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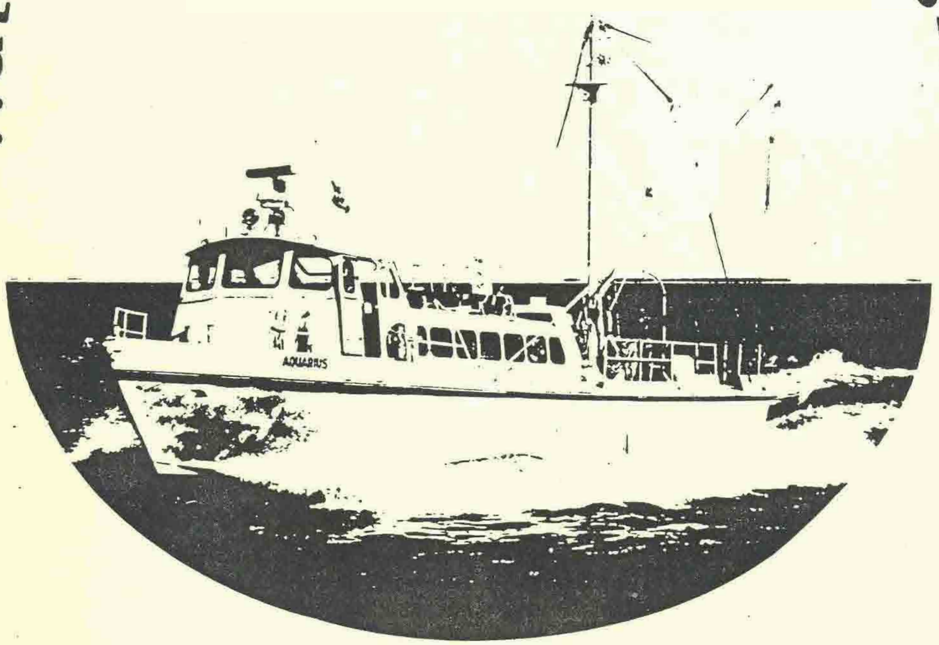
Chesapeake Bay

Water Quality Monitoring Program

ECOSYSTEMS PROCESSES COMPONENT (EPC)



LEVEL ONE DATA REPORT #6

PART 1: Interpretive Report

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MARYLAND DEPARTMENT OF THE ENVIRONMENT

MARYLAND CHESAPEAKE BAY WATER QUALITY MONITORING PROGRAM

ECOSYSTEM PROCESSES COMPONENT (EPC)
LEVEL I REPORT NO. 6

(January 1988 - December 1988)

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1. ABSTRACT

1.1 Program Objectives

The primary objectives of the Ecosystem Processes Component (EPC) of the Maryland Chesapeake Bay Water Quality Monitoring Program are to:

1) characterize the present state of the bay (including spatial and seasonal variation) relative to sediment-water nutrient exchanges and oxygen consumption and the rate at which organic and inorganic particulate materials reach deep waters and the sediment surface.
2) determine the long-term trends that might develop in sediment-water exchanges and vertical deposition rates in response to pollution control programs.
3) integrate the information collected in this program with other elements of the monitoring program to gain a better understanding of the processes affecting Chesapeake Bay water quality and its impact on living resources.

Measurements of sediment-water nutrient and oxygen exchanges are made on a quarterly basis at four locations in the mainstem Bay, and at two key locations in each of three major tributary rivers (Patuxent, Choptank, and Potomac). Vertical deposition rates are monitored at one mainstem Bay location, in the central anoxic region. Measurements are made almost continuously during the spring, summer and fall periods, with a lower frequency during the winter. Activities in this program have been coordinated with other components of the Maryland Chesapeake Bay Water Quality Monitoring Program in terms of station locations, sampling frequency, methodologies, data storage and transmission, reporting schedules and data synthesis. This report integrates data from the Jan 1988 - Dec 1988 period with data collected since Jul 1984.

1.2 Justification

Sediment-water processes and deposition of organic matter to the sediment surface are major features of estuarine nutrient cycles and play an important role in determining water quality and habitat conditions. For example, during

summer periods, when water quality conditions are typically poorest (i.e. anoxic conditions in deep water, algal blooms), sediment releases of nutrients (e.g. nitrogen, phosphorus) and consumption of oxygen are often highest as is the rate of organic matter deposition to the deep waters of the Bay. To a considerable extent, it is the magnitude of these processes which determines nutrient and oxygen water quality conditions in many zones of the Bay. Ultimately, these processes are driven by inputs of organic matter and nutrients from both natural and anthropogenic sources. If water quality management programs are instituted and loadings decrease, changes in the magnitude of the processes monitored in this program will serve as a guide in determining the effectiveness of strategies aimed at improving Bay water quality and habitat conditions.

2. INTRODUCTION

During the past decade much has been learned about the effects of nutrient inputs (e.g. nitrogen, phosphorus, silica), from both natural and anthropogenic sources, on such important estuarine processes as phytoplankton production and oxygen status (Nixon, 1981; D'Elia et al., 1983). While our understanding is not complete, important pathways regulating these processes have been identified and related to water quality conditions. For example, annual algal primary production and maximum algal biomass levels in many estuaries (including portions of Chesapeake Bay) are related to the magnitude of nutrient loading from all types of sources (Boynton et al., 1982a). Also, high, and at times excessive, algal production is sustained through the summer and fall periods by the benthic recycling of essential nutrients. Similarly, sediment oxygen demand (SOD) is related to the amount of organic matter reaching the sediment surface and the magnitude of this demand is sufficiently high in many regions to be a major oxygen sink (Hargrave, 1969; Kemp and Boynton, 1980).

The delay between nutrient additions and the response of algal communities suggests that there are mechanisms to retain nutrients in estuaries such as the Chesapeake. These nutrients can be mobilized for use at later dates. Research conducted in Chesapeake Bay and other estuaries indicates that estuarine sediments can act as both important storages and sources for nutrients as well as important sites of intense oxygen consumption (Kemp and Boynton, 1984). For example, during summer periods in the Choptank and Patuxent estuaries, 40-70% of the total oxygen utilization was associated with sediments and 25-70% of algal nitrogen demand was supplied from estuarine sediments (Boynton et al., 1982b). Processes of this magnitude have a pronounced effect on estuarine water quality and habitat conditions. In terms of storage, sediments in much of Chesapeake Bay, especially the upper Bay and tributary rivers, contain large amounts of carbon, nitrogen, phosphorus and other compounds. A large percentage of this material appears to reach the sediments during the warm periods of the year. Some portion of this same material is available to regenerative processes; and therefore, eventually becomes available for continued algal utilization. Nutrients and other materials deposited or buried in sediments represent the potential "water quality memory" of the Bay.

2.1 Justification

Processes associated with estuarine sediments have a considerable influence on water quality and habitat conditions in the Bay and its tributaries. Nutrients and organic matter enter the Bay from a variety of sources, including sewage treatment plant effluents, fluvial inputs, local non-point drainage and direct rainfall on Bay waters. These dissolved nutrients are rapidly incorporated into particulate matter via biological, chemical, and physical mechanisms. Much of this particulate material then sinks to the bottom and is remineralized. Essential nutrients released during the decomposition of organic matter may then be utilized by algal communities. A portion of these communities then sinks to the bottom, contributing to the development of anoxic conditions and loss of habitat for important infaunal, shellfish and demersal fish communities. The regenerative capacities and the potentially large nutrient storages in bottom sediments insure a large return flux of nutrients from sediments to the water column and sustain continued phytoplankton growth, deposition of organics to deep waters and anoxic conditions typically associated with eutrophication of estuarine systems.

Within the context of this model a monitoring study of deposition, sediment oxygen demand and sediment nutrient regeneration has been initiated. The working hypothesis is that if nutrient and organic matter loading to the Bay decreases then the cycle of deposition to sediments, sediment oxygen demand, release of nutrients and continued high algal production will also decrease. Since benthic processes exert important influences on water quality conditions, changes in these processes will serve as important indications of the effectiveness of nutrient control actions.

2.2 Objectives

The primary objectives of the Ecosystem Processes Component (EPC) of the Maryland Chesapeake Bay Water Quality Monitoring Program are to:

1) characterize the present state of the bay (including spatial and seasonal variation) relative to sediment-water nutrient exchanges and oxygen consumption and the rate at which organic and inorganic particulate materials reach deep waters and the sediment surface.

2) determine the long-term trends in sediment water exchanges and vertical deposition rates in response to pollution control programs.

3) integrate the information collected in this program with other elements of the monitoring program to gain a better understanding of the processes affecting Chesapeake Bay water quality and its impact on living resources.

3. PROJECT DESCRIPTION

3.1 Sampling Locations + Dates

3.1.1 General

past and present

Figure 3-1 shows the sampling locations for ~~both~~ ~~the~~ sediment oxygen and nutrient exchange study (SONE) station and ~~the~~ vertical flux study (VFX) stations. Brief descriptions and exact locations of SONE and VFX stations are given in Table 3-1 referenced to MDE station numbers. (1) From 1984 to .... Four of the 10 stations ~~sampled as part of the SONE study~~ are located along the salinity gradient in the mainstem Bay between Point No Point (north of the mouth of the Potomac River) and Still Pond Neck (20 km south of the Susquehanna River mouth). Two additional stations are located in each of three tributary rivers (Patuxent, Choptank and Potomac), one in the turbidity maximum or transition zone and one in the lower mesohaline region. (2) (3) The current VFX monitoring study station is located in the mainstem of the Bay in the central anoxic region (Fig. 3-1). Scratch (3) ?

3.1.2 Justification of Station Locations

Locations of SONE stations (Fig. 3-1 and Table 3-1) were selected based on prior knowledge of the general patterns of sediment-water nutrient and oxygen exchanges in Chesapeake Bay. Several earlier studies (Boynton et al., 1980, 1984 and Boynton and Kemp, 1985) reported the following: 1) along the mainstem of the Bay, fluxes were moderate in the upper Bay, reached a maxima in the mid-Bay and were lower in the higher salinity regions and, 2) fluxes in the transition zone of tributaries were much larger than those observed in the higher salinity downstream portions of tributaries. Hence, from 1984 through June 1989 a series of stations were located along the mainstem from Still Pond Neck in the upper Bay to Point No Point near the mouth of the Potomac River. A pair of stations were established in three tributaries (Potomac, Patuxent, and Choptank), one in the transition zone and one in the lower estuary. In all cases, station locations were selected to have depths and sediment characteristics representative of the estuarine zone being monitored. (4) ff

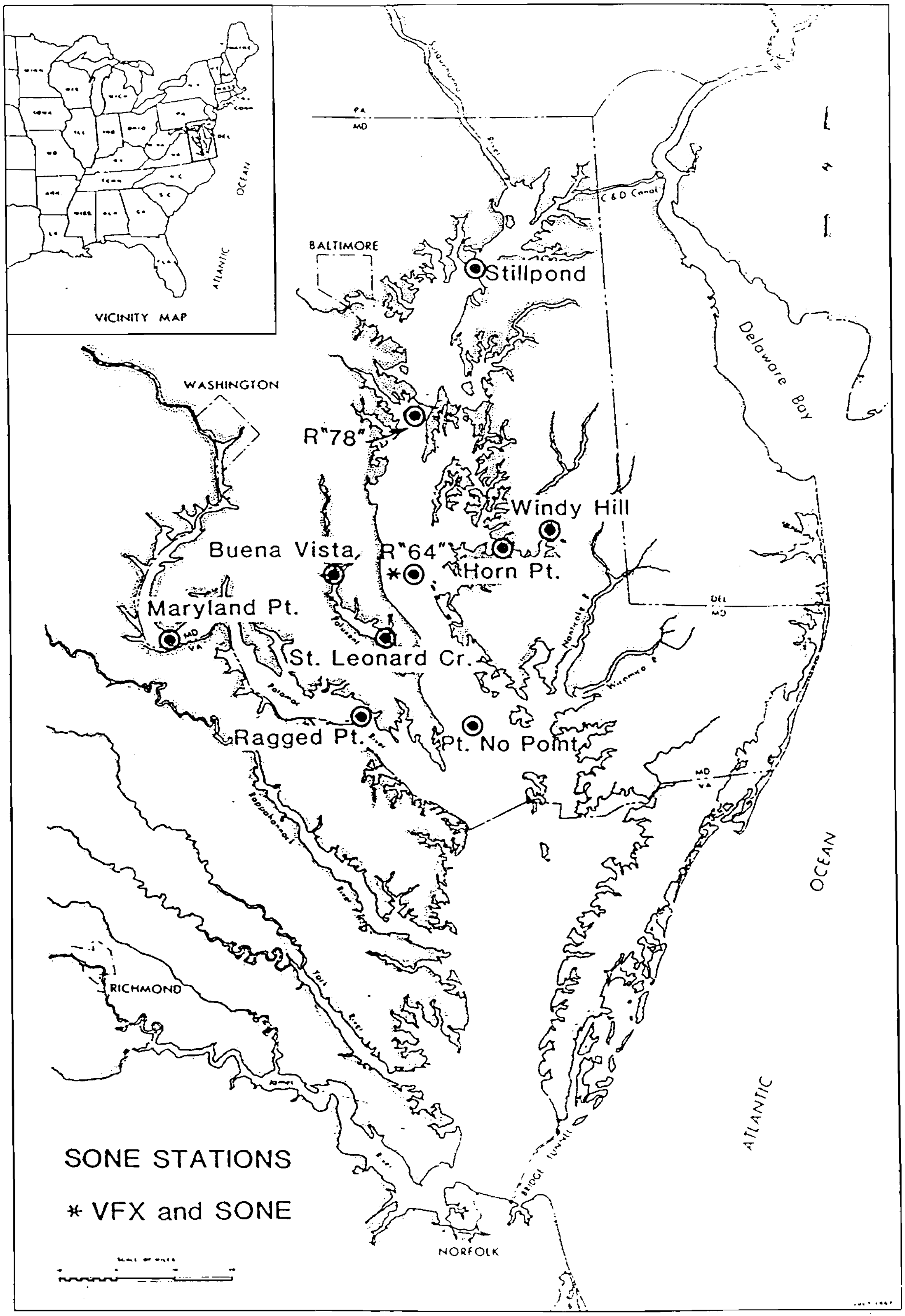


Fig. 3-1. Locations of SONE and VFX monitoring stations in the Maryland portion of Chesapeake Bay.

Table 3-1. Locations and descriptions of stations sampled as part of the Ecosystem Processes Component of the Monitoring Program.

Bay Sediment	Station Name	Code Name (Nearest MDE Station)	General Location	Latitude and Longitude[1]	Average Bottom Depth, m	Salinity Characteristics
Patuxent River	St. Leonard Creek	St. Leo (XDE 2792)	7.5 naut. mi of upstream of Patuxent River mouth	$38^{\circ}22.88'$ $76^{\circ}30.06'$	6-7	Mesohaline
	Buena Vista	Bu. Vista (XDE 9401)	0.75 naut. mi N of Rt. 231 Bridge at Benedict, MD.	$38^{\circ}31.12'$ $76^{\circ}39.82'$	5-6	Oligohaline
Choptank River	Horn Point	Horn Pt. (MET5.2)	4.0 naut. mi downstream of Rt. 50 bridge at Cambridge, MD.	$38^{\circ}37.18$ $76^{\circ}08.09'$	8-9	Mesohaline
	Windy Hill	Wind. Hil. (NONE)	10.0 naut. mi upstream of Rt. 50 bridge at Cambridge, MD.	$38^{\circ}41.45'$ $75^{\circ}58.30'$	3-4	Oligohaline
Potomac River	Ragged Point	Rag. Pt. (XBE 9541)	1.5 naut. mi WNW of BW "51B"	$38^{\circ}09.86'$ $76^{\circ}35.52'$	16-17	Mesohaline
	Maryland Point	Md. Pt. (XDA 1177)	1250 yds. SE of buoy R-18	$38^{\circ}21.37'$ $77^{\circ}11.49$	10-11	Oligohaline
Chesapeake Mainstem	Point No Point	Pt. No Pt. (MCB5.2)	3.2 naut. mi E of Pt. No Pt.	$38^{\circ}o7.99'$ $76^{\circ}15.13'$	14-15	Mesohaline
	Buoy[2] R-64	R-64 (MCB4.3C)	300 yds. NE of channel buoy R-64	$38^{\circ}33.59'$ $76^{\circ}25.63'$	16-17	Mesohaline
	Buoy R-78	R-78 (MCB3.3C)	200 yrds. NNW of channel buoy "78"	$38^{\circ}57.81'$ $76^{\circ}23.62'$	15-16	Oligo-Mesohaline
	Still Pond	Stil. Pd. (MCB2.2)	700 yds. W of channel marker "41"	$39^{\circ}20.87'$ $76^{\circ}10.87'$	10-11	Oligohaline

1 Second of latitude and longitude are expressed as hundreths of a minute.
2 Also serves as the VFX Station.

In a few instances (Patuxent stations and Choptank station at Horn Point) SONE stations are not located exactly at the same site as other Maryland Chesapeake Bay Water Quality Monitoring Program stations, although they are close (≤ 10 km). The prime reason for including these stations was the considerable amount of benthic flux data available from the SONE sites selected in the Patuxent and Choptank that could be used by the monitoring program. 5 The reasons In all cases our stations and the MDE stations are in the same estuarine zone. Benthic fluxes are reasonably similar over small spatial scales (10-20 km) within estuarine zones of similar salinity, sediments type, and depth; therefore, this program retains a high degree of comparability with other program components (Boynton et al., 1982b).

The use of sediment trap methodology to determine the net vertical flux of particulate material is restricted to the deeper portions of the Bay. In shallower areas local resuspension of bottom sediments is sufficiently large to mask the downward flux of "new" material. Hence, sediment traps are not a useful tool in the upper reaches of the mainstem bay and in many tributary areas. 6 The current sediment trap array is positioned near the center of the region experiencing seasonal anoxia (Fig. 3-1) to monitor the vertical flux of particulate organics reaching deeper waters. This location is close to, but does not exactly coincide with, MDE station 4.3.C in this area. Since sediment traps are moored pieces of gear and exposed to damage or loss by commercial boat traffic, the location was selected to be out of main traffic lanes, but still remain close to the MDE station.

3.2 Sampling Frequency

The sampling frequency for the SONE portion of this program is based on the seasonal patterns of sediment water exchanges observed in previous studies conducted in the Chesapeake Bay region (Kemp and Boynton, 1980; Kemp and Boynton, 1981; Boynton et al., 1982b; and, Boynton and Kemp, 1985). These studies indicated several distinct periods over an annual cycle including: 2) a period influenced by the presence of a large macrofaunal community (June ~~spring~~-early ~~summer~~), 3) a period during which macrofaunal biomass is low but water temperature and water column metabolic activity high with anoxia prevalent in deeper waters (July/ Aug) +4) a period in the fall when anoxia is not present and macrofaunal community abundance is low but re-establishing ~~and~~ (Oct/Nov) (4) an early spring period (Apr-May) when the spring phytoplankton bloom occurs, and water column nutrient concentrations are high (particularly nitrate). 7 Previous studies ~~also indicate that~~ short-term temporal (day-month) variation in these exchanges is small; ~~however,~~ considerable differences in the magnitude and characteristics of fluxes ~~appear~~ among distinctively different estuarine zones (~~i.e. tidal fresh vs. mesohaline regions~~). In ~~light~~ of these results, the monitoring design adopted for ~~the SONE~~ study involves quarterly ~~measurements~~, as ~~described~~ above, distributed in zones characteristic of mainstem Chesapeake Bay and ~~tributary~~ rivers.

The selection of sampling frequency for the VFX (organic deposition) monitoring program is governed by different constraints, although compatible with SONE sampling frequencies. Net depositional rates appear largest during the warm seasons of the year (Apr-Oct) and are considerably lower during winter periods (Nov-Mar). Resuspension of near-bottom sediments and organics in one tributary of the Bay (Patuxent) followed a similar pattern (Boynton et al., 1982b; Kemp and Boynton, 1984). However, some variability occurs in warm season depositional rates, probably due to algal blooms of short duration (days-week), variation in zooplankton grazing rates (week-month) and other, less well described, features of the Bay. Given the importance of obtaining interannual estimates of organic matter deposition rates to deep waters of the Bay, sampling is almost continuous during spring-fall (Mar-Nov) and only occasionally during the winter (Dec-Feb). Direct measurements of organic deposition to Bay sediments were monitored 19 to 30 times per year. To coordinate vertical deposition rate measurements with SONE measurements, sediment-water exchanges are monitored at the end of each intensive VFX deployment period. VFX measurements also coincide with other Monitoring Program sampling activities. The sampling schedule for the period Jan - Dec 1988 is shown in Table 3-2 for this component of the Monitoring Program.

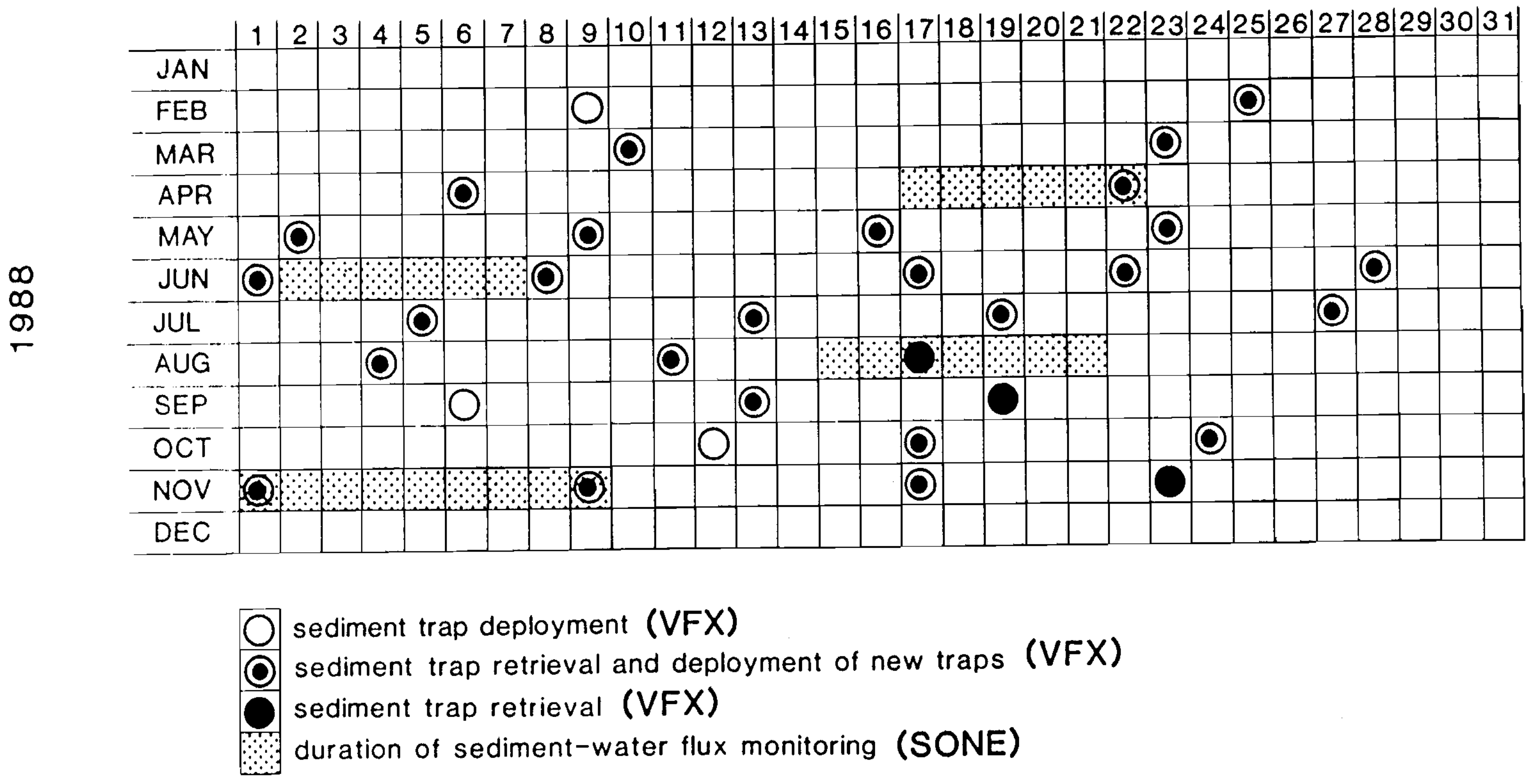


Table 3-2. Sampling schedule for the period January-December 1988.

3.3 Field Methods

Details concerning methodologies are described in the Ecosystem Processes Component Study Plan (Garber et. al, 1987). The following section provides an overview of field activities.

3.3.1 SONE Study

3.3.1.1 Water Column Profiles. At each of the 10 SONE stations, vertical water column profiles of temperature, salinity and oxygen are obtained at 2 m intervals from the surface to the bottom immediately prior to obtaining intact sediment cores for incubation. Near-surface ($\pm$ 1m) and near-bottom ($\pm$ 1m) water samples are also collected using a high volume submersible pump system. Samples are filtered, where appropriate, using 0.7 μm GF/F filter pads, and immediately frozen. Samples are analyzed for the following dissolved nutrients and particulate materials: ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), dissolved inorganic phosphorous (PO_4^{-3}), silicious acid ($Si(OH)_4$), particulate carbon (PC), particulate nitrogen (PN), particulate phosphorous (PP), chlorophyll-a and seston.

3.3.1.2 Sediment Cores. Intact sediment cores are obtained at each SONE station using a modified Bouma box corer. After deployment and retrieval of the box corer, the plexiglass liner containing the sediment sample is removed and visually inspected for disturbance. A satisfactory core is placed in a darkened, water-filled holding incubator prior to further processing.

Three intact cores are used to estimate net exchanges of oxygen and dissolved nutrients between sediments and overlying waters (Fig. 3-3). Prior to beginning incubation, the overlying water in a core is replaced by bottom water to insure that water quality conditions in the core closely approximate in-situ conditions. Gentle circulation of water, with no induction of sediment resuspension, is maintained in the cores during the measurement period via the stirring devices attached to the O_2 probes. The cores are placed in a darkened water bath to maintain ambient temperature. Oxygen concentrations

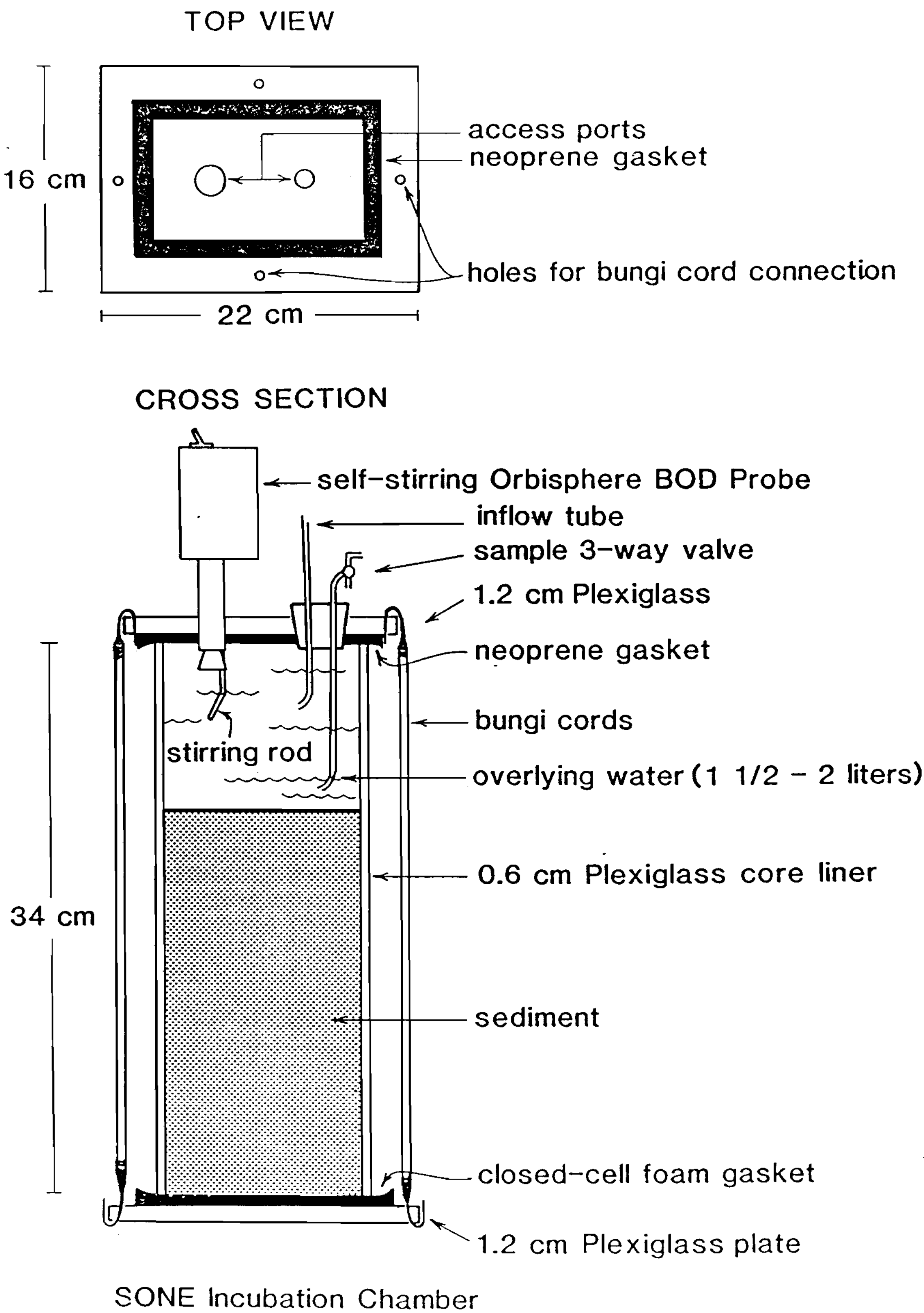


Fig. 3-3. Schematic diagram of the incubation chamber used in SONE program.

are recorded and water samples (35 ml) are extracted from each core every 30 or 60 minutes (depending on the rate of oxygen uptake) over the 2-5 hour incubation period. During the incubation period, 5 water samples are extracted from each core. As a nutrient sample is extracted from a core, an equal amount of ambient bottom water is added. An opaque plexiglass liner filled with bottom water, incubated, and sampled as described above serves as a blank. Water samples are filtered and immediately frozen for later analysis for NH_4^+, NO_3^-, NO_2^-, PO_4^{-3} and $Si(OH)_4$ concentrations. Nutrient and oxygen fluxes are estimated by calculating the mean rate of change in concentration over the incubation period and then converting the volumetric rate to a flux using the volume:area ratio of each core.

3.3.1.3 Sediment Profiles: At each SONE station an intact sediment core is used to measure Eh at 1 cm intervals to about 10 cm. Additionally, surficial sediments are sampled for particulate nitrogen, particulate carbon, particulate phosphorous, and chlorophyll concentrations.

3.3.3 VFX Study

At the VFX station, a water column profile of temperature, salinity and oxygen is obtained at 2 m intervals from 0.5 meters to 1 meter off of the bottom to characterize the column's general physical features. Water samples are also collected at 3 depths using a submersible pump system. Routinely, a sample is taken from near-bottom and near-surface waters, and at the depth of the mouth of the middle sediment trap. Water samples are analyzed for particulate materials including PC, PN, PP, chlorophyll-*a* and seston. These data provide descriptions of the particulate matter in the field at that moment and are useful in evaluating results developed from sediment trap collections.

3.3.3.1 Sediment Sampling. During previous VFX monitoring cruises a surficial sediment sample (surface 1cm) was obtained using either a Van Veen grab or the Bouma box corer. During this reporting period the Bouma corer was used exclusively because it obtains a better surficial sediment sample. Sediment samples are later analyzed to determine PC, PN and PP concentrations and chlorophyll-a content. Subsamples are also examined to determine the composition of surficial sediment particulates (e.g. algal species, zooplankton fecal pellets, etc.)

3.3.3.2 VFX Sampling. The sampling device used to develop estimates of the vertical flux of particulate materials has a surface buoy connected to a lead or concrete anchor-weight (200 kg) by a series of stainless steel cables (0.8 cm diameter, Fig. 3-4). The array is maintained in a vertical position through the water column by 2 sub-surface buoys (45 cm diameter, 40 kg positive buoyancy and 33 cm diameter, 16 kg positive buoyancy). Collecting frames with cups are attached at about 5 m and 9 m beneath the water surface to obtain estimates of vertical flux of particulates from the surface euphotic zone to the pycnocline and flux across the pycnocline to deep waters.

The sediment trap string is routinely deployed and retrieved using CEES research vessels with normal sampling periods lasting 1-2 weeks. At the end of a sampling period, collecting cups are retrieved by hoisting the entire array to shipboard. Cups are not capped prior to retrieval. After fouling organisms are removed from the frames, new cups are attached and the array lowered back into the water.

The contents of a collecting cup are removed and aliquots taken for determination of PC, PN, PP, chlorophyll-a and seston concentrations. Additionally, a 10 ml sample is preserved using a modified Lugol's solution, and later examined to determine characteristics of collected particulate material (e.g. algal speciation, zooplankton fecal pellets, etc.).

Particulate material concentrations in sampling cups are converted to vertical flux to the depth at which the collecting cup was suspended by consideration of the cross-sectional area of the collecting cup, deployment time and sample and subsample volumes. Further details concerning this monitoring program are provided in Boynton et al. (1985) and Garber et al. (1987).

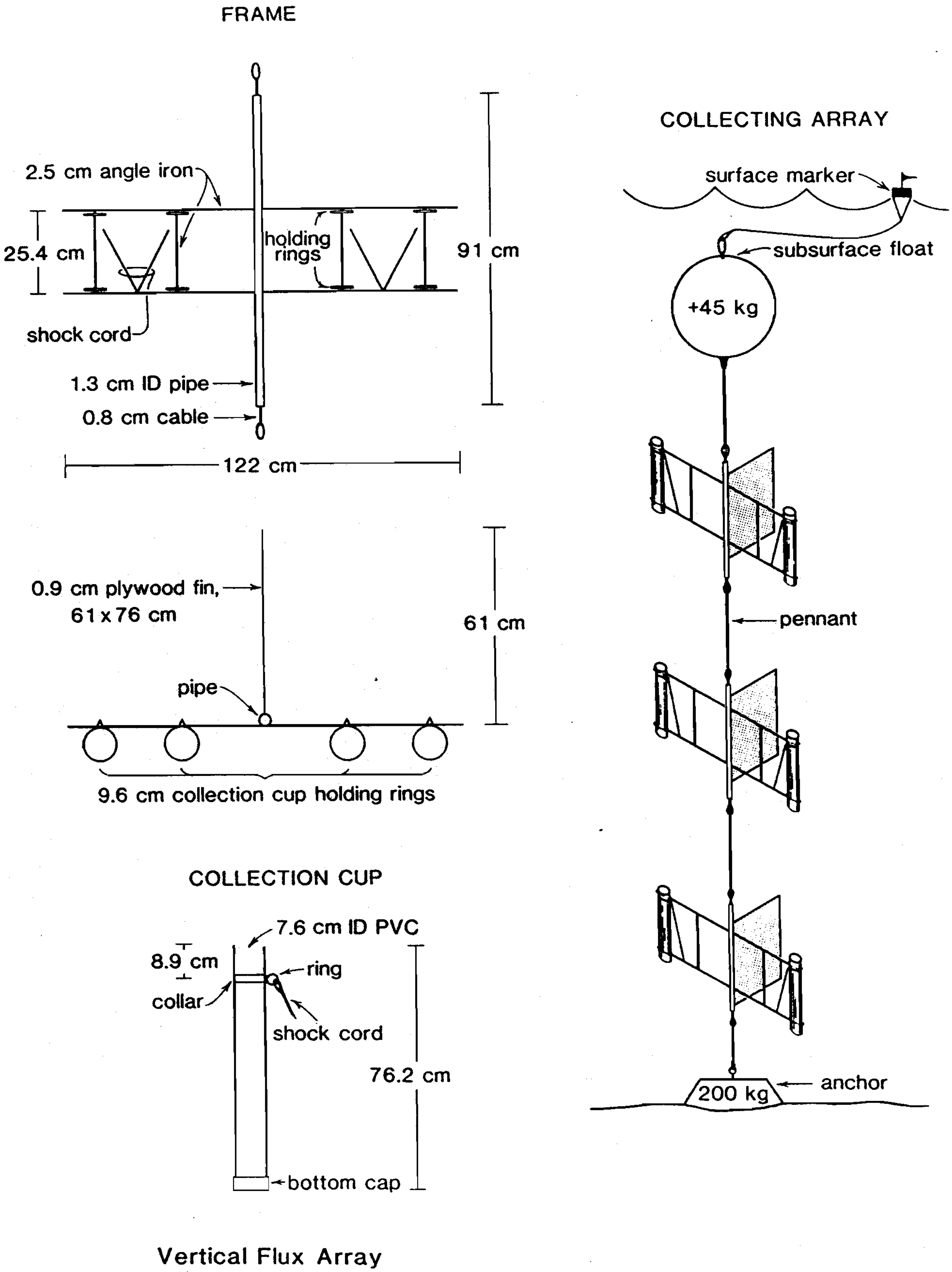


Fig. 3-4. Schematic diagram of the sediment trap used in VFX monitoring.

3.3.4 Chemical Analyses

In brief, methods for the determinations of dissolved and particulate nutrients are as follows: NO_3^-, NO_2^-, NH_4^+ and PO_4^{-3} are measured using the automated method of EPA (1979); silicious acid is determined using the Technicon Industrial System (1977) method; PP concentrations are obtained by acid digestion of muffled-dry samples (Aspila et al. 1976); PC and PN samples are analyzed using a model 240B Perkin-Elmer Elemental Analyzer; biogenic silica is measured using the method of Paasche (1973); methods of Strickland and Parsons (1972) and Shoaf and Lium (1976) are followed for chlorophyll a analysis; total suspended solids are determined by the gravimetric technique of EPA (1979).

3.4 Level I Analysis

3.4.1 SONE Study

Level I interim reports include tabular listings of all variables measured. At each SONE station, sediment Eh, net sediment-water nutrient and oxygen flux, surface and bottom water dissolved nutrient concentrations and vertical profiles (2 m intervals) of dissolved oxygen, temperature and salinity are reported. Summary statistics including means and standard deviations are provided for nutrient and oxygen flux data. Additionally, preliminary interpretations of data are presented.

3.4.2 VFX Study

Each level I report includes tabular listing of all variables measured. Specifically, at each VFX station deposition of particulate materials to collection cup depth, characterization of surficial sediments, particulate material concentration in the water column and vertical profiles (2 m intervals) of dissolved oxygen, temperature and salinity are reported. Additionally, preliminary interpretations of the data set are presented.

4. CONTINUED CONSIDERATIONS OF HISTORICAL PATTERNS OF SOC AND NH_4^+ FLUX

In our previous Level I report (Boynton et al. 1988) we identified several locations in the bay where sufficient sediment flux data were available to allow initiation of an investigation of historical patterns. Data collected at these stations prior to Aug 1984 were compared to more recent data collected in the MDE monitoring program. Several patterns emerged and we have continued to pursue these types of comparisons and to relate trends in sediment fluxes to patterns of river flow.

4.1 Patuxent River Patterns

At the Buena Vista station, patterns of sediment oxygen consumption (SOC) and ammonium regeneration were relatively distinct in the earlier period (1978-1980) with annual maxima occurring in mid-Jul and late Aug, respectively (Fig. 4-1). In the more recent period for which annual data are available (1983-1988), rates are lower with seasonal peaks occurring about two months earlier in late Apr and mid-June, respectively. Ammonium and SOC data collected in 1988 were near the lower portion of the range of values observed during the 1984-1987 period. SOC fluxes were quite low throughout the year. The overall trend is highlighted in Fig. 4-2 where the ranges of rates in the two time periods are outlined and mean values of recently collected data (1988) are shown. The overall trend indicates that interannual temperature patterns are not a major factor. However, SOC and NH_4^+ fluxes at this station were lower during 1988. This decrease in flux magnitude may be due to lower levels of non-point run-off (as proposed in our conceptual model).

At the St. Leonard Creek station in the lower Patuxent the seasonal temperature pattern in 1988 was very similar to that observed in previous years (Fig. 4-3). In fact, there has been only one significant departure (May, 1981) from an otherwise smooth pattern.

However, it appears that a different pattern is developing in more recent as compared to older SOD data. In the early 1980's SOD reached maximum levels (2-3 g O_2 $m^{-2}d^{-1}$) in the spring with slightly lower rates in the summer (Fig. 4-3

Since 1987 SOD levels are lower throughout the year except in the fall and there is only a slight indication of a spring peak. Ammonium fluxes were very low in the spring and fall of 1988. Late spring and summer fluxes were comparable to those recorded in the late 1980's.

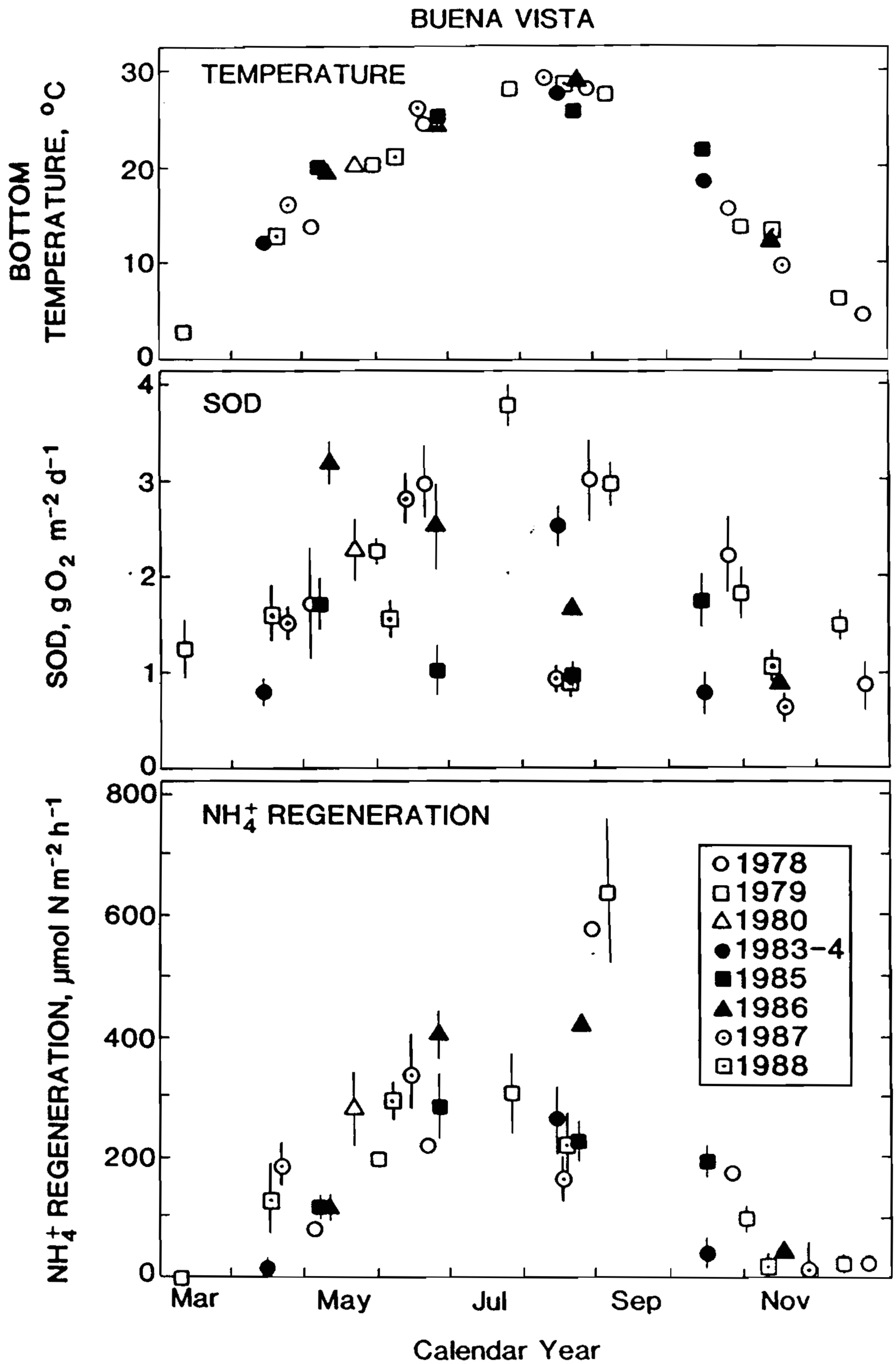


Fig. 4-1. Annual patterns of water temperature, sediment oxygen demand (SOD) and ammonium regeneration from sediemnts for the Buena Vista station in the Patuxent River estuary between 1978 and 1988. Given are means and standard deviations for three replicate measurements.

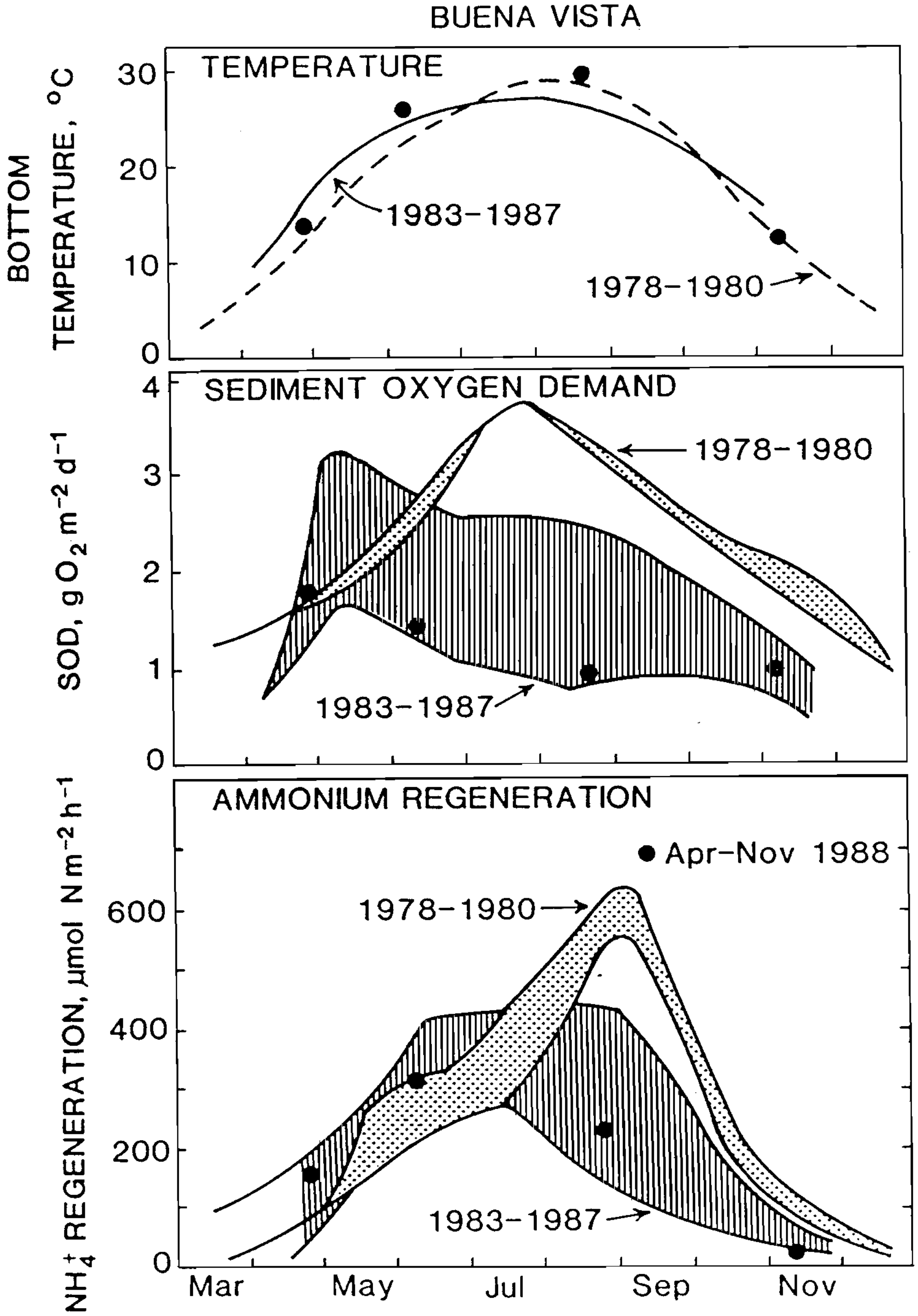


Fig. 4-2. Annual patterns for mean water temperature and ranges in SOD and ammonium regeneration at Buena Vista for several time periods: 1978-1980; 1983-1987; and 1988 (shown as separate symbols).

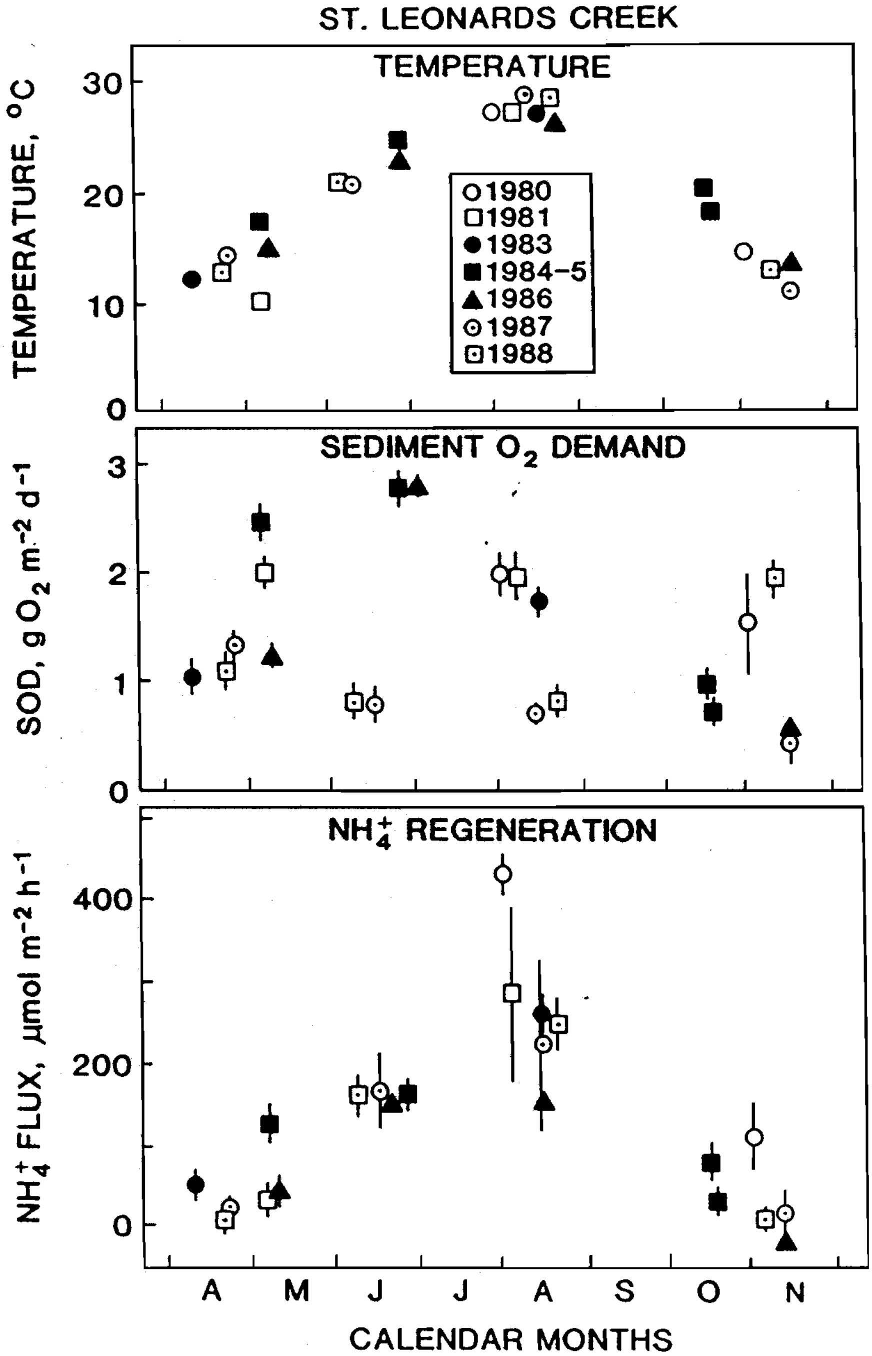


Fig. 4-3. Annual patterns of water temperature, SOD and ammonium regeneration from sediments for St. Leonards Creek Station in the Patuxent River estuary between 1980 and 1988. Given are the means and standard deviations for three replicate flux measurements.

4.2 Potential Factors Regulating Flux Patterns

In our previous Level I report we considered the possibility that changes in the magnitude and seasonality of sediment-water fluxes at two locations in the Patuxent estuary were in response to alterations in temperature or river flows between the early 1978-1983 period and the more recent 1984-1988 period. Some temperature differences between the earlier and recent periods were found. Spring temperatures were somewhat higher in the recent period, while peak summer values were higher in the earlier period (an exception: data collected during Aug 1986). However, the temperature differences observed between the two periods could at best explain about 30% of the observed flux differences (assuming a Q_{10} of 2.0). Other factors are clearly involved.

Annual mean flow of the Patuxent (as monitored at the Bowie, Md. gauge) was substantially higher from 1978-1980 (ca. 520 cfs) compared to the 1983-1985 period (ca. 380 cfs). Flows during 1986 and 1987 were even lower (ca. 250 cfs) and it appears that 1988 flows were also low although quantitative data are not yet available. This flow data coincides with the greater annual mean values of SOC and ammonium regeneration at Buena Vista in the earlier period (Fig. 4-4). The above correlation is consistent with a simple conceptual model which postulates a direct chain of influence: river flow delivers dissolved nutrients which support plankton production, some of which is deposited to the sediment surface, thereby fueling SOC and NH_4^+ regeneration (e.g. Boynton et al. 1982b). However, the observed seasonal shifts would not necessarily be predicted from this model. In fact, data presented by Cory (1974) for primary production in the Patuxent near Buena Vista indicate the opposite response to increased nutrient loading from sewage effluents, that is, the time of maximal rates shifted from spring to summer. River flow, however, also peaked 3 months earlier in the 1978-1980 period compared to 1983-1986 (Fig. 4-4), and in combination with the temperature differences, might account for the seasonal shift in fluxes. This explanation would require a 3-4 month lag between time of peak river flow and peak sediment-water fluxes, which is consistent with the previously described scheme relating nutrient inputs, productivity an sediment-water fluxes (Kemp and Boynton 1984).

In the context of the model presented above, flux data collected at the Buena Vista site during 1986-87 (May-Nov 1986 and Apr-Jun 1987) tended to be high, while river flow (and associated nutrient loading from diffuse sources) was the lowest during the time periods considered and temperatures were near record highs. For example, SOC in May, 1986 was in excess of 3g O_2 $m^{-2}d^{-1}$ while NH_4^+ flux was about 400 μg-at N $m^{-2}h^{-1}$ in Jun and Aug. The SOC value is the highest on record for this time period at the Buena Vista site and the NH_4^+ fluxes were exceeded only by measurements made in Aug 1978 and 1979 (Fig. 4-1). River flow in 1987 was also low and fluxes were lower with spring peaks. At this point, the linear cause-effect model described earlier is still applicable. Specifically, temporal patterns of SOC follow the pattern for low-flow years with peak values in the early spring followed by lower rates in the summer with ammonium flux values following a similar pattern. The important point to emerge from the analysis is that in low nutrient loading years (e.g. 1986) benthic fluxes tend to be lower with highest fluxes occurring in spring, whereas in years of higher loading, highest benthic fluxes occur later in summer. Thus high summer fluxes from the sediments could promote continuation of hypoxic-anoxic conditions characteristic of earlier periods (e.g. 1978-1980).

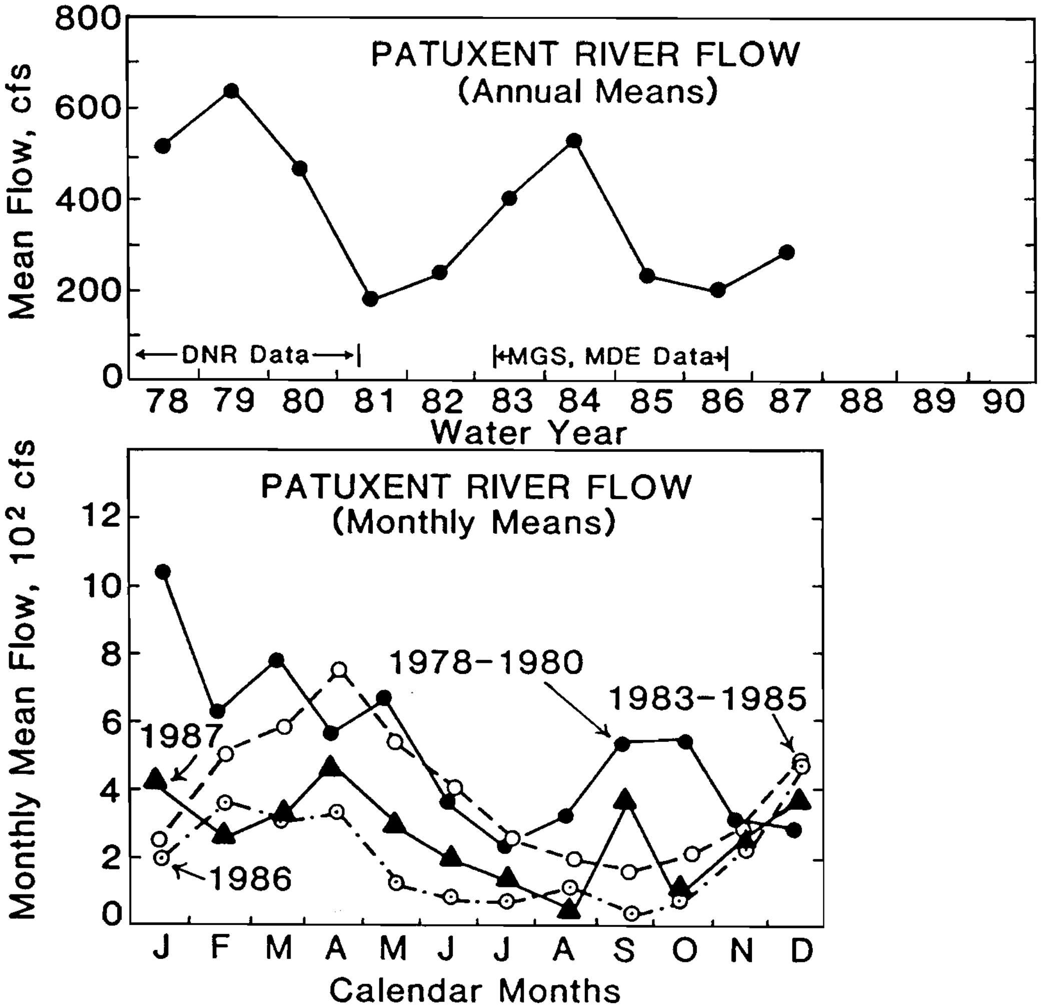


Fig. 4-4. Patuxent River flow (from gauging station near Bowie, Md.): (a) annual means for 1978-1987; (b) monthly means (and ranges in some cases) for 4 time periods.

4.3 Sediment Flux Patterns in the Bay and Lower Tributaries

Summer (Aug) and spring (May) rates of SOC and ammonium regeneration for stations in the open Bay and in the lower tributaries between 1980-1981, 1985, 1986, 1987 and 1988 are shown in Fig. 4-5. SOC fluxes were higher in both summer and spring of the earlier period. Since 1985 there has been a general trend towards lower SOC values at most stations.

NH_4^+ fluxes appear more complex. For example, fluxes were generally low ($<100 \mu g$-at N $m^{-2}h^{-1}$) in the spring (May) at all stations regardless of river flow conditions. However, there was considerable variability among years in summer NH_4^+ flux, but fluxes at all stations were much larger than those observed in the spring.

Annual peak flows of the Susquehanna River (Fig. 4-6) were almost twice as high in 1980, 1981, 1986 and 1987 as in 1985 and 1988. Thus, we currently have data encompassing a modest range of river flows. The next logical step is to initiate analyses wherein nutrient loadings from fluvial sources are compared to sediment fluxes for appropriate time periods.

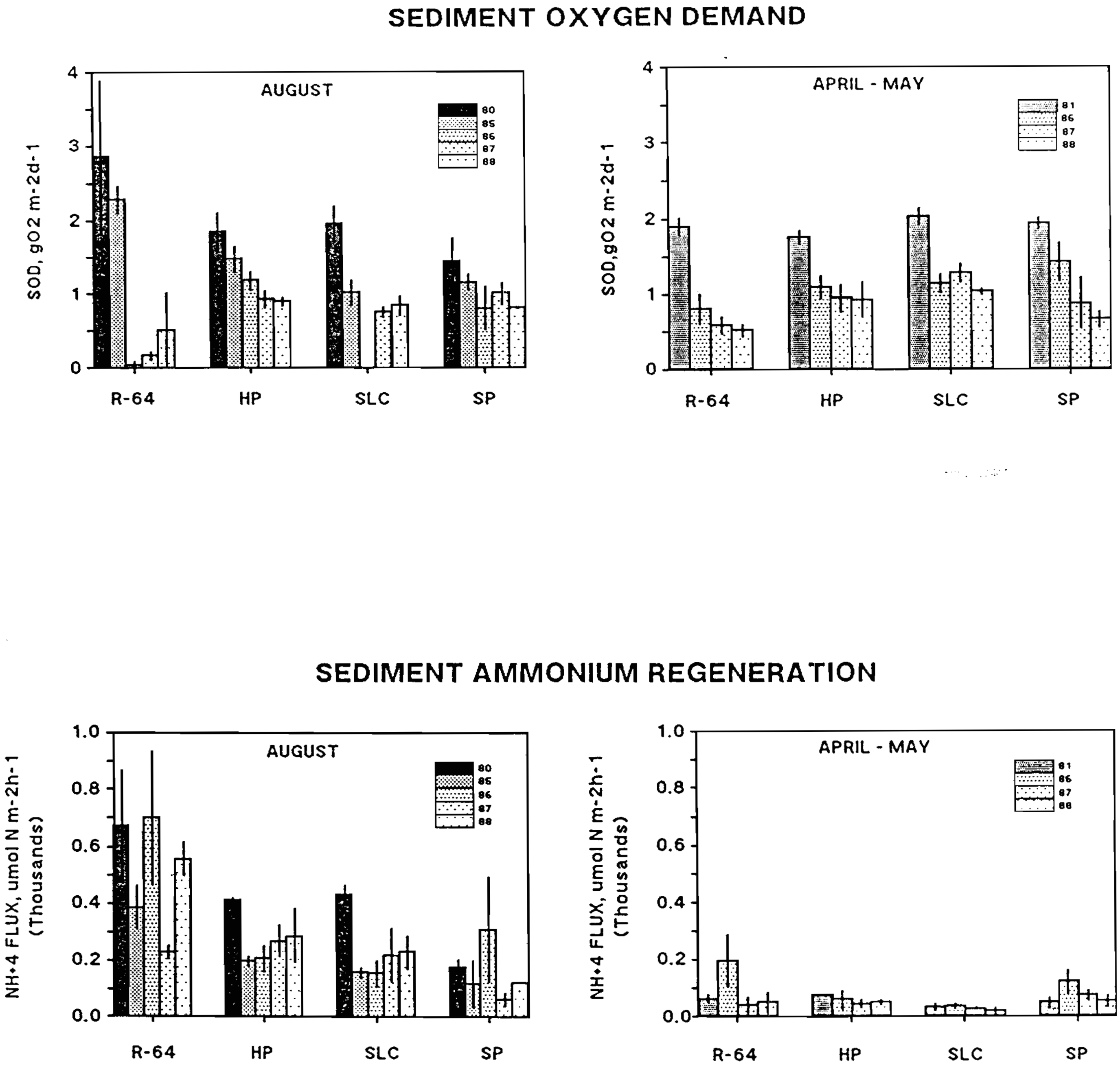


Fig. 4-5. Sediment oxygen demand and ammonium regeneration from sediments at two open Bay stations (R-64; Still Poind, SP) and two stations near the mouths of tributaries (St. Leonard's Creek, SLC; Horn Point, HP) for 4-5 time periods. Given are means and standard deviations for three replicate measurements.

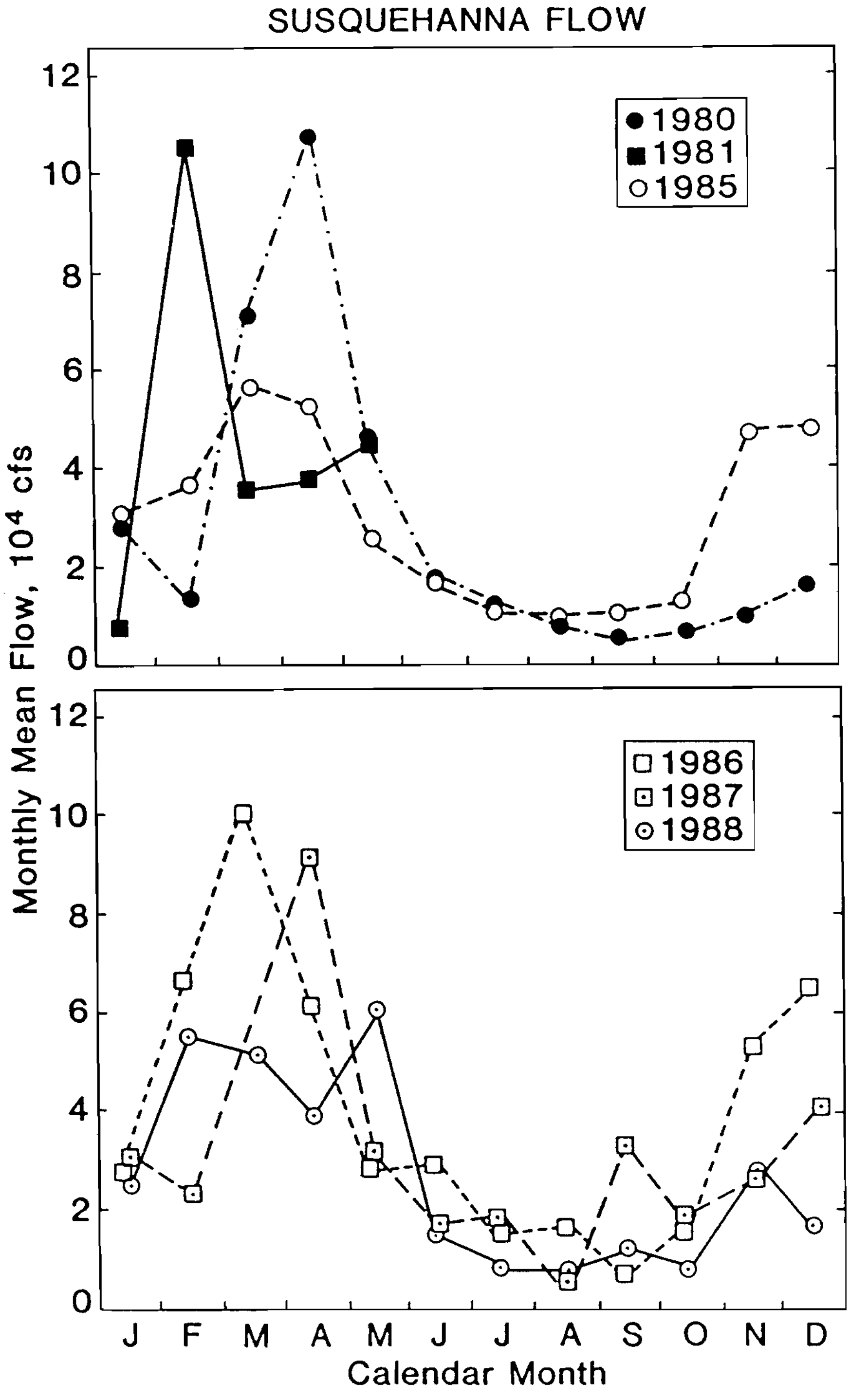


Fig. 4-6. Monthly mean value for Susquehana River flow in 1980, 1981, 1985, 1986,1987 and 1988.

5. MONITORING PARTICLE DEPOSITION RATES (VFX)

Particle deposition rates have been measured at Station R-64 in the mesohaline reach of Chesapeake Bay since the summer of 1984. All data are currently available from Jul, 1984 through Dec, 1988. In this report we emphasize intraannual and interannual patterns using this data set. Our purpose here is to establish a sound understanding of annual cycles and begin exploration of year-to-year trends.

5.1 Seasonal Patterns of Deposition Rates

Although some small differences are evident in the seasonal pattern of carbon and chlorophyll deposition rates, data for the years 1985 and 1986 are essentially similar (Fig. 5-1). Three periods of peak deposition are repeated in the two years, one in spring (Apr), one in summer (Aug) and one in autumn (Oct-Nov). Relatively low rates occur in winter (Jan-Mar) and in late spring (May-Jun). Also, deposition rates are apparently low in late summer (Sep) and later autumn (Dec); however, data are limited for these periods. In general, the magnitude of each of these seasonal peak deposition rates is similar (10-15 mg Chl $m^{-2}d^{-1}$); however, the spring and autumn events were relatively larger in 1985. As discussed in the following section, deposition data collected in 1987 exhibit the exact same pattern (i.e. 3 deposition pulses) while 1988 data were similar but there was no evidence of a fall pulse. (fig. 5-3)

The consistency in seasonal patterns of deposition for 1985 and 1986 is remarkable in view of the differences in primary production cycles for the two years (Fig. 5-1). Hydrologically, Susquehanna River flow in both years was low relative to the 30-year mean (Malone et al. 1987). The maximum monthly flow in the spring freshet was, however, about twice as large in 1986 compared to 1985. Phytoplankton production in 1986 exhibited a smooth seasonal cycle directly correlated to temperature, while in 1985 production was generally higher, with elevated rates also occurring in early fall coincident with the peak deposition event. No obvious relationship occurs between production and deposition on the indicated weekly to monthly time-scales. Malone et al. (1986), however, observed a significant correlation between sediment deposition rates at Station R-64 and phytoplankton production at two sites flanking the sediment trap array to the east and to the west (10 m depth).

Annual deposition cycles reported for many coastal waters in northern Europe are dominated by a single large event associated with the spring phytoplankton bloom (Smetacek 1984; Wassmann 1984). In other coastal systems, two major deposition events have been observed, one in spring and the other in summer (Steele and Baird 1972; Hargrave and Taguchi 1978; Forsskahl et al. 1982) or autumn (Webster et al. 1975). For several of these descriptions of annual cycles, periods of peak deposition generally correspond to periods of maximum phytoplankton production (Steele and Baird 1972; Hargrave and Taguchi 1978; Forsskahl et al. 1982). For other systems peak summer production rates are not accompanied by high deposition values (Smetacek 1984). In many lakes a strong temporal correspondence between plankton production and carbon deposition has been observed (Bloesch et al. 1977).

Although peak rates of phytoplankton production occurred in mid-to late summer in 1985 and 1986, maximum densities of chlorophyll (integrated over the euphotic zone) were consistently observed in early Apr (Fig. 5-1). Temporal trends in chlorophyll deposition rates tended to correspond to trends in chlorophyll stocks in the euphotic zone during spring. Although chlorophyll stocks were lower in the summer of 1985 and 1986, an indication of increasing concentrations during the deposition events of both summers exists. In fact, by combining data from the two years, significant correlations between chlorophyll stocks and deposition rates were observed for both spring (Mar-Jun) and summer (Jul-Aug) periods (Fig. 5-2). Interestingly, the slope of the summer correlation is twice that for the spring relationship. These slopes indicate that algal deposition reflects turnover times of phytoplankton stocks in euphotic zone of 7 and 14 days for summer and spring, respectively. Although sediment-trap data presented for other coastal systems suggest possible correlations between chlorophyll stocks and deposition (e.g. Steele and Baird 1972; Wassmann 1984), no previous studies have reported quantitative relations. Based on a more limited data set, however, Kamp-Nielsen (1980) has presented similar correlations with seasonally varying slopes.

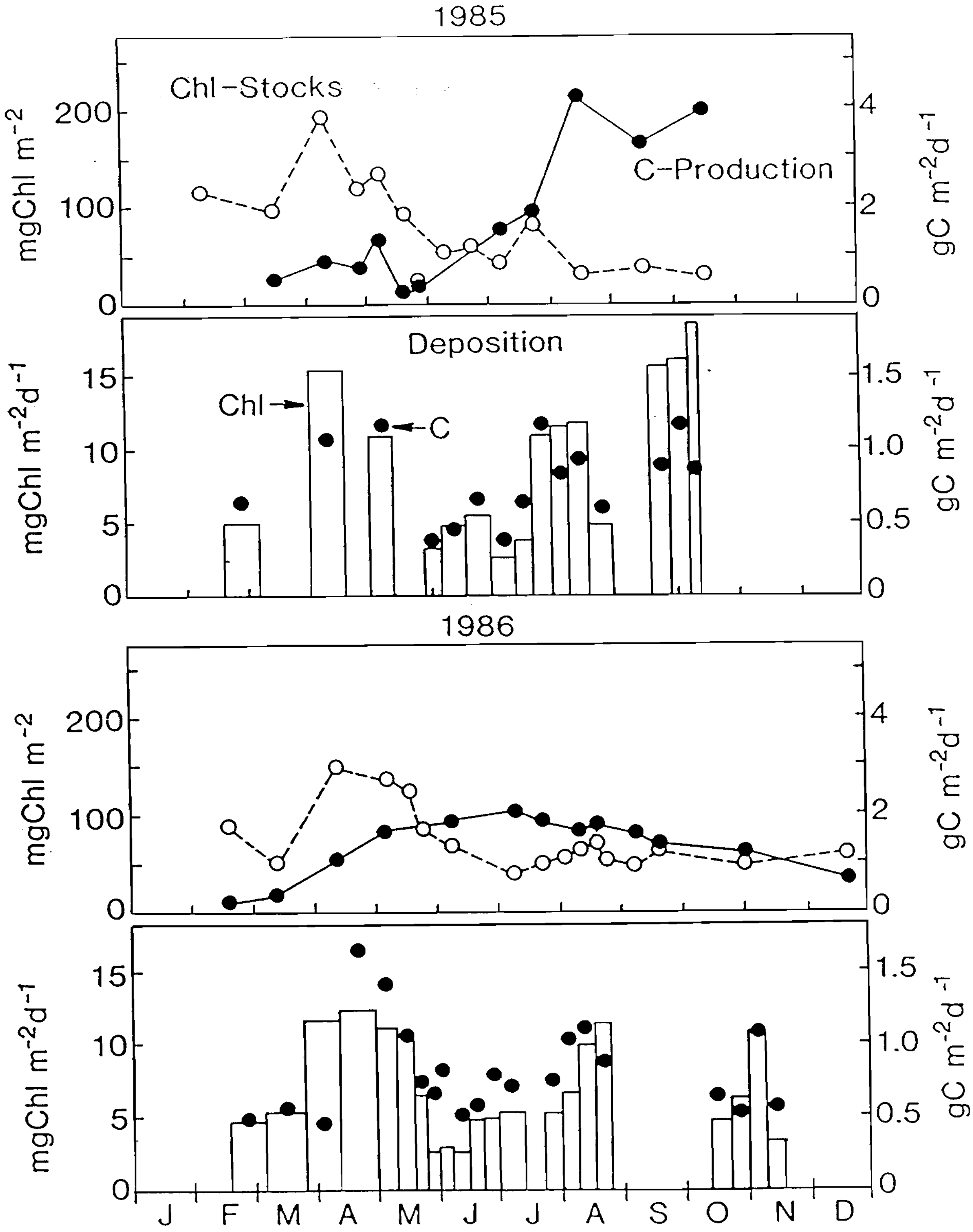


Fig. 5-1. Seasonal trends of phytoplankton chlorophyll and carbon-fixation (Malone et al. 1987) in relation to deposition of chlorophyll (bars) and carbon (points) for 1985 and 1986 at Station R-64 in mesohaline portion of Chesapeake Bay.

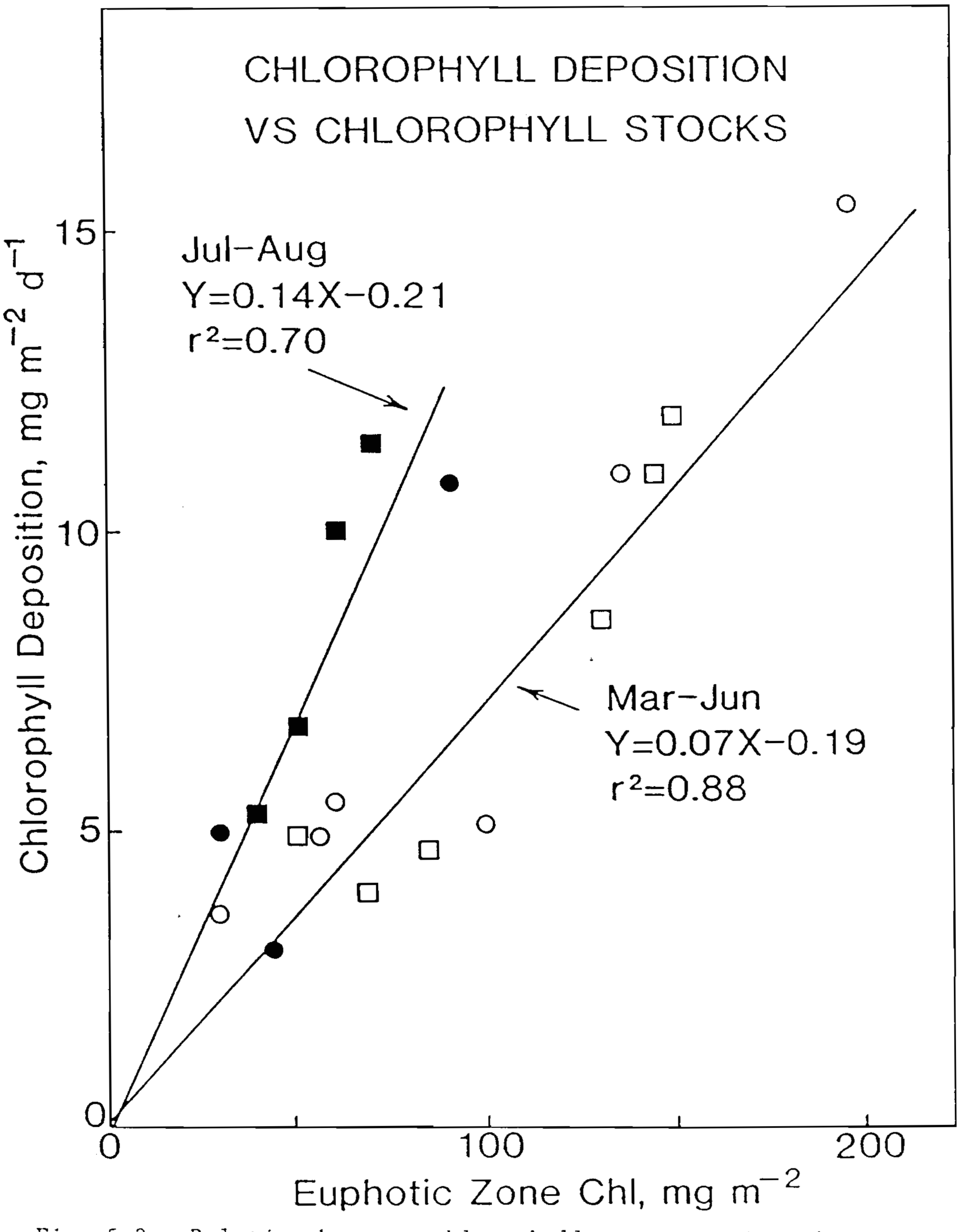


Fig. 5-2. Relation between chlorophyll concentrations in water column (integrated over euphotic zone) and chlorophyll deposition rates for spring (open symbols) and summer (closed symbols) in 1985 (circles) and 1986 (squares) at Sta. R-64 in mesohaline portion of Chesapeake Bay.

5.2 Interannual Patterns of Deposition Rates

Annual patterns of particulate carbon (PC) flux to the mid-depth trap (located near the base of the pycnocline) for the period 1984-1988 are shown in Fig. 5-3. During this period, values ranged from 0.3 to 1.6 $gCm^{-2}d^{-1}$; the majority of values were between 0.5 and 1.0 $gCm^{-2}d^{-1}$. In general, deposition values in all years tended to be highest in the spring.

We now have sufficient data to begin to link the sources of organic matter (primarily phytoplanktonic production in overlying waters) with deposition events among years. A reasonably strong signal has emerged which indicates that a very large percentage of the spring bloom (Mar-Apr) is deposited to deeper waters where as a considerably smaller fraction of new organic matter is deposited during the summer period (Jun-Aug). Specifically, during spring periods from 1985-1988 from 42 to 140% of plankton production was captured in the traps; during corresponding summer seasons from 18 to 47% was captured in collecting cups. Thus, the picture which has emerged for these two time periods is one wherein most material appears to sink to deep waters in the spring (~90%) where as a smaller percentage (~30%) reaches deep water in summer. As indicated in Fig. 5-3 fluxes are substantial (0.8-1.3 $g\ C\ m^{-2}d^{-1}$) during both time periods.

While there is always some degree of variability between years in most variables associated with primary production and algal stocks, there is a remarkably stable interannual pattern of deposition, as indicated in Fig. 5-3. At this point interannual differences appear to be related to the magnitude rather that patterns of deposition. In each year monitored to date there is a clear indication of a spring deposition period, the peak of which occurs from late Apr through early May, despite significant temporal shifts in the timing of peak discharges from the Susquehanna River. Following the spring depositional period, there is 3-4 month period (Jun-Sep) characterized by moderately high and low deposition rates ranging from 0.4-1.3 $g\ C\ m^{-2}d^{-1}$. Finally, there is a consistent fall (Oct-Nov) deposition period although the magnitude and duration of this event is smaller and shorter than the spring event. We have insufficient information to characterize depositional patterns in the winter months (Dec-Feb).

During the period for which we have complete spring through fall deposition data (1985-1988) there have been, as indicated previously, some among-year variations in river flow (and presumably nutrient loading). Specifically, the spring peak in 1985 was very attenuated; in 1986 and 1987 there were clear spring pulses which occurred in early Mar and Apr, respectively; in 1988 the pulse was again attenuated but with small peaks in Feb and May. Qualitatively the pattern of spring river flow is reflected in spring deposition rates. For example, in the springs of 1985-87 there was a single spring peak in river flow (early Mar-Apr) followed by single peaks in deposition (early May). Additionally, peak deposition rates were lower in 1985, a year characterized by lower than normal spring river flow. Finally, in 1988 there was a bimodal freshet (Feb and May) and a bi or tri-modal spring deposition pattern.

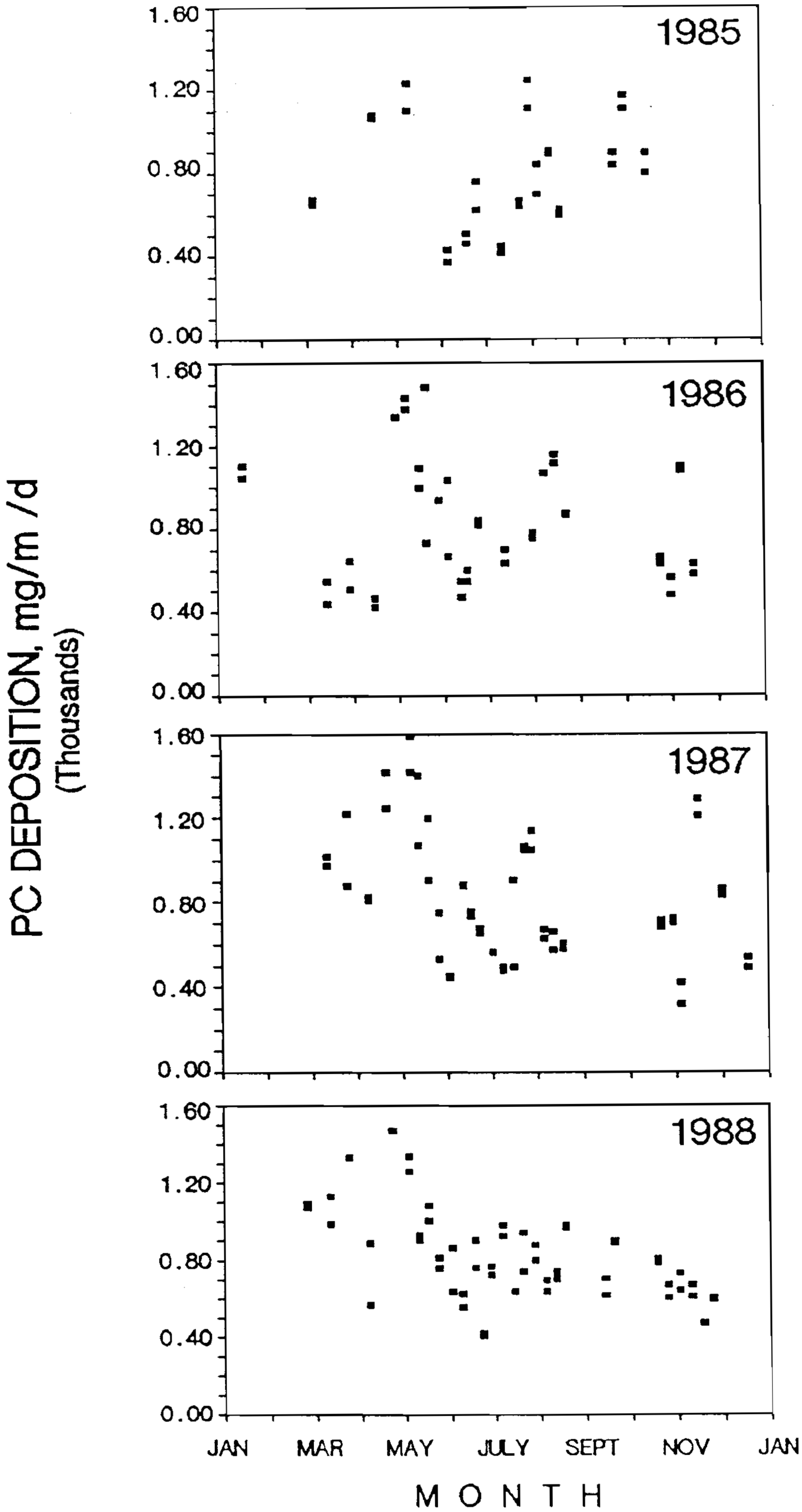


Figure 5-3. Particulate carbon deposition rates (g $Cm^{-2}d^{-1}$) based on mid-trap collections at Station R-64 for the period July 1984 - December 1988.

5.3 Qualitative Character of Sedimenting Particles

Strong seasonal trends were observed in both C:P and N:P ratios of particulate material collected in sediment traps for 1985-1988 (Figs. 5-4 and 5-5). Highest values for both ratios occurred from late winter through late spring; the lowest values in summer through autumn. Comparing ratios with expected proportions based on the Redfield model (e.g. Boynton et al. 1982b), a relative deficiency in phosphorus from winter through summer is apparent. Only in the autumn do values approach Redfield ratios. Ratios of C:N for these sediment trap collections were generally between 7-8, indicating a consistency with expected phytoplankton proportions.

We are not aware of any other reports of phosphorous ratios for marine sediment trap material. However, C:N ratios of sediment trap collections often exceed Redfield proportions, especially in late winter and spring (Webster et al. 1975; Hargrave and Taguchi 1978; Davies and Payne 1984), suggesting possible nitrogen deficiencies in phytoplankton. In contrast, relatively high C:P ratios have been reported for particulate matter collected in sediment traps from lakes, with peak values greatly in excess of Redfield ratios often occurring in summer (White and Wetzel 1975; Gachter and Bloesch 1985). This pattern, evidently widespread for lakes, has been interpreted as indicative of phosphorus limitation for phytoplankton growth (Gachter and Bloesch 1985).

Mean N:P ratios for suspended particles are summarized in Table 5-1 for representative dates and depths. These particulate ratios are compared to ratios of dissolved inorganic N and P in surrounding waters. In addition, concentrations of DIN and DIP are compared to typical values of half-saturation kinetic coefficients for phytoplankton nutrient assimilation. Based on these criteria, phosphorus deficiency and growth limitation is suggested for all but several dates. At these times particulate N:P ratios also approach Redfield proportions. It is possible that an extreme phosphorus (or possible silicon) deficiency in the spring contributes to rapid settling of algal cells (Smetacek 1985).

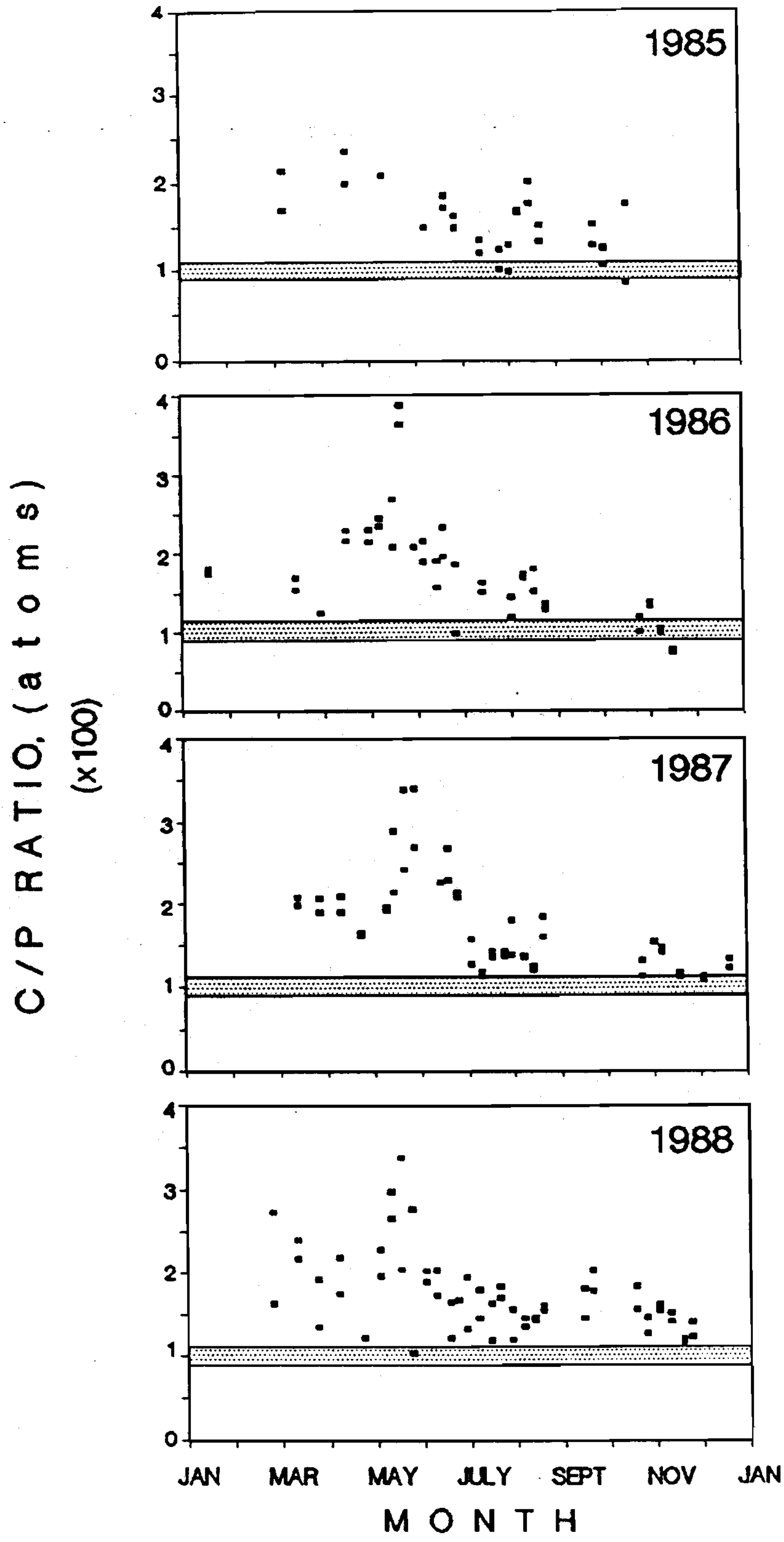


Figure 5-4. Particulate carbon to phosphorus (C:P) ratios (atomic) based on materia collected in surface traps for the period July 1984 - December 1988. The horizontal line on each panel represents a Redfield C:P ratio of about 100.

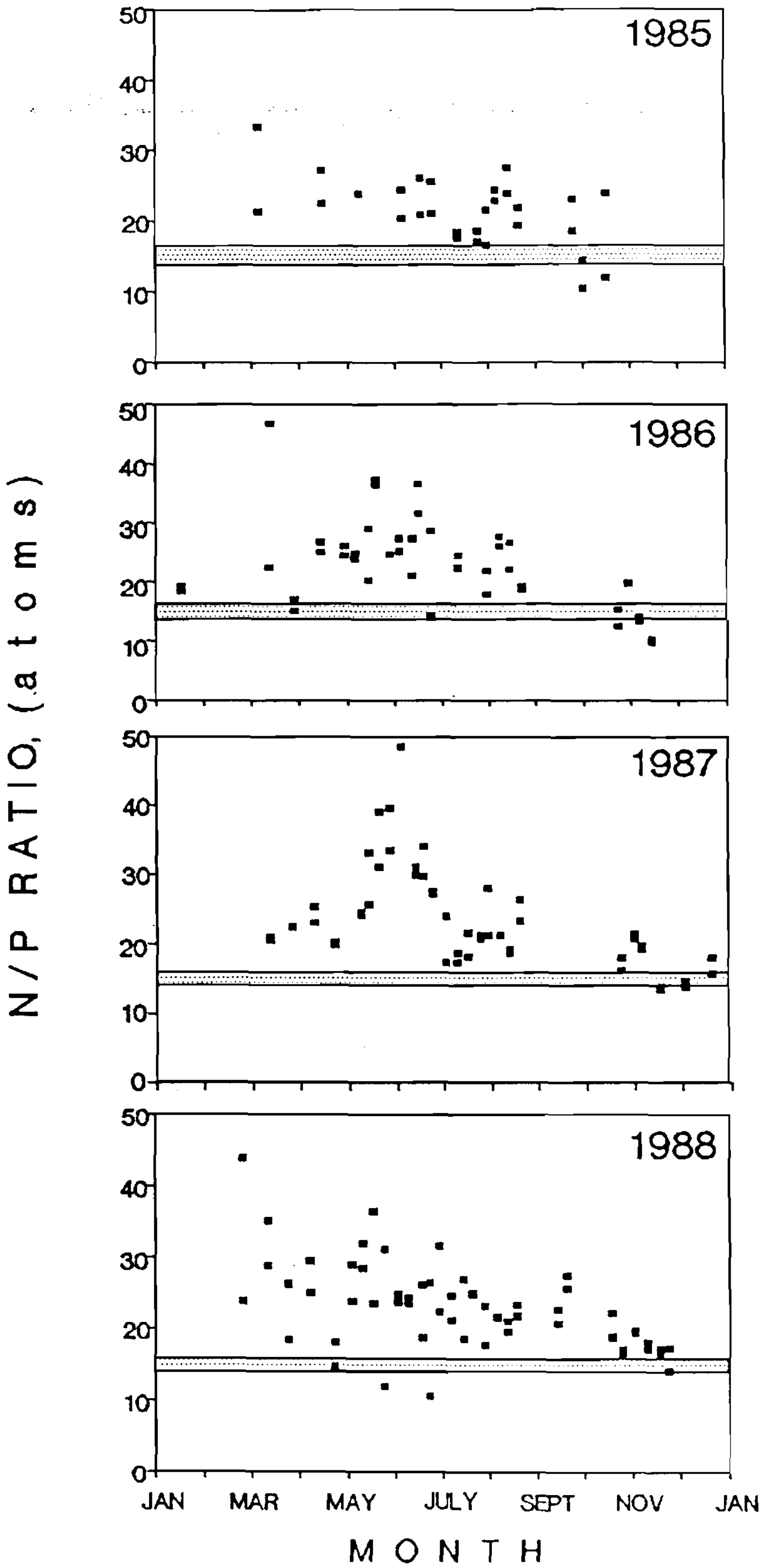


Figure 5-5. Particulate nitrogen to phosphorous (N:P) ratios (atomic) based on material collected in surface traps for the period July 1984 - December 1988. The horizontal line on each panel represents a Redfield N:P ratio of about 16.

Table 5-1. Selected indicator variables for nitrogen versus phosphorus limitations on phytoplankton growth in mesohaline Chesapeake Bay for representative seasons in 1986-198~~8~~9.

Date		Dissolved Inorganic Nutrients: Concentration (uM)*		Uptake Kinetics#		N:P	Particulate Nutrient+: N:P in Photic Zone	
mg/l → uM = x1000/AT. WHT.		N (÷14)	P (÷31)	$N:K_{sn}$	$P:K_{sp}$	(Atoms)	0-4 m	
1986	Apr	22.7	0.1	>>1.0	<1.0	206 (22.7÷.1)	38	VFX
	Jun	7.0	0.2	>1.0	~1.0	29	34	DATA
	Aug	2.8	1.2	>1.0	>1.0	2	27	AVERAGED
	Oct	6.9	0.1	>1.0	<1.0	49	27	
1987	Apr	28.9	0.10	>>1.0	<1.0	289	59	- P limiting?
	Jun	0.7	0.19	~1.0	~1.0	3.5	18	
	Aug	1.55	0.13	~1.0	<1.0	11.2	18	
	Oct	14.1	0.31	>>1.0	~1.0	45.5	28	
1988	Apr	68.3	0.13	>>1.0	<1.0	525	16:1	← Redfield Ratio!
	Jun	0.67	0.22	~1.0 Possibly N-limiting	~1.0	2.6	21	
	Aug	1.1	0.11	~1.0	<1.0	10.4	26	
	Oct	6.7	0.11	>>1.0	<1.0	61.0	29	

* Concentrations in surface (0-1 m) waters at "R-64" from MDE (1988, unpublished); N is $[NH_4^+]$ plus $[NO_2^-]$ plus $[NO_3^-]$, and P is $[PO_4^{3-}]$.

\# Ratios of inorganic nutrient concentrations to half-saturation coefficients, K_{sn} and K_{sp}, for uptake of N and P by phytoplankton assemblages (Taft et al. 1975; McCarthy et al. 1977). K_{sp} taken as 0.2 μM and K_{sn} as 0.5 μM.

\+ N:P ratios (atoms) for seston at station "R-64" for approximately the same dates in 1986-1988.

A comparison of vertical distributions of C:P and N:P ratios for suspended and trap-collected particulates in the water column reveals a remarkable consistency in trends for both ratios during both 1985 and 1986 (Fig. 5-6). Ratios for seston and trapped material tend to decrease with depth, exceeding Redfield Ratios in the euphotic zone (0-10m) while conforming with these ratios in the lower layer. In Apr, water column seston ratios are generally higher than trapped seston ratios. Vertical trends in Jun of 1986 resemble those of the previous Apr, while in Jun of 1985 the trends were similar to those observed later in the summer (Aug). This may reflect the higher spring run-off and stronger vertical stratification in 1986. These vertical patterns of C:P and N:P in seston and trapped particulates reflect nutrient dynamics in the mesohaline region of Chesapeake Bay. Explanations are, however, not straightforward, and we are limited to speculations. Gachter and Bloesch (1985) have considered several explanations for similar vertical decreases in C:P ratio of suspended and trapped particles in lakes. One conclusion is that settling organic particles (phytoplankton and phytodetritus) take-up dissolved inorganic phosphorus (DIP) from the water column (Gachter and Mares 1985). Uptake of DIP may occur through a combination of physical-chemical sorption, algal assimilation, or bacterial assimilation associated with decomposing algal cells. Another possible explanation would be resuspension of bottom sediments. However, C:P ratios of bottom water seston were often lower than bottom sediment ratios. Also, resuspension does not explain how ratios in bottom sediments were so consistently low (below Redfield Ratios). Concentrations of DIP tend to be directly related to water depth in a given site in the mesohaline Bay (Magnien et al., unpubl.), thus, supporting the proposed pattern of increased uptake (kinetic or equilibrium) with depth.

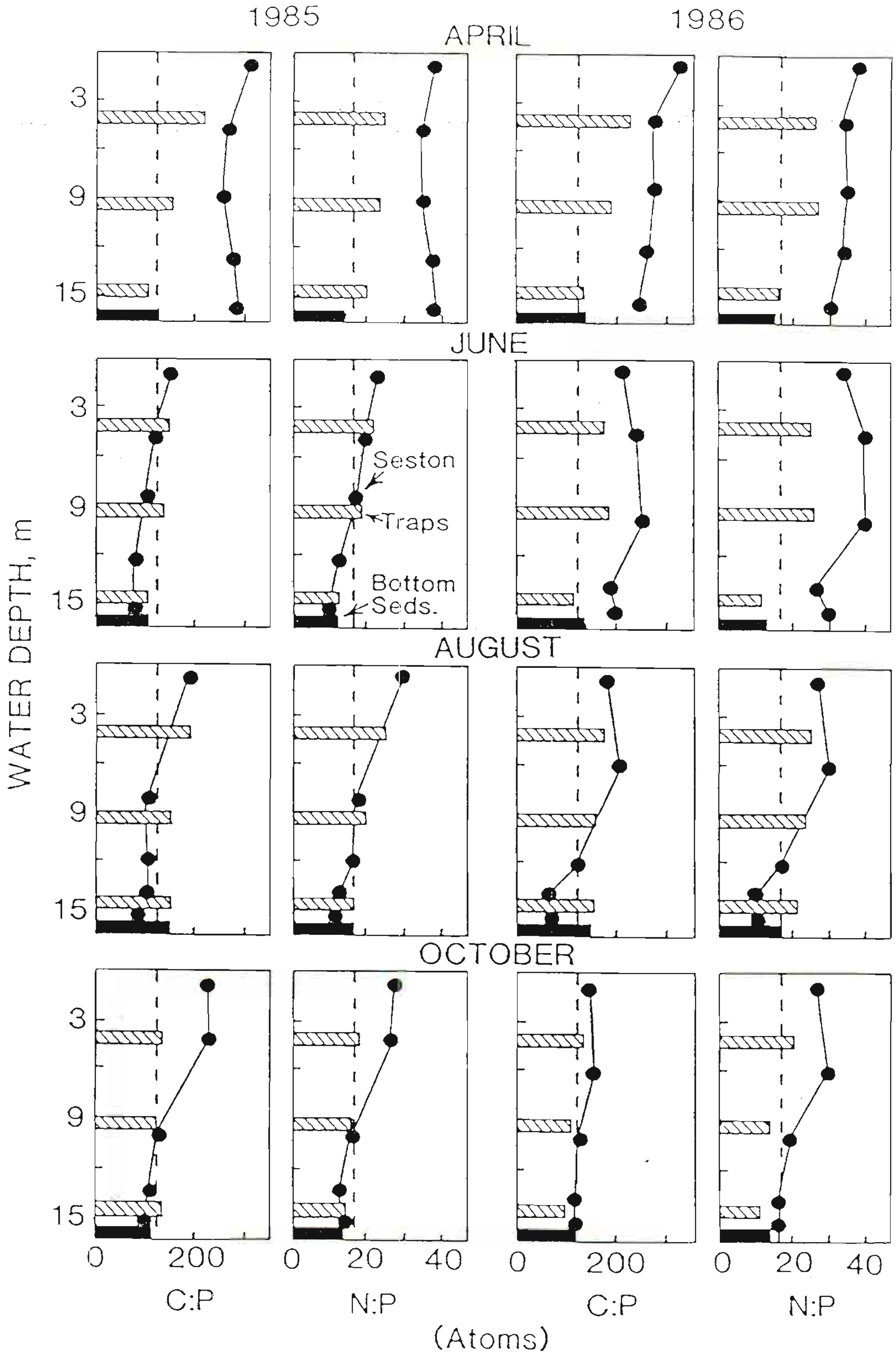


Fig. 5-6 Vertical distributions of elemental C:P and N:P ratios (atomic) of particulate material: suspended in water column (points); collected in sediment traps (cross-hatched bars); and deposited on bottom sediments (darkened bars). Data are for four representative dates in two years (1985 and 1986) from Sta. R-64 in mesohaline portion of Chesapeake Bay. Dashed line indicates expected ratios for phytoplankton.

Although we have shown that particle deposition at Station R-64 is strongly related with phytoplankton standing stocks (Fig. 5-2), broader sedimentological effects occur resulting from algal sedimentation. In general, sedimenting particles at this site contain about 10 percent organic carbon by weight. Phytoplankton biomass, in contrast, tends to be approximately 50 percent organic carbon, indicating that phytoplankton probably constitute less than 20 percent of the mass of deposited material. Thus, while most of the deposited material is probably lithogenic in origin, the annual cycle is driven by phytoplankton dynamics (Honjo 1982). Others have suggested a mechanism of mutual flocculation of algae and inorganic clays (Avnimelech et al. 1982) which may account for this pattern (Smetacek 1985).

5.4 Sediment Trap Measurements of Net Deposition

For several decades sediment traps have been used effectively to estimate new deposition in lakes (Bloesch and Burns 1980). In many aquatic systems and especially for coastal marine environments, resuspension of bottom sediments complicates interpretation of sediment trap collection rates (Steele and Baird 1972). A simple scheme, using organic fraction as an index to differentiate between bottom resuspension versus pelagic sources, has been employed for sediment trap deployments in lacustrine (Gasith 1975) and marine (Taguchi 1982) environments. In these systems resuspension accounted for 60-70 percent of the total sediment trap collection rate. Apparently, traps deployed in deep waters remotely located from littoral areas are less influenced by resuspension (Bloesch and Burns 1980).

Sediment trap data from Station R-64 have been corrected using this approach for representative dates over the course of the 1985 season (Table 5.2). This calculation suggests that resuspension accounts for 15 and 40 percent of the total dry weight of material collected in upper and middle traps, respectively. In computing this resuspension correction, bottom sediments at the trap deployment site were assumed to represent all resuspended material collected (2-3 percent organic). In fact, bottom sediments had similar organic content at both the R-64 (20 m) and the adjacent

Table 5-2. Estimation of fraction of material collected in sediment traps originating from bottom sediment resuspension for selected deployment periods in 1985.

Deployment Period	Percent Organic Content† Seston (f_t) Mid	Seston (f_t) Top	Trap (f_s) Mid	Trap (f_s) Top	Bottom Seds (f_R)	Correction for Resuspension* Mid	Correction for Resuspension* Top
Feb 19-Mar 5	13.9	15.0	13.3	19.5	2.9	0.85	1.00
Apr 30-May 8	10.4	7.9	6.5	17.2	2.7	0.49	1.00
Jun 5-18	12.7	12.1#	9.5	11.9	2.9	0.68	0.98
Jul 24-30	9.2	14.3	6.9	9.3	2.5	0.66	0.58
Aug 13-20	9.3	11.9	6.3	9.7	2.4	0.57	0.77
Oct 1-16	11.3	8.9	5.7	6.8	2.4	0.37	0.68
Mean						0.62	0.84

*Correction factor = $\frac{\text{New Carbon Deposited}}{\text{Total Carbon Deposited}} = (f_s - f_R)\ (f_t - f_R)^{-1}$ based on Gasith (1975).

#Estimated from mean of 27 May - Jun 18.

†"Top" refers to upper layer 0-5 m depth; "mid" refers to 4-10 m depth region.

Dares Beach (10 m) stations. Bottom sediment characteristics are in general, similar along a cross-bay transect in this portion of the estuary at water column depths >5 m (Ward 1985). The closest shoal areas (with <5 m depths) are greater than 10 km from the sediment trap deployment site.

The resuspension corrections for organic carbon deposition rates are lower than those for total dry weight deposition since the ratio of organic carbon content in seston versus bottom sediments is about 5:1 (Table 5.2). Chlorophyll content (as a percent of dry weight) of seston is much higher than that in bottom sediments, because the pigment decomposes rapidly once it reaches the bottom. The ratio of chlorophyll content in seston to bottom sediments ranged from 25:1 to 100:1 during 1985. Therefore, resuspension contributions to the chlorophyll weight collected in traps can be considered negligible. Consequently, chlorophyll deposition rates do not need to be corrected, and composition ratios (C:Chl, N:Chl, etc.) can be applied to chlorophyll rates to estimate deposition of other materials. For 1985 data, annual deposition of organic carbon estimated in relation to chlorophyll sedimentation was similar to that based on resuspension corrections (Table 5.2.).

Annual rates of sediment accumulation calculated from the sediment trap data can be compared with estimates of net sediment deposition derived from other geochemical tracer techniques. (Table 5.3). In 1985, sediment accumulated below Station R-64 at a rate of approximately 4 mm y^{-1}. Since organic carbon comprises 10-15 percent (Table 5.2) of the dry weight of deposited material, total organic weight would be 20-30 percent. Assuming that most of this organic matter is remineralized, the long-term net deposition rate would be ca. 3 mm y^{-1}, which is within the range of values estimated by geochronologic techniques (^{210}Pb) for this region of Chesapeake Bay (Officer et al. 1984). This agreement between methods suggests that sediment trap data are not distorted by systematic methodological errors, and that measured rates are reasonably representative of actual net deposition. Similar close comparisons between ^{210}Pb and sediment trap rates were reported for two Swiss lakes (Bloesch and Burns 1982).

Table 5-3. Calculation of total annual deposition rates in traps for comparison with geochronological estimates of long-term sediment accumulation.

Time Period	Daily Carbon Deposition[a] ($gC\ m^{-2}\ d^{-1}$)	Ratio[b] (gDW:gC)	Total Dry Wt. Deposition[c] ($gDW\ cm^{-2}\ y^{-1}$)	Bulk Density[d] ($g\ cm^{-3}$)	Sediment Accumulation ($cm\ y^{-1}$)
Mar-Nov (275 d)	0.8	10	0.22	0.65	0.34
Dec-Feb (90 d)	0.3	20	0.05	0.65	0.08
Annual (365 d)	0.6	—	0.27[e]	—	0.42

[a]Estimated from mean of values summarized for 4 time periods; also estimated from all 1986 sediment trap data as simple mean, corrected for resuspension by 0.85 (Gasith 1975).

[b]Estimated by time-weighted averaging of percent carbon data, where (Apr, 1010 (10%) + Jun, 440 (10%) + Aug, 870 (13%) + Sep, 460 (5%) ÷ 2760 = 10.0% C, and (Dec-Feb) = 5% C.

[c]Note that $10^4\ cm^2 = 1\ m^2$.

[d]Typical value based on measurements of sediments at "R64"; $\rho_b = \rho_s (1-\phi) = 2.6 (1-0.75) = 0.65\ g\ cm^{-3}$.

[e]Compare to value of 0.1-0.3 g DW $cm^{-2}\ y^{-1}$ given by Officer et al. (1984).

6. SEDIMENT OXYGEN DEMAND AND NUTRIENT FLUXES

Sediment fluxes considered in this section were collected during the first five years of MDE monitoring, from Aug 1984 to Dec 1988 (SONE Cruises 1-18). This data base now comprises 18 sets of flux measurements and supporting environmental data for each of the ten SONE stations. In this section we examine these data for general patterns of flux variability and spatial and temporal patterns in SOC and nutrient fluxes.

In the following discussion several levels of data aggregation are employed to examine spatial and temporal patterns in the benthic flux data: "average station flux" refers to the average of all flux measurements made over the four year period at an individual station; "average monthly flux" is the flux at a particular station averaging all data available for a particular month. The most aggregated level, "average location flux", refers to the average of all fluxes at one of four classes of stations: (1) Upper Tributaries (Buena Vista, Windy Hill, Maryland Pt.), (2) Lower Tributaries (St. Leonard, Horn Pt., Ragged Pt.), (3) Mid-Mainstem Bay (R-78, R-64, Pt. No Pt.), and (4) Upper Mainstem Bay (Still Pond). The upper bay region, as characterized by the Still Pond station, was separated from the other mainstem stations and treated alone because the characteristics of this region (depth, hydrodynamics, sediment characteristics, and redox regime) are distinct from those found at the other three mainstem bay stations. Where appropriate, data from SONE cruises 13 - 18 (Aug and Nov, 1987 and calendar 1988) are shown separately.

6.1 Variability in Benthic Flux Measurements

Sediment-water exchanges of dissolved oxygen and inorganic nutrients (SONE Monitoring) were determined four times per year, during the spring through fall, at each of ten stations in the Maryland portion of Chesapeake Bay. Station locations and flux measurement procedures were described in Section 3. For this report we conducted a thorough review of the sediment flux data base, re-verifying data files and computer algorithms used to generate the sediment fluxes. As before, if the the results from a sediment core did not meet specific quality-control criteria these data were excluded from further analysis. About 4% of the flux data, which now consists of 2700 individual flux determinations, failed to meet the criteria for "interpretable" fluxes, and had to be removed from the data base. The success rate for flux measurements since the inception of the monitoring program has therefore been about 96%.

In earlier Level I Reports (e.g. Boynton et al. 1986) the analysis of sediment flux data was based on averages of the three flux determinations made during each visit to the SONE monitoring stations. For this report, as in our previous report, the flux data have not been averaged; the results from all cores were considered individually in various plotting routines and statistical analyses. These data are given in Appendices 4 and 5.

The coefficient of variation [CV = (std. dev./mean) x100] is a useful statistic for comparing the relative variability among sets of similar measurements (Snedecor and Cochran 1967). An estimate of overall variability in the flux data can therefore be obtained by comparing CV's for all flux measurements made at each station (i.e., combining the data from all SONE cruises) with those determined for a typical set of three replicate measurements from an individual cruise (Table 6-1 and 6-2). This exercise revealed that the variability within each set of flux measurements ranged between 49-368% for all fluxes except N+N. The much higher variability associated with N+N fluxes resulted because of sporatic large fluxes either into or out of sediments driven by high N+N concentrations in the water column or nitrification in sediments, respectively. It must be pointed out that the variability in Table 6-1, as indicated by coefficients of variation, includes not only the variability associated with a single triplicated flux measurement but also variability associated with season of the year. As we show later in this section (Figs 6-2 through 6-6) there are strong seasonal variations associated with most fluxes and variations among stations in the magnitude of fluxes. We have also determined CV's for several typical flux measurements at a specific station (Table 6-2). In this case, where variability associated with seasonality is not included, CV's were much lower ranging between 7-22%, except for N+N fluxes which were again higher. For comparison, the CV's for some environmental variables such as bottom water temperature, salinity, oxygen and NH_4^+ concentrations, determined in conjunction with the benthic fluxes at the SONE stations, ranged from 10-100% (Table 6-3).

Table 6-1. Comparison of coefficients of variation (%) of sediment fluxes from SONE cruises 2-18.

Station	O_2	NH_4^+	N+N	DIP	SI
ST. LEO	67	81	152	126	70
BUENA VISTA	49	63	184	100	64
HORN PT.	70	64	218	125	62
WINDY HILL	50	96	2594	125	56
RAGGED PT.	88	79	22753	105	60
MARYLAND PT.	60	96	163	368	73
PT. NO PT.	78	72	1417	197	62
R-64	82	88	439	126	60
R-78	65	91	1282	190	67
STILL POND	59	119	316	140	90
Average	67	85	752*	160	66
Total # of fluxes	459	454	459	445	455

* Does not include data from Ragged Point.

Table 6-2. Flux characterizations (mean, std. dev., coef. var.) developed from data collected in June and August, 1988 at the Buena Vista station (upper Patuxent River).

Station		O_2	NH_4^+	N+N	DIP	SI
June 1988	$\overline{X}$	-1.46	291.2	-1.41	15.23	335.5
	SD	0.17	21.5	1.99	3.33	56.4
	CV	11.64	7.4	141.42	21.88	16.8
Aug 1988	$\overline{X}$	-0.80	214.3	-2.22	50.26	523.1
	SD	0.10	43.3	4.63	5.51	86.0
	CV	13.15	20.2	208.55	10.97	16.4

$SD = \sigma n-1$

$CV = \frac{SD}{\overline{X}} \times 100$

Add June + Aug 1989

7

Table 6-3. Coefficients of variations of some typical water quality characteristics of near-bottom water at station R-64 determined with a sampling design identical to that of SONE flux measurements (n=30 to 36).

Station	$[O_2]$	$[NH_4^+]$	Temperature	Salinity
ST. LEONARD	50	54	23	12
BUENA VISTA	30	114	21	16
HORN PT.	27	87	24	19
WINDY HILL	18	81	22	27
RAGGED PT.	78	70	24	10
MARYLAND PT.	26	59	22	43
PT. NO PT.	69	61	24	12
R-64	93	47	27	14
R-78	88	36	28	15
STILL POND	22	54	25	58

The CV calculations reflect the overall within-station variability in sediment fluxes. They also indicate that the within-station variability for oxygen and nutrient fluxes was remarkably uniform among the ten SONE stations. Oxygen and silicate fluxes exhibited the least overall variability (CV's of ~66%); the flux of nitrate + nitrite (N+N) was the most variable (CV in excess of 750%) of the benthic nutrient fluxes. With the exception of N+N flux, seasonal and site-related variability encountered during SONE monitoring produced CV's that ranged between 66-160%. This degree of total variability in the measured fluxes appears to be inherent in field measurements of ecological process and is consistent with previous measurements of sediment-water fluxes in Chesapeake Bay (Boynton and Kemp 1985, Callendar and Hammond 1982) and other temperate estuaries (Nixon et al. 1976).

6.2 Spatial Patterns in Station-Averaged Fluxes of Oxygen and Nutrients

6.2.1 Sediment oxygen consumption (SOC).

Station averages of sediment oxygen consumption (SOC) at the ten SONE stations ranged between -0.70 and -1.68 g O_2 m^{-2} d^{-1} during SONE cruises 2-18 (Table 6-4). During the calendar year 1988, SOC ranged from -0.01 to -1.92 g O_2 $m^{-2}d^{-1}$. These rates of benthic oxygen consumption are moderate to large when compared with SOC rates reported for other temperate estuaries (Table 6-5). It is important to note that SONE monitoring does not include measurements during the winter. Comparisons of our station averages with other seasonally or annually averaged flux data, which may include winter measurements, should therefore be done cautiously. Since completion of the BEST program (see Garber et al. 1989) it is now clear that SOC is low, as are nutrient fluxes in the mainstem Bay, when temperatures are below 10^{o}C.

As the SONE data base has grown, our ability to identify differences among groups of stations has improved dramatically. Oxygen flux data considered in earlier Level 1 Reports (e.g. Boynton et al. 1987) suggested that SOC tended to be highest at the shallow tributary stations and lower in the deeper mainstem bay, but statistically significant between-station

Table 6-4 Average station fluxes (means and std. dev.) for SONE Monitoring Stations. Means in the table were determined using data from SONE cruises 2-18. Units are: for O_2 flux ($gO_2m^{-2}d^{-1}$); for all others ($uMm^{-2}hr^{-1}$ as N, P or Si).

	O_2 FLUX		NH_4^+ FLUX		N+N FLUX		DIP FLUX		SI FLUX	
STATION	AVG.	SD	AVG.	SD	AVG.	SD	AVG.	SD	AVG.	SD
ST. LEONARD	-1.31	0.93	102.3	83.1	18.2	27.7	7.00	8.88	319	226
BUENA VISTA	-1.56	0.78	201.0	127.8	12.8	23.7	16.53	16.58	303	194
HORN PT.	-1.39	0.98	162.0	105.2	19.2	41.9	7.07	8.90	337	212
WINDY HILL	-1.68	0.85	187.8	181.6	2.5	65.0	18.39	23.02	413	232
RAGGED PT.	-0.87	0.77	269.6	213.7	-0.2	41.2	20.32	21.36	233	141
MARYLAND PT.	-1.04	0.63	161.2	155.0	-45.1	73.8	3.59	13.26	251	186
PT. NO PT.	-0.82	0.64	122.9	89.2	-1.3	19.1	5.02	9.94	332	206
R-64	-0.70	0.57	256.2	226.3	-5.4	24.0	27.85	35.16	405	243
R-78	-0.58	0.38	102.9	94.2	-2.8	36.1	9.39	17.88	182	123
STILL POND	-1.06	0.63	92.2	110.3	-41.1	130.5	3.31	4.65	148	134

Table 6-5. Comparison of oxygen, DIN, and DIP fluxes at SONE monitoring stations with summer rates of oxygen and nutrient fluxes from various near-shore marine systems.

	SOC g/m2/d	NH_4^+ Flux umol/m2/d	DIP Flux umol/m2/d	Ref.
Loch Ewe, Scotland	0.6-1.05	20-80		1
Buzzard's Bay, MA	1.42	125	-15	1
Eel Pond, MA	1.08	85	16	1
Narragansett Bay, RI	1.80	200	30-50	1
Long Island Sound, CN		50-200	5-20	1
New York Bight, NY	0.84	25	2	1
Patuxent River Estuary, MD	3.03	710	48	1
Pamlico River Estuary, NC		45		1
South River Estuary, NC	1.57	250	17	1
Cape Blanc, West Africa		235	50	1
Vostoc Bay, USSR	1.08	150	20	1
Maisuru Bay, Japan		13-32		1
Kaneohe Bay, HA	0.46	54	3	1
La Jolla Bight, CA		40	6	1
Yaquina Bay mudflat, OR	-6.0-6.8	-91-204	-5-19	2
Chesapeake Bay, MD				
Upper tributaries	1.5	163	11	3
Lower tributaries	1.4	210	11	3
Mainstem bay	0.9	125	12	3
Upper bay (Still Pond)	1.3	90	2	3

References: 1, Modified from Table 1 in Nixon 1981
2, Collins 1986
3, Location means from SONE Monitoring, this report

differences were obscured by within-station variability. The inclusion of additional data further strengthened the finding of differences in SOC rates in some of the tributaries and the mainstem bay. As shown in Fig. 6-1a, SONE stations could be separated into two groups based on average station SOC: high average SOC's were found in the Patuxent River, Choptank River, and the upper bay station at Still Pond. Significantly lower rates occurred in the Potomac River and mid-mainstem bay. The division between the two groups occurred at SOC rates of 1.1-1.3 g O_2 $m^{-2}d^{-1}$. Lowest average SOC rates occurred at Station R-78. It is not clear why SOC and other nutrient fluxes at this station should be significantly lower than the other mid-mainstem stations. We have noticed that sediment at R-78 contains noticeable amounts of slag-like material; it seems possible that aerobic benthic activity at this station may be suppressed by anthopogenic pollutants.

6.2.2 Dissolved inorganic nitrogen fluxes

6.2.2.1 **Ammonium flux.** The results of SONE monitoring are consistent with earlier studies in Chesapeake Bay (Boynton et al. 1980) and elsewhere (Nixon et al. 1976, Hammond et al. 1985, Zeitzschel 1980) in showing that NH_4^+ generally dominates benthic flux of fixed inorganic nitrogen in productive temperate estuaries. The release of NH_4^+ from sediments at the SONE stations was generally many times greater than the net exchange of nitrate + nitrite. At most stations NH_4^+ flux accounted for 70-100% of the total DIN flux (the sum of NH_4^+ + nitrate + nitrite) from the sediment. There were two exceptions: NH_4^+ fluxes at Maryland Pt. and Still Pond contributed a smaller fraction to the net exchange of DIN.

Average station fluxes of NH_4^+ ranged from 92 μg-at $m^{-2}h^{-1}$ at Still Pond to 270 μg-at $m^{-2}h^{-1}$ at Ragged Pt (Table 6-4 and Fig. 6-1). In our previous report we were unable to identify obvious spatial patterns in the averaged NH_4^+ fluxes except to note that the fluxes in the lower Potomac at Ragged Pt. were significantly greater than those found at the other SONE monitoring stations. As shown in Fig 6-1, this spatial pattern in NH_4^+ fluxes at the SONE stations is becoming clearer. As before, with the exceptions of Ragged Pt. and R-78, the average flux at most stations fell between 100-200 μg-at

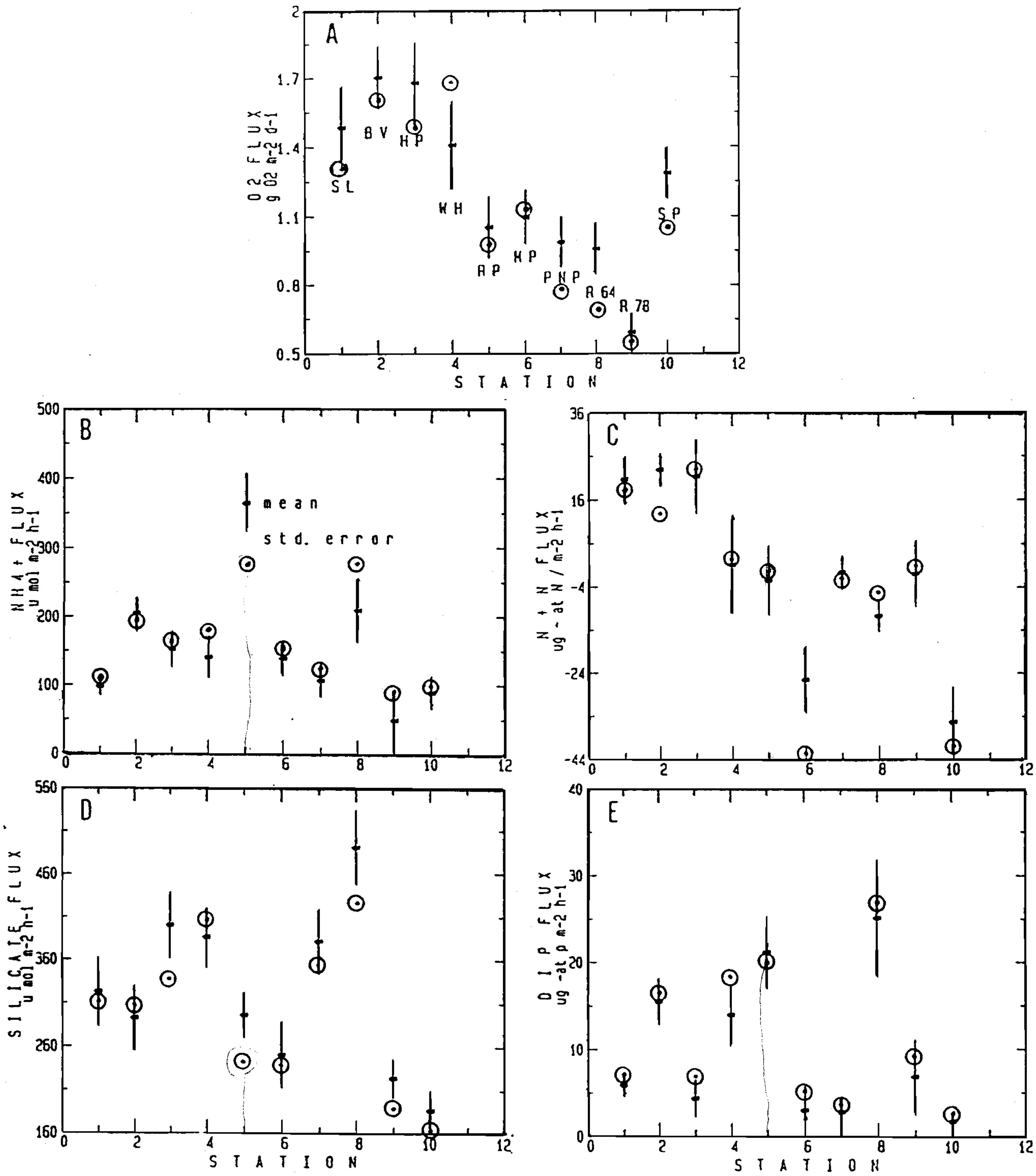


Fig. 6-1. Average station fluxes of oxygen and inorganic nutrients at SONE monitoring stations. Panels show the mean (± std. error) all determinations of each flux for each station. Average fluxes for calendar 1988 are shown as open circles.

$m^{-2}h^{-1}$. Two of the stations exhibiting the highest rates of NH_4^+ release from the sediments (Ragged Pt. and R-64) are subject to summer anoxia. Station R-78 is also subject to summer anoxia, but, as noted above with reference to low SOC rates, NH_4^+ fluxes at this station appear to be anomalously low. Relatively high fluxes were also found at Buena Vista, which remains aerobic all year. The factors responsible for these between-station differences are not clear. Ammonium fluxes appear to be controlled by multiple interacting environmental variables including temperature, the concentration gradient of NH_4^+ across the sediment-water interface, redox state of the sediments and overlying water, activity of the benthic organisms, and the rate of deposition of particulate nitrogen.

6.2.2.2 **Nitrate + nitrite (N+N) flux.** Unlike NH_4^+, N+N fluxes followed more pronounced spatial patterns (Fig. 6-1, Table 6-4) which included shifts in direction of the fluxes across the sediment-water interface. The calculation of average station fluxes revealed that the behavior of N+N differed among three groups stations. Tributary stations in the Patuxent and lower Choptank were characterized by the net release of N+N from the sediment to the water at rates that averaged around 15μg-at $m^{-2}h^{-1}$. In contrast, the overall flux of N+N was into the sediment in the upper Potomac and the uppermost mainstem bay. N+N flux was highly variable at the remainder of the stations, resulting in station-averaged fluxes that were approximately zero. N+N fluxes for individual cores ranged from maximum sediment release of 384 μg-at $m^{-2}h^{-1}$ in the lower Choptank (Horn Pt.) in Aug 1988 to the maximum sediment uptakes of -343 μg-at $m^{-2}h^{-1}$ at Maryland Point in Aug 1988. However, most N+N fluxes fell within an envelope bounded by -45 to +20 μg-at $m^{-2}h^{-1}$ (Fig. 6-1).

The net flux N+N reflects the combined effects of complex chemical and biological factors that regulate NH_4^+ production, nitrification, denitrification, and the fluxes of solutes across the sediment interface. Nitrate concentration in waters over the sediments can influence the measured rate of N+N uptake by limiting the amount of nitrate available for nitrate metabolism (and denitrification) as well as influencing diffusion-driven flux of nitrate at the sediment surface. Highest rates of sediment uptake of N+N (i.e., the most negative rates of N+N flux) occur at two upper estuary stations (Maryland Pt. and Still Pd.) that were also characterized by the highest levels of dissolved nitrate in the water over the sediments. Other factors obviously influence N+N fluxes in other regions of the bay. For example, although nitrate concentrations in bottom water at the upper tributary station in the Choptank River (Windy Hill) were relatively high, the average N+N flux at that station were not strongly negative. Oxygen content of the overlying water and sediment redox regime undoubtedly influence N+N exchange dynamics by influencing the nitrogen-transforming activities of the benthic microbial community. Ammonium oxidation is the first step in the formation of nitrate. Sediments throughout the bay appear to produce an abundance of NH_4^+, so it seem unlikely that the first step of nitrification, NH_4^+ oxidation, would be limited by NH_4^+ availability. However, nitrification is an obligately aerobic process, while nitrate metabolism occurs under predominantly anaerobic conditions. The rate of N+N uptake must ultimately be limited by N+N availability. The rates of NH_4^+ oxidation (nitrification) and nitrate reduction (especially denitrification) are strongly coupled, especially when sources of "new" nitrate from river flow diminish after the spring freshet. We can speculate that the net releases of N+N observed in the Patuxent and Choptank tributaries reflect predominantly oxidized environments both in the surficial sediments and the overlying water. Such conditions would favor sediment-associated nitrification over denitrification, hence the net release of nitrate from the sediments. At other locations in the bay, the redox environment appears to shift between oxic and anoxic conditions, the former favoring nitrification, the latter nitrate metabolism and denitrification. Nitrate formation and consumption appear at times to be in balance. This results in no net flux of N+N at the sediment surface. However, along the mainstem bay where hypoxic and anoxic conditions prevail during the summer, the balance apparently shifts away from nitrate metabolism and little net removal of N+N from the overlying water occurs. At these stations NH_4^+ regeneration appears to be the only significant route of nitrogen remineralization occurring in the sediments.

6.2.3 Dissolved inorganic phosphorus (DIP) flux

During the first four years of SONE monitoring DIP fluxes ranged from sediment uptakes of -24 µg-at $m^{-2}h^{-1}$ at Maryland Point in Aug 1988, to sediment releases of DIP of 128 µg-at $m^{-2}h^{-1}$ at R-64 in Jun 1986. Although sediment uptake of DIP occurred at all but one station (Ragged Pt.) at some time during the monitoring period, station averaged fluxes of DIP were always positive, that is, the net flux of DIP at all stations is predominantly from the sediment to the overlying water (Table 6-4, Fig. 6-1). Four-year station-averaged DIP fluxes at the ten SONE stations ranged from about 3 µg-at $m^{-2}h^{-1}$ at Still Pd. to 28 µg-at $m^{-2}h^{-1}$ at R-64 (Table 6-4). As shown in Fig. 6-1, SONE stations could be separated into two groups by the calculation of station-average DIP fluxes: in one group consisting of the higher salinity stations in the Patuxent, Choptank, and lower bay, the average DIP fluxes were less than 7 µg-at P $m^{-2}h^{-1}$. The remaining four stations (the lower salinity regions of the Patuxent and Choptank, the high salinity region of the Potomac, and the mid-bay at R-64) were characterized by station averaged fluxes in excess of 10 µg-at P $m^{-2}h^{-1}$. These results suggest that relatively high DIP fluxes occur in the low salinity reaches of some tributaries (the upper Potomac may be an exception) as well as the regions of the bay that experience summer anoxia. Again, the results from R-78 do not fit this scheme. The mean DIP flux at R-78 appears to be low for a region that is hydrographically similar to R-64.

Finding the mechanisms that seem to "turn on" and "turn off" DIP fluxes is clearly crucial to understanding phosphorus dynamics at the sediment-water interface. We have shown that the redox environment of the sediment and overlying water is one such important factor, particularly in the mainstem bay (Boynton et al. 1988). However, the DIP flux data collected to date suggest that the mechanisms regulating DIP fluxes probably differ at various locations within the bay. For example, DIP fluxes tended to be highest along the deeper reaches of the mainstem bay and cooler water? the upper tributaries. The release of DIP from sediments along the deep mainstem bay is most likely associated with the

the drop in redox potential that accompanies the depletion of oxygen in the overlying water. Such release of DIP from sediments during anoxic conditions is a well known process in lakes and fjords and involves the redox-driven dissolution of iron phosphates and other compounds (Krom and Berner 1980, Klump and Martens 1981). It seems unlikely that a similar mechanism controls the relatively large fluxes of DIP from sediments in the upper tributaries because the overlying water in these regions is always well-oxygenated.

While we remain unable to define the processes that regulate DIP fluxes precisely, the magnitude of these fluxes are often sufficient to influence the concentration of DIP in the overlying water (cf. Nixon et al. 1980). Consequently, the benthic flux of DIP could influence the amount of DIP available for phytoplankton production, as well as altering the the ratio of DIP to DIN in bay waters.

6.2.4 Dissolved silicate flux

The flux of silicate from individual cores during the monitoring period ranged from 0 to over 1100 μg-at Si $m^{-2}h^{-1}$. The highest rates of silicate flux in individual sediment cores were observed at the lower bay stations (R-64 and Pt. No Pt.) in Jun 1985. Station averaged fluxes for all the stations were always positive (i.e., from the sediment to the water) and of the order of 150-450 μg-at Si $m^{-2}h^{-1}$ (Table 6-4, Fig. 6-1). The addition of more recent data to the monitoring data base reinforced the spatial pattern in silicate fluxes described in our previous Level 1 Report (Boynton et al. 1988). Highest fluxes occurred along the deep mainstem bay and Choptank River. Lowest fluxes were observed at the uppermost mainstem bay station (Still Pond). Although the differences in average silicate fluxes at the upper and lower stations within a tributary were not statistically significant, average fluxes at the lower tributary stations were consistently lower than those observed at the upper station. This pattern remains when ~~wont~~ the data are aggregated into location averages (Table 6-6). Silicate fluxes at the four major regions appears to increase in parallel with increasing salinity: Still Pond < Upper Tribs. < Lower Tribs. < Mainstem Bay. This pattern is consistent with a conceptual model which would predict increasing silicate cycling in higher salinity regimes in parallel with the increasingly important role of diatom production in the phytoplankton communities along and estuarine salinity gradient.

6.3 Temporal Patterns In Benthic Fluxes

6.3.1 Seasonal patterns in benthic fluxes at SONE stations

Our sampling schedule of four measurements per year, skewed toward the summer, is not adequate to clearly define annual patterns of benthic fluxes. Nevertheless, the seasonal component of variability in SONE measurements is potentially important and needs to be defined in order to define year-to-year trends in the data. In our previous Level 1 report (Boynton et al. 1988) some indication of bay-wide seasonality in SOC rates was indicated by examining data averaged by month for all stations and years. For this report we combined the flux data for all years by month for each station. The purpose of this exercise was to identify patterns of seasonality in the flux data. The results of this analysis are presented as a series of box-and-whisker plots in Figs. 6-2 through 6-6. In each plot vertical bars give the range of data; the median is given by the horizontal line in each box; the boxes themselves give the range of each quartile above and below the median. Thus 50% of the data for each flux is enclosed within the box. Data falling more than 1.5 times the quartile range from the median are shown with an asterisk as "outliers." Data (mean of three replicates) for SONE cruises 13 and 14 (Aug and Nov, 1987) are shown as bold circles and data from calendar 1988 as open circles in Figs. 6-2 through 6-6.

The results of this effort to identify seasonal signals in the flux data indicate that no single seasonal pattern adequately describes changes in fluxes that occur at the SONE stations throughout the year (Table 6-7). The caveat here is that our sampling program was not designed to produce a high resolution seasonal picture. Nonetheless, some intriguing differences emerge among the SONE stations for each of the flux measurements. For example, there was a clear indication of seasonality in all nutrient fluxes in the upper

Choptank (Windy Hill) while essentially no seasonality could be discerned in nutrient fluxes in the upper mainstem bay (Still Pond).

Most stations except those in the lower mainstem bay exhibited some seasonality in SOC in which the highest rates of SOC occurred in May or Jun. This pattern emerged most clearly at Horn Pt. (Fig. 6-2). The intriguing feature of this pattern is that it is out of phase with the cycle of bottom water temperature--which reaches seasonal peaks at most stations in Aug--by 2-3 months. The upper Potomac appeared to be unique in that the seasonal maximum in SOC was shifted towards late summer (Fig. 6-2). At stations subject to periodic anoxia, seasonal patterns of SOC were strongly influenced by the timing and duration of low-oxygen conditions and the occurrence of re-aeration events. These factors contributed to the high variability in summer SOC rates observed at Ragged Pt., R-64 and R-78 (Fig. 6-2). In almost all cases, fluxes observed in 1988 tended to be lower than in previous years. Indications are that river flow in 1988 was below average. With low flows, we would expect nutrient loadings to be low and hence deposition of organic matter and the subsequent release of nutrients to also be low. Indications are that the 1988 SOC data fit the conceptual model discussed earlier.

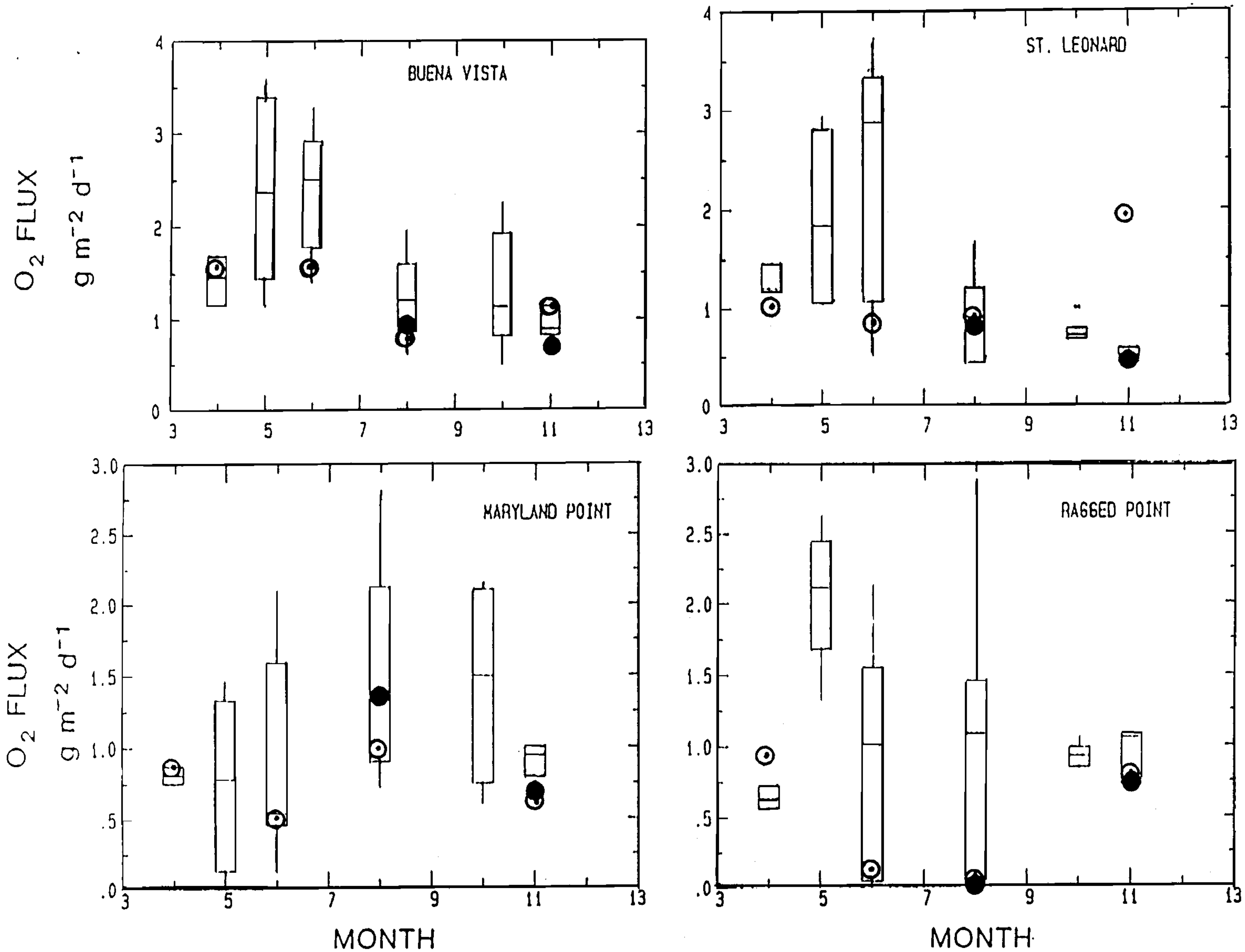


Figure 6-2a. Seasonal variations in sediment-water oxygen fluxes at SONE monitoring stations in the Patuxent and Potomac Rivers. Explanation of box-and-whisker presentation of data is given in text. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included included in developing the box-and-whisker plots.

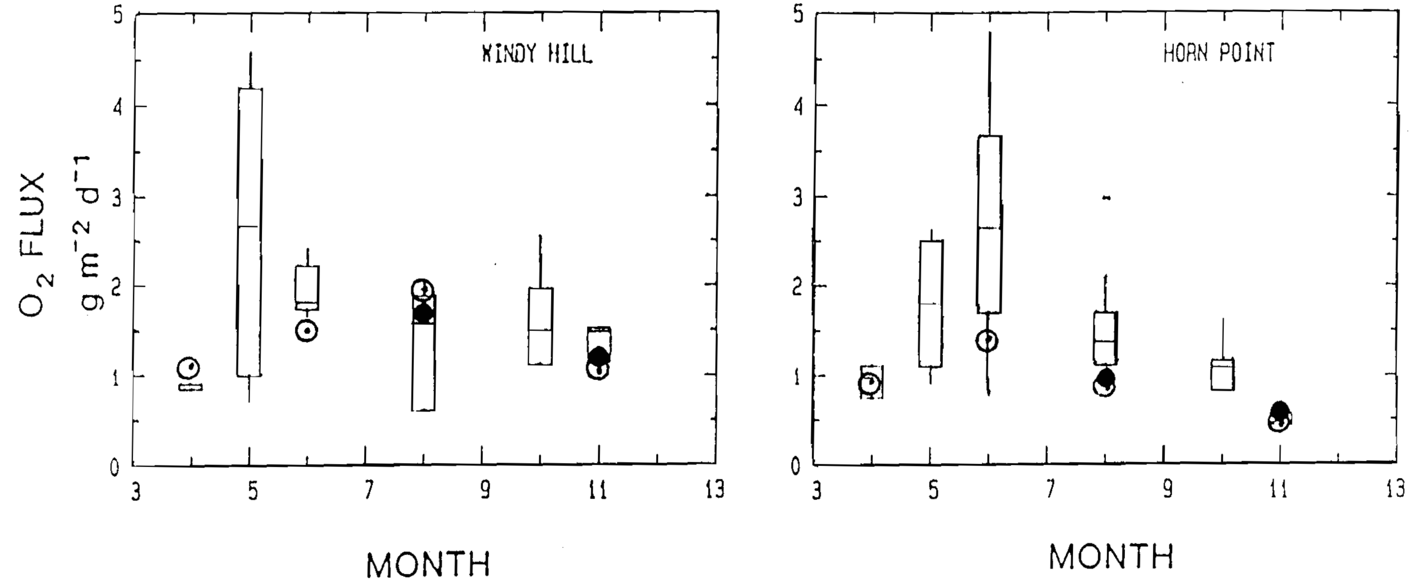


Figure 6-2b. Seasonal variation in sediment-water oxygen fluxes at SONE monitoring stations in the Choptank River. The solid circles (●) and the open circles (⊙) represent flux means for August and November, 1987 and 1988, respectively and were not included in developing the box-and-whisker plots.

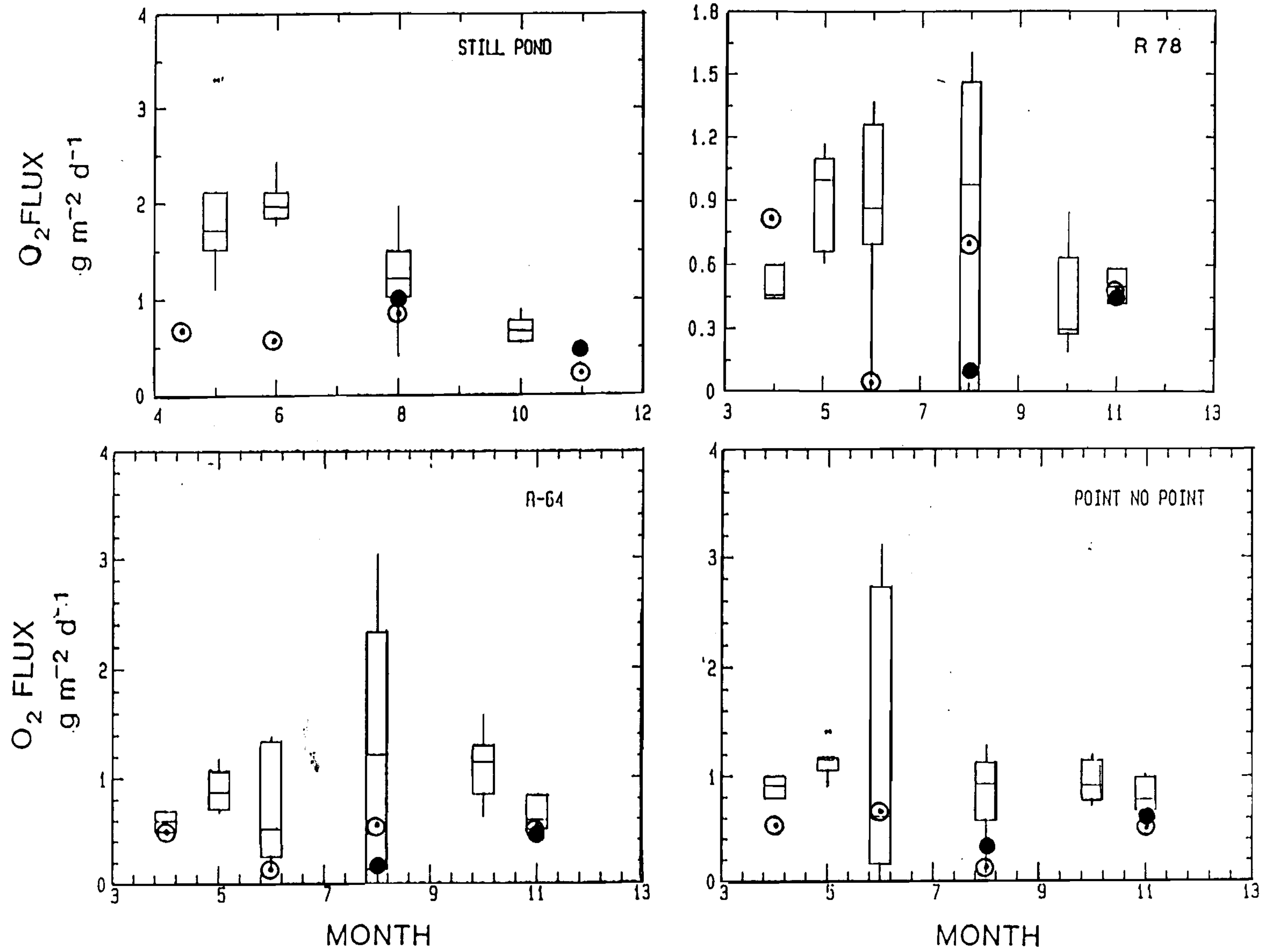


Figure 6-2c. Seasonal variations in sediment-water oxygen fluxes at SONE monitoring stations in the Maryland portion of the mainstem Chesapeake Bay. The solid circles (●) and the open circles (⊙) represent flux means for August and November, 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

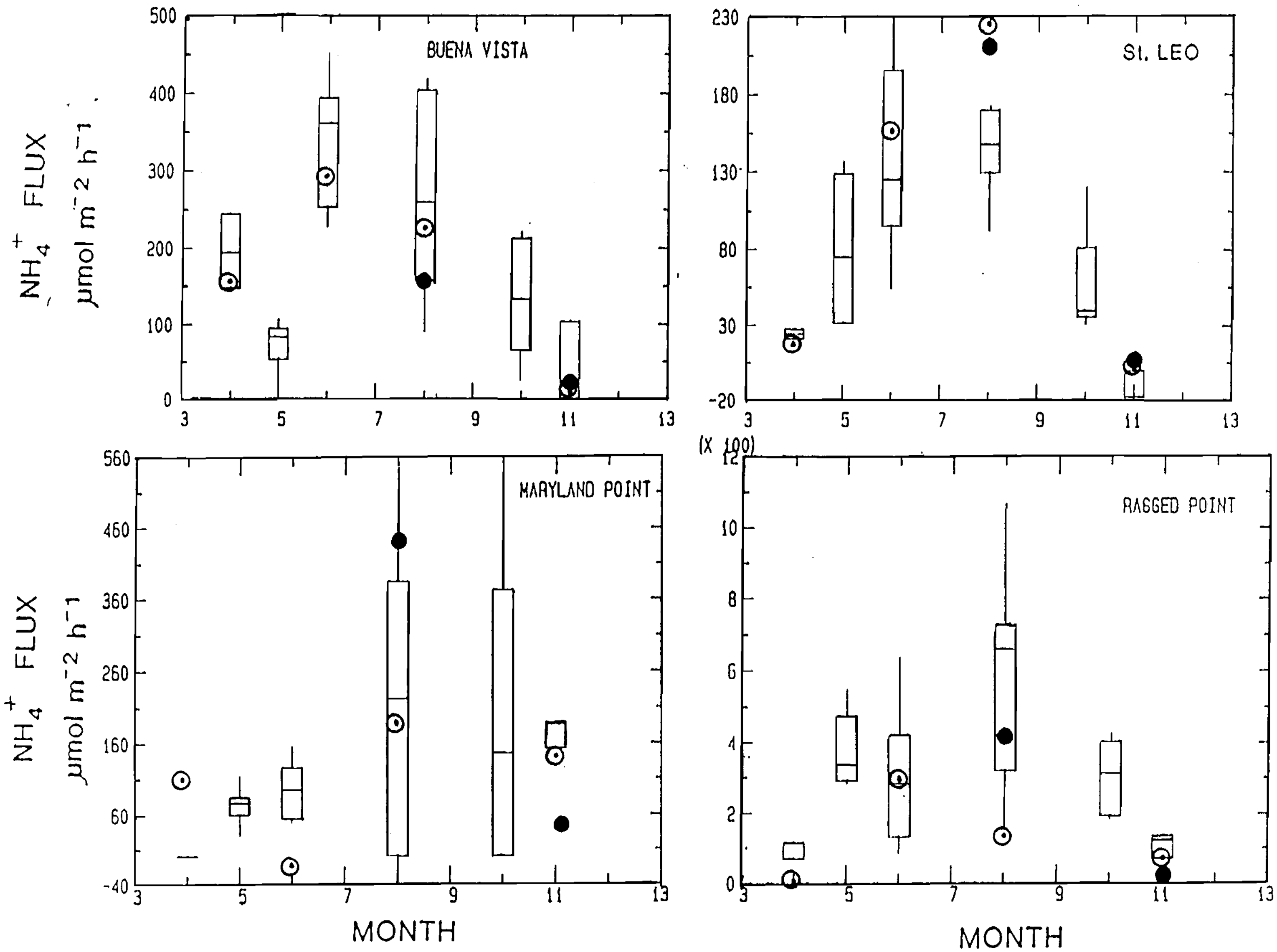


Figure 6-3a. Seasonal variations in sediment-water ammonium fluxes at SONE monitoring stations in the Patuxent and Potomac Rivers. Explanation of box-and-whisker presentation of data is given in text. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

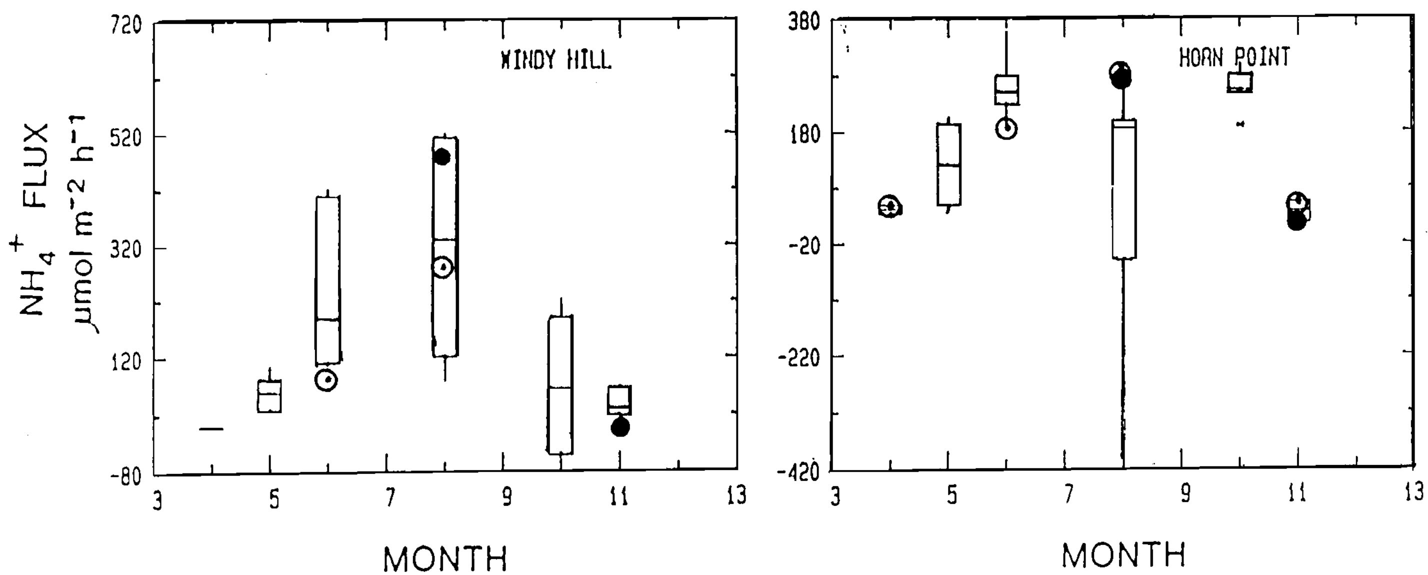


Figure 6-3b. Seasonal variations in sediment-water ammonium fluxes at SONE monitoring stations in the Chooptank River. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

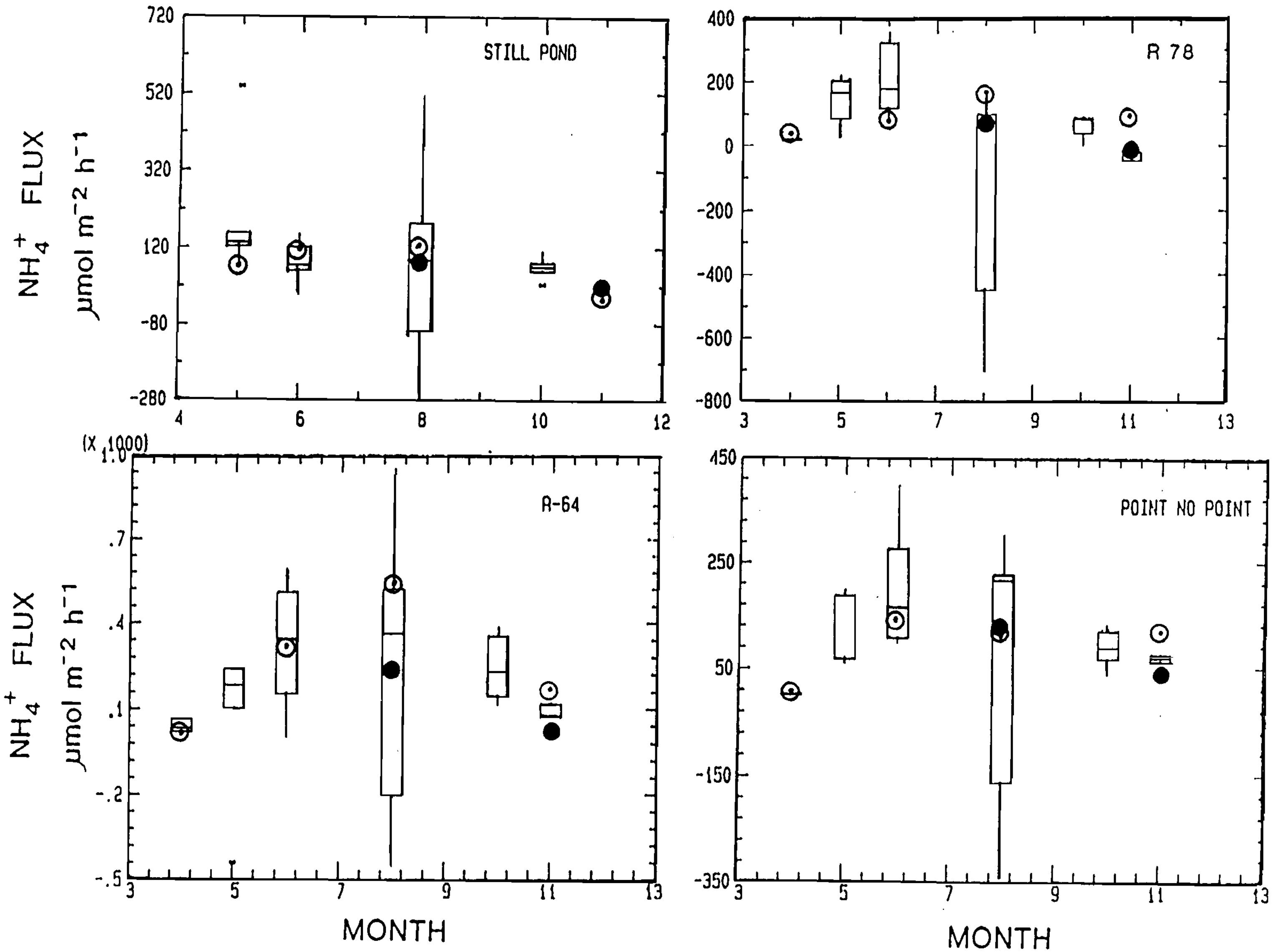


Figure 6-3c. Seasonal variation in sediment-water ammonium fluxes at SONE monitoring stations in the Maryland portion of the Chesapeake Bay. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

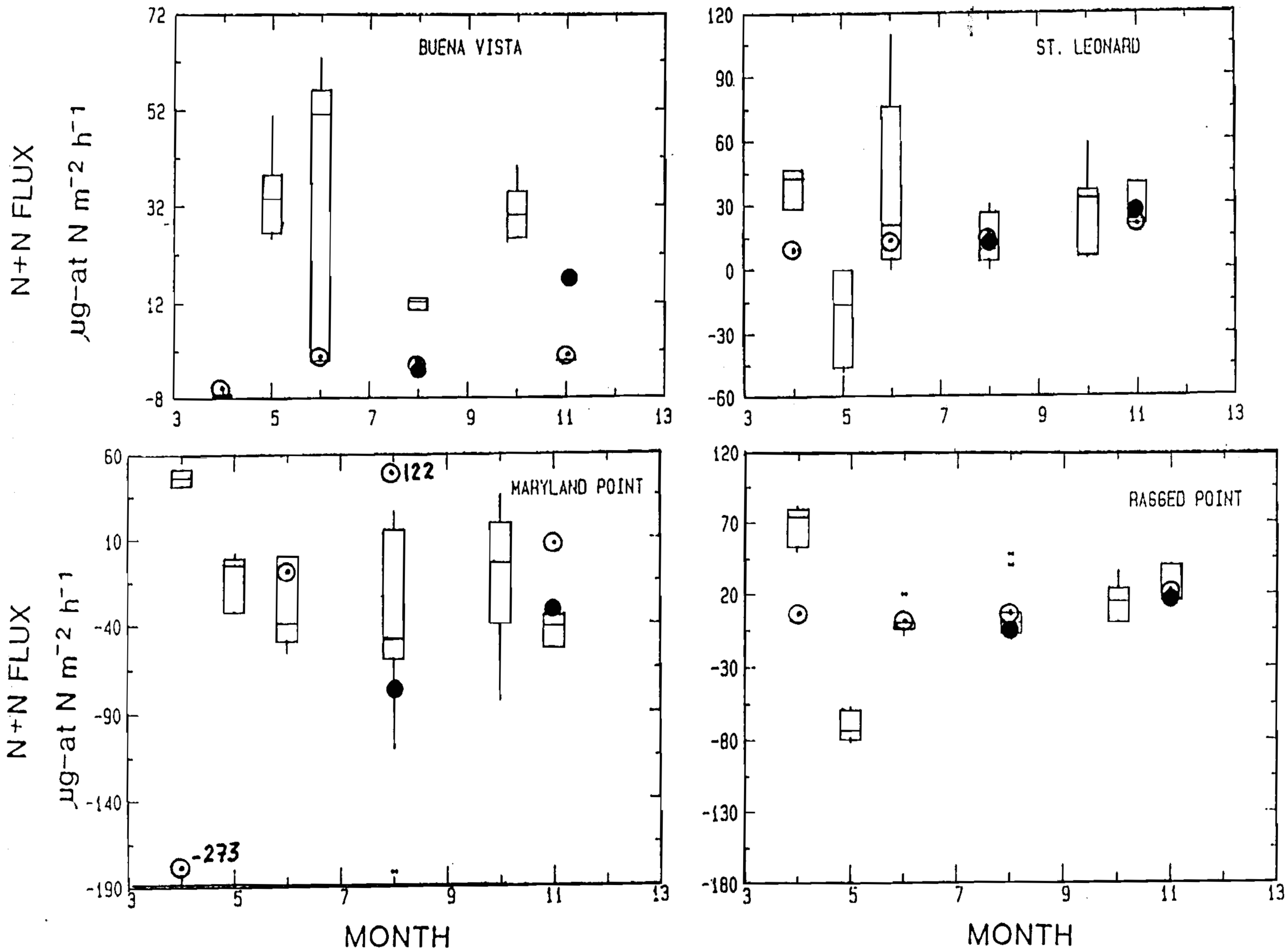


Figure 6-4a. Seasonal variations in sediment-water nitrate + nitrite (N+N) fluxes at SONE monitoring stations in the Patuxent and Potomac Rivers. Explanation of box-and-wisker presentation of data is given in text. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

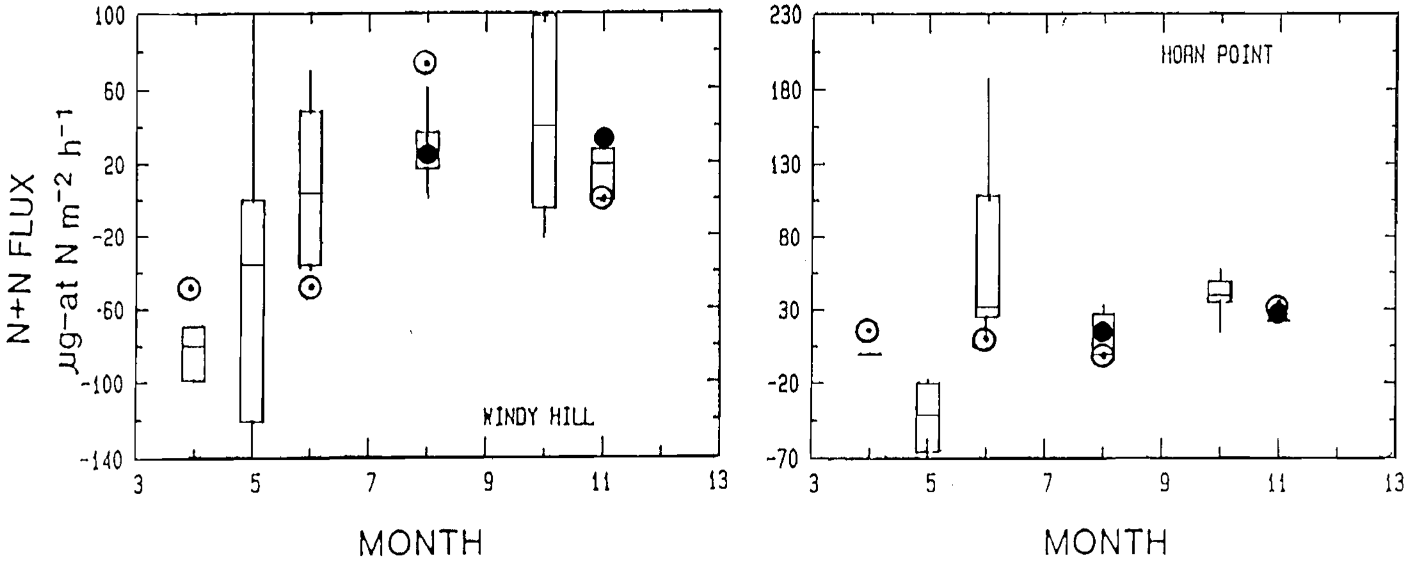


Figure 6-4b. Seasonal variations in sediment-water nitrate + nitrite (N+N) fluxes at SONE monitoring stations in the Choptank River. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

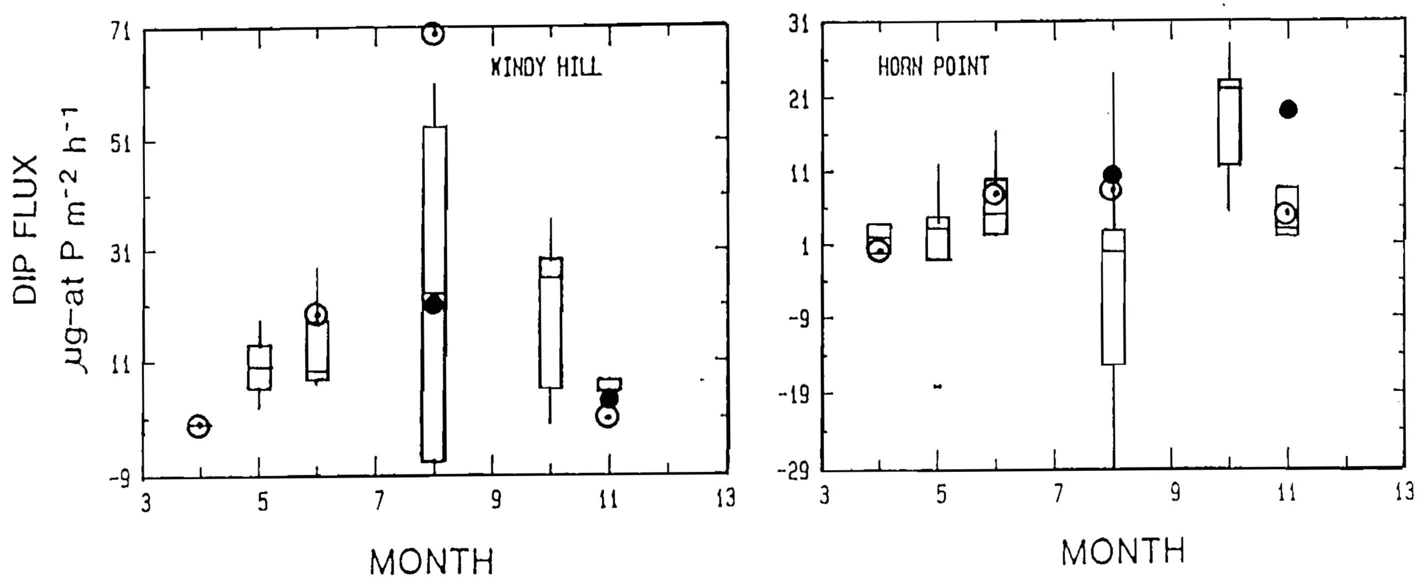


Figure 6-5b. Seasonal variations in sediment-water DIP fluxes at SONE monitoring stations in the Choptank River. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

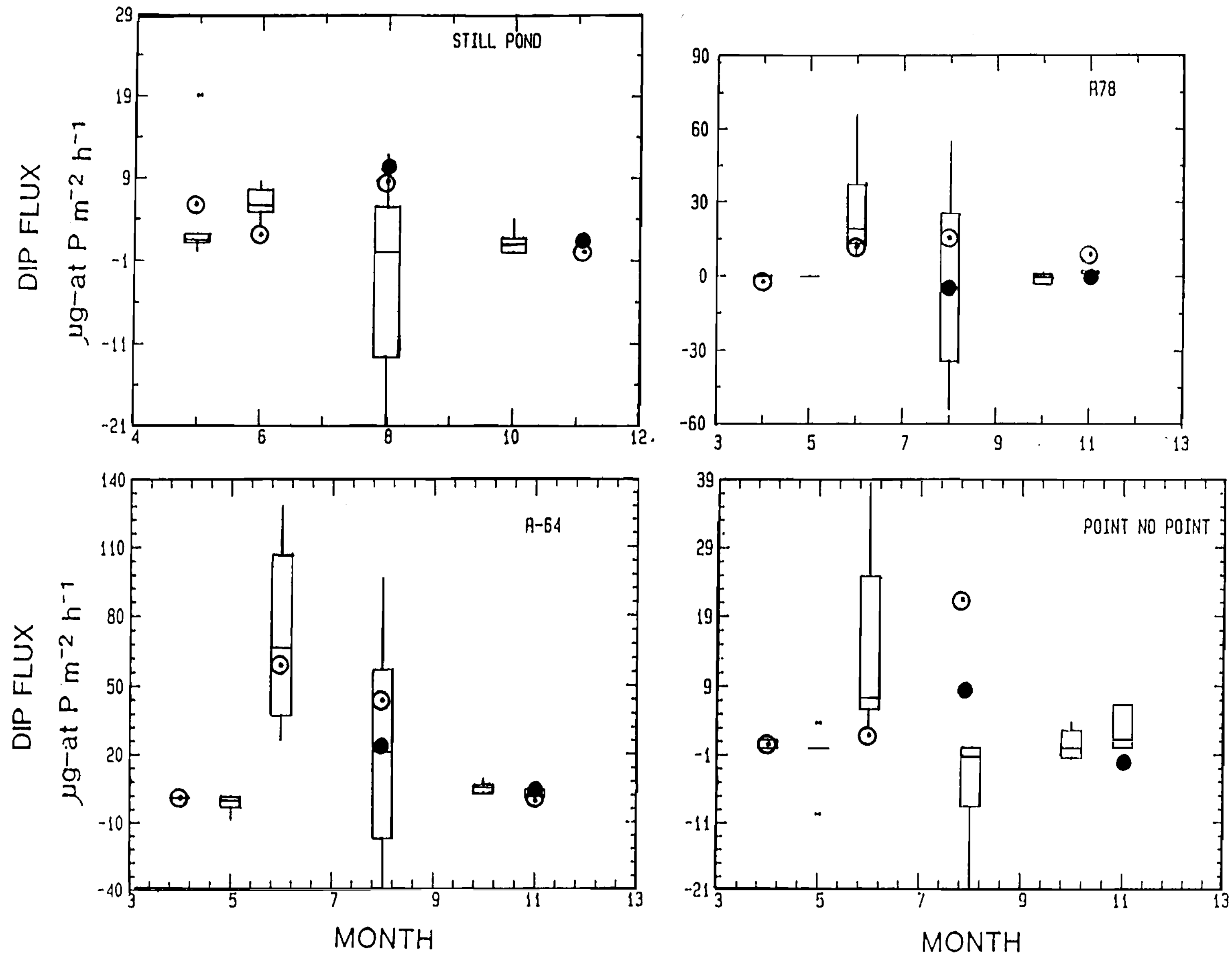


Figure 6-5c. Seasonal variations in sediment-water DIP fluxes at SONE monitoring stations in the Maryland portion of the mainstem Chesapeake Bay. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

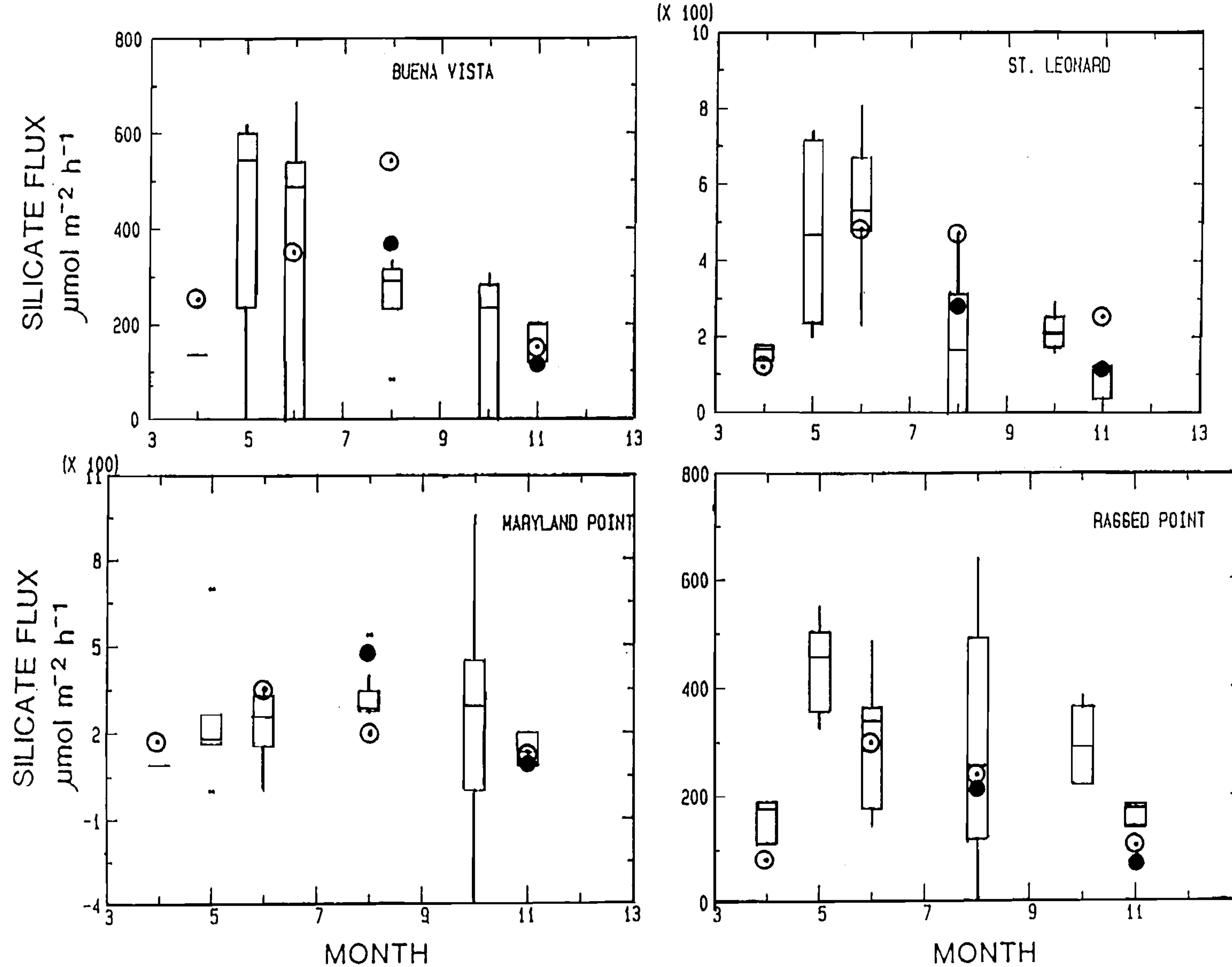


Figure 6-6a. Seasonal variations in sediment-water silicate fluxes at SONE monitoring stations in the Patuxent and Potomac Rivers. Explanation of box-and-whisker presentation of data is given in text. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

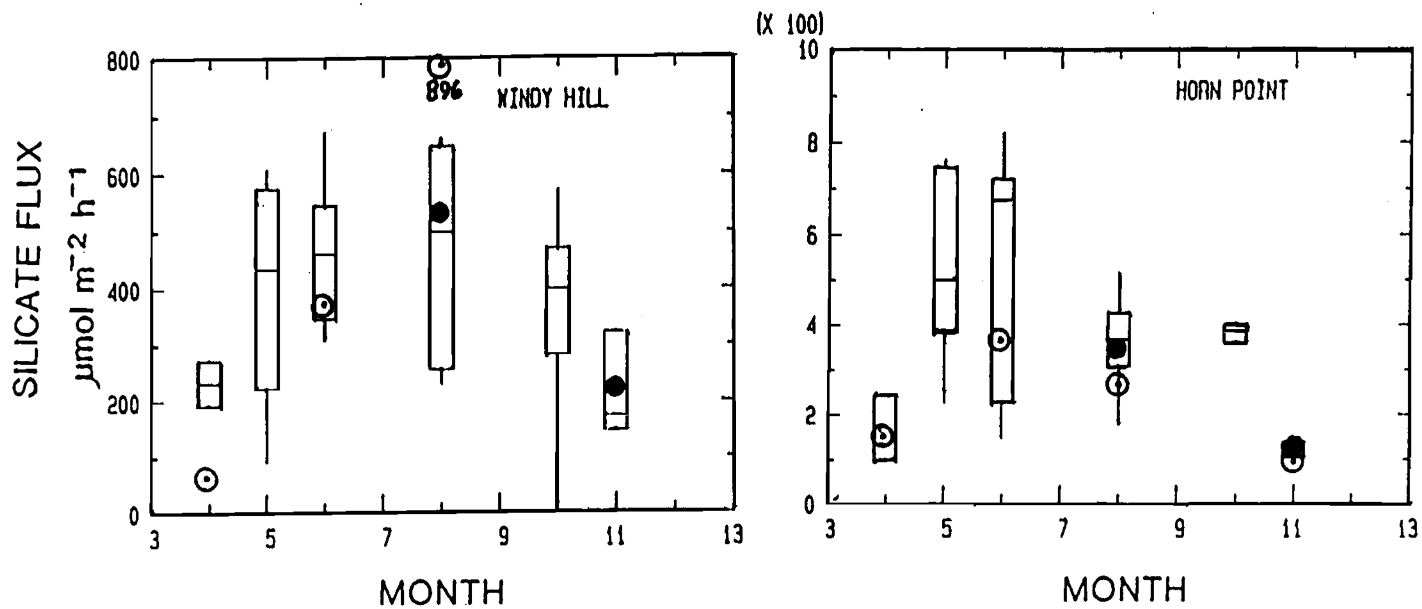


Figure 6-6b. Seasonal variations in sediment-water silicate fluxes at SONE monitoring stations in the Patuxent and Potomac Rivers. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

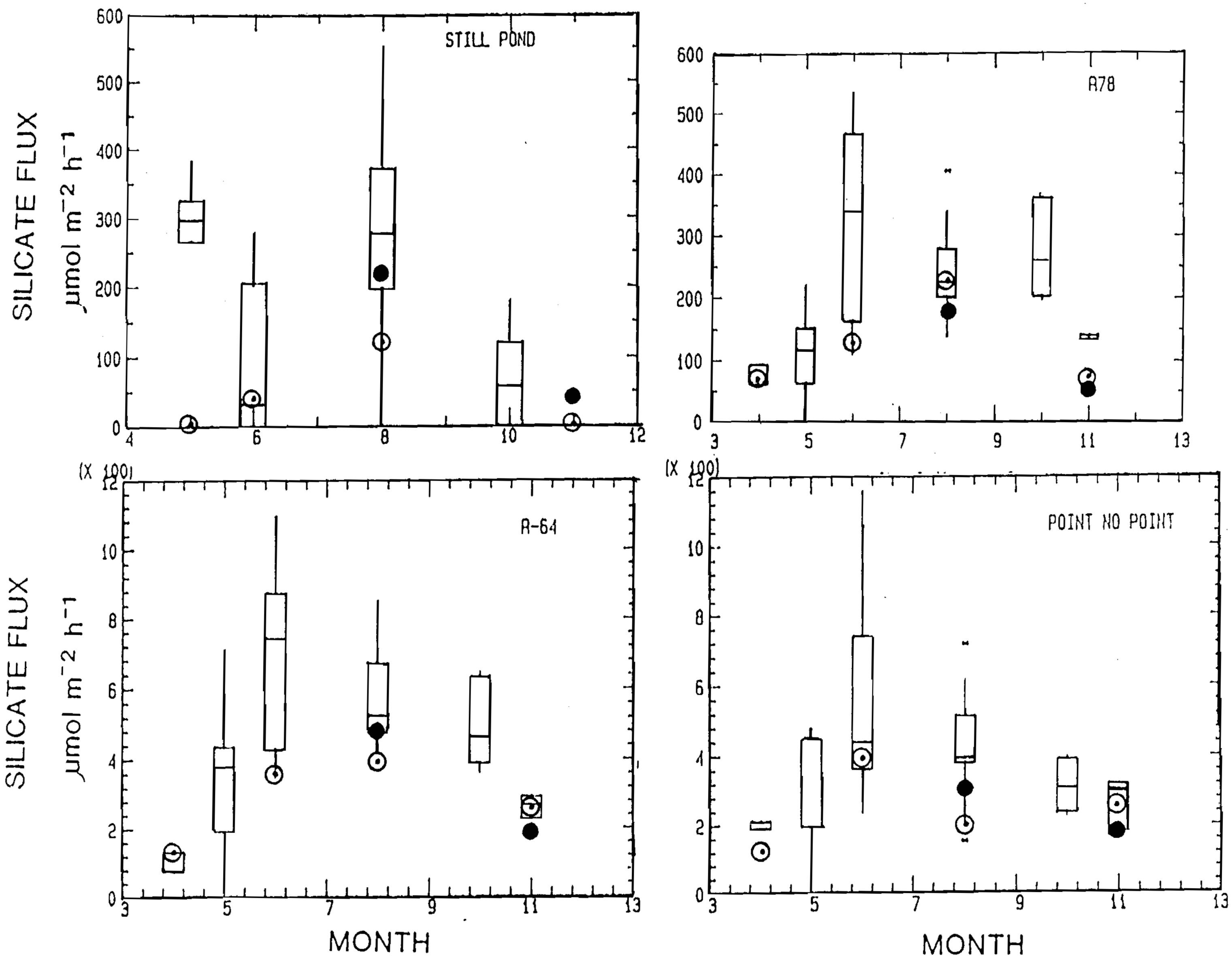


Figure 6-6c. Seasonal variations in sediment-water silicate fluxes at SONE monitoring stations in the Maryland portion of the maianstem Chesapeake Bay. The solid circles (●) and open circles (⊙) represent flux means for August and November 1987 and 1988, respectively, and were not included in developing the box-and-whisker plots.

Table 6-6. Average location fluxes (means and std. dev.). Table reports the average of sediment fluxes at SONE monitoring stations grouped by location for SONE cruises 1-12.

	O2 FLUX		NH4+ FLUX		N+N FLUX		DIP FLUX		SI FLUX	
LOCATION	AVG.	SD	AVG.	SD	AVG.	SD	AVG.	SD	AVG.	SD
Upper Tributaries	-1.5	0.9	163	154	-1	50	11	17	307	212
Lower Tributaries	-1.4	1.0	210	212	13	45	11	18	338	212
Mesohaline Mainstem bay	-0.9	0.6	125	234	-4	32	12	30	367	239
Upper Mainstem bay	-1.3	0.6	90	142	-35	47	2	7	187	140

Table 6- 7. Summary of temporal patterns of sediment fluxes at SONE monitoring stations. This table summarizes data presented in Fig. 6-2 - 6-6 by indicating the month (5=May, 6=June, etc.) or months of seasonal maximum. Additional notations are explained in table footnotes.

	SOC	NH_4^+	N + N	DIP	Si
BUENA VISTA	6	6	6,10 (B)	6	5
ST. LEONARD	6	8!	NS	6!	6!
MD. PT.	8-10	8	4	NS	10
RAGGED PT.	5?	8	4(+),5(-)	8	NS
WINDY HILL	5?	8!	10!	8!	8!
HORN PT.	6!	?	NS	10	6
STILL PD.	6	NS	NS	NS	NS
R78	NS	6?	5(-),10(+)	6?	6
R64	NS	8	5(-),10(+)	6	6!
PT. NO PT.	NS	8	5(-),10(+)	6	6!

? = questionable seasonal pattern
NS = no apparent seasonality
! = well-defined seasonal pattern
(-) = sediment uptake; (+)= sediment release
(B) = bimodal seasonal pattern

Ammonium fluxes at most of the SONE stations followed fairly straightforward seasonal patterns with maximum rates of sediment release occurring in Aug. The best examples of this pattern were observed at the lower Patuxent, lower Potomac, and upper Choptank Rivers (Fig. 6-3). Essentially the same pattern of NH_4^+ fluxes were observed at mainstem stations R-64 and Pt. No Pt. (Fig. 6-3). Exceptions to this pattern were observed in the upper Patuxent and mainstem station R-78 where the seasonal peak in NH_4^+ flux occurred earlier in summer. No seasonal pattern could be discerned at Still Pond. It appears that the seasonal cycles of oxygen uptake and NH_4^+ release from the sediment may be out of phase by 2-3 months in the lower tributaries and mid-mainstem bay. Again, 1988 data support previous findings.

Temporal variations in nitrate + nitrite (N+N) fluxes were generally complex and differed widely among the SONE monitoring stations (Fig. 6-4, Table 6-7). The kinds of seasonal patterns in N+N flux included: (1) no apparent cycle (Still Pond), (2) pronounced uni-modal change from sediment uptake in spring to maximum sediment release in fall (Windy Hill), (3) a bimodal pattern with periods of sediment release in spring and fall (Buena Vista), and (4) the most common pattern, best illustrated by the data from Ragged Pt. (Fig. 6-4), included a rapid shift from positive or near-zero sediment N+N flux to strong sediment uptake in spring. This was then followed by a shift toward sediment release in summer and fall. Some variation of this "check-mark"-like seasonal cycle occurred at St. Leonard, Horn Pt., and all the mainstem bay stations except Still Pond. The salient feature of seasonality in N+N flux at many of the stations appears to be the shift from strong sediment uptake in spring to positive or near-zero net flux in summer and fall. The occurrence of a sediment N+N sink in spring coincides with the high concentrations of N+N in the water column introduced into the bay and tributaries during the spring freshet. Whether the sediments serve as a net source or sink of N+N still needs to be resolved. However, net N+N fluxes are small in comparison to the flux of NH_4^+ at all places except, perhaps, the very low salinity reaches of bay. Since NH_4^+ fluxes were almost always from the sediment to the overlying water, the magnitude of N+N fluxes, either positive or negative, has a minor effect on the total flux of remineralized inorganic nitrogen from bay sediments.

Seasonal variations in DIP fluxes also followed a variety of patterns (Fig. 6-5, Table 6-7). In some regions the cycle followed a fairly simple cycle with periods of maximum sediment release occurring either in Jun (both Patuxent stations), Aug (Windy Hill), or Nov (Horn Pt.). Along the mainstem bay DIP fluxes were generally low in spring and fall, with highest fluxes from the sediment to the overlying water occurring in Jun. DIP fluxes in Aug along the mainstem bay are highly variable. These patterns are consistent with the view that the large sediment-water exchanges of DIP observed in the lower Potomac and along the mainstem bay are associated with low oxygen in the overlying water.

Spatial and temporal patterns in fluxes of dissolved silicate (Fig. 6-6, Table 6-7) were among the most striking and easily interpretable of all the nutrients considered in the SONE monitoring program, including recently collected data. Both the magnitude and seasonality of silicate fluxes increased with increasing salinity. Thus, with the notable exception of the upper Choptank little seasonality was apparent in the silicate fluxes from the low salinity regions of the Patuxent, Potomac, and mainstem bay. In contrast, a very clear seasonal cycle emerged from the silicate data from the lower tributaries (e.g. St. Leonard, Fig. 6-6) and mesohaline mainstem bay. The sequence of patterns in silicate fluxes as one proceeds down the mainstem bay is particularly striking. These seasonal and spatial patterns in silicate fluxes point to the coupling of diatoms production in the plankton and silicate remineralization in the sediments. The patterns observed at mainstem stations R-64 and Pt. No Pt. show that remineralization of silicate peaks in early summer as water temperatures are rising, then tapers off in summer even though water temperatures remain high. This clearly suggests a strong interaction between silicate deposition following the spring diatom blooms and water temperature as factors that regulate benthic silicate fluxes.

6.3.2 Interannual trends in sediment fluxes

As stated in the introduction, one of the primary objectives of the Ecosystem Processes Component of the bay monitoring program is to identify long-term trends in sediment deposition and benthic fluxes in the Maryland portion of Chesapeake Bay. This report covers data collected from Aug 1984 through Nov 1988--a period of four calendar years and one partial year (1984). Although it is still early in the monitoring program, and dramatic changes in nutrient control strategies have not been implemented throughout the Northern Chesapeake basin, it seemed appropriate to begin to examine these data for interannual trends.

The technique employed for this initial examination of the data was to compute the mean station flux for calendar years 1985 through 1988. These statistics were then plotted (Figs. 6-7 through 6-11) and examined for trends.

Mean station SOC fluxes ranged from about 0.4 g O_2 $m^{-2}d^{-1}$ to 3.2 g O_2 m^{-2} d^{-1} (Fig. 6-7) and were generally higher in the Patuxent and Choptank Rivers than at other sites throughout the four year period. With the single exception of the Buena Vista station in the Patuxent River, there was a clear interannual trend between 1985 and 1988 towards lower SOC at the remaining stations. In almost all cases the maximum differences in SOC rates among years was large and statistically significant (Figs. 6-12 and 6-13).

Strong interannual trends were also evident for fluxes of NH_4^+ (Fig. 6-8). During the four year period mean annual fluxes ranged from about 430 μg-at $m^{-2}h^{-1}$ in the lower Potomac in 1986 to 40 μ-at $m^{-2}h^{-1}$ in the upper bay in 1987. Highest fluxes were observed in areas exposed to strong seasonal oxygen depletion (e.g. R-64 and Ragged Pt) while fluxes were lower in the lowest and highest salinity portions of the mainstem bay. There was a clear interannual trend towards lower annual mean fluxes of NH_4^+ at stations in the Potomac River and along the main axis of the bay, similar to the trend observed for SOC rates. However, NH_4^+ fluxes at both stations in the Patuxent and the higher salinity station in the Choptank (Horn Point) were quite

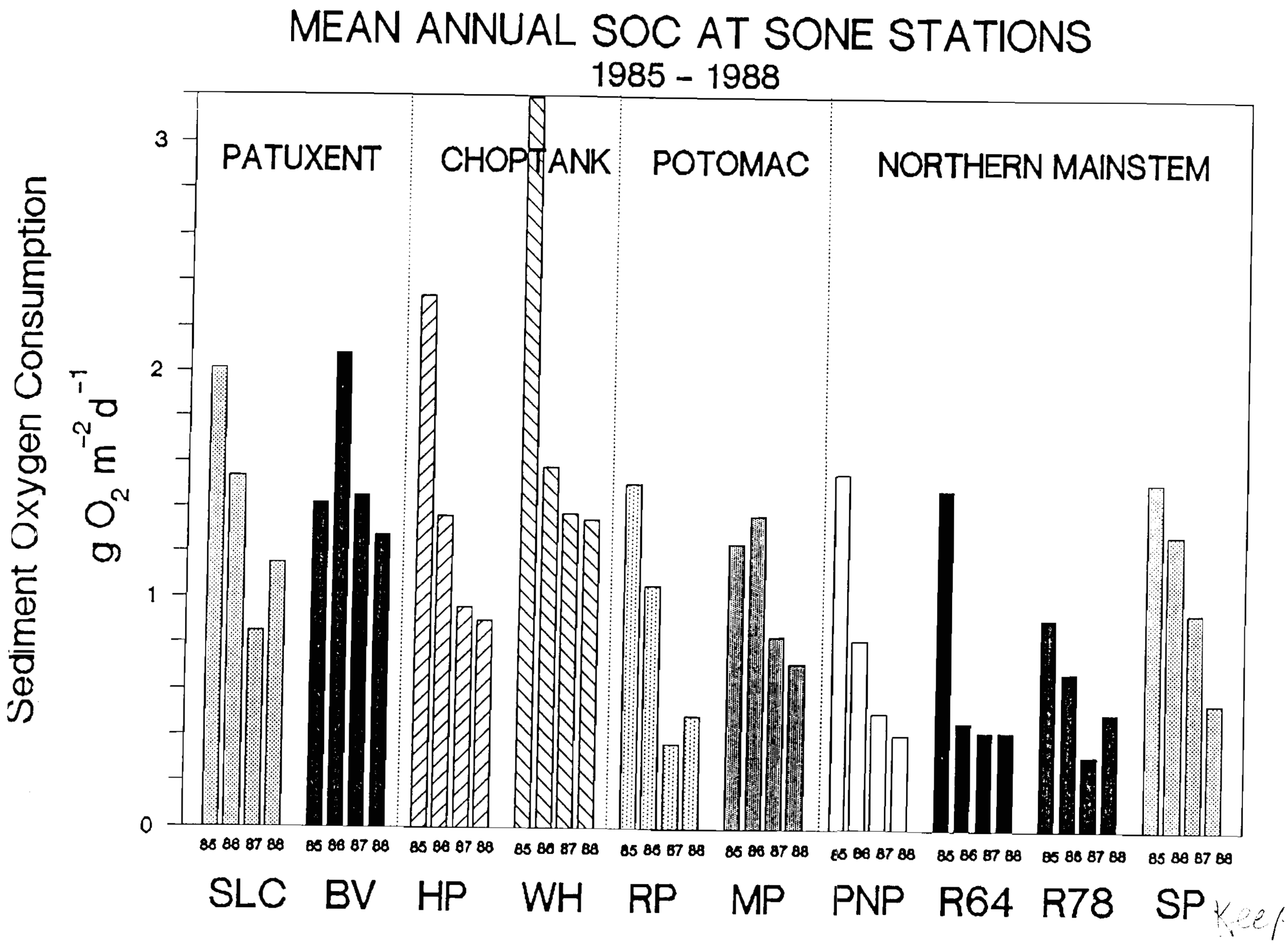


Fig. 6-7. Bar graph showing trends in annual means of sediment oxygen comsumption rates at SONE monitoring stations, 1985-1988. Station abbreviations: SLC, St. Leonard Creek; BV, Buena Vista; HP, Horn Point; WH Windy Hill; RP, Ragged Point; MP, Maryland Point; PNP Point No Point; R64, Buoy R-64; R78, Buoy R-78; SP, Still Pond.

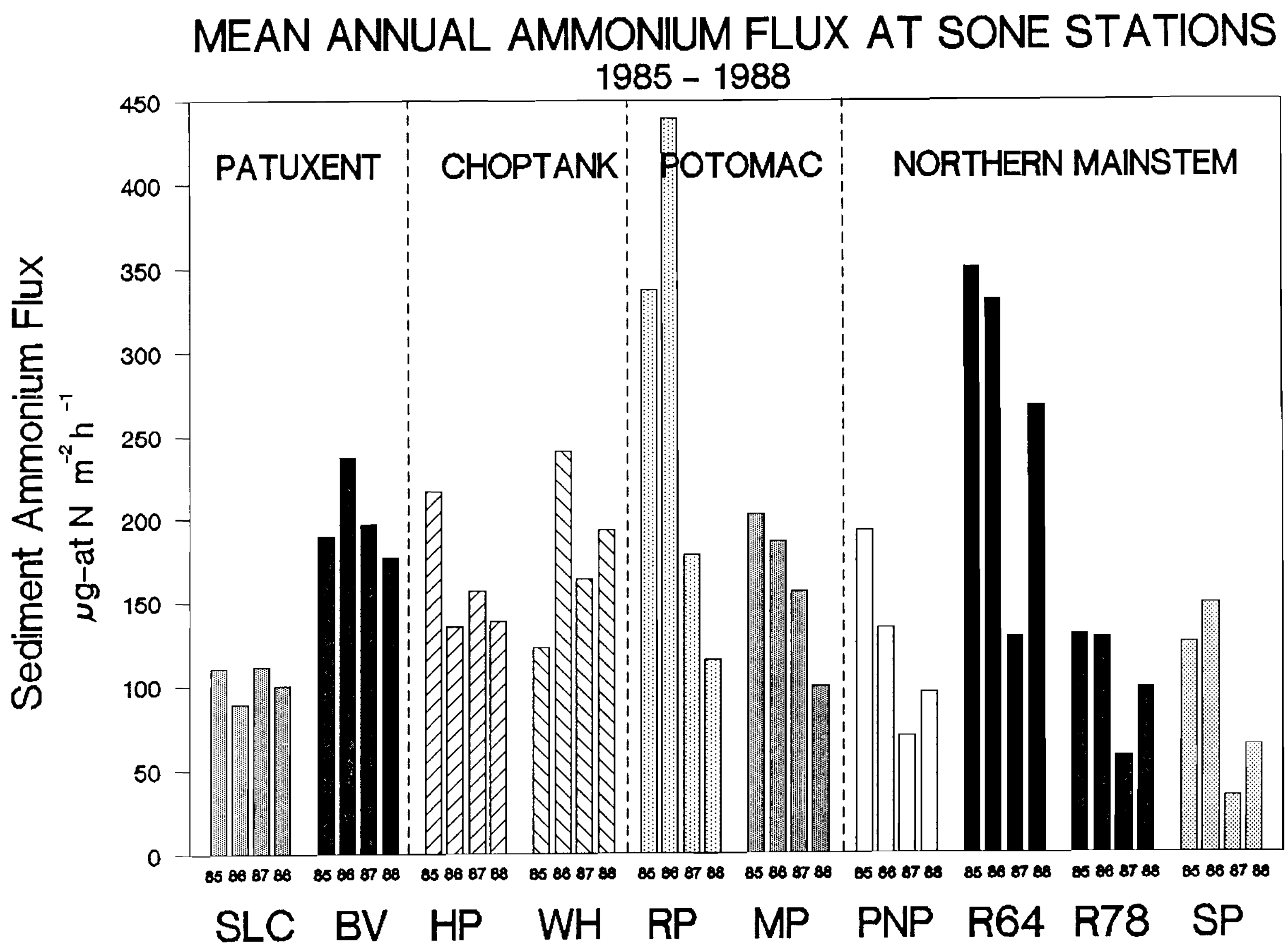


Fig. 6-8. Bar graphs showing trends in annual means of sediment water ammonium fluxes at SONE monitoring stations, 1985-1988. Station abbreviations as in Fig. 6-7.

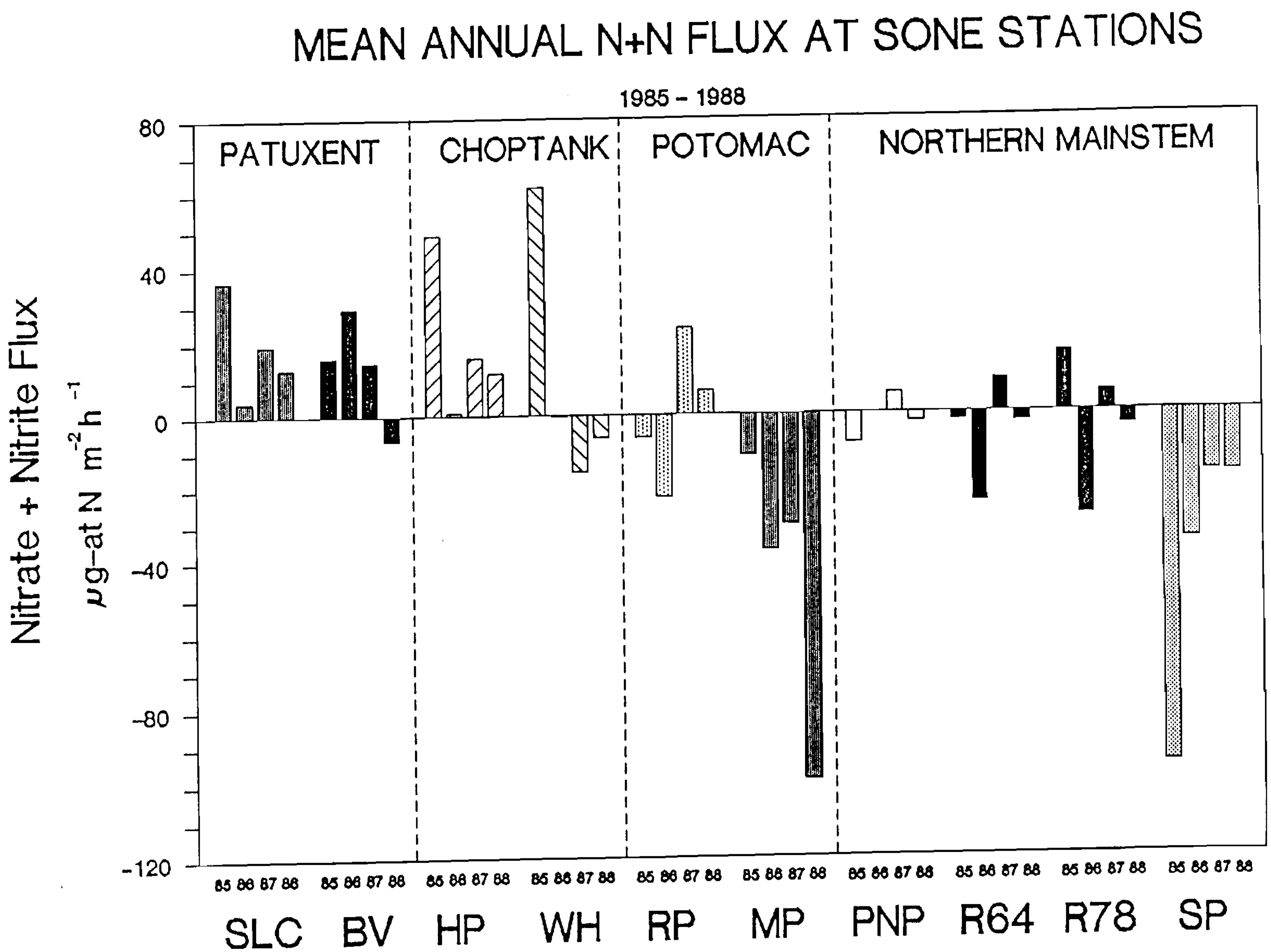


Fig. 6-9. Bar graphs showing trends in annual means of sediment-water nitrate and nitrite (N+N) fluxes at SONE monitoring stations, 1985-1988. Station abbreviations as in Fig. 6-7.

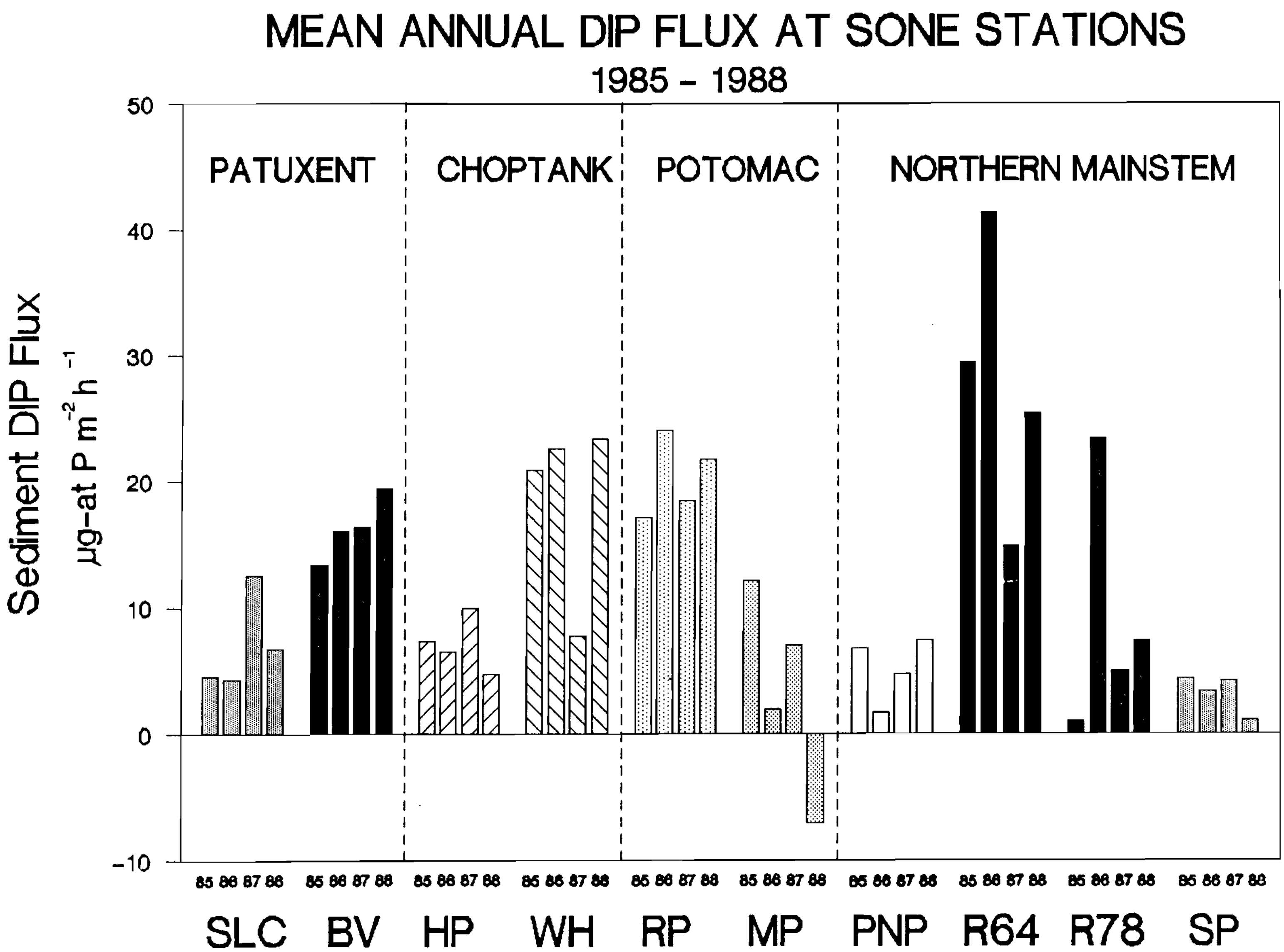


Fig. 6-10 Bar graph showing trends in annual means of sediment-water dissolved inorganic phosphorous (DIP) fluxes at SONE monitoring stations, 1985-1988. Station abbreviations as in Fig. 6-7.

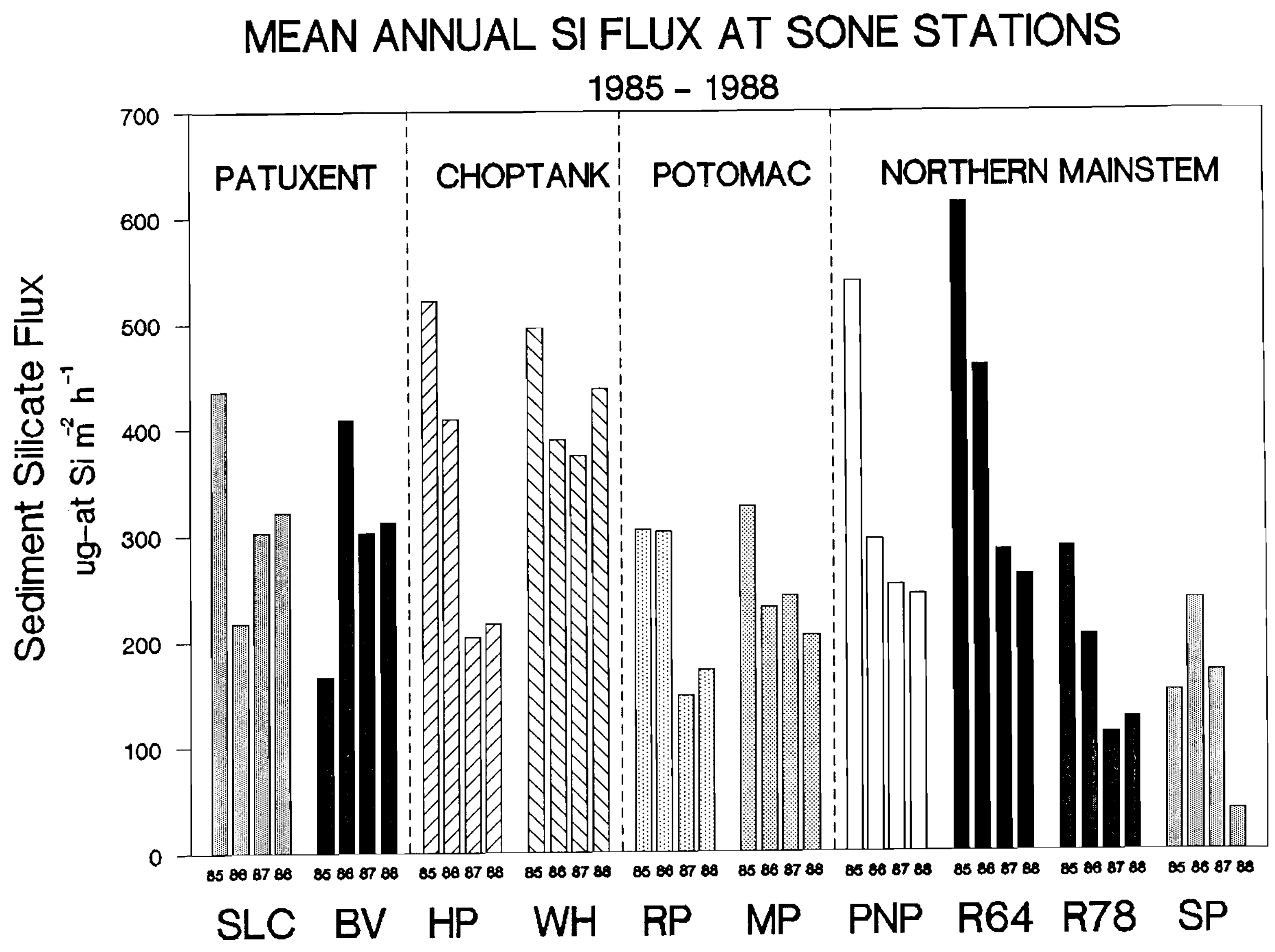


Fig. 6-11 Bar graphs showing trends in annual means of sediment-water dissolved silicate (Si) fluxes at SONE monitoring stations 1985-1988. Station abbreviations as in Fig. 6-7.

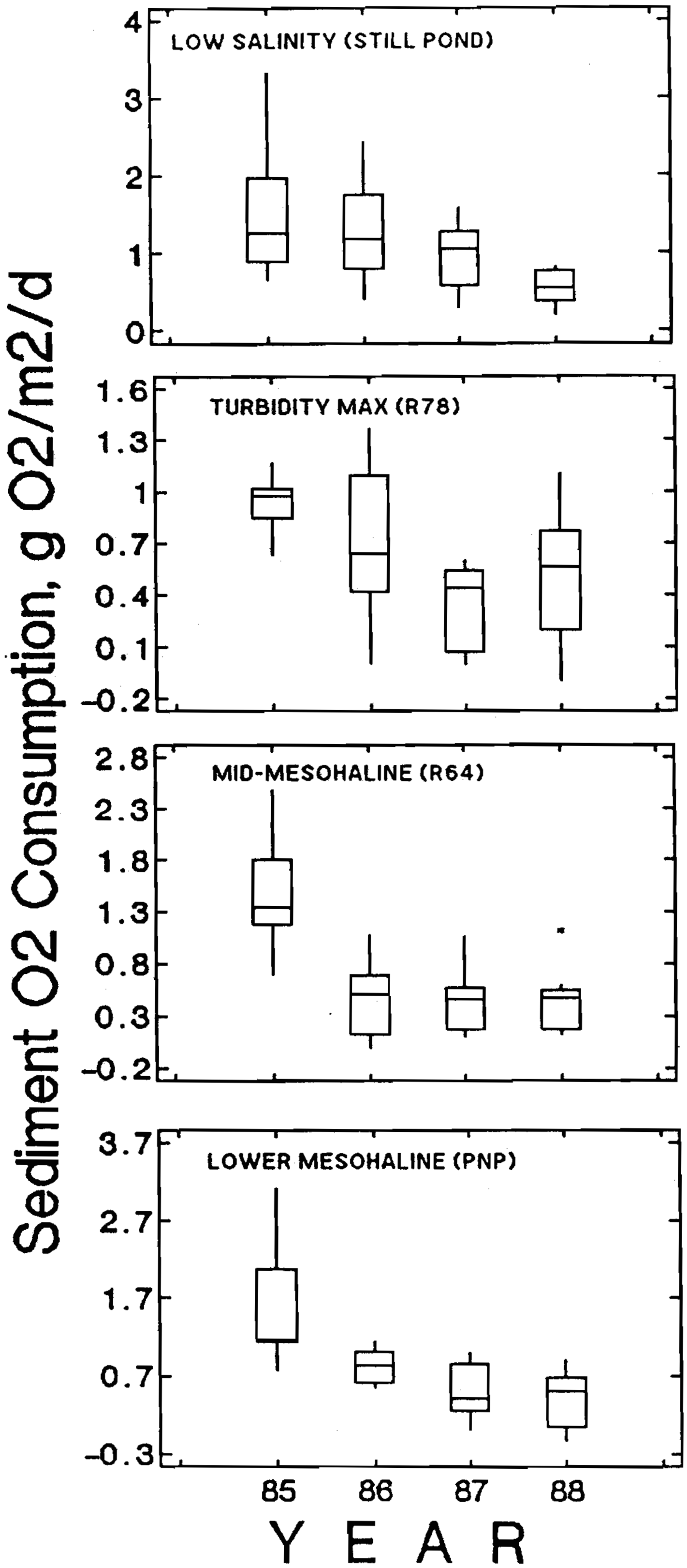
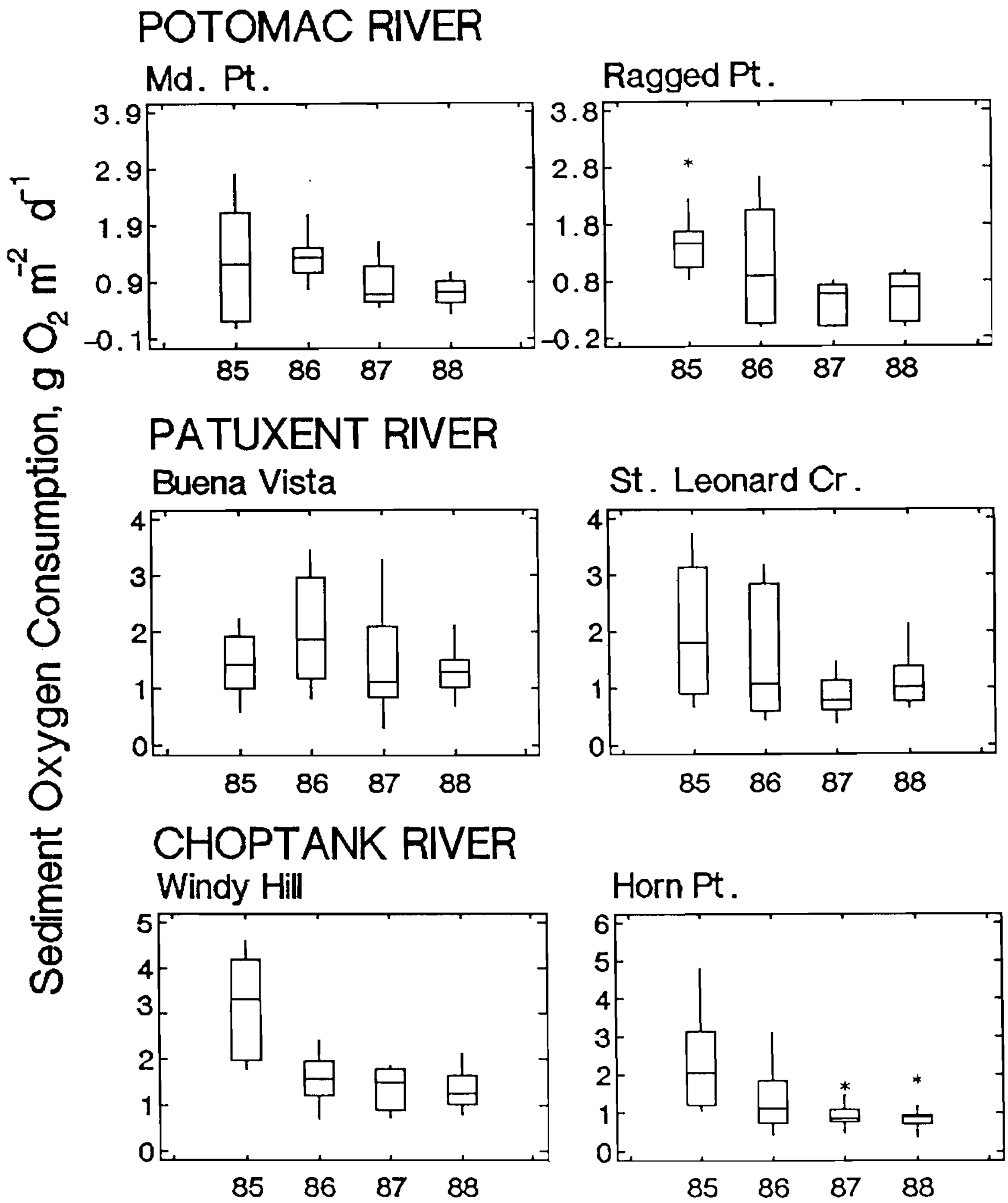


Fig. 6-12. Box and whisker plots giving the range, median and quartile ranges of sediment oxygen consumption measurements at mainstem bay stations during calendar years 1985 to 1988.



Dif. 6-13. Box and whisker plots giving the range, median, and quartile ranges of sediment oxygen consumption rates at SONE tributary stations during calendar years 1985-1988.

constant throughout the period 1985-1988. The low salinity station in the Choptank (Windy Hill) exhibited a somewhat erratic pattern but fluxes generally increased over the four year period.

We initially did not expect to detect strong interannual trends in NO_3^- fluxes, in part because fluxes tended to be small and because fluxes could be directed either into or from sediments. Despite these characteristics, some striking interannual patterns emerged. First, at the three mainstem stations which experience seasonal oxygen depletion (i.e. Point No Pt, R-64 and R-78) the interannual pattern of NO_3^- fluxes was almost identical between 1985 and 1988 (Fig. 6-9). Second, the patterns in the Patuxent and Choptank Rivers, particularly at the lower estuarine stations, were very similar with NO_3^- fluxes from sediments to water decreasing over the years and in some cases actually changing direction (i.e. NO_3^- fluxes were directed into sediments at Windy Hill in 1987 and 1988). Finally, NO_3^- fluxes were always directed into sediments in the upper Potomac and upper bay. Clear interannual patterns were evident for both stations wherein fluxes increased over the years in the upper Potomac and decreased at Still Pond.

Interannual trends in PO_4^- fluxes were also apparent but the similarity of trends among stations observed for other nutrient species was not evident (Fig. 6-10). For example, there was an indication of increasing PO_4^- fluxes in the Patuxent River, particularly at the upper river station. However, fluxes in the Choptank River and lower Potomac were quite constant (with one exception) during the four year period. An interannual pattern of generally decreasing fluxes was observed in the upper Potomac and in the mainstem bay at stations R-64, R-78 and Still Pond.

As we found with SOC rates, there were consistent and strong interannual patterns in Si fluxes. With the exception of stations in the Patuxent River, Si fluxes generally decreased during the 1985-1988 period (Fig. 6-11). The pattern of decreasing annual mean fluxes of Si was strongest at the mainstem bay stations where overall declines in fluxes were by factors of 2 to 6.

The message we glean from examination of these annual rates is that it is quite possible to detect interannual differences in the magnitude of sediment-water fluxes. In the data base we currently have the trend for most variables is toward decreased or constant fluxes. Secondly, and perhaps more important in the long-run, there are some very substantial commonalties in trends among nutrient species being measured and among monitoring sites. This suggests that whatever factors are influencing the magnitude of sediment-water exchanges they are operative at most or all of our sites. At the outset of the monitoring program we outlined a conceptual model which would generally apply throughout the bay wherein nutrient loading from all sources ultimately regulated phytoplankton production and biomass. This, in turn, influenced deposition rates which impacted sediment-water fluxes and these fluxes contributed to establishing water quality conditions in the bay. Now that we are confident that interannual descriptions of sediment-water exchanges are possible, we have begun to synthesize data from our study and other portions of the monitoring program towards the goal of being able to better understand the set of linkages which serve to establish water quality conditions (Fig. 6-14). We have summarized results from an initial examination of data collected from a mid-bay location (R-64). In this case there are some strong correlations between annual nutrient loading rates, primary production and sediment-water nutrient and oxygen fluxes. Chlorophyll deposition only partially fits the expected pattern indicating that some additional factor(s) is involved. However, the clear indication is that the conceptual model is largely correct and that further examination of linkages is warranted towards the overall goal of providing guidance during implementation of water quality improvement programs.

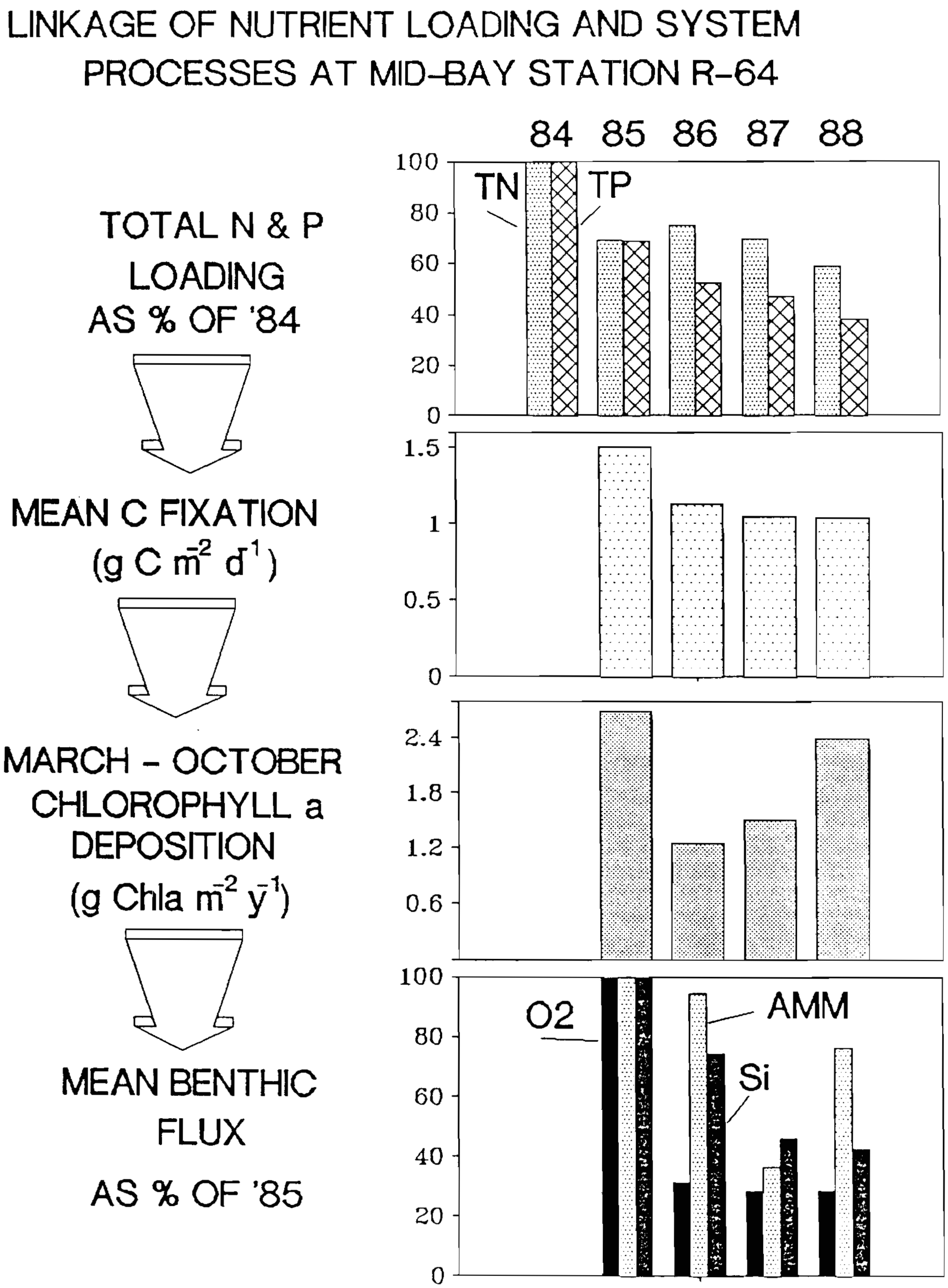


Fig. 6-14. Mean annual rates of nutrient loading (TN=total nitrogen; TP=total phosphorous), primary production, deposition and sediment-water nutrient and oxygen exchanges at station R-64 in the mid-bay region.

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