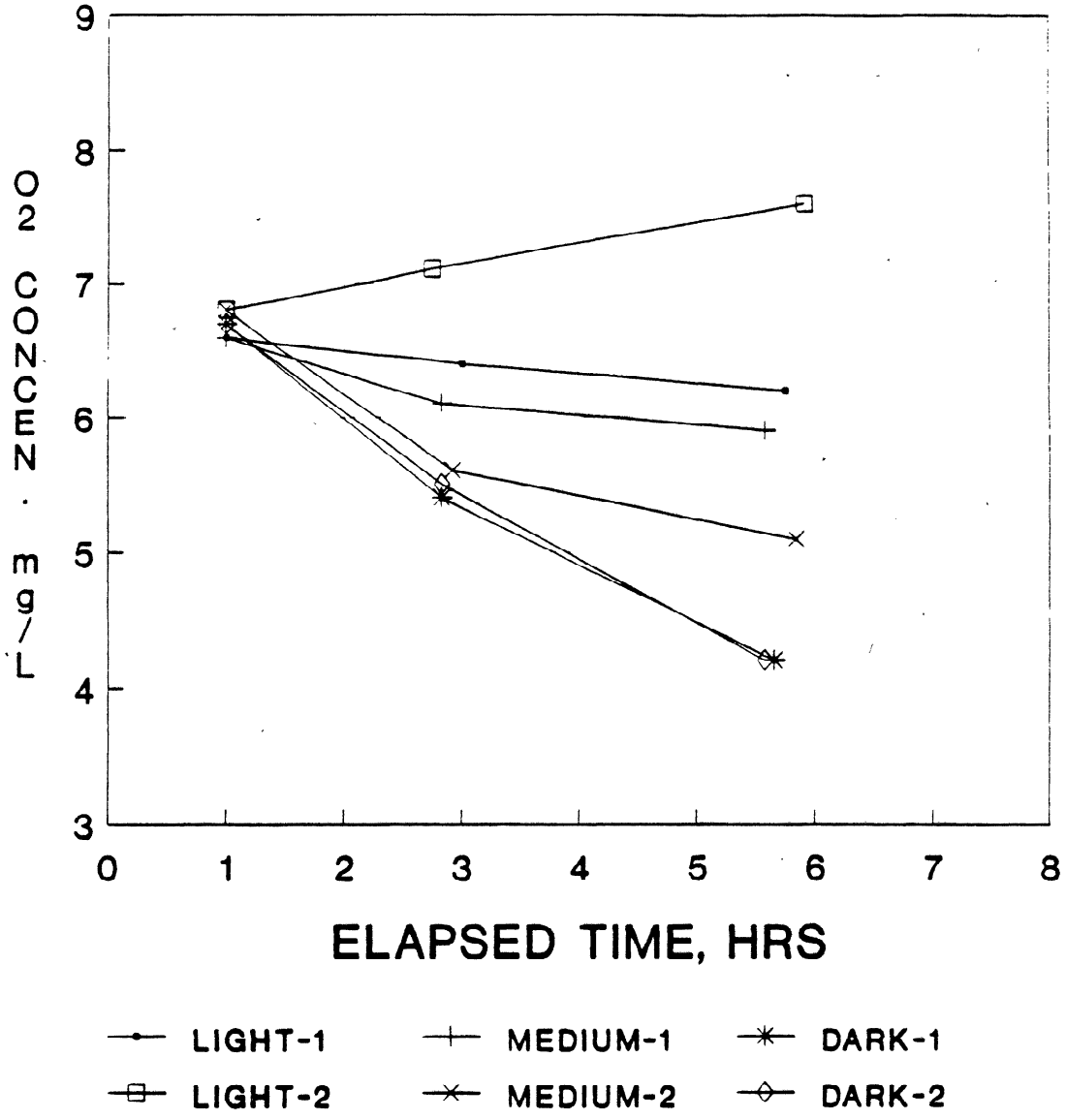

Figure 4a. Oxygen concentration (mg O_2/L) versus time in <u>in</u> <u>situ</u> benthic chambers at vegetated site 1 in Barnegat Bay, September 1988.

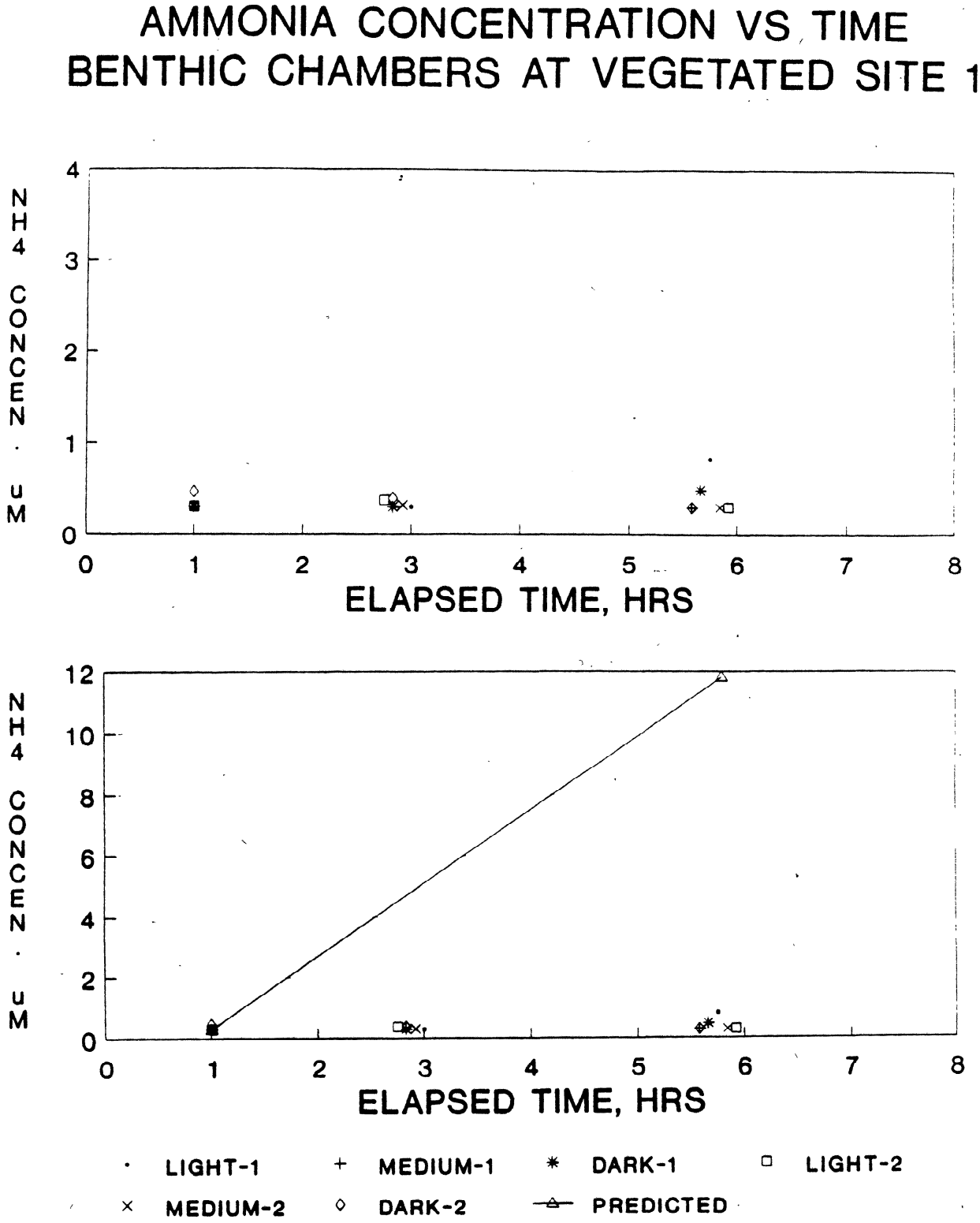

Figure 4b. Measured (top) and measured and predicted (bottom) ammonia concentration (uM) versus time in in situ benthic chambers at vegetated site 1 in Barnegat Bay, September 1988. The line connecting triangles represents predicted ammonia concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

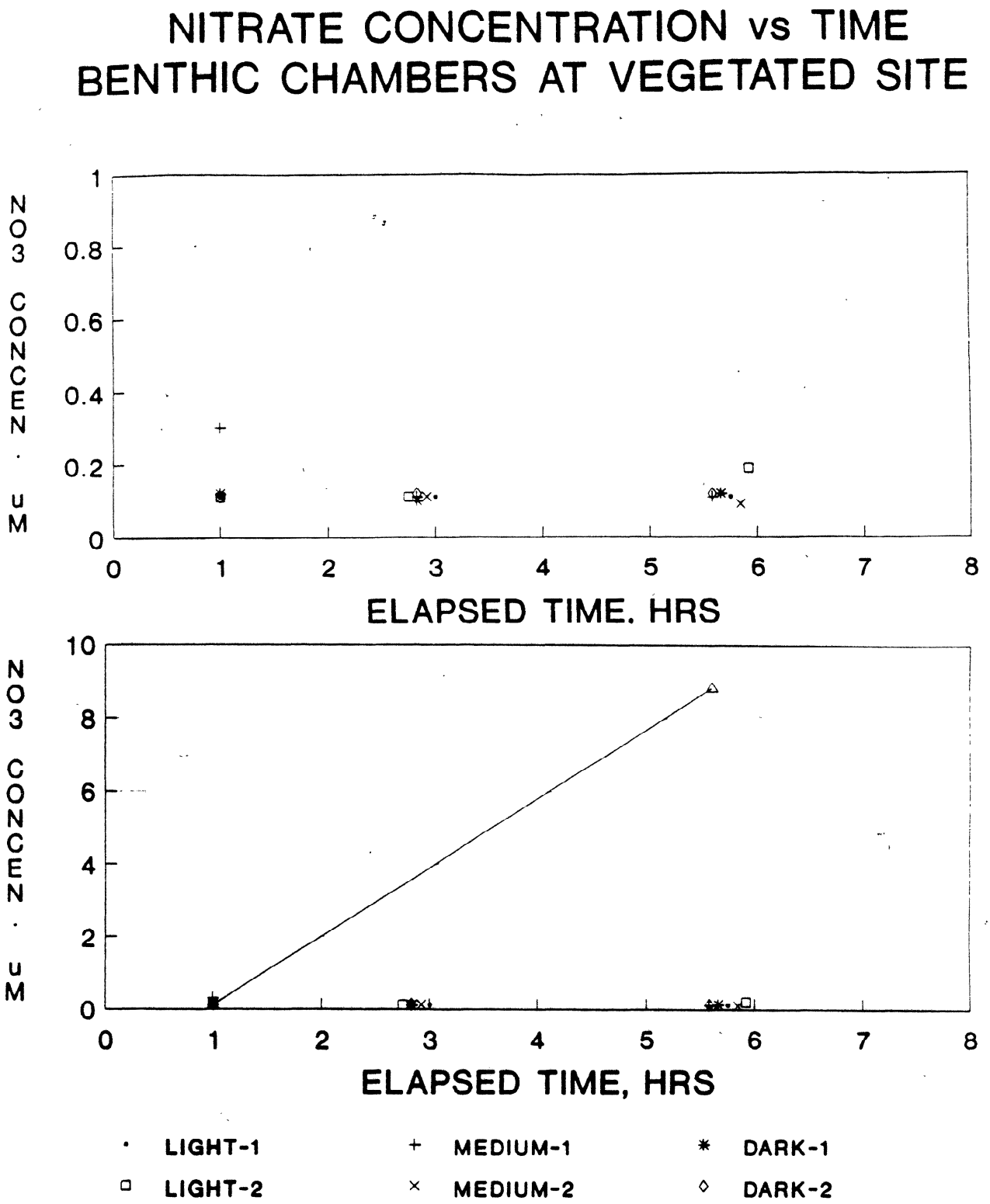

Figure 4c. Measured (top) and measured and predicted (bottom) nitrate concentration (uM) versus time in <u>in situ</u> benthic chambers at vegetated site 1 in Barnegat Bay, September 1988. The line connecting triangles represents predicted nitrate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

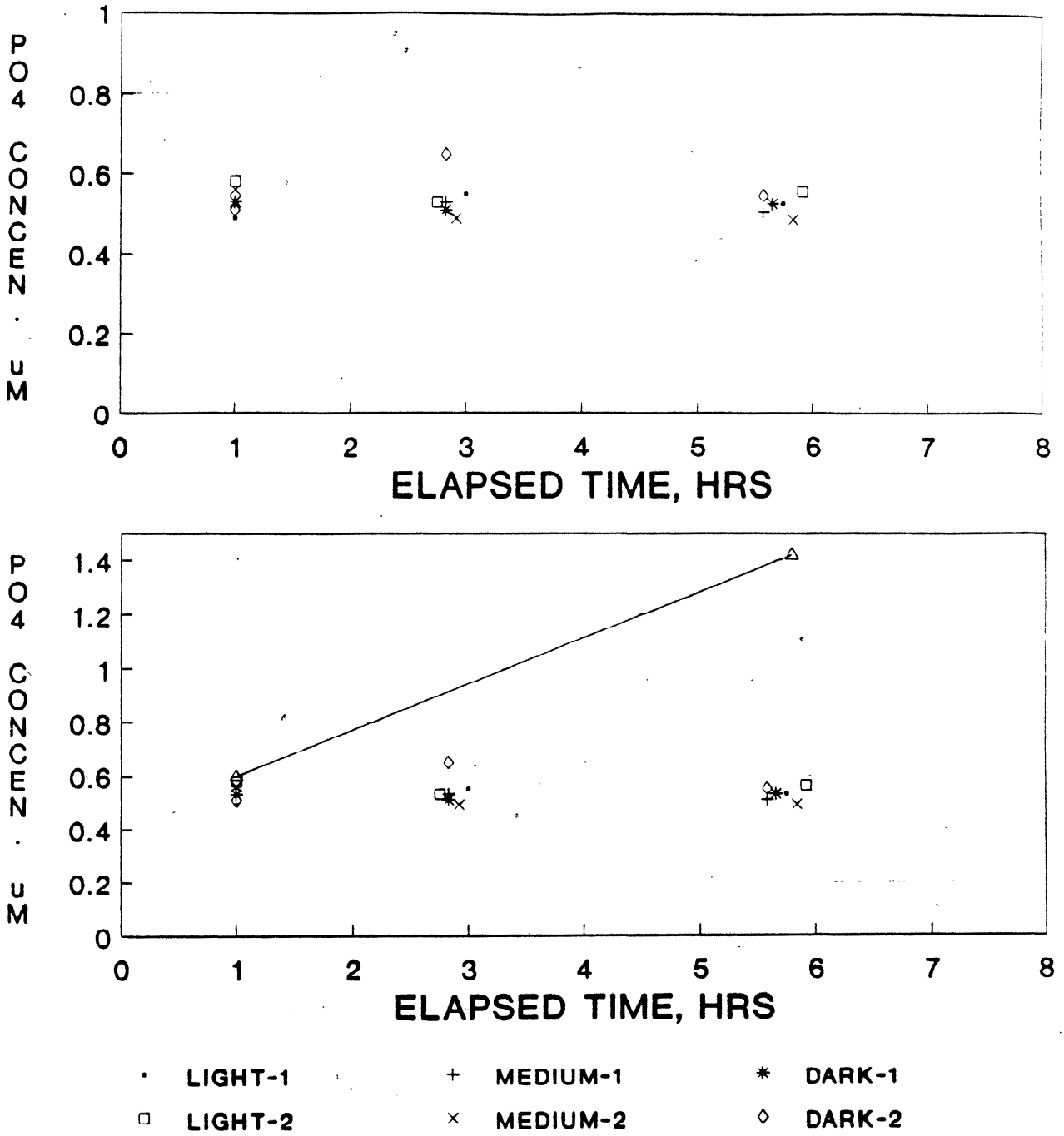

Figure 4d. Measured (top) and measured and predicted (bottom) phosphate concentration (uM) versus time in in situ benthic chambers at vegetated site 1 in Barnegat Bay, September 1988. The line connecting triangles represents predicted phosphate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:P ratio of 212 (atoms), see eq. 1 in text.

OXYGEN CONCENTRATION vs TIME BENTHIC CHAMBERS AT VEGETATED SITE 2

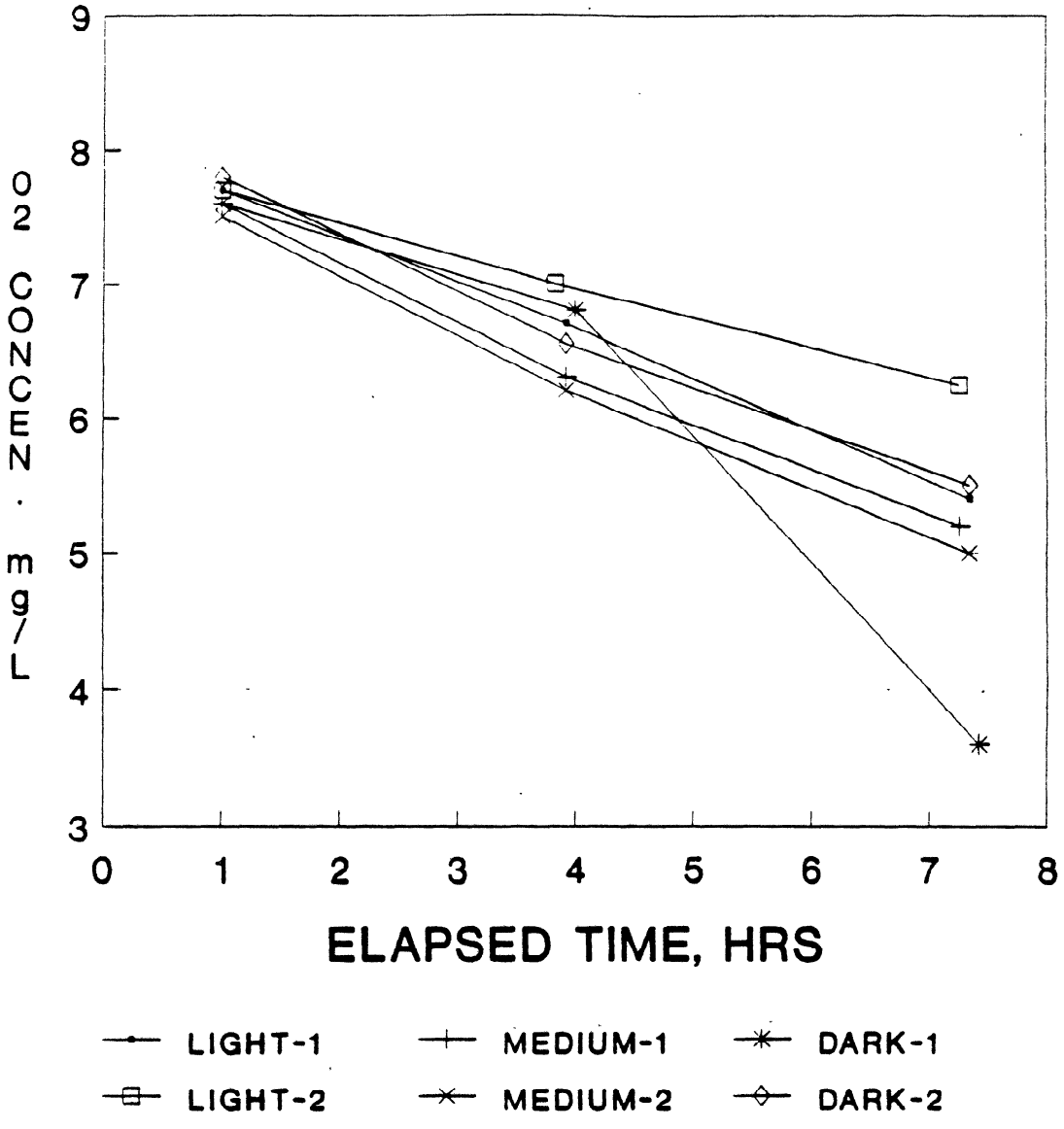

Figure 5a. Oxygen concentration (mg O_2/L) versus time in <u>in situ</u> benthic chambers at vegetated site 2 in Barnegat Bay, September 1988.

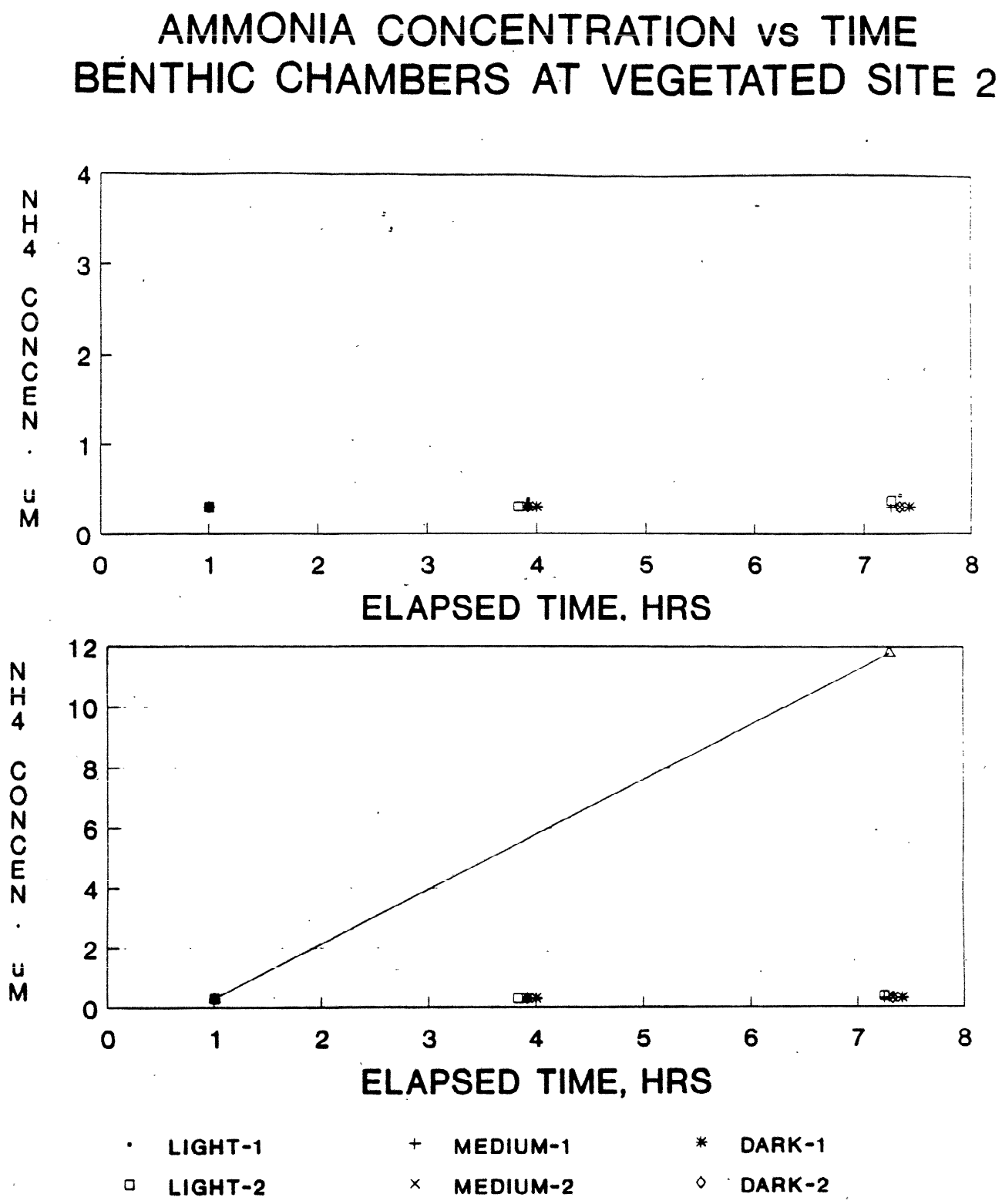

Figure 5b. Measured (top) and measured and predicted (bottom) ammonia concentration (uM) versus time in in situ benthic chambers at vegetated site 2 in Barnegat Bay, September 1988. The line connecting triangles represents predicted ammonia concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

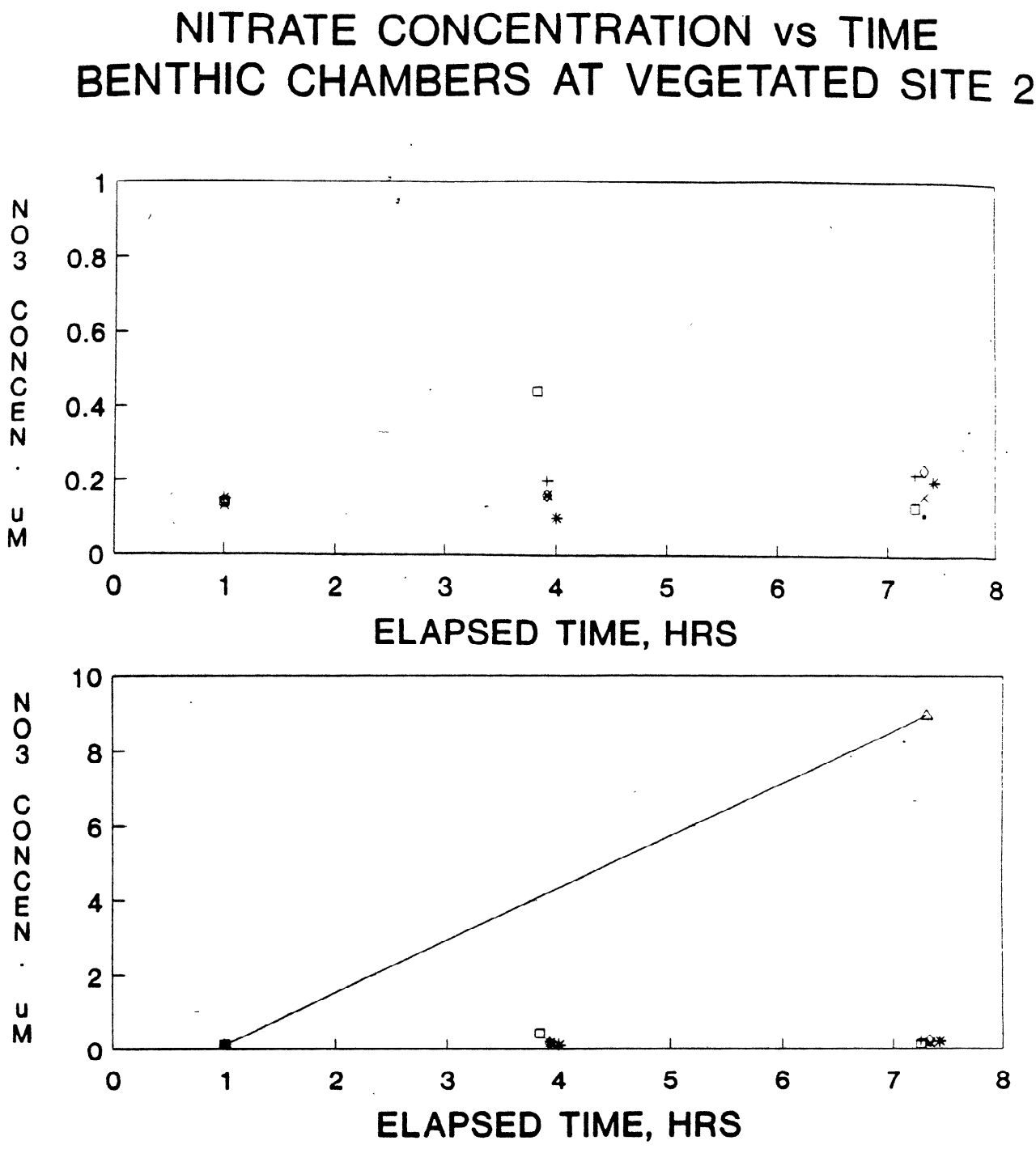

Figure 5c. Measured (top) and measured and predicted (bottom) nitrate concentration (uM) versus time in <u>in situ</u> benthic chambers at vegetated site 2 in Barnegat Bay, September 1988. The line connecting triangles represents predicted nitrate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

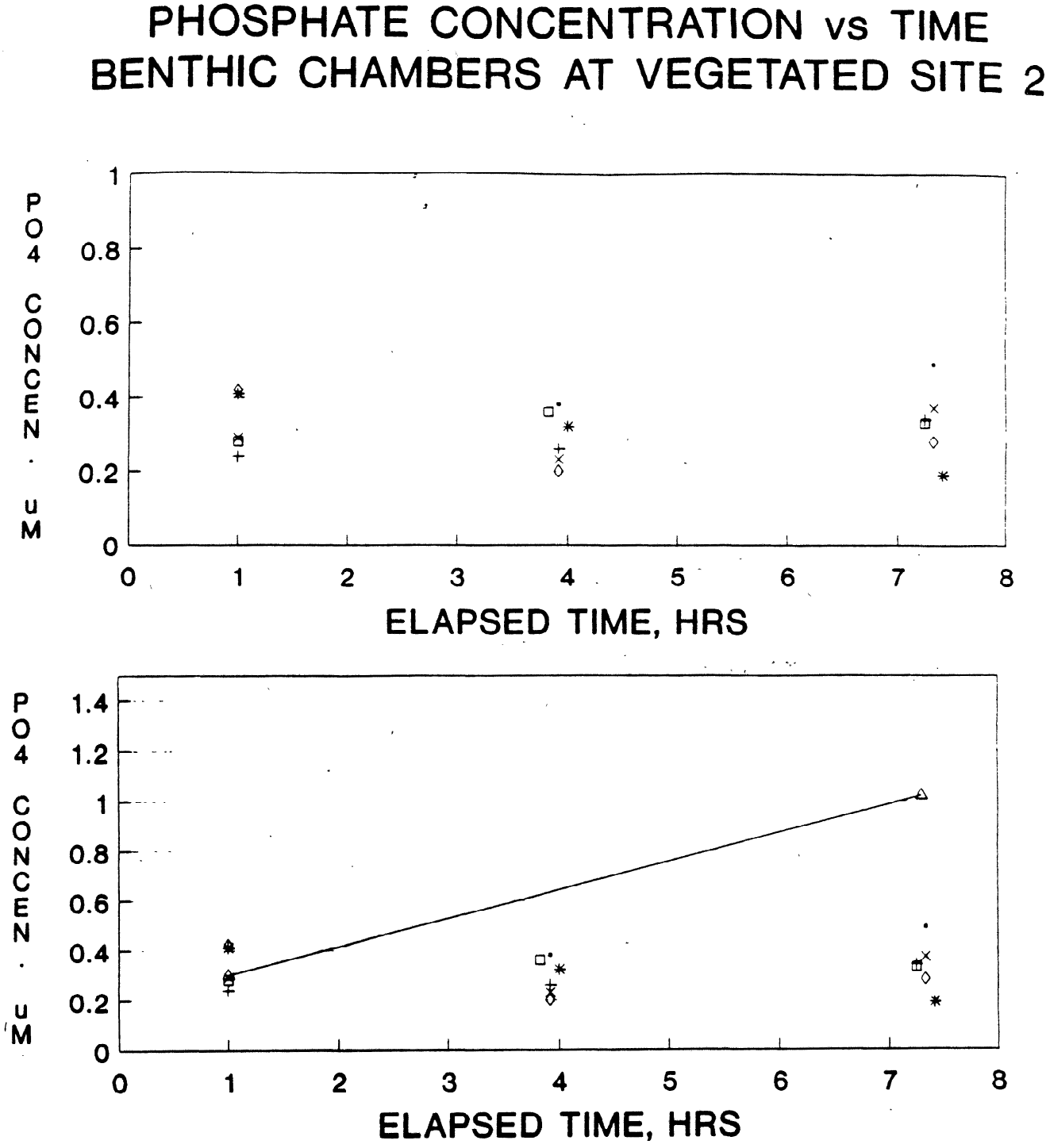

Figure 5d. Measured (top) and measured and predicted (bottom) phosphate concentration (uM) versus time in in situ benthic chambers at vegetated site 2 in Barnegat Bay, September 1988. The line connecting triangles represents predicted phosphate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:P ratio of 212 (atoms), see eq. 1 in text.

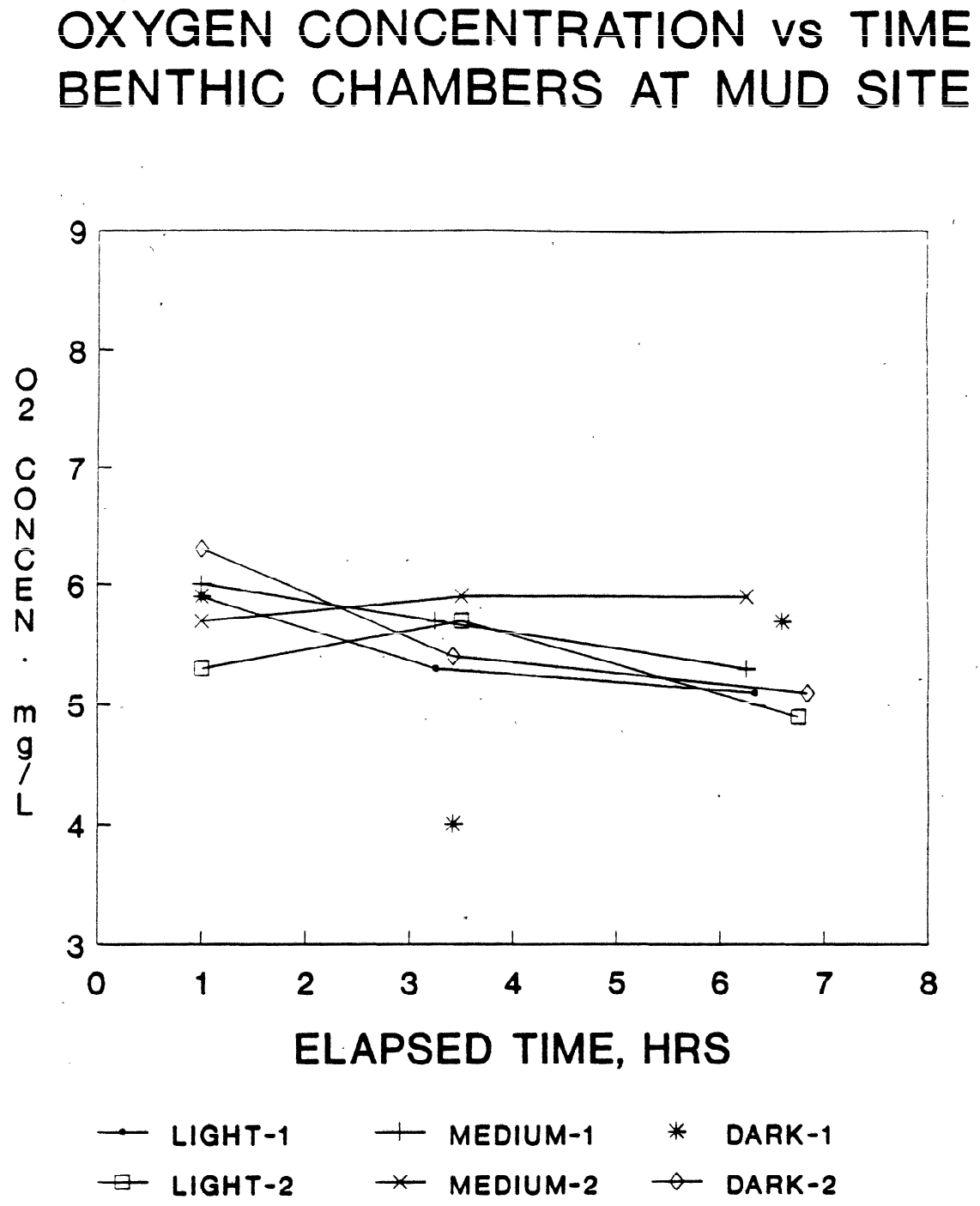

Figure 6a. Oxygen concentration (mg O_2/L) versus time in <u>in situ</u> benthic chambers at the silt-clay (mud) site in Barnegat Bay, September 1988.

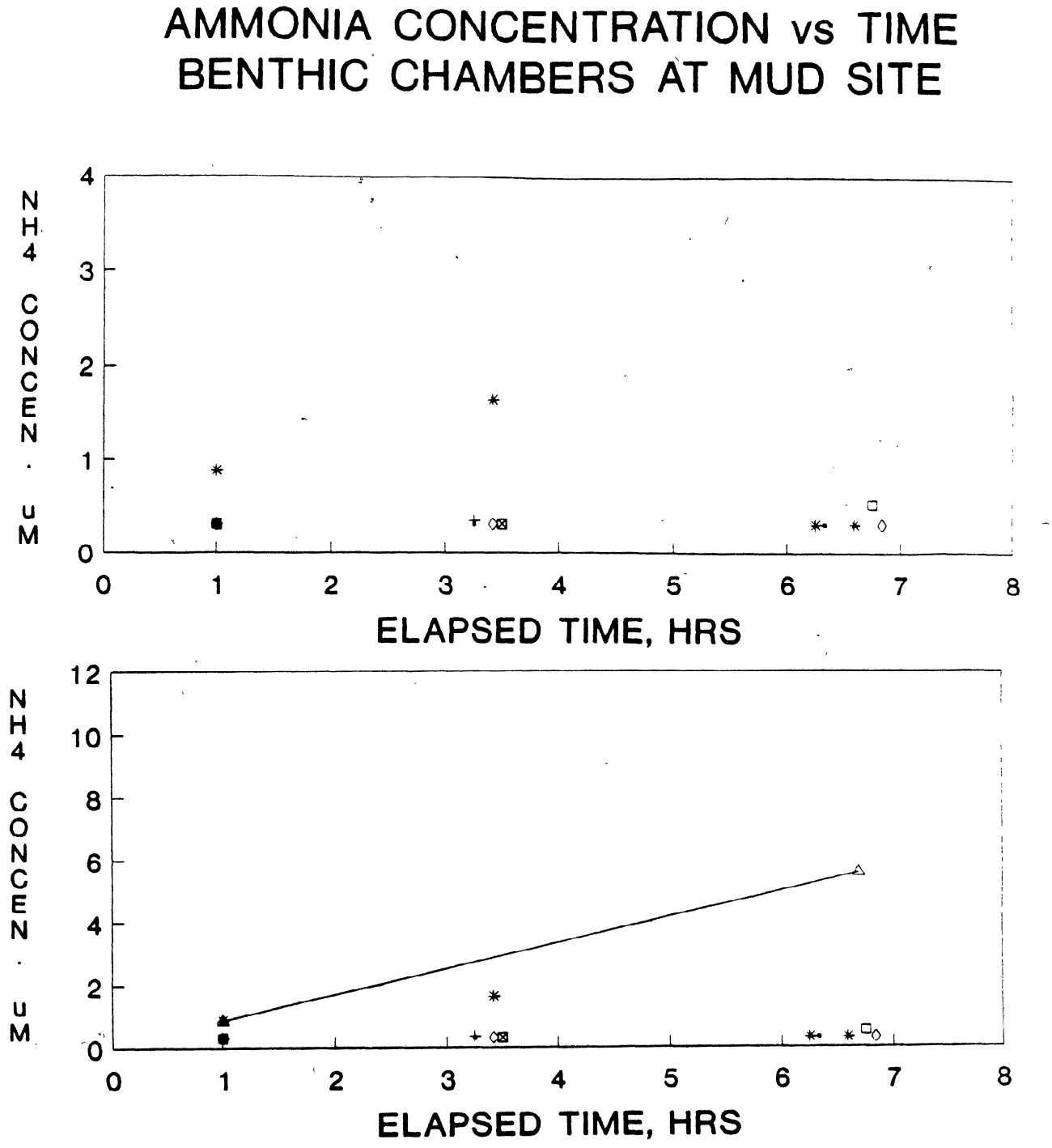

Figure 6b. Measured (top) and measured and predicted (bottom) ammonia concentration (uM) versus time in <u>in situ</u> benthic chambers at the silt-clay site in Barnegat Bay, September 1988. The line connecting triangles represents predicted ammonia concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

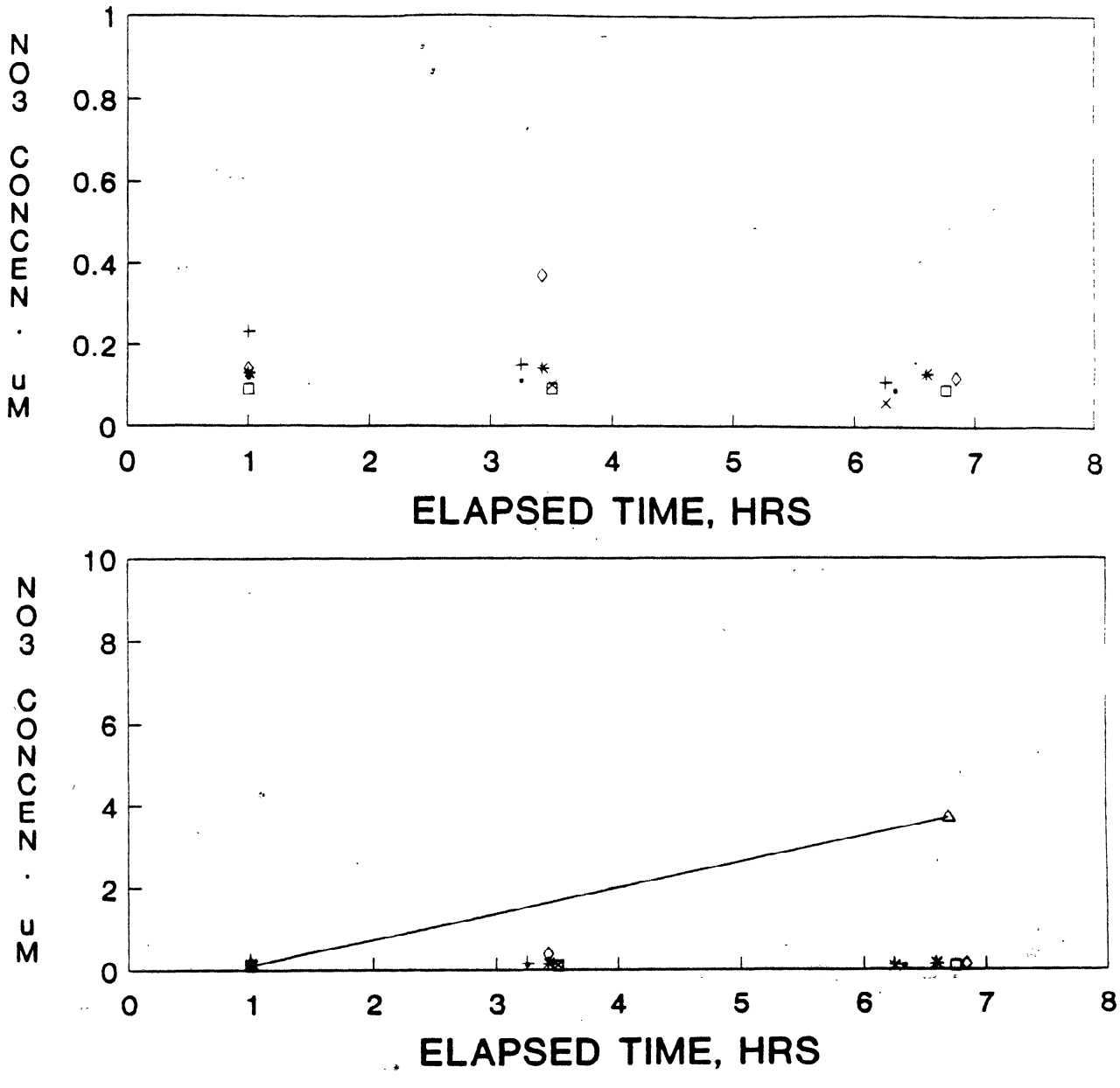

Figure 6c. Measured (top) and measured and predicted (bottom) nitrate concentration (uM) versus time in <u>in situ</u> benthic chambers at the silt-clay (mud) site in Barnegat Bay, September 1988. The line connecting triangles represents predicted nitrate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

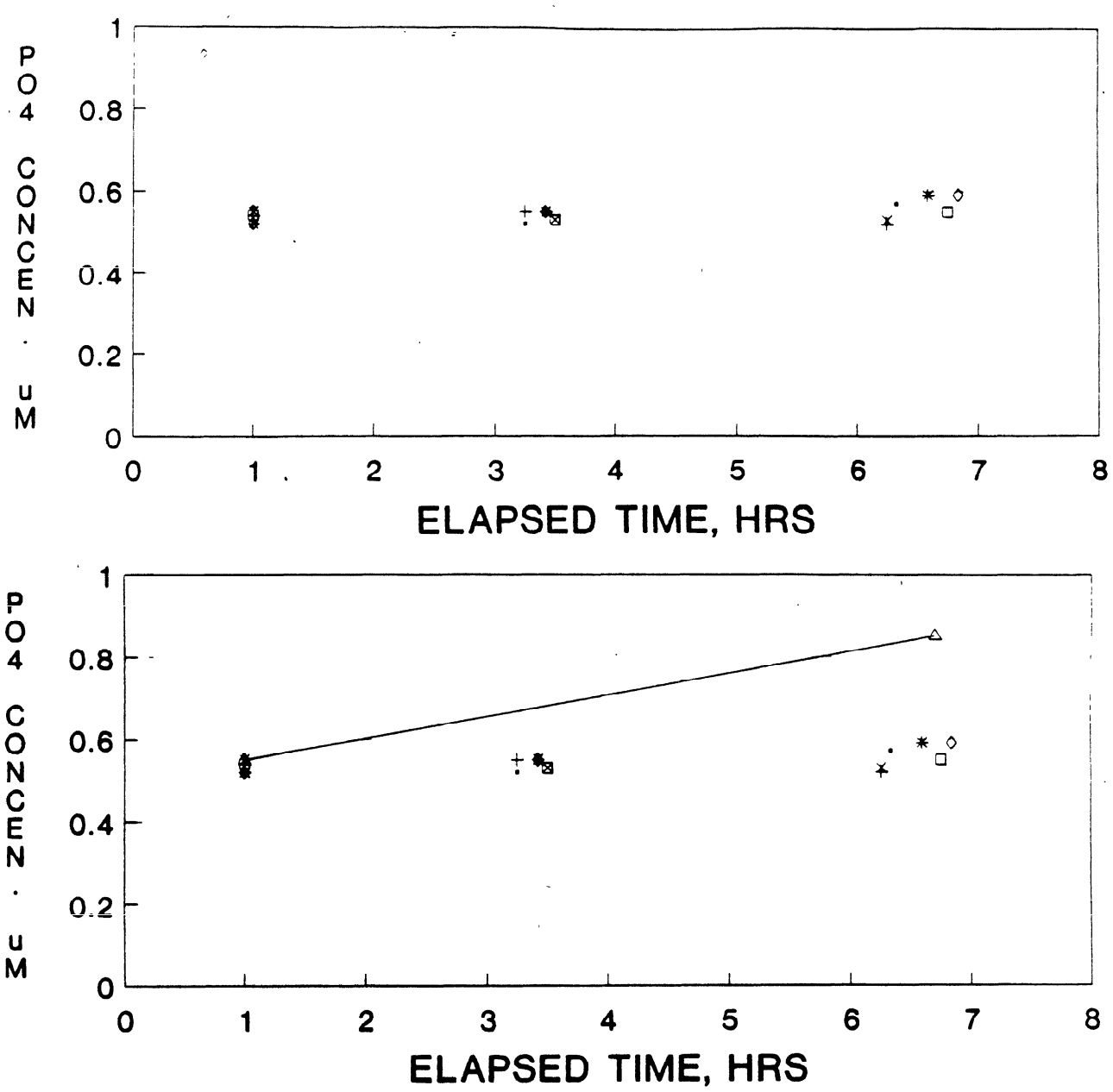

Figure 6d. Measured (top) and measured and predicted (bottom) phosphate concentration (uM) versus time in <u>in situ</u> benthic chambers at the silt-clay (mud) site in Barnegat Bay, September 1988. The line connecting triangles represents predicted phosphate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:P ratio of 212 (atoms), see eq. 1 in text.

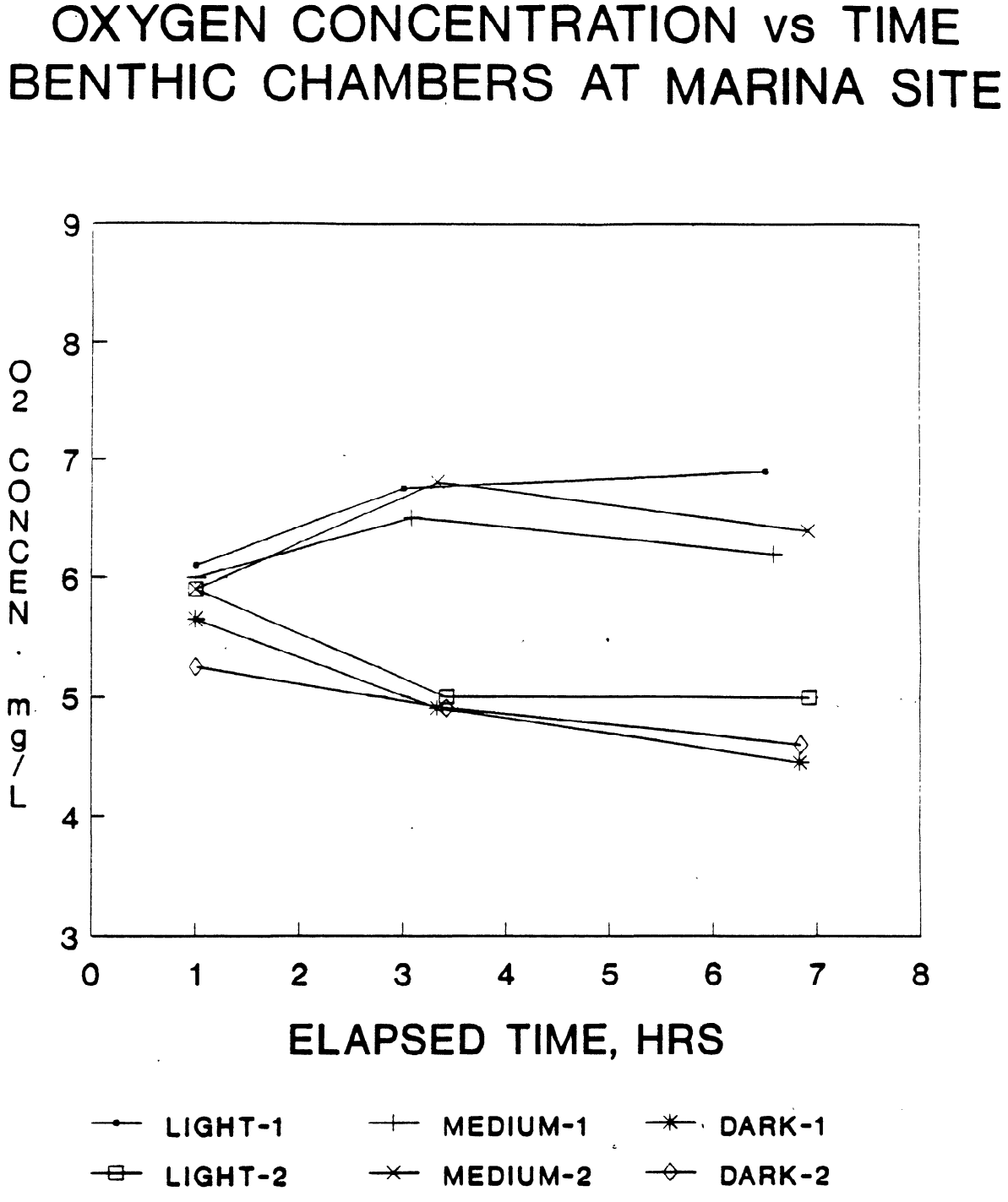

Figure 7a. Oxygen concentration (mg O_2/L) versus time in <u>in situ</u> benthic chambers at the marina site in Barnegat Bay, September 1988.

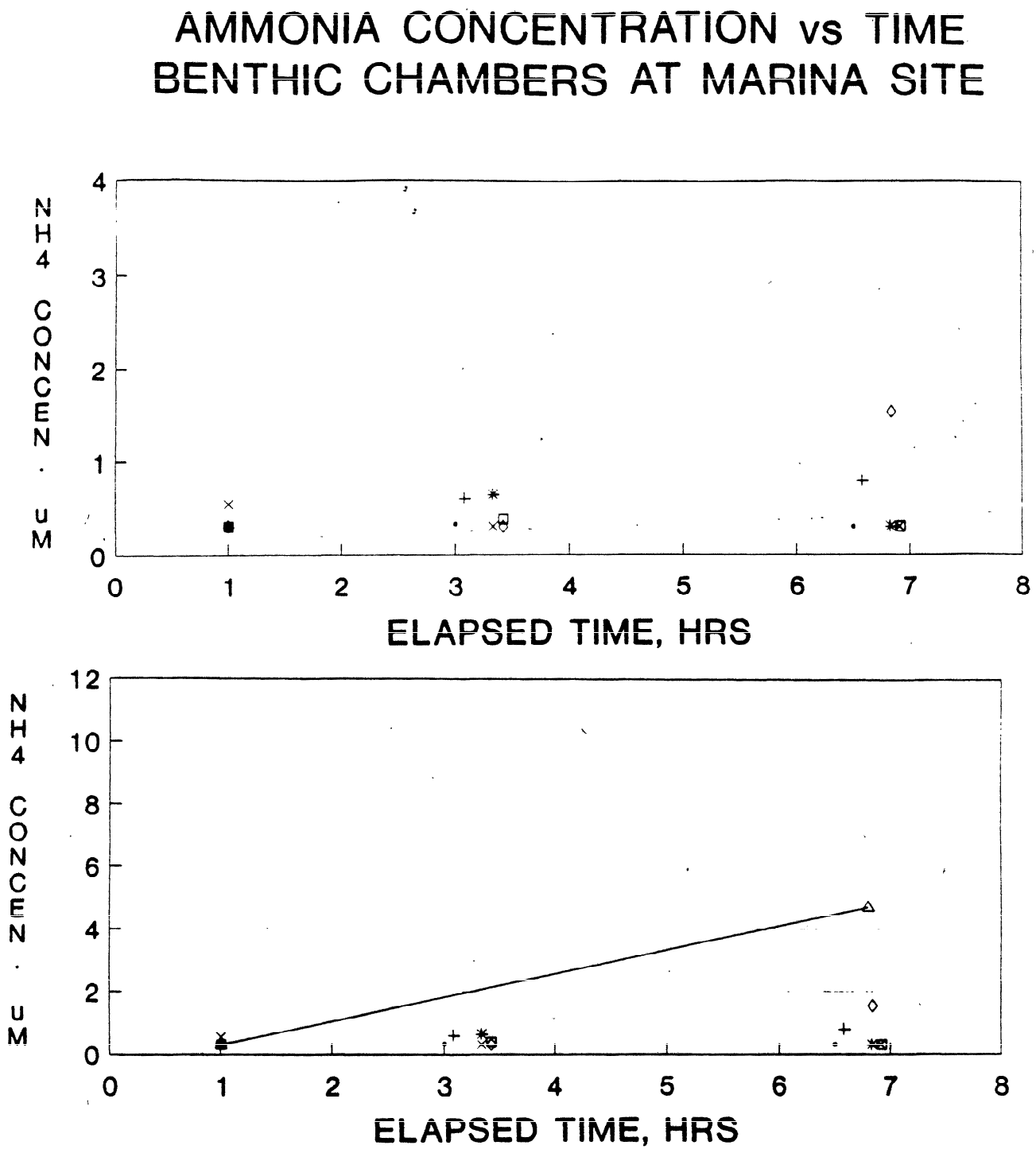

Figure 7b. Measured (top) and measured and predicted (bottom) ammonia concentration (uM) versus time in <u>in situ</u> benthic chambers at the marina site in Barnegat Bay, September 1988. The line connecting triangles represents predicted ammonia concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.

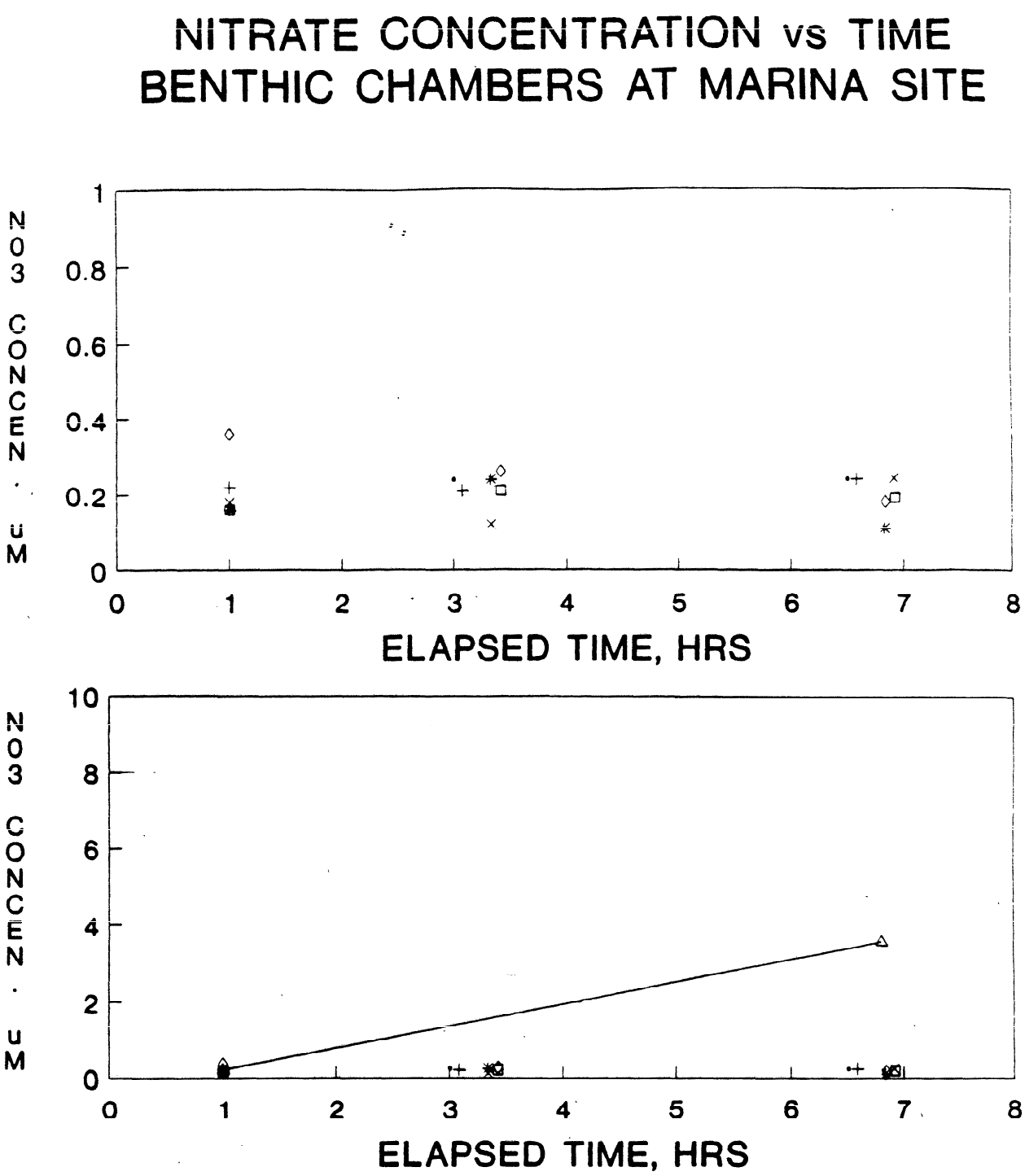

Figure 7c. **Measured (top) and measured and predicted (bottom) nitrate concentration (uM) versus time in <u>in situ</u> benthic chambers at the marina site in Barnegat Bay, September 1988. The line connecting triangles <u>represents predicted</u> nitrate <u>concentration</u> in the dark chambers based on the measured O_2 uptake in the dark and an O:N ratio of 17.25 (atoms), see eqs. 1 and 3 in text.**

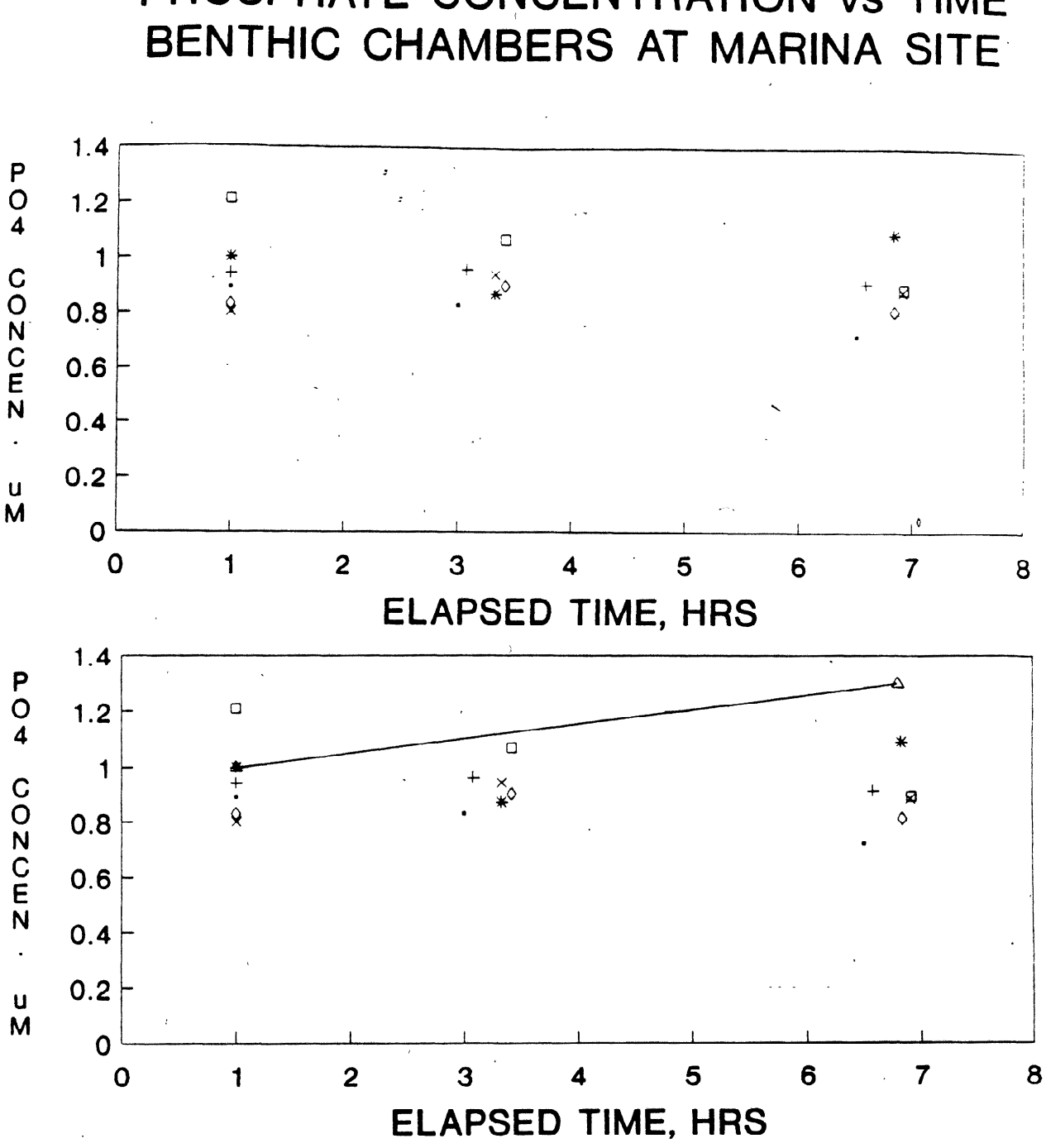

Figure 7d. Measured (top) and measured and predicted (bottom) phosphate concentration (uM) versus time in <u>in situ</u> benthic chambers at the marina site in Barnegat Bay, September 1988. The line connecting triangles represents predicted phosphate concentration in the dark chambers based on the measured O_2 uptake in the dark and an O:P ratio of 212 (atoms), see eq. 1 in text.

Table 2. Measured (M) and predicted (P) sediment-water fluxes of ammonia, nitrate plus nitrite, and phosphate at four locations in Barnegat Bay, September 1988. Measurements made in situ with clear benthic chambers (L1, L2), chambers with 50% light transmittance (M1, M2) or with dark chambers (D1, D2). Fluxes are reported as 0 if the slope of the regression line of concentrations versus time was not significantly different from zero at 0.10 level. Predicted nutrient flux rates were calculated based on measured oxygen consumption rates in the dark and the Redfield (1934) ratio for the decomposition of organic matter O:N:P = 212:16:1 (by atoms) for NH_4 and PO_4 or 276:16:1 (by atoms) for NO_3 (assuming N mineralized released as all ammonia or all nitrate).

	NH_4		NO_3		PO_4	
Site/Treatment	(M)	(P)	(M)	(P)	(M)	(P)
Vegetated Site 1						
L1	0		0		0	
L2	0		0		0	
M1	0		0		0	
M2	0		<2		0	
D1	0	266	0	205	0	17
D2	-4	286	0	220	0	18
Silt-Clay Site						
L1	0		<2		0	
L2	0		0		0	
M1	0		0		0	
M2	0		<2		0	
D1	0	19	0	14	<2	1
D2	0	93	0	71	<2	6
Marine						
L1	0		0		-3	
L2	0		0		-5	
M1	0		0		0	
M2	0		0		0	
D1	0	99	0	76	0	6
D2	0	54	0	424	0	3
Vegetated Site 2						
L1	0		0		4	
L2	0		0		0	
M1	0		0		0	
M2	0		0		0	
D1	0	143	0	110	-4	9
D2	0	220	0	154	0	13

<2 refers to slope significantly different from 0, but calculated flux between -2 and +2.

Table 3. Planktonic net primary production rates in Barnegat Bay outside and inside water column enclosures. Rates are calculated from light/dark bottle oxygen concentration changes; bottles were incubated *in situ* at 30 cm below water surface for approximately 4 h.

Location	Date Primary Production Measured	Date Enclosure Deployed	Total Water Depth (m)	Incubation Period	Net O_2 Production ($mg\ O/m^3/h$) Outside	Inside
Vegetated Site 1	8/31/88	8/30/88	1.5	1030-1420 h	500	475
	9/01/88	8/30/88		1000-1410 h	500	425
	9/02/88	8/30/88		1030-1430 h	250	450
	9/15/88	9/13/88		1000-1400 h	275	250
	9/16/88	9/13/88		1000-1345 h	400	475
Silt-Clay Site	9/22/88		2.3	1330-1730 h	250	
Marina Site	9/26/88		0.8	1015-1440 h	400	
Vegetated Site 2	9/29/88		1.2	1100-1500 h	250	

Table 4. Measured particulate N and P deposition rates and N:P ratio at vegetated site 1; data are from sediment trap collections in water column enclosures. Particulate C deposition rates were calculated assuming a C:N ratio of 106:16 (Redfield 1934). See text for a detailed description of methods.

Date	(ug-at $m^{-2}h^{-1}$)			mmol $m^{-2}d^{-1}$			N:P
	N	P	C	N	P	C	
09/01/88	94	8	623	2.3	0.19	15	12
09/02/88	196	12	1299	4.7	0.29	31	16
09/16/88	125	4	828	3.0	0.1	20	31
09/20/88	97	4.5	643	2.3	0.11	15	22
09/22/88	383	20	2537	9.2	0.48	61	19
10/03/88	158	5	1047	3.8	0.12	25	32
Average	176	8.9	1163	4.2	0.21	28	22
Avg. w/o 09/22/88	134	6.7	888	3.2	0.16	21	

DISCUSSION

External inputs of inorganic nitrogen (ammonia and nitrate) and phosphorus (phosphate) to estuaries are assimilated by phytoplankton and/or benthic algae and seagrasses during primary production. The organic matter thus produced is consumed by organisms in the food web. Metabolism of organic matter by organisms results in the release of inorganic N and P (recycling) which can be used again for primary production. External ('new') inputs of nitrogen and phosphorus to most estuaries and other near shore marine systems are usually not sufficient to supply the nutrients needed to support annual primary production rates; rapid in situ recycling of nitrogen and phosphorus from organic matter decomposition supplies a major portion of the nutrients used by the algae and aquatic vegetation (Nixon 1981; Boynton et al. 1982). Both the water column (Harrison 1978, Caperon et al. 1979; Glibert 1982) and the sediments (Rowe et al. 1975; Nixon et al. 1976; Blackburn and Henriksen 1983) are important sites for organic matter decomposition, and thus, nitrogen and phosphorus recycling. As outlined in the Introduction, the sediments can also be important in removing N and P through permanent burial and/or denitrification.

The major objective of the present study was to begin to assess the importance of the sediments in Barnegat Bay as a source or sink (removal site) for nutrients (N and P). To that end, sediment-water fluxes of nutrients were measured at four locations and compared to predicted flux rates based on rates of organic matter decomposition (measured as dark O_2 consumption; see detailed explanation below). In addition, rates of organic matter decomposition in the sediments were compared to rates of organic matter deposition to the sediments from the water column (combination of dead and dying phytoplankton, zooplankton faecal pellets, detritus, etc.). Rates of organic matter deposition were compared to organic matter production in the water (primary production rates). Finally, phytoplankton nutrient requirements were compared to the recycling of nutrients from the sediments.

During the decomposition of organic matter in the presence of dissolved oxygen, ammonia (and nitrate) and phosphate are released and oxygen is consumed. According to Richards (1965) the decomposition of typical organic matter can be described stoichiometrically by the following equation:

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 106O_2 = 106CO_2 + 16NH_3 + H_3PO_4 + 106H_2O$$

(Eq. 1 from Introduction).

According to this equation 106 moles (212 atoms) of oxygen are consumed and 16 moles of nitrogen and 1 mole of phosphate are released for every mole of organic matter consumed resulting in a ratio of C:O:N:P of 106:212:16:1 by atoms. This ratio is referred to as the Redfield ratio for the decomposition of organic matter

(Redfield 1934). Although there is some variation in the environment, this ratio has been shown to be a good estimate of the average C:N:P ratio of planktonic and sediment organic matter in estuaries.

The NH_3 produced may be further oxidized by nitrifying bacteria according to the equation:

$$16NH_3 + 32O_2 = 16HNO_3 + 16H_2O \qquad \text{(Eq. 3)}.$$

Using equations 1 and 3, and knowing the amount of oxygen consumed, one can estimate the amount of organic matter consumed and the amount of nitrogen (ammonia plus nitrate) and phosphate released in a system. In addition, if there is photosynthesis occurring in a system, the amount of nitrogen and phosphorus assimilated for production of new organic matter can be estimated from the oxygen production rate according to the equation for photosynthesis:

$$106CO_2 + 16NH_3 + H_3PO_4 + 106H_2O = (CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 106O_2$$
(Eq. 2 from Introduction).

In shallow coastal lagoons, such as Barnegat Bay, not only is photosynthesis occurring in the water column, but where sufficient light reaches the surface sediments, benthic algae and rooted macrophytes (e.g., Zostera) can also contribute to photosynthetic production of organic matter. In sediments such as those, oxygen consumption in the dark is a measure of organic matter decomposition. In the light, the sediment-water oxygen flux is the sum of the consumption of oxygen during decomposition and the production of oxygen during photosynthesis.

The measurements of benthic oxygen consumption rates in the dark at the four locations in Barnegat Bay demonstrated that significant amounts of organic matter are being decomposed at all locations sampled (Table 1). While there is considerable uncertainty in drawing conclusions about differences between sites based on only one sampling period, oxygen consumption rates appear to be higher at the two vegetated sites than at the silt-clay or marina sites. Rates of sediment oxygen consumption in Barnegat Bay are within the range of rates reported for other estuarine sediments at similar times of the year (Table 5).

Benthic photosynthesis was active at two locations, the vegetated site 1 and the marina (Figs. 4a and 6a; Table 1). At both locations, there was net photosynthesis in the light chambers, as illustrated by a net increase in oxygen in the light chambers. Rates of benthic gross photosynthesis (sum of net oxygen production in light and oxygen consumption in the dark) were approximately 4720 ug-at O $m^{-2}h^{-1}$ (75 mg O $m^{-2}h^{-1}$) and 1860 ug-at O $m^{-2}h^{-1}$ (30 mg O $m^{-2}h^{-1}$) at the vegetated and marina sites, respectively. These rates are considerably less than the measured

Table 5. Sediment-water oxygen and nutrient fluxes (ug-at $m^{-2}h^{-1}$) measured under dark conditions in various estuaries.

Location	Sediment Type	Date	O_2	NH_4 + NO_{3+2}	PO_4	Reference
Potter Pond, RI (coastal lagoon)	mud and sand	annual average	-749	42	0.6	Nowicki and Nixon 1985b
	mud	summer		400	40	Nowicki and Nixon 1985b
	sand	summer		50	5	Nowicki and Nixon 1985b
Absecon Bay, NJ	mud	9/20/79		515 NH_4 only		Durand 1984
		10/18/79		334 NH_4 only		Durand 1984
South River Estuary, NC	silt-clay	9/77-12/78	-3540	114	6.25	Fisher et al. 1982
Neuse River Estuary, NC	silt-clay	9/77-12/78	-3020	227	14.0	Fisher et al. 1982
Ochlockonee Bay, FL	silt-clay	6/84	-1083	82	<1	Seitzinger 1987
Narragansett Bay, RI	silt-clay	9/72	-3125	190	10	Nixon et al. 1976, 1980
Barnegat Bay, NJ	vegetated, silty-sand	9/20/88	-3660	<4	<2	this study
	silt-clay	9/28/88	-2270	<4	≤4	this study
	sandy-silt (marina)	9/22/88	-740	<4	<2	this study
		9/26/88	-1015	<4	<2	this study

planktonic primary production rates at the vegetated site (250-500 mg O $m^{-3}h^{-1}$) or the marina (400 mg O $m^{-3}h^{-1}$) (Table 3). Water depths at these two sites were approximately 1 m. Thus, a comparison of phytoplankton primary production rates (m^{-3}) with benthic primary production rates (m^{-2}) can be made directly by assuming that the phytoplankton rate m^{-3} over 1 m depth is approximately equivalent to a rate m^{-2} (i.e., a m^{-3} is 1 m deep by 1 m^2).

While significant amounts of organic matter are being decomposed in the sediments in Barnegat Bay, very little if any measurable nitrogen or phosphorus was released from the sediments to the water column (Figs. 4b-d through 7b-d; Table 2). Based on the amount of oxygen consumed, substantial increases in phosphate and ammonia or nitrate concentrations would be predicted (based on eqs. 1 and 3) inside the benthic dark incubation chambers. The expected concentration increases in the dark chambers are indicated on the bottom graph in Figures 4b-d through 7b-d. For example, at the vegetated site 1, the average oxygen consumption in the dark chambers was -3660 ug-at $m^{-2}h^{-1}$; the predicted N and P release based on the Redfield ratio would have been 276 ug-at NH_4 $m^{-2}h^{-1}$ (or 212 ug-at NO_3 $m^{-2}h^{-1}$) and 17.25 ug-at P $m^{-2}h^{-1}$ (Table 2). This would have resulted in an increase of 11.5 uM ammonia (or 8.8 uM nitrate) and 0.72 uM phosphate over the approximately 4.6-h incubation period. However, as the bottom graphs in Figures 4b-d through 7b-d demonstrate, N or P concentration changes were insignificant relative to predicted changes. In fact, in all but a few cases, there was no significant (alpha = 0.10) change in ammonia, nitrate or phosphate in the benthic chambers, and in the few cases in which there were measurable fluxes, they were small relative to predicted fluxes (Table 2).

Based on the available data, during the late summer/early fall, the sediments in Barnegat Bay do not appear to be a source of nutrients for phytoplankton in the Bay, but rather, they appear to be a sink (removal or retention site) for both nitrogen and phosphorus. This conclusion is based on benthic flux measurements which show little or no release of either N or P compared to release rates predicted based on organic matter decomposition rates as discussed above. We do not have sufficient data to say whether the sediments are a long-term sink for N and P or a short-term storage site for N and P which may be released to the water at a later time. To our knowledge no other estuarine sediments have been reported to be such an efficient sink for N or P. Some examples of N and P release rates from estuarine sediments are presented in Table 5 for comparison. Further studies over an annual cycle are now underway to clarify the temporal scales over which Barnegat Bay sediments are sinks for N and P. Specific studies examining the mechanisms responsible for N and P removal (e.g., denitrification, N or P burial, etc.) are warranted.

There are a number of mechanisms that could be responsible for the lack of N or P release from the sediments including: (1) N and/or P may be assimilated by actively growing benthic algae and macrophytes (this N and P could be released to the water later during decomposition), (2) P may be buried in the sediments in an inorganic mineral form, (3) N may be lost as N_2 through denitrification. We have no direct evidence concerning the mechanism(s) involved in this unusual pattern. However, some insight into the mechanism(s) involved may be obtained by a comparison of the data at the various locations. If the reason that N and P were not measurably released from the sediments following decomposition of organic matter was due to uptake of N and P by actively growing benthic algae and/or macrophytes, then N and P should have been released at the two sites that did not exhibit benthic photosynthesis, i.e. the silt-clay site and the vegetated site 2. (The "vegetated" site 2 was covered with mats of macroalgae and seagrass which appeared to be decomposing.) We can not rule out denitrification as a sink for N released during benthic metabolism nor do we have, as yet, any information on burial of N and P in the sediments. Investigation of the mechanisms involved is clearly needed if measurements over an annual cycle indicate continued removal of N and P in the sediments.

Plankton primary production rates ranged from 250 to 400 mg O $m^{-3}h^{-1}$ during late September at the four locations (Table 3). These rates are similar to those reported by Mountford (1971) in Barnegat Bay at a location approximately 5 km south of Oyster Creek during 1969-1970 (11 September - 7 October 1969, 177-387 mg O $m^{-3}h^{-1}$; 18 September - 6 October 1970, 69-247 mg O $m^{-3}h^{-1}$) using similar techniques as in the present study. No other previous measurements of primary production rates were found for Barnegat Bay.

Ammonia, nitrate and phosphate concentrations in the water were low at all locations studied (Table 6). Concentrations of ammonia were less than or equal to 0.6 uM, nitrate plus nitrite concentrations were 1.0 uM or less, and phosphate concentrations were 0.5 uM or less except at the marina where the concentration was 1.0 uM. The ammonia and nitrate plus nitrite concentrations are similar to the mean concentrations between 13 June 1973 and 4 November 1974 reported for a station in lower Barnegat Bay by Durand (1984). He reported mean ammonia concentrations of 0.7 uM and mean nitrate plus nitrite concentrations of 0.6 uM. No phosphate concentrations were reported. Phosphate concentrations measured in samples collected 7 October 1986 near the Point Pleasant Bridge were approximately 0.5 uM (Key et al. 1988). The low nutrient concentrations found in Barnegat Bay during the current study suggest that there are significant sinks for nitrogen and phosphorus in the Bay. The sediment-water nutrient flux data indicate that the sediments may be an important removal site, at least during the fall, in the Bay. Future studies of the

Table 6. Water column nutrient concentrations (uM) in Barnegat Bay. See text and Figure 1 for station locations. Numbers are average values for three replicate samples. Minimum detectable concentrations are NH_4: 0.3 uM; NO_3 + NO_2: 0.1 uM; PO_4: 0.08 uM. Our NH_4 detection limits are typically <0.125 uM. However, there were considerable amounts of dissolved substances in Barnegat Bay water which absorbed at 640 nm, resulting in high turbidity blanks and an increase in the minimum detection limit.

Location	Date	NH_4	NO_3	PO_4	N:P
Vegetated Site 1	9/20/88	$\leq$0.4	1.0	0.5	$\leq$2.8
Silt-clay Site	9/22/88	$\leq$0.3	0.4	0.5	$\leq$1.4
Marina Site	9/26/88	$\leq$0.6	0.2	1.0	$\leq$0.8
Vegetated Site 2	9/29/88	$\leq$0.3	0.7	0.3	$\leq$3.3

magnitude of external nutrient inputs from point and non-point sources to the Bay are needed.

Monthly nutrient concentration data during 1972 reported by Makai (1973) for four stations between the Mantoloking Bridge and the Toms River Bridge provide a different historical picture of nutrient concentrations in the Bay. Ammonia concentrations ranging from 0.84 to 1.2 ppm NH_4 (47-67 uM), no detectable nitrate or nitrite, and ortho-phosphate concentrations ranging from 0.06 to 0.18 ppm (0.6-1.9 uM or 1.9-5.8 uM depending on whether the units were ppm PO_4 or ppm P) were reported for the September 1972 sample period (Makai 1973). It is somewhat difficult to interpret the data reported by Makai at this point because the report in hand is an incomplete copy and details of the analytical procedure have not been located. We are currently trying to locate this information.

The N:P ratio of inorganic nutrients in the Bay in September 1988 was low, 3.3:1 or less (Table 6) relative to the 16:1 ratio considered to be required for phytoplankton production. The N:P ratio of inorganic nutrients is often used to infer which nutrient is most limiting for algal production (e.g. if the N:P ratio is considerably less than 16:1, nitrogen is considered to be most limiting). Based on the limited data available at this time, nitrogen appears to be the nutrient limiting phytoplankton production in the Bay. Plankton N and/or P nutrient enrichment studies would be useful to clarify this point.

The data from this study were used to develop a preliminary evaluation of nutrient processes in the Bay. To that end, a preliminary budget of C, N and P was constructed for the vegetated site 1, based on the planktonic and benthic primary production data, particulate N and P deposition rates, and benthic metabolism data from this study (Table 7). Construction of budgets at this time is useful for checking internal consistency or reasonableness of data, for guiding future research, as well as for beginning to provide insights into the processes controlling nutrient dynamics and possibly eutrophication in the Bay. However, it MUST be kept in mind that this is a preliminary budget as only data from one point in time (September 1988) were used. Once data are available over an annual cycle, a more accurate picture can be constructed. Assumptions used in the construction of these budgets are listed in Table 7.

The budgets presented in Table 7 suggest the following: The measured deposition of organic N and P to the sediments is approximately 20%-25% of the rate of organic matter production by phytoplankton. This implies that approximately 20-25% of phytoplankton production is deposited to the sediments for use by benthic organisms (as dead algae, zooplankton, faecal pellets, detritus, etc.). The amount of organic matter (C, N and P) being decomposed in the sediments is about twice as great as the amount

Table 7. Preliminary budgets for C, N and P at vegetated site 1 in Barnegat Bay, September 1988. See text for measurement and calculation details. Note that units are mmol $m^{-2}d^{-1}$ in contrast to units in other parts of text of ug-at $m^{-2}h^{-1}$ (mmol $m^{-2}d^{-1}$ x $10^3/24$ = ug-at $m^{-2}h^{-1}$).

	mmol $m^{-2}d^{-1}$		
	C	N	P
Plankton Primary Prod.[1] (C, N and P assimilated)	90	14	0.8
Deposition[2]	21	3	0.2
Benthic Primary Prod.[3] (C, N and P assimilated)	19	3	0.2
Benthic Metabolism[4] (gross)	44	7	0.4
Predicted Release[5] (net)	25	4	0.2
Measured Release		0	0

[1]The calculated C, N and P assimilation rates were based on the average measured primary production rates (O_2 production) and an assumed C:O:N:P ratio of 212:106:16:1 by atoms (Redfield 1934, eq. 2); Measured O_2 production rates were assumed to occur for 8 h per day throughout the top 1 m.
[2]See Table 4.
[3]Based on gross primary production measurements from light/dark benthic chambers and a C:O:N:P ratio of 212:106:16:1 (Redfield 1934).
[4]Organic matter decomposed over 24 h calculated based on dark O_2 consumption and Redfield O:C:N:P ratio (eq. 1).
[5]Calculated as difference between predicted N and P release from benthic metabolism and N and P assimilated by benthic primary production.

of organic matter deposited to the sediments at this time. This may be a result of time lags in the system, e.g., organic matter deposited earlier in the year when planktonic primary production rates were higher may be being decomposed at this time along with newly deposited organic matter. However, it is also likely that benthic primary production is supplying the additional organic matter. Benthic primary production at this site was supplying approximately equal amounts of organic matter as was supplied (deposited) from planktonic production. In fact, the sum of the measured deposition of organic matter and the measured production of organic matter in the sediments was equal to the measured rate of metabolism of organic matter in the sediments. What continues to be unexplained is that there was essentially no release of nitrogen or phosphorus from the sediments. Some of the N and P may be assimilated by benthic algae and seagrasses. However, the estimated N and P requirement for the measured benthic primary production was only about half of the amount that should have been released from benthic metabolism leaving considerable amounts of N and P unaccounted for.

The amount of N and P mineralized in the sediments (gross benthic metabolism) was approximately half of the estimated planktonic primary production N and P requirement (Table 7). The plankton are likely nutrient-limited as nutrient concentrations were very low in the water column (Table 6). Thus, if the N and P mineralized in the sediments were released to the water, primary production in the water would be expected to increase. Investigation into the mechanism(s) responsible for this efficient sink for N and P in the sediments is warranted, as it is likely important in maintaining low nutrient concentrations in the water column in the Bay. To understand the potential importance of this sink for N and P, the following comparison is useful. The release of 7 mmol N $m^{-2}d^{-1}$ and 0.4 mmol P $m^{-2}d^{-1}$ from the sediments (expected due to benthic metabolism; Table 7) would be equivalent to an increase in concentration of N and P in the water of approximately 5 uM N/day and 0.3 uM P/day (assuming a 1.5-m deep water column and assuming no uptake by the algae), which is relatively large, especially for N, compared to the measured concentrations at this time of <1.5 uM ammonia plus nitrate and 0.5 uM phosphate (Table 6).

While external N and P input rates to Barnegat Bay have not as yet been measured, we can gain some insight into the minimum rates of input at this time from the N and P removal rates in the sediment. Water column N and P standing stocks are not sufficient to sustain the rate of N and P removed in the sediments, as seen from the previous calculation. This suggests, then, that external inputs to the Bay from point and non-point sources are at least 4 mmol N $m^{-2}d^{-1}$ and 0.2 mmol P $m^{-2}d^{-1}$. These rates are similar to those reported for a number of other estuaries that receive considerable inputs of nutrients from pollution sources, and include Narragansett Bay (approximately 3 mmol N $m^{-2}d^{-1}$),

Delaware Bay (approximately 5 mmol N $m^{-2}d^{-1}$), and Chesapeake Bay (1 mmol N $m^{-2}d^{-1}$) (Nixon 1981).

Future Studies

We are currently conducting studies over an annual cycle of planktonic and benthic primary production, organic matter deposition, benthic metabolism and sediment-water nutrient fluxes at two locations in the upper Bay, the vegetated site 1 and silt-clay site (same as year I studies). We are also measuring N and P net burial rates at two locations in the Bay. In addition, water column nutrient concentrations and primary production rates at four locations throughout the Bay are being measured by NJDEP DSR personnel. Together, these studies will provide considerable additional insight into the temporal pattern of nutrient cycling in Barnegat Bay and into the importance of the sediments as a sink for N and P.

Future studies are warranted that will more fully address the mechanisms responsible for N and P removal in both the vegetated and silt-clay unvegetated sediments, as well as the potential for the sediments to continue to remove N and P as nutrient inputs to the Bay increase as a result of continued development of the surrounding watershed. Quantification of the current rates of external inputs of N and P to the Bay from the major point and non-point sources is also necessary in order to understand the effect that a given rate of increase in N and/or P inputs to the Bay may have on the water quality and biological production of Barnegat Bay.

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