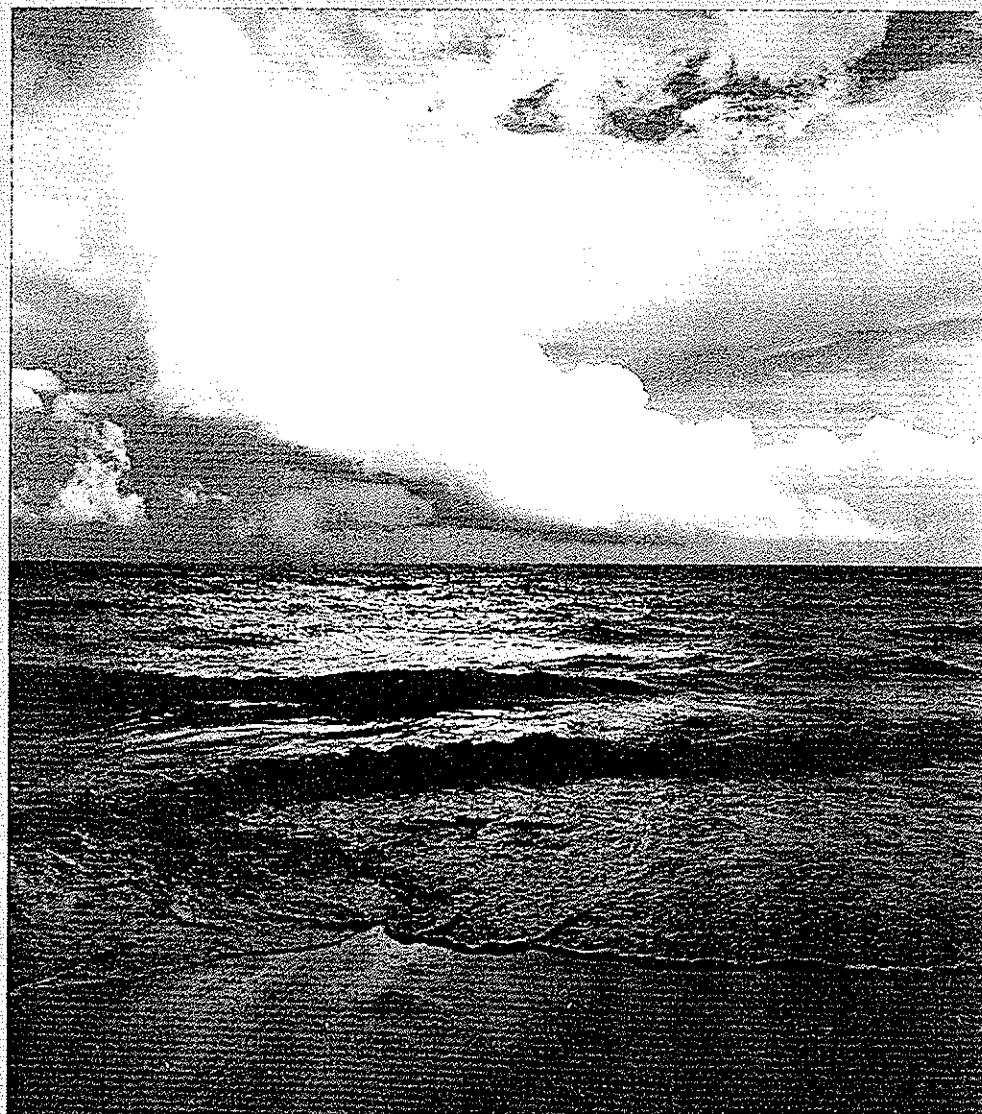
The State of the Chesapeake Bay
Second Annual Monitoring Report

COMPENDIUM



1984 1985

STATE OF THE CHESAPEAKE BAY
SECOND ANNUAL MONITORING REPORT

COMPENDIUM

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CASE HISTORY

INTRODUCTION

The second report from the Chesapeake Bay Program Monitoring Subcommittee summarizes data collected from June 1984 through September 1985 at over 165 stations Bay-wide for the new coordinated monitoring program. This initial effort represents the baseline for a large, complex, and rapidly growing store of information.

This Compendium volume is intended to accompany the State of Chesapeake Bay summary report, amplifying the contribution of each group involved in this complex overall monitoring effort. Weaving these discrete and more technically oriented documents together has been the job of the summary report.

Like the summary report, this report is organized so the reader can follow discussion of the Bay's problems and progress in a logical sequence. First, the physical and chemical observations characterize the Bay system and its major tributaries. These physical and chemical characteristics underly the movement and transformation of materials we're concerned about in the water column.

Chapters on sediments and toxics discuss the current understanding of how materials enter and leave the sediments and outline the distribution of toxic materials we have been monitoring in the Bay.

In logical sequence, the chapters on living resources appear next, because we believe the Bay's living resources rely on the habitat quality, which is often limited by what is in the waters and sediments.

We follow the food chain: the phytoplankton, which synthesize nutrients into algal biomass; the zooplankton, which are primary consumers; and the benthic (bottom-dwelling) organisms and submerged aquatic vegetation that are also vital elements of the Bay's food base. Another step up the food chain brings us to fisheries and waterfowl.

Much interest has surrounded the Patuxent River, which served as a catalyst in focusing attention on many of the Bay's problems. As in the summary report, the Patuxent Story is developed as a case history.

This Compendium demands more of the reader than does its summary report, because the constituent chapters cover topics in greater technical detail. Still, these chapters are themselves simplifications, as we approximate an understanding of the Bay's complex systems. We hope this understanding will be broadened and deepened as monitoring progresses over its intended course of 10 to 15 years.

Chemical and Physical Monitoring of the Chesapeake Bay Mainstem and Tributaries

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In the summer of 1984 the states of Maryland and Virginia, with federal and state funding support, initiated a Bay-wide program of water-quality monitoring in the mainstem and tributaries of Chesapeake Bay. The most intensive portion of the program included chemical and physical measurements to define water-column conditions and river inputs.

The water-quality monitoring program addresses three major objectives: (1) to characterize existing water quality Bay-wide (establish a present baseline); (2) to determine trends in water quality that might develop in response to management actions or additional sources of pollution; and (3) to integrate the analysis of various monitoring components, with a view toward achieving a more comprehensive understanding of the processes affecting water quality and the linkage with living resources. The monitoring data are also being utilized in mathematical models to forecast the response of the Bay to possible management actions.

Because of the size and complexity of the Chesapeake Bay, it will be several years before any of these objectives (such as the baseline characterization) can be considered satisfied, and some objectives (determination of trends) will require continued monitoring as long as management actions are being evaluated. We believe that a strong, technically defensible baseline characterization (objective 1) of the entire Bay system is achievable with monitoring data in approximately five to seven years. Detecting trends in the system using historical data will be possible when the present baseline characterization is established.

Already, however, the monitoring program has produced a wealth of information that provides an unprecedented system-wide view and an initial evaluation of objective 1. In the past two years we have also gained a much better understanding of conditions and processes such as deep-water hypoxia, year-round patterns of nutrient concentrations and phytoplankton populations, and the widely differing loading characteristics of major tributaries. We present these initial findings as an example of this monitoring program's potential for serving the needs of management and as evidence of the advancement in our scientific understanding of Chesapeake Bay water quality, both elements being necessary to steer a prudent course in our restoration efforts.

Future reports will contain more comprehensive analyses as the monitoring record provides more of the information necessary to reach the program's stated objectives. A work group of the Chesapeake Bay Program Monitoring Subcommittee is currently evaluating statistical techniques to objectively and rigorously analyze the water-column monitoring data relative to its objectives. This group is utilizing the first 15 months of chemical/physical monitoring data, and conclusions will be forthcoming by the end of 1986. Data have also been analyzed over the past year

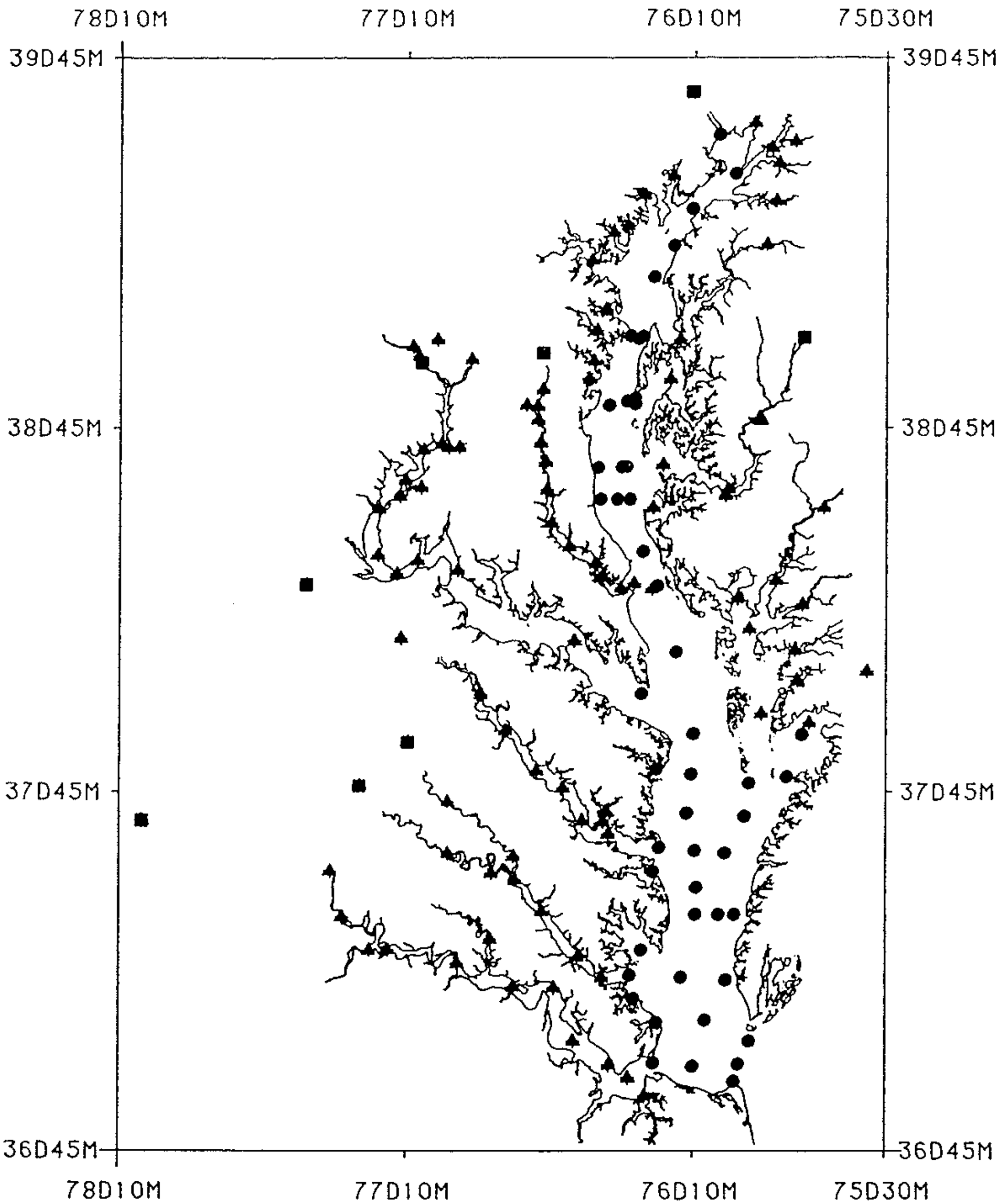


Figure 1. Map of all water-quality monitoring stations in the Chesapeake Bay. Squares represent fall line stations of the U. S. Geological Survey, triangles represent tributary stations, and circles represent mainstem stations.

to evaluate the accuracy of different estimation techniques for calculating river loads. There will also be a need for careful reconstruction of the historical record, a process initiated and reported upon at the culmination of the EPA Chesapeake Bay Program (EPA 1982). Additional reports, including spatial and temporal detail of the water quality results not possible in this chapter, have been produced or are forthcoming from the State agencies or research institutions responsible for conducting the monitoring studies described here.

PROGRAM DESCRIPTION

A brief description of the chemical/physical monitoring program will be outlined here; more complete documentation is available in the Chesapeake Bay Program Monitoring Subcommittee Report (1985). Monitoring is conducted at a comprehensive network of stations in the mainstem and tributaries (Figure 1). In the mainstem and most larger tributaries, ambient water quality measurements are made twice monthly except in winter months; in other locations, water samples are collected monthly. The water column is profiled on-station for salinity, dissolved oxygen (DO), temperature, and pH. A Secchi depth is determined at each station as a measure of water transparency. Water samples are collected near the surface and bottom at all stations. Depending upon the depth and degree of density stratification at each station, additional samples are collected above and below the pycnocline to provide two representative samples in both the surface mixed layer and the bottom mixed layer. Because the pycnocline position in the water column can vary, its depth is determined at each stratified station before collection of the additional grab samples above and below this boundary. All water samples are chemically analyzed for nitrogen, phosphorus, carbon, and silica constituents, total suspended solids, and chlorophyll.

The river-input monitoring stations are located above the tidal influence of eight major tributaries, four in Virginia and four in Maryland (Figure 1). River flow at all sites is continuously monitored by the U.S. Geological Survey. Monitoring of the constituents listed above is conducted at least monthly at all stations, and at the four Maryland sites monitoring is also conducted intensively during storm events. Additionally, at the Susquehanna, Patuxent, and Choptank sites, daily observations of suspended sediment concentration, water temperature, conductivity, and pH are recorded.

RESULTS AND DISCUSSION

Physical Characteristics

The circulation and physical structure of the Chesapeake Bay water mass is controlled by the complex interaction of several external factors including river flows, meteorological conditions, tidal cycles, and topography. Freshwater input is thus an important piece of monitoring information because of the control it exerts on water quality through its influence on circulation, density stratification, and the loading of sediments, nutrients, and other pollutants delivered to the estuary. River flows from major tributaries into the Bay have been monitored for many years by the U.S. Geological Survey. As an indication of the freshwater flow conditions during the first 15 months of the water quality monitoring program, present flows can be compared with the long-term average flow for the Susquehanna River, which contributes 50% of the fresh water entering the Bay. Over the past 17 years the flow of the Susquehanna at Conowingo Dam has averaged 42,840 cubic feet per second (cfs). For 1984 and 1985, average flows were, respectively, 20% above and 30% below normal. There were major seasonal differences between these two years, with 1984 having much higher summer flows than 1985. Monthly average flows from the six largest tributaries during 1984 and 1985 are presented in Figure 2. Together, these rivers contribute 92% of the freshwater flow entering the Bay.

Patterns of river flow in each tributary to the Bay are unique because rainfall, topography, land use, and other factors differ between basins. For example, in the Patuxent River, flow comparisons between 1984 and 1985 were quite different from those in the Susquehanna River. Flows in 1984 were close to average (421 cfs), whereas 1985 flows were 50% below average. The James and Rappahannock Rivers, however, experienced higher than normal flows during 1984 (34% and 54%, respectively) due to above-average winter and summer discharge. Between the fall of 1984 and October of 1985 the James and Rappahannock Rivers experienced dry conditions, with flows 20% and 35% below normal, respectively. In November 1985 tropical storm Juan produced heavy rainfall in some Chesapeake Bay watersheds. The Potomac and James Rivers were most profoundly affected by this storm (see Figure 2), which produced major floods in these basins.

River flow can affect water quality in many ways. When river flow is reduced, salinities typically increase in the estuary as sea water intrudes further into the system. The surface-to-bottom difference in salinity,

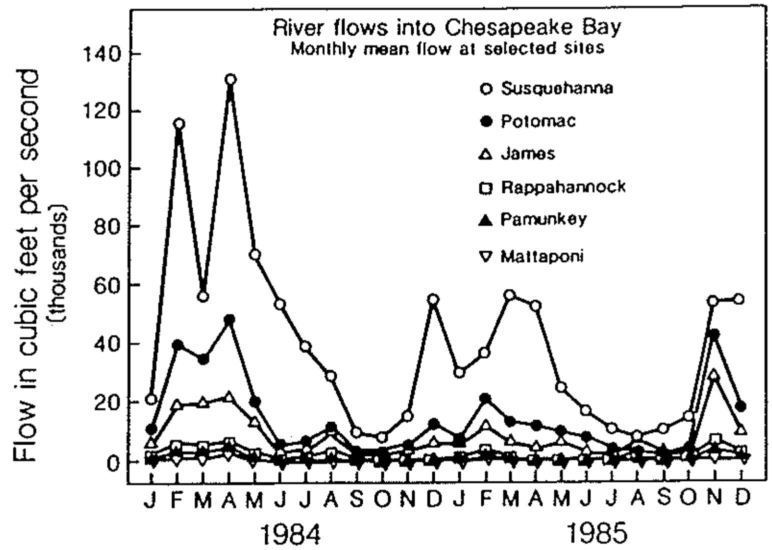


Figure 2. Monthly mean flows for six major Chesapeake Bay tributaries, January 1984 through December 1985.

which has a dominant influence on density stratification, also decreases, promoting increased mixing between surface and bottom waters that can affect oxygen and nutrient concentrations. These flow and stratification patterns thus have important implications for living resources and their habitats, nutrient dynamics, and phytoplankton growth.

Salinity. In the summer of 1985, surface salinities in the deep-trough region of the mainstem were approximately 6 parts per thousand (ppt) higher, and bottom salinities were about 3 ppt higher, than in the high-flow summer of 1984 (Figure 3). Thus, in the lower-flow summer of 1985, salinities were higher and the vertical salinity gradient was less pronounced. Similarly, in the Patuxent estuary, salinity was higher (4-7 ppt) and stratification was reduced in 1985 in comparison with 1984 (Figure 4). In the Rappahannock River the same pattern of increased stratification and reduced salinity can be observed for 1984 relative to 1985 (Figure 4). The effect of differences in surface-to-bottom salinity, and hence density stratification, between the two summers can be seen in bottom water oxygen concentrations (to be discussed in the next section).

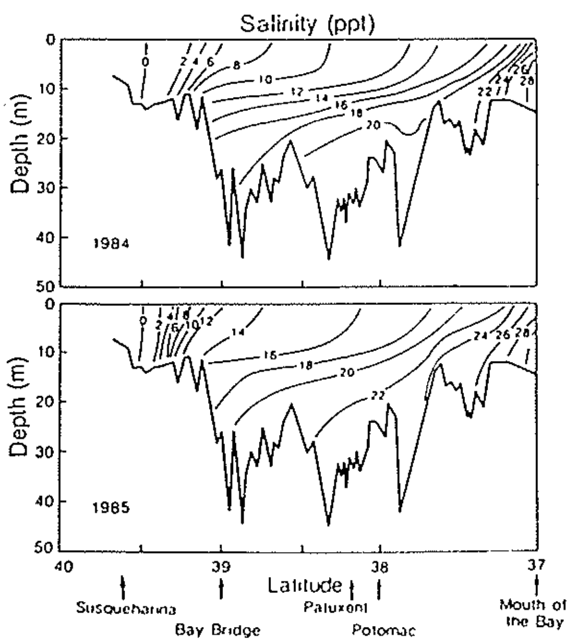


Figure 3. Average longitudinal profile for salinity in the Chesapeake Bay mainstem, summers of 1984 and 1985.

Suspended solids. Suspended solids in the water column, another important indicator of water quality, are derived from several sources and have a variety of impacts. Suspended solids reduce light penetration and transparency and thereby reduce the active or habitable zones for phytoplankton and submerged aquatic vegetation. Water transparency is considered the primary factor limiting phytoplankton growth in some regions of the mainstem and tributaries during certain seasons. As with many other water-quality constituents, the contribution of inorganic solids suspended in the water column is often influenced by river inputs. Areas of high mixing, such as near the upstream extent of salinity intrusion in the mainstem and tributaries, often have a peak in suspended solids called the turbidity maximum, where resuspension of bottom sediments contributes to high levels of suspended solids. In the mainstem of the Chesapeake Bay this turbidity maximum region is between Pooles

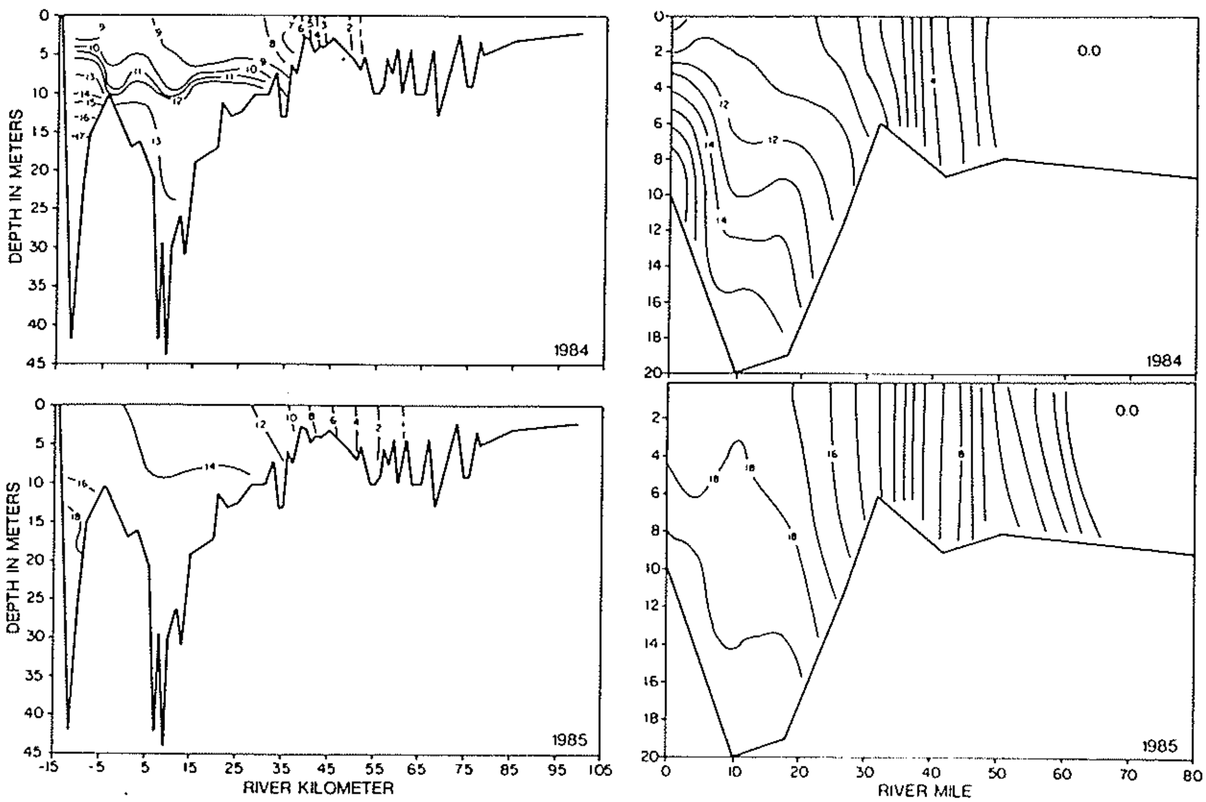


Figure 4. Average longitudinal profile for salinity (ppt) in the Patuxent River (left) and the Rappahannock River (right), summers of 1984 (top) and 1985 (bottom).

Island and Turkey Point, at a latitude of about 39° 21' (Schubel 1968), where Secchi depths are typically 0.2-0.5 m (Figure 5) and total suspended solids are generally 15-25 mg/liter in surface waters. In the lower Bay, Secchi depths increase to 1-4 m and total suspended solids decrease to about 5-10 mg/liter. Down-bay from the influence of river-borne inorganic sediment loads and the turbidity maximum region, phytoplankton populations become increasingly important in affecting water clarity. This point was demonstrated in early summer 1984 and spring 1985 when increases in turbidity in the mainstem below its confluence with the Potomac river (Figure 5) coincided with surface phytoplankton blooms (see Figure 8).

In the major tributary estuaries of the Bay, patterns for turbidity and suspended solids comparable with those seen in the mainstem are typically observed from the turbidity maximum zone to the confluence with the mainstem. In the Patuxent, the turbidity maximum zone is near Lower Marlboro between river kilometers 45 and 65. Median concentrations of suspended solids peak in the spring at >80 mg/liter, and Secchi depths are ≤0.2 m. In the lower Patuxent,

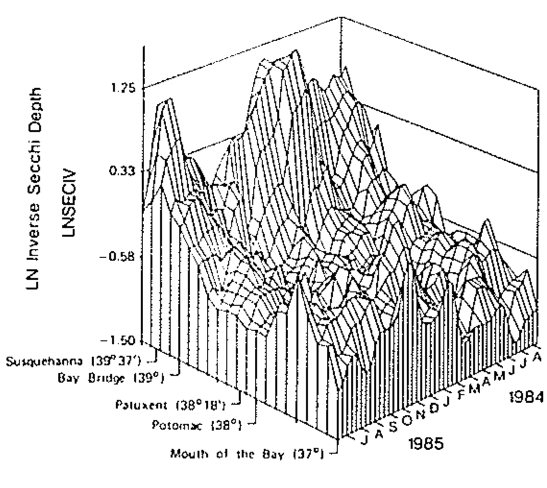


Figure 5. Turbidity as measured by Secchi depths along the axis of the mainstem Chesapeake Bay from July 1984 through September 1985. Secchi depth is expressed as the natural log of the inverse Secchi depth so that increasing turbidity is displayed as a positive response. The axis is labeled with this derivative as well as the actual Secchi depth in meters.

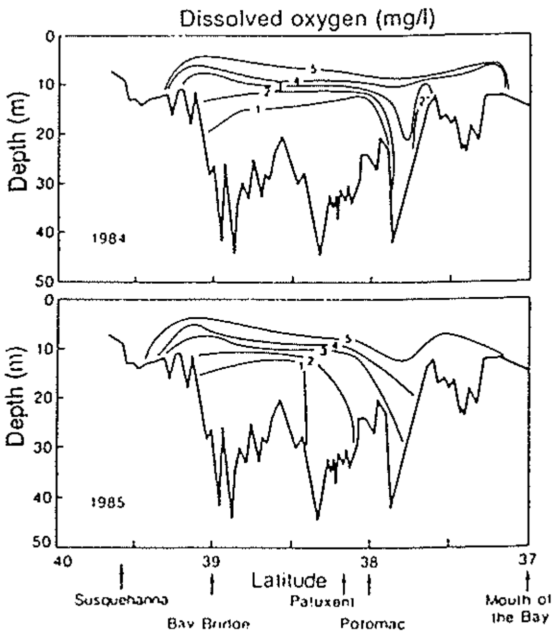


Figure 6. Average longitudinal profile for dissolved oxygen in the Chesapeake Bay mainstem, summers of 1984 and 1985.

the concentrations of suspended solids decrease and Secchi depths increase to levels comparable with those in the mainstem of the Chesapeake. The Rappahannock and James have similar Secchi depths in tidal freshwater areas (~0.5 m) but the Rappahannock exhibits a much greater downstream increase in Secchi depth (1.4-2.0 m) than the James (0.9-1.4 m). This difference may be due to the higher sediment load contributed from above the fall line and the impact of extensive development along the lower James River.

Unlike the mainstem, many Chesapeake Bay tributaries, such as the Patuxent, Potomac, and James Rivers have large stretches of tidal freshwater that can sustain extensive bloom populations of algae upstream from the turbidity maximum region; these blooms can dramatically reduce light penetration and increase suspended solids.

Dissolved Oxygen Characteristics

In general, the Bay and its major estuarine tributaries exhibit similar DO characteristics in comparable salinity regions. Throughout much of the year, when water temperatures are low and the water column is well mixed, oxygen concentrations are high. But in the late spring and summer, high oxygen demand from the sediment and water column combines with limited downward mixing of oxygen to deplete the oxygen in deeper waters.

As mentioned above, vertical density stratification strongly influences the DO characteristics of the estuary. The higher flows from the Susquehanna River in summer 1984 caused stronger vertical salinity gradients in the mainstem than those of summer 1985 (Figure 3). The average DO profiles (Figure 6) for the 1984 and 1985 summers illustrate the influence of stratification on DO conditions. There were several differences between the two years, especially in the spatial extent of hypoxic waters (here defined as water with <1.0 mg of DO/liter). In 1984, unlike 1985, hypoxic water extended well into the Virginia portion of the Bay, reaching as far south as the mouth of the Rappahannock River. Periodic reoxygenation events were more frequent in 1985 than in 1984 because of the weaker vertical density stratification in 1985; thus the duration of anoxic conditions was reduced during the summer of 1985.

In the Rappahannock River, the higher density stratification in summer 1984 appeared to have effects on bottom-water concentrations of DO similar to those observed in the mainstem; summer DO depletion was much more severe and prolonged in 1984 (Figure 7). In the Patuxent, differences in stratification between the summers of 1984 and 1985 did not effect DO levels as obviously as in the mainstem of the Bay (Figure 7). The observed difference between the behavior of the Patuxent and that of the Bay is indicative of the influence of factors other than salinity stratification, such as topographic differences, localized storm events, and periodic exchanges with mainstem waters. The influence of low-DO waters from the Bay can be seen in Figure 6 (top), where the isoclines indicate that deeper waters from the mainstem may have intruded into the lower Patuxent.

Discussion of low DO in subpycnocline waters of the Chesapeake Bay (Seliger et al. 1985, Officer et al. 1984, and Taft et al. 1980) has included perspectives on the major forcing functions responsible for this phenomenon as well as historical perspectives. Recent research efforts by numerous investigators working in the deep-trough region are likely to shed additional light on the complex processes acting to initiate and sustain anoxic and hypoxic conditions in this region (e. g., Tuttle et al. 1985). The monitoring results for the summers of 1984 and 1985 have also provided a new perspective, indicating that DO concentrations below the pycnocline may be more dynamic than previously assumed (Magnien et al. 1985). This possibly will lead to a re-evaluation and perhaps a different interpretation of historical data with limited temporal coverage. Even during the summer of 1984, when density stratification was unusually strong, two major re-aeration events were documented in the

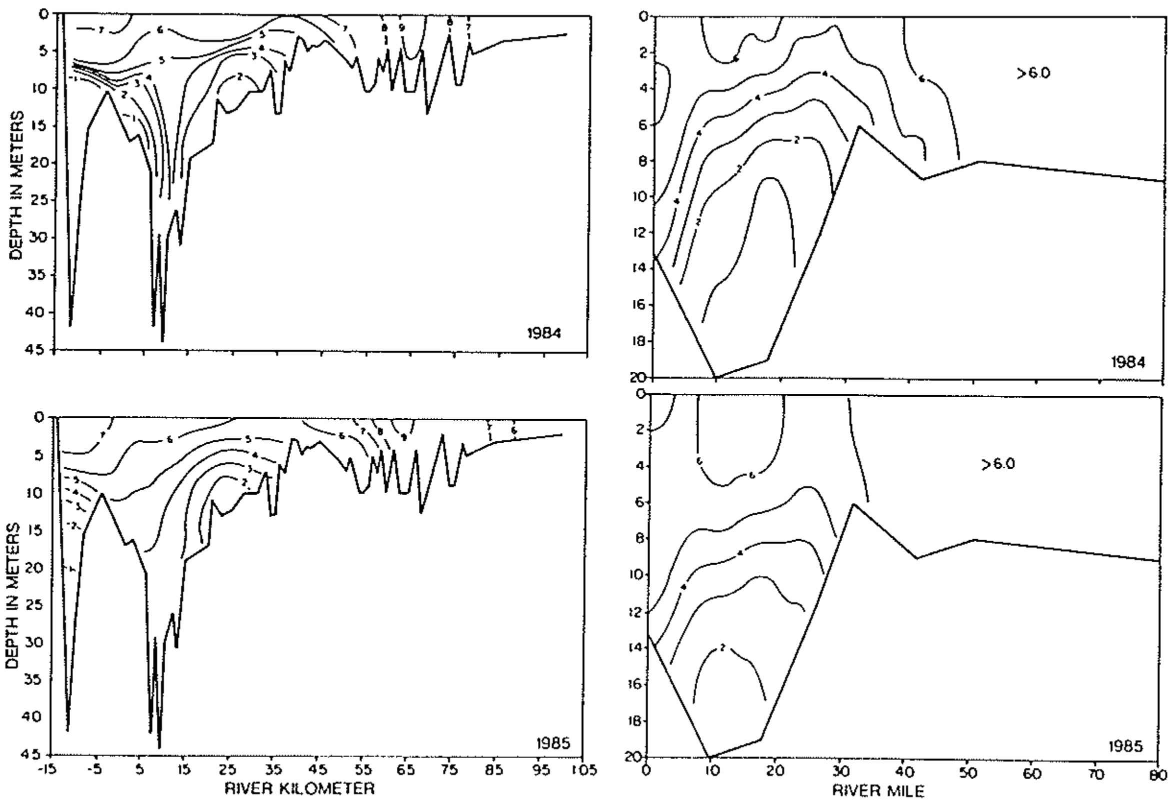


Figure 7. Average longitudinal profile for dissolved oxygen (mg/liter) in the Patuxent River (A, B) and the Rappahannock River (C, D), summers of 1984 and 1985.

deep-trough region, one in early July and one in early August. Several re-aeration events were also noticed during the summer of 1985. The enhanced temporal and spatial resolution of bottom-water DO data relative to previous studies is a major advantage of the current program.

Chlorophyll Characteristics

The concentration of chlorophyll *a*, the major photosynthetic pigment, provides a measure of phytoplankton biomass levels in the water column. In mainstem waters, the highest levels throughout the water column are generally observed in late winter and spring when chlorophyll *a* levels reach 15-40 µg/liter in both surface and bottom waters, with peaks of >50 µg/liter in the region just above the Annapolis Bay Bridge (Figure 8). This high level of phytoplankton biomass and its subsequent decline at the end of spring coincide with the onset of increasing stratification and decreasing DO concentrations in bottom waters. This large pool of organic matter is probably an important contributor to spring oxygen demand in both the water column and sediments and therefore may play a large role in the establishment of summer hypoxia in the deep-trough region. Chlorophyll *a* levels in surface waters during the other seasons are generally 5-15 µg/liter, with higher values near the Bay Bridge (see nutrient discussion, below). Bottom waters in stratified areas during summer, unlike winter and spring, generally have very low chlorophyll *a* levels due to rapid degradation of cells that settle below the euphotic zone. In addition to the lack of light in bottom waters, the high temperatures and low oxygen levels during summer provide inhospitable conditions for phytoplankton.

Mean seasonal concentrations of chlorophyll were calculated using time divisions that correspond to fairly predictable changes in some of the major factors dominating water quality: temperature, density stratification/DO, and river flow. Winter was defined as December, January, and February; spring as March, April, and May; summer as June, July, August, and the first half of September; and fall as the second half of September, October, and November. These seasonal divisions are also used for the seasonal nutrient averages presented below.

In the lower Patuxent estuary, chlorophyll concentrations were similar to those observed in the

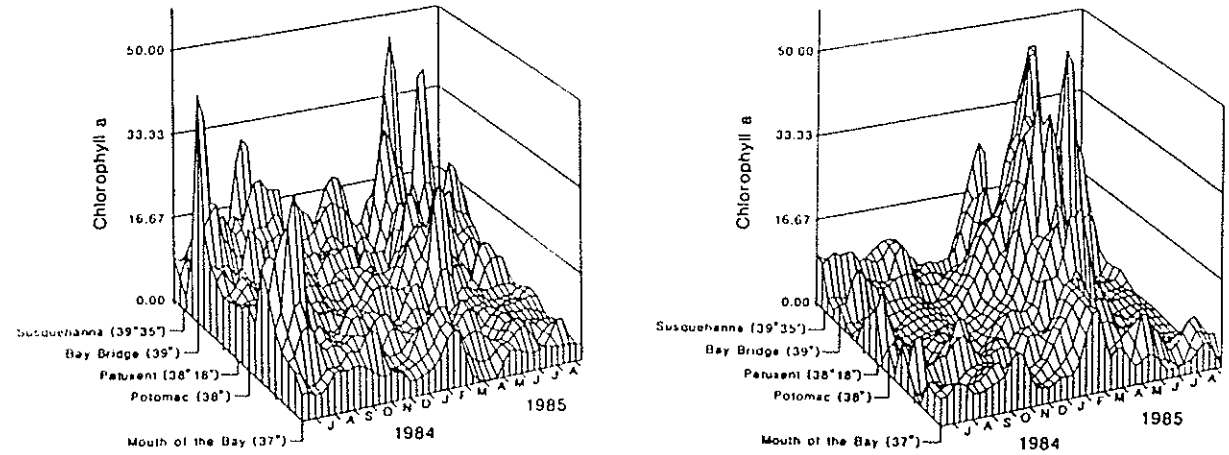


Figure 8. Active chlorophyll *a* (mg/liter) along the axis of the mainstem from July 1984 through September 1985 in surface (left) and bottom (right) waters.

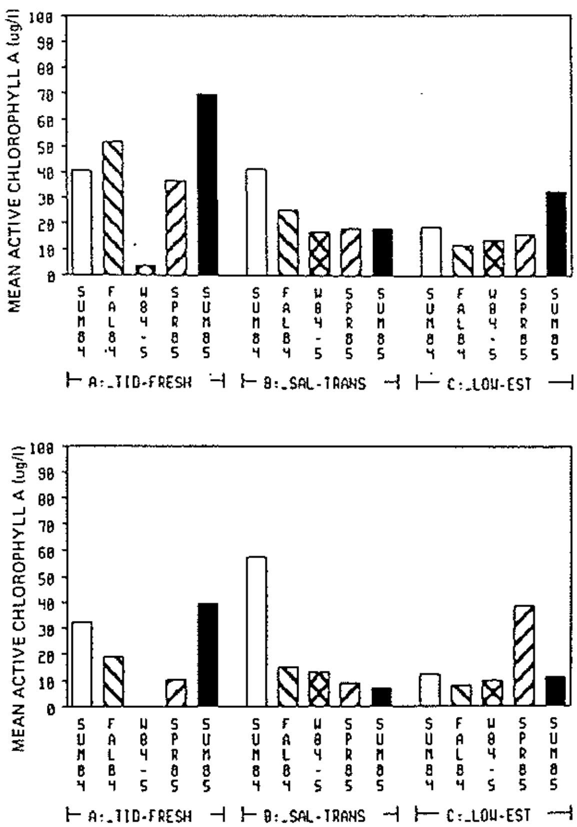


Figure 9. Seasonal mean levels of chlorophyll *a* in surface waters for tidal freshwater, salinity-transition, and lower estuarine zones of the Patuxent (top) and Potomac (bottom) Rivers, summer 1984 through summer 1985.

Bay beyond its mouth (Figure 9). However, above the turbidity maximum zone in lower-salinity regions, chlorophyll concentrations were typically much higher than in the lower estuary, and maximal concentrations in this upper tidal zone were observed in the warmer seasons. By contrast, winter chlorophyll levels were much higher in the salinity transition region and the lower estuary than in the tidal freshwater area because water temperatures are higher and ice cover less frequent downriver. The influence of annual differences in external conditions (such as river flow, sediment load, and solar radiation) can be seen, in that peak chlorophyll concentrations during summer 1985 in the tidal freshwater region were noticeably higher than those in 1984.

In tidal freshwater portions of the Potomac estuary, concentrations of chlorophyll *a* reached bloom levels of around 100 µg/liter mid-channel in the summer of 1985. Blue-green algal species were responsible for most of this bloom (Magnien and Curtis 1985), as in others seen in the Potomac during previous years (Thomann et al. 1985). General seasonal and regional patterns in the Potomac were similar to those in the Patuxent, although average concentrations were generally lower in the Potomac in all three salinity zones. A bloom of >90 µg of chlorophyll *a*/liter in the lower Potomac estuary during May of 1985 coupled with sustained values of >15 µg/liter raised average concentrations for the spring to almost 40 µg/liter.

In the James and the Rappahannock, 1985 summer average concentrations of chlorophyll *a* decreased from 20-50 µg/liter and 20-40 µg/liter, respectively, in the tidal freshwater regions to <10 μg/liter downstream near the river mouths. In general the Patuxent and Potomac have higher chlorophyll concentrations than the James or Rappahannock, although occasionally the tidal freshwater region of the James experiences blooms in the 70-100 μg/liter range.

Nutrient Characteristics

There are two primary categories of external sources of nutrients to the estuary: point sources such as sewage treatment plants and industry, and numerous nonpoint (or indirect) sources, primarily runoff and groundwater. Point-source discharges that enter directly into the estuary exert local influences on water quality and are of obvious importance. Both point and nonpoint sources enter the free-flowing portions of tributaries and thus affect the river-borne loads to the estuary. The strong influence of rivers on nutrient characteristics of the Bay and its tributaries can be seen in the strong nutrient-concentration gradients between the upper and lower reaches of many estuaries. The degree of influence is closely related to the strength of the river flow.

The nutrient characteristics of the Bay and its tributary estuaries are also greatly influenced by the recycling of nutrients. Nutrient recycling from the sediments and the water column are both important factors in controlling nutrient dynamics and thus the concentrations in the water column (Nixon 1981). The influence of nutrient recycling can be seen most dramatically in elevated ammonium and orthophosphate concentrations that appear in stratified, hypoxic bottom waters during the summer because regeneration rates of these inorganic constituents exceed uptake by organisms. More typically, regeneration of inorganic nitrogen and phosphorus is tightly linked with uptake by phytoplankton, so that ambient concentrations of these nutrients may remain low, with rapid turnover of these small pools.

Nitrogen. In the mainstem Bay, total nitrogen (TN) levels of surface waters show the strong influence of nitrogen inputs from the Susquehanna River, with values of 1-2 mg/liter at the head of the Bay and 0.4-0.7 mg/liter in the lower Bay (Figure 10). Most of this gradient is driven by changes in soluble oxidized inorganic nitrogen species (nitrite plus nitrate), which range from around 1 mg/liter in the upper Bay to near detection limits in the lower Bay (Figure 11). During summer stratification, when regeneration rates of nitrogen as ammonium from sediments and the water column are high and uptake below the pycnocline is relatively low, this nitrogen species accumulates in bottom waters (Figure 12). This pattern differs markedly from that of surface waters, where this preferred source of nitrogen for growing phytoplankton (Pennock 1985; McCarthy et al. 1977) is usually present only in small quantities.

The high concentration of ammonium in bottom waters can serve as a source of nitrogen for summer algal growth in the euphotic zone as it mixes upward across the pycnocline. Vertical mixing between bottom and surface layers in estuaries has been shown to be particularly active in areas that have sharp changes in bottom topography (Gardner and Smith 1978). An example of this phenomenon for the Bay is at the head of the deep-trough region near the Annapolis Bay Bridge, where the mid-channel shallows

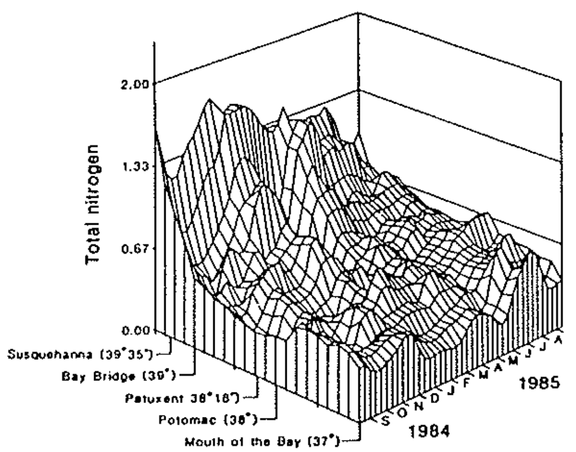


Figure 10. Total nitrogen (mg/liter) in surface waters along the axis of the mainstem Chesapeake Bay from July 1984 through September 1985.

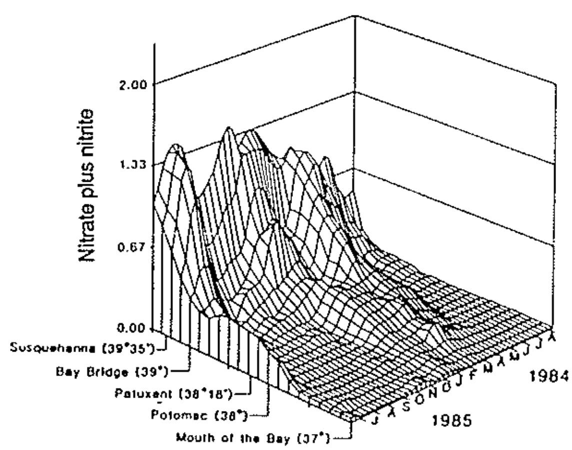


Figure 11. Nitrite plus nitrate (mg/liter) in surface waters along the axis of the mainstem Chesapeake Bay from July 1984 through September 1985.

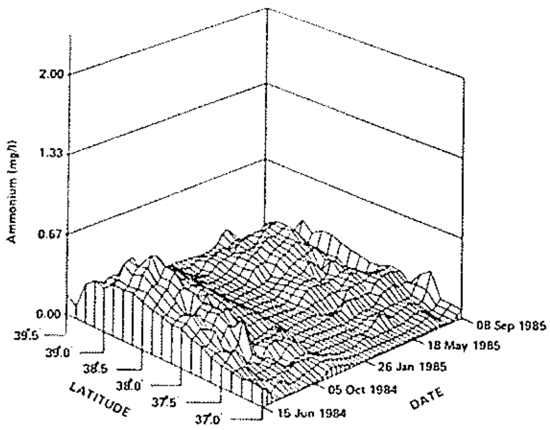


Figure 12. Ammonium (mg/liter) in bottom waters along the axis of the mainstem Chesapeake Bay from July 1984 through September 1985.

from about 100 ft to 50 ft and the width of the Bay constricts. Active vertical mixing in this region can be inferred from the diverging salinity isoclines in the pycnocline region (Figure 3). Therefore, in summer months, when bottom-water concentrations of inorganic nitrogen (see above) and phosphorus (see below) are high and surface water concentrations are generally low, this region could be expected to be an active zone for phytoplankton growth. This expectation is confirmed by the monitoring results (see Figure 8) and by the observations of others (Sellner et al. 1986; Tyler and Seliger 1978); this region generally experiences the highest algal levels present in mainstem waters during summer months.

In the Patuxent and Potomac Rivers, the concentration of TN is higher in the tidal freshwater regions than in the upper Bay, with values generally ≥ 2 mg/liter (Figure 13). In the tidal freshwater portions of the Rappahannock and James, however, total nitrogen concentrations are comparable with or slightly less than that found at the head of the mainstem (Figure 13). TN declines somewhat in the salinity transition regions of all the tributaries and then declines further in the lower estuaries, to levels (0.5-1.0 mg/liter), comparable with those in the lower portions of the mainstem. The nitrogen enrichment found to various extents in the tidal freshwater regions of the tributaries

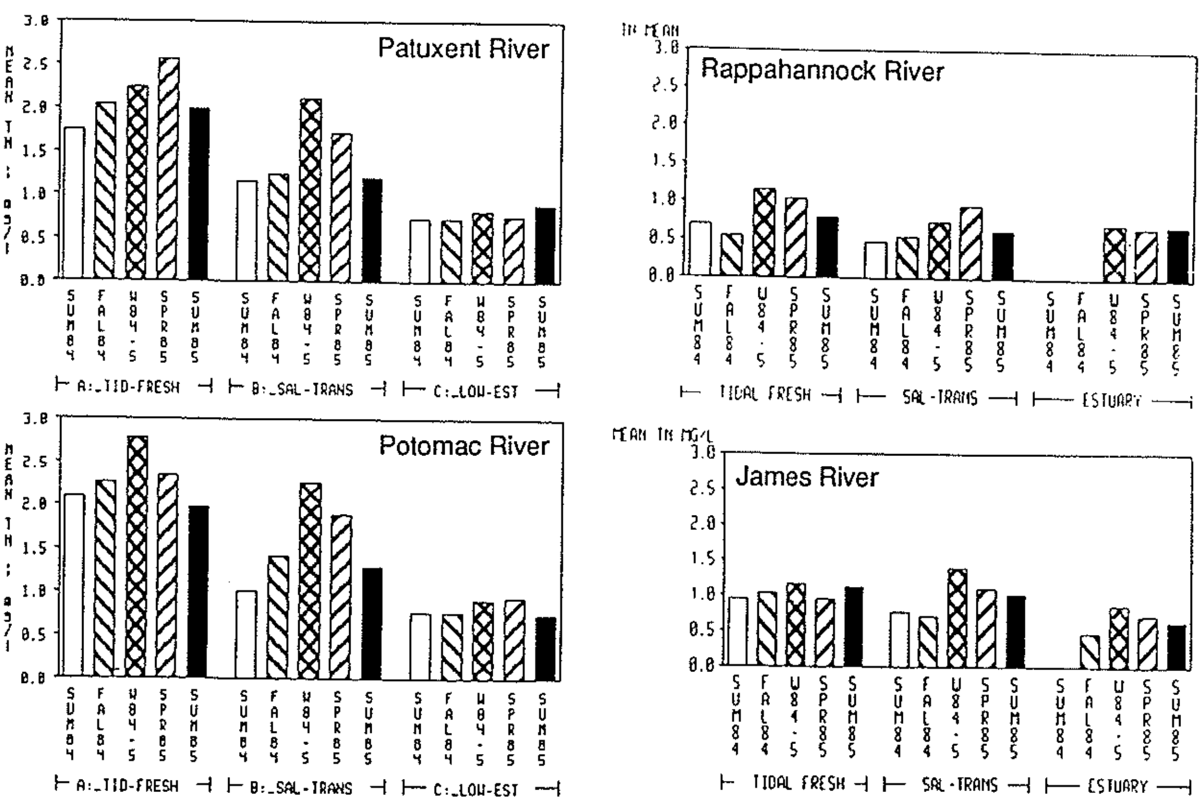


Figure 13. Seasonal means of total nitrogen averaged through the water column for tidal freshwater, salinity-transition, and lower estuarine zones of the Patuxent, Potomac, Rappahannock, and James Rivers, summer 1984 through summer 1985.

is the result of both nonpoint- and point-source impacts associated with high-density development in some of the upper tributary basins. Peaks in TN found during the winter and spring high-flow period (Figure 13) can be attributed to the high nonpoint-source loads delivered to the estuary at these times.

Phosphorus. Like nitrogen, total phosphorus (TP) shows a north-to-south gradient in concentration, although it is not as well defined. Total phosphorus peaks in surface waters in the turbidity-maximum region at about 0.05-0.08 mg/liter and declines down-bay to concentrations generally <0.04 mg/liter. During summer hypoxia in the deep-trough region, phosphorus fluxes from the sediments into the water column as insoluble iron-oxide complexes are reduced and soluble orthophosphorus is released. This process greatly increases orthophosphorus in bottom waters (Figure 14) and contributes to a summer maximum in total phosphorus throughout the water column. This summer maximum has been observed by others in the Chesapeake Bay mainstem (Taft and Taylor 1976 a and b). These high orthophosphate concentrations, like ammonium in bottom waters, can serve to nourish summer algal populations in the euphotic zone as bottom waters gradually or episodically mix with surface waters. There may be a barrier, however, to the passage of orthophosphate to oxygenated surface waters, because insoluble iron-oxide complexes can once again form in this region and precipitate.

Total phosphorus concentrations in the tributaries point to some appreciable differences between rivers. Of the four major tributaries reviewed here (Figure 15), the Patuxent River has the highest total phosphorus concentrations for the study period in all three salinity zones. Concentrations in the tidal freshwater, salinity transition, and lower estuarine zones are approximately 0.30-0.35, 0.25, and 0.1 mg/liter, respectively. The Potomac and James Rivers both have total phosphorus concentrations of approximately 0.15, 0.1-0.2, and 0.05-0.010 mg/liter in these zones. The lowest total phosphorus concentrations are found in the Rappahannock River, where concentrations in the three zones are approximately 0.05-0.10, 0.05-0.10, and 0.03-0.05 mg/liter. Seasonal changes in the lower estuaries, where DO is depleted and orthophosphorus is released from sediments as discussed above for the mainstem, do not in general support a total phosphorus maximum in summer for the tributaries except possibly the Potomac River; even in the Potomac the summer values are only slightly higher than values in other seasons.

Nutrient limitation. The control of excessive growth of phytoplankton (or eutrophication) in the Chesapeake Bay and tributaries is one of the most significant water-quality issues confronting Bay

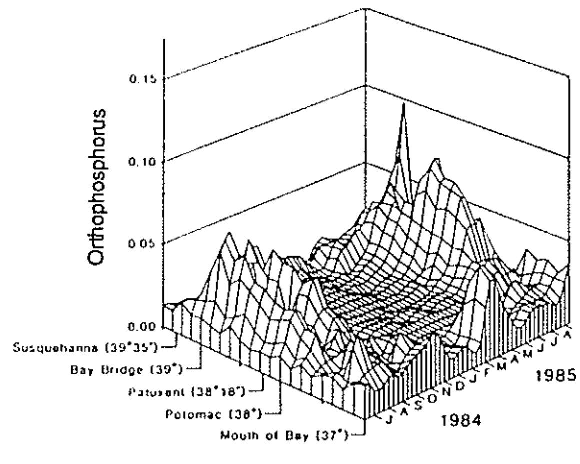


Figure 14. Orthophosphorus (mg/liter) in bottom waters along the axis of the mainstem from July 1984 through September 1985.

managers. The results of actions to reverse or at least slow down the eutrophication process will be viewed as one measure of our success in the restoration of the Chesapeake Bay.

An examination of the relative availability of nitrogen to phosphorus in atomic units provides a rough but useful index of the potential for controlling phytoplankton growth through nutrient reduction. It must be recognized, however, that there are other factors, such as light, temperature, grazing, bacterial competition for nutrients, and mixing, which also play significant roles in the regulation of algal production in the Chesapeake Bay. For the data presented here, atomic ratios of TN to TP can be calculated to examine the *potential* for nitrogen vs. phosphorus nutrient limitation and to rank the various tributaries and mainstem regions in this regard. Although there is some variability in the ratio of utilization of nitrogen to phosphorus by phytoplankton, the Redfield ratio of 16:1 for N:P (Redfield 1934) is generally accepted as an average value. Typically, ratios >16:1 are considered to be representative of regions that may be phosphorus-limited, and ratios that are <16:1 are considered potentially nitrogen-limited.

In the mainstem, TN:TP atomic ratios are almost always above the Redfield ratio. A minimum is reached in the lower Bay toward the end of the summer when ratios are in the 20s or 30s. Ratios of dissolved inorganic nitrogen to dissolved inorganic phosphorus follow the same general pattern as the total fractions, although values may approach or go slightly below the Redfield ratio in late summer in the lower Bay. In the tributaries, TN:TP atomic ratios calculated for annual averages for the Patuxent and James Rivers are generally near the Redfield ratio. In the Potomac and Rappahannock Rivers, TN:TP ratios are well above

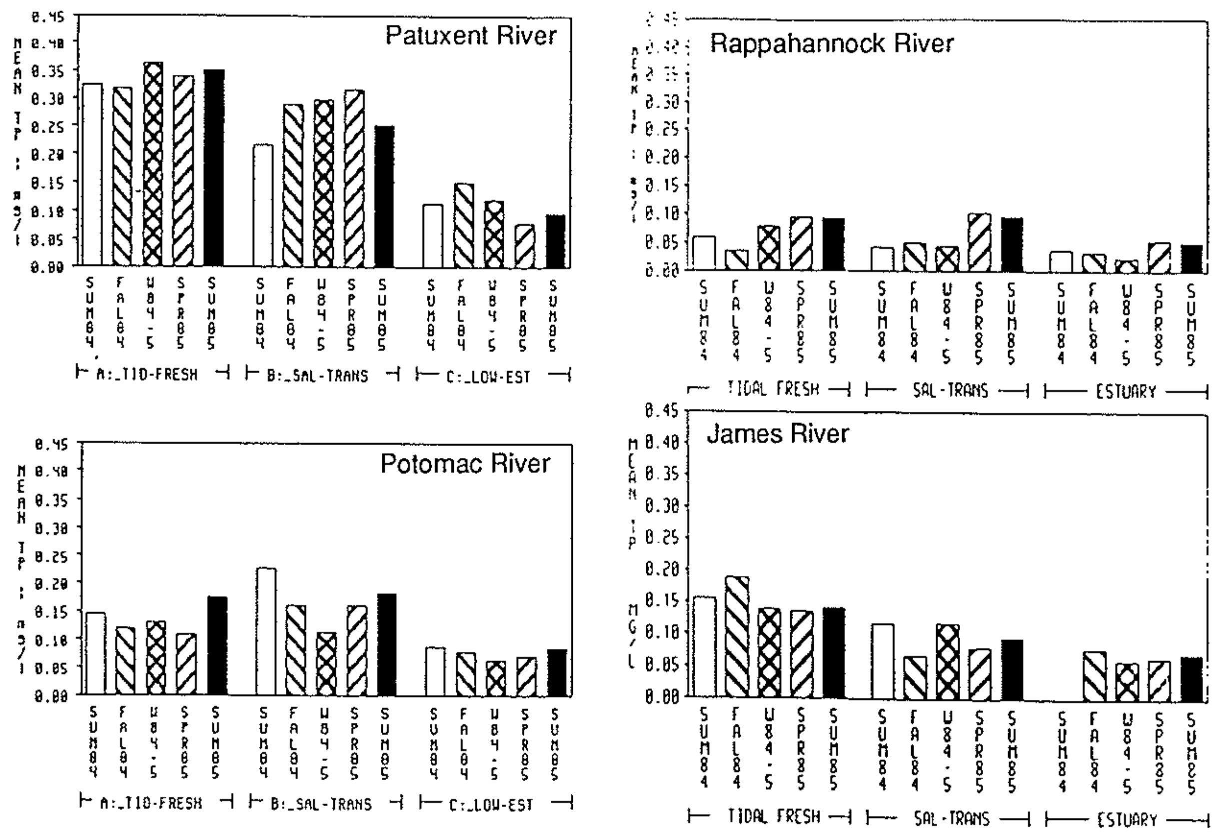


Figure 15. Seasonal means for total phosphorus averaged through the water column for tidal freshwater, salinity-transition, and lower estuarine zones of the Patuxent, Potomac, Rappahannock, and James Rivers, summer 1984 through summer 1985.

the Redfield ratio in all salinity zones. Because of seasonal peaks in nitrogen, generally in winter and spring, ratios in both the mainstem and tributaries follow a relative seasonal cycle of higher in winter and spring and lower in summer and fall.

Nutrient ratios from the monitoring program indicate that phosphorus has the *potential* for limiting algal populations throughout the Chesapeake Bay system in winter, spring, and fall. Nitrogen, along with phosphorus, has the *potential* for limiting algal growth in the lower estuarine portions of the system during the summer. There is also some variability between regions of the Chesapeake Bay estuary, with greater relative potential for nitrogen limitation in the lower Bay and greater relative potential for phosphorus limitation in the upper Bay.

The concept of nutrient limitation is an issue of considerable interest because of the obvious management implications. Theoretically, algal biomass can be controlled if the level of one nutrient can be reduced to growth-limiting concentrations. Therefore, if the "correct" nutrient is targeted for point-source and/or nonpoint-source control, significant improvements in water quality are possible. However, caution must be exercised in interpreting N:P ratios for a management strategy. One must also look beyond the computed ratios to the absolute concentrations of nitrogen and phosphorus in the water column. In addition, we still do not understand fully how nutrients are transported from the point of entry (typically in the free-flowing or tidal freshwater reaches) to the mesohaline, stratified portions of the estuaries. We must also recognize that the factors mentioned previously also play a role in the regulation of algal production.

River Input Loading Characteristics

As discussed above, the amount and quality of river water entering the Bay and its tributary estuaries from the surrounding watersheds are important factors influencing the water quality of the Chesapeake Bay. Thus, the watersheds around the Bay are the focus of various measures for point- and nonpoint-source pollution control. Existing conditions must be clearly established so that continued monitoring can verify the effectiveness of nutrient control measures taken in the watersheds. In addition, information on the location, magnitude, and timing of the river-borne pollutant loads is critical to efforts to understand the processes affecting water quality in the Chesapeake Bay.

It is neither practical nor necessary to monitor every tributary to the Bay in order to accomplish the objectives of this monitoring program. Careful selection of the rivers to be monitored will insure that the range of different sources of runoff contribution to the Bay and its tributary estuaries are represented and that the results can be extrapolated to provide a reasonably accurate estimate of river-borne pollutant loading to the Bay as a whole. In Maryland, four tributaries, the Susquehanna, Choptank, Patuxent, and Potomac, are being monitored to provide the necessary data. In Virginia, the James, Rappahannock, Mattaponi, and Pamunkey Rivers are being monitored.

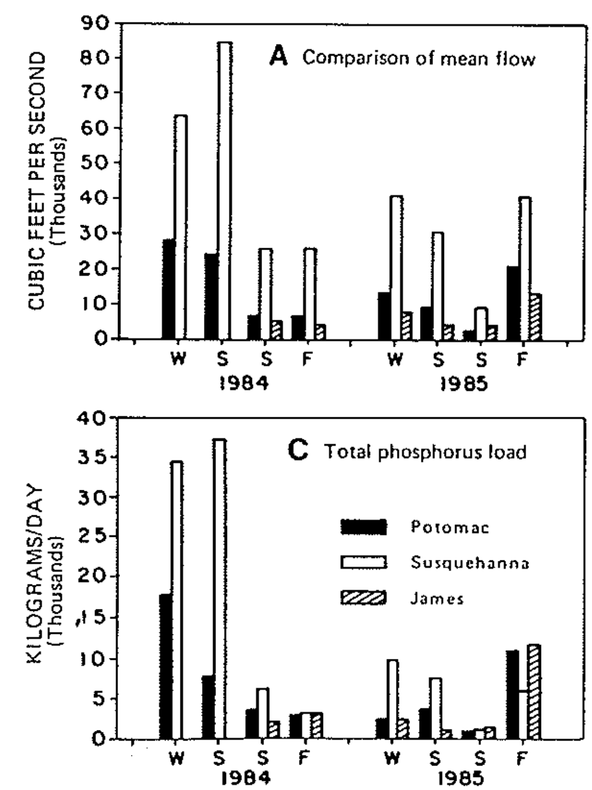
The characteristics of water flowing in a river are constantly changing, and just as it is not practical to monitor every river flowing into the Bay, it is not practical to monitor water-quality characteristics continuously over time. By carefully selecting sampling times, however, it is possible to characterize the river for a range of conditions and then extrapolate the data to fill in temporal gaps in sampling coverage.

In general, river flows can be divided into two basic categories, baseflow and storm events. Under baseflow conditions the river is fed primarily from groundwater, and the volume of water and its water quality characteristics are relatively stable. During a storm event, however, the volume of water flowing in a river increases tremendously as baseflow is supplemented and overwhelmed by direct runoff of rainfall. As the river rises and falls the concentrations of pollutants in the water can change radically. To get an accurate estimate of the pollutant load from a particular storm it is necessary to take numerous samples during the course of the storm.

Because the volume of water delivered to the estuary is much greater during storm events, the loads of associated pollutants are also much larger than loads carried by baseflow. This difference can be seen clearly by comparing pollutant loads delivered in wet and dry years. Unfortunately, few monitoring programs in the past have emphasized storm-event sampling because of the additional effort and expense involved.

This component of the monitoring program is designed to take into account contributions from both storm events and baseflow to characterize accurately the major nutrient species and sediment loads passing the stations discussed above.

Estimates of seasonal loads of total nitrogen and total phosphorus are shown (Figure 16) for the Susquehanna, Potomac, and James Rivers for 1984 and



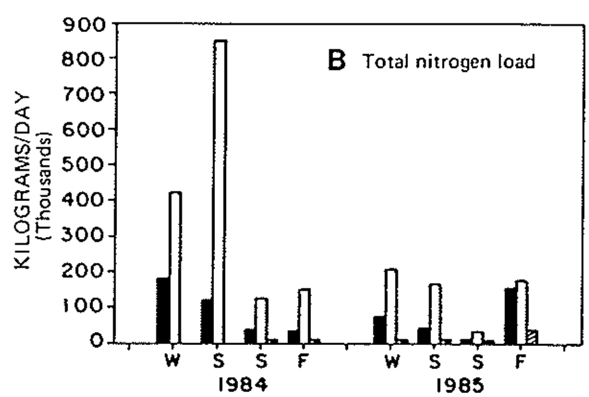


Figure 16. Comparison of seasonal mean flow (A), total nitrogen load (B), and total phosphorus load (C) for the Potomac, Susquehanna, and James Rivers in 1984 and 1985.

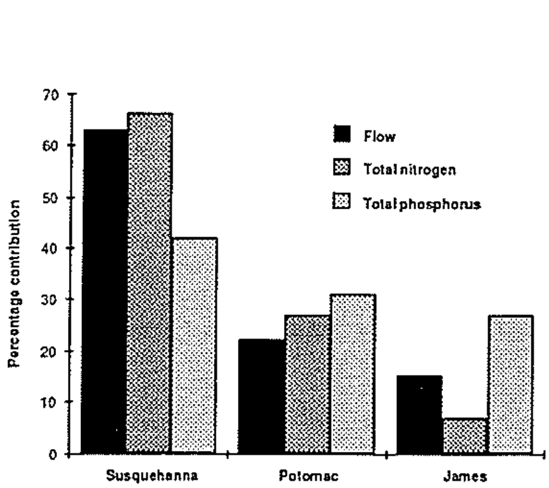


Figure 17. Comparison of average 1984-1985 flow, total nitrogen contribution, and total phosphorus contribution of the Susquehanna, Potomac, and James Rivers.

1985. Because of differences in the amount of data available, more confidence should be placed in the estimates given for the Potomac and Susquehanna than for the James.

Together, these three rivers represent 84% of the freshwater flow into the Bay. The exact proportion of the total river input load represented by these rivers must be determined by extrapolation of the monitoring data to cover unmonitored portions of the Chesapeake Bay watershed. Methods of extrapolation range from simple flow-based techniques to sophisticated watershed computer models.

On the basis of the monitoring data it is apparent that simple flow-based extrapolation would not be very accurate. This point is illustrated by a comparison of 1984-1985 flow and nutrient loads of the Susquehanna, Potomac, and James (Figure 17). It is clear that of these three rivers, the Susquehanna was the major contributor of flow and nutrients to the Bay. Its TN and TP loads, however, were not in proportion to its flow. The Susquehanna contributed slightly more of the TN and approximately 20% less of the TP than would be expected if flow alone determined nutrient load. The Potomac and James Rivers contributed a higher percentage of TP than would be expected on the basis of their flows.

The strong seasonal influence of changing river flows on nutrient loads is evident in Figure 16. In seasons when river flow is high, nutrient loads are also high. For example, approximately 80% of the flow and nutrient loads delivered to the estuary by the Susquehanna and Potomac Rivers in 1984 came in the winter and spring. However, in 1985, the fall season loads were more significant, particularly on the Potomac and James Rivers, where the effects of a major hurricane could be observed.

To put the 1984 and 1985 river pollutant loads in an historical perspective, estimates of annual loads of total nitrogen and total phosphorus from the Susquehanna and the Potomac are presented in Figure 18. The Susquehanna estimates for 1978, 1981, 1982, and 1983 are based on a fairly limited set of data collected by the Maryland Office of Environmental Programs (OEP). In 1979 and 1980 the U. S. Geological Survey (USGS) conducted a much more intensive monitoring program and obtained more reliable loading estimates. In general, estimates for the Potomac are based on much more data, and more confidence can be placed in the Potomac estimates than in those for the Susquehanna.

In order to get a rough estimate of the degree of uncertainty associated with annual estimates based on limited data, the loads estimated using 1979 and 1980 USGS data can be compared with loads estimated based on the OEP data. The annual loads based on OEP data alone were more accurate for total nitrogen than for total phosphorus. However, as might be expected, in a wet year (1979) the estimates were less accurate (10% underestimate of TN, 30% underestimate of TP) than in a dry year (1980, 3% underestimate of TN, <1% difference for TP). In spite of these uncertainties, the comparison of historical data is useful in illustrating the annual variation in the relative magnitude of the nonpoint-source nutrient contributions of the two largest rivers on the Bay.

During the period 1978-1985 both rivers went through a cycle of high and low flows, with peak flows in 1978-1979 and 1983-1984. Nutrient loads followed the same general pattern, although the 1983-1984 loads, particularly the 1984 TN load on the Susquehanna, were somewhat higher than the 1978-1979 loads. This difference could be taken as indicative of increased river-borne nutrient loads in more recent years. However, given the uncertainty of the earlier load estimates in particular, this possibility cannot be quantitatively verified. If the enhanced monitoring of river input continues, it will be possible to verify such trends.

On average over the 1978-1985 period, the Susquehanna contributed 75% of the flow, 72% of the TN, and 66% of the TP contributed by the two rivers combined. Like the seasonal load estimates shown above, longer-term annual estimates show that the Susquehanna River contributed less TP than expected based on the relative flow contribution of the two rivers.

The long-term annual loading estimates shown above also support the observation that although flow is important, by itself it is not an accurate predictor of pollutant loads. Factors unique to each watershed influence the timing and magnitude of storm flows, the extent of erosion, and the magnitude of the nutrient loads delivered to the estuary.

In order to accurately extrapolate river-input monitoring data to obtain loading estimates for unmonitored parts of the Chesapeake Bay basin, differences in topography, soils, density of development, land-use practices, point-source discharges, and in-stream biological processes must be taken into account. The best means of extrapolating the monitoring data to cover unmonitored areas is generally considered to be a computer model that can take all of the above factors into account. Efforts to develop such a model are currently under way in several portions of the Chesapeake Bay watershed and for the Bay watershed as a whole.

CONCLUSIONS

Results from the first 15 months of water-quality monitoring have already provided a much more comprehensive understanding of the present condition of the Chesapeake Bay estuary than had existed previously. Bay-wide synoptic sampling at a frequency of up to 20 times per year has permitted substantial resolution of the spatial and temporal dynamics in water quality, a necessary step in addressing the objectives of characterizing the system and detecting trends. The linkage of traditional chemical/physical monitoring of ambient water quality with river inputs and other important biological and process-oriented monitoring elements, as presented in the other chapters, provides a more complete picture of water quality and a crucial understanding of factors regulating water quality. The monitoring program also provides a framework into which the general principles discovered in research efforts, which typically concentrate on intensive analysis of more limited space and time scales, can be expanded to include a Bay-wide perspective.

The comprehensive approach to monitoring the Bay also permits a quantitative assessment of much of the "natural variability" in Chesapeake Bay water quality, a term used as a catch-all for the often large season-to-season or year-to-year variations that are not due to man's activities. It will be necessary to account for the effects of much of this natural variability on water-quality measurements and to look beyond this "noise" to discern the actual trends caused by human influences. It is only in a comprehensive program

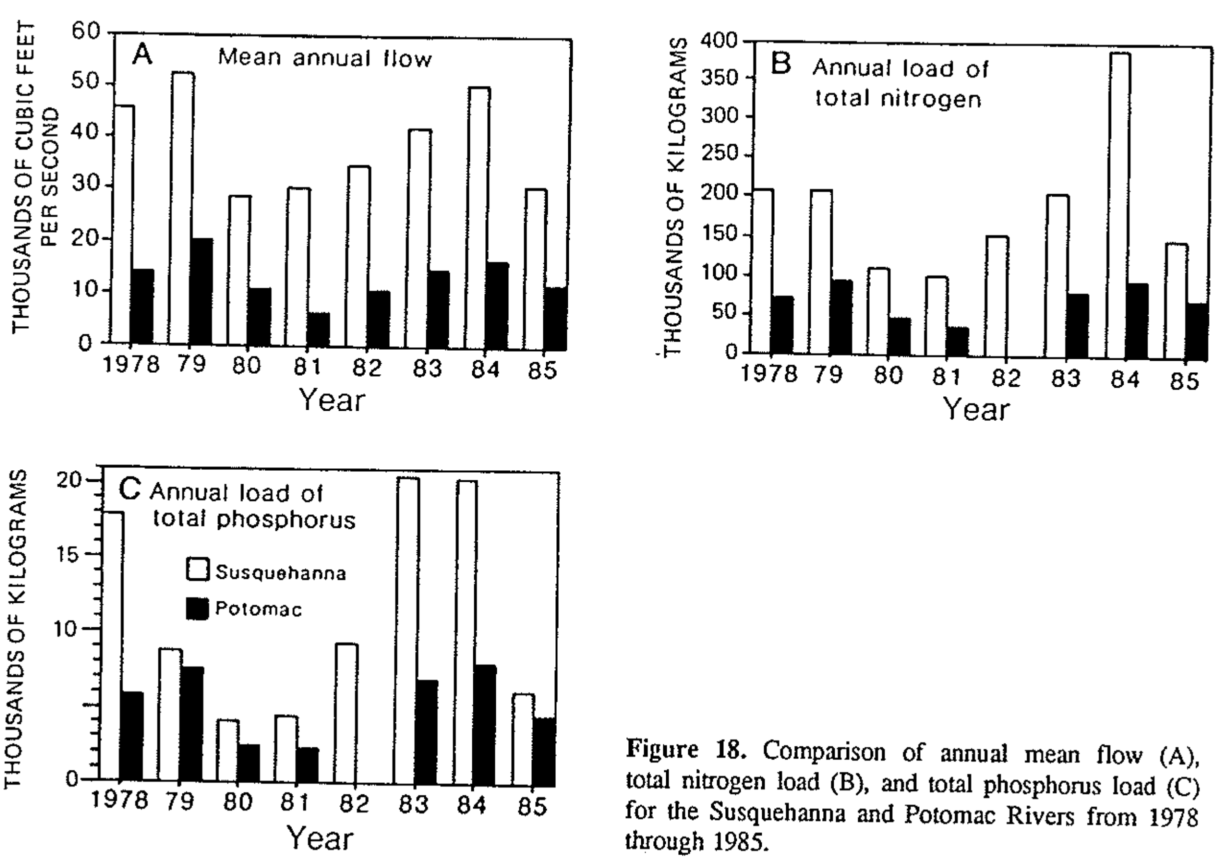


Figure 18. Comparison of annual mean flow (A), total nitrogen load (B), and total phosphorus load (C) for the Susquehanna and Potomac Rivers from 1978 through 1985.

with an ecological perspective, such as the one presently in place, that we can hope to capture the subtle responses to our management actions in the Chesapeake Bay.

ACKNOWLEDGEMENTS

Many individuals and institutions in both Maryland and Virginia provided professional support in the development and implementation of the monitoring programs described in this document and continue to sustain the ongoing water-quality monitoring efforts. Funding for the program comes from Maryland, Virginia, and the U.S. Environmental Protection Agency (EPA).

The Chesapeake Bay Water Quality Monitoring Program in Maryland is administered by the Maryland Office of Environmental Programs' (OEP) Water Management Administration. The Modeling and Analysis Division in OEP's Planning and Evaluation Program is responsible for the monitoring program's implementation, management, data processing, and data analysis. The Division of Water Quality Monitoring and individuals in the Modeling and Analysis Division are responsible for the tributary and mainstem sampling activities. Personnel from the U. S. Geological Survey (USGS) office in Towson, Md. sample river-input stations on the Susquehanna, Patuxent, and Choptank Rivers. The river-input station on the Potomac is operated in conjunction with the Metropolitan Washington Council of Governments and the Occoquan Monitoring Laboratory in Manassas, Va.

The Laboratory Administration of the Maryland Department of Health and Mental Hygiene in Baltimore, the University of Maryland's Chesapeake Biological Laboratory in Solomons, the EPA's Central Regional Laboratory in Annapolis, Md., the USGS Central Laboratories in Georgia and Colorado, and the Occoquan Monitoring Laboratory all provided valuable services for the chemical analysis of water samples collected in Maryland.

The Chesapeake Bay Water Quality Monitoring Program in Virginia is administered by the Virginia State Water Control Board. The Chesapeake Bay Program staff of the Virginia Water Control Board are responsible for the implementation and management of the program. Within the tributary program, the Tidewater and Piedmont Regional Offices are responsible for the sampling activities and the Division of Consolidated Laboratory Services is responsible for the chemical analyses. The Division of Information Services, Virginia Water Control Board, provides data-processing support for the tributary program. The sampling activities and chemical analyses for the Fall Line program were conducted by USGS. The Virginia Institute of Marine Science and Old Dominion University - Applied Marine Research Laboratory provided the field sampling, laboratory analyses, and data processing for those water-quality stations located in the Virginia portion of the Chesapeake Bay mainstem.

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The District of Columbia's Water Quality Monitoring Program

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The Water Quality Monitoring Program of the District of Columbia's Department of Consumer and Regulatory Affairs, Environmental Control Division, assesses the pollutant load and long-term trends in water column response to various control strategies in District waters. The program is designed to: (1) characterize current baseline water quality; and (2) generate reliable scientific information to aid in the future management decisions concerning (a) protection of the public from the potential health hazards of polluted waters; (b) protection of District waters from environmental pollutants; and (c) maintenance and expansion of the current uses of District waters as a valuable resource.

METHODS

The District monitors 77 stations: 27 on the Potomac River, 28 on the Anacostia, and 22 on Rock Creek and other smaller tributaries within the District. In addition, the Chesapeake & Ohio Canal, the Washington Ship Channel, and the Tidal Basin are sampled.

Dissolved oxygen (DO), water temperature, conductivity, and pH are measured at all stations. Surface samples for water chemistry are taken at all stations on the Potomac, five stations on the Anacostia, two stations on Rock Creek, and all tributary stations. Parameters routinely monitored include Secchi disk transparency, total suspended solids, turbidity, concentration of total organic carbon (TOC), concentration of DO, alkalinity, biological oxygen demand (BOD), nutrients, coliform bacteria, chlorophyll *a*, and pheophytin *a*. Selected river stations are also sampled to determine diversity and abundance of phytoplankton and zooplankton. Samples are taken four times a year at all water chemistry stations for analyses of selected metals.

The District's water monitoring activities are coordinated with Virginia's Water Control Board and Maryland's Office of Environmental Programs, in conjunction with EPA's Chesapeake Bay Program and the Metropolitan Washington Council of Governments.

WATER QUALITY

Potomac River

The water quality of the District's portion of the Potomac River has improved in recent years, as evidenced by increased recreational use of the river for boating, fishing, and wind surfing. Pollutant inputs that still affect the Potomac in Washington include discharges from wastewater treatment plants (the largest being the Blue Plains advanced wastewater treatment plant), overflows from combined sewers (CSOs), and land runoff from upstream and urban sources.

Averaged water quality data collected in 1985 from seven sampling stations on the Potomac River along the Washington reach are presented in Figure 1. Overall, the water quality of the Potomac River at Washington in 1985 was good. DO, a fundamental indicator of water quality, remained >8 mg/liter on the average throughout the Washington reach. Slight sags in DO around Georgetown near the mouth of Rock Creek (river mile 97.25) and below the Anacostia confluence (river mile 92.50) were probably due to CSO discharges from Rock Creek and the Anacostia to the Potomac. Also, effluent from sewage treatment plants discharging to the Potomac below river mile 92.50 may have contributed to lower DO levels.

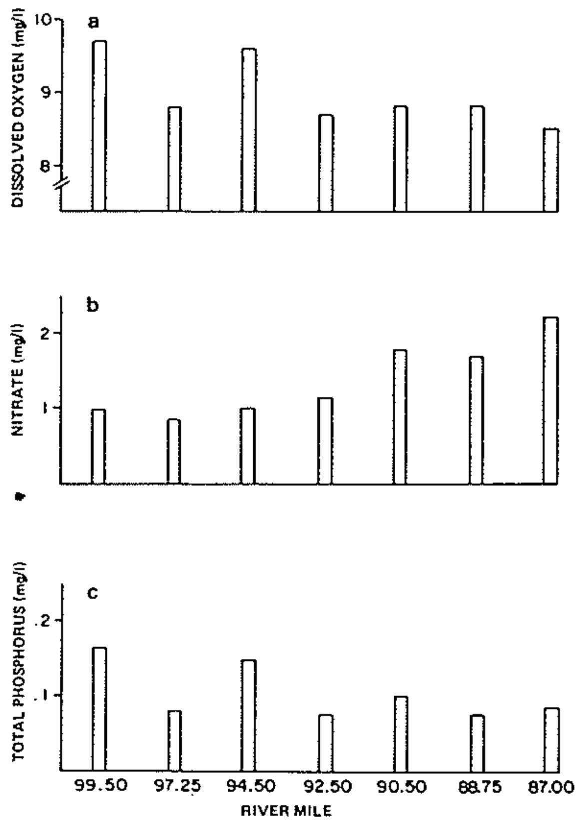

Figure 1. Annual average concentrations of dissolved oxygen, nitrate, and total phosphorus in the Potomac River, by river mile. The x-axis is not proportional to actual distance.

Higher 1985 averages for total phosphorus observed around Fletcher's Boathouse, where the Potomac River enters the District (river mile 99.50), suggest that inputs of nutrient-laden sediments from upstream sources may contribute to the nutrient load of the Potomac. Increases in nitrate levels at river mile 90.50 and below were possibly responses to discharges from sewage treatment plants in the area, particularly the added nitrates from the online nitrification process at Blue Plains.

Average 1985 Secchi disk transparencies for the Potomac at Washington (Figure 2) ranged from 0.6 m at Woodrow Wilson Bridge (river mile 88.75) to just over 1.1 m around Georgetown and the 14th Street Bridge (river miles 97.25 and 94.50). Clarity decreased significantly below the Anacostia River confluence (river mile 92.50), and the impact of sediment-laden waters of the Anacostia on the Potomac may be the cause of reduced transparencies in this region, especially after high-flow events.

Five years' data on DO and water temperature measured at Fletcher's Boathouse, where the Potomac enters the District, and downstream at Woodrow Wilson Bridge are presented in Figure 3. Concentrations at the two stations were similar. No long-term trend in DO concentration could be discerned at either station. Yearly variation in DO levels reflected seasonal changes in water temperature, the result of reduced solubility of oxygen in water at higher temperatures. Summer DO values >5 mg/liter are considered good, and these levels in the Potomac River reflect a recovery from the problems of low DO observed in the 1960s and 1970s.

Monitoring data for 15 years are available for the District's Potomac River station at Rosier Bluff (river mile 87.00), about a mile downstream of the Blue

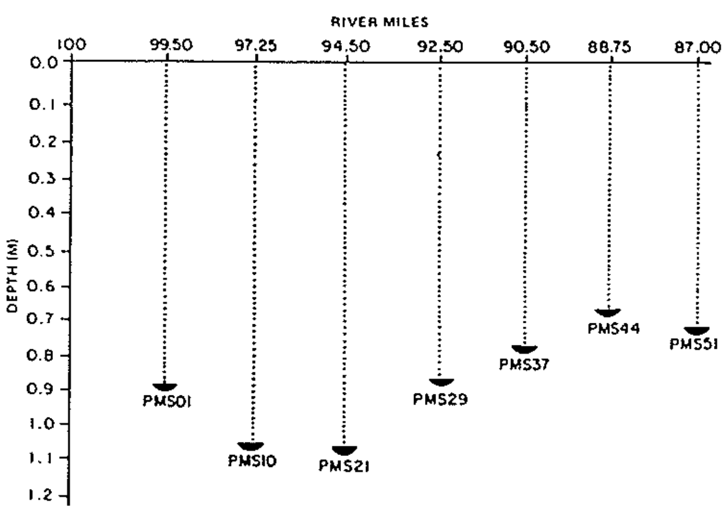

Figure 2. Average Secchi depth in 1985 at Potomac River core stations. The x-axis is not proportional to actual distance.

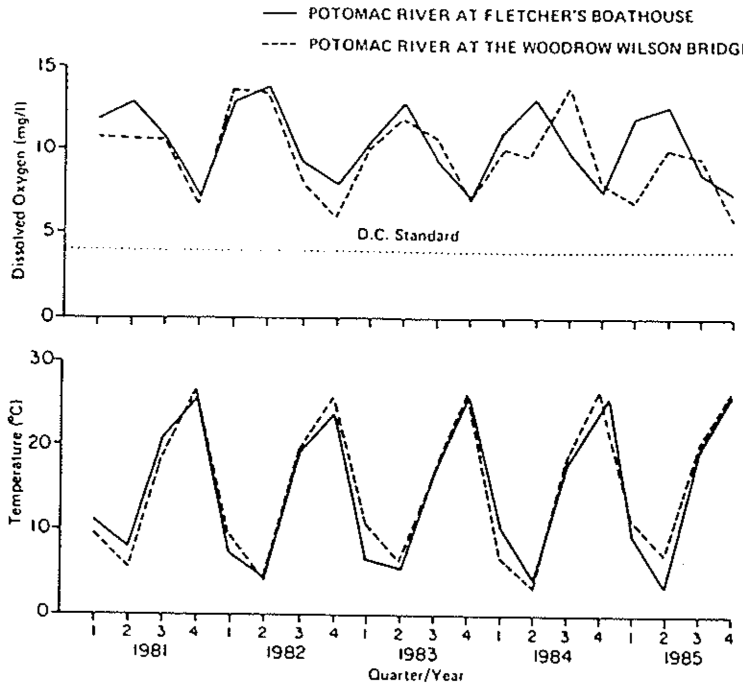

Figure 3. Quarterly average concentration of dissolved oxygen (top) and quarterly average water temperature (bottom) in the Potomac River at Fletcher's Boathouse and at the Woodrow Wilson Bridge.

Plains outfall (Figures 4 and 5). This water quality information provides an indirect assessment of long-term changes in river water quality resulting from improvements made at Blue Plains over the last decade. Modifications to the secondary activated-sludge reactors and aerators, resulting in improved removal of residual BOD and solids, were completed in 1972. The addition of ferric chloride to the secondary reactors for phosphorus removal began in 1974. In July 1980 nitrification went online.

Trend data suggest that Potomac River water quality at Rosier Bluff has improved since 1971. Average annual levels of DO have increased from a low of 3.5 mg/liter in 1971 to >7 mg/liter in recent years (Figure 4). Correspondingly, BOD has decreased. The reduction in BOD, possibly due to lower discharges of BOD-producing materials at Blue Plains, has resulted in higher levels of DO.

Yearly average concentrations of total Kjeldahl nitrogen (TKN), total phosphorus, and ammonia have decreased since 1971 (Figure 5). The Blue Plains sewage treatment plant is the principal discharger of nutrients to District waters. Because of improvements in treatment processes over the last decade, the pollutant loading of total phosphorus and TKN to the Potomac River from this source has been reduced. In particular, the installation of a sludge-dewatering centrifuge at Blue Plains has increased the plant's capability to remove sludge as well as phosphorus.

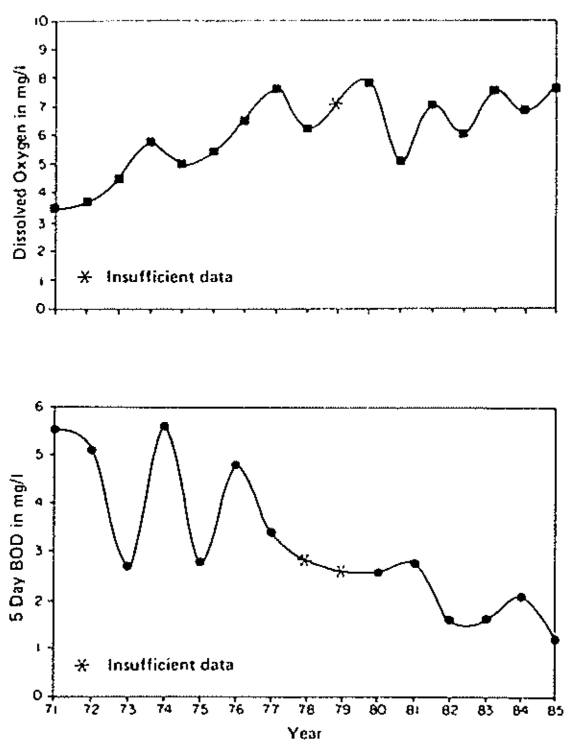

Figure 4. Annual means of dissolved oxygen (top); and annual means for five-day biological oxygen demand (bottom) in the Potomac estuary at Rosier Bluff.

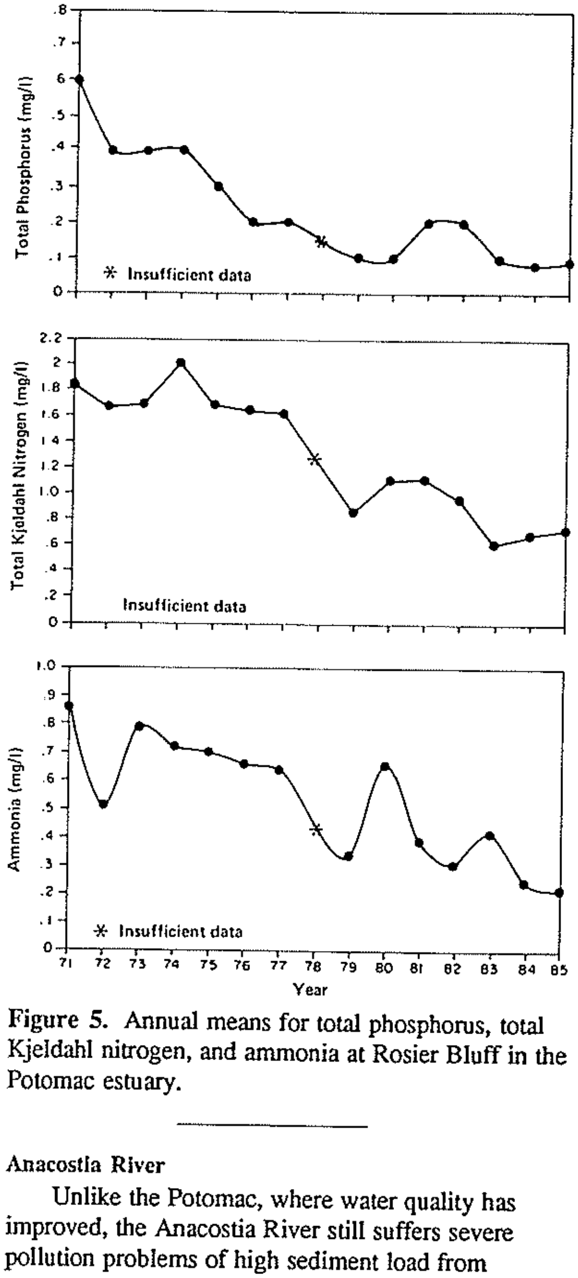

Figure 5. Annual means for total phosphorus, total Kjeldahl nitrogen, and ammonia at Rosier Bluff in the Potomac estuary.

Anacostia River

Unlike the Potomac, where water quality has improved, the Anacostia River still suffers severe pollution problems of high sediment load from upstream and urban sources, as well as bacterial contamination from CSOs, with associated depression of DO levels.

Average Secchi depths in the Anacostia River in 1985 are plotted spatially in Figure 6. The stretch of the river from the District line (river mile 99.25) to the Pennsylvania Avenue Bridge (river mile 96.00) is characterized by low water clarity, generally <0.3 m. The high turbidity of water in this section of the river is primarily due to a high sediment load from upstream; stream-bank erosion and CSOs in the District may also contribute to this problem. A clear spatial trend of increased water clarity is evident from the Pennsylvania Avenue Bridge (river mile 96.00) to the Potomac River confluence at Hains Point (river mile 92.50). The Potomac influences this lower section of the Anacostia through tidal action and resulting dilution. Reduced water clarity in the Anacostia is considered a major water-quality problem.

Figure 7 presents the temporal and spatial distribution of DO concentrations in the Anacostia River for 1985. Concentrations measured at each station exhibit the natural variation in DO associated with fluctuation in water temperature. Seasonal variation in temperature alone cannot account for the extremely low DO levels in the river in May, extending from the District line to Pennsylvania Avenue Bridge. Probably CSO discharges in this reach are the cause of such low DO levels.

Nutrient levels in the Anacostia are important indicators of water quality, because the presence of desirable or undesirable flora and fauna depends largely on the availability of macronutrients. In addition, the Anacostia is the largest tributary to the upper Potomac estuary, and as a result, the nutrient load from this source can have a critical influence on Potomac River concentrations. Figure 8 presents the spatial distribution of selected nutrients reported from the Anacostia for water year 1985.

Measured concentrations of TKN and ammonia appear to be similar to those in other sections of the upper estuary. Both TKN and ammonia are reduced downstream, possibly because of the long retention time of Anacostia River water. The upper reach of the

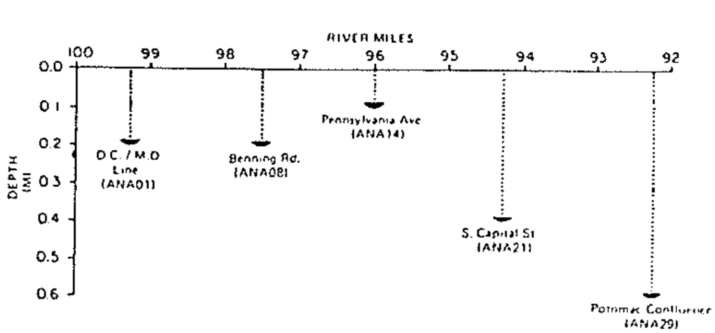

Figure 6. Average Secchi depth for 1985 in the Anacostia River, by river mile.

river, known for its pollution problems because of CSO discharges, exhibited higher TKN and ammonia concentrations. The highest TKN values were observed at the Pennsylvania Avenue Bridge (a wider and less protected section of the river) and may be attributed to wind and tidal action. Although point and nonpoint sources within the District may be responsible for high TKN and ammonia values, upstream loading seems to contribute to this problem as well.

When the un-ionized fraction of ammonia (NH_3) is estimated from measured total ammonia, the District standard of 0.02 mg/liter is frequently violated in the tidal estuary. The high concentrations of un-ionized

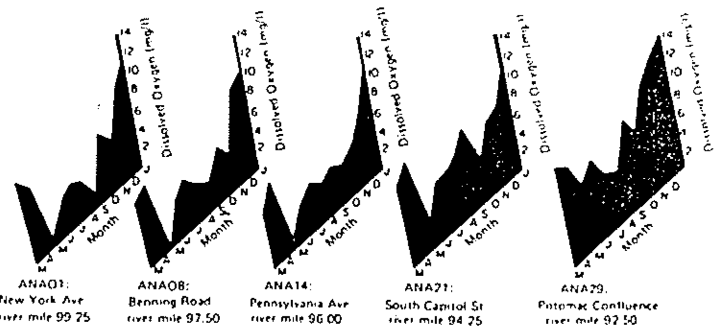

Figure 7. Average concentrations of dissolved oxygen in the Anacostia River from March 1985 through January 1986, by river mile and month.

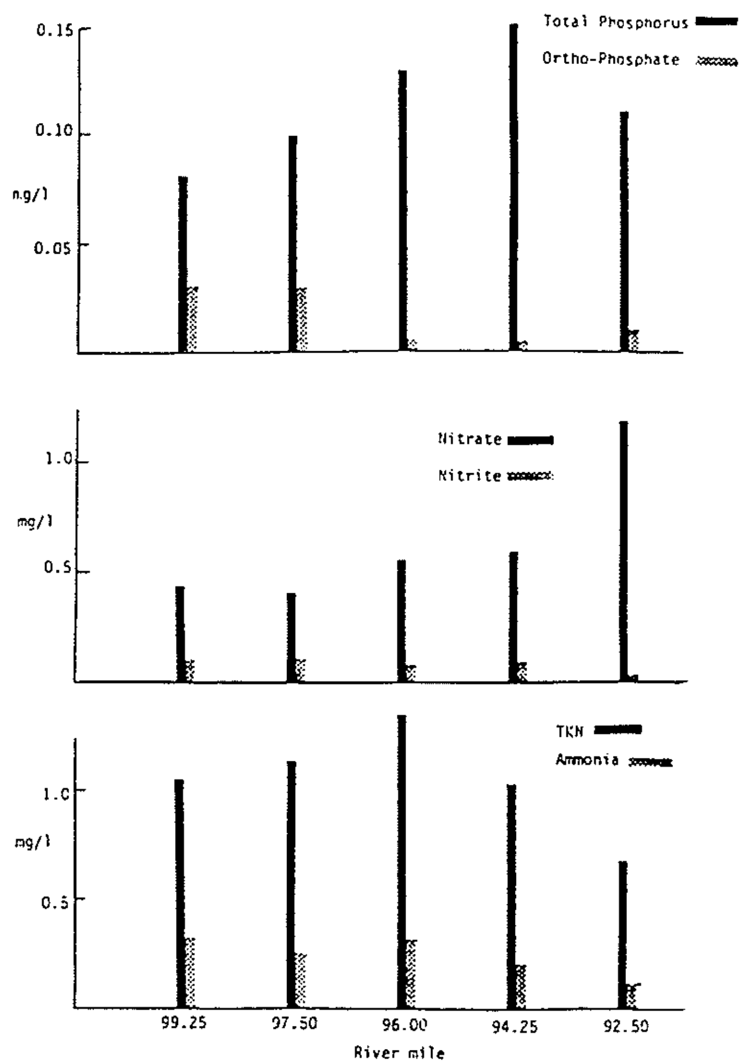

Figure 8. Spatial distribution of selected nutrients in 1985 in the Anacostia River from the District of Columbia/Maryland line to the confluence with the Potomac. Values reported represent averaged spring and summer concentrations. The x-axis is not proportional to actual distance.

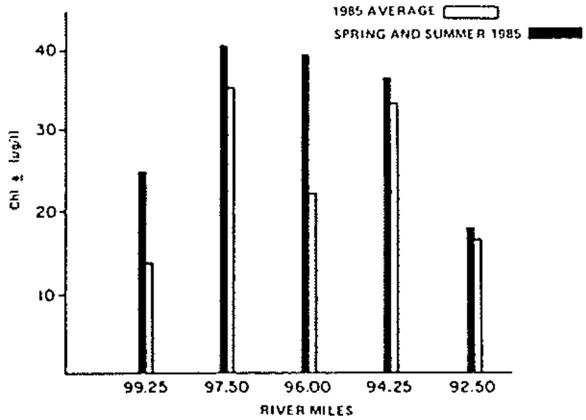

Figure 9. Spatial distribution of chlorophyll *a* in the Anacostia River from the District of Columbia/Maryland line to the confluence with the Potomac River.

ammonia in the Anacostia are disturbing, as it is considered to be toxic to a variety of fish species. The NH_3 fraction of total ammonia increases with rising temperature and pH. This relationship exacerbates the impact on aquatic organisms in the warm summer months when DO often falls below critical levels.

Mean nitrate concentrations during the spring and summer of 1985 ranged from a low of 0.43 mg/liter at the District line to a high of 1.18 mg/liter at the Potomac River confluence. Nitrate levels rose with movement downstream. The sharpest increase was observed between the South Capitol Street Bridge (river mile 94.25) and the confluence. Average spring and summer concentrations of nitrate were about 50% lower than those in the Potomac River. In contrast to nitrate, nitrite levels decreased in concentration with movement downstream.

To detect a possible trend in phosphorus concentrations along the Anacostia River, average spring and summer concentrations of total phosphorus and orthophosphate were plotted spatially (Figure 8). Total phosphorus ranged from 0.08 to 0.15 mg/liter, whereas orthophosphate remained ≤0.03 mg/liter. Total phosphorus values were higher in the Anacostia than in the Potomac River, especially along that reach of the river most frequently affected by CSO discharges. Variation in total phosphorus concentration closely resembles variation of TKN, total suspended solids, and other parameters associated with sewage and high sediment.

Orthophosphate, the biologically available phosphorus, was found in lower concentrations in the Anacostia than in the Potomac River. Orthophosphate concentrations also increased with movement downstream, with the highest values reported near the Anacostia's mouth. This region is influenced by Potomac River water through tidal action. Extremely low concentrations in the upper reach during spring and summer may be due to utilization by plants.

Chlorophyll *a* concentrations in the Anacostia River are presented in Figure 9. Data are plotted by river mile as yearly means and as spring and summer means for 1985. During the spring and summer, chlorophyll concentrations averaged about 40 µg/liter from Benning Road (river mile 97.50) to the South Capitol Street Bridge (river mile 94.25). Values fell below 30 µg/liter at the District line and at the Potomac River confluence. Yearly averages, although lower, followed the same pattern. These levels of chlorophyll suggest the presence of a moderately dense phytoplankton population in the tidal Anacostia. Although nutrient levels in the river can support higher plankton densities, factors such as low water clarity probably limit population size.

To assess a possible yearly trend in water clarity, Secchi depth measurements for the last five years from the District line (river mile 99.25) were compared with similar readings from the Pennsylvania Avenue Bridge (river mile 96.00) (Table 1). Secchi depth values were noticeably low in both locations, possibly because of upstream erosion, downstream runoff, and sediment

Table 1. Secchi depth measurements by quarter for 1981-1985 at the District of Columbia line and at the Pennsylvania Avenue Bridge.

	1981				1982				1983				1984				1985			
Location	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
D.C. Line	.1	.2	.1	.1	.1	.3	--	--	.2	.2	.2	.3	.2	.2	.2	.3	.3	--	.3	.3
Penn. Ave. Bridge	.3	.1	.1	.1	.1	.3	--	--	.2	.1	.2	.3	.2	.1	.2	.3	.3	.2	.3	.4

resuspension. A review of the data reveals that Secchi depth has increased slightly over the years at both locations.

The concentrations of DO at the District line and the Pennsylvania Avenue Bridge for the last five years are compared in Figure 10. Although DO has been higher upstream over the years, values for the two stations failed to reveal any temporal trend during this period.

Bacterial contamination is a common water-quality problem in urban streams. High levels of fecal coliform organisms indicate the presence of more harmful bacteria and other pathogens. Because of potential public health hazards and the frequency of CSO discharges to the Anacostia, data collected since 1969 are reviewed. The geometric mean of monthly data calculated as quarterly means is presented in Table 2.

Fecal coliform values at both stations were high and frequently exceeded 1000 MPN (most probable number)/ml, the District standard for secondary-contact recreation. However, the frequency of violation has decreased in recent years. This improvement is more obvious at the District line than at the Pennsylvania Avenue Bridge. Although high bacteria levels along the District portion of the Anacostia show the effects of CSO discharges, the presence of high numbers at the District line (upstream of the District's CSOs) indicates a contribution to the problem from upstream sources.

In 1984 the District of Columbia and the State of Maryland signed the "Anacostia Watershed Restoration Strategy Agreement". This agreement calls for the cleanup of the Anacostia River through CSO abatement measures within the District and implementation of soil erosion control measures in the Anacostia watershed. Some of these projects have already begun. It is hoped that these measures will lead to water-quality improvements similar to those observed in the Potomac River in recent years.

CLEANUP EFFORTS

To alleviate the water pollution problems caused by CSOs, the District of Columbia has initiated a two-phase CSO abatement program that, after completion around the year 2000, is anticipated to reduce the frequency of CSOs by 33%. Phase I, begun in 1984 and expected to be completed by 1990, consists of the construction of a swirl concentrator facility near RFK Stadium, the installation of inflatable barriers at certain CSO outlets, the modification of selected overflow points to increase weir height, and the separation of combined sewers in the region adjacent to Rock Creek near the National Zoo. Water quality benefits derived from Phase I improvements will be evaluated before Phase II is implemented.

Living Resources

The monitoring program annually collects and analyzes fish tissue for the presence of priority pollutants and heavy metals. The highest priority of

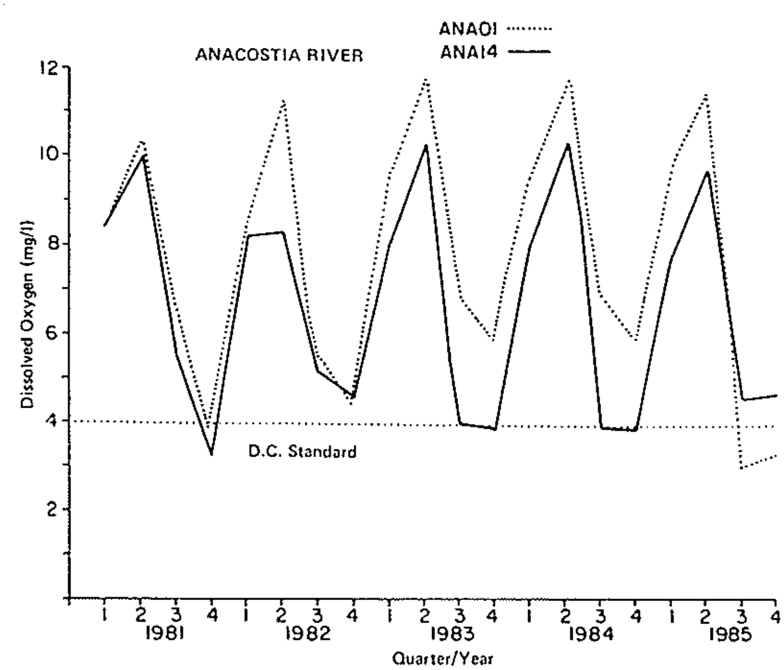

Figure 10. Quarterly average concentrations of dissolved oxygen in the Anacostia River at the District of Columbia/Maryland line (ANA01) and at the Pennsylvania Avenue Bridge (ANA14).

the fish-tissue analysis program has always been the protection of public health through its emphasis on fish edibility. In keeping with this focus, fish species have been chosen to reflect culinary preferences. Fish targeted include bottom feeders such as channel catfish or carp; predators such as pumpkinseed, white perch, or small/large-mouth bass; and semianadromous fish such as herring. Each sample consists of at least five whole fish of the same species caught at the same location.

Although any absolute statements of trend relating to tissue content are by necessity limited by the analytical and sample collection methodologies employed, a few obvious long-term trends are apparent. Table 3 compares 1980 and 1985 fish tissue data for whole catfish collected in the Potomac and

Table 2. Quarterly mean fecal coliform levels (most probable number, mpn) on the Anacostia River at the District of Columbia line and at the Pennsylvania Avenue Bridge.

Year	Quarter	D.C. Line	Penn. Ave.	Year	Quarter	D.C. Line	Penn. Ave.
1968	1	-	-	1977	1	1,300	170
	2	-	-		2	1,700	4,100
	3	6,900	170,000		3	5,700	5,800
	4	1,000	4,600		4	3,000	6,100
1969	1	1,900	1,800	1978	1	4,700	2,700
	2	2,600	1,900		2	270	550
	3	24,000	4,500		3	2,900	2,600
	4	3,300	1,700		4	850	2,200
1970	1	5,800	2,300	1979	1	11,000*	4,500*
	2	15,000	3,700		2	370*	240*
	3	6,700	4,100		3	2,500	8,000
	4	2,500	1,000		4	5,100*	4,800*
1971	1	11,000	9,300	1980	1		170*
	2	2,500	1,000		2	930*	350*
	3	5,500	12,000		3	1,900*	1,100*
	4	5,600	4,300		4	990*	7,900*
1972	1	3,600	4,000	1981	1	160*	130*
	2	1,900	1,500		2	66	220
	3	73,000	8,200		3	3,500	8,000
	4	730	2,800		4	810	1,500
1973	1	5,300	4,000	1982	1	1,600*	180*
	2	1,100	8,400		2	-	-
	3	7,100	6,200		3	-	-
	4	7,300	7,500		4	-	-
1974	1	5,400	13,000	1983	1	1,900	140,000*
	2	7,200	7,100		2	-	-
	3	12,000	7,100		3	160*	3,300*
	4	2,600	1,400		4	520	4,900
1975	1	6,900	11,000	1984	1	960*	21,000
	2	1,500	1,600		2	3,200	-
	3	1,400	1,100		3	960*	-
	4	5,600	9,000		4	2,800*	-
1976	1	7,200	22,000	1985	1	4,900*	35,000*
	2	780	700		2	-	-
	3	1,500	1,100		3	558	2,084
	4	1,400	2,000		4	442	1,914

NOTE. Quarters: 1 = December (preceding year), January, February; 2 = March, April, May; 3 = June, July, August; 4 = September, October, November.

*Quarterly means calculated from fewer than three data points.

Anacostia Rivers. These data suggest a general reduction in detectable tissue contaminants from 1980 to 1985, with the exception of PCBs and the heavy metals lead and mercury. All contaminant levels are below action levels of the Food and Drug Administration.

Besides ambient monitoring activities, the District funds regional research institutions for water quality projects of special interest. One project recently completed by the University of the District of Columbia was a 1984 summer survey of mollusc populations of the Potomac and Anacostia River in the District. Eleven species of molluscs were identified, including 6 clam, 4 snail and 1 mussel species. No molluscs were found in the upper Anacostia River. This report included a more detailed study of the population distribution of the asiatic clam *Corbicula fluminea*, an introduced species in the Potomac River.

The District has been surveying its waters for submerged aquatic vegetation (SAV) since 1984 because of the recent reappearance of these plants in the Potomac River and other tributaries. These surveys indicate the presence of *Hydrilla verticillata* in District waters. Distribution of *Hydrilla* has been patchy, occurring mainly in the shallow southern portions of the Potomac River. *Hydrilla* appears to be spreading. Along the eastern bank, *Hydrilla* bed size has increased over the past two years and now extends to just north of Oxon Cove. During June and July 1986, healthy beds of Eurasian watermilfoil (*Myriophyllum spicatum*) were observed interspersed

Table 3. Levels of contaminants (parts per million) in tissues from whole catfish collected in the Potomac and Anacostia Rivers in 1980 and 1985.

	Potomac River			Anacostia River		
Tissue contaminant	1980	1985	Change	1980	1985	Change
Aldrin	0.0	0.0	none	0.0	0.0	none
Alpha BHC	0.0	0.0	none	0.02	0.0	decrease
Alpha endosulfan	---	0.0	---	---	0.0	---
Beta BHC	---	0.0	---	---	0.0	---
Beta endosulfan	---	0.0	---	---	0.0	---
Chlordane	0.0	0.0	none	0.0	0.0	none
4,4'DDD	0.18	0.0	decrease	0.30	0.0	decrease
4,4'DDE	0.07	0.0	decrease	0.27	0.0	decrease
4,4'DDT	0.28	0.0	decrease	0.43	0.0	decrease
Delta BHC	---	0.0	---	---	0.0	---
Dieldrin	0.0	0.0	none	0.0	0.0	none
Endosulfan sulfate	---	0.0	---	---	0.0	---
Endrin	0.0	0.0	none	0.07	0.0	decrease
Endrin aldehyde	---	0.0	---	---	0.0	---
Gamma BHC	0.01	0.0	none	0.01	0.0	decrease
Heptachlor	---	0.0	---	---	0.0	---
Heptachlor epoxide	0.03	0.0	decrease	0.03	0.0	decrease
Hexachlorobenzene	0.0	---	---	0.0	---	---
Methoxychlor	0.0	---	---	0.0	---	---
Toxaphene	---	0.0	---	---	0.0	---
PCBs	0.0	1.54	increase	0.0	0.07	increase
(Metals)						
Arsenic	0.0	0.0	none	0.0	0.0	none
Cadmium	0.0	0.0	none	0.01	0.0	decrease
Chromium	1.75	0.0	decrease	2.4	1.9	decrease
Copper	0.75	0.0	decrease	2.3	3.3	increase
Lead	0.17	0.45	increase	0.38	2.0	increase
Mercury	0.004	0.8	---	0.0	0.2	increase
Selenium	---	0.0	---	---	0.0	---
Zinc	---	45.0	---	---	87.1	---

with *Hydrilla* just below the Woodrow Wilson Bridge; however, by August *Hydrilla* predominated in this area.

The District also has a historical bed of wild celery (*Vallisneria americana*) in the Washington Ship Channel. Other species of SAV observed included *Ceratophyllum*, *Zannichellia*, and *Heteranthera*. No quantitative area estimates have been made of SAV coverage in the District. The return of SAV indicates improved water quality, and its presence is viewed as beneficial to aquatic life.

Assessment of Nutrient Sources from the Mainstem and Selected Watersheds in the Susquehanna River Basin, October 1984 through September 1985

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Susquehanna River Basin Commission
Harrisburg, Pennsylvania

The Susquehanna River Basin Commission began a five-year study in October 1984, in cooperation with the Pennsylvania Department of Environmental Resources (PA DER) and the U. S. Geological Survey (USGS). The study was designed to provide data on nutrient and sediment loading for the mainstem Susquehanna River and its major tributaries in the central and lower basin, and data on nutrient and sediment runoff from small watersheds representing each of the land uses prevalent in these areas of the basin. Except for Pequea Creek, these data have not previously been collected for tributaries to the mainstem Susquehanna.

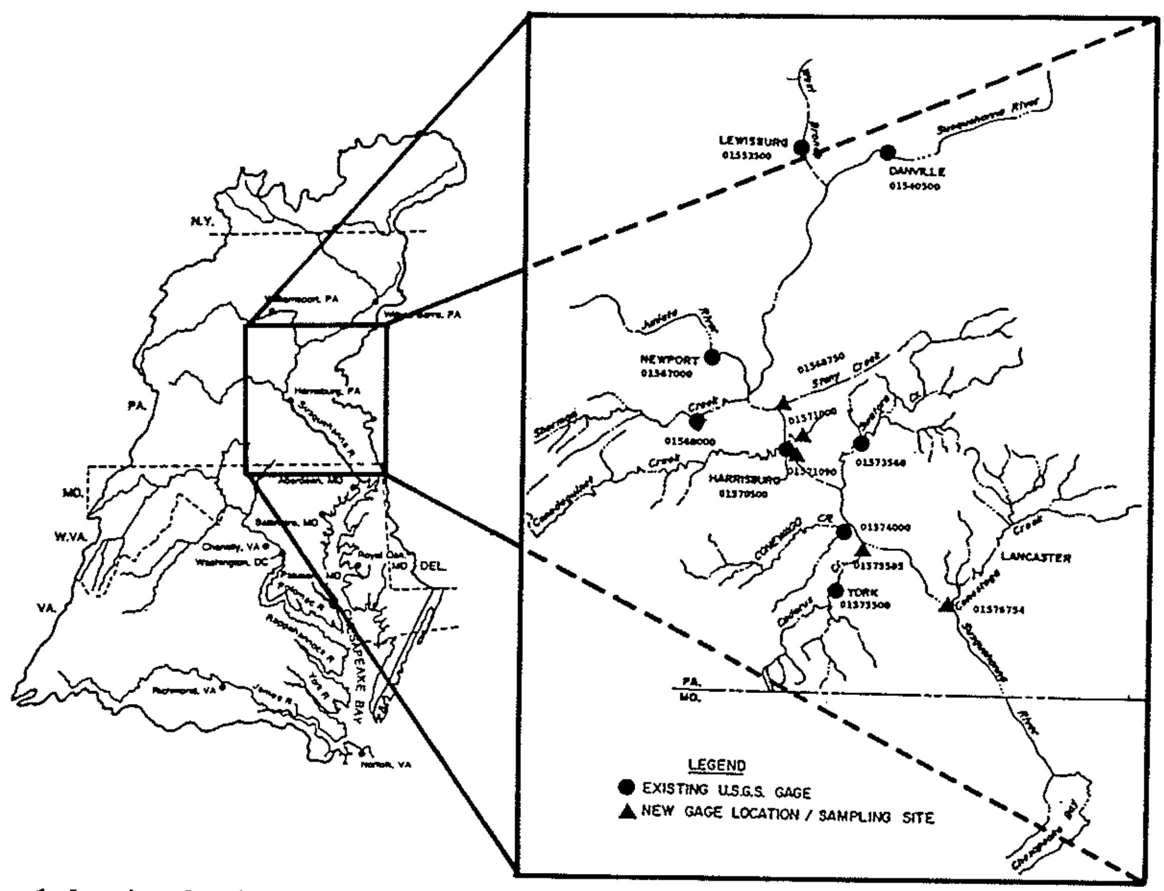

Figure 1. Location of nutrient monitoring stations in the Susquehanna River Basin.

Table 1. Nutrient and sediment loading after hurricane Gloria in the Conestoga River, with a discharge rate of 2,772 cfs, and Codorus Creek, with a discharge rate of 1,240 cfs.

	Concentration (mg/liter)			Loads (tons/day)		
Location	TN	TP	SS	TN	TP	SS
Conestoga	10.29	2.06	1,236	77.1	15.4	9,255
Codorus	3.81	0.89	565	12.77	3.01	1,892

NOTE: TN= total nitrates and nitrites; TP= total phosphorus; SS= suspended sediment.

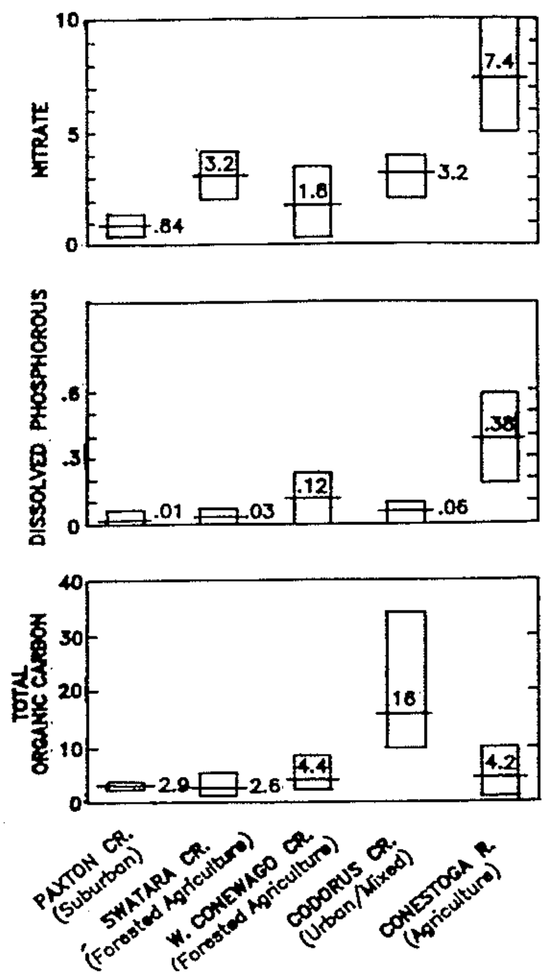

Figure 2. Baseflow concentration ranges.

Nutrient and sediment loading is being documented on a seasonal and individual storm basis at seven gaged river and stream sites ranging from Danville on the Susquehanna River to the lower reaches of the Conestoga River. Nutrient runoff data are being collected from selected watersheds representative of specific land use that will enable refinement of the Chesapeake Bay Program's (CBP) nonpoint source model. The four watersheds selected for this purpose are Paxton, Stoney, Sherman, and Codorus Creeks (Figure 1).

Objectives of the study are (1) to provide data for refinement of the CBP watershed model; (2) to determine the relative contribution of nutrients and suspended sediment from individual tributaries representing various land uses in the lower Susquehanna River basin; (3) to determine the seasonal variation in nutrient and suspended-sediment discharges; and (4) to determine the distribution of nutrient discharges between dissolved and particulate phases during storm runoff and baseflow.

METHODS

Baseflow is sampled monthly as necessary to supplement ongoing monitoring by PA DER and USGS. Five major storm events are to be sampled during the rising and falling stream stages (six samples per storm). Field and laboratory determination are made for the following physical characteristics and constituents at most of the monitoring sites: water temperature, specific conductance, suspended sediment, total organic carbon, total nitrite and nitrate, total and dissolved ammonia, total and dissolved Kjeldahl nitrogen, total and dissolved phosphorus, and dissolved orthophosphate.

All water quality data collected are stored in the U.S. Environmental Protection Agency STORET and the Chesapeake Bay Program data base (CHESSEE).

DISCUSSION

Comparison of baseflow nutrient concentrations from selected tributary stream stations (Figure 2) shows that nutrient concentrations are highest from the agricultural watersheds, with the greatest nutrient concentrations from the Conestoga River. Codorus Creek also has a high concentration of organic carbon, from a large paper manufacturing plant in the watershed. Codorus Creek watershed is representative of a mixed land use with a large urban and suburban population.

Because storms were infrequent during the study period, only one major storm was sampled. Storm-flow nutrient data from a 15-hour rainfall generated by hurricane Gloria are shown in Table 1 for the Conestoga River and lower Codorus Creek monitoring sites. The other monitoring stations received relatively little rainfall. The Conestoga River watershed received about 6 inches of rainfall spread fairly uniformly over the watershed. The Codorus Creek watershed received up to 8 inches on the eastern side, but less than 2 inches on the western side. After the data were normalized on a square-mile basis and adjusted for the difference in rainfall, there was about three times more nutrient loading from the Conestoga River than Codorus Creek, a difference reflecting the intense agricultural land use and animal population in the Conestoga River watershed.

A comparison of nutrient concentrations for these tributaries over a storm hydrograph is shown in Figure 3. Concentrations for total nitrite plus nitrate were immediately depressed with storm runoff and did not increase until after the storm. Total phosphorus immediately increased with increased sediment discharge, while the dissolved phosphorus remained relatively unchanged.

Nutrient concentrations at the mainstem Susquehanna River monitoring sites at Harrisburg and Conowingo Dam (Maryland) are compared in Figure 4.

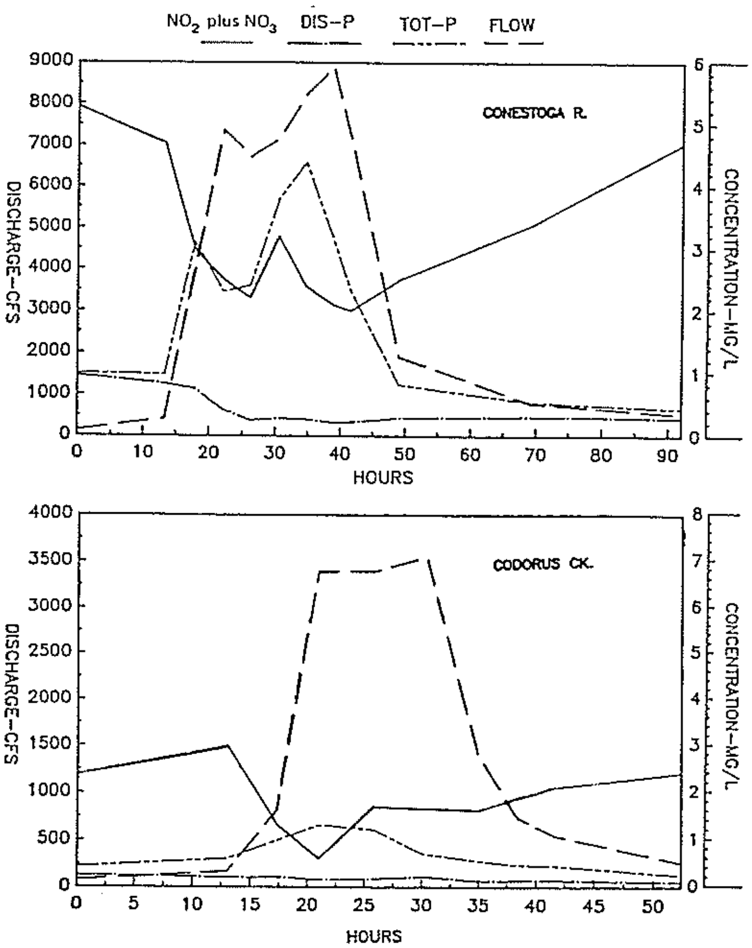

Figure 3. Nutrient concentrations over the hurricane Gloria stormflow hydrograph, September 26-29, 1985.

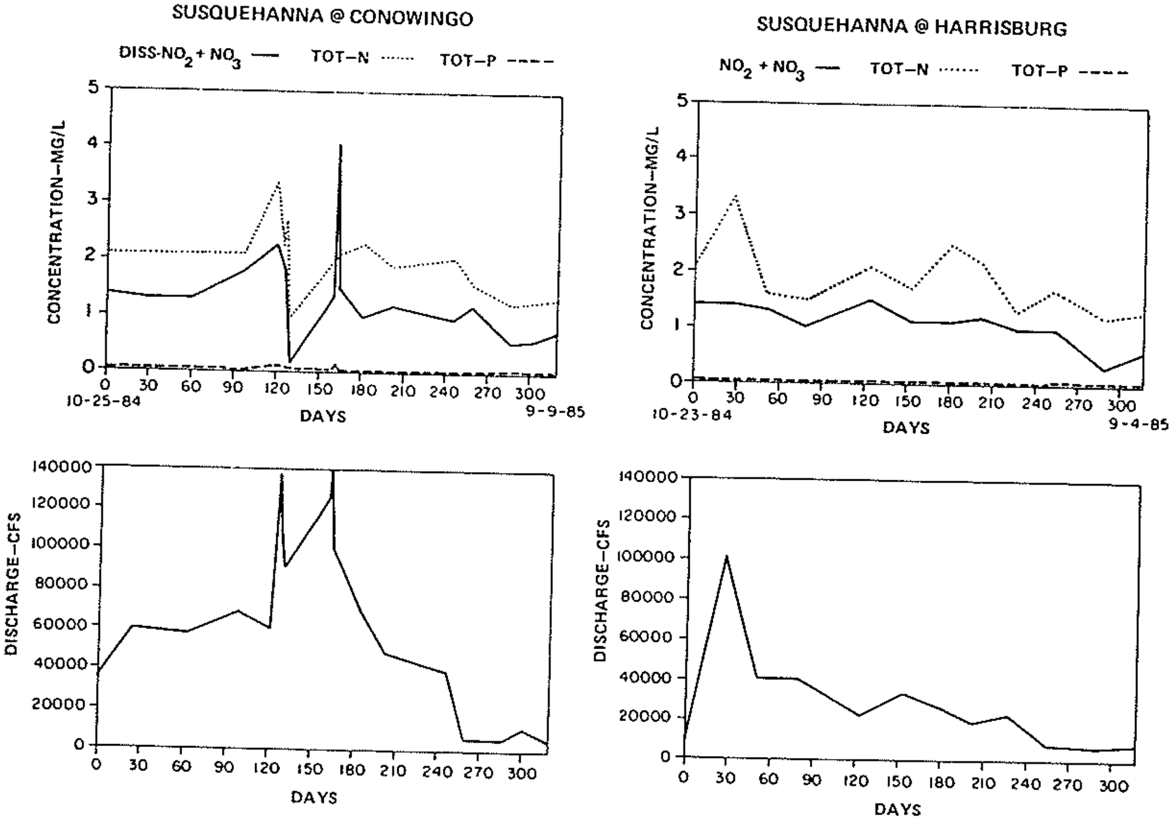

Figure 4. Flow hydrograph and nutrient concentrations for the Susquehanna River at Harrisburg and Conowingo Dam, October 1984 to September 1985.

The graph shows nearly equivalent total nitrogen and phosphorus concentrations and increased concentrations of dissolved nitrite plus nitrate between Harrisburg and the downstream Conowingo Dam station. This finding is supported by those of Lang (1982) and is attributed to nutrient contributions from the predominantly agricultural watersheds downstream of Harrisburg.

CONCLUSIONS

The Conestoga River drainage basin contributes more nutrients to the Susquehanna River than do other equivalent-sized watersheds, because of the intense agricultural use of the watershed. The concentration of nitrogen species during storm-flow is inverse to flow in Conestoga River and Codorus Creek watersheds. This pattern is due to the significant nitrite and nitrate contribution from the groundwater component.

LITERATURE CITED

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Chesapeake Bay Circulation Survey

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In August 1981 the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) began a 30-month circulation survey of the Chesapeake Bay from its entrance to the Susquehanna River, through the Chesapeake and Delaware Canal and into the Delaware River (Browne and Fisher 1986). A circulation survey of an estuary involves the measurement of parameters that describe or cause the water movement within the estuary. The data collected include tides, currents, water conductivity, water temperature, and meteorological parameters.

The Chesapeake Bay circulation survey was divided into three phases representing the three years of operations. All phases of the program involved only the Bay proper; none of the tributaries were surveyed. Phase 1 of the survey was conducted during August to December 1981 between a line from Cedar Point to the Nanticoke River on the north, and a line between Smith Point and Pocomoke Sound on the south. Phase 2 was conducted from April to December 1982 in the area from the entrance of the Chesapeake Bay northward to the Smith Point-Pocomoke Sound border. Phase 3, conducted from April to December 1983, covered the area from the Cedar Point-Nanticoke River entrance boundary to the northern extent of the Bay including Port Deposit and the Chesapeake and Delaware (C & D) Canal.

In addition to the field effort conducted from the NOAA vessel Ferrel, four long-term current meter stations were occupied continuously, even through the winter months. Station 40 in the entrance to the Bay was deployed in September 1981; station 65 in the Wolf Trap area in December 1981; station 36 in the mid-Bay off the mouth of the Patuxent River, in September 1981; and station 121 in the trench off Kent Island, in November 1982. In the winter and when the Ferrel was unavailable, these stations were maintained by cooperative efforts with the Atlantic Marine Center, NOS, and Old Dominion University for station 40; with the Virginia Institute of Marine Science for station 65; and with the Maryland Department of Natural Resources for stations 36 and 121 (Figure 1).

During the project, current meter data and data on conductivity, temperature, and depth (CTD) were collected at 132 locations (Figures 1-5). Tide data were collected at nine control stations and 36 subordinate stations (Figures 6-9). Meteorological data were collected at two locations during each season (Figures 6-8). The final Chesapeake Bay data set consists of 685 current data files, 31 meteorological data files, 844 CTD data files, and tide data from 45 locations in the Bay.

The NOS Delaware River and Bay circulation survey in 1984 and 1985 reoccupied two current stations and two tide stations in the C&D Canal, as

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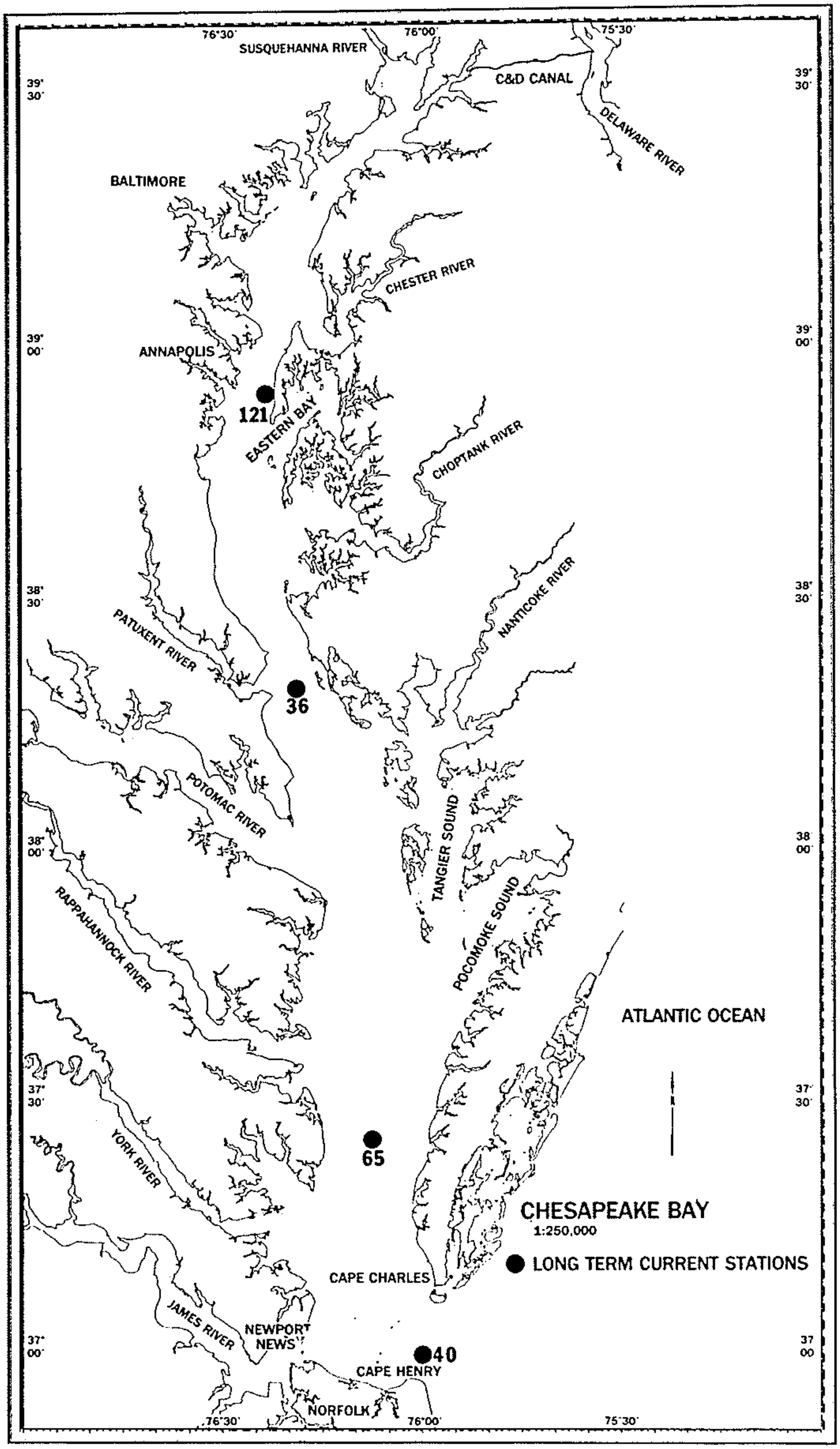
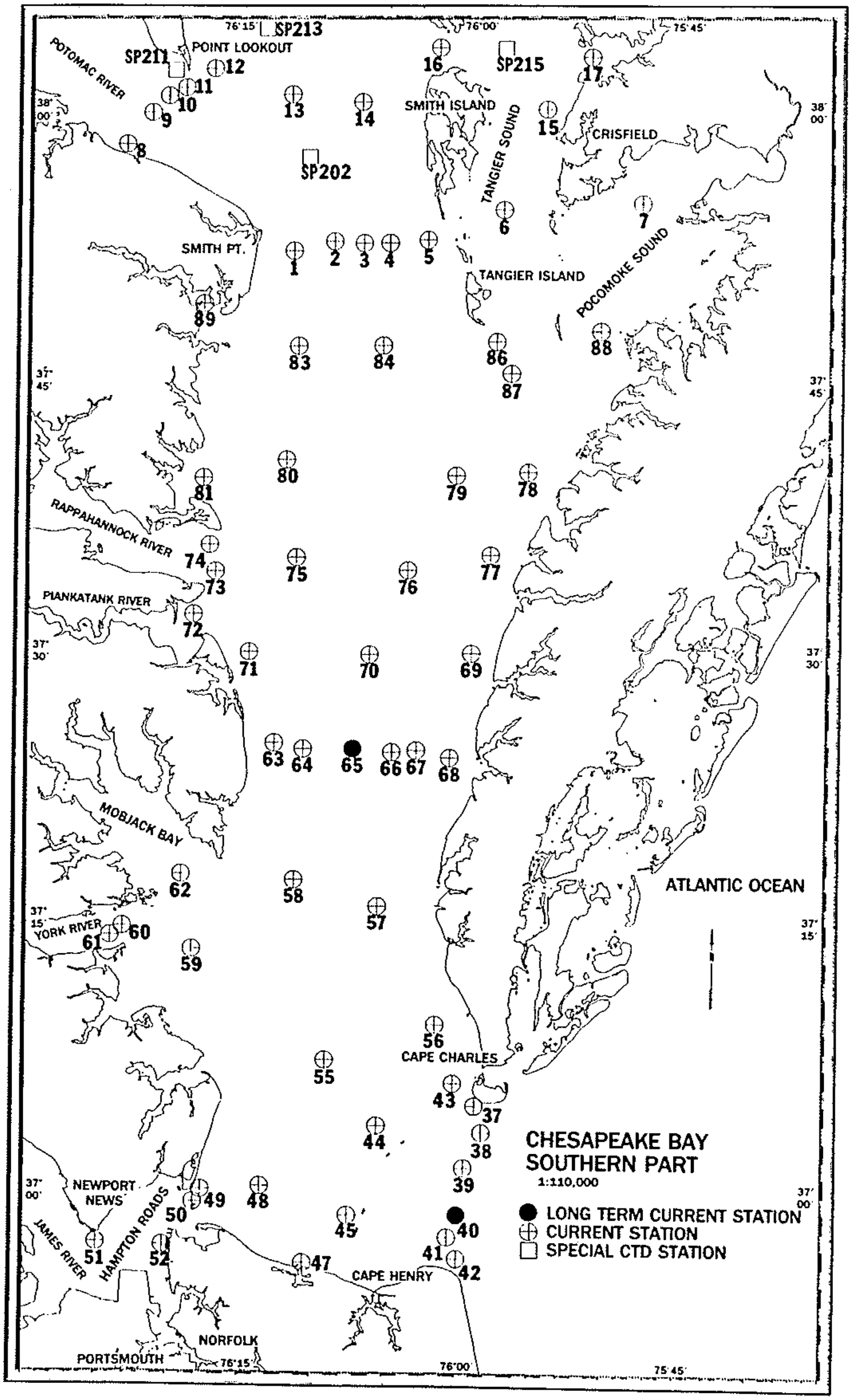
Figure 1 (overleaf). Long-term current stations deployed throughout a circulation study of the Chesapeake Bay.

Figure 2 (over, facing page). Current stations deployed in phase 2 of a circulation study of the Chesapeake Bay.


76°30'
76°00'
75°30'
SUSQUEHANNA RIVER
C&D CANAL
DELAWARE RIVER
39° 30'
BALTIMORE
CHESTER RIVER
39° 00'
ANNAPOLIS
121
EASTERN BAY
CHOPTANK RIVER
NANTICOKE RIVER
38° 30'
PATUXENT RIVER
36
POTOMAC RIVER
TANGIER SOUND
38° 00'
RAPPAHANNOCK RIVER
POCOMOKE SOUND
ATLANTIC OCEAN
37° 30'
YORK RIVER
65
CHESAPEAKE BAY
1:250,000
LONG TERM CURRENT STATIONS
CAPE CHARLES
JAMES RIVER
NEWPORT NEWS
40
CAPE HENRY
37° 00'
NORFOLK



76°15'
SP213
76°00'
75°45'
POTOMAC RIVER
SP211
POINT LOOKOUT
12
11
10
9
8
38° 00'
13
14
16
SP215
17
SMITH ISLAND
TANGIER SOUND
15
CRISFIELD
SP202
6
7
SMITH PT.
1
2
3
4
5
TANGIER ISLAND
POCOMOKE SOUND
89
83
84
86
87
88
37° 45'
80
81
79
78
RAPPAHANNOCK RIVER
74
73
75
76
77
PIANKATANK RIVER
72
37° 30'
71
70
69
63
64
65
66
67
68
MOBJACK BAY
62
58
57
ATLANTIC OCEAN
37° 15'
YORK RIVER
61
60
59
56
CAPE CHARLES
55
43
37
44
38
CHESAPEAKE BAY
SOUTHERN PART
1:110,000
39
37° 00'
NEWPORT NEWS
49
48
50
HAMPTON ROADS
JAMES RIVER
45
40
LONG TERM CURRENT STATION
CURRENT STATION
SPECIAL CTD STATION
51
52
47
41
42
CAPE HENRY
NORFOLK
PORTSMOUTH

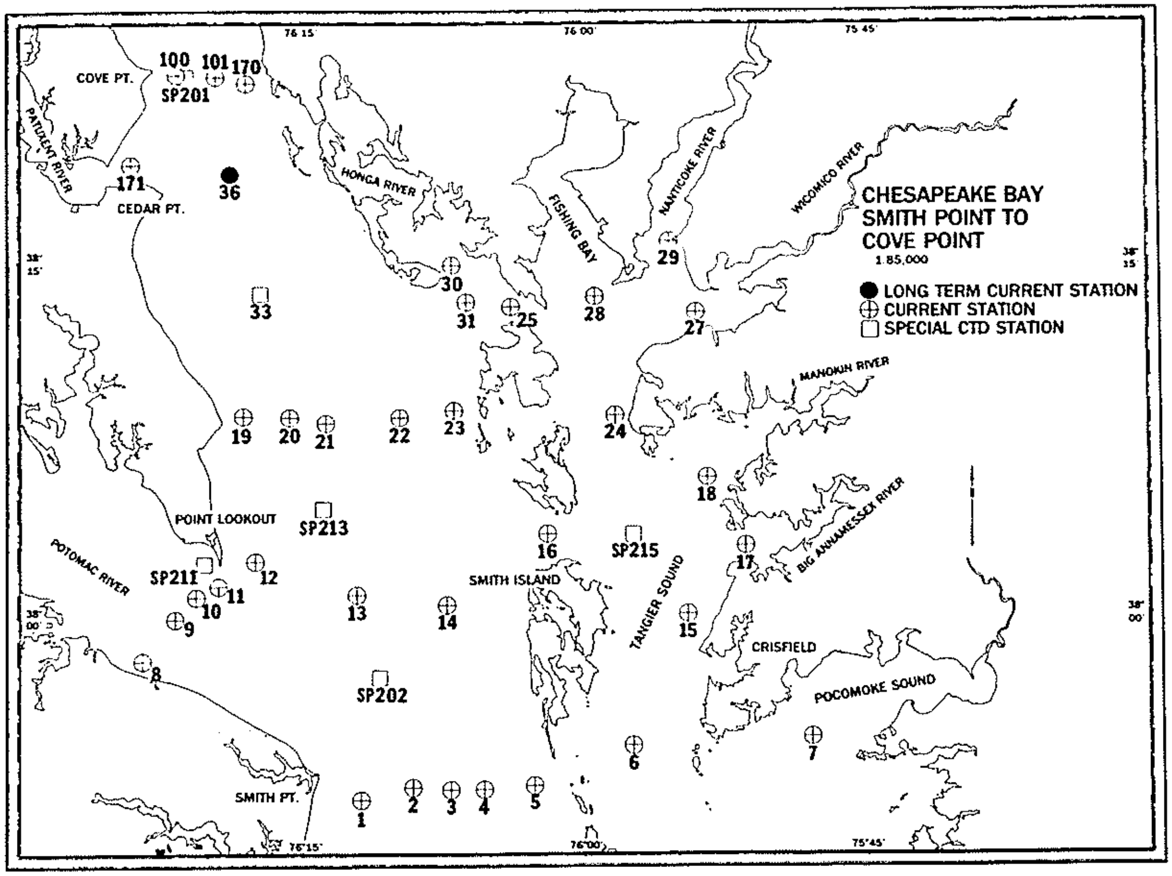


Figure 3. Current stations deployed in phase 1 of a circulation study of the Chesapeake Bay.

well as two current stations in the Elk River (Klavans et al. 1986).

CURRENT DATA

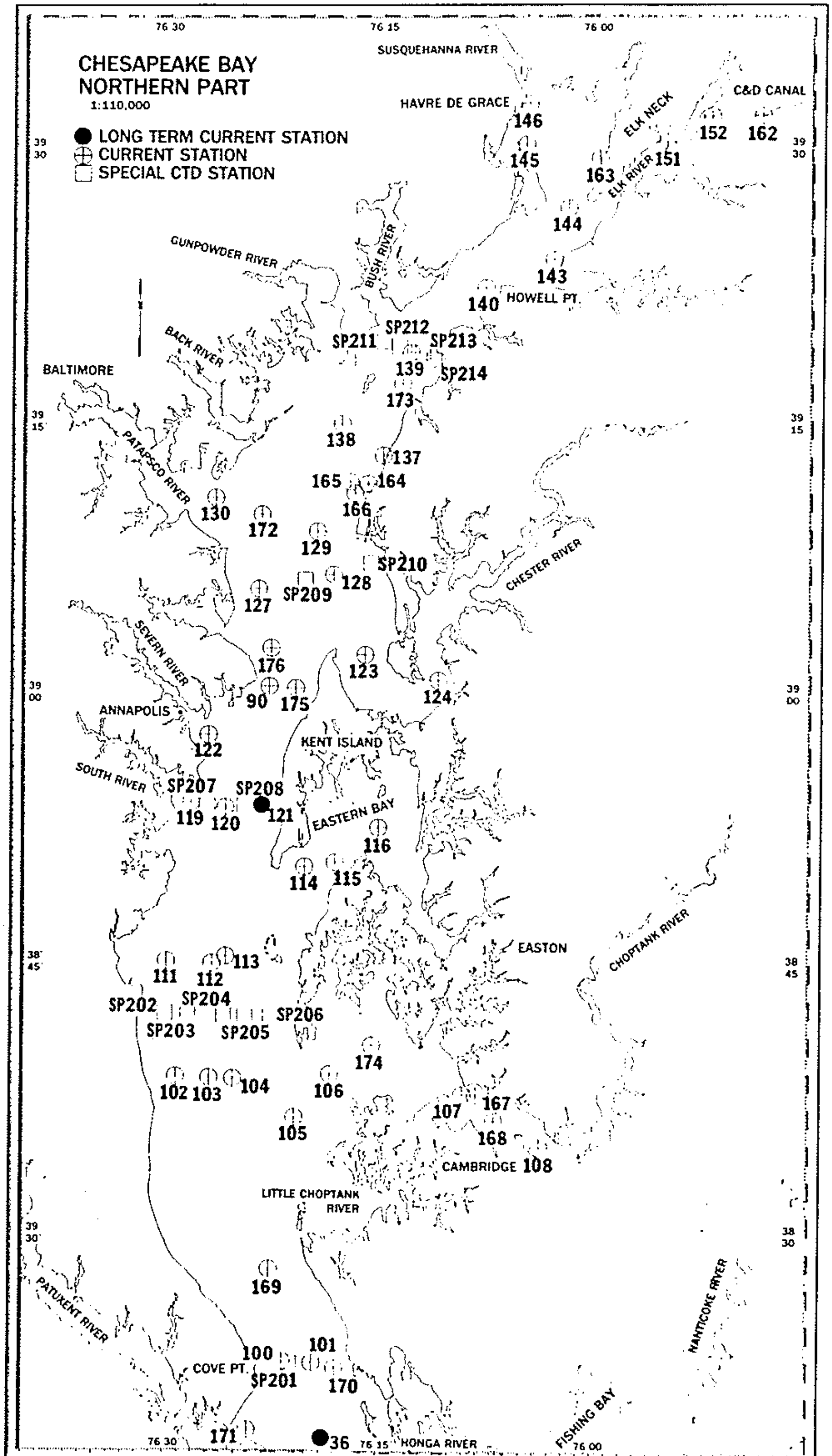
The current meters used were Grundy model 9021-C current meters, which recorded on a 3-inch diameter, 1/4-inch wide magnetic tape in 10-bit binary code. The meter serial number, current direction, current speed, temperature, sample count or time in hours and minutes, conductivity, and (for some meters) pressure were recorded. The instrument was rated for 2,000-meter depth service.

The surface meter was 15 feet (4.6 meters) below mean low water, and the bottom meter was generally 5 feet (1.5 meters) above the bottom.

The processed data were sent to the National Oceanographic Data Center for archival and dissemination. Analysis results will appear in the 1988 edition of the *Tidal Current Tables, Atlantic Coast of North America*, from which current predictions will be obtainable for these current station locations. The results of other analyses of these data will be published in a technical report by mid-1987.

The locations of current stations deployed in all three phases of the Chesapeake Bay survey are shown in Figures 2-6. Long-term current stations deployed throughout the survey are depicted in Figure 1. Phase 1 current station locations are depicted in Figure 3. Phase 2 current station locations are depicted in Figure 2. Phase 3 current station locations are depicted in Figures 4 and 5. Scheduling for all phases of the survey was based on the desire for

Figure 4 (facing page). Current stations deployed in the northern part of the Chesapeake Bay during phase 3 of a circulation study.



CHESAPEAKE BAY
NORTHERN PART
1:110,000
LONG TERM CURRENT STATION
CURRENT STATION
SPECIAL CTD STATION
SUSQUEHANNA RIVER
HAVRE DE GRACE
C&D CANAL
ELK NECK
ELK RIVER
GUNPOWDER RIVER
BUSH RIVER
HOWELL PT.
BACK RIVER
BALTIMORE
PATAPSCO RIVER
CHESTER RIVER
SEVERN RIVER
ANNAPOLIS
KENT ISLAND
SOUTH RIVER
EASTERN BAY
EASTON
CHOPTANK RIVER
CAMBRIDGE
LITTLE CHOPTANK RIVER
PATUXENT RIVER
COVE PT.
NANTICOKE RIVER
FISHING BAY
HONGA RIVER

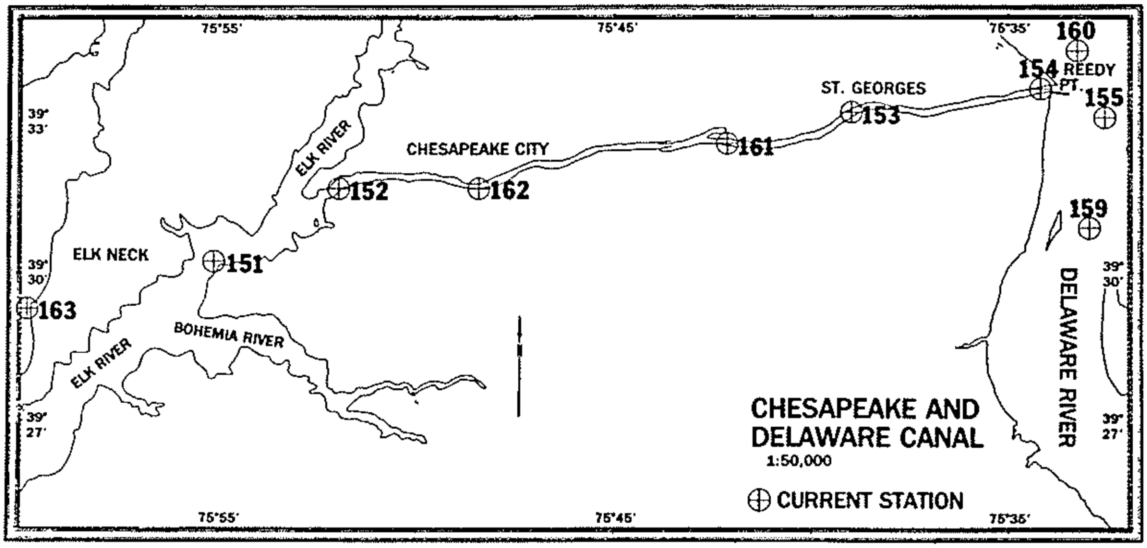


Figure 5. Current stations deployed in the Chesapeake and Delaware Canal during phase 3 of a circulation study.

simultaneous observations within the constraints of field logistics.

CONDUCTIVITY AND TEMPERATURE DATA

The Grundy 9400 CTD profiling system was used for long-period (13-hour time series) observations at a few single station sites, for observations at stations forming a linear transect, and for single casts at current meter station sites. The sampling rate was once every 10 minutes, the same as that for current speed and current direction. CTD casts were taken twice at all current stations, once during slack before flood, and once during slack before ebb during current station deployment or recovery operations. CTD transects were conducted to follow the progression of the tidal wave so that the water density structure of the survey area at the two extremes of the tide could be examined.

METEOROLOGICAL DATA

Sensors of wind speed and direction were mounted at 7-13 meters above the water surface, temperature sensors on mast arms below that, and the pressure sensor within the base housing.

Throughout the study period, all data loggers were set at a sampling rate of six observations per hour. The time-series data sets included time-averaged wind speed and instantaneous readings of wind direction, air temperature, barometric pressure, and the maximum wind speed observed during the sampling period.

As described by Wang (1979), wind forcing has a significant effect on the overall circulation of the Chesapeake Bay: a strong wind speed at a prevailing direction can totally override tidal and density-induced circulation patterns in the Bay.

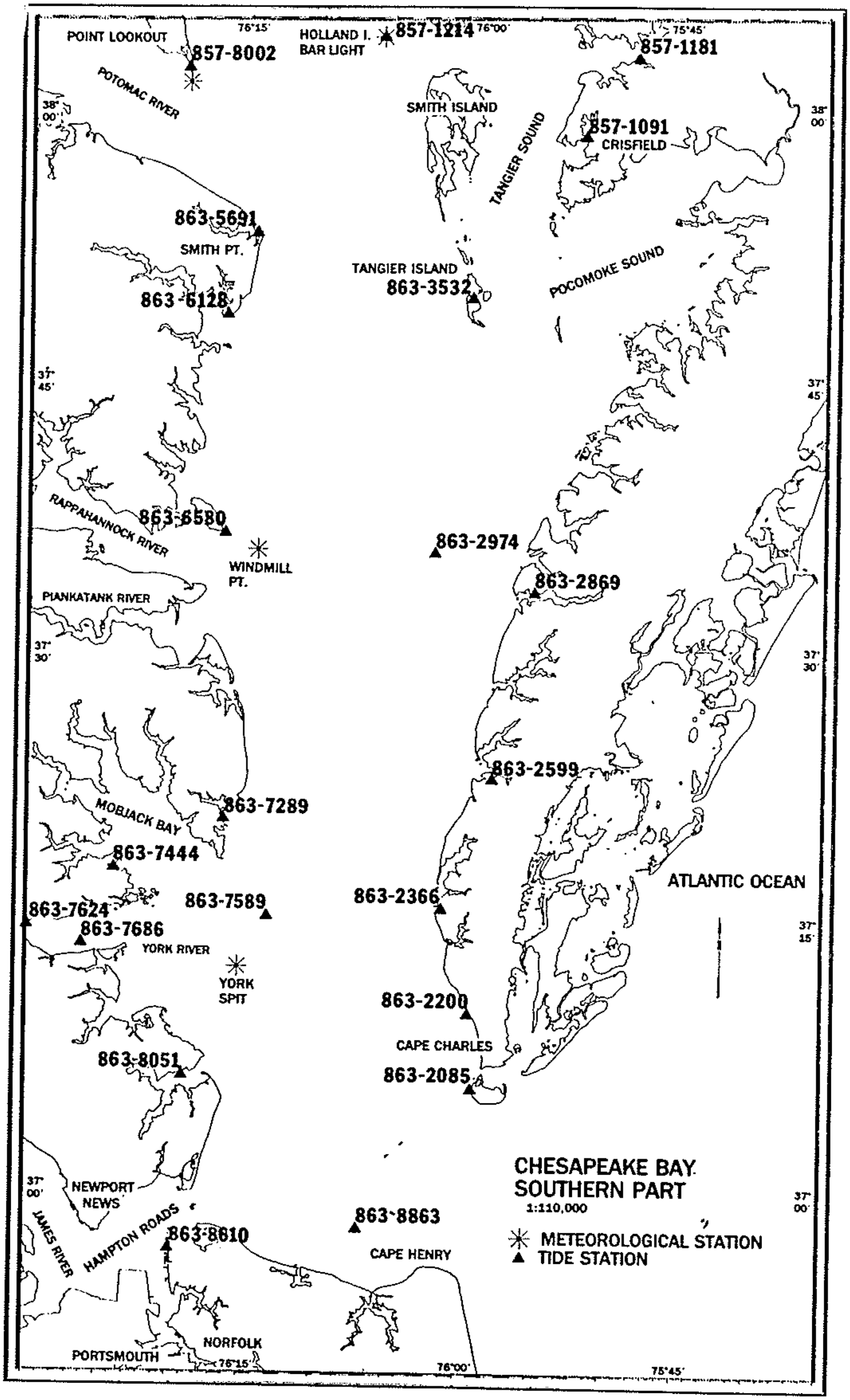
The need for high-quality wind data was considered sufficiently critical to justify having two Aanderaa meterological stations deployed during each phase of the survey. Station locations are indicated in Figures 6-8.

TIDE DATA

Two types of tide gages were used during the Chesapeake Bay circulation survey: an ADR (analog-digital-recorder) and a bubbler (gas-purged).

Processed monthly tabulations (high and low waters and tidal data) from each station are verified for staff-marigram relationship, and equivalent 19-year mean values are computed through simultaneous

Figure 6 (facing page). Locations of meteorological stations and tide gages deployed in the southern part of the Chesapeake Bay during a circulation study.


POINT LOOKOUT
857-8002
76°15'
HOLLAND I. BAR LIGHT
857-1214
76°00'
75°45'
857-1181
POTOMAC RIVER
38° 00'
SMITH ISLAND
TANGIER SOUND
857-1091
CRISFIELD
863-5691
SMITH PT.
TANGIER ISLAND
863-3532
POCOMOKE SOUND
863-6128
37° 45'
RAPPAHANNOCK RIVER
863-6580
WINDMILL PT.
863-2974
863-2869
PIANKATANK RIVER
37° 30'
863-2599
MOBJACK BAY
863-7289
863-7444
ATLANTIC OCEAN
863-7624
863-7589
863-2366
863-7686
YORK RIVER
37° 15'
YORK SPIT
863-2200
CAPE CHARLES
863-8051
863-2085
CHESAPEAKE BAY
SOUTHERN PART
1:110,000
METEOROLOGICAL STATION
TIDE STATION
37° 00'
NEWPORT NEWS
JAMES RIVER
HAMPTON ROADS
863-8610
863-8863
CAPE HENRY
NORFOLK
PORTSMOUTH
76°15'
76°00'
75°45'

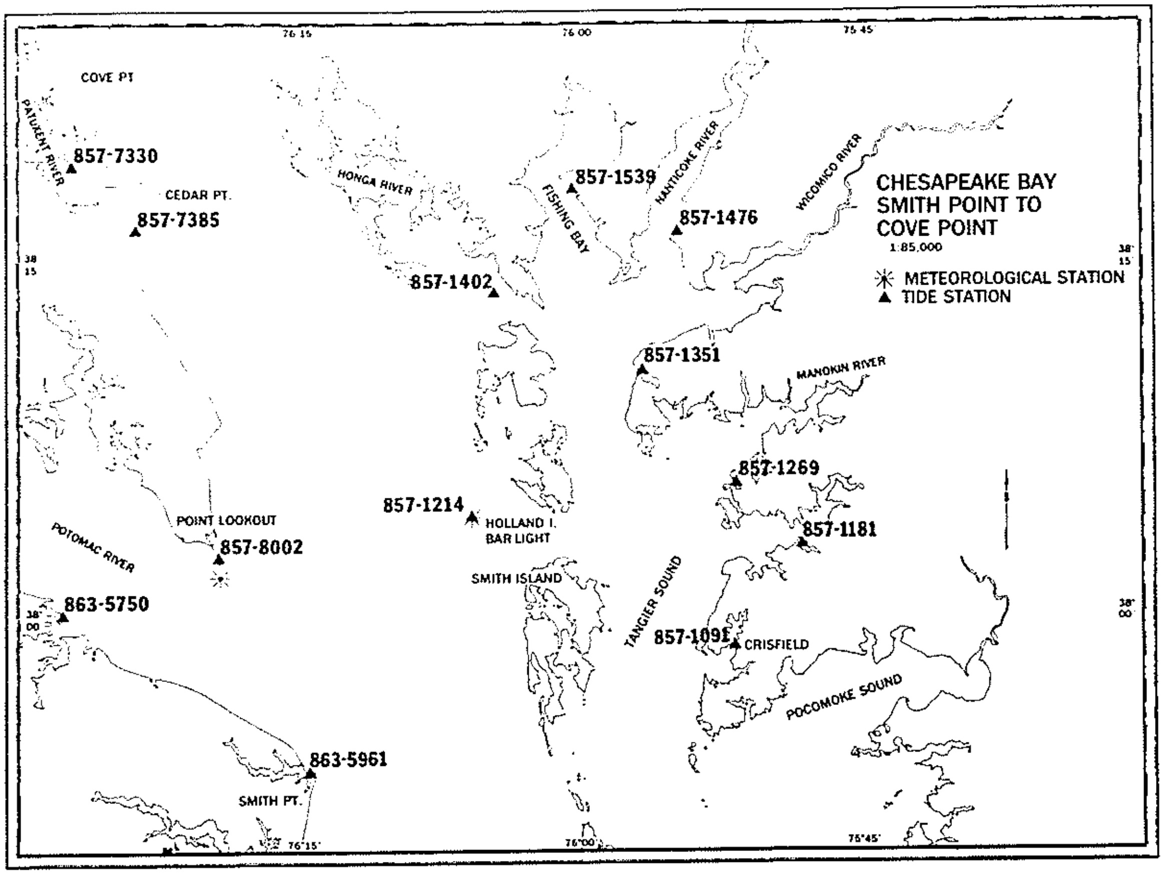


Figure 7. Locations of meteorological stations and tide gages deployed between Smith Point and Cove Point during a circulation study of the Chesapeake Bay.

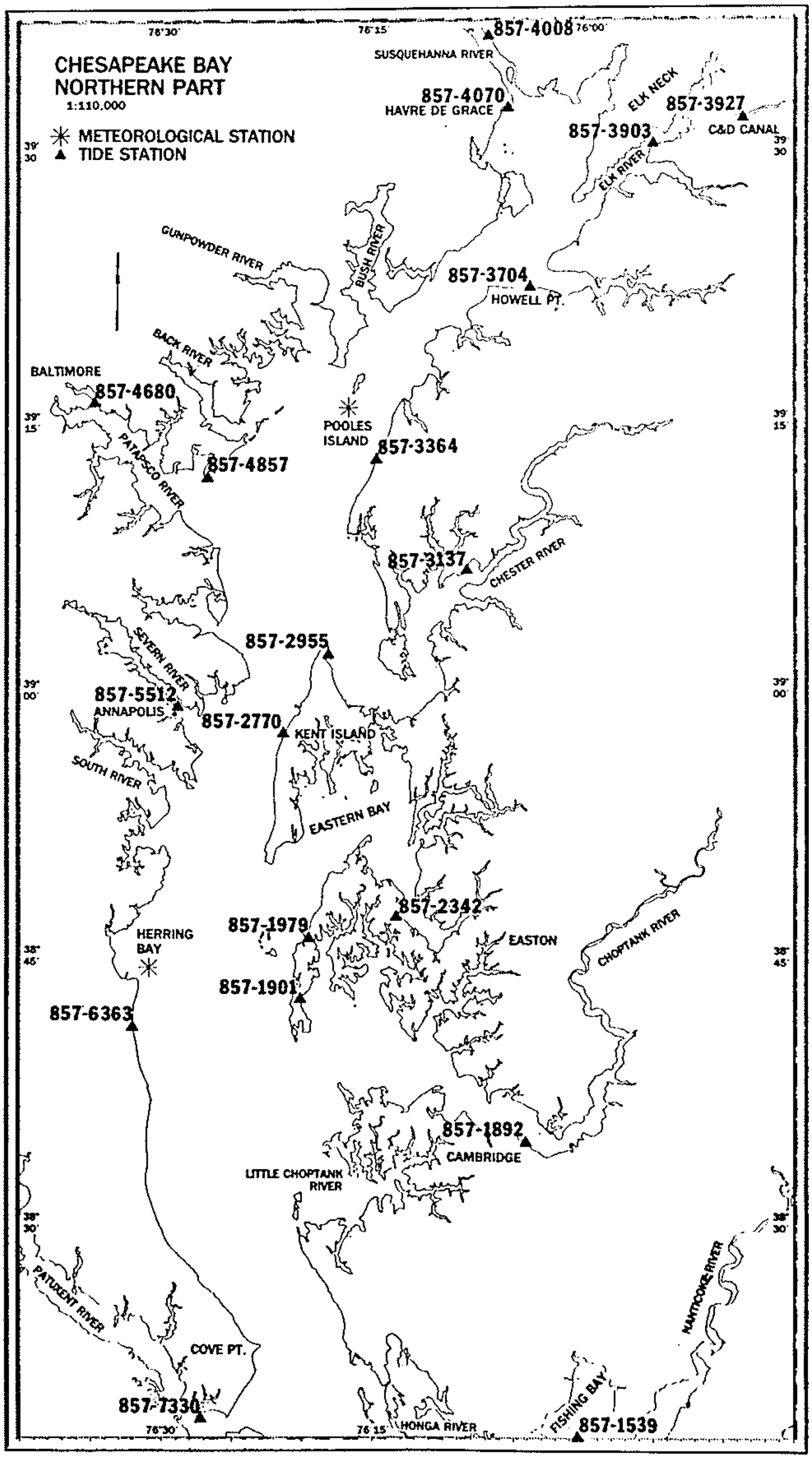
comparison with the appropriate tide control station. Tidal benchmark elevations are established by referencing these benchmarks to the computed tidal data. New elevations for historical benchmarks are used to check any vertical land movement that may have occurred. The relationships between tidal data and the National Geodetic Vertical Control Network are also computed when level connections can be made to geodetic benchmarks.

The locations of tide gages occupied during the Chesapeake Bay circulation survey are shown in Figures 6-9. All stations were occupied for at least 30 days and some were in place for a year or more. The shorter-period tide stations were usually installed simultaneously with nearby current stations.

HISTORICAL DATA

The NOS has collected current data in the Chesapeake Bay and its tributaries since the early 1900s. The early surveys were designed to fulfill specific requirements for relatively small areas. Not until the 1981-1983 survey was there a systematic survey of the entire Bay. Duration of observations for the early stations was generally one to five days. The instruments used were primarily current poles, Price current meters, and Roberts radio current meters. The resulting data records were processed and analyzed manually. The records are archived at NOS in the form of hand-plotted time series graphs.

Figure 8 (facing page). Locations of meteorological stations and tide gages deployed in the northern part of the Chesapeake Bay during a circulation study.


CHESAPEAKE BAY
NORTHERN PART
1:110,000
METEOROLOGICAL STATION
TIDE STATION
857-4008
SUSQUEHANNA RIVER
857-4070
HAVRE DE GRACE
ELK NECK
857-3927
C&D CANAL
857-3903
ELK RIVER
GUNPOWDER RIVER
BUSH RIVER
857-3704
HOWELL PT.
BACK RIVER
BALTIMORE
857-4680
POOLES ISLAND
857-3364
PATAPSCO RIVER
857-4857
857-3137
CHESTER RIVER
857-2955
SEVERN RIVER
857-5512
ANNAPOLIS
857-2770
KENT ISLAND
SOUTH RIVER
EASTERN BAY
857-2342
857-1979
EASTON
HERRING BAY
CHOPTANK RIVER
857-1901
857-6363
857-1892
CAMBRIDGE
LITTLE CHOPTANK RIVER
PATUXENT RIVER
NANTICOKE RIVER
COVE PT.
FISHING BAY
857-7330
HONGA RIVER
857-1539

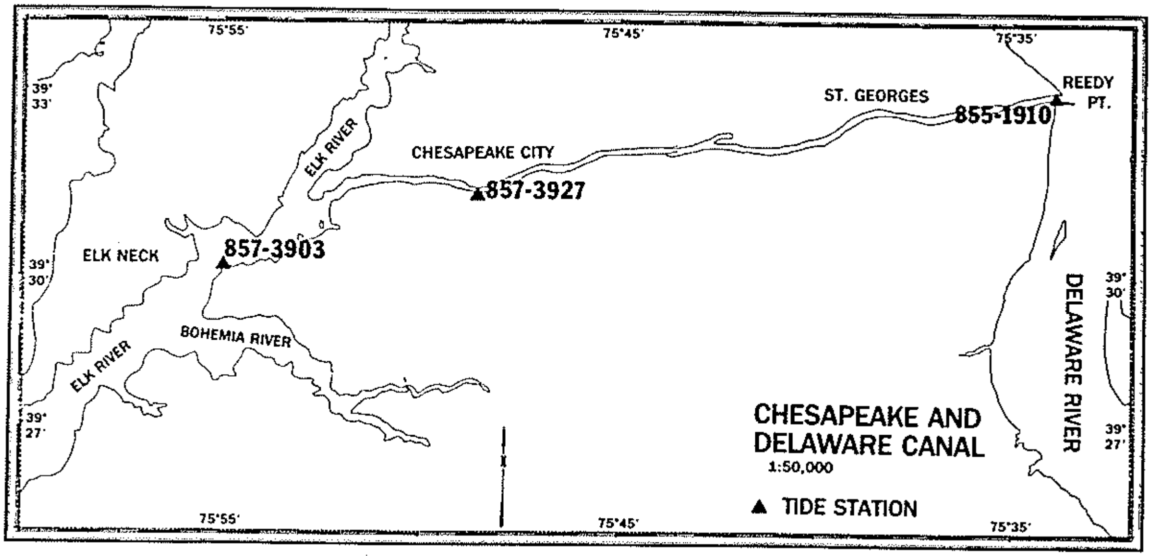


Figure 9. Locations of tide stations deployed in the Chesapeake and Delaware Canal during a circulation study of the Chesapeake Bay.

Information concerning historical methods of current measurement can be found in *Manual of Current Observations*, U.S. Coast and Geodetic Survey, S.P. 215, 1950. Predictions and mean values for some of these historical current stations can be found in *Tidal Current Tables, Atlantic Coast of North America*, published by NOS.

Tide Data

In contrast to historical current data, the historical tide data set is rather extensive. Although some records date prior to 1900, the major efforts in tide measurement were made in the mid-1940s, mid-1950s and mid- to late 1970s. The duration of observations range from two weeks to one year for subordinate tide stations, and to decades for control tide stations. Clock-wound portable and standard automatic tide gages and gas-purging pressure gages were the instrumentation in efforts before the 1970s.

The 1981-1983 Chesapeake Bay circulation survey gave NOS and users simultaneous tide and current measurements and updated tide predictions and tidal data in the Bay.

Descriptions of historic tide-measuring devices can be found in *Manual of Tide Observation*, U.S. Coast and Géodetic Survey, Pub. 20-1, 1965, or in *Tidal Datum Planes*, U.S. Coast and Geodetic Survey, S.P. 135, 1951. Predictions and mean ranges for some of these historical tide stations can be found in *Tide Tables, East Coast of North and South America Including Greenland*, published by NOS.

Historical current and tide data may be obtained by writing NOAA/NOS, Director, Office of Oceanography and Marine Assessment, 6001 Executive Boulevard, Rockville, Maryland 20852.

NOS PRODUCTS

Standard NOS products resulting from the Chesapeake Bay circulation survey include the updating of predictions for table 1 entries of the Tide and Tidal Current Tables, Atlantic Coast of North America. Predictions for the reference current station at the entrance of the Bay (station 40) will be updated from analysis of approximately 11 months of data. The old reference station "Baltimore Harbor Approach" is being replaced as a reference current station by current station no. 121 located off Kent Island in the Bay itself. Predictions for this reference station will be based on analysis of approximately eight months of data.

Table 2 entries in the tide and tidal current tables will be increased in number and upgraded by analyses of much more accurate and longer-duration data series in the past. These analyses together with updated predictions for the two reference stations will provide a dramatic increase in the accuracy of the tide and tidal current predictions throughout the Bay.

The entire data set, except tide data, was sent to and is available from the National Oceanographic Data Center, Page Building #1, 2001 Wisconsin Avenue, N.W., Washington, D.C. 20235. Tide data may be obtained from the Director, Office of Oceanography and Marine Assessment, 6001 Executive Boulevard, Rockville, Maryland 20852.

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Sediment and Water Column Interaction in the Chesapeake Bay

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During the past decade much has been learned about the effects of nutrient inputs (e.g., nitrogen, phosphorus, and silica) on estuarine processes such as phytoplankton production and oxygen status (Nixon 1981; D'Elia et al. 1983; Kemp and Boynton 1984). While our understanding is not complete, important pathways regulating these processes have been identified. For example, annual primary production of algae and maximal levels of algal biomass in many estuaries, including portions of the Bay, are related to the magnitude of nutrient loading (Boynton et al. 1982a). High, and at times excessive, phytoplankton production is partially sustained through the summer and fall by the recycling of nutrients that have entered the estuary previously. Similarly, sediment oxygen demand (SOD) has been found to be related to the amount of organic matter reaching the sediment surface and in many sediments is a major oxygen sink (Hargrave 1969; Kemp and Boynton 1980).

The Ecosystem Processes Component of the Maryland Chesapeake Bay Water Quality Monitoring Program focuses on the exchange of organic matter, oxygen, and nutrients between Bay waters and sediments. We now know that many sediment communities, including commercially important populations of shellfish and demersal fish, are nourished by organic matter produced in the overlying water. At the same time, the photosynthetic production of many estuaries, including portions of the Chesapeake Bay, depends on the release of fertilizing nutrients--the dissolved inorganic forms of nitrogen (N), phosphorus (P), and silicon (Si)--from Bay sediments.

The nature of coupling of benthic and pelagic components in the Chesapeake ecosystem can be illustrated by considering the overall equations for the photosynthetic formation of organic matter in Bay waters and the consumption of organic matter in Bay sediments. Photosynthesis can be represented as:

carbon dioxide + water + inorganic nutrients ----->
(N, P, Si)
organic matter + oxygen

Similarly, the basic equation describing the oxygen-consuming activities of estuarine bottom communities is simply the reverse of the same equation:

organic matter + oxygen ----> carbon dioxide + water + energy + inorganic nutrients
(N, P, Si)

The two equations above the demonstrate the linking or "coupling" between the Bay water's pelagic and benthic communities by oxygen and nutrient exchanges. In practical terms, this coupling is reflected in the potential productivity of Bay waters and the oxygen-consuming nature of most Bay sediments.

These equations also suggest the means by which essential nutrients cycle between estuarine waters and sediments. Dissolved phosphate, nitrate, ammonium, and silicate are introduced into Bay waters from rivers, land runoff, sewage effluents, and rainfall. These nutrients may then be taken out of solution and converted into particulate forms during the photosynthetic production of organic matter. Physical processes, such as flocculation and sorption reactions, may also lead to the removal of dissolved nutrients and organic matter onto estuarine sediment particles. A significant portion of the suspended material in estuarine waters sinks, eventually reaching the Bay bottom where much of the easily decomposable organic matter is consumed by benthic organisms. As the above equation demonstrates, this process is accompanied by the consumption of oxygen and the release of "remineralized" inorganic nutrients. The build-up of remineralized nutrients in Bay sediments produces a return flux of nutrients from the sediments back to the overlying water. Remineralized nutrients

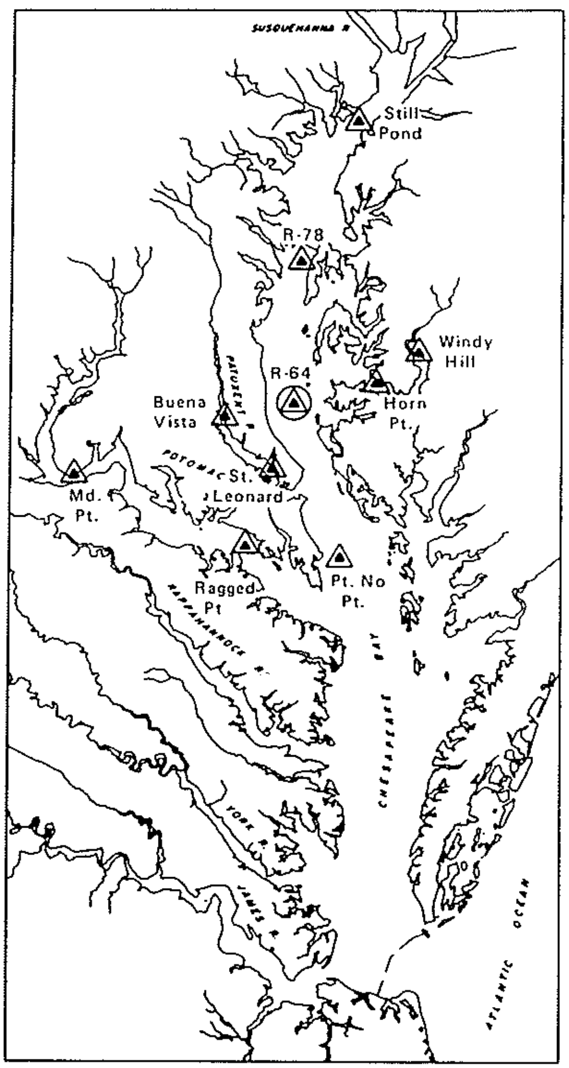

Figure 1. Sampling stations for the SONE study. The circled station (R64) is also the location of the sediment trap array.

may then mix upwards into the sunlit portions of the water column where they can support additional photosynthetic production. These links between nutrient loading, sediment nutrient exchange dynamics, and water quality provide the motivation and justification for monitoring of long-term trends in deposition of organic matter and sediment-water exchanges of oxygen and nutrients.

METHODS

Sampling locations for both the sediment oxygen and nutrient exchange (SONE) study and the deposition study are shown in Figure 1. Several earlier studies (Boynton et al. 1980; Kemp and Boynton 1984; Boynton and Kemp 1985) reported the following: (1) along the mainstem, nutrient fluxes were moderate in the upper Bay, reached a maximum in the mid-Bay and decreased in the high-salinity lower mid-Bay region; and (2) nutrient fluxes in the transition zone of tributaries were larger than those observed in the higher-salinity downstream portions of tributaries. On this basis, a series of stations were located along the mainstem from Still Pond in the upper Bay to Point No Point near the mouth of the Potomac River. Stations were also established in the Potomac, Patuxent, and Choptank Rivers, one in the river-estuary transition zone and one in the lower estuary of each tributary. In all cases, station locations were selected for depths and sediment characteristics representative of the estuarine zone being monitored.

Sampling frequency was based on the seasonal patterns of sediment-water exchanges observed in previous studies (Kemp and Boynton 1980, 1981; Boynton et al. 1982b; Boynton and Kemp 1985). These studies indicated that there are several distinct periods over an annual cycle, including: (1) a period influenced by the presence of a large macrofaunal community (spring-early summer), (2) a period during which macrofaunal biomass is low but water temperature and water-column metabolic activity are high and anoxia is prevalent in deeper waters (August), (3) a period in the fall when anoxia was not present and macrofaunal community abundance was low but reestablishing, and (4) an early spring period (April-May) when the spring phytoplankton bloom occurs, and nutrients (particularly nitrate) are high in the water column. Previous studies have also indicated that short-term (daily or monthly) variation in these exchanges is small. In light of these previous studies nutrient flux is measured quarterly using intact sediment cores obtained at each sediment flux station. These cores are incubated on shipboard at ambient

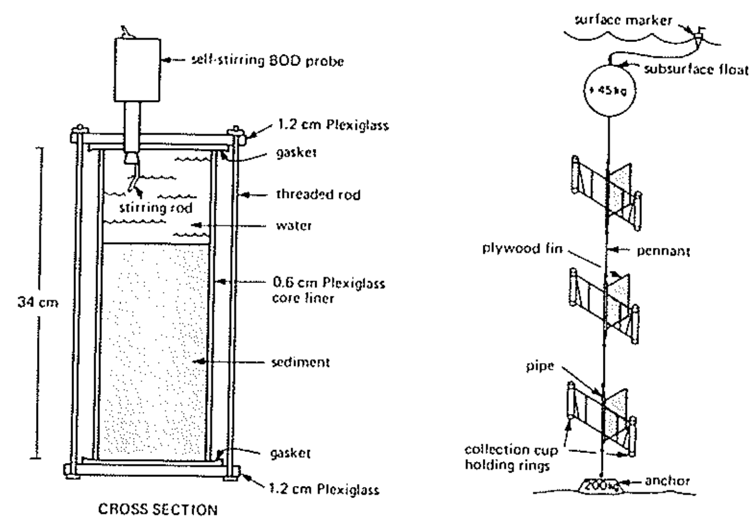

Figure 2. Incubation chamber for studies of sediment oxygen demand and nutrient flux (left) and collecting array for studies of vertical flux (right).

temperatures for 3-5 hours. Changes in oxygen and nutrient concentrations in water overlying sediments are used to estimate net exchanges between Bay sediments and waters (Figure 2 left).

Sediment trap arrays are used to determine the net vertical flux of particulate material to the deeper portions of the Bay. In shallower areas local resuspension of bottom sediments masks the downward flux of "new" material. Arrays (Figure 2 right) are deployed at about 5, 9, and 14 m beneath the water surface to obtain estimates of vertical flux of particulates from the surface euphotic zone to the pycnocline, flux across the pycnocline to deep waters, and flux of materials associated with the near bottom (which includes local resuspension of sediments as well as net deposition). Previous studies have shown that depositional rates are greatest from April through October and considerably lower in the winter (November-March). 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). There is some variability in warm-season deposition rates, probably due to algal blooms (lasting a few days to a week), variation in zooplankton grazing rates (over the course of a week or a month), and other, less well described, features of the Bay. Because it is important to obtain interannual estimates for the rate of deposition of organic matter to deep waters of the Bay, vertical flux sampling is almost continuous in the summer (July-August), of shorter duration during the generally smaller bloom periods of the spring and fall, and only occasional during the low-productivity, low-depositional period of the winter. Measurements of the vertical deposition rate are coordinated with measurements of sediment flux; water column and sediment are also sampled for dissolved nutrients and physical variables. At the vertical deposition station (R64), the particulate matter field of the water column is characterized and a sediment sample is taken when the deposition-rate array is retrieved. The collecting array is deployed one to two weeks for each sample.

RESULTS AND DISCUSSION

The first annual cycle of nutrient flux determinations and vertical flux measurements was completed in July 1985, and the second cycle of sampling is under way. This report summarizes the information gathered in the early stages of this effort, such as seasonal patterns and interrelationships among the study parameters, and attempts to interpret these data in terms of our original model of benthic-pelagic coupling.

Water Column Characteristics

Bottom salinities ranged from 0.7 parts per thousand (ppt) at the northernmost mainstem Bay station in May, to 19.8 ppt at the mainstem Bay station R64 in August; they were generally higher in the summer-fall period than in spring, as expected. Vertical differences in salinity were greatest at the deeper stations (>14 m) and were most pronounced in August (Figure 3 top).

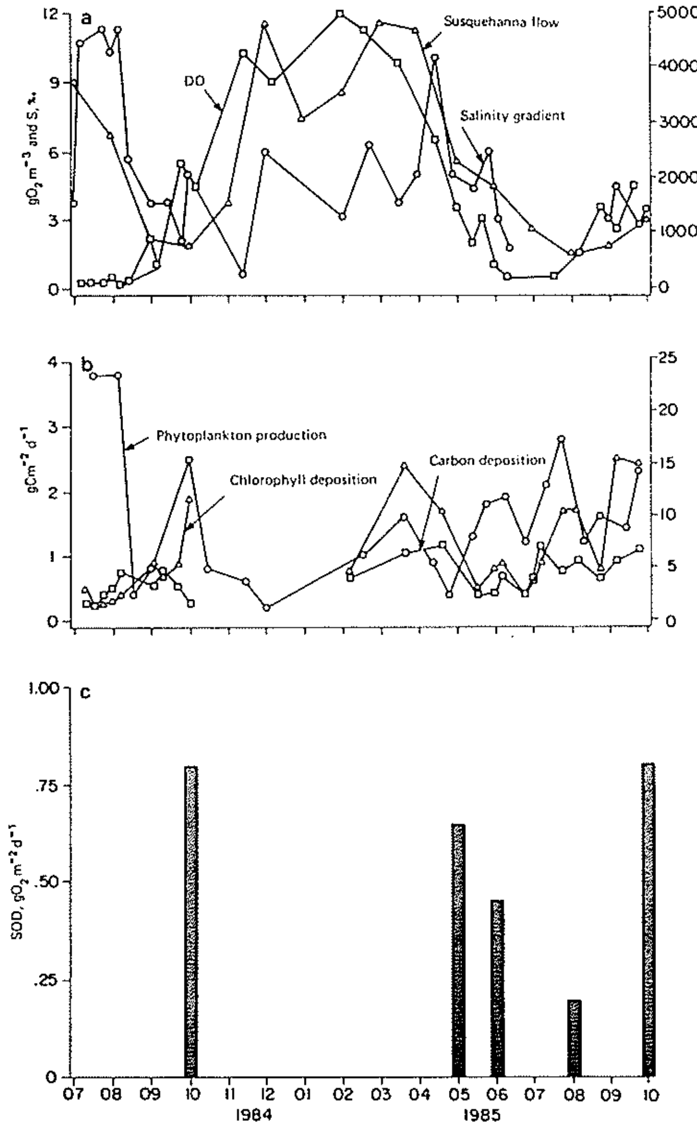

Figure 3. Data for mid-Bay, deep-water station R64: salinity gradient, Susquehanna River flow, and deep-water dissolved oxygen levels (top); phytoplankton production and deep-water deposition of carbon and chlorophyll (middle); and sediment oxygen demand (bottom).

Bottom-water concentrations of oxygen at mid-Bay station R64 ranged from near-zero in late summer (July-August) to 12 mg/liter in February (Figure 3 top). Oxygen was generally lowest in summer and highest in winter at all SONE stations. Vertical differences in oxygen concentration were very pronounced (as much as 2.4-9.3 mg/liter) at the deep stations throughout the sampling period and much less pronounced at the remaining sites, particularly in May and June. In general, oxygen and nutrient gradients were greatest at sites where the vertical salinity gradient was large, a relationship indicating the important influence of density structure on water quality.

Concentrations of dissolved nutrients in bottom water were quite variable, probably reflecting the complex interactions of various sources, sinks, and the water-column density structure. Generally, ammonia concentrations were highest, at times very high (>20 uM), at the deep stations, in August and June. Nitrate concentrations were consistently higher at low-salinity sites than in the mid-Bay regions, reflecting the riverine source of this compound. Surface concentrations of nitrate were also generally higher than bottom concentrations.

Concentrations of dissolved inorganic phosphorus (DIP) appeared to be somewhat higher during the summer and late spring than at other times. Tributary values were not noticeably different from those observed at other sites, in contrast to the differences observed in nitrate. Vertical differences in DIP were small, except during the late summer at some of the deeper stations.

Sediment Characteristics

The redox status of surficial sediments has an important influence on the nature and magnitude of sediment-water nutrient exchanges. For example, nitrification may proceed under oxidizing conditions (+Eh), whereas under reducing conditions (-Eh) denitrification is possible (if any nitrate is available) and release of DIP from sediments may be enhanced.

Measurements of Eh in surficial sediments (depth 1-2 cm) exhibited strong seasonal and spatial trends. In these sediments Eh was highest in the fall (+264 to 364 mV) and generally decreased through the spring to minimal values in late summer (-142 mV). With few exceptions, Eh values were lower at the deep stations in August and June.

In August the sediment profile of Eh was negative below 1 cm at all stations. In spring and fall, however, positive Eh values were observed to depths of 8 cm at the shallow stations (<10 m). At the deeper stations (>10 m), positive Eh values were observed down to sediment depths of 7 cm in October, 5 cm in May, and 3 cm in June. During the first year of monitoring a strong seasonal cycle was observed; Eh was highest during the fall and decreased to a summer minimum. This seasonal trend was most pronounced at the deeper stations.

There was considerable variability in particulate nutrient concentrations in surficial sediments, probably as a result of aperiodic depositional events and a complex of regenerative processes. Particulate carbon values (percentage of dry sediment by weight) ranged from 1.1% to 10.4%, with values commonly in the range of 2% to 4%. Additional insights regarding the sources of deposited organic particulates can be gained by examining the relative amounts of carbon, nitrogen, and phosphorus in this material. Phytoplankton typically have composition ratios (carbon: nitrogen: phosphorus) on the order of 100:16:1 (atomic), whereas terrestrial detritus ratios have greater relative amounts of carbon.

There was evidence of substantial phosphorus enrichment in surficial sediments at the upper river sites in the Patuxent and Potomac (carbon: phosphorus = 42-62) but not in the Choptank. Although it is unclear why this pattern was not observed in the Choptank, low ratios (relative to probable source materials) may be the result of phosphorus sorption-flocculation reactions known to occur in low-salinity estuarine sites. Ratios of carbon to phosphorus closely approximated phytoplanktonic detritus at most mid-Bay and tributary stations (carbon: phosphorus = 103-172) and were usually higher at the upper Bay station; this pattern suggests a mixture of terrestrial and phytoplanktonic detritus in deposited materials in the upper Bay.

Ratios of carbon to nitrogen in surficial sediments ranged from about 7 to 26 during the monitoring period. Surficial sediments at mesohaline tributary stations commonly had carbon: nitrogen ratios <10, while at upper tributary stations values were often between 10 and 20. Deep stations (>14 m) always had carbon: nitrogen ratios of <10. The northernmost mainstem Bay station always had ratios >18, a difference possibly reflecting again the influence of terrestrial material and/or more rapid loss of nitrogen at this low-salinity site.

Vertical Flux

The seasonal patterns of phytoplankton production and deposition are shown for station R64 (Figure 3 middle). The ephemeral nature of late summer and early fall blooms is evidenced by the high phytoplankton production in October 1984. The two warm seasons of high sedimentation rates corresponded generally to periods of high phytoplankton biomass, but deposition to the middle sediment trap occurred somewhat later than phytoplankton production. A significant fraction of this organic fallout originates in the plankton blooms, and in similar fashion high deposition rates in spring and mid-summer 1985 occurred later than significant blooms of the phytoplankton. Peaks in chlorophyll *a* deposition also trail phytoplankton blooms, and suggest that many intact (ungrazed) algal cells sink from the euphotic zone. A similar conclusion was reached for regions of the Baltic Sea by Smetacek (1985).

The fraction of primary production sinking below the pycnocline can be estimated by comparing the maximal rate of late summer phytoplankton production (about 4 g carbon/m^2) with the peak rate of organic carbon deposition during that period (about 0.8 g/m^2 per day). Comparison suggests that about 20% of daily primary production sinks out of the upper layer of the water column to fuel oxygen-consuming respiration in deeper waters and sediments. Similar calculations for other periods reveal that trap collections represented 30%-50% of the summer carbon production in the overlying water. These estimates are similar to those reported for other marine ecosystems (Smetacek 1980; Taguchi 1982; Bishop and Marra 1984; Davies and Payne 1984; Downs and Lorenzen 1985).

Sediment Oxygen Demand (SOD)

SOD at station R64 exhibited a strong seasonal cycle marked by highest oxygen uptake rates in late spring and fall (Figure 3 bottom). Our studies and those of others (Nixon 1981; Zeitzschel 1980) indicate that SOD is strongly temperature-dependent and also dependent on ambient oxygen concentrations, particularly when oxygen is in short supply. Assuming that the average SOD at station R64 was about 0.8 g oxygen/m^2 per day and that phytoplankton production in that region was about 450 g carbon/m^2 per year, we estimate (respiratory quotient = 1.0) that aerobic carbon consumption by mid-Bay sediment communities could represent about 25% of primary production of the overlying waters. Anaerobic processes such as sulfate reduction, not measured by the SOD technique, probably consume an equal or greater amount of organic matter in Bay sediments. Similar values from a variety of other coastal marine systems (Nixon 1981) serve to illustrate once again that the bottom community can represent significant sinks of oxygen and organic carbon in the Bay ecosystem.

SOD measurements during the first year of sediment flux monitoring ranged between 0.45 and 3.9 g oxygen/m^2 per day, well within the range of measurements from other productive estuarine systems. Oxygen uptake rates in tributary sediments were generally greater than those in the mainstem (Figure 4). SOD rates in the upper Bay were higher than those in mid-Bay regions. SOD rates were almost always high in spring and early summer and low in the late summer and fall. Spatial variability in SOD rates can probably be attributed to environmental factors such as water temperature and depth, and to organic loading rates in the overlying water that are known to influence sediment oxygen concentrations. For example, SOD was always low (<0.7 g oxygen/m^2 per day) when oxygen concentrations in the overlying water were <2.5 mg/liter. On the other hand, low SOD rates were often found when ambient levels of dissolved oxygen were much higher. It seems likely that SOD rates are ultimately regulated by a combination of interacting environmental factors.

Nutrient Flux

In this section, positive fluxes indicate a net release of dissolved nitrogen or phosphorus from sediment into the water column, whereas negative fluxes (denoted by a minus sign) indicate a net flux of nutrient from the water column into the sediments (by convention, SOD measurements, which are actually negative oxygen fluxes, are reported without a minus sign).

In general exchanges of nutrients to and from sediments appeared to exert a strong influence on water quality, especially in the mid-Bay transition zone (segments CB-3, CB-4, and CB-5). Ammonium was the most dominant form of inorganic nitrogen released from sediments (Figure 4). Sediment-water ammonium exchanges were always positive, with fluxes ranging up to +435 µg-atoms nitrogen/m^2 per hour. Highest values to date were noted at the deepest mainstem Bay stations in the later spring. Since ammonium is readily taken up by many groups of phytoplankton, algal production may be fueled by the net flux of ammonium from sediments. This process may be particularly important during periods of water-column stratification, when phytoplankton production may be limited by the amount of nitrogen that can break through the stratification barrier.

Nitrate can flow either from sediments into the water column (positive nitrate flux values) or from water into sediments (negative nitrate flux values), depending on chemical conditions and microbial populations near the sediment-water interface. Under oxidizing conditions, the ammonium produced by sediment decay can be nitrified (oxidized to nitrite, then to nitrate) and at times (fall periods) can be released to the overlying water. Under reducing conditions, any nitrate in the lower water column tends to diffuse into the sediments (negative nitrate flux values), where it can be denitrified (converted to nitrogen gas). Nitrate flux values ranged from +147 to -100 mg-atoms nitrogen/m^2 per hour and, while smaller than ammonium fluxes, still had a strong impact on water quality (Figure 4). Inorganic nitrogen fluxes thus exhibited complex, variable patterns: always positive in upper Bay and Patuxent waters, and variable elsewhere. Generally, large positive ammonium fluxes may be expected to contribute significantly to mid-Bay algal productivity.

Phosphorus fluxes ranged from 87 to -28 mg-atoms phosphorus/m^2 per hour. Positive phosphorus flux typically is highest in summer with warmer temperatures and the outset of hypoxia in deeper Bay waters. Somewhat anomalous negative phosphorus flux values were observed at tributary sites in August 1984, and may be the result of sorption-flocculation processes. Fluxes of silicious acid, another important nutrient, are always positive (140 to 956 mg-atoms silica/m^2 per hour), with highest rates at deep mainstem Bay sites in late spring (Figure 4). In portions of the Bay silica flux appears to be directly proportional to salinity, as reported for other areas, because dissolution of silica in sediments is enhanced as salinity increases.

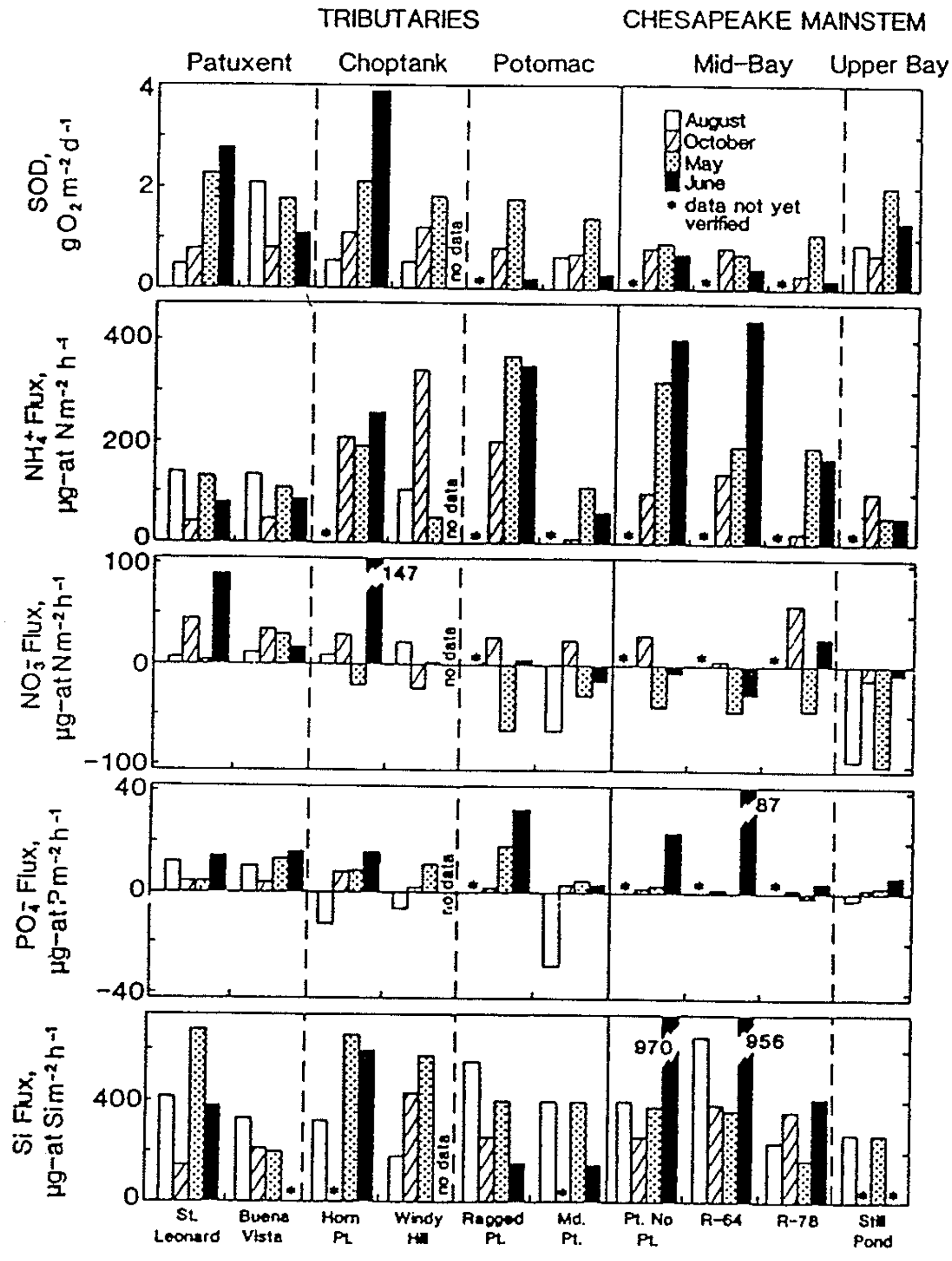

Figure 4. Average sediment-water exchanges of oxygen (SOD), ammonium (NH_4+), nitrate (NO_3-), dissolved inorganic phosphorus (PO_4-), and silicious acid (Si) for the period August 1984 to June 1985. Negative values indicate fluxes from water to sediments, except for SOD, for which all fluxes are from water to sediment.

CONCLUSION

The linkage between benthic and pelagic systems can be characterized as a positive feedback loop. The regenerative capacities of bottom communities, together with the potentially large return flux of nutrients from estuarine sediments, can sustain phytoplankton production when other sources of inorganic nutrients are diminished. Enhanced production in the upper water column can lead to even greater deposition of organic matter to deeper waters and sediments. This deposition in turn can fuel greater oxygen-consuming metabolic activities, thereby increasing the release of fertilizing nutrients. Unchecked, the cycle of production, deposition, consumption, and remineralization contributes to anoxia in both sediments and bottom waters, eventually leading to the deterioration of aquatic habitats characteristic of eutrophying estuarine systems.

The concept of benthic-pelagic coupling outlined above predicts the following: if total loadings of nutrients and organic matter to Bay waters decrease, then deposition of organic matter to Bay sediments, sediment oxygen demand, and the return flux of remineralized nutrients will also decrease. Benthic processes therefore not only contribute to changes in water quality, but also serve as important indicators of these changes. In practical terms, the effectiveness of controls on nutrient loading will be reflected by changes in the rate of deposition of organic matter to Bay sediments and by changes in the rates of metabolic activities in sediment communities. These links between nutrient loading, sediment nutrient exchange dynamics, and water quality provide the motivation and justification for monitoring of long-term trends in deposition of organic matter and sediment-water exchanges of oxygen and nutrients.

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Toxicant Monitoring in the Upper Chesapeake Bay

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In order to establish causality between habitat pollution and a declining productivity of several commercially and recreationally important fisheries in the Chesapeake Bay, a benthic survey program aimed at monitoring organic and metal toxicants was implemented within the Maryland boundaries of the Bay. Sediments, clams (*Macoma balthica*), and worms (*Nereis succinea*) collected from eight stations from the north and central portion of the Bay during 1984 and 1985 were analyzed for the presence of 13 chlorinated insecticides, 6 polychlorinated biphenyl (PCB) congeners, 16 polynuclear aromatic hydrocarbons (PAHs), 6 herbicides, 3 phosphorothioate triesters, and 10 trace metals. The results of these analyses are being used in three ways: to map the occurrence and distribution of toxicants in Bay sediments and biota; to delineate seasonal and long-term changes in toxicant levels; and to develop relationships between total toxicant concentrations in sediments and toxicant concentrations in the biota as an estimate of bioavailability. If we are to measure long-term trends in toxicant input, as part of a Bay restoration program, we must understand all the factors that regulate the exposure of the benthic food web to toxicants. We will need to understand the pathways by which these toxicants are bioaccumulated by estuarine organisms.

The objectives of the benthic monitoring program have been to identify and quantify 44 trace organic chemicals and 10 metals in sediments, clams, and worms at eight Bay stations, and to measure bottom salinity, temperature, pH, sediment grain size, and sediment organic carbon and organic nitrogen content at each station. The objective of these measurements is to characterize the physical and chemical factors that affect the bioavailability and bioaccumulation by animals at the lower end of the food web. In addition, we plan intensive sampling of four Bay stations to define intra-site temporal variability. The sampling stations selected encompass a range of sediment physical properties, proximity to industrialized regions, and runoff characteristics. With this sampling regime continued over several seasonal cycles, we intend to define toxicant concentrations in the Bay; to detect changes in benthic toxicant levels in response to both point- and nonpoint-source pollution-management practices; and to develop models to predict the bioaccumulation of sediment-associated toxicants by benthic fauna.

SAMPLING AND ANALYSIS

Sediments, clams (*Macoma*), and worms (*Nereis*) from nine northern and central Chesapeake Bay stations (S1 [Baltimore Harbor], Lat. 39° 12.47', Long. 72° 31.47'; S2 [Curtis Point], Lat. 38° 51.38', Long. 76° 29.13; S3 [Holland Point], Lat. 38° 42.81', Long. 76° 30.81; S4 [Benoni Point], Lat. 38° 39.65', Long. 76° 13.54'; S5 [Calvert Cliffs], Lat. 38° 39.65', Long. 76° 26.60'; S6 [Drum Point], Lat. 38° 19.18', Long. 76° 25.78'; S7 [Clay Island], Lat. 38° 13.33', Long. 75° 56.32'; S8 [Cornfield Point], Lat. 38° 03.37', Long. 76° 21.60'; and S9 [Chalk Point], Lat. 38° 33.96', Long. 76° 40.57') were collected by hydraulic grab during November 1984, April 1985, and September 1985 and were stored in the laboratory at -20° C until analysis.

Frozen sediment was thawed and air-dried to a constant weight and ground to 0.25 mm by mortar and pestle. Ground sediment was extracted with *n*-hexane: Me_2 CO (1:1, vol/vol) in an ultrasonic bath and subjected sequentially to solid-phase extraction (SPE™; J. T. Baker) aromatic sulfonic acid chromatography and Florisil column chromatography.

Animals were thawed, shucked (clams), blotted with tissue, weighed, and macerated in 20 g of anhydrous sodium sulfate:sand (1:1, vol/vol) by mortar

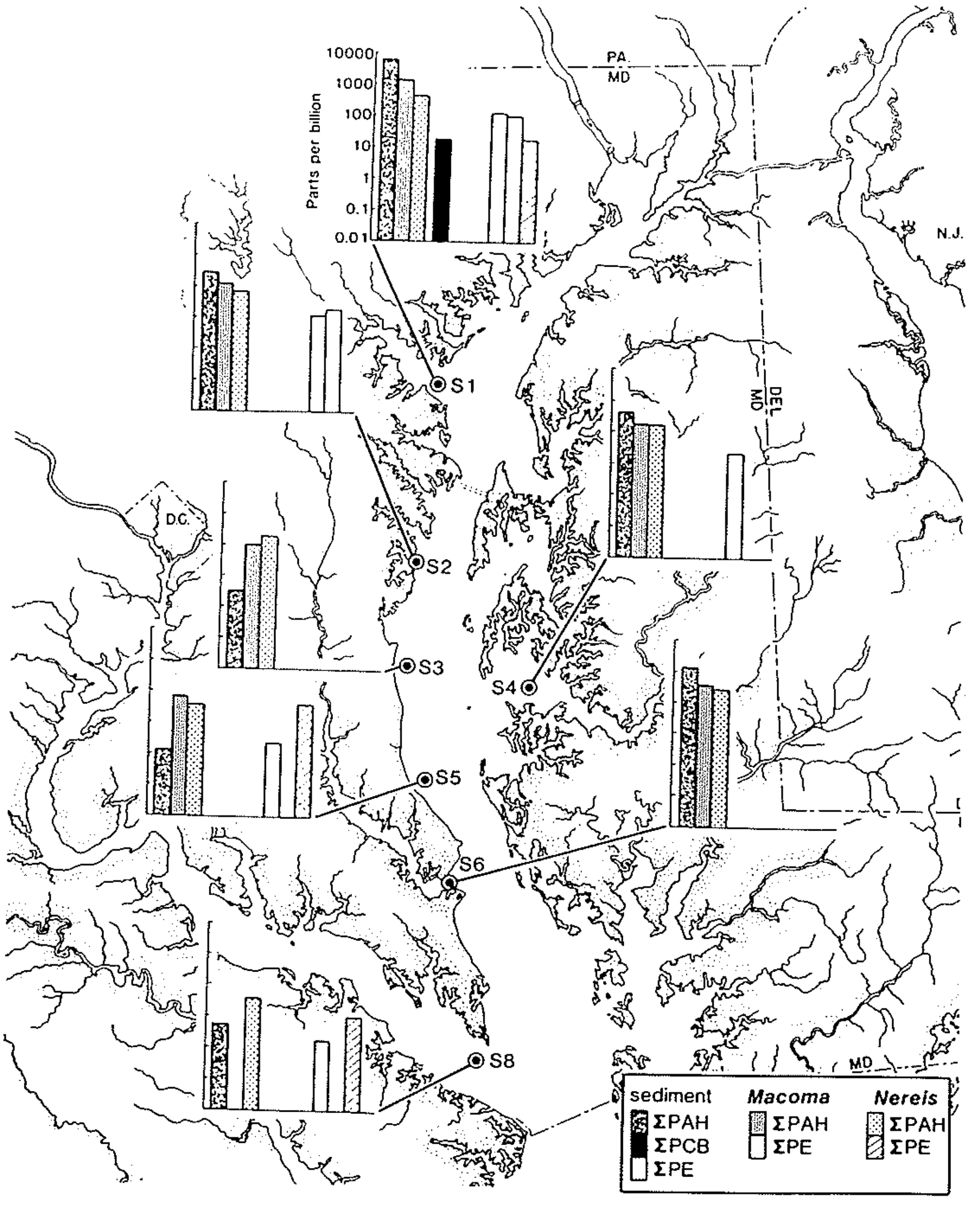
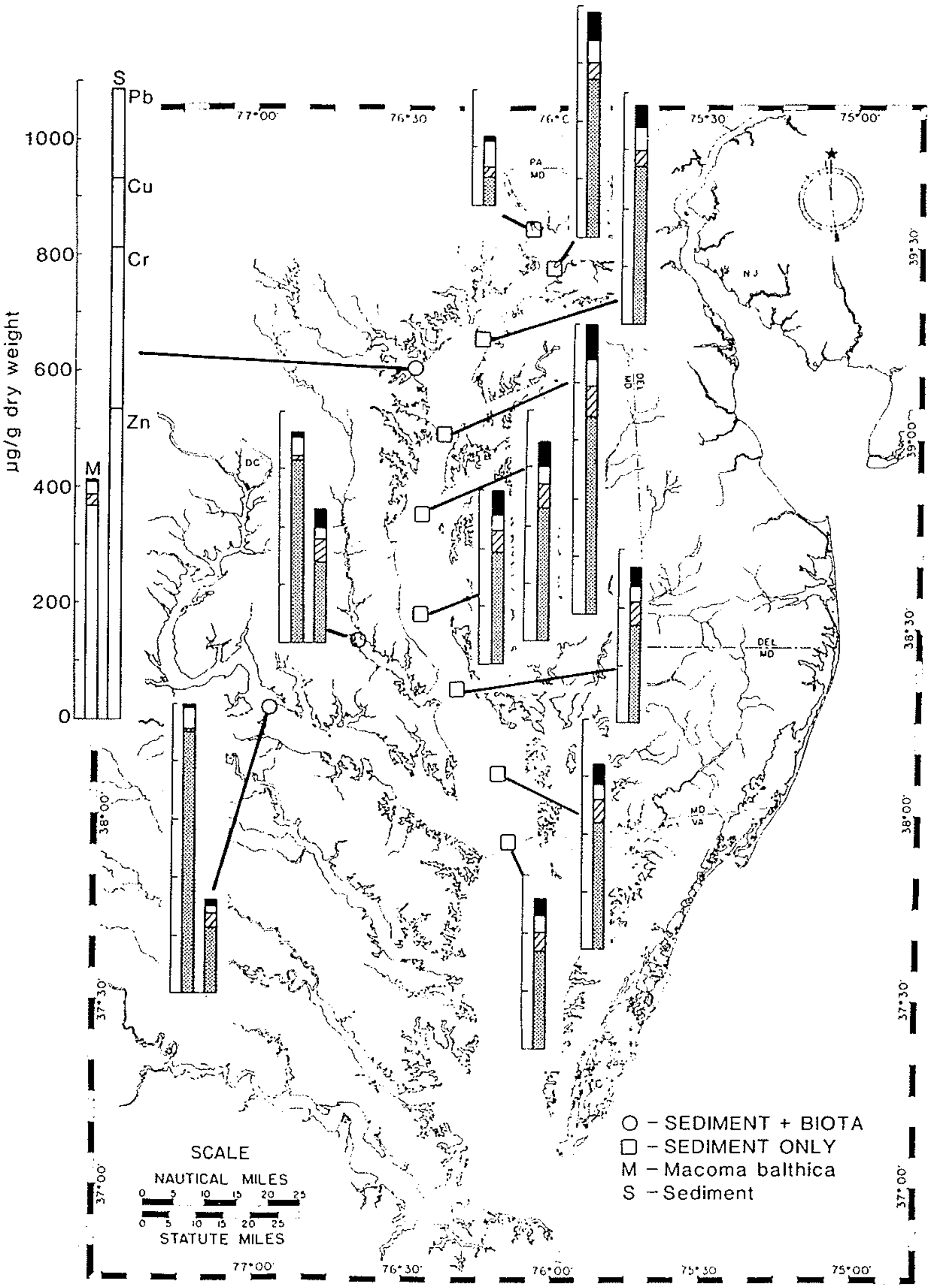


Figure 1. Levels of polynuclear aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), and total herbicides and insecticides (PE) in sediments and biota from the northern Chesapeake Bay.

Figure 2 (facing page). Average concentrations of chromium, copper, lead, and zinc in sediment and *Macoma balthica* from the northern Chesapeake Bay.



μg/g dry weight
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39°30'
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PA
MD
NJ
DC
DEL
MD
MD
VA
SCALE
NAUTICAL MILES
0 5 10 15 20 25
0 5 10 15 20 25
STATUTE MILES
○ - SEDIMENT + BIOTA
□ - SEDIMENT ONLY
M - Macoma balthica
S - Sediment

and pestle, and were extracted and treated exactly as was sediment.

Florisil chromatography provided two separate fractions upon elution with *n*-hexane and 50% ethyl acetate into *n*-hexane. Both fractions were analyzed for the presence of organic contaminants by gas chromatography/mass spectrometry. Samples for metal analysis were subsamples of those taken for organic analysis. Samples were frozen pending analysis. Samples of sediment and biota were dried, weighed, and wet-oxidized with redistilled nitric acid before trace metal determination by flame and graphite-furnace atomic-absorption spectroscopy.

RESULTS AND DISCUSSION

Of the 44 possible organic pollutants, 26 were detected in the samples collected in April and September 1985. August 1984 organic chemical data are incomplete and are not addressed here. The occurrence and concentration of individual pollutants in sediments and biota varied widely at seven of the nine stations sampled (Figure 1). PAHs were the most prominent organic contaminants detected at each station. PAH concentrations in sediments ranged from 10,000 ppb in Baltimore Harbor (station 1) to <1 ppb at station 8. Pesticides were detected in sediments and

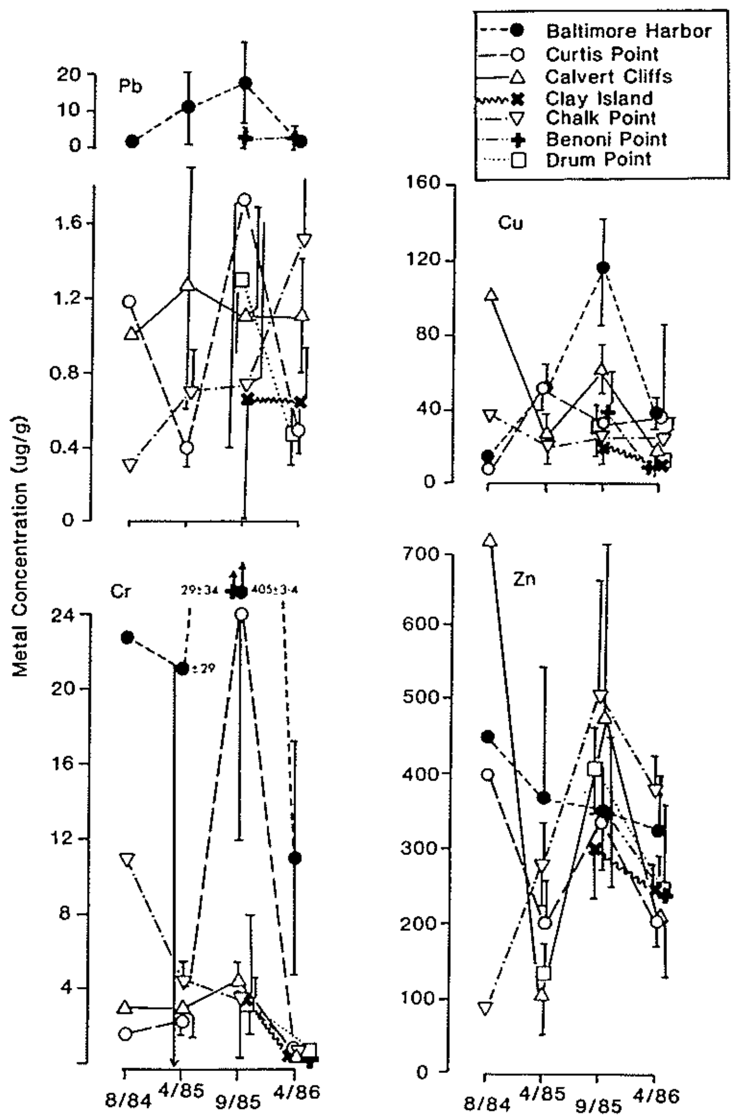

Figure 3. Temporal changes in concentrations of chromium, copper, lead, and zinc in *Macoma balthica* from the northern Chesapeake Bay.

biota at four of the seven stations. PCBs were detected only in Baltimore Harbor sediments.

High concentrations of trace metals were also found at the Baltimore Harbor (Key Bridge) site. Figure 2 shows average 1985-1986 concentrations of the four most abundant trace metals in sediments and *M. balthica*. However, for several metals, concentrations in biota and sediments show considerable seasonal variability. Temporal changes in concentrations of copper, zinc, lead, and chromium in *Macoma* are shown in Figure 3 and indicate large fluctuations over the period of study. Fluctuations in *Nereis* were of similar extent but a different pattern. Reasons for these fluctuations are currently under investigation. Some fluctuation is methodological and must be eliminated in a long-term study. For example, the importance of effective gut purging before analysis was shown when it was accomplished in *Macoma* satisfactorily in April 1986, less satisfactorily in August 1984: it resulted in a distinct clustering and lowering of measured concentrations of some metals, e.g., chromium. A standardized gut purging procedure will be incorporated into all future studies. The normal pattern of seasonal variability due to differences in germinal and somatic growth (as well as physical factors such as run-off) remains to be evaluated, although more can be said concerning physico-chemical factors affecting toxicant uptake.

Both clams and worms living in relatively sandy sediments (low in silt/clay and organic carbon) possessed lower body burdens of organic chemicals than animals living in sediments high in organic carbon and low in sand. The latter sediments contained higher toxicant concentrations, especially in areas near heavy industrial activity; these associations suggest that bioaccumulation is dependent upon a combination of toxicant concentrations in the sediment, sediment organic content, and grain size. Despite modifying factors, it appears that concentrations of organic toxicants in biotic tissue may depend upon toxicant concentrations in sediment (Figure 4). Since PAHs were the most abundant contaminants Baywide, they provided the best data for developing simple models.

For metals, the relationship between body burdens and sediment concentrations was found to be inconsistent; however, we anticipate our understanding of this relationship will improve, as artifacts such as gut sediment are removed and our knowledge of seasonality expands. In the physical environment, it is clear that sediment type has an influence on metal concentration, with lower concentrations of metals seen in sandy sediments and higher levels in silty sediments (Figure 5). A way of correcting for this effect is to normalize the data to a world "average shale". Metal concentrations are thus described in terms of an enrichment factor (EF) defined as:

$$EF = \frac{(x/Fe)\ \text{sediment}}{(x^1/Fe^1)\ \text{earth's crust}}$$

where x and Fe represent concentrations of trace metal and iron in the sediment sample under investigation, and x^1 and Fe^1 are concentrations given by Turekian and Wedepohl (1961) for an average shale. EFs for eight trace metals at seven northern Bay stations are shown in Figure 6 for August 1984 through April 1986. At Baltimore Harbor, Curtis Point, and Calvert Cliffs, wide divergence is seen in EF. Further work is

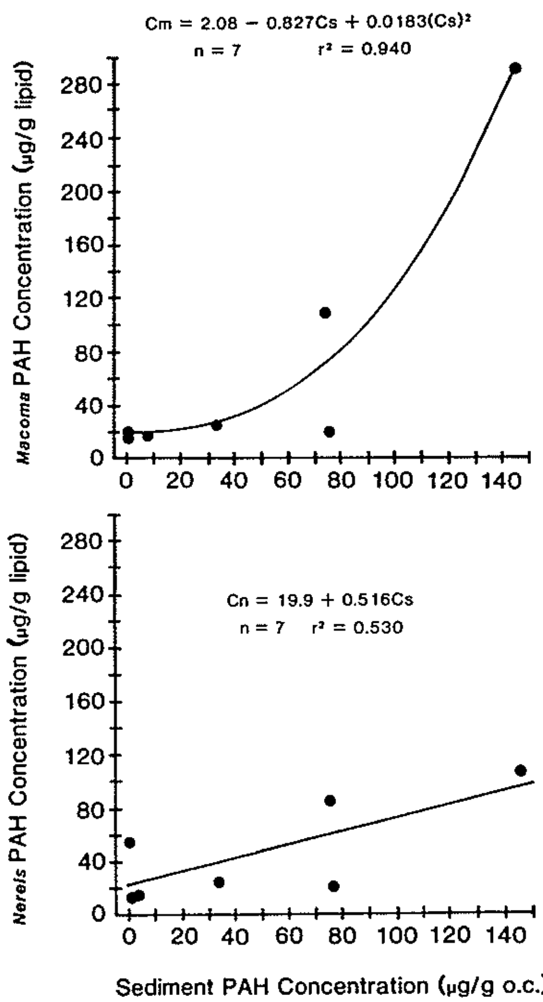

Figure 4. Relationship between polyaromatic hydrocarbon (PAH) concentrations in sediment and in associated fauna (*Macoma balthica* and *Nereis succinea*). Concentrations are in µg/kg (ppb).

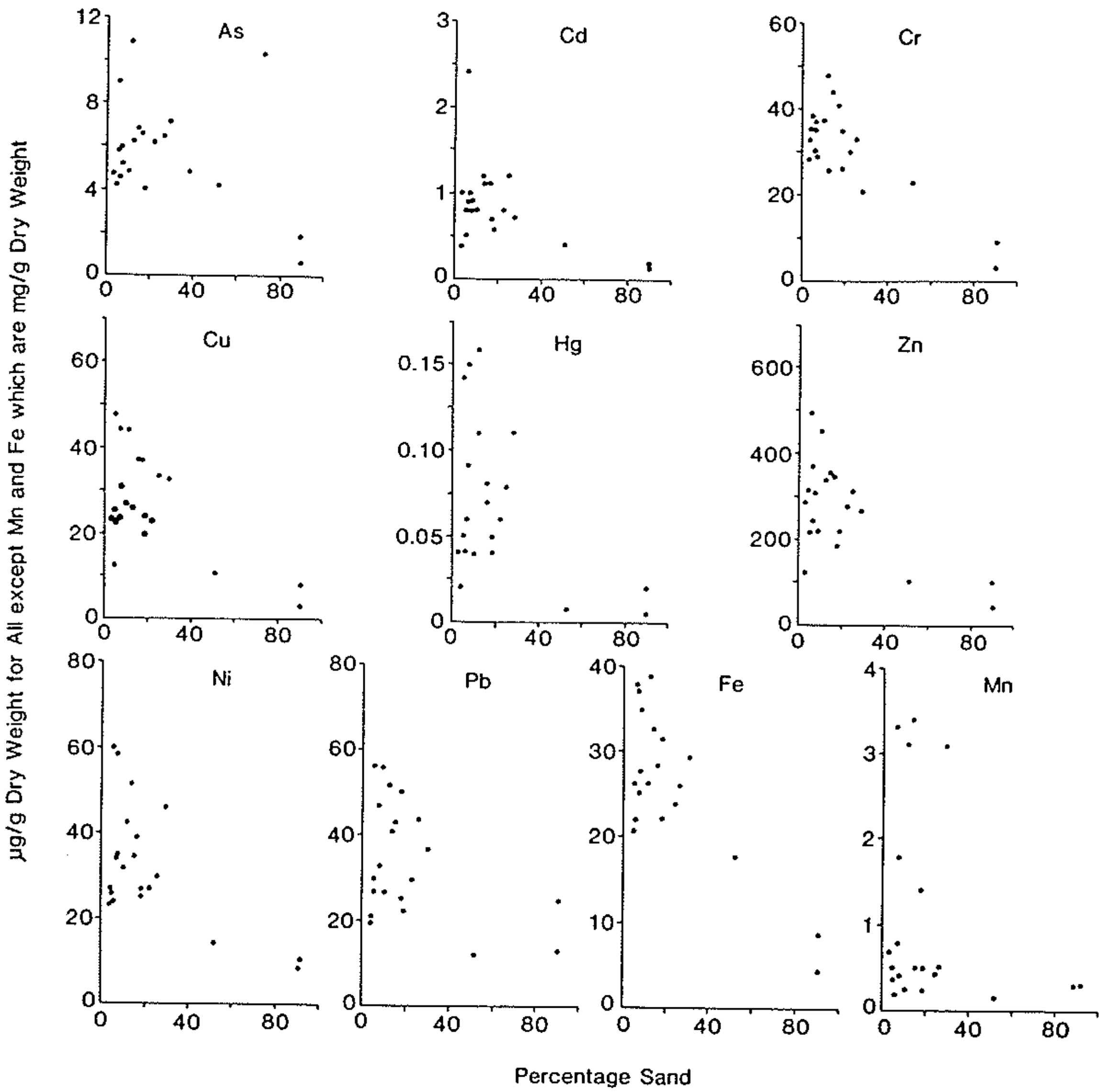

Figure 5. Relationship between concentrations of trace metals in sediment and particulate profile as represented by percentage of sand.

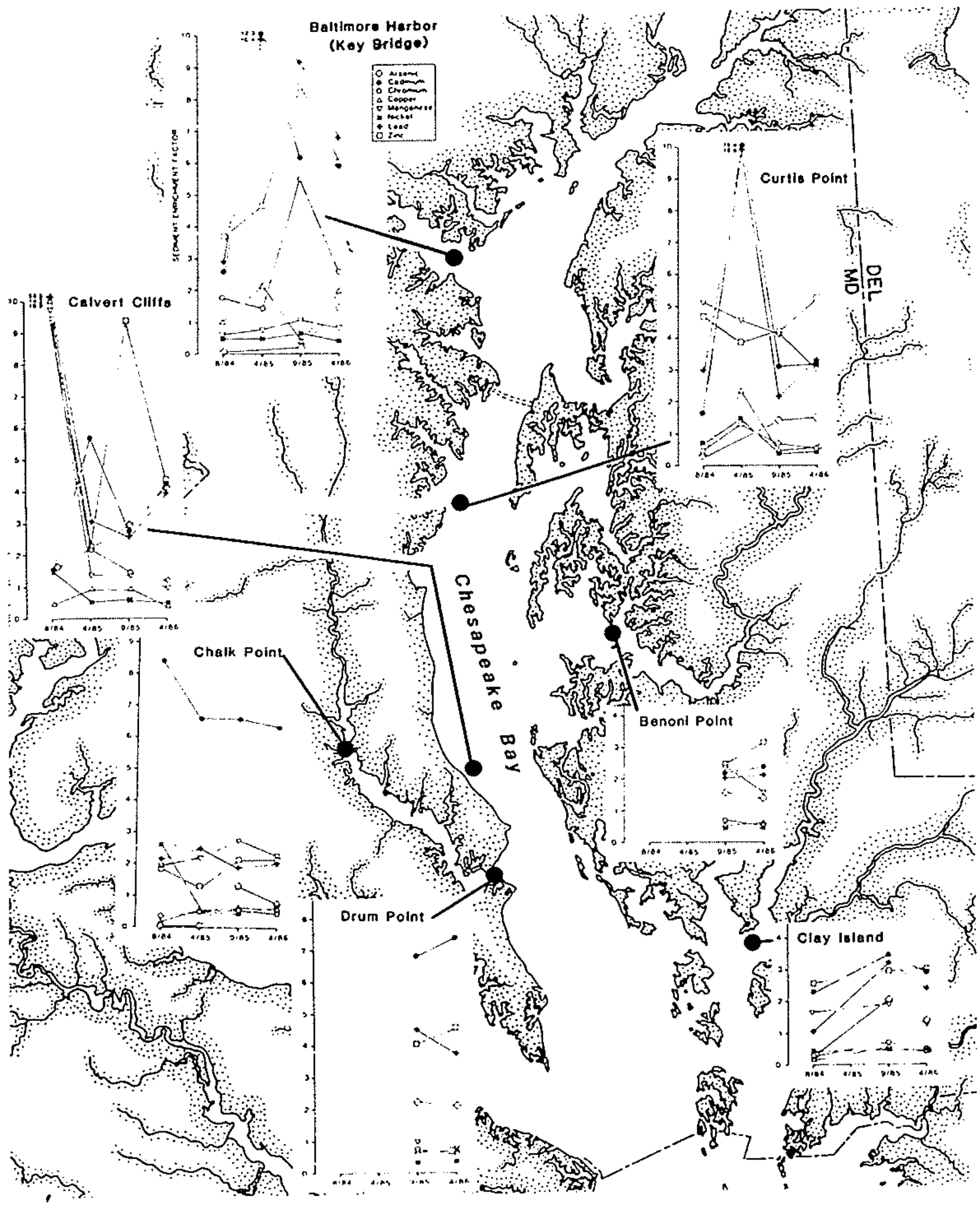

Figure 6. Enrichment factors (EF) for eight trace metals in surficial sediments from seven northern Chesapeake Bay stations. (For derivation of enrichment factor, see text).

required to assess the influence of intra-site variability on these data as well as on data from biota.

Once seasonal variability in toxicant concentrations in sediment and biota can be factored into a relationship between these two ecosystem components, we need to construct a model defining bioavailability. Such a model must include a set of natural physico-chemical characteristics having a significant effect on toxic chemical concentration in the abiotic and biotic environments in order to assess accurately the effect of differential chemical contamination. The initial goals of this program are to provide the components of this model, so that criteria for sediment quality can ultimately be developed.

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Organic Chemicals in Sediments from the Lower Chesapeake Bay

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Many of the toxic organic chemicals affecting the marine environment are hydrophobic and associate with sediments. Sediments can accumulate the substances over long intervals and store them after the original source of the toxic material has been eliminated. Contaminated sediments can provide small but damaging amounts of the toxicant to the overlying water for decades. For example, more than 10 years after the discovery of Kepone in the James River, Virginia, much of the James' fisheries is still closed because Kepone levels are above federal action levels.

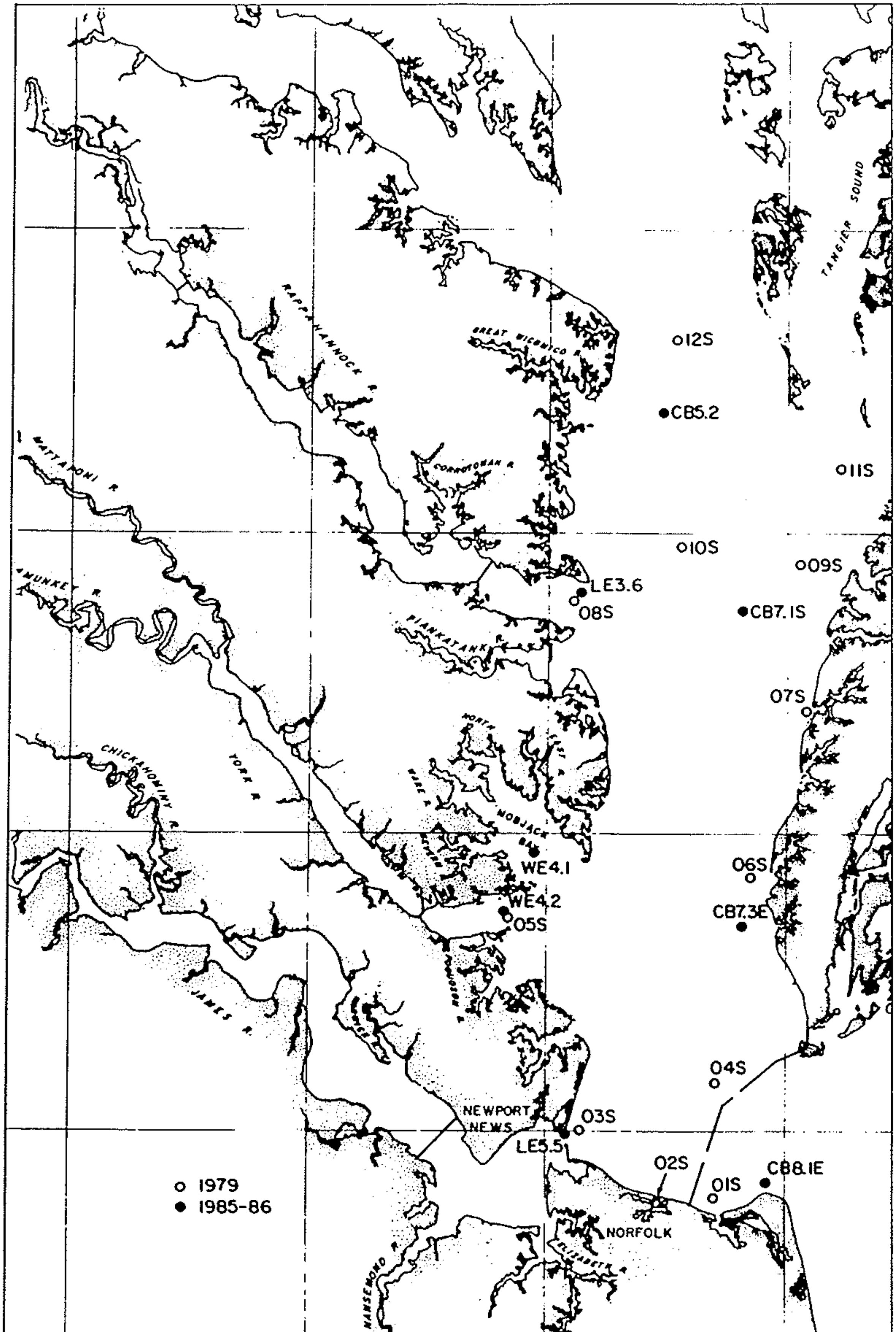
Monitoring programs for detection of hazardous organic chemicals in aquatic systems often take advantage of the accumulating and storing capability of bottom sediments. Concentrations of the chemicals are usually higher in the sediments than in water, thus facilitating analytical detection and quantitation, and the sediments integrate over time. This latter property enhances the detection of intermittent discharges, which otherwise may go undetected if water samples are not collected during a discharge event.

In the late 1970s, the first comprehensive monitoring program for toxic organic chemicals in the Chesapeake Bay was undertaken in the mainstem. Previously, most of the monitoring efforts of Virginia and Maryland scientists had focused on the tributaries because the human population densities are greater and agricultural activities more extensive on the rivers. The Bay proper was largely ignored. Funding from Virginia and the first Chesapeake Bay Program allowed scientists to develop and use chemical analytical methodologies to quantify and track hundreds of organic compounds in Bay sediments. The first set of samples was taken in the spring of 1979; the second in the fall of the same year. More samples were obtained in 1984 and 1985 with assistance from the second Chesapeake Bay program; findings of these studies are reported here.

SAMPLING

The sediment sampling locations are shown in Figure 1. Because one intent of the monitoring program was to determine the trace chemical content of the sediments, it was necessary to take precautions against contaminating the sample during collection. To achieve this, a stainless steel Smith-MacIntyre grab sampler was used. Before each sample was taken, the sampler was thoroughly rinsed with ambient water and then with "distilled in glass" methanol.

Another intent of the program was to determine temporal and spatial trends in concentrations, should they exist. Because the sedimentation rate in the mainstem of the Bay is usually lower than in its tributaries, recently deposited contaminants likely would be present in the uppermost portion of the sediment column. Therefore, after the sampler was returned to the surface, only the top 2 cm of sediment was removed. These sediments were placed in cleaned glass jars with Teflon-lined lids for storage. The samples were immediately refrigerated and were transferred to the laboratory within eight hours of collection. To compensate for small-scale inhomogeneities in the bottom sediments, five separate samples were collected at each site on each sampling event. For analysis, equal subsamples from each of the five replicates were composited and mixed to produce a sample. The composite samples were stored at -4^{o} C.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CORROTOMAN R.
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YORK R.
NORTH
EAST R.
WARE R.
MOBJACK BAY
POQUOSON R.
JAMES R.
NANSEMOND R.
ELIZABETH R.
NEWPORT NEWS
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o12S
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08S
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07S
WE4.1
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02S
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o 1979
● 1985-86
77°00'
50'
40'
30'
20'
10'
76°00'

Table 1. Particle size distributions for bottom sediments collected in 1984 and 1985.

	Sand and coarser (%)		Silt (%)		Clay (%)	
Station	1984	1985	1984	1985	1984	1985
CB 5.2	29.6	0.8	22.5	44.8	47.9	54.5
CB 7.15	20.6	20.6	49.0	50.0	30.4	29.3
LE 3.6	5.8	10.3	53.1	54.2	41.1	35.5
WE 4.1	4.2	4.4	53.8	57.1	42.1	38.5
WE 4.2	3.8	8.8	38.6	46.1	57.6	45.1
CB 7.3E	95.3	88.4	1.6	5.2	3.1	6.4
LE 5.5	34.4	96.3	26.2	0.9	39.4	2.0
CB 8.1E	75.2	82.2	13.9	9.8	10.8	9.0

ANALYTICAL METHODOLOGY

The first step of the analytic procedure was to remove water by freeze drying. A known amount of 1,1'binaphthyl was added to the dried samples, which allowed the analysts to compensate for varying extraction yields and losses. The samples were soxhlet extracted with dichloromethane to separate organic chemicals from the sediments.

Because sediments contain naturally occurring or biogenic organic substances, "clean-up" steps are usually required to separate these from the anthropogenic compounds of interest. This separation was achieved with gel permeation chromatography. The extracts were then separated into aliphatic, aromatic, and polar fractions by subjecting each "cleaned" extract to high-performance liquid chromatography. The aromatic and polar fractions were analyzed by glass capillary gas chromatography and glass capillary gas chromatography-mass spectrometry.

A detailed description of the analytical methodology can be found in Bieri et al. (1981).

RESULTS

The ability of sediment to assimilate and store chemicals is related to the particle-size distributions in the sediments. Finer-grained sediments contain a relatively higher surface area per unit mass than do coarser grained ones. Therefore, all other factors being equal, surface-associated chemicals are more concentrated in finer grained sediments. In addition, finer grained sediments will usually contain a higher proportion of naturally occurring organic matter. It follows that chemicals that partition to these natural organics would be more abundant in finer grained sediments.

Because of these factors, it is important to determine the particle size distribution in the sediment samples so that chemical concentrations found at one site can be compared with those at another. The particle size distributions for samples collected in 1984 and 1985 are shown in Table 1.

Hundreds of compounds were detected in some of the samples. Almost all of these were in the aromatic fraction. Table 2 lists some of the more abundant compounds for the four sampling periods. It should be noted that the stations sampled in 1984 and 1985 do not coincide exactly with those sampled in the 1979 program. Also, the analytical methodology was slightly modified after 1979 to resolve more compounds. Therefore, some caution is advised in comparing the 1979 data with those obtained later.

The concentrations of the total resolved aromatic fraction for all the sampling periods using data from the 1979 sample stations closest to those from 1984 and 1985 are given in Figure 2. It is important to reiterate the caution on comparing 1979 data with those from 1984 and 1985.

DISCUSSION

No polar compounds were detected in any of the samples; discussion will focus on the aromatic compounds. The most abundant compounds detected

Figure 1 (facing page). Location of stations in the lower Chesapeake Bay sampled for organic chemicals in sediments in 1979 and in 1985-1986.

in all four surveys were polynuclear aromatic hydrocarbons (PAHs). PAHs produced during the combustion of carbonaceous fuels such as coal, oil, and wood are called pyrogenic; others are naturally derived. Finding that most PAHs detected in the four surveys were pyrogenic probably reflects a broad-scale, low-level input from the atmosphere as well as riverine sources.

The fraction of naturally derived PAHs was low (4-8%) at all stations. This finding agrees with a study of several Chesapeake Bay tributaries (deFur 1985) in which the percentage of natural compounds in surface sediments was observed to decrease with movement downriver in all cases. The reasons for this decrease are not known.

The spatial distribution of concentrations appears to reflect both the particle size distribution in the sediments and input from rivers. Coarser-grained sediments, such as those found at stations CB 8.1E and CB 7.3E, contained low PAH levels. An exception to this general trend was for station LE 5.5 during the 1985 sampling. This station will be discussed below. The samples collected near river mouths were generally higher in PAH concentration than those further away, probably because the rivers deliver PAHs produced throughout their drainage basin.

There are too few stations to draw far-reaching conclusions about an area the size of the southern Chesapeake Bay, but some information may be gained by comparing the four samplings. Most stations showed a slight decrease in total concentration in 1985, but the changes were too small to be significant. As mentioned previously, the 1979 samples were not from the same sites as those collected later. The largest change was at station LE 5.5 in the Hampton Roads entrance, where total PAHs increased by a factor of approximately four. Qualitatively, this sample was similar to both the previous samples and the other stations in the present sampling, with all containing the array of pyrogenic

Table 2. Concentrations (mg/kg, or ppb) of compounds detected in sediments at stations LE 3.6, WE 4.2 and LE 5.5.

	Station LE 3.6				Station WE 4.2				Station LE 5.5			
Compound	Spring 1979	Fall 1979	1984	1985	Spring 1979	Fall 1979	1984	1985	Spring 1979	Fall 1979	1984	1985
Phenanthrene	10	24	28	29	5	8	26	32	11	47	22	100
Fluoranthene	16	59	63	56	26	16	54	58	29	52	51	410
Pyrene	12	58	64	55	21	18	49	67	34	46	40	380
Benzo(a)-fluorene	3	13	24	15	7	4	13	13	13	25	16	130
Benzo(a)-anthracene	5	30	29	16	12	9	28	17	18	30	21	140
Chrysene/triphenylene	7	39	44	29	18	16	39	34	37	47	35	170
Benzo(j,b,k) fluoranthenes						--	--			--	--	
Benzo(e)-pyrene	5	2	27	17	2	11	25	17	2	1	23	93
Benzo(a)-pyrene	4	35	33	19	18	12	26	19	22	18	23	130
Perylene	11	39	46	21	21	22	44	34	26	8	42	36
Benzo-(g,h,i)-	3	17	28	12	15	8	31	23	15	6	18	46

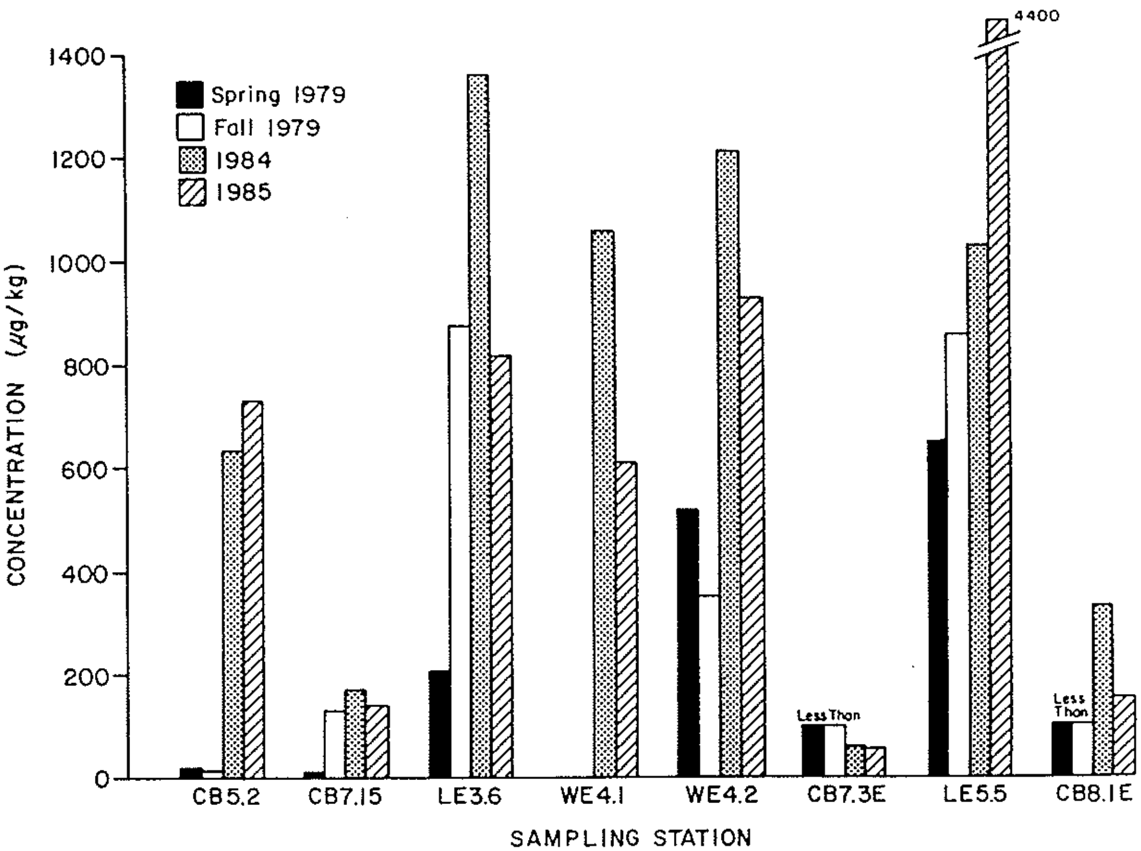

Figure 2. Concentrations of total resolved aromatic fraction in bottom sediments from the Chesapeake Bay.

PAHs referred to earlier. As transport of sediment and associated pollutants is dependent upon such variables as river flow, rainfall, dredging activities, and weather-induced circulation, the organic content of estuarine sediments may be highly variable over time. Recent flooding in the James River may have contributed large amounts of PAHs from there, as the observed total was similar to totals found in the upper James River in previous studies (Smith et al. 1985). The available data suggest that the increase in aromatic content from 1984 to 1985 should not be viewed as more than a natural fluctuation in sediment concentration.

Although PAH concentrations varied slightly between samplings, the variations were not large, and total PAH content at all stations was not excessively high. It is very likely that the differences were not significant.

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Organic Compounds and Metals in Selected Fish, Bivalve Molluscs, and Sediments of the Chesapeake Bay: Preliminary Results from the National Status and Trends Program

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The National Status and Trends Program (NS&T) of the National Oceanic and Atmospheric Administration (NOAA) makes a wide range of environmental measurements to assess impacts of human activity on coastal and estuarine regions. A major element of the program is evaluation of the effects of anthropogenic inputs into marine environments.

One source of concern is bioaccumulation, the process of biological uptake and retention by organisms of chemical contaminants from food, water, contact with sediments, or any combination of exposure pathways (Tetra Tech 1985). Many high-molecular-weight organic compounds that are not rapidly metabolized, as well as metals, tend to accumulate in body tissues of organisms. Some of these chemicals are concentrated many thousands of times above environmental levels; such concentrated levels are potentially high enough to cause acute or chronic disorders in members of an affected population.

Major components of the NS&T Program include: a benthic surveillance project, to assess chemical contaminants in surficial (upper 3 cm) bottom sediments and in livers of bottom-feeding fish, and histopathological disorders in those bottomfish, at approximately 50 locations around the coastal United States; a mussel watch project, to assess chemical contaminants in sediments and bivalve tissues, at 150 sites nationwide; and a historical database project, to consolidate data on body burden for chlorinated organic compounds from a wide range of federal, state, and local sources into a single, easily accessible database. Each of these component projects yields data relevant to assessing bioaccumulation and broader related impacts in the Chesapeake Bay. The NS&T program is completing analyses from early sampling cycles, and preliminary interpretive efforts by the Ocean Assessments Division of NOAA have begun. Some results from the Chesapeake Bay, and preliminary interpretations of them, are summarized below.

1984 BENTHIC SURVEILLANCE RESULTS

The target fish in the Chesapeake Bay was the juvenile Atlantic croaker *(Micropogonias undulatus)*, which was also sampled at benthic surveillance sites in eight other areas. Trawl samples in the Chesapeake Bay were made in July 1984. Uptake and metabolic processes involving contaminants may differ with species. Therefore, comparisons of contaminant body burden data from the Chesapeake Bay are restricted to other sites where Atlantic croaker were collected and analyzed: Pamlico Sound, NC; Charleston Harbor, SC; Mobile Bay, AL; Mississippi River Delta, LA; Galveston Bay, TX; San Antonio Bay, TX; Corpus Christi Bay, TX; and Lower Laguna Madre, TX. Figure 1 illustrates NS&T bottom trawl locations and sediment sampling sites in the Chesapeake Bay for 1984, the first year for sampling under the benthic surveillance project.

Analyses of bottom sediments and croaker liver tissue for polychlorinated biphenyls (PCBs) are incomplete. Final results will include total concentration values for PCBs by level of chlorination (e.g., dichlorobiphenyls). Results for eight congeners

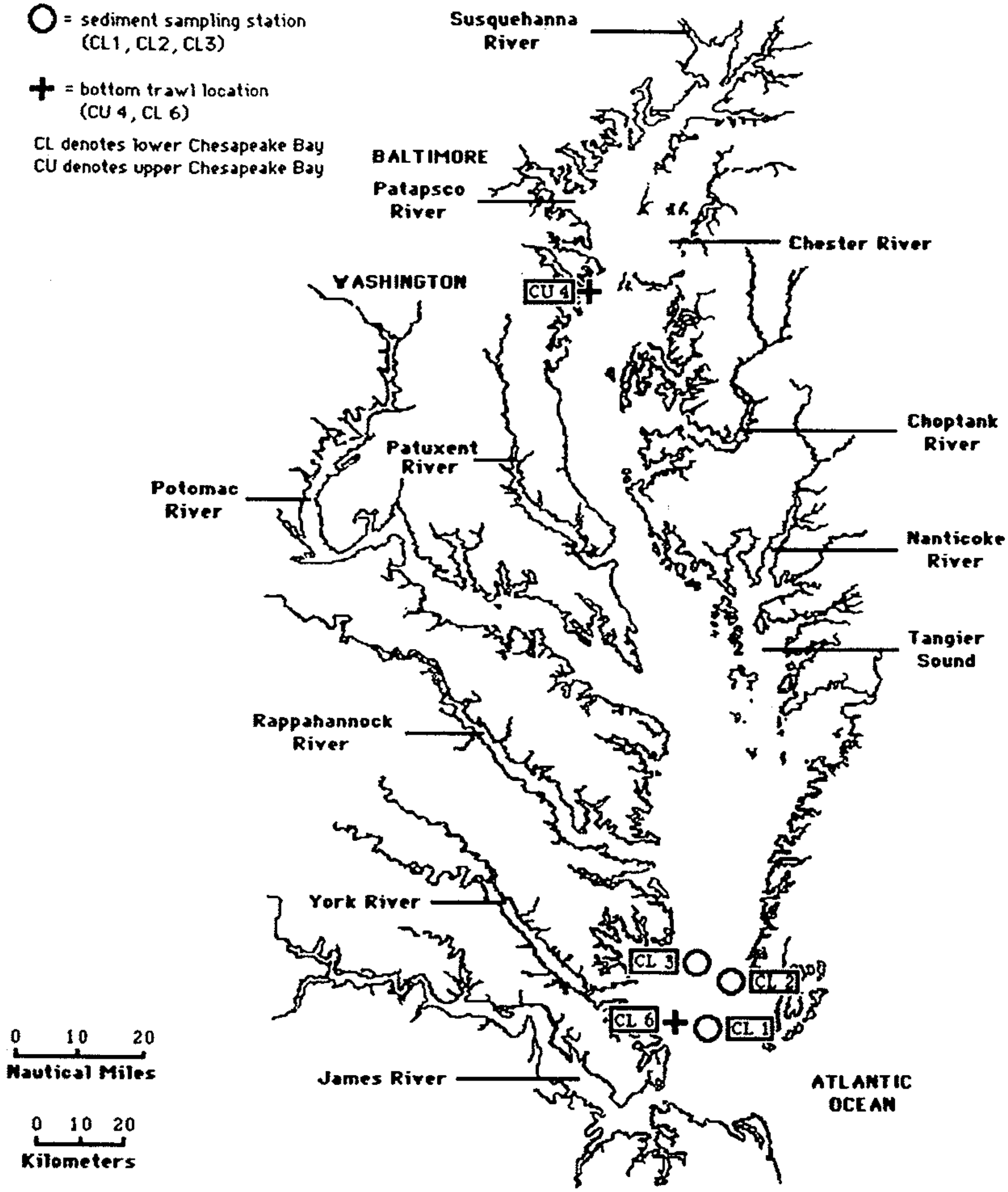
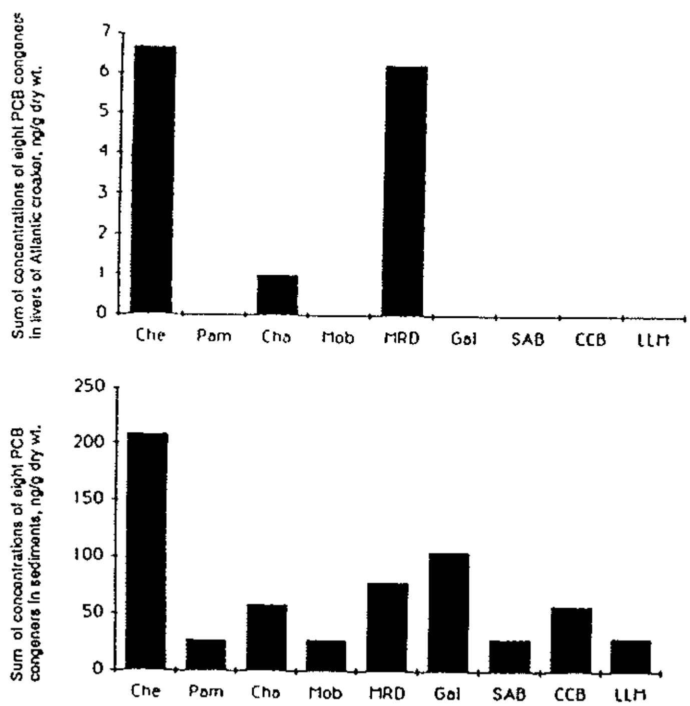


Figure 1. NS&T stations for bottom trawling and sediment sampling in the upper (CU) and lower (CL) Chesapeake Bay in 1984.

Figure 2. Sums of concentrations of eight congeners of polychlorinated biphenyls (those used as calibration standards) in sediments and in livers of Atlantic croaker at NS&T benthic surveillance sites. LLM = Lower Laguna Madre, TX; CCB = Corpus Christi, TX; SAB = San Antonio Bay TX; Gal = Galveston Bay, TX; MRD = Mississippi River Delta, LA; Mob = Mobile Bay, AL; Cha = Charleston Harbor; Pam = Pamlico Sound, NC; Che = Chesapeake Bay, VA.



utilized as calibration standards[1] are available now. Preliminary assessments of sediment residues and body burdens for Atlantic croaker are therefore possible, at least on a relative basis. Of the nine sites examined here the one in the lower Chesapeake Bay yielded the highest values (6.70 ng/g dry weight) for the sum of eight PCB congeners in sediment. Concentrations at six of the locations were below analytical detection limits. Values for the sum of the same eight congeners were also highest for Atlantic croaker from the Chesapeake Bay. The croaker liver tissues from the Chesapeake Bay contained higher sum concentrations, by at least a factor of 2 (209 ng/g dry weight) than did liver tissues from the other eight sites (Figure 2).

The Chesapeake Bay is the only site of the nine where data for total PCB values, not just the sum of calibration standard congeners, are available. Three composites of 10 livers each (30 fish total) were analyzed. Values for the three composites were 887, 965, and 1,470 ng/g dry weight. The congener PCB concentration of 6.70 ng/g dry weight corresponded to a total PCB value of 51.4 ng/g dry weight, while the congener PCB concentration of 209 ng/g dry weight for liver tissue was associated with a total PCB value of 1110 ng/g dry weight.

Results are also available for total PCBs for other parts of the country, although not for areas along the southeast Atlantic and Gulf of Mexico. These data, from sites along the northeast Atlantic and the Pacific coasts, permit a broader perspective on PCB contamination in the Chesapeake Bay than does the relatively small subset of results from the nine croaker sites. The total PCB concentration in sediments from the Chesapeake Bay site was lower than at 12 of the 29 benthic surveillance sites for which the results are available. The total PCB concentration in sediment of 51.4 ng/g dry weight in the Chesapeake Bay was at the lower end of the range of available results (3.19 ng/g dry weight at Coos Bay, OR, to 17.1 ng/g dry weight at Boston Harbor, MA).

DDT and its primary metabolites, DDE and DDD, have been identified as having a very great potential for bioaccumulation (Dillon and Gibson 1985; Ballou et al. 1985; Konasewich et al. 1982). Total DDT (tDDT) is considered here as the sum of DDT, DDD, and DDE concentrations. Results for tDDT are used in the benthic surveillance project for preliminary assessment of bioaccumulation in the Chesapeake Bay.

Sediment concentrations of tDDT at the nine sites where Atlantic croaker were sampled ranged from below detection, at the four Texas sites, to 7 ng/g dry

[1] 2,4-dichlorobiphenyl; 2,5,4 - trichlorobiphenyl; 2,4,2, 4-tetrachlorobiphenyl; 2,4,5,2,5-pentachlorobiphenyl; 2,4,5,2,4,5-hexachlorobiphenyl; 2,3,4,5,6,2,5-heptachlorobiphenyl; 2,3,4,5,2,3,4,5-octachlorobiphenyl; and 2,3,4,5,6,2,3,4,5-nonachlorobiphenyl.

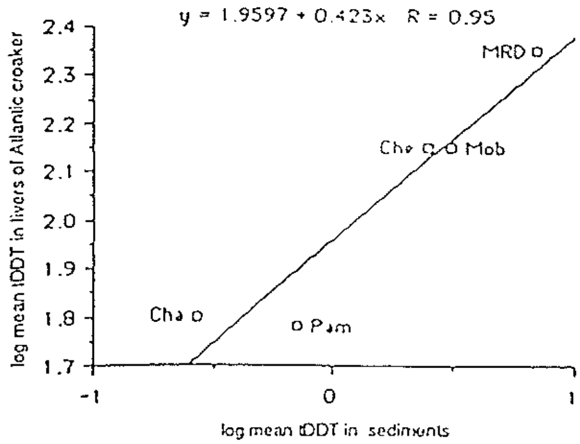


Figure 3. Scatter plot of log mean tDDT level in Atlantic croaker liver vs. log mean tDDT level in sediment (where tDDT in sediment is above detection levels), for NS&T benthic surveillance sites. For identification of sites, see Figure 2.

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weight, at the Mississippi River Delta site. Croaker liver concentrations of tDDT ranged from 29 ng/g dry weight, at the San Antonio Bay site, to 224 ng/g dry weight, at the Mississippi River Delta site. By comparison, the sediment value and the liver value for the Chesapeake Bay site were 3 ng/g dry weight and 140 ng/g dry weight, respectively. Statistical analysis of the relationship, using Spearman's rank correlation coefficient procedure (Johnson 1984) yielded a significant positive coefficient of correlation of 0.752, at the 95% confidence level, between tDDTs in sediment and tDDTs in Atlantic croaker livers. Although this correlation is evidence of a relationship between tDDT in sediments and tDDTs in livers of Atlantic croaker, it is not a statement that concentrations in livers of Atlantic croaker result from sediment concentrations.

However, Matsumura has demonstrated that concentrations of DDT in fish are at least in part dependent on environmental levels, and has illustrated the relation by plotting log DDT body burden vs. log environmental concentration (Matsumura 1977). Benthic surveillance results for sites where Atlantic croaker was the target species and sediment concentrations were detectable yielded a scatter plot of log mean liver tDDT vs. log sediment tDDT (Figure 3), showing good fit of the linear regression line (r=0.95), and providing more direct evidence of a link between sediment concentrations and body burdens of tDDT. Nevertheless, this evidence should be interpreted with caution, because the sample size was limited, and other influences are known to affect contaminant uptake in fish (e.g., temperature and presence of other chemicals).

Interpretation of histopathological results presents a problem. Causal relationships with environmental factors are difficult to infer. Also, there are inherent species differences in histopathogy; that is, certain types of disorders appear to be more prevalent in some species than in others. Given these caveats, however, correlations can be calculated, using Spearman's rank correlation coefficient procedure. Such a calculation shows a significant positive correlation coefficient of 0.86, at a 98% confidence level, between total measured concentrations of aromatic hydrocarbons in sediment and occurrence of five histopathological disorder [2] (in terms of summed percentage) in Atlantic croaker from the seven benthic surveillance sites where the species was examined for histopathology. The site in the lower Chesapeake Bay, where the concentration of aromatic hydrocarbons in sediment is 219 ng/g dry weight, ranked third with respect to such concentrations in sediment at all sites measured (the range is from below detection limits, at the Lower Laguna Madre site, to 803 ng/g dry weight, at the Charleston Harbor site). However, that site ranked first for the sum of percentage occurrence of the selected disorders. Of the many histopathological disorders observed in bottomfish, it is the preneoplastic and neoplastic (roughly "precancerous" and "cancerous") lesions that have been correlated significantly with environmental contamination (Malins et al. 1984; Murchelano and Wolke 1985). When approximately 100 Atlantic croaker and spot *(Leiostomus xanthurus)* from locations in the upper and lower Chesapeake Bay (38° 57.8'N/76° 25.2'W and 37° 10.1'N/76° 14.7'W) were examined, no lesions of these types were found.

1986 MUSSEL WATCH RESULTS

Preliminary results from NS&T mussel watch sampling include data from six Chesapeake Bay sites (Figure 4) for major and trace elements in sediments and in American oyster *(Crassostrea virginica)* tissue. Data for organic compounds will be available in the future.

Evaluation of results for metal concentrations in estuarine sediments must take into account natural variability and the associated difficulties in determining

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2 Cholangitis, hepatic necrosis, necrotizing granuloma in the kidney, hyaline degeneration, and melanin-macrophage proliferation in the kidney.

background or "base-line" concentrations. Goldberg et al. (1979) used ratios of metal to aluminum to assess temporal trends of contamination in the Savannah River estuary; others have agreed that this is a useful approach for evaluation of anthropogenic inputs (H.L. Windom, Skidaway Institute of Oceanography, pers. comm.). NS&T results for six trace elements (Ag, Cd, Cr, Cu, Hg, and Pb) plotted against aluminum in sediments of the six Chesapeake Bay mussel watch sites were compared with 1984 results for sediments from 15 benthic surveillance sites along the southeast Atlantic and Gulf coasts. From plots of metal-to-aluminum ratios, certain inferences can be made. Scatter-plot distributions for the ratio (Figure 5) showed patterns similar to those for sites along the southeast Atlantic and Gulf coasts; however, values for

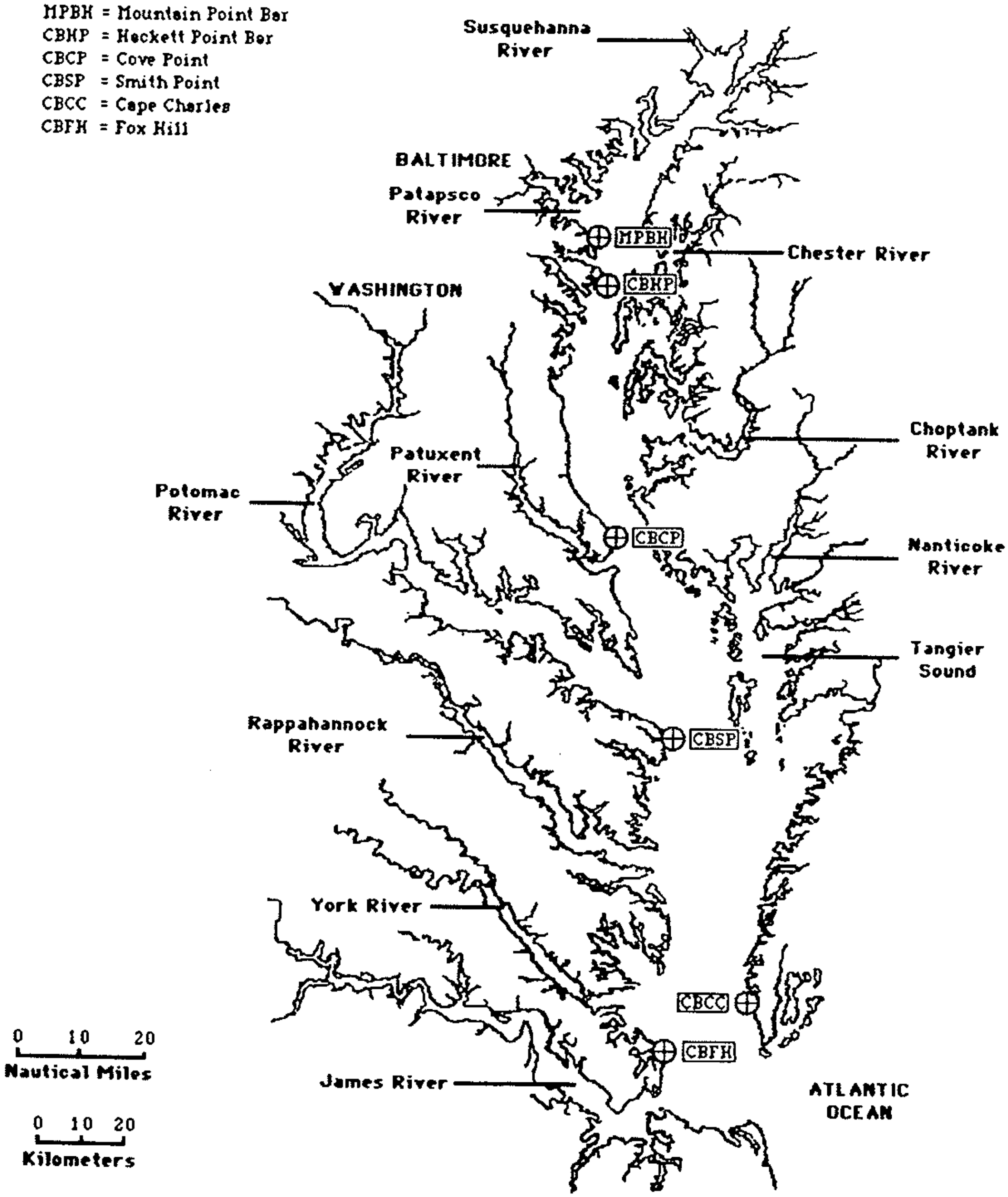


Figure 4. NS&T mussel watch locations in the Chesapeake Bay, 1986.

stations within the Mountain Point Bar and Hackett Point sites in the upper Chesapeake Bay. indicated levels of Ag, Cu, Hg, and Pb higher than those at the other 19 sites. Individual station values for the Mountain Point Bar and Hackett Point station for Cd and Cr also were above the linear regression line of "normal" values.

Body burden data for several metals (Ag, Cd, Cu, Ni, Sn, and Zn) showed a general spatial trend of increasing concentration in tissue with increasing distance up the bay (northward). Results for Cu, Ag, and Sn showed an order of magnitude increase in concentration between the Cape Charles site at the southeast end of Chesapeake Bay and the Mountain Point Bar site south of Baltimore. The three other trace elements show a similar but less pronounced trend. This pattern for body burden data parallels that for metal contamination of sediments.

In contrast to the pattern for metal concentrations in oyster tissue, the pattern for As is the inverse, with the minimum at the Mountain Point Bar site, and the maximum at the Cape Charles site. Figure 6 shows spatial patterns for seven metals. Mean concentration values for all 16 major and trace element analytes in bivalves are listed in Table 1, with associated ranges. As results for elements in bivalves become available for other mussel watch sites, the relative importance of these Chesapeake Bay results should become clearer.

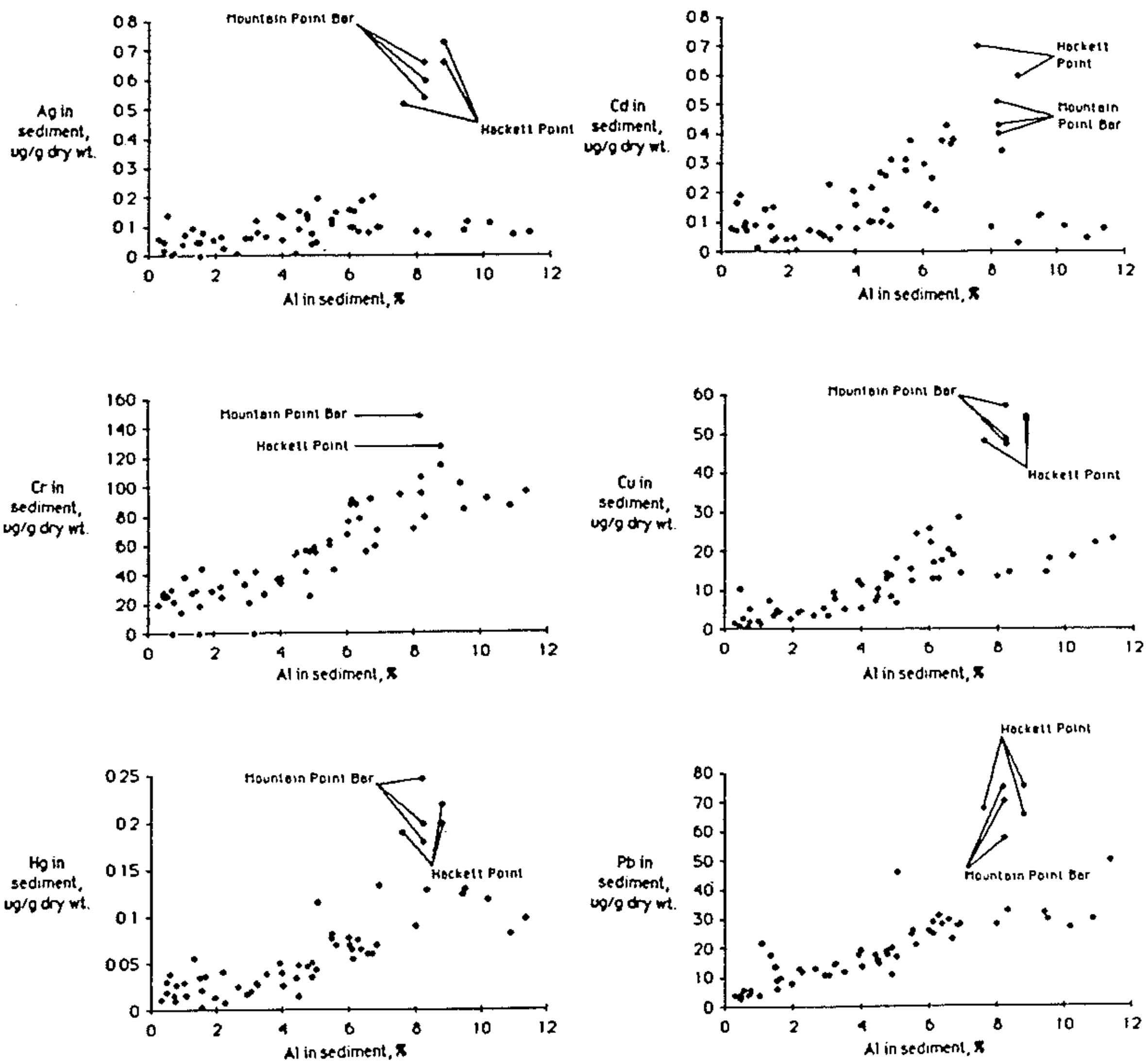
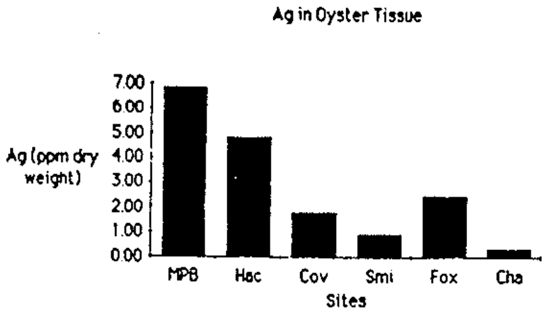
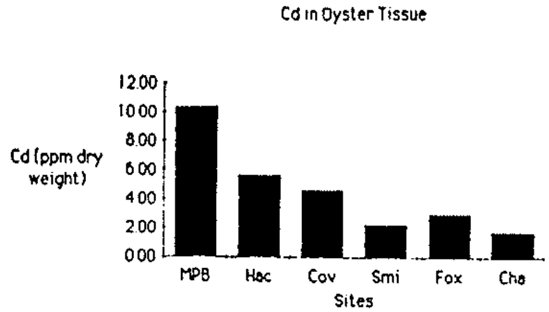
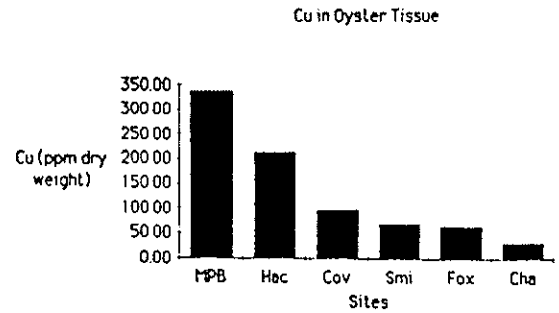


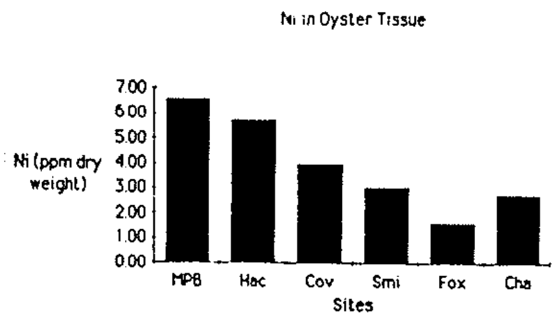
Figure 5. Scatter plots of concentrations of selected metals against aluminum for sediments. Stations of note for the upper Chesapeake Bay are identified.

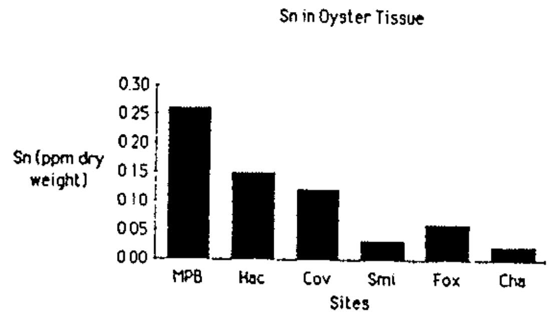
Figure 6 (facing page). Body burden levels of selected metals in *Crassostrea virginica* at NS&T mussel watch sites in the Chesapeake Bay.

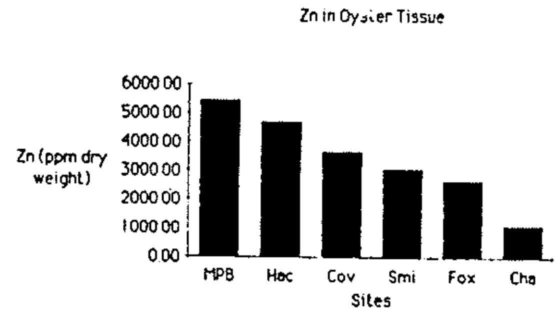




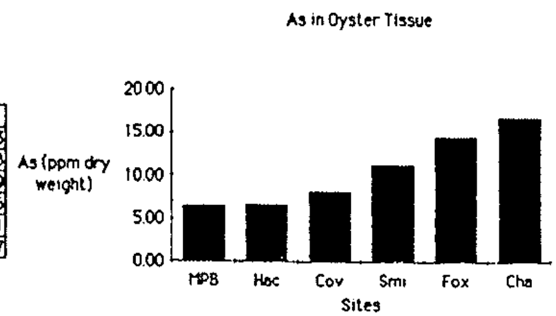








Site Abbrev.	Site Name	Lat. (N)	Long. (W)
MPB	Mountain Point Bar	39 04.42	76 24.73
Hac	Hackett Point	38 59.06	76 24.08
Cov	Cove Point	38 18.81	76 23.09
Smi	Smith Point	37 47.63	76 17.06
Fox	Fox Hill	37 05.97	76 18.71
Cha	Cape Charles	37 17.63	76 00.57



CHESAPEAKE BAY DATA IN THE NS&T HISTORICAL DATABASE

The NS&T historical data base will include data for about 4,000 Chesapeake Bay samples taken since 1965; about 1,100 Chesapeake Bay samples have been entered already. The largest portion of these data are for the American oyster (*C. virginica*), represented by some 770 data points.

The most spatially and temporally complete data sets for the Chesapeake Bay that are available in the database are from surveys of contaminants in shellfish by Butler (1973) and Butler et al. (1978) (Figures 7 and 8). From Butler (1973) data, it is obvious that

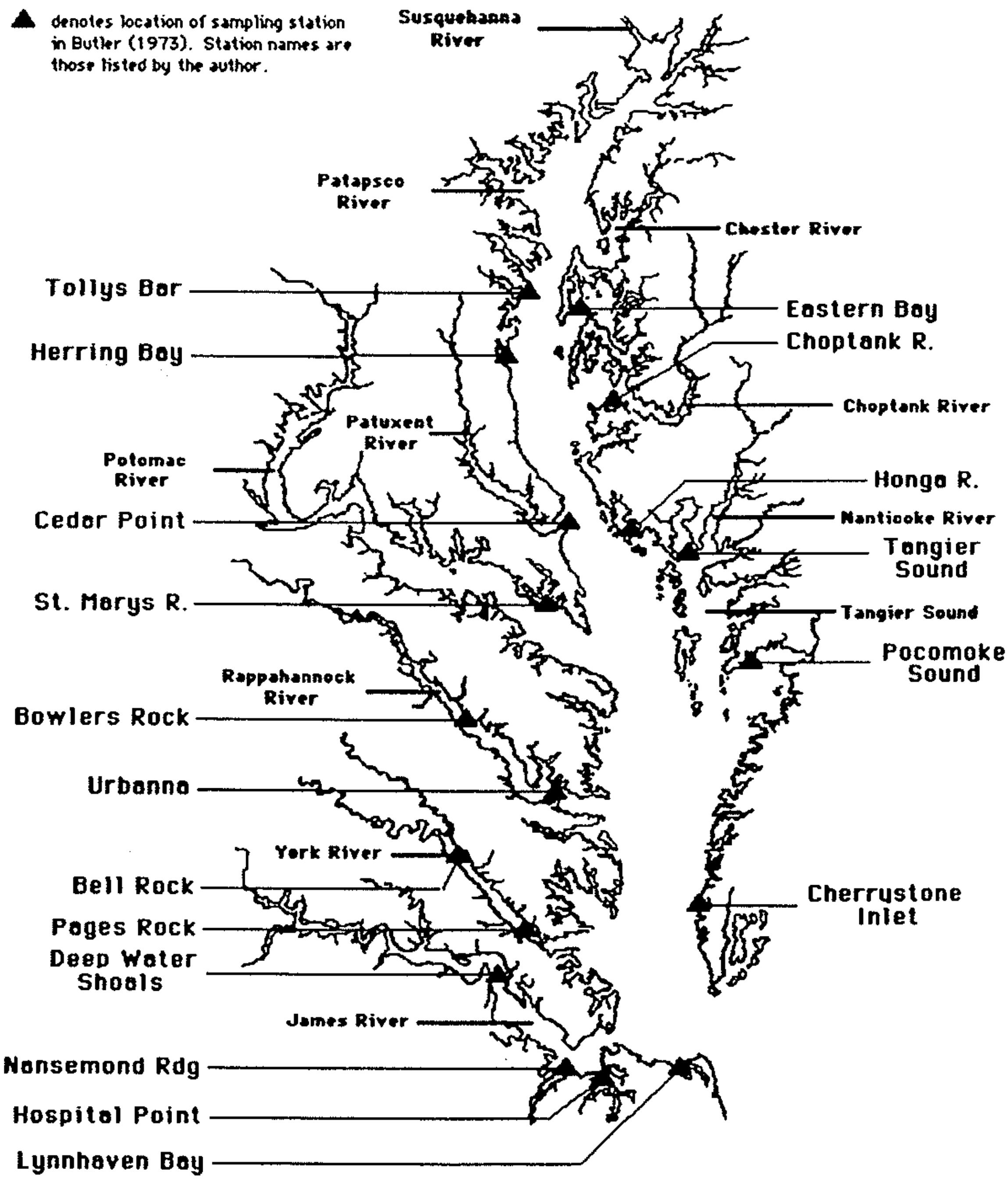


Figure 7. Locations and names of sample sites for Butler shellfish stuay contained in NS&T historical database.

Table 1. Body burden levels of major and trace elements in tissues of the American oyster (*Crassostrea virginica)* at NS&T mussel watch sites in the Chesapeake Bay.

Element	Mountain Pt.	Hackett Pt.	Cove Pt.
	Mean (range) analyte values (µg/g dry weight, n = 3)		
Aluminum	18.6 (13.7-22.0)	16.10 (6.02-32.2)	28.2 (14.1-54.5)
Silver	6.88 (6.5-7.3)	4.86 (4.41-5.14)	1.81 (1.72-1.97)
Arsenic	6.52 (6.04-7.16)	6.64 (6.37-7.01)	8.12 (7.07-9.04)
Cadmium	10.40 (9.47-11.0)	5.67 (5.34-6.16)	4.68 (4.38-4.86)
Chromium	0.88 (0.8-0.99)	0.27 (0.23-0.29)	0.18 (0.15-0.21)
Copper	340 (315-374)	213 (197-229)	97.80 (89.9-109)
Iron	170 (165-177)	170 (156-192)	221 (208-235)
Mercury	0.02 (0.02-0.03)	0.01 (0.00-0.02)	0.04 (0.04)
Manganese	9.13 (7.3-10.4)	6.83 (5.2-8.5)	8.93 (6.4-11.2)
Nickel	6.57 (6.21-7.18)	5.73 (5.26-6.08)	3.98 (3.3-4.73)
Lead	0.34 0.27-0.40)	0.31 (0.27-0.34)	0.31 (0.23-0.43)
Selenium	3.60 (3.29-4.03)	3.07 (2.71-3.26)	3.11 (2.63-3.44)
Silicon	<467 (<450-<490)	<457 (<440-<480)	<477 (<460-<500)
Tin	0.26 (0.24-0.28)	0.15 (0.04-0.21)	0.12 (0.11-0.13)
Thallium	<0.02 (<0.02)	<0.02 (<0.02)	<0.02 (<0.02)
Zinc	5480 (4960-5780)	4730 (4280-5200)	3960 (3300-4190)

Element	Smith Pt.	Fox Hill	Cape Charles
	Mean (range) analyte values (µg/g dry weight, n = 3)		
Aluminum	21.5 (16-31.8)	53.1 (50.2-55.5)	51.4 (42.1-69.7)
Silver	0.92 (0.86-0.98)	2.48 (2.29-2.62)	0.38 (0.38-0.39)
Arsenic	11.20 (10.7-11.9)	14.5 (13.7-15.2)	16.7 16.2-17.7)
Cadmium	2.25 (2.2-2.29)	2.96 (2.91-3.04)	1.77 (1.68-1.84)
Chromium	0.12 (0.11-0.12)	0.19 (0.18-0.20)	0.15 (0.11-0.17)
Copper	71.1 (64.6-79.4)	66.90 (58.2-77.4)	31.8 (31.3-32.2)
Iron	174 (162-189)	253 (248-258)	177 (170-187)
Mercury	9.63 (8.2-10.5)	15.10 (13.1-16.8)	7.87 (5.6-11.2)
Nickel	3.06 (2.75-3.28)	1.62 (1.34-1.99)	2.78 (2.42-3.04)
Lead	0.17 (0.09-0.22)	0.30 (0.18-0.42)	0.23 (0.02-0.36)
Selenium	3.79 (3.59-4.13)	2.04 (1.48-2.40)	1.76 (1.57-1.89)
Silicon	<530 (<500-<560)	<603 (<570-<620)	<527 (<500-<540)
Tin	0.03 (0.03-0.04)	0.06 (0.06-0.07)	0.02 (0.02-0.03)
Thallium	<0.02 (<0.02)	<0.02 (<0.02)	<0.02 (<0.02)
Zinc	3100 (2810-3490)	2690 (2391-3225)	1120 (1080-1160)

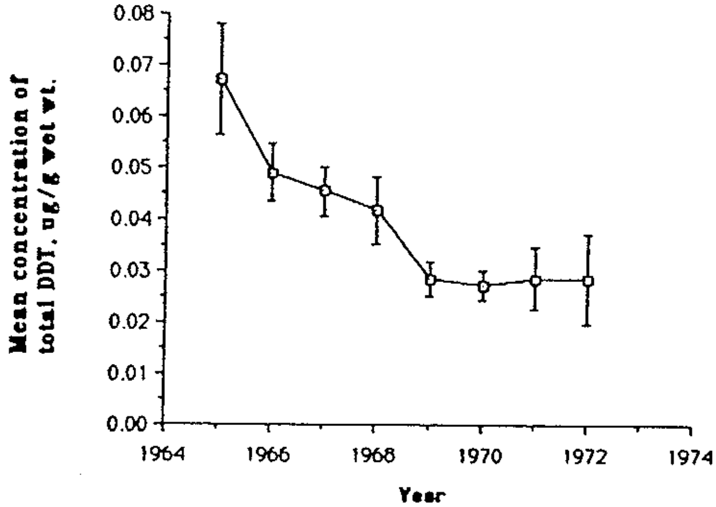


Figure 8. Temporal trend of mean concentrations of total DDT in tissue of *Crassostrea virginica* in Chesapeake Bay (Butler 1973). Error bars indicate standard error. Data are contained in NS&T historical database.

tDDT in Chesapeake Bay American oysters decreased from 1965 to 1972. More recent data, also contained in the NS&T database, from Butler et al. (1978) and Farrington et al. (1982) indicate that in 1976 and 1977, levels of DDE (a relatively persistent DDT metabolite) in Chesapeake Bay oysters were either very low (0.7-3.6 ppb wet weight) or below detection limits.[3]

SUMMARY

Chemical data from the NS&T program are becoming available for broad-scale statistical treatment and interpretation. Initial results from this long-term effort should be regarded as preliminary. It is difficult to draw firm conclusions; results of attempts at meaningful evaluation are subject to change as more results are generated. Further expected data from NS&T projects that will be important in assessing the health of the Chesapeake Bay are:

Benthic Surveillance. Concentrations of major and trace elements in liver tissue of selected bottomfish; complete assessments of PCB concentrations in sediments and liver tissues of selected bottomfish.

Mussel Watch. Concentrations of selected elements and organic compounds in sediments and oyster tissue.

Historical Database. A vast quantity of data and information on contaminant burdens of selected fish and shellfish, primarily acquired from state agencies, and currently being entered into the NS&T historical database.

Conclusions Based on NS&T Program Data. Results that are currently available allow the following observations that pertain to the Chesapeake Bay:

(1) DDT in sediments is correlated significantly with DDT in liver tissue of Atlantic croaker for nine benthic surveillance sites.

(2) Based on benthic surveillance results, the relationship between DDT in liver tissue of Atlantic croaker and DDT in sediments can be expressed, in a log-log plot, by the equation $y = 1.9597 + 0.423X$.

(3) There is a significant positive correlation between concentrations of aromatic hydrocarbons in sediments and occurrences of selected histopathological disorders in Atlantic croaker for seven benthic surveillance sites, including the one in the Chesapeake Bay.

(4) Other histopathological disorders that have been found to correlate with environmental contamination by organic compounds were not observed in Chesapeake Bay samples of Atlantic croaker and spot.

(5) Sediment and oyster samples from mussel watch sites in the upper Chesapeake Bay have higher concentrations of trace elements than other Chesapeake sites and other locations along the southeast Atlantic and Gulf coast regions.

(6) Concentrations of DDT and DDT metabolites in oyster tissue declined from 1965 to 1977.

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[3] The wet weight data of Farrington et al. (1982) were converted to dry weight values for comparison to Butler's data using a factor, suggested by Farrington et al., of 50 ng/g dry weight = 6 ng/g wet weight.

The NS&T program provides assessments of discrete portions of the marine environment, which, when integrated over time and area, can enable large-scale trends to be discerned. As results of the NS&T program help in framing intensive examinations of the coastal and estuarine environment, they complement ongoing and future research investigations of the Chesapeake Bay.

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Phytoplankton and Microzooplankton in the Upper Chesapeake Bay

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The plankton portion of the Chesapeake Bay Water Quality Program was initiated in August 1984 from the Benedict Estuarine Research Laboratory (BERL) of The Academy of Natural Sciences. The BERL field program was undertaken in conjunction with field efforts conducted by the field staff of the Maryland Office of Environmental Programs (MD OEP) in the Maryland portion of Chesapeake Bay and the Patuxent, Potomac, Patapsco, Chester, and Choptank Rivers. The sampling program was designed to measure water quality and specific plankton components (see below) at 16 primary stations generally located in three distinct physical segments of the main Bay and tributaries, i.e., fresh headwater regions, saline regions of the lower Bay and mouths of the principal tributaries, and the transition or mixing regions between these two salinity extremes (Figure 1).

The plankton program was designed to collect data in four distinct elements: (1) species composition and density of phytoplankton, (2) species composition and density of microzooplankton (>44 µm), (3) primary production, and (4) vertical and horizontal distributions of chlorophyll, at the 16 primary stations 16-18 times over the year. Samples were collected monthly from October through March (dependent on open water in the winter) and biweekly from April through September. At each station, vertical distributions of temperature and salinity determined sampling depths for a "surface mixed layer" above the pycnocline and a sub-pycnocline "bottom layer". Water from five depths in each layer was pooled in composite samples twice at each station, yielding two surface replicates and two bottom replicates subsequently subsampled for phytoplankton. Water from these same depths was also pumped through 44-µm mesh nets to collect microzooplankton, initially generating two surface and two bottom samples. Laboratory analyses of these samples proved too time-consuming, however, and the two surface samples were composited into one, the two bottom into another.

Estimates of primary production and chlorophyll were obtained from the surface composite samples collected at each of the primary stations, with use of ^{14}C techniques modified from Strickland and Parsons (1972), with short incubation periods in on-deck, water-cooled incubators equipped with cool-white fluorescent lighting. Integrated rates of carbon fixation were subsequently estimated by the method of Keefe et al. (1981) employing euphotic zone depth and mean day length for each month.

With use of *in vivo* fluorescence techniques and subsequent calibration with active chlorophyll *a* from discrete samples collected simultaneously, vertical distributions of chlorophyll were obtained at each of the primary stations and at several other stations in the mainstem Bay and Patuxent River routinely sampled in the OEP water-quality field program (see Appendix 3 for additional secondary stations). In addition, horizontal distributions of chlorophyll were obtained during ship transit between stations in the mainstem Bay and Patuxent River with use of flow-through *in vivo* fluorescence techniques.

This report summarizes chlorophyll *a* and primary production data for August 1984 through March 1986, and phytoplankton and microzooplankton data for August 1984 through July 1985. Data are presented for the upper Bay mainstem followed by summaries for the upper Bay's principal tributaries, the Potomac and Patuxent Rivers.

PHYTOPLANKTON

Maryland Portion of the Chesapeake Bay

Distinct spatial and temporal patterns were observed in all phytoplankton parameters in the Bay mainstem. Spatial heterogeneity probably reflects the horizontal distribution of fresh water from the Susquehanna River down-bay and the effects of bottom topography on circulation. Temporal patterns are a product of seasonal distributions of light and hence water temperature and water-column stratification/destratification. These same factors probably control plankton distributions in the tributaries as well.

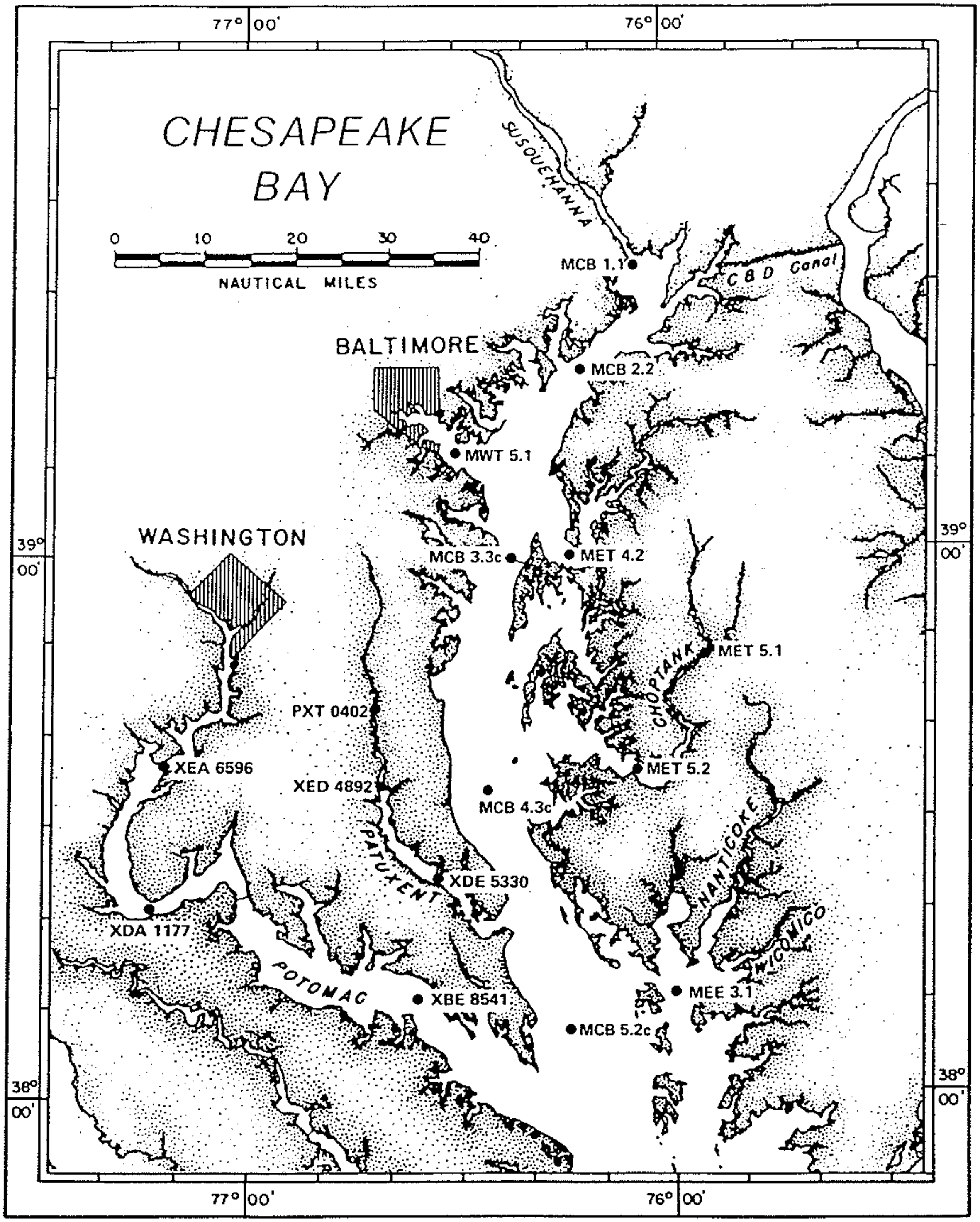


Figure 1. Primary station locations in the phytoplankton and microzooplankton component of the Chesapeake Bay Water Quality Program.

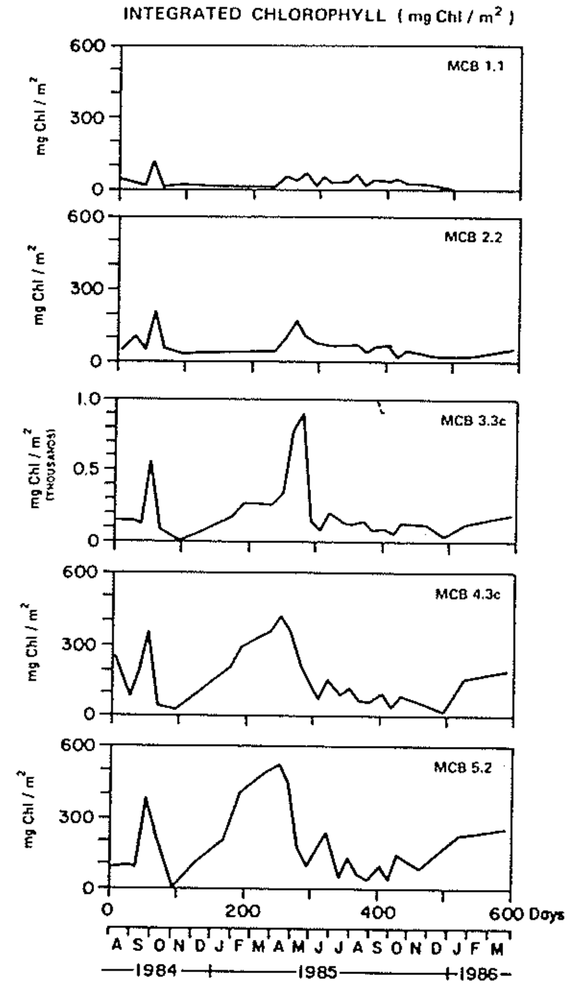


Figure 2. Integrated chlorophyll concentrations (mg/m^2) in the mainstem of the Chesapeake Bay from August 1984 through March 1986. Stations MCB 1.1 and MCB 2.2 represent freshwater and oligohaline (mixing or transition zone) regions, respectively; MCB 3.3C, MCB 4.3C, and MCB 5.2 represent mesohaline stations.

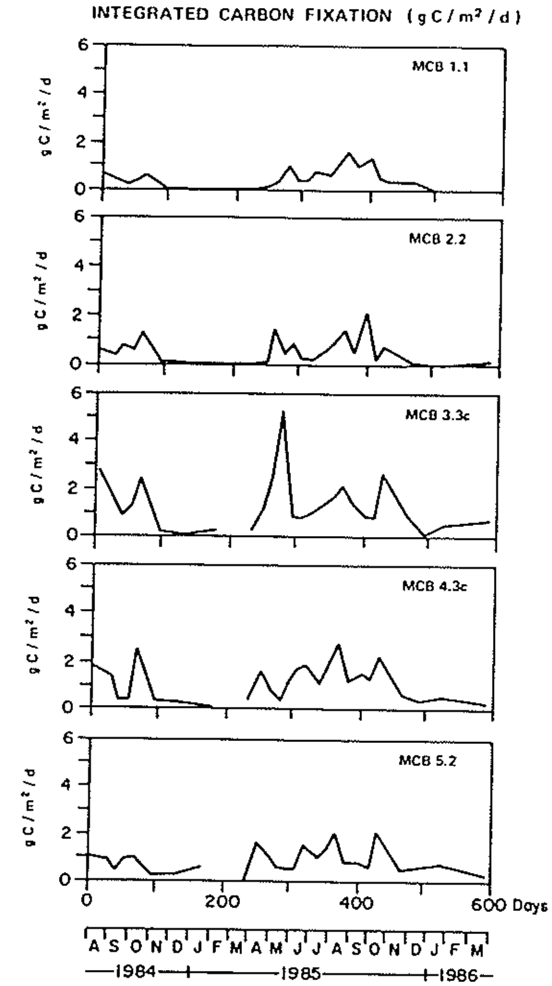


Figure 3. Integrated primary production (gC/m^2 per day) in the mainstem of the Chesapeake Bay from August 1984 through March 1986. Stations MCB 1.1 and MCB 2.2 represent freshwater and oligohaline (mixing or transition zone) regions, respectively; MCB 3.3C, MCB 4.3C, and MCB 5.2 represent mesohaline stations.

Relative to the lower mesohaline portions of the Bay, the freshwater (MCB 1.1) and oligohaline (MCB 2.2) regions were characterized by low chlorophyll concentrations and primary production over the 20-month period. These lower values reflected high turbidity in the water column as well as shallow water depths. However, as noted in the three stations in the lower Maryland portion of the Bay, levels of chlorophyll (Figure 2) and carbon fixation (Figure 3) were high during late summer and early fall and during the late winter and spring periods, a pattern typical of temperate regions. Levels of chlorophyll in the upper Bay (MCB 1.1) were always <120 mg/m^2, with concentrations <25 mg/m^2 from October through December 1984. In the region of the turbidity maximum (MCB 2.2), chlorophyll levels were higher, with fall and spring maxima at concentrations of 212 and 169 mg/m^2, respectively. Carbon fixation at both stations also followed the same pattern, with spring and fall peaks (Figure 3). However, higher water temperatures and light during the summer permitted continued photosynthetic carbon fixation, which resulted in elevated summer rates, another pattern typical of temperate phytoplankton assemblages. Carbon fixation in the fall reached approximately 0.6 and 1.2 gC/m^2 per day for assemblages at MCB 1.1

and MCB 2.2, respectively, declining to minimal rates (<0.1 gC/m^2 per day) in samples collected during ice-free winter periods. Maximal summer rates were 1.6 and 2.2 gC/m^2 per day at the two stations.

Phytoplankton densities throughout the Bay were dominated by small, unidentified coccoid cells, tentatively assigned to the cyanobacteria (blue-green algae) (Figure 4). Total cell densities at MCB 1.1 and MCB 2.2 ranged from 7.1-44.2 x 10^6 cells/liter from August through October, then increased in November to 236 x 10^6 and 51 x 10^6 cells/liter, respectively. The increase was attributable to the small coccoid cells, with >231 x 10^6 and 43 x 10^6 cells/liter in the samples from the two stations. After ice thaw, in March 1985, total cell densities at the upper Bay station were 4.1 and 6.6 x 10^6 cells/liter in the surface and bottom samples, respectively. Densities subsequently increased through May, with diatoms (unidentified pennates and several centrics, including *Cyclotella* spp.) displacing the small unidentified coccoid as the dominant phytoplankton group in April and early May. The small coccoid thereafter resumed dominance through the summer, with total cell densities reaching 86 x 10^6 cells/liter in the surface mixed layer at MCB 1.1 on 24 July 1985. Major differences between phytoplankton assemblages in the two upper Bay stations were attributable to an abundance of chlorophytes (*Scenedesmus quadricauda*) at MCB 1.1 and their absence at MCB 2.2, as well as large variations in total contributions of cyanobacteria.

Station MCB 3.3C was characterized by the highest chlorophyll *a* concentrations (Figure 2) and carbon fixation rates (Figure 4), probably because this station lies at the up-Bay portion of the deep trough. This sharp transition from the Bay's deep trough to depths of 8-10 m appears to result in aperiodic mixing, possibly through passage and breaking of internal waves common to the Bay (Brandt et al. 1985; Dubbel et al. 1985; Sarabun et al. 1985). Turbulence in this area probably leads to the elevated phytoplankton standing crops and production. Chlorophyll had two distinct maxima, in late September 1984 (544 mg/m^2) and early May 1985 (923 mg/m^2). The peaks coincided with periods of diatom-dominated phytoplankton assemblages, although total phytoplankton densities were not high in the fall of 1984 (6.8 and 28 x 10^6 cells/liter, surface and bottom, respectively). High rates of carbon fixation were routinely recorded at this station, with rates of 0.9-2.7 gCm^2 per day in fall 1984 and rates >5.2 gC/m^2 per day during early May 1985. Two other peaks, 2.1 and 2.6 gC/m^2 per day, were observed at this station on 7 August and 8 October 1985, respectively.

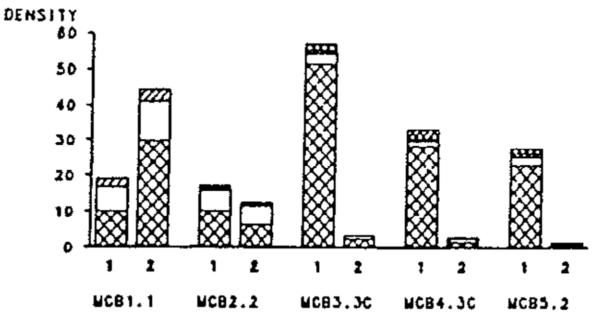
Small coccoid cells dominated the phytoplankton assemblages at MCB 3.3C most of the year (Figure 4). These cells were the most numerous microalgae in August, November, and December 1984 and January, March, and late May through July 1985. Eukaryote phytoplankton densities were usually <10 x 10^6/liter from August through December and after the spring bloom. Diatoms were the most abundant eukaryote group, dominating the assemblage in September and October 1984, with *Cyclotella* spp., *Thalassiosira* spp., and *Leptocylindrus minimus* the principal representatives. In February 1985 diatoms, and the dinoflagellates *Prorocentrum minimum* and *Katodinium rotundatum*, dominated, with the winter halophiles *Ceratulina pelagica, Skeletonema costatum, Rhizosolenia* spp., and *Chaetoceros* sp. most common. During the spring bloom in April and early May, these dinoflagellates and diatom taxa, including *Cyclotella* sp., were the major eukaryotes present.

Diatom abundance can generally be associated with water-column mixing after destratification in the fall and spring, and with the transport of shelf-Bay mouth assemblages up-bay in deeper, more saline water during the winter. This latter phenomenon, deep-water up-bay transport, can be seen in the higher diatom densities in sub-pycnocline waters from January through April 1985. For example, diatoms in the surface mixed layer and below the pycnocline were 9.8 and 25.8 x 10^6 /liter, respectively, in February 1985. Vertical distributions of chlorophyll (Appendices 1 and 2) also indicated higher phytoplankton densities below the pycnocline during January and February.

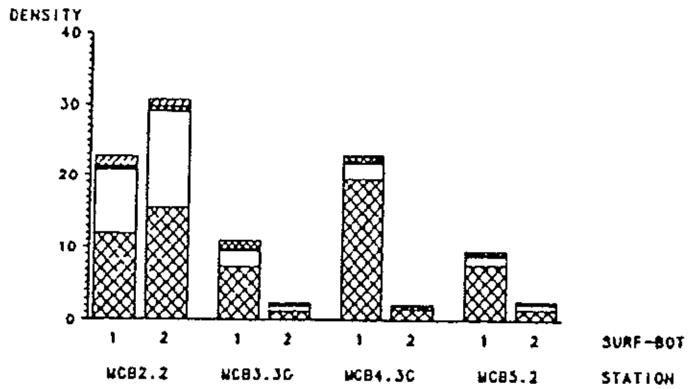
Phytoplankton from stations MCB 4.3C and MCB 5.2 followed the same patterns observed in the upper Bay. Two seasonal maxima were noted, in late September 1984 and April 1985. Concentrations of chlorophyll, principally from diatoms (Figure 2), reached 360 and 384 mg/m^2 for the two stations in September and 420 and 520 mg/m^2 in April. Carbon fixation also followed the seasonal trend noted in the upper Bay stations, although the rates were lower and

Figure 4 (facing page, following two pages). Phytoplankton distributions (cell densities x 10^6/liter) in five taxonomic groups (cyanobacteria, diatoms, dinoflagellates, microflagellates, and other miscellaneous taxa) for surface (1) and bottom (2) samples from five stations in the mainstem of the Chesapeake Bay, August 1984 through July 1985. Total bar height represents numbers of phytoplankton/station. Stations MCB 1.1 and MCB 2.2 represent freshwater and oligohaline (mixing or transiton zone) regions, respectively; MCB 3.3C, MCB 4.3C, and MCB 5.2 represent mesohaline stations.

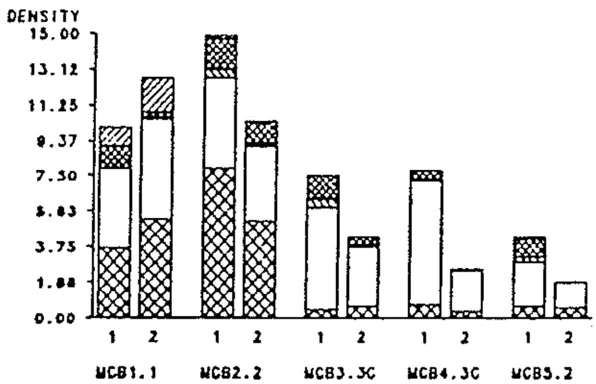
MAIN BAY – EARLY AUGUST 1984



MAIN BAY – LATE AUGUST 1984



MAIN BAY – EARLY SEPTEMBER 1984



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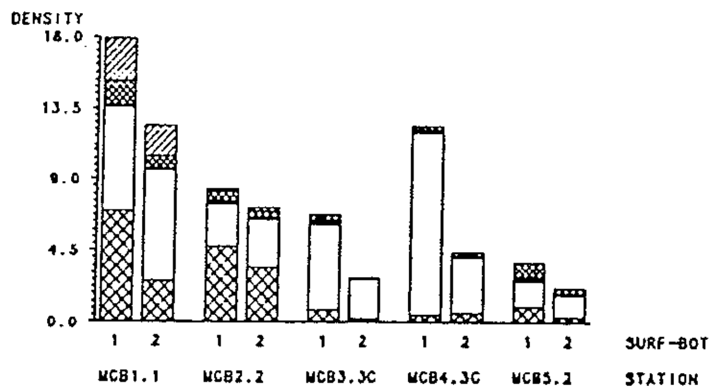
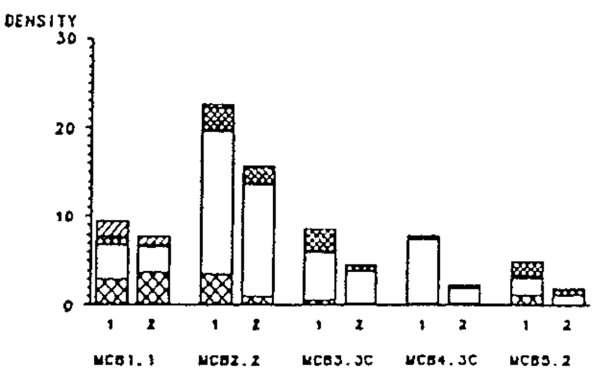
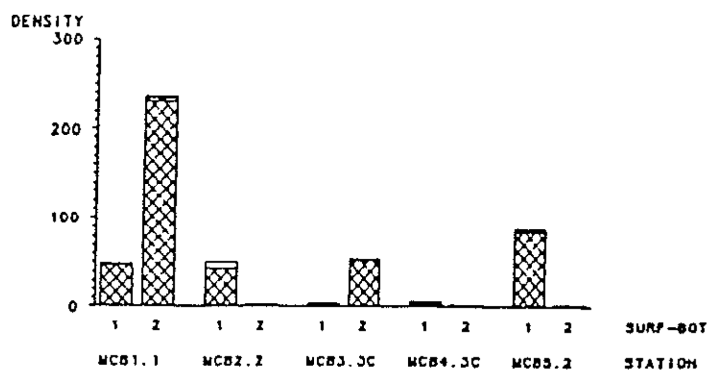


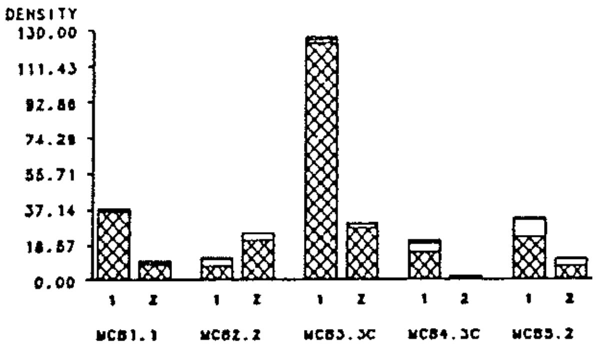
MAIN BAY – OCTOBER 1984



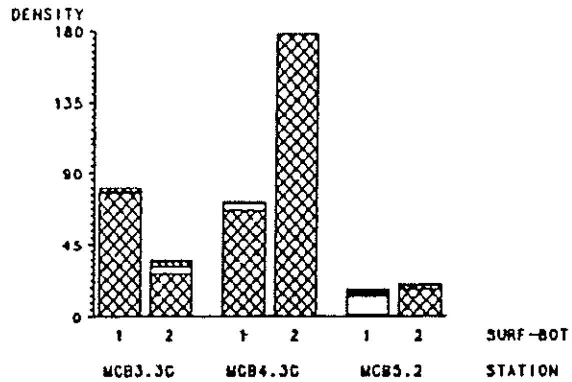
MAIN BAY – NOVEMBER 1984



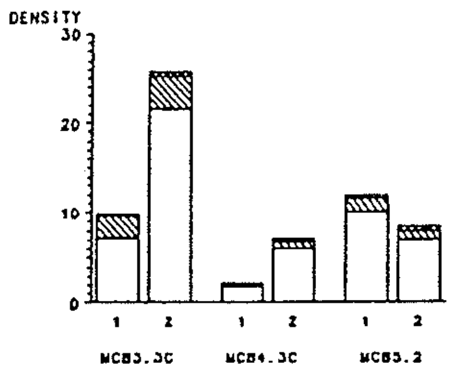
MAIN BAY – DECEMBER 1984



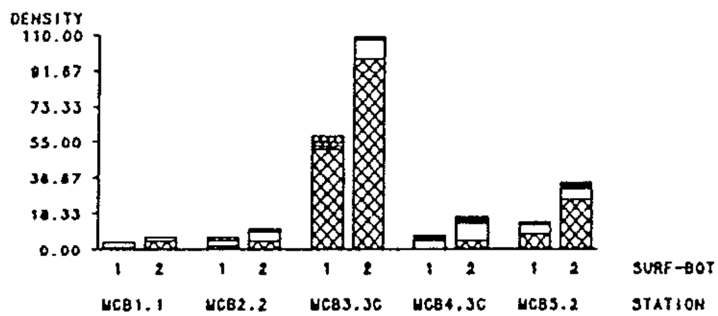
MAIN BAY – JANUARY 1985



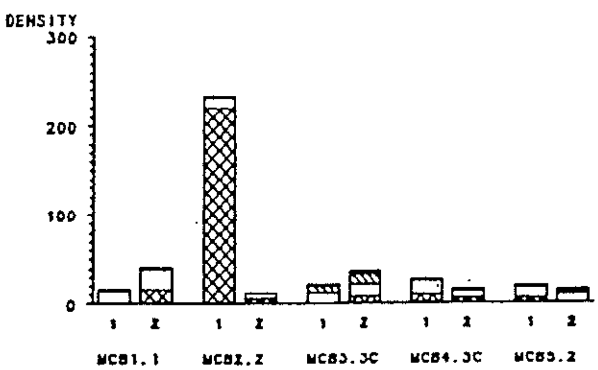
MAIN BAY – FEBRUARY 1985



MAIN BAY – MARCH 1985



MAIN BAY – EARLY APRIL 1985



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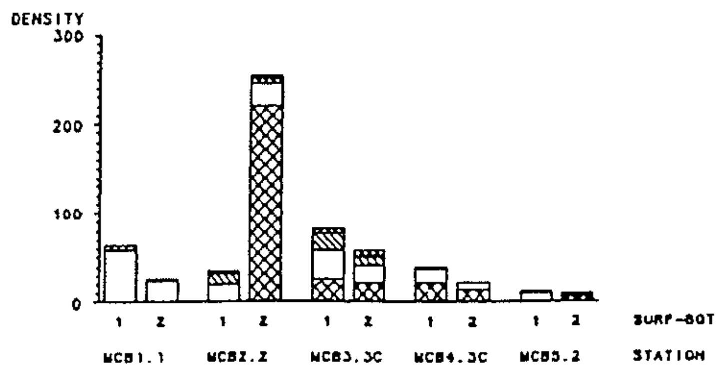

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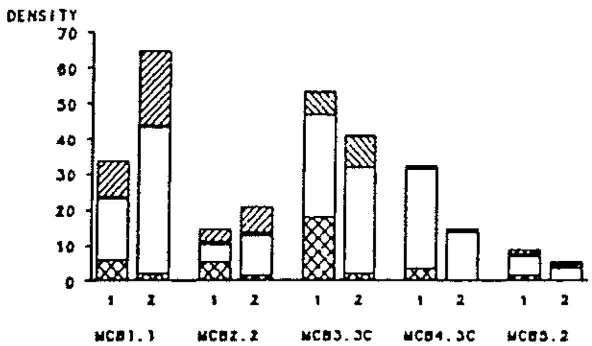

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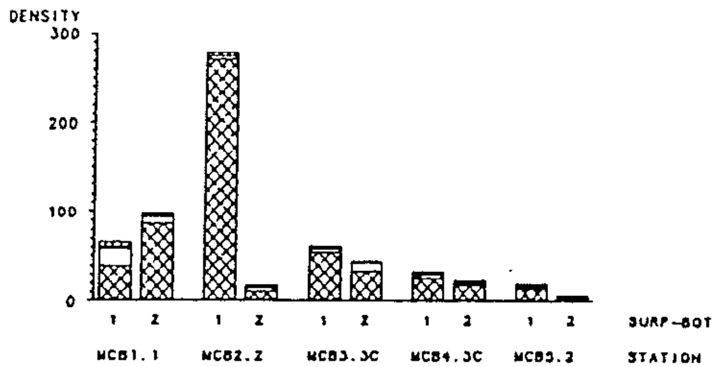
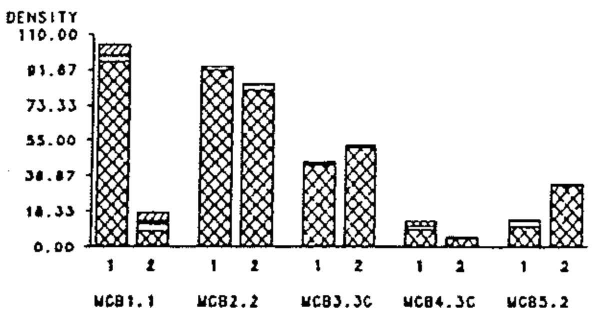
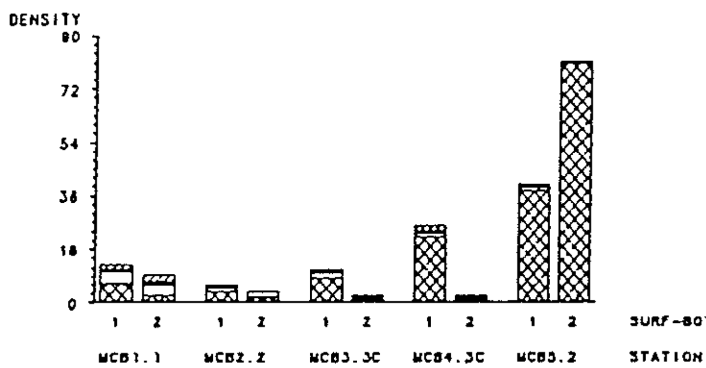


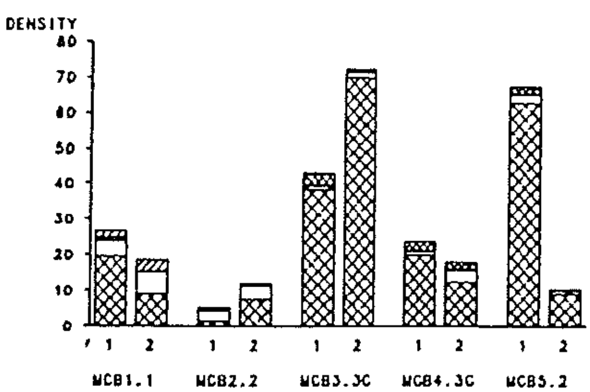
MAIN BAY – EARLY JUNE 1985



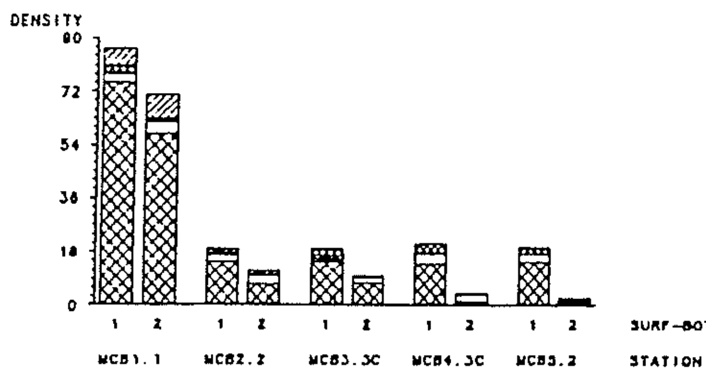
MAIN BAY – LATE JUNE 1985



MAIN BAY – EARLY JULY 1985



MAIN BAY – LATE JULY 1985



GROUP CYANOBACT MICROFLAG DIATOMS OTHER DINOFLAG the fixation rates were of similar magnitude over the summer months (Figure 3). Maximum daily rates declined from slightly less than 3 gC/m^2 at MCB 4.3C to just over 2 gC/m^2 at MCB 5.2.

Over the year, total cell densities at the two stations in the lower mainstem Bay were lower than those in the upper Bay. Small coccoids again dominated cell densities on several occasions, with 85.6 x 10^6 cells/liter at MCB 5.2 in November (97% of total cells) and 178.9 x 10^6 cells/liter in January at MCB 4.3C (100% of the assemblage). Diatoms were the principal eukaryote group and contributed up to 81% of total cell densities in the spring bloom (see Appendix 3 for relative abundance data), with centric

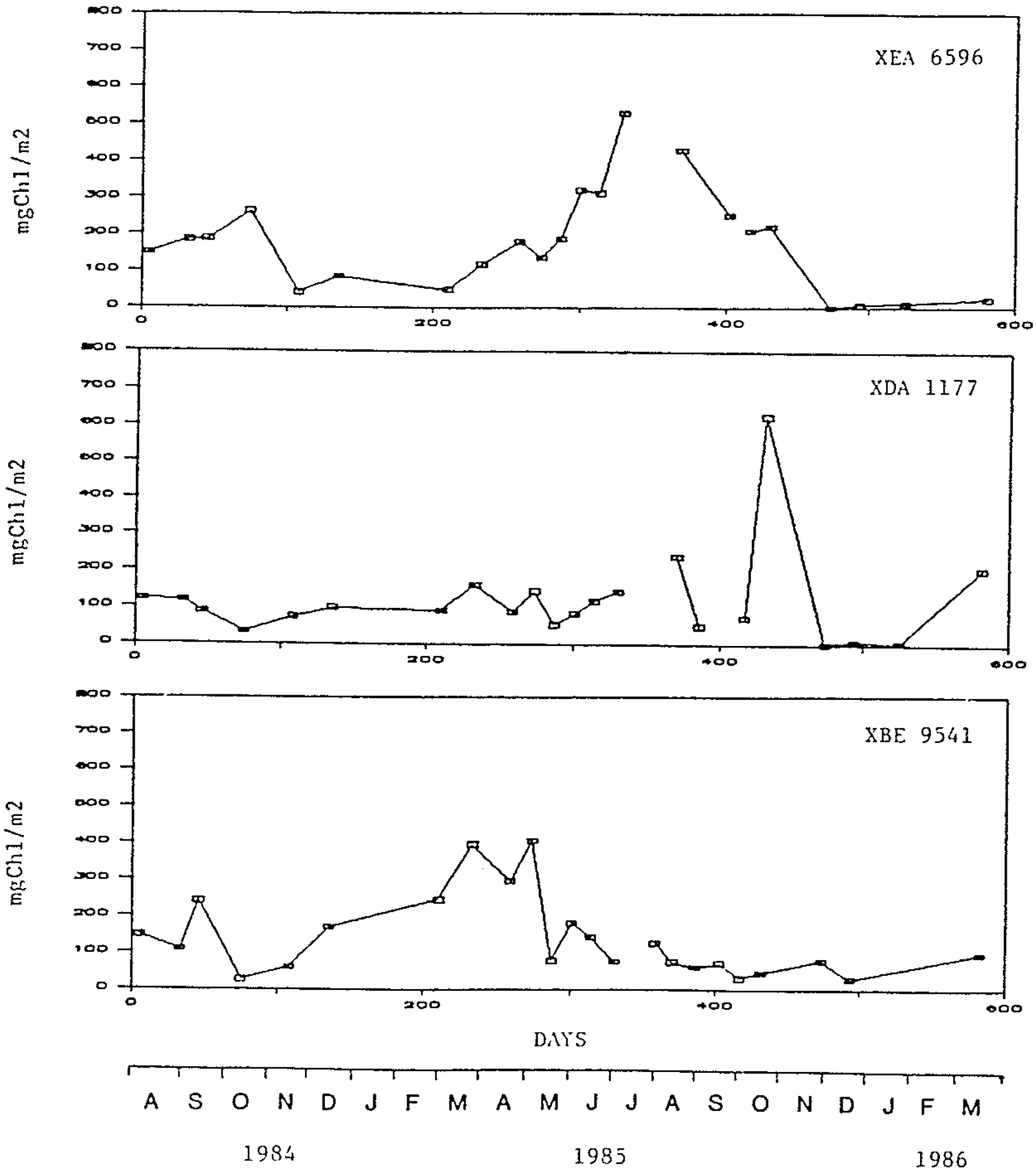


Figure 5. Integrated chlorophyll concentrations (mg/m^2) in the Potomac River from August 1984 through March 1986. Stations XEA 6596, XDA 1177, and XBE 9541 represent freshwater, oligohaline (mixing or transition zone), and mesohaline regions of the river/estuary, respectively.

diatoms, e.g., *Cyclotella* sp. and *Thalassiosira* sp., the primary taxa.

Potomac River

Phytoplankton in the Potomac River in 1985 were characterized by high densities of bloom-forming cyanobacteria, specifically *Microcystis aeruginosa.* Development of the bloom is schematically presented in the distribution of chlorophyll over time in Figure 5, station XEA 6596. Chlorophyll concentrations in the bloom reached 529 mg/m^2 on 25 June; integrated concentrations likely reached much higher levels

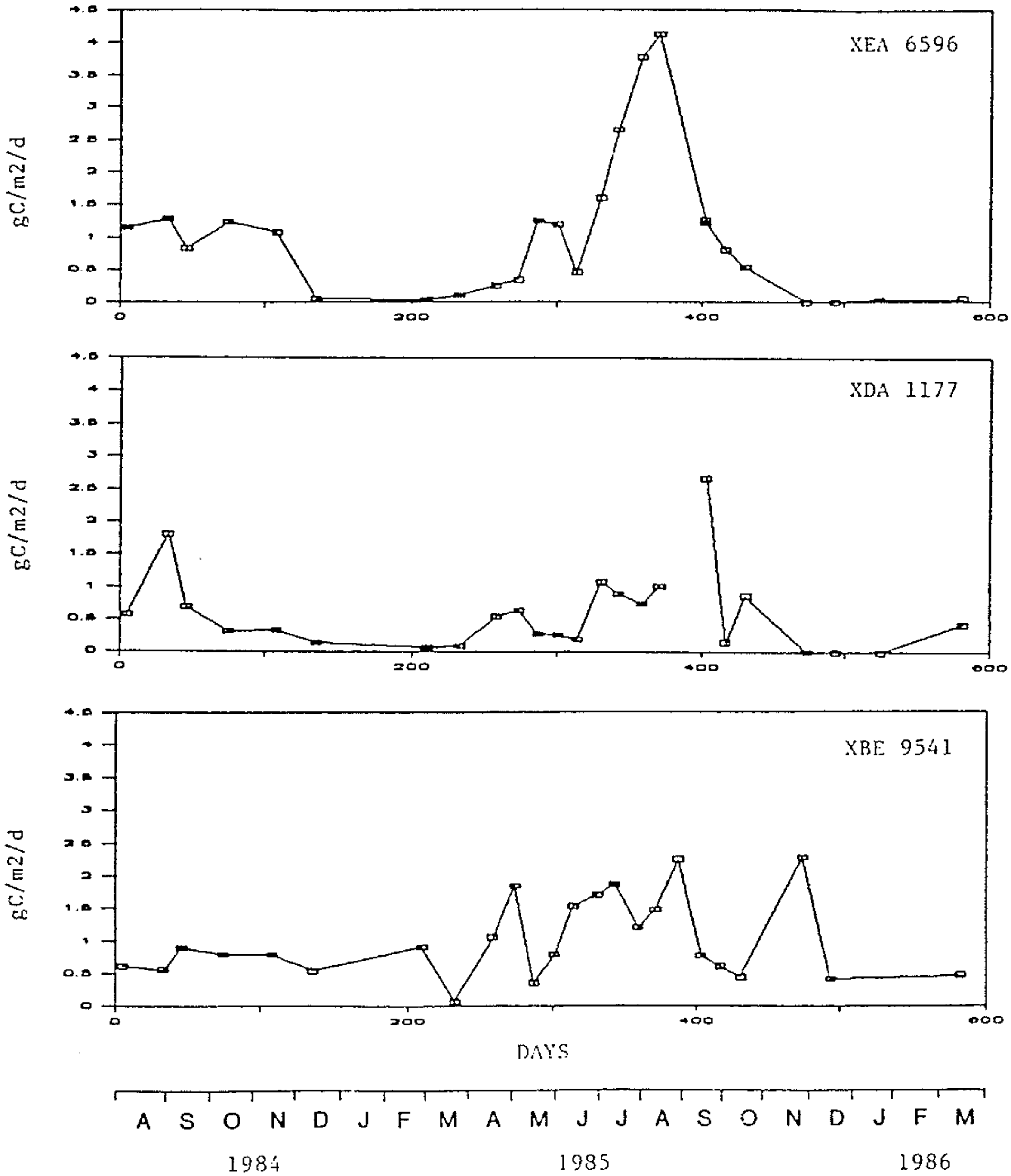


Figure 6. Integrated primary production (gC/m^2 per day) in the Potomac River from August 1984 through March 1986. Stations XEA 6596, XDA 1177, and XBE 9541 represent freshwater, oligohaline (mixing or transition zone), and mesohaline regions of the river/estuary, respectively.

during July, as surface concentrations were 275 and 281 mg/m^3 on 8 July and 24 July, respectively. However, vertical profiles of chlorophyll were not obtained in July because of equipment failure.

Carbon fixation rates at station XEA 6596 paralleled the seasonal distribution of chlorophyll (Figure 6) with a peak at 4.1 gC/m^2 per day on 6 August 1985. Two other seasonal maxima were apparent, in late summer 1984 (0.8-1.3 gC/m^2 per day) and in May 1985 (1.2-1.3 gC/m^2 per day). The late summer 1984 maximum was accompanied by high densities of cyanobacteria (12.6-120.8 x 10^6 cells/liter) and chlorophyll. Diatoms contributed substantially to the phytoplankton assemblages in May, with an average relative abundance of 32% and 50% in surface and bottom samples, respectively (Figure 7; Appendix 3).

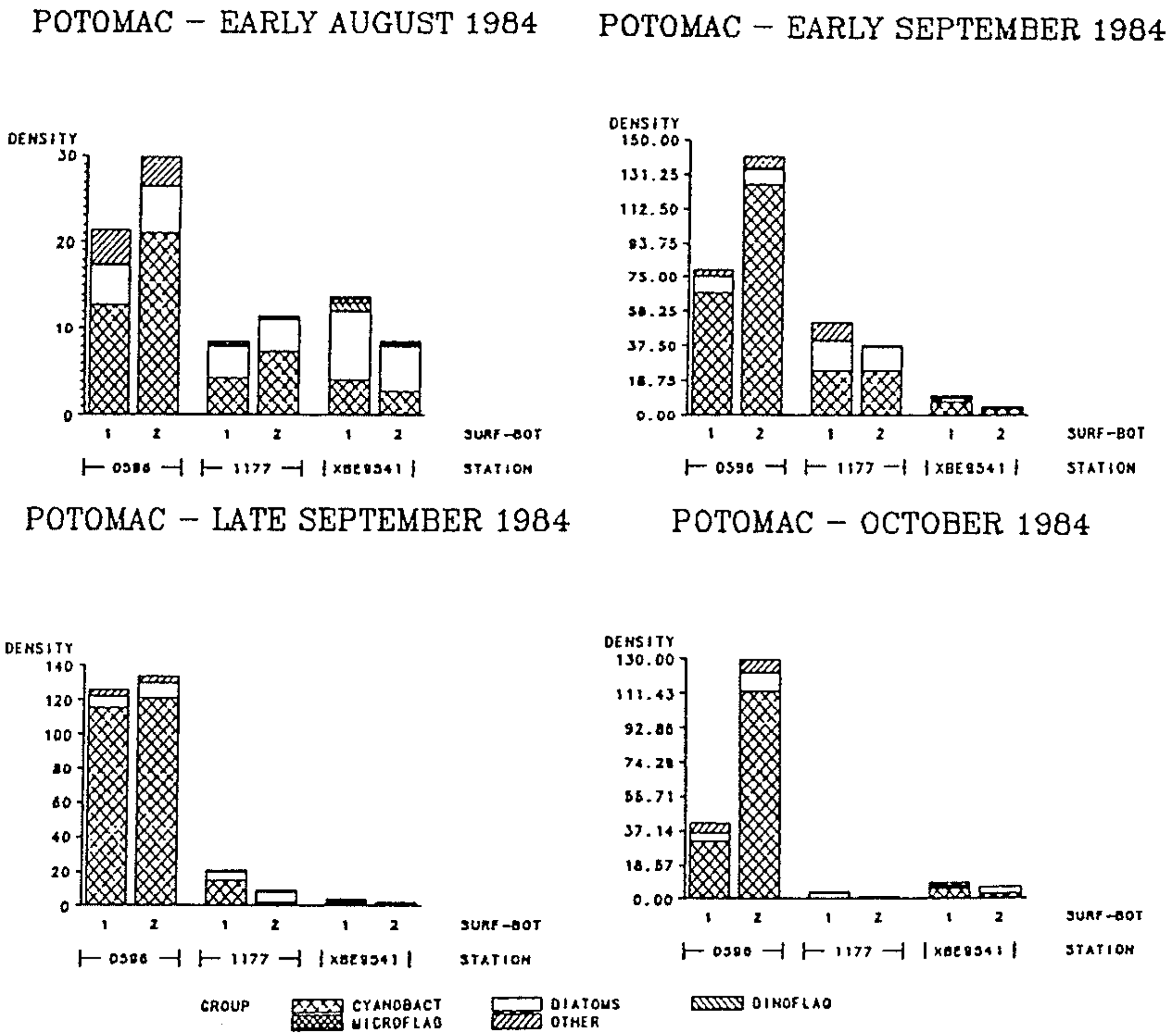
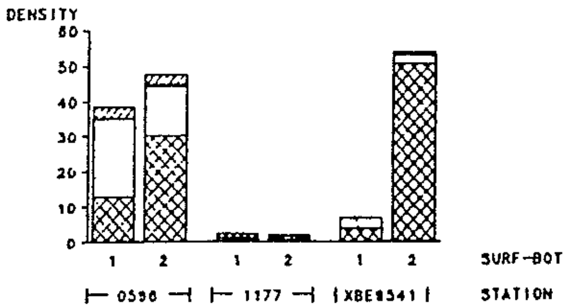
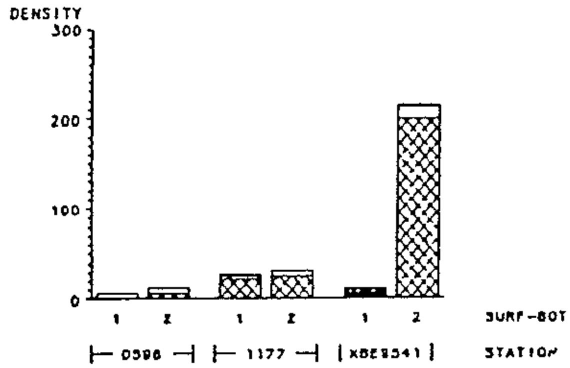


Figure 7 (above, facing page, overleaf). Phytoplankton distributions (cells x 10^6/liter) in the five taxonomic groups (cyanobacteria, diatoms, dinoflagellates, microflagellates, and other miscellaneous taxa) in surface (1) and bottom (2) samples from three stations in the Potomac River from August 1984 through July 1985. Total bar height represents the numbers of phytoplankton/station. Stations XEA 6596, XDA 1177, and XBE 9541 represent freshwater, oligohaline (mixing or transition zone), and mesohaline regions of the river/estuary, respectively.

POTOMAC – NOVEMBER 1984



POTOMAC – DECEMBER 1984



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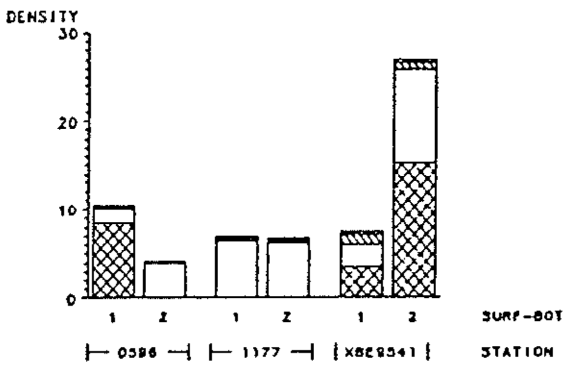

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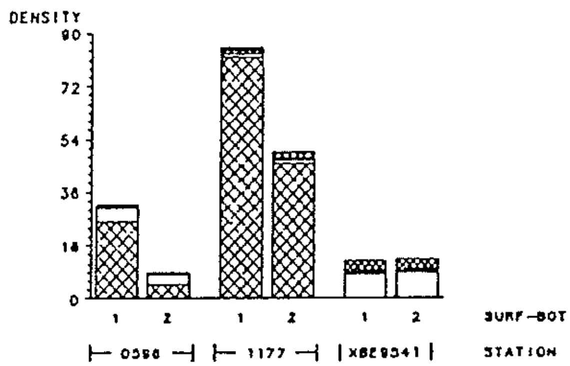

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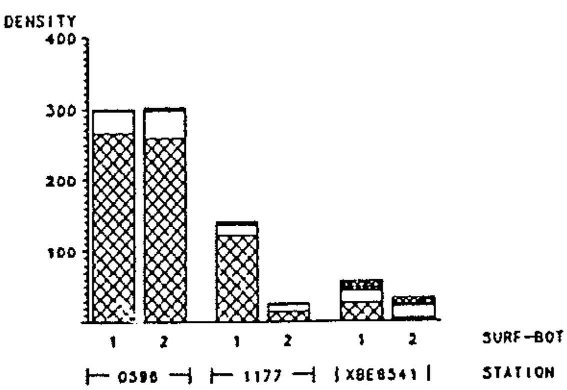

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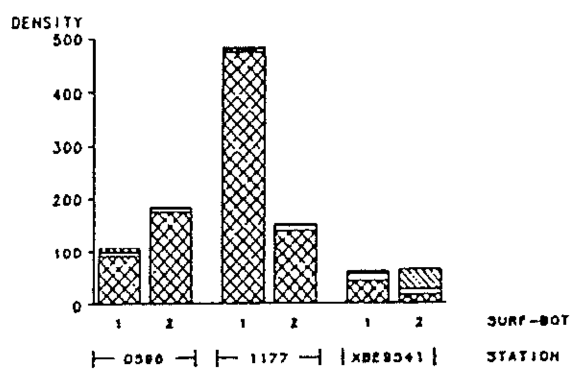

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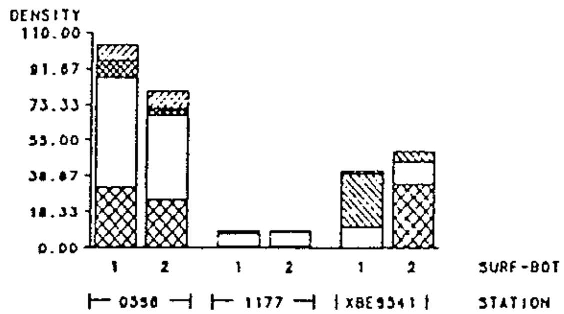

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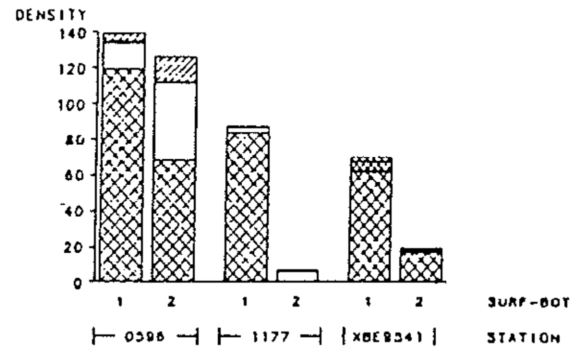

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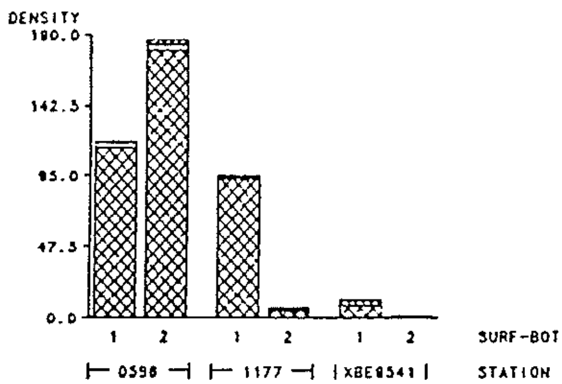

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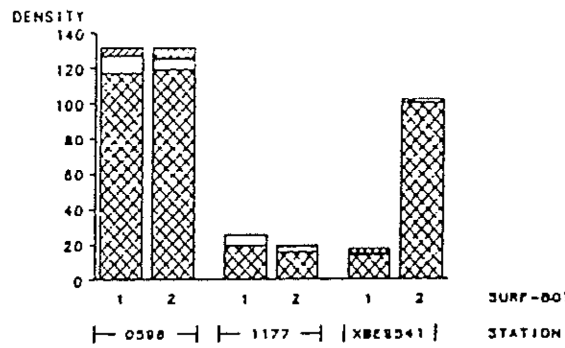

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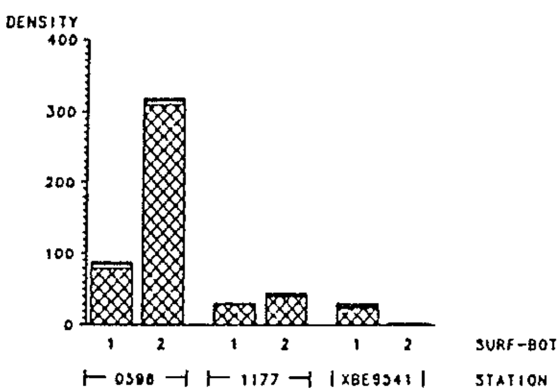

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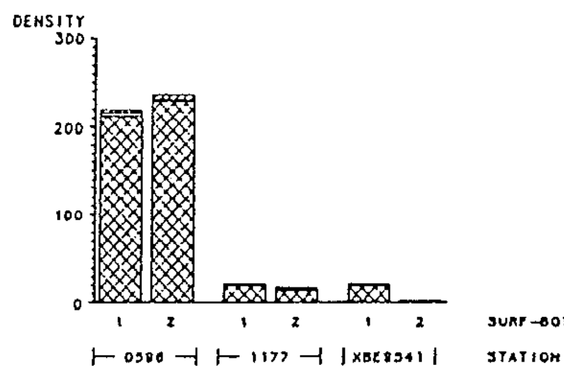


Seasonal signals in chlorophyll were much less obvious in the oligohaline (station XDA 1177) and mesohaline (station XBE 9541) regions of the Potomac (Figure 5). Chlorophyll concentrations at the two stations did decline from late summer to fall in 1984. Concentrations increased again during the winter and early spring to maximal levels at station XBE 9541 in May 1985 (407 mg/m^2), but declined thereafter to concentrations <200 mg/m^2 from May 1985 through March 1986. Patterns at station XDA 1177 were intermediate between those observed at stations XEA 6596 and XBE 9541: after a small spring signal, chlorophyll concentrations were typified by a repetition of small increases and dramatic declines. Maximal values were noted in October 1985 with concentrations of 627 mg/m^2 .

Carbon fixation rates (Figure 6) at station XDA 1177 followed the same pattern observed in the distribution of chlorophyll, but the pattern at station XBE 9541 was much more irregular. The spring peak in diatoms was accompanied by a maximum in carbon fixation (1.8 gC/m^2 per day) followed by a decline in production (0.4 gC/m^2 per day) and chlorophyll. Carbon fixation subsequently increased and persisted at 1.2-2.2 gC/m^2 per day through August 1985.

Microcystis aeruginosa dominated phytoplankton in the Potomac in 1985. This bloom-former probably accounted for the chlorophyll and carbon fixation rates noted in the upper Potomac, with advection seaward leading to occasionally elevated chlorophyll levels at the transition zone station, XDA 1177. Total cell densities in the lower Potomac ranged from 1.1 to 216 x 10^6 cells/liter for the study period (Figure 7), with the small 1-3 µm coccoid cells forming the principal component of the assemblage in bottom samples during November and December 1984 and February 1985. Surface samples rich in these small cells were noted in April and in late May through July 1985. Diatoms were numerically dominant in bottom waters during March and April 1985, whereas dinoflagellates (primarily *P. minimum*) contributed 59% and 62% of total cells on 30 April and 13 May 1985, respectively.

Patuxent River

The seasonal distributions of chlorophyll and carbon fixation in the Patuxent River stations were similar to those observed in the Potomac. Chlorophyll concentrations were very high in the upper Patuxent, (PXT 0402) reaching 807 mg/m^2 in late September 1984 and 1619 mg/m^2 on 28 August 1985. The spring increase in chlorophyll accompanied the vernal increase in diatoms and the small coccoid cells, with chlorophyll of 402-506 mg/m^2 (Figure 8). Station XED 4892 (in the mixing or transition zone of the Patuxent) had much lower chlorophyll levels, with only one value >200 mg/m^2 over the entire study period; however, even with reduced chlorophyll levels, highest levels were observed during the spring and late summer. Chlorophyll at the mesohaline station (XDE 5339), typified by large variations from date to date, also showed strong seasonality with maxima in late summer 1984, spring 1985, and winters of 1985 and 1986.

Not surprisingly, primary production (Figure 9) generally followed the seasonal distribution of chlorophyll with the exception of a chlorophyll peak in February 1985 (425 mg/m^2). At this time, water temperatures and available light would have limited photosynthesis, thereby yielding low fixation rates (0.6 gC/m^2 per day). Peaks in carbon fixation in the Patuxent River were higher and more frequent than in any other region of the Bay or Potomac. Daily rates in these maxima reached 5.8, 3.9, and 4.4 gC/m^2 per day at stations PXT 0402, XED 4892, and XDE 5339, respectively.

Small coccoid cells and diatoms dominated total cell densities in August and early September 1984 (Figure 10); diatoms became the sole dominant in late September and October with 133 x 10^6 cells/liter at station PXT 0402 on 24 September. *Melosira* sp., *Cyclotella* sp., and *L. minimus* were the dominant taxa. As noted in the mainstem Bay and Potomac, the unidentified coccoids increased, forming the principal phytoplankton group in most months thereafter (369 x 10^6 cells/liter in surface waters at station PXT 0402 on 10 December). Diatom densities increased in April 1985, reaching 58.4 x 10^6 cells/liter at station PXT 0402, but even these high densities contributed only 31% of total cell numbers because of the overwhelming abundance of the 1-3 µm coccoid cells.

MICROZOOPLANKTON

The distributions, abundances, and seasonal cycle of microzooplankton in the mainstem of the Maryland portion of the Chesapeake Bay and in the Potomac River are discussed below. In this report, only those organisms between 45 and 200 µm are included. The microzooplankton have been divided into the following taxonomic groups: rotifers, tintinnine ciliates, copepod nauplii, sarcodinids, nonloricate ciliates, and other microzooplankters. As the distributions and abundances in the Potomac and mainstem Bay were similar for stations in the freshwater (MCB 1.1, XEA 6596), transition (MCB 2.2, XDA 1177), and mesohaline (MCB 3.3C, MCB 4.3C, MCB 5.2, XBE 9541) zones, the discussion below will concern the combined (averaged) data for the three zones unless noted otherwise. The data are listed in Appendix 4, Tables 1-9, and are represented graphically here in Figure 11 and in Appendix 4, Figures 14-45.

Total microzooplankton numbers varied greatly (differing by over three orders of magnitude) over all dates, depths, and stations, ranging from <10 to >5,500 per liter. In general, a bimodal distribution of microzooplankton abundance occurred seasonally, with peak abundances in spring and fall.

Salinity Gradient

Averaged over all months and depths for which data are available (from August 1984 to July 1985) total microzooplankton numbers decreased from the

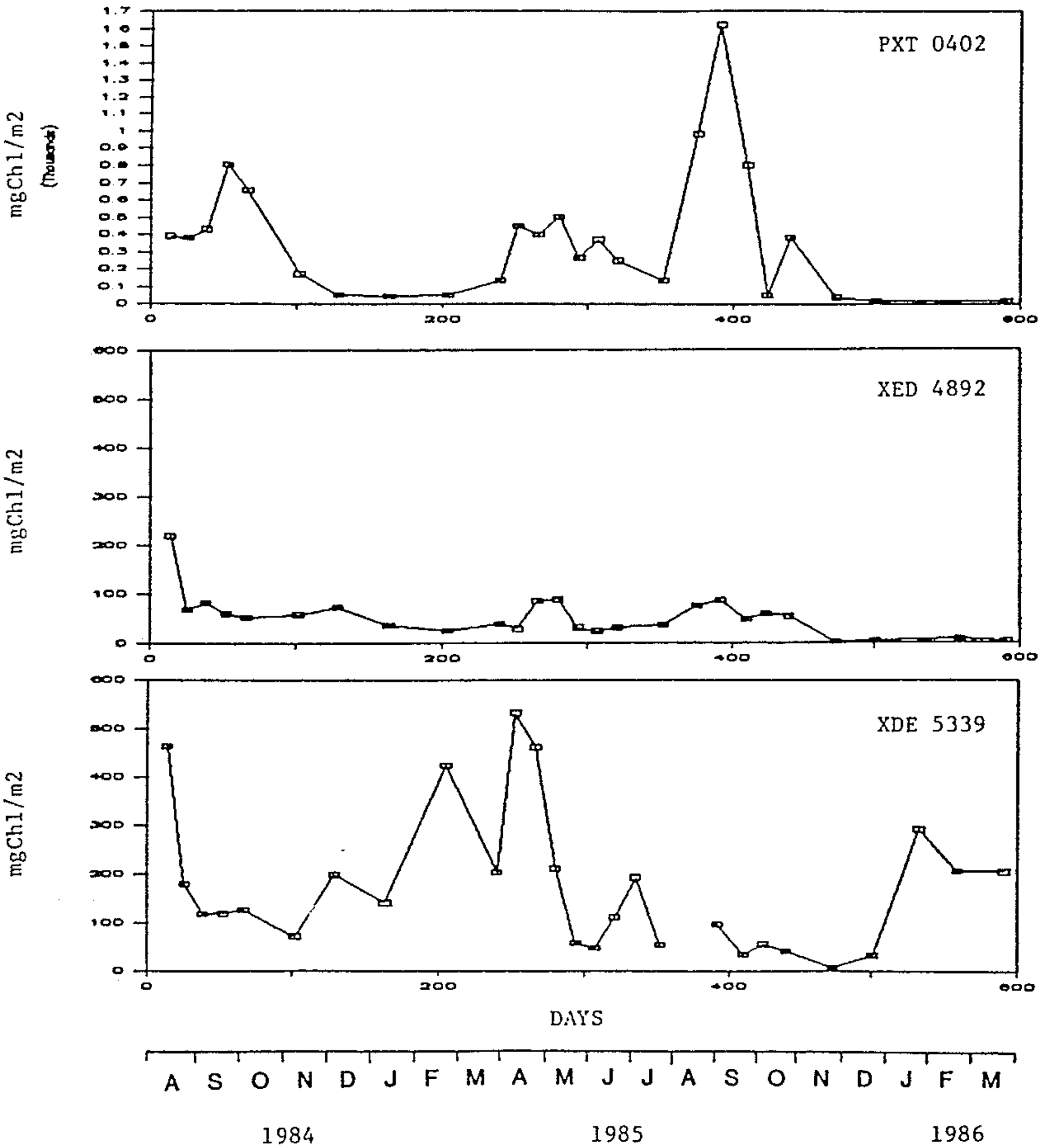


Figure 8. Integrated chlorophyll concentrations (mg/m^2) in the Patuxent River from August 1984 through March 1986. Stations PXT 0402, XED 4892, and XDE 5339 represent freshwater, oligohaline (mixing or transiton zone), and mesohaline regions of the river/estuary, respectively.

freshwater stations to the higher-salinity stations (freshwater, 374/1iter; transition zone, 292/1iter excluding May; mesohaline, 143/1iter) although month-to-month variations in this pattern did occur. One important exception was at station MCB 2.2 in May when the total microzooplankton numbers averaged 4,400/1iter, mostly because of a bloom of the tintinnine ciliate *Tintinnopsis fimbriata*.

Rotifers were very dominant at the freshwater station (83% of total microzooplankton >45 μm in size when averaged over all depths and months), decreased sharply at the transition zone (5.6%, or 16%

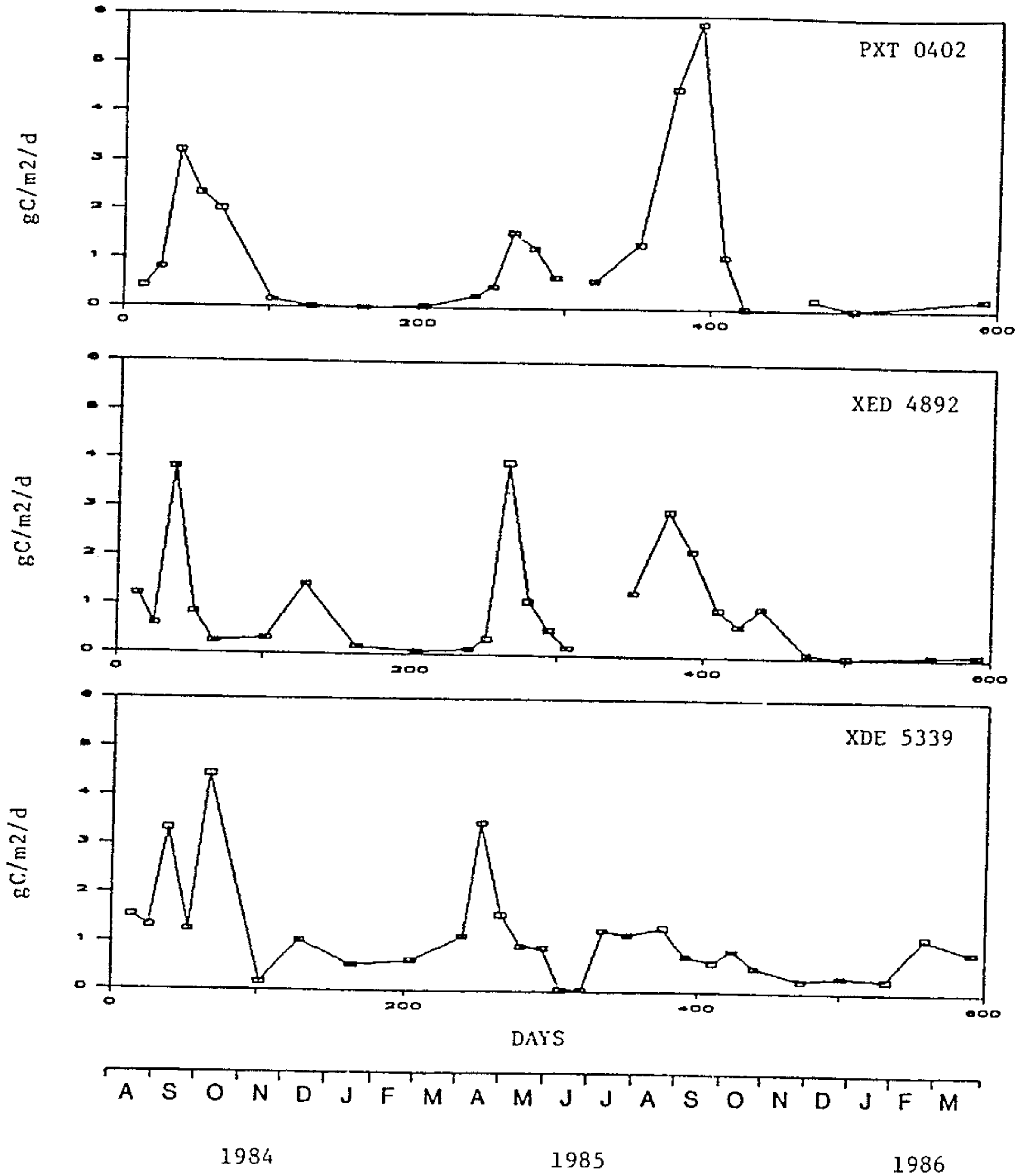


Figure 9. Integrated primary production (gC/m^2 per day) in the Patuxent River from August 1984 through March 1986. Stations PXT 0402, XED 4892, and XDE 5339 represent freshwater, oligohaline (mixing or transition zone), and mesohaline regions of the river/estuary, respectively.

excluding the tintinnine ciliate bloom in May) and were important at the mesohaline stations (45%). The taxa of rotifers were quite diverse in the freshwater station but were mostly represented by species of *Synchaeta* in the mesohaline zone. Tintinnids >45 µm were least numerous in the freshwater zone (2.2%), most numerous in the transition zone (81%, or 45% excluding the tintinnine ciliate bloom in May), and at an intermediate level in the mesohaline region (18%). The copepod nauplii were best represented in the more saline areas with 33%, 10% (or 30% excluding May), and 6% of total microzooplankton in the mesohaline, transition, and freshwater stations, respectively. However, they were most abundant at the transition zone (freshwater, 21/1iter; transition, 88/1iter; mesohaline, 47/1iter). On average, the sarcodinids, nonloricate ciliates, and other microzooplankton (including bivalve larvae, etc.) represented <10% of the microzooplankton although they were important during particular months at certain stations (see Appendix 4, Figures 14-21).

Seasonal Cycle

Total microzooplankton densities generally showed a bimodal seasonal distribution, with peak abundances in spring and fall. This pattern was most evident at the freshwater stations and less obvious down-bay (or down-river). Less significant peaks in abundance were also observed in summer and winter.

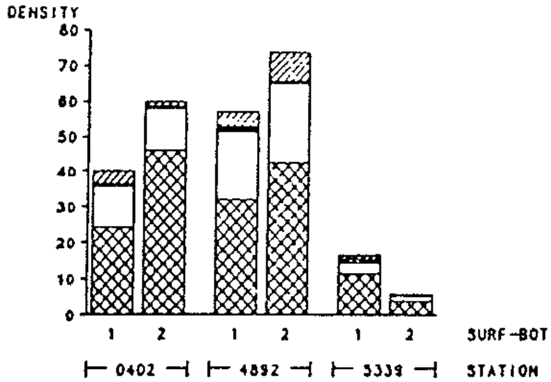
In the freshwater zone, densities were highest (854/liter) in October and dropped only slightly (696/liter) in November. There was also a significant peak (670/liter) in August. The spring maximum occurred in May (457/1iter) and June (357/1iter). Microzooplankton numbers were depressed in February (77/1iter) and March (81/1iter). Rotifers were responsible for all peaks in abundance although copepod nauplii were dominant in March. Rotifers followed the same pattern as the total microzooplankton but were reduced to only 4/1iter during March when copepod nauplii dominated the microzooplankton and reached 68/1iter. Other groups of microzooplankton were generally insignificant,although the sarcodinids were present in reasonable numbers (>40/1iter) in August, November, and December.

Unlike the freshwater zone, the transition or oligohaline zone had its greatest peak in abundance in the spring (May, 4,063/1iter), and the peak was predominantly composed of the tintinnine ciliate *T. fimbriata*. A fall maximum (496/liter) occurred in September, a summer maximum (596/liter) in July, and a winter maximum (418/liter) in December. Rotifers were not dominant in this zone except in February when they represented slightly greater than 50% of the total numbers. The maximal number of rotifers occurred in December. Tintinnine ciliates occurred in bloom proportions in May, reaching 6,142/1iter. They also dominated the microzooplankton in July (543/1iter) and showed moderate abundances in September (223/1iter), December (185/1iter), and June (217/1iter). Tintinnines were found at extremely low numbers (<3/liter) numbers in February through April when copepod nauplii were abundant. They were also very scarce in August when only a moderate number of nauplii were present. They achieved moderate abundance (223/1iter) in September in the presence of relatively abundant copepod nauplii (162/1iter). Peak abundances for copepod nauplii were in September (161/1iter) and March (268/1iter). The March peak was much less pronounced at the mainstem Bay station (88/1iter) than in the Potomac River (448/1iter). In September and October, pelycepod larvae, which made up most of the "other" category, represented 13% and 18% (66 and 32/1iter) of the microzooplankton, respectively.

The mesohaline zone had lower overall abundances than the other two zones and showed less seasonal difference in total microzooplankton numbers. Only a fall peak was observed (September, 298/1iter). Microzooplankton numbers were slightly depressed in February (76/1iter) and June (51/1iter). Rotifers were dominant between December and June and reached peak abundances in January (130/1iter). In general, the tintinnines >45 µm in size were poorly represented at these stations and dominant only in September (144/1iter). The average number of tintinnines was <10/1iter during January, May, June, and July. Copepod nauplii were dominant in October (132/1iter), November (64/1iter), and July (89/1); nauplii numbers were lowest during January, February, and May. The microzooplankton taxa other than rotifers, tintinnines, and copepod nauplii did not make a significant contribution at these stations.

Figure 10 (facing page, following two pages). Phytoplankton distributions (cells x 10^6) in five taxonomic groups (cyanobacteria, diatoms, dinoflagellates, microflagellates, and other miscellaneous taxa) in surface (1) and bottom (2) samples from the Patuxent River from August 1984 through July 1985. Total bar height represents numbers of phytoplankton/station. Stations PXT 0402, XED 4892, and XDE 5339 represent freshwater, oligohaline (mixing or transition zone), and mesohaline regions of the river/estuary, respectively.

PATUXENT – EARLY AUGUST 1984



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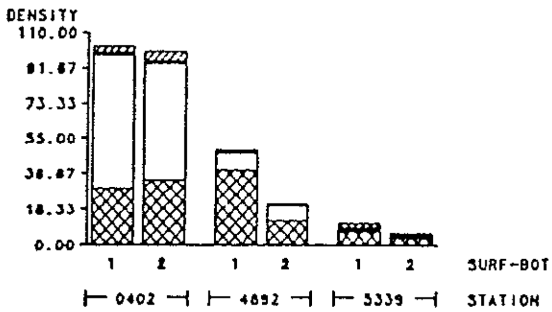

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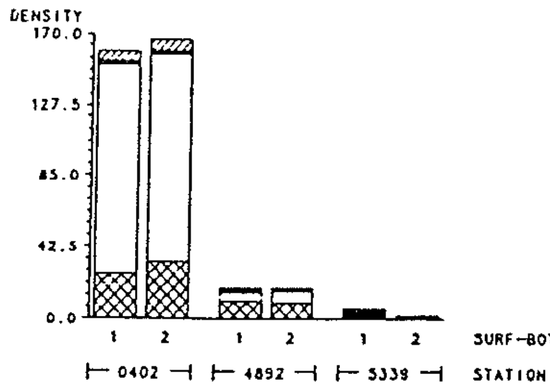
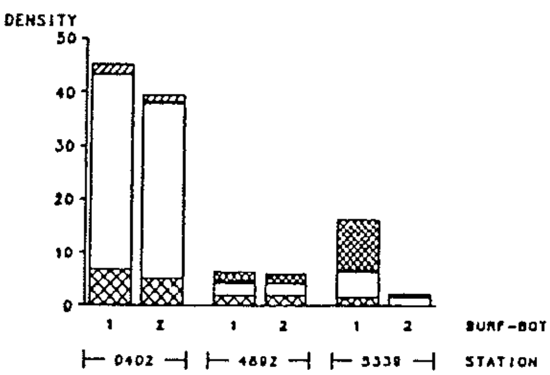
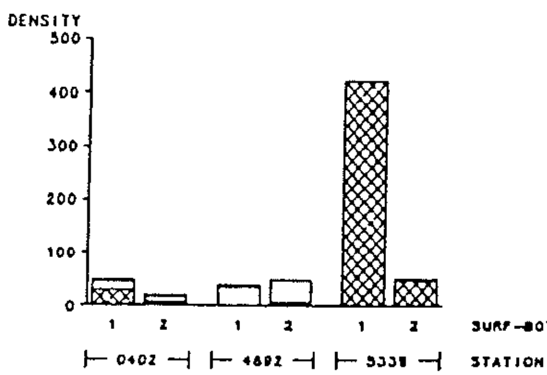


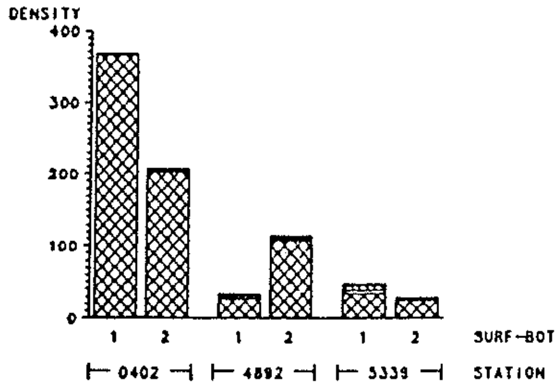
PATUXENT – OCTOBER 1984



PATUXENT – NOVEMBER 1984



PATUXENT – DECEMBER 1984



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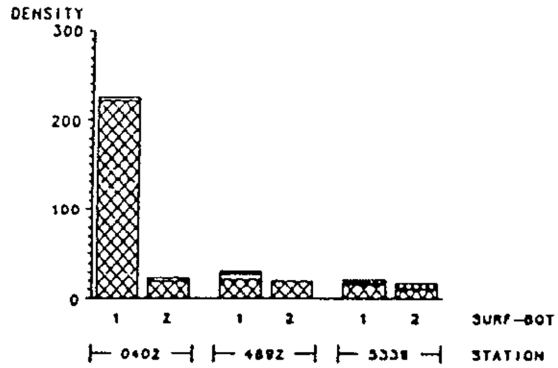

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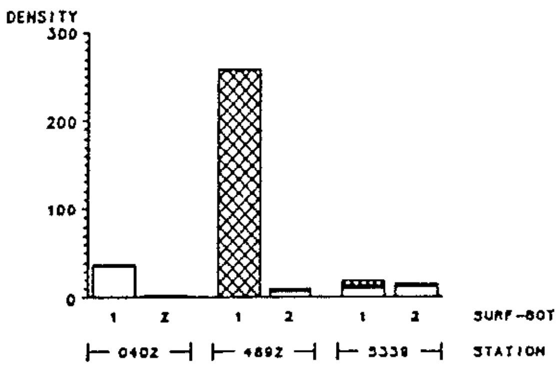
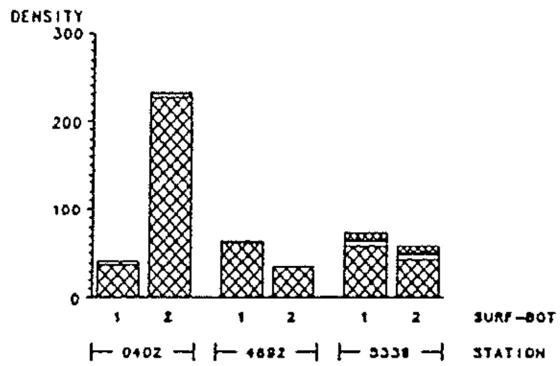


PATUXENT – MARCH 1985



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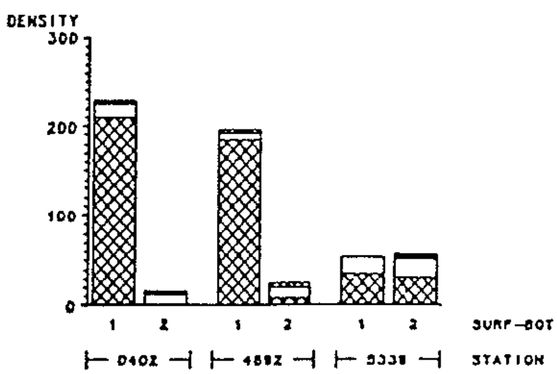

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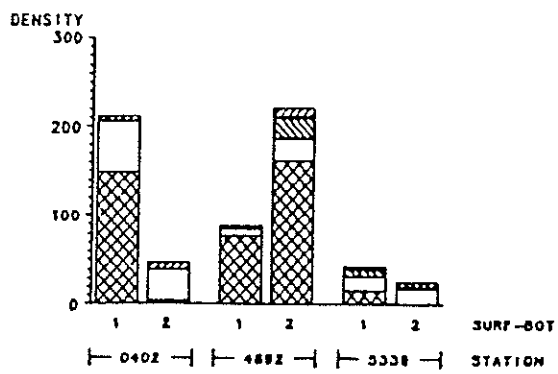

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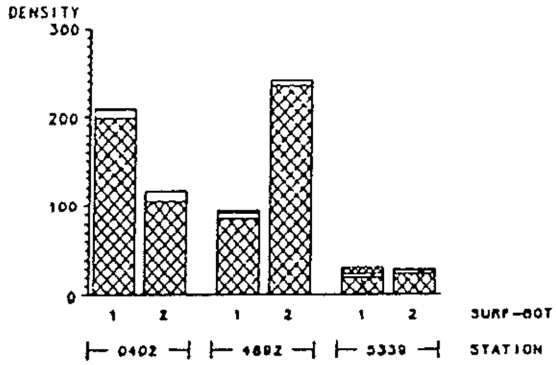

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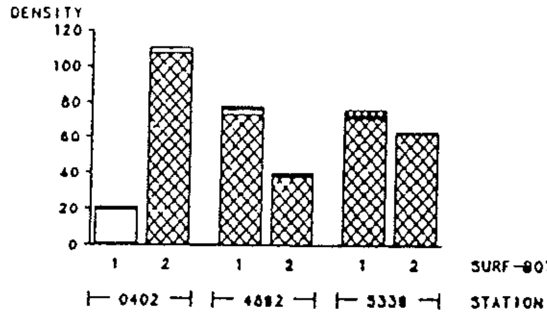

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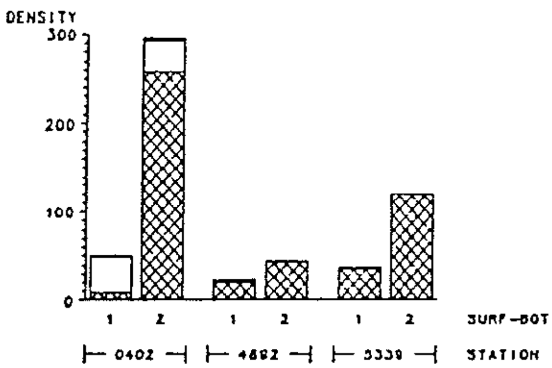

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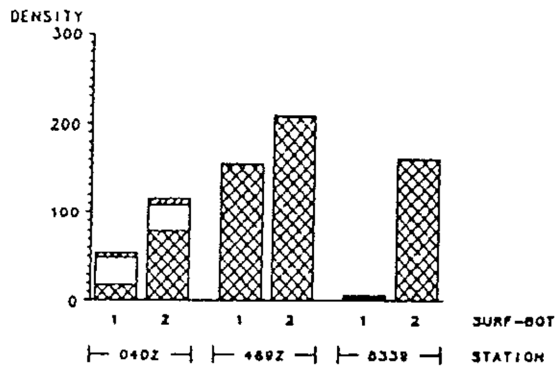

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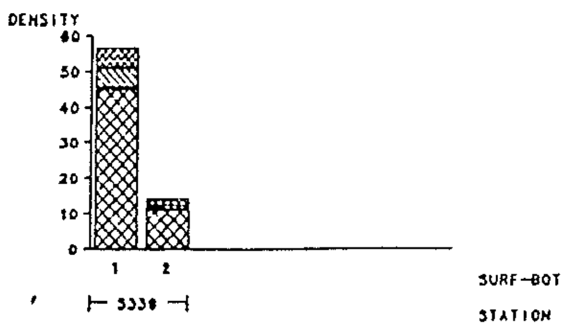

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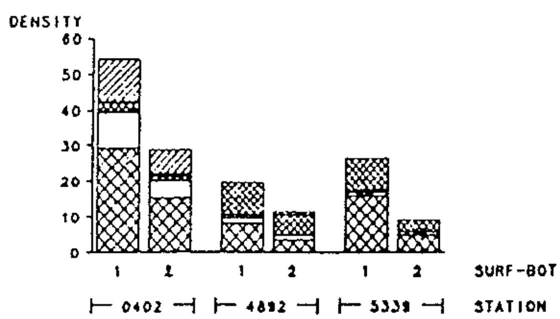
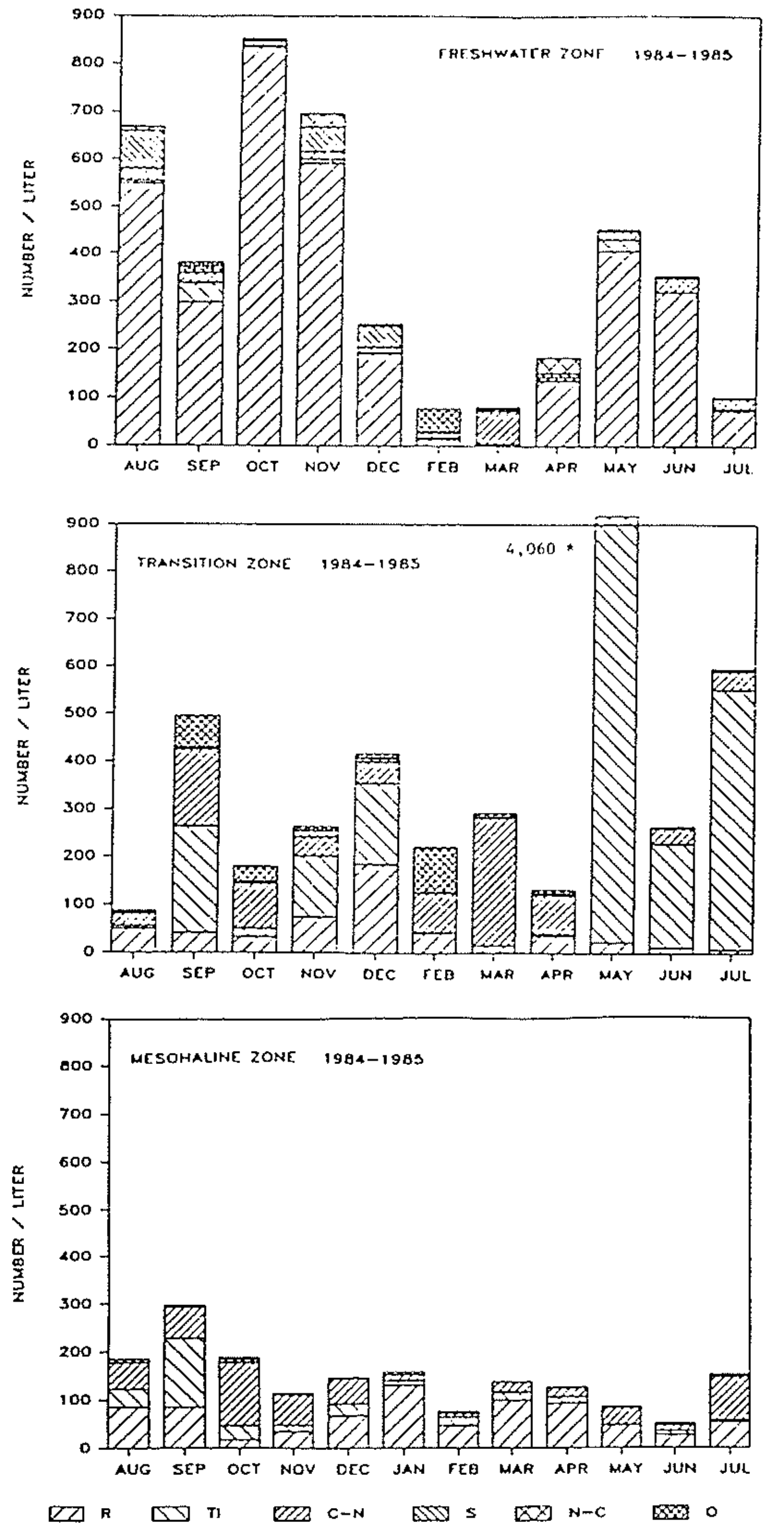


Relationships with Other Plankton Components. In the freshwater zone (Figure 11), the fall (October-September) and spring (May) peaks in microzooplankton followed peaks (September and April) in chlorophyll *a* concentration and carbon fixation (Figures 2 and 3). Diatoms and blue-green algae were the dominant phytoplankton during both these times (Figure 4). The depression of microzooplankton in February and March coincided with increased numbers of total copepod nauplii (Figure 11) and high



Figures 11. Seasonal abundance of microzooplankton for the tidal freshwater zone (stations MCB 1.1 and XEA 6596), oligohaline transition zone (stations MCB 2.2 and XDA 1177), and mesohaline zone (stations MCB 3.3C, MCB 4.3C, MCB 5.2C, and XBE 9541). R = rotifers, Ti = tintinnines, C-N = copepod nauplii, S = sarcodinids, N-C = non-loricate ciliates, O = other microzooplankton.

concentrations of adult and copepodite populations of *Eurytemora affinis* (Jacobs et al. 1985).

The bloom of tintinnine ciliates in the transition zone in May followed an increase in chlorophyll *a* concentration and primary production in April. Again, blue-green algae and diatoms were the dominant phytoplankton taxa. The September microzooplankton increase coincided with an increase in phytoplankton. As in the freshwater zone, the low numbers of non-copepod microzooplankton in February and March coincided with high *E. affinis* abundance.

In the mesohaline zone, a September increase in microzooplankton coincided with an increase in chlorophyll *a*, predominantly due to diatoms. Phytoplankton increased significantly in the spring in this zone (although maximal levels were much less than at MCB 3.3, for instance), but the microzooplankton did not show a corresponding increase. Copepods (predominantly *Acartia* spp.) and barnacle nauplii were abundant and may have limited microzooplankton numbers.

These relationships have not yet been analyzed statistically and do not prove cause and effect. For instance, the microzooplankton may be responding to increases in bacterial and heterotrophic flagellates associated with the phytoplankton blooms rather than to direct feeding on the phytoplankton. These relationships do suggest that the microzooplankton are in some way linked to the other plankton components and are an important and integral part of the plankton ecosystem. The high abundances of microzooplankton, especially at the fresh and transition zone stations in spring and fall, suggest that they are important consumers and secondary producers in the Chesapeake Bay ecosystem. They may also be important food items for commercial fish and shellfish species as well as for the larger zooplankton.

DISCUSSION

Phytoplankton and microzooplankton in the Chesapeake Bay and its principal tributaries experience seasonal distributions characteristic of temperate zone plankton assemblages. Bimodal distributions of eukaryotic phytoplankton taxa (particularly diatoms), chlorophyll, primary production, and microzooplankton assemblages were observed in the mainstem Bay and the Potomac River; similar patterns were noted in the Patuxent River for phytoplankton parameters as well.

Carbon fixation rates observed over the 20-month program indicated that the Bay and its tributaries are very productive systems, with daily fixation rates for the summer >1 gC/m^2 over most of the region. For comparison, rates at MCB 4.3 C were comparable to rates measured previously off Calvert Cliffs (Mihursky et al., 1977; Sellner, in review). Chlorophyll standing stocks were also very high, exceeding 100 mg/m^2 for most stations during the productive summer months. Winter chlorophyll levels were substantial, with high pigment levels in the deeper bottom waters of the Bay, reflecting the up-bay transport of plankton from the continental shelf and Bay mouth, i.e., cold-water diatom assemblages, as well as the recirculating *P. minimum* population described by Tyler and Seliger (1978).

Small, 1-3 µm coccoid cells (tentatively assigned to the cyanobacteria) dominated total cell densities throughout most of the year. Large increases in these small cells were observed in November and April-May as well as over the summer in the mainstem Bay and Potomac. Substantial contributions from eukaryotes were noted only in late summer and fall in the mainstem Bay and Patuxent, at all stations in February, and during the spring bloom in April and May 1985. The decline in the numbers of eukaryotes appeared to coincide with established seasonal increases in mesoplanktonic suspension feeders in the system, as discussed below.

Distributions of microzooplankton were comparable in similar salinity regimes (fresh, oligohaline, and mesohaline) of the Bay and Potomac River. Rotifers dominated fresh waters, declining in the transition zone, then increasing with different taxa (*Synchaeta* spp.) in the mesohaline regions. Tintinnines were most prevalent in oligohaline and mesohaline waters. The potential role of microzooplankton in the food web of the two systems is apparent through the increase in microzooplankton that accompanies increases in cyanobacteria and diatoms during the late winter and spring, followed by the rapid decline of the microheterotrophs as densities of copepod nauplii (present study) and adult *E. affinis* reach their maximum for the year (Jacobs et al. 1985). Similarly, the decline in microzooplankton observed from June to July could be attributable to post-phytoplankton bloom increases in suspension feeding mesoplankton such as *Acartia tonsa* in oligohaline and mesohaline areas (Herman et al. 1968; Heinle 1972; Olson in review) and cladocerans and *E. affinis* in freshwater regions (Sellner and Horwitz 1983; Buchanan and Schloss 1983). For example, Jacobs et al. (1986) report *A. tonsa* densities of 15.4 x 103 and 24.7-38.8 x 103 for these two regions in July, suggesting high grazing pressure by this taxa.

A combination of high year-round chlorophyll concentrations and high primary production from spring through fall yields a continuous supply of labile, edible phytoplankton carbon for production in higher trophic levels in the water column (e.g., fish) and the benthos (e.g., shellfish, demersal fish). Some of the phytoplankton could prove either unsatisfactory (e.g., too small, unpalatable, or non-nutritious, as perhaps the 1-3 µm coccoid cell that dominated phytoplankton assemblages Bay-wide) for meso- or macroplanktonic secondary producers normally consumed by commercially valuable stocks or too abundant for consumption by meso- and macro-suspension feeders in the system. Some mix of these two options could lead to sedimentation of a large supply of viable phytoplankton carbon and nitrogen to sub-pycnocline waters in the mainstem Bay and tributaries (see Boynton et al. 1985 a,b). The effective removal of these deeper waters from reaeration (e.g., wind-induced mixing, diffusion from the atmosphere, and photosynthetic oxygen production) leads to gradual oxygen depletion from the oxidation of this settling phytoplankton material. With natural stratification in the Chesapeake Bay and its tributaries, high year-round phytoplankton stocks coupled with low utilization rates in the water column and micro-aerobic bottom waters will favor continued development of anoxia in bottom waters.

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The Appendix has not been included with this report. However, copies are available from:

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Chesapeake Bay Liaison Office
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Annapolis, MD 21403.

Mesozooplankton in the Upper Chesapeake Bay: August 1984-December 1985

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Zooplankton are primary grazers on phytoplankton and constitute an important food source for organisms at higher trophic levels, including early life stages of fish such as striped bass, white perch, croaker, menhaden, and spot (Smith 1947; Raney 1952; June and Carlson 1971; Chao and Musick 1977; Westin and Rogers 1978; Lippson et al. 1979; Beaven and Mihursky 1980). Environmental perturbations, either natural or anthropogenic, that modify zooplankton distributions can alter food web relationships and indirectly affect fishery stocks.

Changing concentrations and ratios of nitrogen and phosphorus, and other changes in water quality, may lead to relatively rapid physiological changes in metabolism and growth rates of planktonic algae. Such changes are frequently accompanied by shifts in the density and species composition of zooplankton, as well as changes in levels of carbon transferred to higher trophic levels. Therefore, taxonomic composition, densities, and biomass of the zooplankton often can serve as biological indicators of water quality. Furthermore, major reductions or changes in zooplankton abundance or biomass result in a modification of the kinds and amounts of food available to larval and juvenile fish. Long-term shifts in zooplankton populations could therefore alter the habitat value of spawning and nursery areas of valuable resource species, ultimately affecting the composition and catch of commercial fisheries.

Changes in species composition and biomass of the plankton in the Chesapeake Bay not only reflect long-term trends in water quality, but also may provide indicators of short-term conditions, perhaps more so than the concentrations of the parameters themselves. For example, decreased nutrient loadings may not appear as lower nutrient concentrations in the water, but rather as immediate changes (days) in species composition and biomass of the phytoplankton and zooplankton. The plankton can thus be considered initial integrators of water quality and may indicate how changes in water quality may affect higher trophic levels.

The objectives of the mesozooplankton component of the Chesapeake Bay monitoring program are: to characterize the existing mesozooplankton community of the Maryland portion of the Chesapeake Bay over a variety of freshwater and estuarine habitats; to detect and monitor changes in mesozooplankton abundance, species composition, community structure, and biomass in relation to effects of proposed management actions; and to provide a database consistent with those prepared for other study elements of the Chesapeake Bay monitoring program, thereby providing a mechanism for examining and establishing relationships between zooplankton, other trophic levels, and water quality parameters.

METHODS

Sampling sites

Mesozooplankton samples were collected monthly at 16 stations (Figure 1) between August 1984 and December 1985. Collections at each station were taken in conjunction with Office of Environmental Programs (OEP) water-quality and Academy of Natural Sciences of Philadelphia (ANSP) phytoplankton/microzooplankton sampling efforts. Five stations in the mainstem Bay were selected, with the northernmost station near the mouth of the Susquehanna River and the southernmost station east of Point No Point, north of the mouth of the Potomac River. On the western shore of the Bay, seven stations were sampled. Three of these stations were located on the Patuxent River and three were on the Potomac River. They ranged in salinity from relatively freshwater upriver habitats to truly estuarine downriver habitats. The remaining western shore

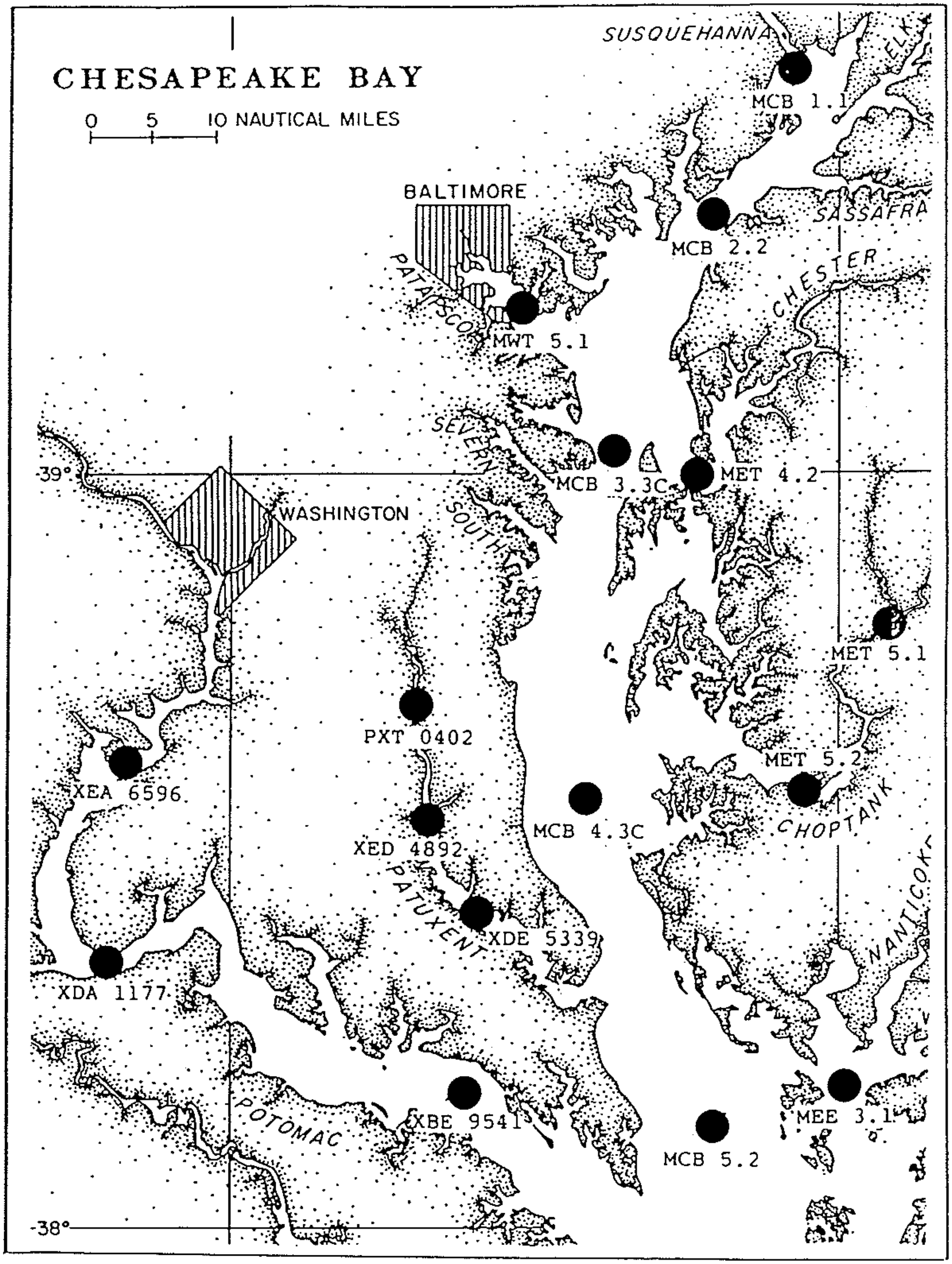

Figure 1. Location of mesozooplankton sampling stations in the upper Chesapeake Bay.

station was located in the Patapsco River near the Key Bridge. Eastern Shore tributary collections were taken at the mouth of the Chester River, at two stations in the Choptank River, and at one station in Tangier Sound.

Parameters

The density of individual species (number/m^3) and species composition of the mesozooplankton community were determined from preserved samples. After determination of the settled volume (ml/m^3), mesozooplankton samples were subsampled in the laboratory to facilitate species identification and enumeration. Three subsamples (usually 1-2 ml for the first subsample, 5 and 10 ml for second and third subsamples, respectively) were removed with Hensen-Stempel pipettes, and all organisms in each aliquot were identified and counted (number/aliquot). Counts for each species were calculated as total numbers per cubic meter of water sampled (number/m^3).

Frozen samples were used to measure total mesozooplankton biomass, expressed as dry weight (mg/m^3) and ash-free dry weight (mg/m^3). Ctenophore and jellyfish counts (number/m^3) and volumes (ml/m^3) were determined in the field.

Field and laboratory methods

Samples were collected at all 16 stations once a month in conjunction with OEP water-quality measurements and ANSP phytoplankton and microzooplankton collections. In some months, inclement weather precluded sampling.

Mesozooplankton samples were obtained by towing a 20-cm bongo net (202-µm mesh net) in a stepped oblique fashion for each replicate tow. The entire water column was sampled by first deploying the gear a few meters from the bottom and raising the net in timed progressive steps, usually 0.5 to 1.5 minutes/step. For stations <8 m in depth, 1-m step intervals were used; steps were 2 m for stations in the depth range of 9-20 m; at stations >20 m in depth, 4-m step intervals were taken. The duration of the tow was 5 minutes during periods of high zooplankton or ctenophore density and 10 minutes during periods of low zooplankton density. The actual volume of water each net filtered was calculated by using flow data from a General Oceanics flowmeter mounted in the mouth of one side of the bongo net.

One taxonomic sample (preserved in 5%-10% formalin) and one biomass sample (frozen in the field) were collected from each bongo tow. Ctenophores, when they were found, were removed from samples in the field, and their numbers and biomass (settled volume) were recorded from the net that was used as the taxonomic sample. Figure 2 summarizes the mesozooplankton processing for taxonomic and biomass samples. Each sample was either concentrated or diluted to a volume that facilitated counting subsamples taken with a Hensen-Stempel pipette.

A hierarchical counting technique was employed to obtain reliable density estimates for less abundant as well as dominant species. This procedure consisted of first counting at least 60 individuals of the most dominant forms (e.g., *Acartia tonsa*) in a small subsample (usually 1-2 ml), followed by 5- and 10-ml subsamples, from which all species that had counts <60 in the previous subsample were counted.

Detritus-free biomass samples were thawed and dried at 60° C to a constant weight. After dry weights (mg/m^3) were recorded, the sample was then transferred to a muffle furnace and heated to 550° C, and the ash-free dry weight was calculated.

Data analysis

The relative abundance of each species of mesozooplankton (number/m^3) was determined from subsample counts by using the following equation:

$$\text{relative abundance} \qquad \#/m^3 = A \times \frac{B}{CD},$$

where A = the number of individuals counted in the subsample, B = dilution volume (ml), C = subsample volume (ml), and D = volume of water filtered (m^3).

The density of macrozooplankton was calculated by enumerating the number of organisms in the entire sample and dividing by the volume of water filtered. Ash-free dry weight (g) was determined as [total dry weight (g)] - [ash weight (g)]. Dry weight and ash-free dry weight values were then converted to mg/m^3 of water sampled.

RESULTS AND DISCUSSION

Analysis of Species Composition for All Stations Combined

Figure 3 shows the monthly changes in species composition, total abundance, and biomass for all stations in the sampling region from August 1984 through December 1985. The analysis of species composition shows a recurring pattern of a dominance shift among the calanoid copepods, *A. tonsa* and *Eurytemora affinis*. During warm summer months, *A. tonsa* constituted most of the samples. In cooler

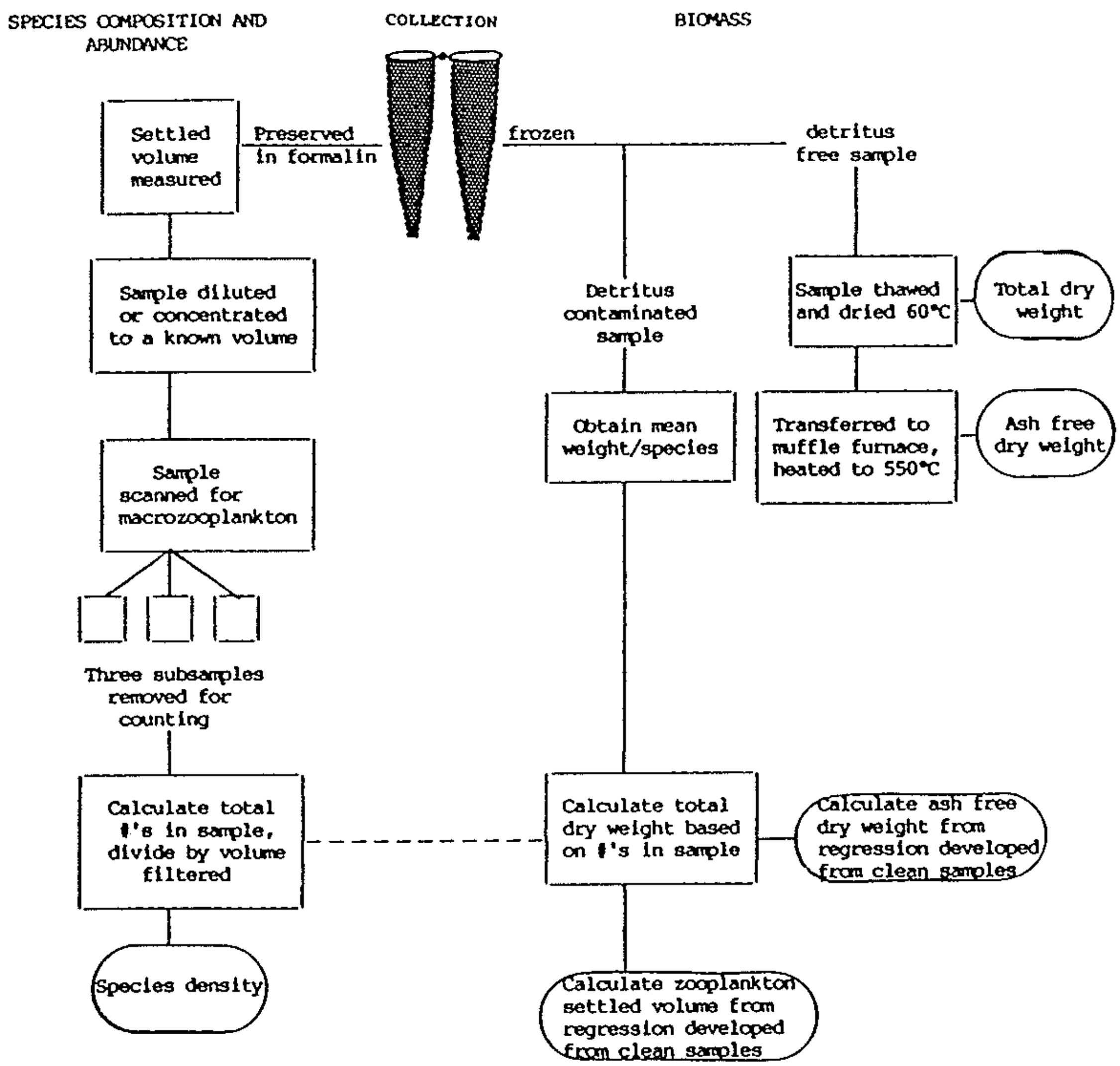

Figure 2. Flow chart illustrating processing for mesozooplankton samples.

wintertime samplings, *E. affinis* was most abundant. This pattern was evident during the first 11 months of the program (August 1984 through June 1985). Subsequent samples from July through December 1985 showed that *E. affinis* again increased in dominance by early winter.

Pulses of polychaete larvae and barnacle nauplii (seen in the "other" category) were apparent when all the data were combined. Analysis by salinity zone showed, however, that these pulses were specific to certain salinity zones.

The mean total abundance and biomass data, averaged over all stations, indicate a cyclical seasonal trend of highest abundances and biomass in summer and late winter seasons followed by either an increasing or decreasing trend in the transitional seasons of fall and spring.

Analysis of Species Composition by Salinity Zone

Salinity is an important environmental factor that limits the distributions of estuarine species, primarily through physiological processes and osmotic stress (Reid 1961). Some organisms have a wide tolerance for changes in salinity (euryhaline) and are found in many salinity zones. Others have a limited ability to withstand salinity changes (stenohaline) and therefore may be distributed within only one zone. Thus, salinity has a pronounced effect on the mesozooplankton community structure. The remainder of this section presents an analysis of mesozooplankton species composition and abundance by salinity zone.

Because the sampling stations were fixed, the salinity at each station varied from month to month depending on the tide state, freshwater input, and local current regimes at the time of sampling. Table 1 shows the salinity categories for each station by month. From August 1984 through December 1985, an average of three stations per month were fresh. An average of only two stations per month were in the oligohaline category, and no samples were collected in this category in January 1985. By far, the majority of samples were collected from mesohaline waters (an average of eight stations per month). Stations in polyhaline water averaged three a month, and no samples were taken in this category during August and September 1984 or during December 1985.

Freshwater zones. Summer collections in the freshwater zone in both 1984 and 1985 contained fewer *E. affinis* collections than in winter, when *E. affinis* made up most of the zooplankton community

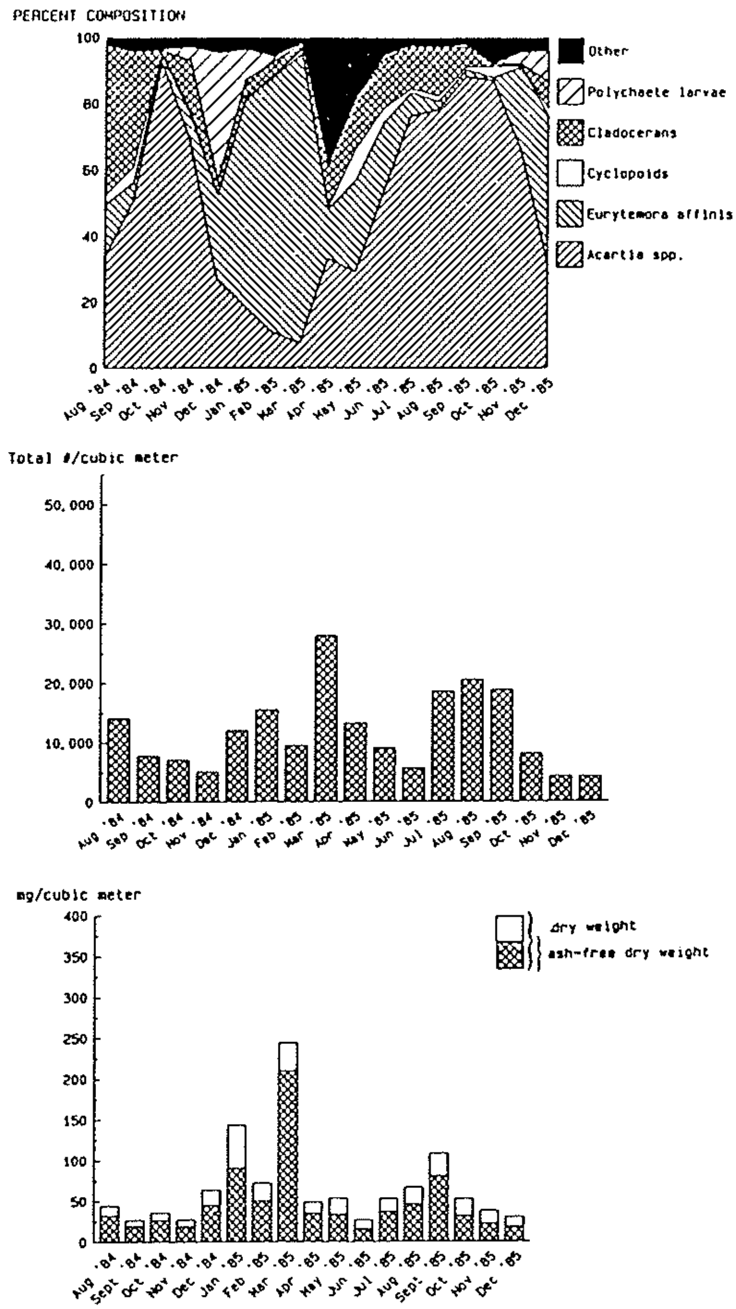

Figure 3. Zooplankton species composition (top), total abundance (middle), and biomass (bottom) for all regions of the sampling area for August 1984 through December 1985.

Table 1. Salinity categories of stations sampling for zooplankton, August 1984 through December 1985.

Station location	1984					1985											
	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mainstem																	
MCB1.1	F	F	F	O	F	*	*	F	F	F	F	F	F	F	F	F	O
MCB2.2	F	O	M	M	M*	*	O	O	O	O	O	O	O>	M	M	M	O
MCB3.3C	M	M	M	P	P	P	P	P	PM	M	M	M	M	P<	P<	M	M
MCB4.3C	M	M	P<	P	P	P	P	P	P	P	P<	M>	P<	P	P	M>	M
MCB5.2	M	M	M	P	P	P	P	P	P	P	P	P	P<	P	P	P	M
Potomac																	
XEA6596	F	F	O	F	F	*	F	F	F	F	F	F	F	O	O	F	F
XDA1177	O	O	M	M	O	*	M<	O	O	O	O	M	M	M	M	F	F
XBE9541	M	M	M	P	M*	M	M	M	M	M	M	M	M	M	M	M	M
Patuxent																	
PXTO402	F	O	O	F	F	F	F	F	F	O	F	O	O	O	O	O	F
XED4892	O	M	M	M	M	M	O	M	M	M	M	M	M	M<	M	M	M
XDE5339	M	M	M	P<	P	P	P	P	M	M	M	M	M	M	M	P	M
Baltimore Harbor																	
MWT5.1	O	M	M>	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Chester River																	
MET4.2	M	M	M	P	P	*	M	M	M	M	M	M	M	M	M	M	M
Choptank River																	
MET5.1	F	O	O	F	F	F	F	F	O	O	O	O	O	O	F	O	F
MET5.2	M	M	P	P	M	M	M	M	M	M	M	M	M	M	M	M	M
Tangier Sound																	
MEE3.1	M	M	M	*	M	M	M>	M	P<	M>	M	M	M	P<	P<	P<	M>

NOTE. F = freshwater, 0.0-0.5 ppt; O = oligohaline, 0.5-5.0 ppt; M = mesohaline, 5.0-18.0 ppt; P = polyhaline, 18.0-30.0 ppt; <indicates salinities are near lower range of category, >indicates average salinities are near upper range of category.
*Samples not taken due to inclement weather or ice cover.

(Figure 4). Cladocerans comprised >50% of the zooplankton collected from August through November 1984 and >60% from April to September 1985. Common cladoceran species included *Bosmina longirostris, Diaphanosoma leuchtenbergianum*, and *Moina micrura*. The cyclopoids *Cyclops vernalis, C. bicuspidatus*, and *Mesocyclops edax* were an important component of the freshwater habitat, making up a significant proportion of the collection during August through October 1984 (>20%) and during May through December 1985 (>10%). *Acartia* spp. were almost never found in freshwater zones, with the exception of two minor influxes in November 1984 and 1985. The freshwater zooplankton community appeared to be much more diverse than those of other salinity zones.

The plots of mean total zooplankton abundance and biomass show a high degree of variability among months and years (Figure 4). Although much of this observed variability can be attributed to natural seasonal and spatial patterns, some bias in density estimates may be introduced as an artifact of the presentation approach in this report. For example, the extremely low densities and biomass values for October 1984 may be due in part to the fact that only one station (MCB 1.1) was located in the freshwater zone, and that station repeatedly had the lowest abundances of any stations over the entire study area. Hence, the density estimate may not reflect a true estimate representative of freshwater locations, but rather the low values associated with a particular station. In most other months, more collections were made in the freshwater zone, providing better abundance and biomass estimates for the region. This imbalance in number of samplings also occurred in the other salinity zones (Table 1).

Oligohaline zones. The shift in dominance from *A. tonsa* in summer to *E. affinis* in winter was clearly evident in the oligohaline collections (Figure 5). An exception to this pattern was seen in December 1985 when the samples were comprised mostly of *Acartia spp.* (only mainstem Bay stations MCB 1.1 and MCB 2.2 were oligohaline). From December 1984 through April 1985 *E. affinis* completely dominated the samples.

Polychaete larvae appeared in the oligohaline collections during December in both years but were more abundant in 1984. In December 1984 almost 30% of all animals collected from this salinity zone were polychaete larvae. In contrast, December 1985 samples from oligohaline waters consisted of only 5% polychaete larvae.

Cladocerans were a major constituent of the oligohaline salinity zone, with greater numbers in summer than winter. The most common cladoceran in the summer months (June-September) of both years was *Moina micrura*, followed by *D. leuchtenbergianum*, *Schapholeberis kingi*, and *B. longirostris*.

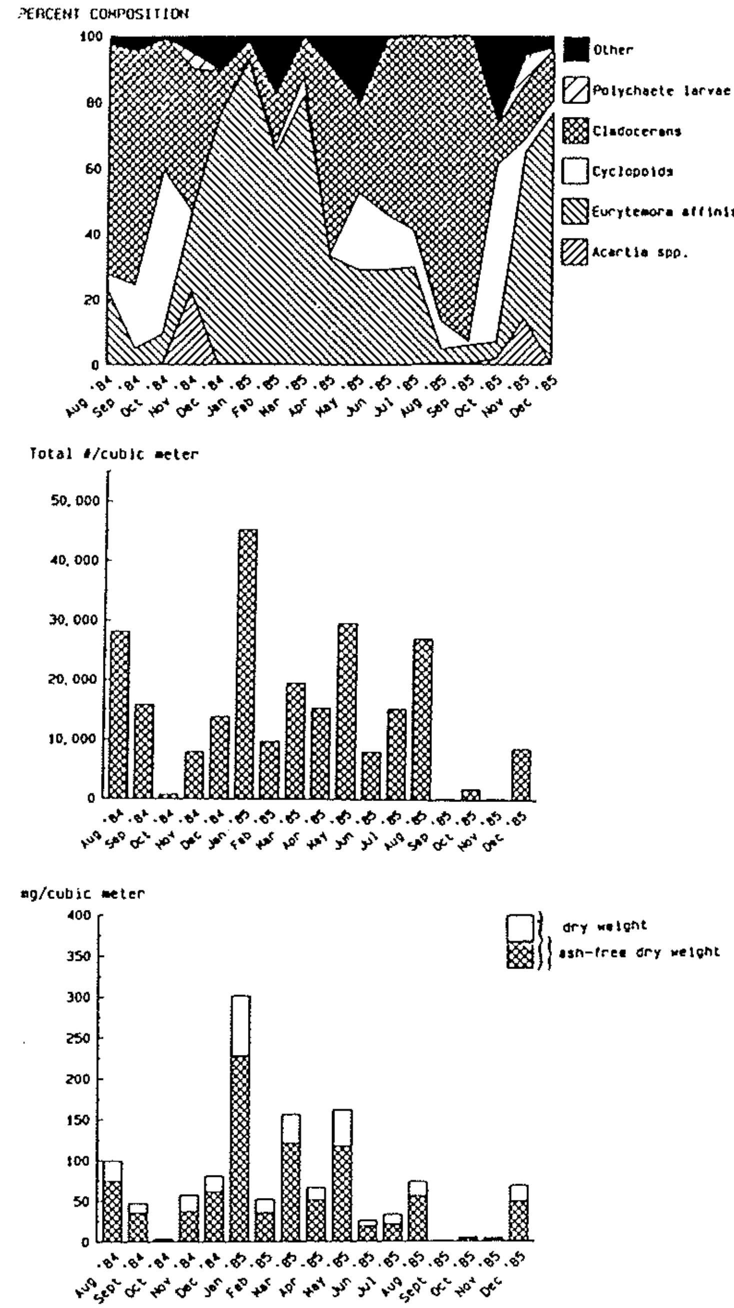

Figure 4. Freshwater species composition (top), total abundance (middle), and biomass (bottom) for August 1984 through December 1985.

Cyclopoid copepods were generally not a major constituent of the oligohaline salinity zone throughout the 17-month period. An exception was November 1984 when cyclopoid copepods (*C. vernalis* and *Mesocyclops edax*) accounted for >40% of the total fraction of organisms collected (Figure 5); however, only one station (MCB 1.1) was oligohaline during this month.

The seasonal analysis of mean total abundance and biomass for the oligohaline zone (Figure 5) showed a cyclical pattern of high densities and biomass during summer and winter, followed by relatively lower values in the fall and spring. Abundances peaked at >50,000/m^3 in February 1985 and 35,000/m^3 in August 1985. These two peaks corresponded to the dominance of *E. affinis* (comprising 98% of total collections) and *Acartia* spp. (comprising 92% of the total collections) in the winter and summer seasons, respectively (Figure 5). Summer samples were dominated by *A. tonsa*, whereas winter samples

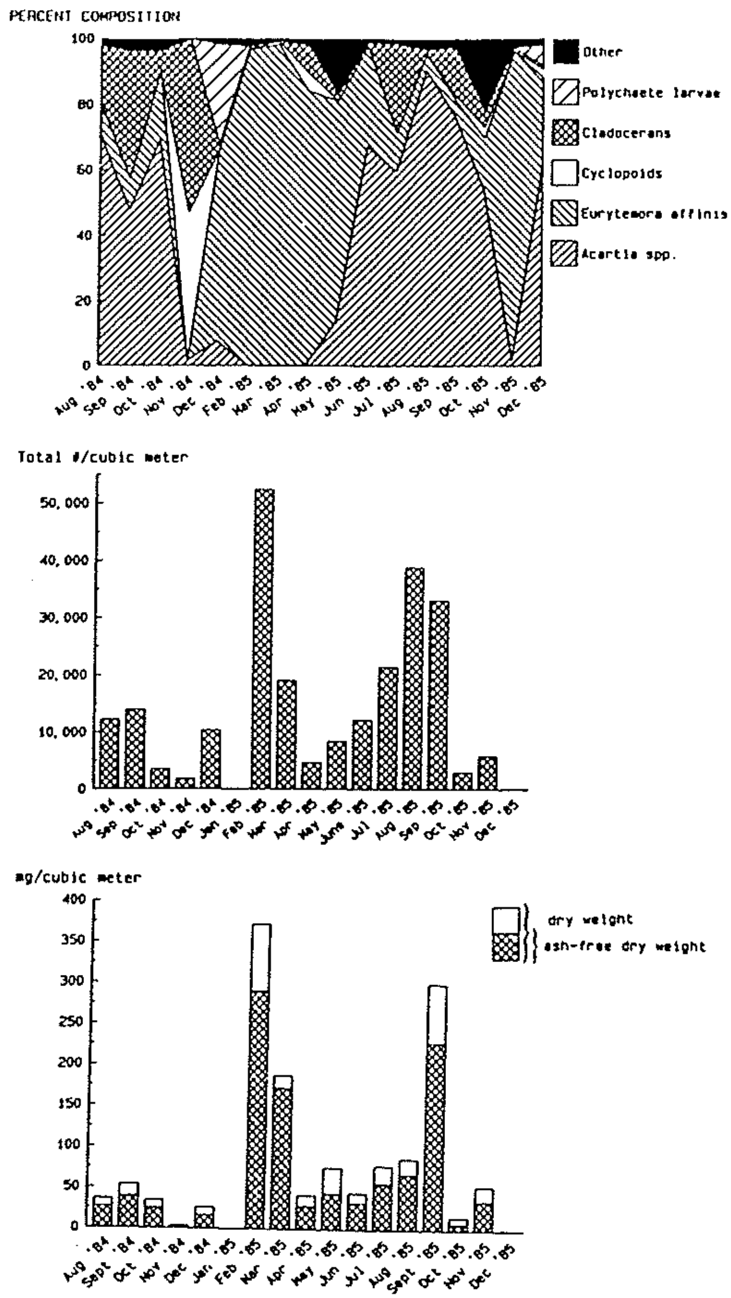

Figure 5. Oligohaline species composition (top), total abundance (middle), and biomass (bottom) for August 1984 through December 1985. No oligohaline stations were sampled in January 1985.

contained both *A. tonsa* and *Acartia clausii*. The designation *Acartia* spp. was applied to winter samples, since nauplii and copepodites could not be identified to species.

Mesohaline zones. The mesohaline habitats generally yielded fewer species than the freshwater and oligohaline zones. The seasonal shift from *E. affinis* dominance in winter to *A. tonsa* in summer was also evident in this higher-salinity habitat (Figure 6), but samples taken in December 1985 indicated that the shift to wintertime *E. affinis* dominance had not yet occurred. Winter dominance of *E. affinis* appeared to be more restricted in time in the mesohaline zones than in the oligohaline or freshwater zones.

The abundance of polychaete larvae during December 1984 was greatest in the mesohaline zone relative to other salinity zones. Collections taken in December 1984 consisted of almost 70% polychaete larvae. Although the densities and the percentage composition were not as large in 1985 as in 1984,

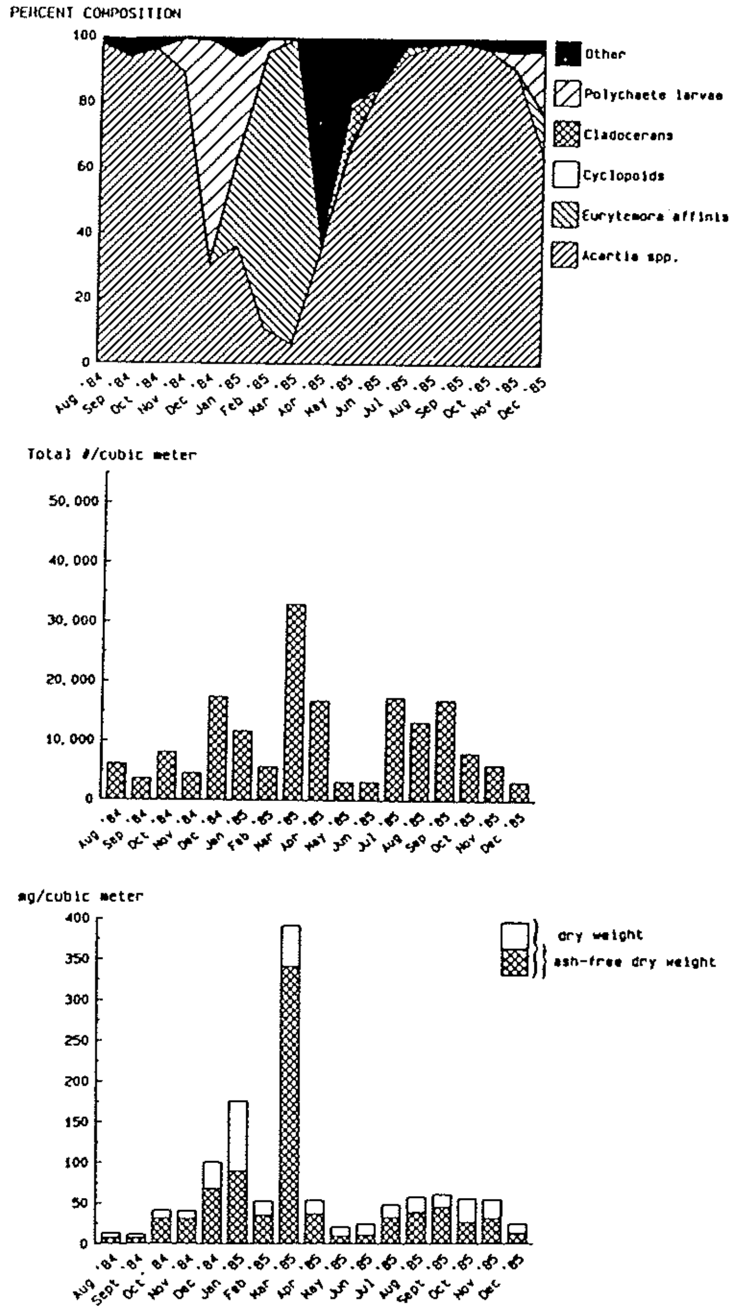

Figure 6. Mesohaline species composition (top), total abundance (middle), and biomass (bottom) for August 1984 through December 1985.

December 1985 samples consisted of almost 20% polychaete larvae, suggesting that these larvae appear in mesohaline waters every year.

A large increase in the percentage composition of the "other" category in April 1985 was due to a pulse of barnacle nauplii (see Appendix I, Tables I-4 through I-6). Sample processing for spring 1986 collections has not proceeded far enough to show whether a similar pulse of barnacle nauplii occurred in April 1986.

The cyclical seasonal pattern of higher summer and winter densities, which was indicated in the analysis of all stations combined and in the oligohaline zone, was not readily apparent in the analysis of mesohaline habitats. Total zooplankton densities and biomass peaked in March 1985 concurrently with an increase in abundance of *E. affinis*. A secondary peak in total abundance in the December 1984 collections was mostly due to an increase in the density of polychaete larvae. Peak total zooplankton abundances

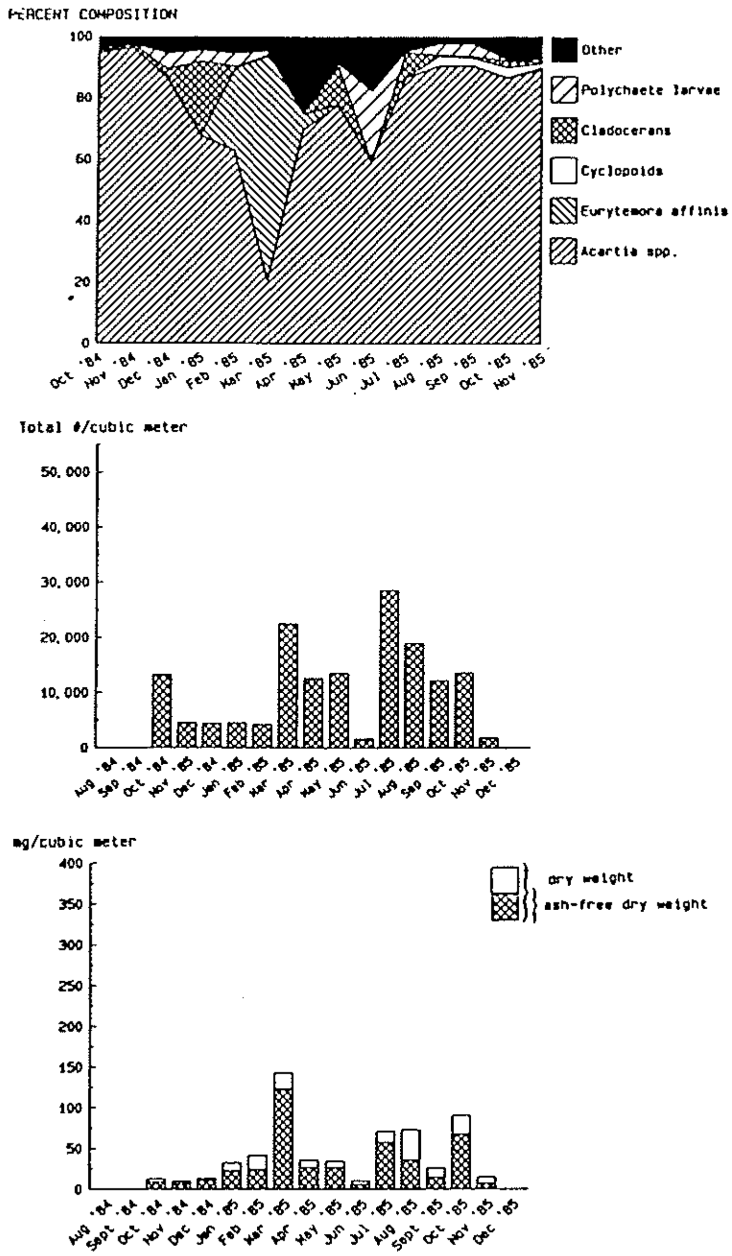

Figure 7. Polyhaline species composition (top), total abundance (middle), and biomass (bottom) for August 1984 through December 1985. No polyhaline stations were sampled in August 1984, September 1984, or December 1985.

and biomass were never established in the summer months of 1984, but were apparent for winter and summer seasons of 1985. In comparison with the oligohaline habitat, the summer 1985 peak in biomass and total density seen in the mesohaline zone was not nearly as pronounced. In general, total mean zooplankton densities and species diversity in the mesohaline habitats were lower than in oligohaline and freshwater habitats.

Polyhaline zones. *Acartia* spp. dominated the polyhaline collections during most seasons (Figure 7). For brief intervals polychaete larvae, *E. affinis*, and barnacle nauplii were abundant, sometimes outnumbering *Acartia spp.* Summer and early winter collections of *Acartia* consisted of the species *A. tonsa*. The winter species, *A. clausii*, appeared in the collections in 1985 only in March and April (Appendix Tables H-1 and I-1); at that time it was more abundant in the polyhaline and mesohaline zones than in the oligohaline zone.

Large numbers of *E. affinis* were present in the polyhaline zone during February and March 1985; most were collected at the downriver Patuxent station (XDE 5339). Densities of *E. affinis* at this station were >4,000/m^3 in February (83% of the total catch, Appendix Table G-3), and >65,000/m^3 in March (87% of the total catch, Appendix Table H-3). Upriver densities of *E. affinis* (at station XED 4892) were also extremely high during February and March (50,000 and 144,000/m^3, respectively).

Studies by Heinle (1969) in the Patuxent River near Benedict showed that although the productivity (weight gain per unit weight per day) of *E. affinis* was low at low temperatures, natural populations had high biomass during periods of low temperature. Riverwide collections by Herman et al. (1968) also showed much higher abundances of *E. affinis* during colder months, but only in areas of low salinity (<12 ppt). The presence of *E. affinis* in the polyhaline zone in the present studies during February and March 1985 suggests either that the species had been transported from upriver habitats or that it has a higher salinity tolerance at low temperatures than previously reported.

The cladoceran *Podon polyphemoides* regularly appeared in the polyhaline habitat throughout the study period. Unlike the other cladoceran species found in the study area, which are mostly freshwater species, *Podon* is a marine cladoceran (of which only six species are found in the Chesapeake Bay [Bryan 1977]). *P. polyphemoides* exhibited periodic increases in percentage composition during January and May of 1985. January 1985 collections consisted of >20% *Podon*; May collections, 10%.

Over the 17-month period, peak zooplankton abundances and biomass in the polyhaline regions were generally lower than in all other salinity categories. Overall seasonal trends in abundance and biomass showed no clear cyclical pattern as in some of the lower salinity zones, but it did not appear that the polyhaline regions were generally less productive.

The pattern of lower abundances observed in the polyhaline zones was not observed in the analysis of the mainstem stations (see below). The mainstem stations generally showed a trend of increasing abundance from the Susquehanna River to the higher-salinity stations in the lower Bay.

Comparison of August-December Periods for 1984 and 1985 by Region and Year

A major objective of the monitoring program is to characterize yearly variations in zooplankton species composition and biomass. An understanding of these "natural" changes is required before any water quality-related changes in zooplankton community structure can be detected. The following sections present a comparison of 1984 and 1985 data for the months of August through December. Because comparative data for only five months are available, the following discussion is intended only to present results that may be indicative of certain patterns rather than to present definitive conclusions. Data for at least two years will likely be needed to accurately characterize this variation.

All months combined. Table 2 presents the mean total zooplankton abundance (number/m^3) for the five-month period by year and region. In 1984, average densities of zooplankton were 62% higher than in 1985. The mean total zooplankton densities for this period were 18,900 and 11,200/m^3 for 1985 and 1984, respectively.

Density estimates of zooplankton for the Potomac River averaged >34,000/m^3 in 1984, but only 7,900/m^3 in 1985. The results of the Patuxent River comparison showed the opposite; 1985 total abundance was about twice as high as 1984 total abundance (15,600 and 7,800/m^3 for 1985 and 1984, respectively).

Among the Patapsco, Chester, Tangier, and Choptank regions, total mean abundance was consistently lower in 1985 than in 1984. The overall decrease in total abundance among these regions in 1985 ranged from 23% to 76% and averaged about 50%.

Yearly comparisons of average abundances found in the mainstem stations also showed slightly lower numbers in 1985 (about 20% less). Station-by-station comparisons showed that densities were 82%, 49%, and 48% lower in 1985 than in 1984 at stations MCB 1.1, MCB 2.2, and MCB 5.2, respectively, but were 42% and 25% higher at stations MCB 3.3C and MCB 4.3C. The uppermost station at the mouth of the Susquehanna was the least productive in both years.

Station by year comparisons. Species compositions and abundance for all stations for the period from August to December were compared for the years 1984 and 1985. Samples taken in the same month and station but in different years often produced very different species compositions. Some of the observed differences were most likely due to changes in salinity at the time of sampling. For instance, in August 1984, at mainstem station MCB 2.2, the collections consisted of a freshwater community of cladocerans, cyclopoids, and *E. affinis*. Sampling in August 1985, when the station was oligohaline, produced mostly *A. tonsa*. Other apparently large year-to-year differences in the abundance of zooplankton at a particular station could be due to differences in natural timing of episodic increases in plankton density and different sample collection dates. For example, the populations of polychaete larvae in the present study have exhibited relatively short-term increases in density, particularly in the oligohaline and mesohaline zones. Although year-to-year comparisons of polychaete larvae density by station showed large differences in abundance at MCB 2.2, XED 4892,

Table 2. Comparison of mean zooplankton densities (number/m^3) by region and station, August-December 1984 and August-December 1985.

Region, station	1984	1985	Difference (%)
Potomac			
XEA6596	62,150	16,091	-74
XDA1177	33,109	4,222	-87
XBE9541	7,565	3,408	-54
Mean	34,274	7,907	-77
Patuxent			
PXT0402	8,505	17,519	+51
XED4892	7,459	10,917	+32
XDE5339	7,443	18,415	+59
Mean	7,802	15,617	+50
Pataspsco			
MWT5.1	17,427	4,215	-76
Chester			
MET4.2	8,420	6,439	-23
Tangier			
MEE3.1	24,093	10,621	-56
Choptank			
MET5.1	60,440	30,440	-49
MET5.2	13,650	16,091	+15
Mean	37,045	23,265	-37
Mainstem			
MCB1.1	2,124	376	-82
MCB2.2	15,462	7,877	-49
MCB3.3C	5,461	9,569	+42
MCB4.3C	10,195	13,752	+25
MCB5.2	19,104	10,102	-48
Mean	10,649	8,335	-20
Grand mean	18,912	11,200	-41

Table 3. Comparison of ctenophore densities (ml/m^3) and total zooplankton density (number/m^3) and dry weight (mg/m^3) in high-salinity zones.

Station, month/year	Ctenophore biomass	Zooplankton density	Zooplankton dry weight
XDE5339			
8/84	20.8	800	3.6
9/84	23.0	2,300	6.1
10/84	1.7	11,000	13.6
XDE5339			
8/85	0.5	22,000	44.6
9/85	0.0	45,000	57.1
10/85	0.0	15,000	202.1
MET4.2			
8/84	22.6	8,900	26.6
9/84	22.8	3,700	14.5
10/84	39.7	120	2.7
MET4.2			
8/85	0.3	10,000	23.1
9/85	1.0	15,000	34.9
10/85	1.3	4,600	18.5
MET5.2			
8/84	34.5	2,500	18.6
9/84	65.7	600	14.5
10/84	3.1	6,500	11.3
MET5.2			
8/85	13.1	24,000	54.2
9/85	0.0	32,000	68.0
10/85	2.2	20,000	32.7
Average, 1984	26.0	4,000	
Average, 1985	2.0	20,800	

MET 5.2, and MEE 3.1, these differences may not reflect actual yearly changes in the population. Sampling resolution was not great enough temporally to determine whether the difference was "real" or merely reflected a shift in the timing of the spawning event.

Ctenophore abundance and biomass. The results of the ctenophore biomass estimates are summarized in Appendix R. Table 3 compares the ctenophore biomass (ml/m^3), zooplankton density, and biomass by month and year for selected stations between August and October 1984 and 1985. Stations at the mouth of the Chester, Choptank, and Patuxent Rivers were selected for this presentation because they consistently produced the highest abundances of ctenophores in the program. The peak season for ctenophores in temperate estuaries normally falls between June and October (Deason and Smayda 1982; Kremer and Nixon 1976; Miller 1974).

Several authors (Deason and Smayda 1982; Kremer 1979; Reeve et al. 1978; Miller 1974; Burrell 1968; Bishop 1967) have studied ctenophore distribution, abundance, and grazing and have concluded that these organisms can exert significant pressure on zooplankton stocks. Initial indicators in the present program (at least for the mesozooplankton component) show similar results. The data summarized in Table 2 indicate that ctenophore biomass was about 13 times higher in 1984 than in 1985. Averaged over the restricted number of stations in this analysis, mean zooplankton densities in 1984 were <20% of densities in 1985. These results suggest that the reduction in the zooplankton standing crop in our study region may be related to ctenophore grazing pressure.

Species Composition and Abundance in the Mainstem Bay

The seasonal trends in total zooplankton abundance for the mainstem stations are presented in Figure 8. Throughout the 17-month sampling period, the lowest zooplankton densities were observed at the uppermost station, MCB 1.1. Among the mainstem stations, a general trend toward higher zooplankton abundances down-Bay was also apparent. A significant Bay-wide peak in zooplankton densities occurred during August and July 1985 at all stations except station MCB 1.1 (near the mouth of the Susquehanna River). Two less prominent peaks in total zooplankton density occurred during August 1984 and April 1985 at stations MCB 5.2 and MCB 4.3C, respectively.

Collections at station MCB 1.1 produced species typically found in a freshwater community. Collections at this station comprised the freshwater cladocerans *B. longirostris, D. leuchtenbergianum, S. kingi, Daphnia retrocurva, Eubosmina coregoni,* and *Ilocrystus* spp., among others. Also commonly found at this station were cyclopoid copepods, which included *C. vernalis, C. bicuspidatus, Mesocyclop edax,* and *Eucyclops agilis.* Collections from stations farther down-bay consisted mostly of species typical of higher salinities, and were usually dominated by *A. tonsa* and to a lesser extent by *Centropages hamatus, Pseudodcaptomus coronatus,* and *Oithona colcarva.* The southernmost mainstem station (MCB 5.2) consistently produced species of marine or higher-salinity origins, such as the calanoid copepods *Centropages furcatus, Temora turbinata,* and *Paracalanus crassirostris,* and the cladoceran *Podon polyphemoides.*

Historical Mesozooplankton Standing Stocks in the Patuxent River, 1963-1964 vs. 1984-1985

An extensive zooplankton survey of the Patuxent River zooplankton community was conducted from July 1963 to February 1965 (Herman et al. 1968; Mihursky et al. 1967). This survey included eight stations ranging from the present program's upriver station at Lower Marlboro (PXT 0402) to the downriver station at Brooms Island (station XDE 5339). Collections were taken with a 370-µm net (no. 2 net) over a 20-month period. Nineteen samplings were taken between October 1963 and December 1964. Thus present mesozooplankton

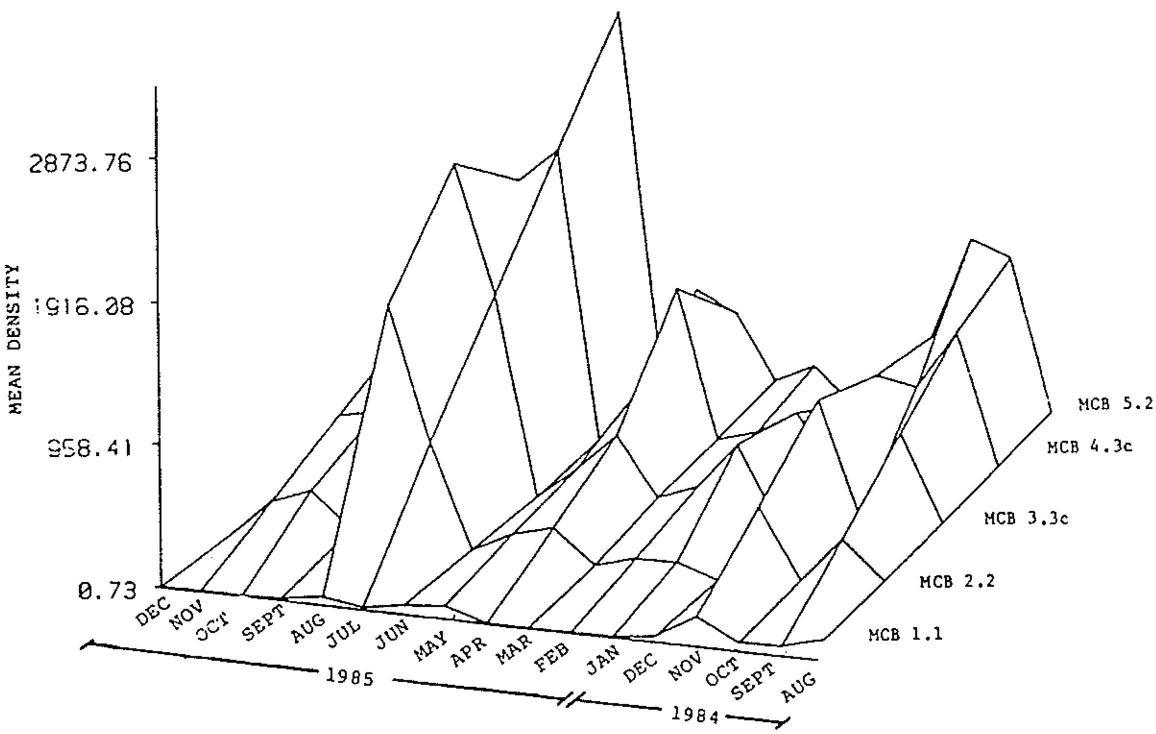

Figure 8. Total mean zooplankton abundance for the mainstem stations for August 1984 to December 1985.

abundances can be compared with those found in the Patuxent River 21 years ago.

Because the mesh sizes of the 1963-1964 survey (370 µm) and the 1984-1985 survey (202 µm) were different, only data on the mean abundances of *Acartia* spp. and *Eurytemora affinis* were selected for this comparison. These species are among the larger mesozooplankton in the Patuxent River, and would be best retained by both mesh sizes. Retention rate studies by Colton et al. (1980) comparing 253-µm and 333-µm nets showed that 1.4 times more *Calanus* and 2.0 times more *Centropages* copepodites were collected with the smaller mesh net, but that the collection efficiencies for adults were about the same. *Acartia* and *Eurytemora* are morphologically similar (in size and shape) to *Calanus* and *Centropages*, respectively.

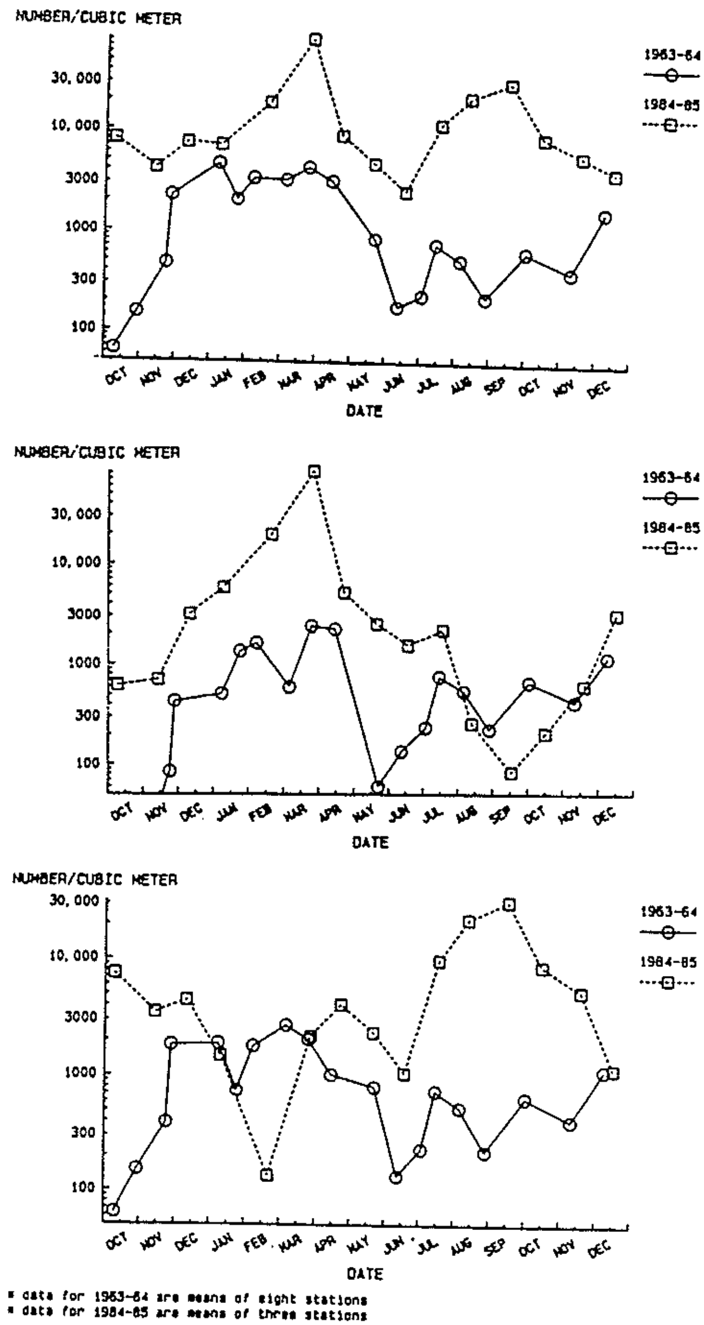

Figure 9. Comparison of mean abundances in the Patuxent River by month for 1963-1964 and 1984-1985 surveys for *Acartia* spp. and *Eurytemora affinis* combined (top), for *E. affinis* only (middle), and *Acartia* spp. only (bottom).

Since the Patuxent River collections are usually a mixture of adults and copepodites of both species, and the two mesh sizes collect adults equally well, the gear bias in the comparison of the two surveys would likely be further reduced. During the 1987 contract period, an attempt will be made to conduct a comparison of a no. 2 net to the 202-µm nets to determine more fully the collection efficiencies of these two mesh sizes and the comparability of the two data sets.

The results of the comparison of 1963-1964 and 1984-1985 data are presented in Figure 9. Averaged over all samples, the combined mean densities of *Acartia.* spp. and *E. affinis* were 1,500/m^3 in the 1963-1964 survey and 15,000/m^3 in the present survey. Whereas the difference in zooplankton abundances between the 1963-1964 and the present surveys was tenfold, the difference in mean density for the August through December periods in 1984 and 1985 period was only twofold. This comparison may suggest that the 20-year difference was much larger than would be expected through natural variation; however, ctenophores were twice as abundant in the 1963-1964 survey (13 ml/liter) as in the present survey (6 ml/liter).

Figure 9 also shows the 1963-1964 and 1984-1985 data comparison for *E. affinis* only and *Acartia* spp. only. The results show that *E. affinis* and *Acartia* spp. were not consistently more abundant in the 1963-1964 survey than in the present survey for all months. However, when individual species densities were averaged over all months, *Acartia* spp. and *E. affinis* were 7.6 and >16 times higher, respectively, in the present survey than in the 1963-1964 survey.

Although the apparent differences over time are probably somewhat gear-related, the zooplankton standing crop of the Patuxent River may have actually increased. An increase in densities could be an indirect result of increases in the nutrient inputs into the system over the 20-year period, which would have stimulated the growth of phytoplankton and thus increased food availability for zooplankton. Although this change does not necessarily imply a negative effect (since more zooplankton means more food available for fish), too much productivity will stress the system when the organisms die and are decayed by oxygen-consuming bacteria.

Over the past 20 years, numerous studies, many of which included plankton sampling, have been conducted in the Chesapeake Bay and its tributaries by the Maryland Department of Natural Resources, Power Plant Siting Program, the EPA, or private industries. Although the methods may have been different from those of the present monitoring program, these historical data sets can provide insights to previous levels of plankton species composition, abundance, and biomass. Historical comparisons, such as the Patuxent example, could therefore be used in assessing the magnitude of long-term shifts in zooplankton abundance relative to short-term oscillations. However, differences between the programs in collection gear, frequency of sampling, and other methods preclude a definitive, quantitative comparison.

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Copies of the Maryland Mesozooplankton Study Appendix have not been included with this report. However, copies are available from

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Plankton Monitoring in Virginian Waters of the Chesapeake Bay

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The plankton monitoring program in the Virginia waters of the Chesapeake Bay comprises monitoring of mesoplankton and phytoplankton at seven mainstem stations and six tributary stations ranging from freshwater to polyhaline environments. Sampling was initiated in the mainstem in July 1985 and in tributaries in March 1986. The program is designed to provide a current and continuing body of data adequate for the detection and interpretation of spatial and temporal trends in the planktonic communities. Not only do these communities form a vital link in the food chains that support the fisheries of the Bay, but also they are the ecological components probably most directly affected by deterioration in water quality. Therefore, the goal of the plankton monitoring program is to provide a means of tracking long-term trends in the ecological conditions of the Bay.

Plankton populations show striking seasonal shifts in species composition, abundance, and diversity, so it is not possible to discern trends that may be of overall ecological significance from the present embryonic data base. Therefore, the following discussion is designed to introduce the plankton monitoring program in Virginia and to present general findings based on the preliminary analysis of data from the reporting period (July-September 1985), a qualitative evaluation of subsequent 1985-1986 data, and information drawn from previous studies.

METHODS

The mainstem plankton monitoring stations in Virginia fall along three east-west transects: a lower pair of stations, LE5.5 and CB7.4, in the mouth of Hampton Roads and the Bay mouth, respectively; a middle transect, stations WE4.2, CB6.4, and CB7.3E, extending from the mouth of the York River to just off Cape Charles City; and an upper pair of stations, LE3.6 and CB6.1, in the mouth of the Rappahannock River and near mid-Bay, respectively. The tributary stations comprise two sites in each of the three primary tributaries: stations RET5.2 and TF5.5 in the James River; RET4.3 and TF4.2 in the York River; and RET3.1 and TF3.3 in the Rappahannock River.

The monthly mesoplankton collections at each of the stations consisted of oblique tows with 202-micron mesh 0.5-m diameter bongo nets. The phytoplankton collections are made two times per month from March through October and monthly from November through February. Composite samples are taken with a diaphragm pump from five depths above and five depths below the pycnocline. Representative subsamples of the composite samples are preserved for analysis. All efforts are made to insure that the plankton collections are coordinated with water-quality monitoring cruises and are performed in a manner comparable with the methods being employed by investigators studying the Maryland waters. Laboratory enumeration procedures are conducted according to the CVS method described by Alden et al. (1982) in order to produce a statistically valid data set. Details of all methods are available from the principal investigators upon request.

MESOPLANKTON

General Characterization of Mesoplankton Fauna

Copepods, especially the calanoid genus *Acartia*, appear to dominate the mesoplankton at most stations in the lower Bay throughout the year. Previous studies (Atkinson 1973; Browne 1974; Jacobs 1978) have indicated that copepods comprise up to 90% of all mesoplankton collected in and around the lower Bay. Furthermore, literature reviews of zooplankton studies conducted throughout the southeastern (Alden 1980) and northeastern (Gerber and Gilfillan 1978) United States have indicated that most estuarine mesoplankton communities are dominated by calanoid copepods, principally *Acartia tonsa*.

In the present study, *A. tonsa* was the most abundant mesoplankter in 39 of 48 mainstem collections during the first eight months of sampling. *A. tonsa* was also prominent in oligohaline and mesohaline tributary stations. Jacobs (1978) reported the virtually complete replacement of *A. tonsa* by *Acartia clausi* in late winter and early spring in the Chesapeake Bay. Data for this period from the present study are not yet available.

During the first three months of sampling, unusually high concentrations of mesoplankters were seen several times. In July, mesoplankton concentrations at the mouth of the York River (WE4.2) and to the east near mid-Bay (CB6.4) were 697,000/m^3 and 763,000/m^3, respectively. The cladoceran, *Podon polyphemoides* and the copepod A. *tonsa* were the dominant species. *P. polyphemoides* was absent to rare at all stations after July until reappearing in smaller numbers in December, a pattern consistent with the biannual abundance peaks described by Barker (1977).

A high August concentration (142,000/m^3) at station LE5.5 in the mouth of Hampton Roads was unusual, in that 29 species or species groups were present in concentrations higher than 900/m^3. These species were led by polychaete trochophore larvae (46,000/m^3) and eggs of the bay anchovy, *Anchoa mitchilli* (19,000/m^3).

Dense mesoplankton concentrations strongly dominated by *A. tonsa* occurred in September at CB6.4 and CB6.1. At the latter station *A. tonsa* approached "monoculture" proportions, exceeding 99% of the 614,000/m^3 concentration of mesoplankters.

The peak densities of mesoplankton observed during the late summer of 1985 were considerably higher than those reported in previous estuarine zooplankton surveys (Gerber and Gilfillan 1978; Alden 1980). Only Heinle (1966), working in the Patuxent River estuary, reported densities of copepods exceeding 100,000/m^3.

Other Prominent Mesoplankton Species

Several additional groups merit discussion because of their periodic abundance and/or apparent ecological significance. In addition to *Podon*, the cladocerans *Evadne tergestina* and *Penilia avirostris* were prominent constituents of the plankton community. *E. tergestina* was nearly ubiquitous in the mainstem during the late summer and was abundant at mid-Bay station CB6.4. *Evadne* was absent after September, a pattern also noted by Barker (1977) during 1971-1972. *P. avirostris* was abundant at stations CB7.4 and CB6.4 from the commencement of sampling in July through September and essentially absent in the lower Bay thereafter, a pattern apparently typical of this species (Barker 1977).

Barnacle larvae were important contributors to the mesoplankton during the first eight months of sampling and reached peak abundance (20,000/m^3) at station WE4.2 in July. Ascidaceans were abundant in August at most stations, and especially at LE5.5 and WE4.2.

Molluscan larvae have presently been identified only as bivalves or gastropods. Bivalve larvae were abundant at station LE5.5 in July and peaked at this station in August when concentrations reached 16,848/m^3. Gastropod larvae were prominent at most stations in July (peak abundance of 13,000/m^3 at station CB6.1) and declined rapidly thereafter.

Anchovy eggs were common throughout the mainstem in July and August and, as mentioned, constituted a prominent portion of the mesoplankton at station LE5.5 in August. Additionally, eggs of hogchoker, *Trinectes maculatus*, were taken in high concentrations (17,000/m^3) at station CB6.4.

Examination of raw data for October 1985 through February 1986 shows increasing concentrations of the copepods *Acartia clausi*, *Paracalanus* spp., and *Centropages* spp. through the fall and winter.

Geographic and Temporal Patterns of Mesoplankton Diversity

Table 1 shows the number of species that occurred in concentrations of >1/m^3, distributed by month and station. Species diversity at all stations reached a maximum in late summer and declined to a minimum in early winter. In general, diversity was greatest at the stations nearest the Bay mouth and at those with high salinity. This pattern was largely produced by the contribution of a larger variety of coastal forms at these stations. The low diversity at station LE5.5 during January and February 1986 was correlated with the lowest salinities and temperatures of the sampling period at that station.

DISCUSSION

The ubiquity and abundance of copepods in the Bay mesoplankton indicates the high likelihood of a

Table 1. Number of species of mesoplankters occurring in concentrations of $\geq 1/m^3$ by station and month from July 1985 through February 1986.

Station	J	A	S	O	N	D	J	F
LE5.5	21	47	38	20	11	15	2	1
CB7.4	44	53	42	27	19	20	7	13
WE4.3	13	23	27	16	7	3	2	12
CB6.4	20	29	15	19	11	10	7	12
LE3.6	16	18	15	9	2	7	6	9
CB6.1	19	17	20	17	10	6	7	10

key trophic role for this group. *Acartia* is known to be an important dietary component of the post-larvae of menhaden and contributes significantly to the diets of the young of a variety of other ecologically and commercially important fish species (Brooks and Dodson 1965; LeBrasseur et al. 1969; Thayer et al. 1974; Kjelson et al. 1975). The most abundant forage fish in the Bay, *A. mitchilli*, preys heavily on copepods. It has been proposed that the concentrations of certain key species of copepod control the survival of many fish species during their transition from larvae to juveniles (Thayer et al. 1974).

The great abundance of copepods also indicates that they must play a major role as predators on both the phytoplankton and microplankton communities. Many copepod species can shift feeding selectivity opportunistically to take advantage of peak concentrations of food organisms (Smayda 1973; Wilson 1973; Poulet 1973, 1974, 1976; Heinle et al. 1966). Considering this ability to maximize feeding efficiency, the very large densities observed during the initial phases of this program, and their role as "fish food," copepods would appear to play a key role in the transfer of energy from primary producers to food chains supporting fisheries of the Bay. Perhaps specific trophic studies would indicate the ecological significance of the unusually high densities of mesoplankton in the energy and nutrient flux of the region.

Virginia has no monitoring program for microzooplankton, a size class that also comprises an unquestionably important trophic link in the planktonic community. During the initial months of sampling we have occasionally taken a large number of clumped tintinnids, but these have not been identified or enumerated.

PHYTOPLANKTON

General Characterization for the Phytoplankton Community

The 116 species identified from the phytoplankton collections represented the following groups: Bacillariophyceae (64 species), Dinophyceae (30), Cyanobacteria (6), Haptophyceae (3), Chlorophyceae (3), Euglenophyceae (4), Cryptophyceae (3), and Prasinophyceae (3). Forms that could not be identified to species were placed under the next highest taxonomic group, with other unidentified cells placed in size categories of <3 µm, 3-5 µm, and 6-10 µm. These groups included many pico- (0.2-2.0 µm) and nanoplankton (2-20 µm) components. The <3 µm category was the most abundant and contained a mixture of cyanobacteria, chlorophytes, prasinophytes, and haptophytes. Reference to picoplankton (<2 µm) alone would include mainly the cyanobacteria.

The July, August, and September collections contained a mixed phytoplankton assemblage. Dominant species in July came from several taxonomic categories including bacillariophyceans, cryptophyceans, dinoflagellates, cyanobacteria, chlorophyceans, and a mixed category of microphytoflagellates. At the Chesapeake Bay entrance (station CB7.4), there was a sharp difference between the compositions of the lower and upper strata of water. The deeper waters contained a greater diversity and concentration of estuarine and shelf species, characterized by large centric diatoms, several *Ceratium* spp., and *Chaetoceros* spp. This vertical pattern was common at other stations along the Bay stem. In contrast, greater similarity in composition with depth was a more common pattern at the tributary stations along the western Bay margin.

Two groups that were abundant in July maintained high concentrations into September. These were the cryptomonads and an assemblage of small (<5 µm) centric diatoms. These diatoms consisted of several *Cyclotella* spp. and *Thalassiosira* spp. Among these were *Thalassiosira oestrupii* var. *venrickae* and *Cyclotella striata*. Also abundant were a variety of micro-phytoflagellates. The other common diatoms at this time included *Skeletonema costatum*, *Leptocylindrus minimum*, *Leptocylindrus danicus*, *Cylindrotheca closterium*, *Rhizosolenia alata*, *Rhizosolenia calcar avis*, *Rhizosolenia stolterfothii*, *Cerataulina pelagica*, *Thalassionema nitzschiodes*, *Hemiaulus sinensis*, *Nitzschia pungens* and *Biddulphia alternans*. Dinoflagellates that were abundant included *Ceratium fusus*, *Ceratium lineatum*, *Ceratium macroceros*, and *Prorocentrum micans*. Other common flagellates were *Eutreptia lanowii*, *Pyramimonas* spp., and several *Cryptomonas* spp.

In association with these phytoplankton changes, a distinct pattern of light transparency was noted with the Secchi disk readings: lowest readings were recorded along the western Bay margin. As these sites were at river mouths, silt load of these river systems may have contributed to these lower readings. In contrast, greater light transparency was found in the deeper waters of the Bay stem, at the Bay entrance, and along the eastern margin.

In summary, this three-month segment of data showed differences in phytoplankton concentrations, diversity, and composition patterns in the lower Chesapeake Bay and differences between the waters above and below the pycnocline. There was evidence of estuarine species being transported in sub-pycnocline waters from the Bay entrance up the Bay stem (Tyler and Seliger 1978). The water column contained high concentrations of a pico-nanoplankton component that was mainly composed of cyanobacteria. Dominant diatoms included the small (<20 µm) *Cyclotella* spp. and *Thalassiosira* spp., plus large centrics entering from the Bay entrance. The July-September collections also showed the beginning for the fall pulse, with *Skeletonema costatum*, *Leptocylindrus minimum*, and *Leptocylindrus danicus* increasing in abundance during these collections. Other major components of this period were *Cryptomonas* spp., several dinoflagellates, and large centric diatoms common to the shelfwaters.

Total Phytoplankton Densities

The total phytoplankton concentrations over this period were highest along the western Bay margin, with lower abundance at the Bay entrance and within the central Bay region (Figure 1). This was also true for the concentrations of diatoms, dinoflagellates, and picoplankton. There was evidence for different vertical distribution patterns for several of the taxonomic groups. The diatoms were more abundant below than above the pycnocline at both the mainstem and tributary stations, whereas the reverse was true for dinoflagellates. The picoplankton component was more abundant in the surface strata than below the pycnocline.

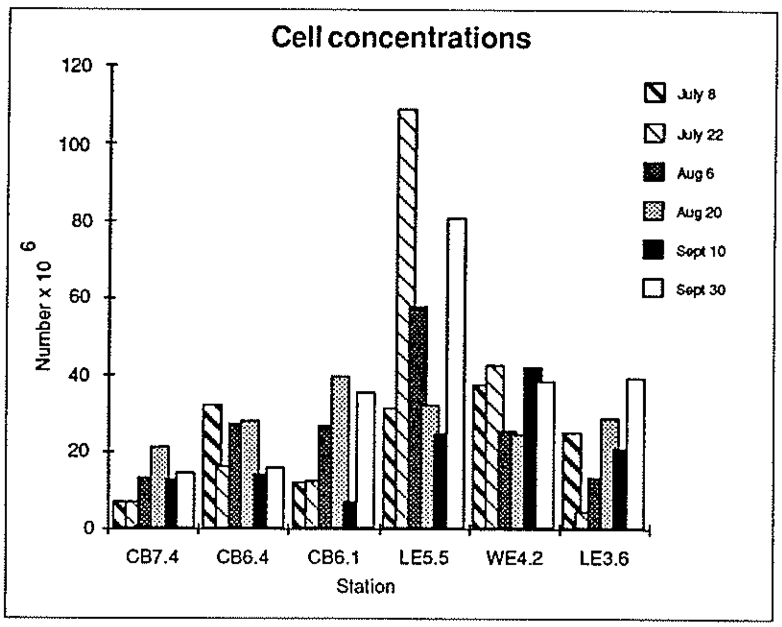

Figure 1. Total phytoplankton concentrations by stations and 1985 collection dates in the lower Chesapeake Bay. Stations CB7.4, CB6.4, and CB6.1 are in the central Bay, from the Bay entrance northward. Stations LE5.5, WE4.2, and LE3.6 are located off the entrances of the James, York, and Rappahannock Rivers, respectively.

There was a general trend for cell concentrations to increase from the Bay entrance into the Bay (Figure 1). During this sampling period, cell concentrations were higher at stations adjacent to the three tributaries than at the central Bay stations. Diatom concentrations increased along the Bay stem below the pycnocline, but varied above the pycnocline. The dinoflagellates had higher concentrations adjacent to the tributaries than in the lower Bay stem above and below the pycnocline.

These observations correspond closely to composition and concentration patterns described for the lower Chesapeake Bay by McCarthy et al. (1974), Van Valkenburg and Flemer (1974), Marshall (1980, 1982), and Marshall and Lacouture (1986). Marshall and Lacouture (1986) described the seasonal growth maxima for this region, noting an extended growth period in late winter-early spring, followed by a changing composition and reduced concentrations in summer. The summer months showed an increase in dinoflagellates, cryptomonads, and cyanobacteria. The development of the fall pulse varied and often blended into the late winter-early spring production. In these past studies *Skeletonema costatum* has been one of the major seasonal dominants, with the picoplankton component ubiquitous and abundant throughout the year. Marshall and Lacouture (1986) also indicated that over the past 60 years the composition and concentrations of Chesapeake Bay phytoplankton have changed, possibly in response to increased levels of nutrient enrichment and eutrophication.

FUTURE DATA ANALYSIS

Although the data set collected within the reporting period (July-September, 1985) was not of sufficient size to warrant sophisticated data analysis, a statistical protocol has been developed to aid in the evaluation and interpretation of significant trends as the data are accumulated. The goals of the statistical analyses are twofold: 1) to characterize significant spatio-temporal patterns of the phytoplankton and zooplankton communities of the study area; and (2) to explore relationships between the phytoplankton, zooplankton, and water-quality patterns.

It is beyond the scope of this report to detail the analytical techniques to be employed in future data analyses, but a brief summary of the overall approach may be in order. The initial phase involves reducing the number of species (phytoplankton or zooplankton) to be analyzed statistically. A computer program based on a data reduction method described by Williams and Stephenson (1973) is employed to provide an objective means of selecting only species that significantly contribute to spatial or temporal patterns in the data. The reduced data set is analyzed by a series of complementary multivariate techniques designed to examine spatio-temporal patterns: classification or "cluster" analysis; principal component analysis (PCA) followed by ordination of confidence ellipses; and a Kinematic graphics/mapping system (4-DIM) with a "time-slicing" mode. The exploration of biological associations and their relationships to environmental patterns will also be accomplished by a series of complementary multivariate techniques: the examination of various combinations of PCA factors from the zooplankton, phytoplankton, and water-quality data sets on the 4-DIM graphics system (time-lag models will also be evaluated visually); linear and nonlinear regression analyses of cluster components (e.g., phytoplankton components on water quality and vice versa; zooplankton on phytoplankton and vice versa); and several multiple discriminant analysis techniques described by Green (1979).

All of the statistical and graphical procedures that will be employed are considered exploratory in nature. Data for several years may be required to characterize major trends fully in the highly variable plankton communities. However, combinations of the analytical procedures will be employed in an attempt to develop hypotheses and characterize patterns throughout the ongoing program.

SUMMARY

The dominant components of the mesoplankton in the Virginian waters of the Chesapeake Bay mainstem during the reporting period were calanoid copepods, principally *A. tonsa*. The cladoceran genera *Podon* and *Evadne* were also prominent constitutents of the mesoplankton. Summer populations were high in mesoplanktonic forms, led by barnacle, gastropod, bivalve, polychaete, and decapod larvae. Diversity of the mesoplankton collections generally decreased from south to north, or from more saline waters to those with lesser salinities. Dominant species and their patterns of occurrence appear to resemble those preliminarily reported for the meso- and polyhaline habitats of the Maryland waters of the Bay.

Perhaps the most striking finding of the mesoplankton study to data has been the high densities of copepods and cladocerans observed at certain of the stations. Considering the apparently important ecological role of these organisms, these peak abundances may be of considerable ecological significance.

The phytoplankton collections for July through September displayed a mixed assemblage of species. The most abundant and ubiquitous group were the pico-nanoplankton, which were composed mainly of cyanobacteria and chlorophyceans, among others. They were numerically dominant at all surface and bottom depths sampled. There were indications of the transport of coastal phytoplankton species into the bottom waters of the Bay mainstem. At the Bay entrance, there was a sharp difference in composition of populations between surface and bottom collections. The deeper waters contained a greater diversity and concentration of shelf species, characterized by large centric diatoms, *Ceratium* spp., and *Chaetoceros* spp. This distribution pattern was also seen at stations along the eastern margin and in the mid-Bay region, suggesting transport via the sub-pycnocline waters. The stations along the western end of the transects displayed greater homogeneity in composition with depth.

The phytoplankton collections from the late months of summer also provided indications of the beginnings of the fall pulse, with *S. costatum*, *L. minimum*, *L. danicus*, and several dinoflagellates increasing in abundance during this quarter.

It should be repeated that these findings are extremely preliminary. Once a substantial data set has been accumulated (i.e., the collections from the 1985-1986 contract period), a comprehensive statistical evaluation will proceed. The spatio-temporal patterns of zooplankton and phytoplankton community structure will be characterized and related to each other, as well as to water-quality trends in the lower Bay.

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Benthic Populations in the Upper Chesapeake Bay

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The Chesapeake Bay is home to an active community of organisms living in association with bottom sediments. This assemblage, collectively known as the benthos, includes familiar organisms such as oysters, clams, and crabs, as well as less familiar forms, including worms, small crustaceans, snails, and anemones. In regions of high phytoplankton productivity, algal biomass produced in the water settles to the sediment surface as detritus and is used in the benthic environment. Much of the particulate carbon and detritus added to the Bay from the surrounding watershed also settles to the bottom and is used by the benthos. The burrowing activities of benthic organisms contribute significantly to the recycling of nutrients buried in the sediments back into the overlying water. These recycled nutrients are frequently an important source supporting primary production in the water. The Chesapeake Bay is a nursery ground for many commercially and recreationally important fish. While on their nursery grounds most of these fish feed on the benthos. Thus benthic organisms are major secondary producers, forming important linkages between primary producers and higher trophic levels, and are an integral part of the Bay ecosystem.

STUDY DESIGN

The benthic element of the water quality monitoring program is designed around the concept that benthic populations are likely to respond to changes in water and sediment quality resulting from efforts to improve the Bay's water quality and restore the health of its living resources. Because benthic organisms live for one to two years, changes in their populations are an integration of changes in environmental conditions over their life span. In addition, because they are relatively immobile, they complete their life cycle within the Bay and in many cases within specific tributaries or regions of the Bay. Thus, their responses to changes in water quality are likely to be region-specific and easily interpreted. Finally, benthic organisms are important intermediate linkages in the Bay food web, and their responses to cleanup actions are likely to be representative of the responses of other living resources. For these reasons benthic organisms are potentially good indicators of the effectiveness of cleanup efforts.

The benthic program element is jointly sponsored by OEP and the Maryland Power Plant Research Program (PPRP) and includes historical PPRP stations for long-term benthic monitoring. PPRP stations along the mainstem of the Bay have been sampled regularly since 1971. PPRP stations in the Potomac and the Patuxent Rivers have been sampled regularly since 1979-1980. Building the current benthic monitoring element around the PPRP long-term benthic monitoring program provided a long-term data record that could be used to place responses due to cleanup in the context of fluctuations associated with natural phenomena.

A major objective of the first several years of the benthic program element is to determine the present status of benthic communities and their relationships to existing anthropogenic and natural environmental conditions. Information obtained during this characterization phase will be used in future years to distinguish changes caused by natural phenomena from improvements brought about by cleanup programs.

Benthic sampling is conducted 10 times per year throughout the mainstem Bay and in all the major tributaries (Figure 1). These stations include the entire range of salinity and sediment types that occur in the Maryland Bay. Physical and chemical properties of the water (e.g., salinity, temperature, dissolved oxygen concentration) and sediments (particle size, carbon content) that affect benthic organisms are measured at

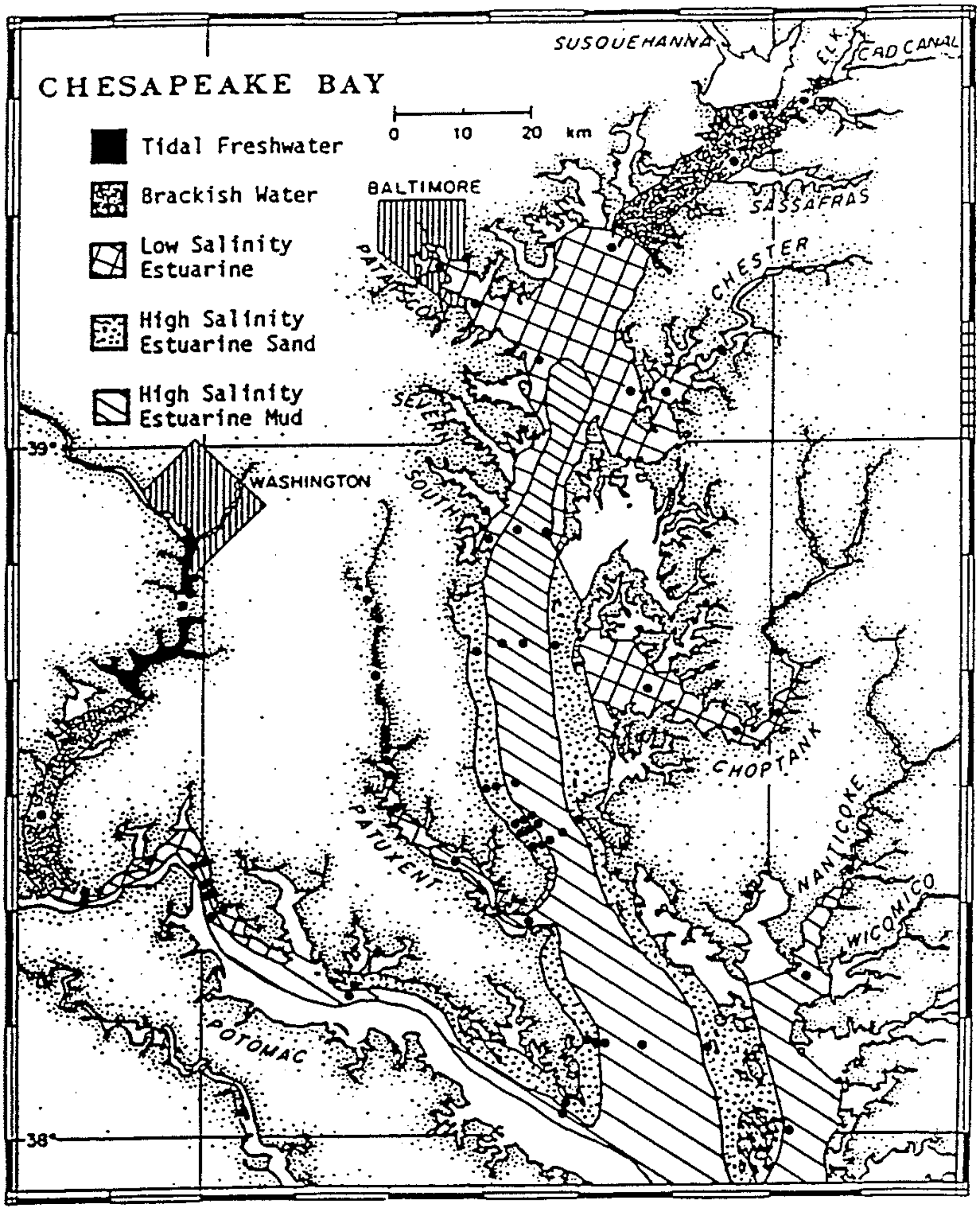


Figure 1. Distribution of benthic communities in the Maryland portion of the Chesapeake Bay. Dots indicate locations of benthic sampling stations. Samples were not collected from regions of the Bay left clear.

each location where samples of the benthos are collected.

RESULTS

Salinity is the major natural environmental factor controlling regional distributional patterns for the Bay benthos. Differences in sediment characteristics and concentrations of bottom dissolved oxygen that occur from nearshore to deepwater habitats control local benthic distributions. Five major assemblages of benthic populations occur along the Bay's salinity and sediment gradients: (1) a tidal freshwater assemblage, (2) a brackish water (transition) assemblage, (3) a low-salinity estuarine assemblage, (4) a high-salinity estuarine sand assemblage, and (5) a high-salinity estuarine mud assemblage (Figure 1).

The tidal freshwater assemblage is limited to the upstream portions of Bay tributaries. Aquatic earthworms, called oligochaetes, and larval insects are numerically dominant in this habitat. The brackish water assemblage occurs in the transition zone between freshwater and estuarine habitats. This transition zone is best developed and of greatest extent in the upper portions of the mainstem Bay and the Potomac River. Both freshwater organisms that tolerate exposure to low salinity and estuarine species that tolerate freshwater are abundant in the brackish habitat. The low-salinity estuarine assemblage is dominated by a mix of marine species tolerant of low salinity and estuarine species. The high-salinity estuarine sand and mud assemblages are distinct assemblages, each dominated by marine species. It is apparent from Figure 1 that most of the Maryland portion of the Bay is inhabited by estuarine assemblages. The above distribution of benthic communities corresponds well to the segmentation scheme that has been developed using measurements of Chesapeake Bay water quality.

Biomass is the collective weight of all benthic animals collected after drying. The spatial distribution of benthic biomass for the Maryland Bay is summarized in Figure 2. The height of the bars represents the average annual amount of benthic biomass per square meter of bottom area. The deep central portion of the Bay and the lower half of the Potomac River support the lowest benthic biomass. Benthic biomass is also low in the deeper regions near the mouths of smaller tributaries. In these habitats, annual abundance and biomass of benthic organisms is depressed because of adverse effects of anoxic bottom waters in the warmer months. The effects of anoxia on the benthos are most apparent just downstream of the Bay Bridge, where anoxia is generally most severe and of greatest duration. Benthic organisms occurring in habitats that experience anoxia are small, rapidly-growing forms that can reproduce in any season.

Shallow habitats along the margins of the main-stem Bay and the lower half of the Potomac River, which do not experience summer anoxia, are characterized by much greater benthic biomass than the adjacent deeper habitats, which do experience summer anoxia (Figure 2). Among the benthic organisms abundant in shallow habitats are small, rapid-growing polychaetes and larger, slower-growing crustaceans, and mollusks.

Benthic biomass is greatest in brackish water and low-salinity estuarine habitats. Much of the suspended sediment and organic input to the Bay is deposited in this habitat (the zone of maximum turbidity). The Macoma clam, *Macoma balthica*, and the brackish water clam, *Rangia cuneata*, comprise most of the benthic biomass in this zone. These clams are particularly well adapted to feeding on microoganisms associated with organically rich, frequently resuspended sediments.

The biomass of benthic organisms fluctuates as much or more over an annual cycle at any one place in the Bay as it does from place to place. The inserts in Figure 2 summarize month-to-month variation for the benthos of typical Bay habitats. In all habitats, benthic biomass peaks in the spring. Factors influencing within-year variation in benthic biomass vary among habitats. Essentially no benthic organisms survive anoxic conditions in deep habitats during summer (Figure 2A). When anoxic conditions dissipate in early fall, deep habitats are repopulated within weeks by small, rapidly-growing polychaetes. Benthic biomass is also low during summer in shallow habitats along the margins of the Bay and its tributaries. Summer low biomass values in shallow habitats are, however, larger than peak biomass values in deep habitats that experience anoxia (Figure 2A and 2C). Annual biomass cycles for shallow habitats appear to be associated with the annual phytoplankton cycle, an association suggesting a direct linkage between shallow-water benthic biomass and lower trophic levels (Figure 2C). A variety of taxa, including polychaetes, crustaceans, and mollusks, contribute to biomass peaks in shallow habitats. Seasonal variation in benthic biomass is reduced in brackish water and low-salinity estuarine habitats near the zone of maximum turbidity (Figure 2B); however, biomass levels in these habitats are always an order of magnitude higher than those in other habitats.

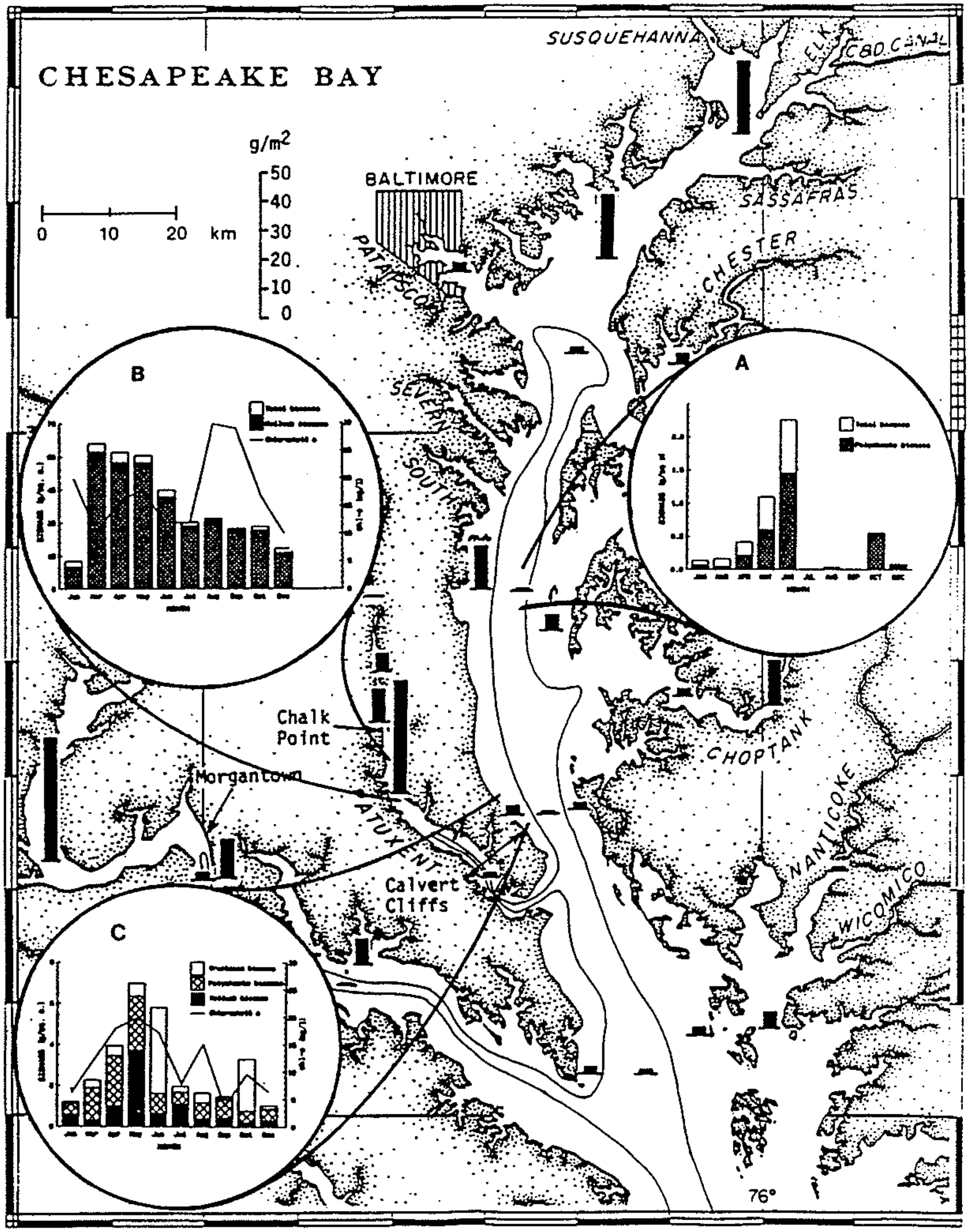


Figure 2. Spatial distribution of average annual benthic biomass in the Maryland portion of the Chesapeake Bay. Bars are average values when multiple stations occurred in a region. The shaded contour shows the region affected during the summer by anoxic bottom waters. Inserts show seasonal distributional patterns for fauna at representative stations.

In the Patuxent River, the abundance of adult *Macoma* clams peaked in 1978-1980 near the zone of maximum turbidity at the same time that suspended sediment and sewage loadings were at the highest levels recorded for this system (Figure 3). As discussed above, *Macoma* biomass is closely linked to the amount of organic material that is produced in or added to the system. Patuxent *Macoma* populations have declined since 1980 as suspended sediment has been upgraded. Declining *Macoma* biomass indicates that the amount of organic material accumulating in Patuxent sediments is decreasing and that water quality is improving. These data suggest that pollution abatement and cleanup programs for the Patuxent River are effectively improving water and sediment quality by limiting inputs and production of organic material. The benthos is responding in a measurable and interpretable way to these improvements and appears to be an early indicator of system-wide improvements.

Natural effects of salinity fluctuations on long-term benthic abundance trends are shown in Figure 4 for the low-salinity estuarine assemblage from the middle reaches of the Potomac River. This figure suggests that year-to-year fluctuation in salinity during the reproductive periods is a major factor influencing long-term trends for benthic organisms. Salinity exerts the most influence over benthic distributions during early life stages shortly after reproduction, because these life stages generally have narrower salinity tolerance ranges than do adults. The long-term distributional pattern shown in Figure 4 is representative of most of the Chesapeake Bay. Long-term benthic responses to salinity and other sources of natural variation must be determined before responses to Bay-wide cleanup can be assessed.

CONCLUSIONS

First, benthic organisms are an important component of the Bay ecosystem, serving as food for fish and crabs and mediating exchange processes

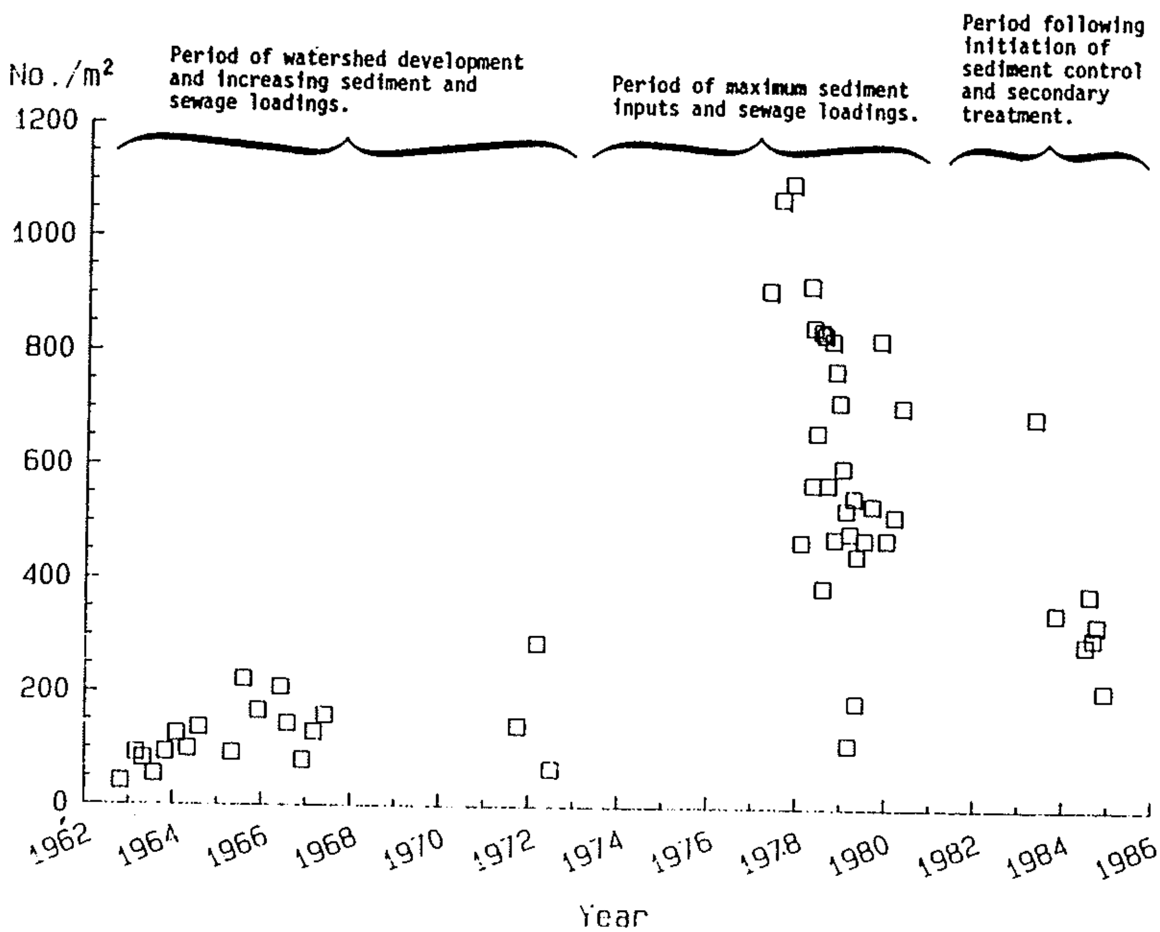
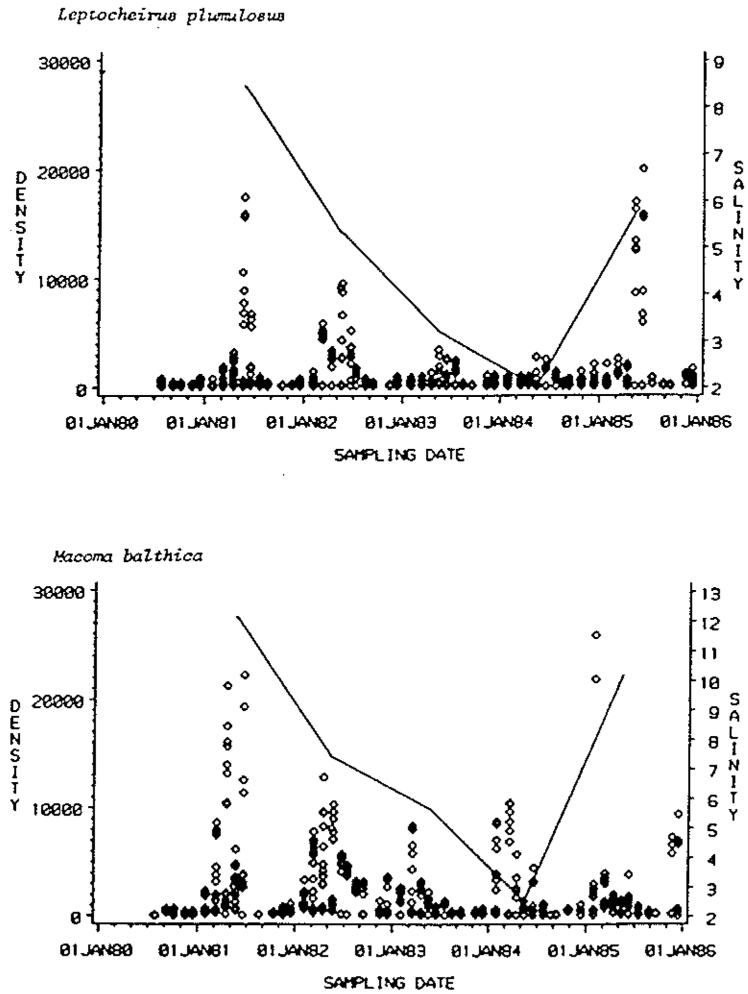


Figure 3. Long-term abundance patterns for adult *Macoma balthica* in the region of maximum turbidity of the Patuxent River.

Figure 4. Long-term abundance pattern for two representative estuarine species in the low-salinity estuarine region of the Potomac River.



between bottom sediments and the overlying water column.

Second, benthic organisms provide a sensitive indicator of water quality that integrates over trophic levels, over time, and over a number of environmental variables.

Third, the impact of low dissolved oxygen waters on bottom habitats is difficult to measure directly but is clearly evident in benthic communities.

Fourth, the long-term response of benthic organisms to reductions in organic inputs and initial clean-up of the Patuxent River has been documented and appears to be favorable.

Finally, benthic responses to pollution abatement can be accurately tracked because natural sources of variation are known and can be partitioned from responses associated with pollution abatement and cleanup programs.

Benthic Biological Monitoring of the Lower Chesapeake Bay

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The benthic biological monitoring program for the Virginia portion of the Chesapeake Bay consists of quarterly cruises to 16 stations in major salinity-sedimentary regions, from the tidal freshwater zone of the tributaries to the polyhaline zone of the mainstem. The purpose of the program is a regional quantitative characterization of the estuarine macrobenthic communities. The long-term goal is to relate spatial and temporal trends of the benthic biota to changes in water quality within the Chesapeake Bay.

This report summarizes general spatial distributional patterns of the macrobenthic communities for data collected from the 1985 cruises (March, June, September, and December). Data collected consisted of estimates of macrobenthic living resources; quantification and characterization of bottom sediments; and measurements of bottom temperature, salinity, and dissolved oxygen.

METHODS

At each station (Figure 1) estimates of macrobenthic community structure were made from three

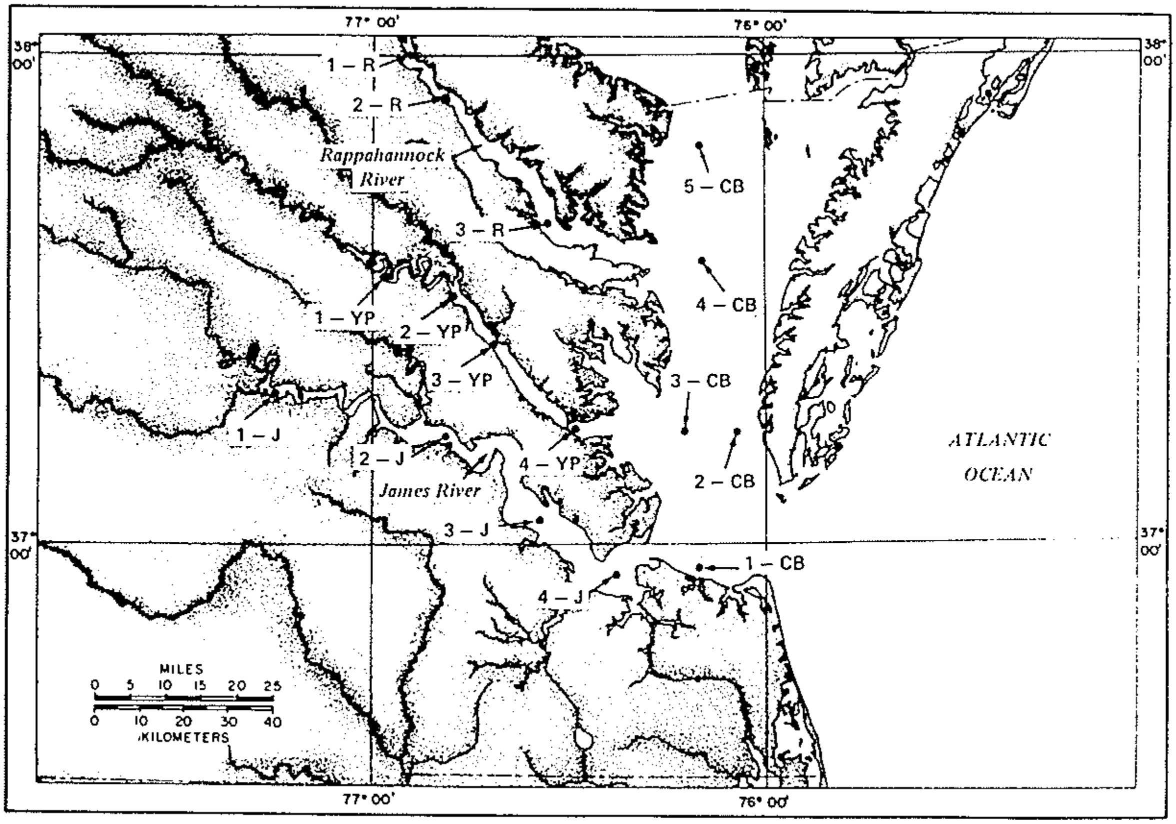


Figure 1. Locations of benthic biological monitoring stations in the lower Chesapeake Bay.

Table 1. Average 1985 salinity and sedimentary parameters for the estuarine site groups, as determined by four quarterly cruises.

Site group	Salinity (parts per thousand)	Median grain diameter (mm)	Silt-clay (%)	Volatile solids (%)
Tidal freshwater	1.13	4.74	74.65	3.85
Transitional	8.26	5.47	90.87	5.04
Mesohaline mud	15.97	4.88	76.33	3.25
Polyhaline silty-sand	21.35	3.09	27.90	0.94
Mainstem mud	21.63	5.29	83.39	2.67
Mainstem silty-sand	27.55	3.98	48.05	0.45

replicate box-core samples taken to a minimum depth of 25 cm below the sediment-water interface. Depth distribution of macrobenthos within the sediment was analyzed by partitioning one of the replicates into the following depth intervals: 0-2, 2-5, 5-10, 10-15, 15-20, and 20-25 cm. All samples were sieved on a 0.5 mm-mesh screen. All species were identified and counted, and biomass was recorded as ash-free dry weight.

Total volatile solids and frequency distribution of sedimentary particle size were estimated from a single sample of the upper 2 cm of sediment from each station on each cruise. For the June cruise the 5-10 cm and 15-20 cm depth intervals of the partitioned replicate were also analyzed.

RESULTS

Depth Distribution

The 16 benthic collection stations were categorized in six site groups based on ranges of bottom salinity and sedimentary parameters (Table 1). Stations were grouped as tidal freshwater (1-J, 1-YP, 1-R); transitional, or region of the turbidity maximum (2-J, 2-YP, 2-R); mesohaline mud (3-J, 3-YP, 3-R); polyhaline silty-sand (4-J, 4-YP); mainstem mud (3-CB, 4-CB, 5-CB); and mainstem silty-sand (1-CB, 2-CB).

In all tributary site groups the number of individuals collected decreased rapidly with depth below the sediment-water interface, with $\geq$94.8% of the total

Table 2. Cumulative percentages of total individuals collected at increasing depth intervals for the six estuarine site groups. Calculations are based on averages for four quarterly cruises for 1985. Stations in group 1 are tidal freshwater stations; in group 2, transitional stations; in group 3, mesohaline mud stations; in group 4, polyhaline silty-sand stations; in group 5, mainstem mud stations; in group 6, mainstem silty-sand stations.

Depth interval (cm)	Site group					
	1	2	3	4	5	6
0-2	69.9	60.9	69.1	73.4	55.5	44.7
2-5	92.2	87.9	87.7	95.6	81.5	66.5
5-10	98.3	94.8	95.5	98.4	92.9	80.9
10-15	99.3	98.0	98.4	98.8	96.8	90.7
15-20	99.6	98.6	99.6	99.6	97.7	96.2
20-25	100.0	100.0	100.0	100.0	100.0	100.0

Table 3. Cumulative percentages for total biomass with increasing depth (in parentheses without bivalves). Calculations are based on averages for four quarterly cruises for 1985. Stations in group 1 are tidal freshwater stations; in group 2, transitional stations; in group 3, mesohaline mud stations; in group 4, polyhaline silty-sand stations; in group 5, mainstem mud stations; in group 6, mainstem silty-sand stations.

Depth interval (cm)	Site group					
	1	2	3	4	5	6
0-2	99.0 (53.2)	15.2 (74.5)	54.2 (69.1)	97.0 (40.6)	33.3	6.9
2-5	99.8 (79.2)	25.5 (89.3)	57.9 (89.6)	98.3 (66.6)	50.9	15.4
5-10	99.9 (93.5)	50.5 (96.0)	67.4 (94.4)	98.9 (77.8)	74.5	48.2
10-15	99.9 (97.4)	81.6 (98.0	92.8 (97.1)	99.3 (86.6)	81.1	70.3
15-20	99.9 (98.7)	99.6 (98.7)	99.8 (99.2)	99.9 (97.8)	87.6	80.7
20-25	100.0	100.0	100.0	100.0	100.0	100.0

individuals within the upper 10 cm (Tables 2 and 3, site groups 1-4). The macrobenthos was found at greater depths in the mainstem, with 92.9% and 80.9% of the total individuals present in the upper 10 cm of the mud and silty-sand site groups, respectively (Tables 2 and 3, site groups 5 and 6).

Biomass profiles within the tributaries were greatly affected by several species of large bivalves. At tidal freshwater and polyhaline silty-sand sites, surface-dwelling bivalves (*Rangia cuneata* and *Mercenaria mercenaria*, respectively) skewed the biomass profile toward the surface intervals, while in the mesohaline portion of the tributaries, bivalves (*Macoma balthica*) skewed the biomass profile toward the deeper depth intervals. These bivalve species usually accounted for >95% of the total biomass but <5% of the total individuals collected. When bivalves were excluded from analysis of the tributary site groups, the mainstem site groups had a larger amount of biomass in the deeper intervals.

The deeper-dwelling fauna of the mainstem silty-sand site group was dominated by (1) large tubiculous maldanid polychaetes, *Clymenella torquata* and *Macroclymene zonalis*; (2) smaller and probably free-burrowing polychaete species, *Ancistrosyllis hartmanae*, *Ancistrosyllis jonesi*, *Gyptis brevipalpa*, *Paleonotus heteroseta* and *Sigambra tentaculata*; (3) the burrowing shrimp, *Upogebia affinis*; and (4) several tube or burrow commensals such as the bivalve *Aligena elevata*, the polychaete *Lepidametria commensalis*, the amphipod *Listriella clymenellae* and the pinnixid crabs *Pinnixa chaetopterana* and *Pinnixa retinens*.

After analysis of the individual collection stations, three stations were identified for special concern: station 5-CB in the mainstem (in site group 5), station 3-R in the Rappahannock River (in site group 3) and station 2-J in James River (in site group 2). These stations had a much shallower-dwelling fauna than other stations within their respective site groups. For station 5-CB, 99.6% of the total individuals and 98.7% of the total biomass were in the upper 5 cm. In September 1985 no organisms were found below 2 cm. For station 3-R, 97.3% of the total individuals and 94.1% of the total biomass were collected in the upper 5 cm. For station 2-J, 100% of the total individuals and biomass were found in the upper 5 cm.

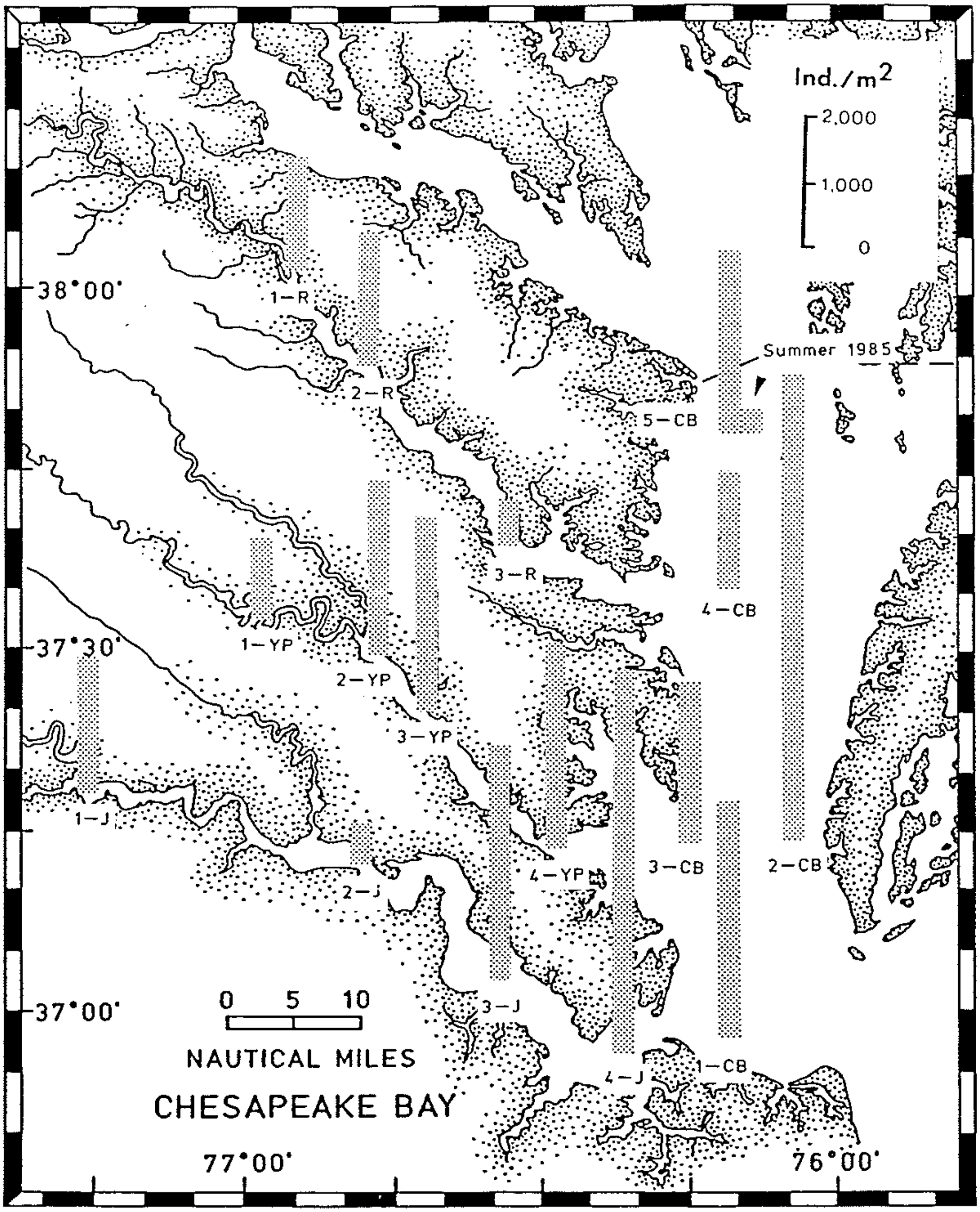
Total Community Parameters

For the three primary community parameters presented (total number of individuals per m^2, total biomass per m^2, and number of species per core) a similar pattern was identified within each of the three major tributaries-- an increase in each parameter going down-estuary. Exceptions to this pattern were stations 3-R and 2-J (Figures 2, 3, and 4). Figure 3 shows the total biomass minus bivalves, because when bivalves were included (Figure 5) the above pattern was obscured by large values of *R. cuneata* at 1-R, of *M. balthica* at 2-YP, and of *M. mercenaria* at 4-J.

Within the mainstem of the Bay the silty-sand stations (1-CB and 2-CB) had more total individuals (Figure 2), higher total biomass (Figure 5), and more species per core (Figure 4). Mainstem mud stations showed a trend of increasing values for total

Figure 2 (below). Mean total number of macrobenthic individuals per m^2 in 1985.

Figure 3 (facing page). Mean values for total biomass (mg/m^2) for 1985 (bivalves excluded). Stations 1-CB and 2-CB are not shown in order to emphasize tributary patterns. Values for these two stations exceeded 19 g/m^2.



community parameters going down-estuary (Figures 2, 4, and 5), especially in September 1985 (Table 4).

Analysis of community parameter values resulted in identification of the same three stations for special concern that the depth distribution analysis had suggested. Table 4 compares total community parameters for stations of special concern with the parameters for stations from similar salinity-sedimentary regions.

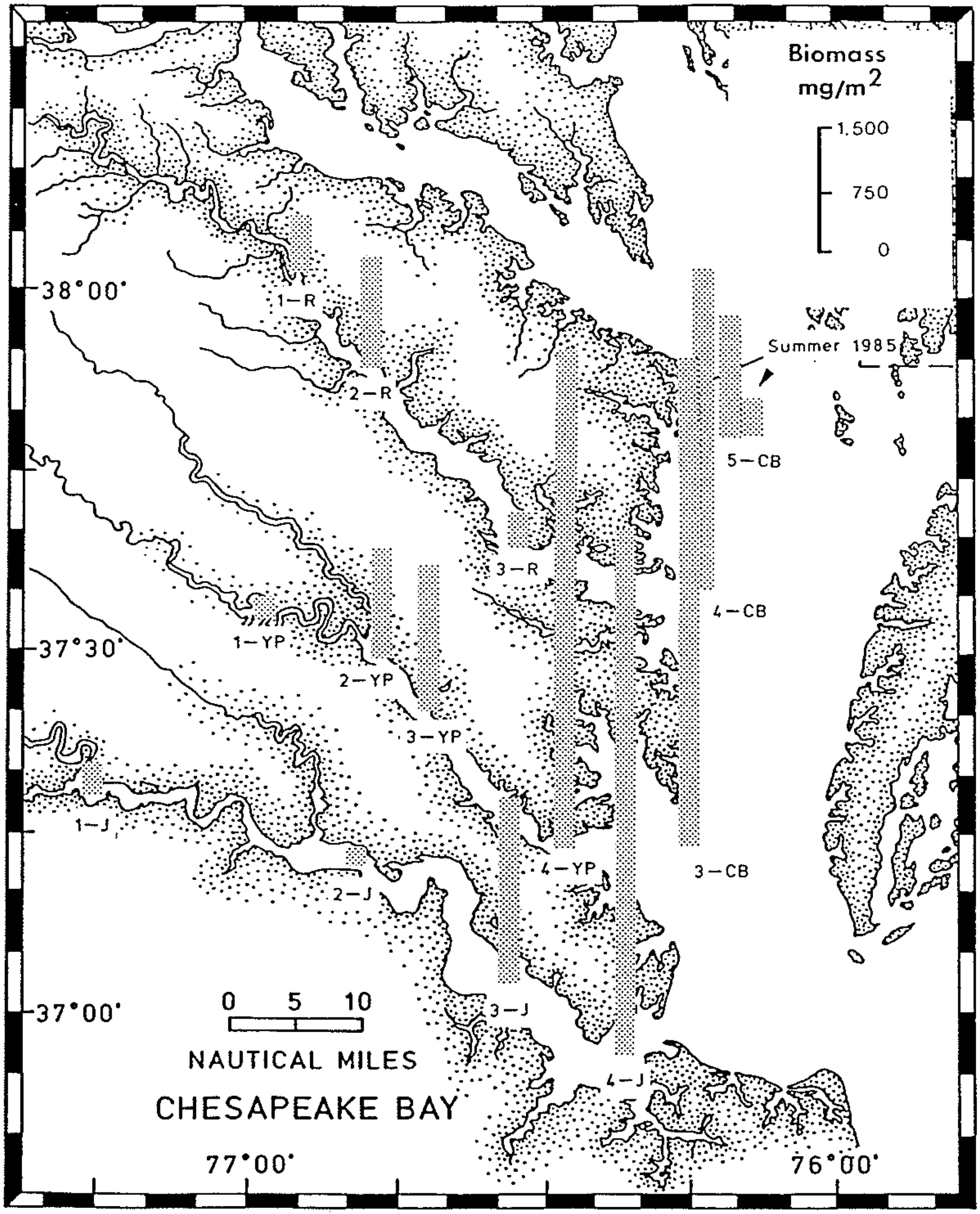
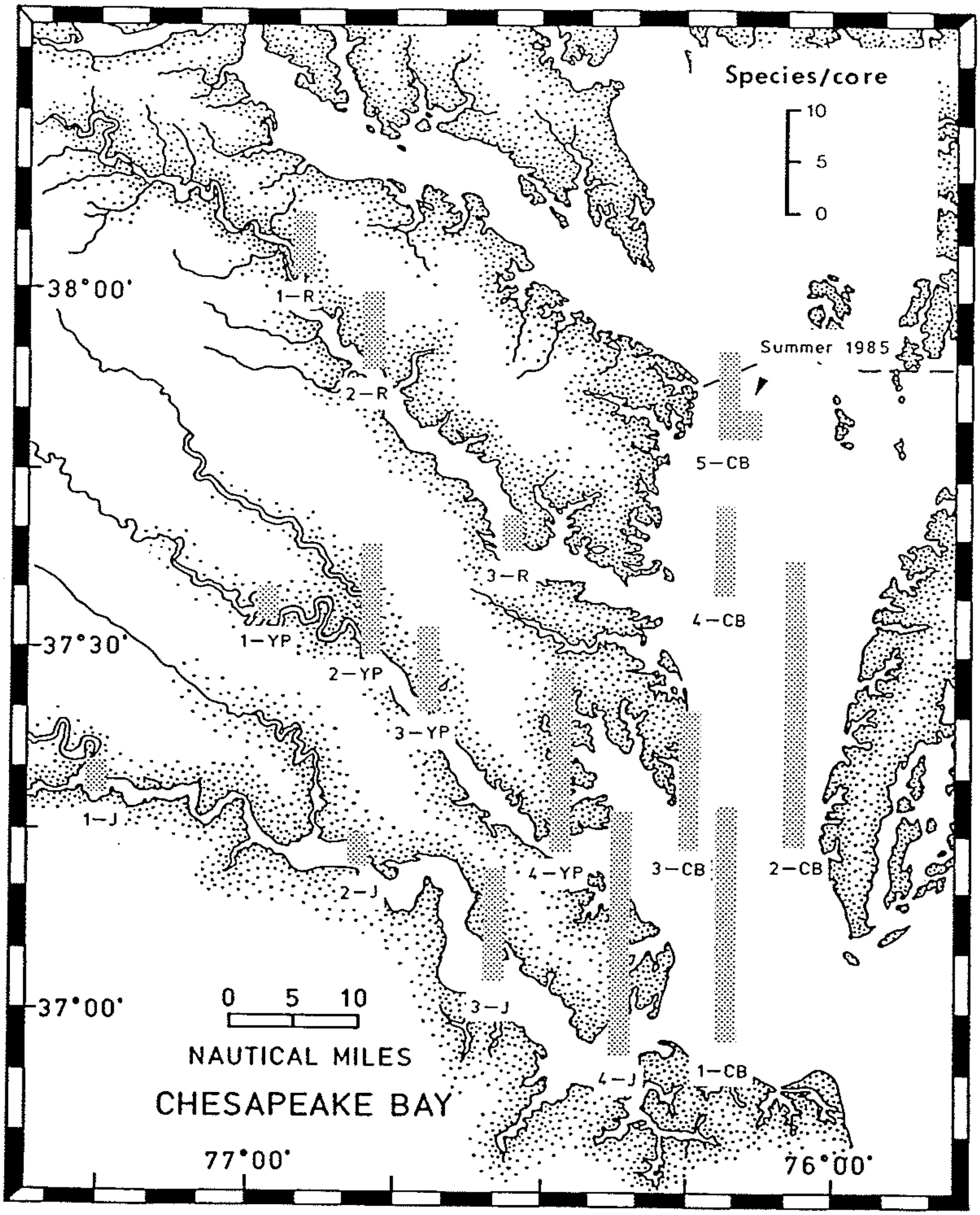


Figure 4 (below). Mean number of species per core in 1985.

Figure 5 (facing page). Mean values for total biomass (g/m^2) for 1985 (bivalves included).



DISCUSSION

The present program is unprecedented in its spatial and temporal coverage. Previous studies of the lower Chesapeake Bay have emphasized single tributaries or portions of the mainstem. Most previous studies were site-specific and had little or no temporal replication. Important studies have covered: the entire James River (Boesch et al. 1976a), portions of the James River (Boesch 1973; Boesch et al. 1976b), the Southern Branch of the Elizabeth River (Hawthorne and Dauer 1983), the entire York River (Boesch 1972; Boesch et

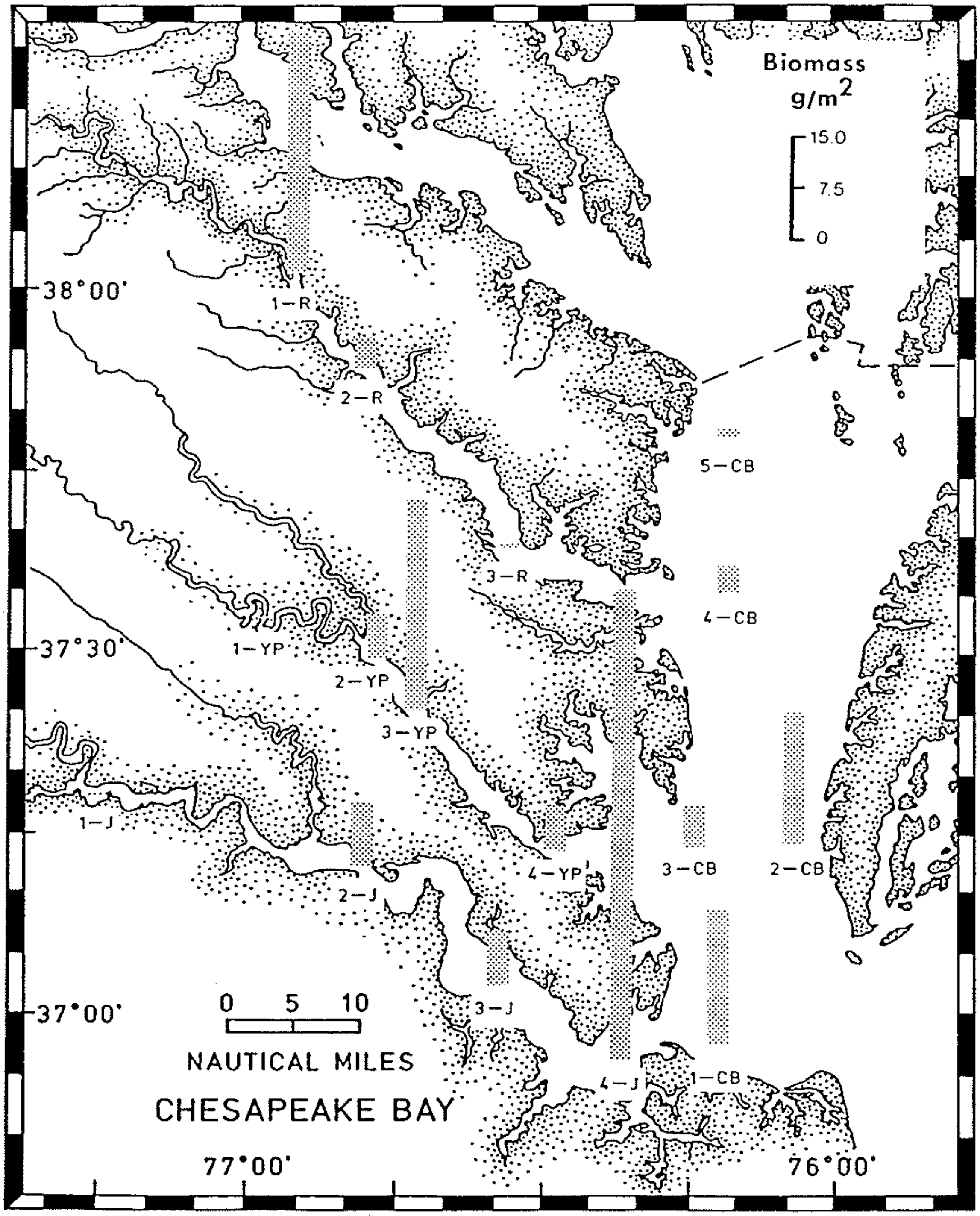


Table 4. Stations of special concern (2-J, 3-R, and 5-CB) in comparison with other stations from similar regions. Values in parentheses are for the September 1985 cruise.

Stations	Annual mean values per sample		
	No. of individuals	Biomass (mg)	No. of species
Transitional, tributaries			
2-J	12.1	4.1	3.4
2-YP	36.7	19.4	9.3
2-R	32.0	24.3	7.9
Mesohaline mud, tributaries			
3-R	11.8	7.5	3.8
3-YP	44.8	32.2	8.8
3-J	53.3	42.9	9.7
Mainstem mud			
5-CB	42.1 (6.3)	25.2 (8.3)	8.3 (4.0)
4-CB	34.8 (18.3)	75.7 (41.3)	10.1 (8.0)
3-CB	46.8 (30.7)	122.5 (97.7)	13.9 (10.3)

al. 1976b), portions of the York River (Boesch et al. 1976b; Virnstein 1979), the Lynnhaven River (Dauer et al. 1979; Tourtellotte and Dauer 1983), several creeks on the bayside of the Eastern Shore (Dauer et al. 1979; Ewing and Dauer 1982), transects across the mainstem of the Bay (Dauer et al. 1984), and the inner continental shelf off the mouth of the Bay (Dauer et al. 1984). Comparisons with historical data are difficult, because before 1979 studies were based on samples sieved on a 1.0-mm screen. The present program is intended to generate a data set of unprecedented spatial and temporal coverage that will allow for future trend analysis.

On the basis of analysis both of the depth distribution within the sediment and of the total community parameters, three regions of the lower Chesapeake Bay were identified for special concern--the deep water channel on the western shore of the Bay, the lower reaches of the Rappahannock River and the transitional region (region of the turbidity maximum) of the James River. The representative stations for each of these regions had macrobenthic communities with lower abundances, fewer species, and a shallower penetration below the sediment-water interface in comparison with stations from regions with similar salinity-sedimentary characteristics. Stress from hypoxic or anoxic events is a potential cause for such shallow-dwelling, low-abundance communities. The Virginia Tributary and Mainstem Water Quality Monitoring Program recorded low values for bottom dissolved oxygen at both the deep-water channel station (5-CB) and the lower Rappahannock River station (3-R). At station 5-CB dissolved oxygen values were <4 parts per million (ppm) for most collection dates between 3 June 1985 and 30 September 1985, with values <2 ppm on 19 August 1985. At station 3-R oxygen values were <4 ppm between 3 June 1985 and 3 September 1985, with several values <2 ppm between 18 June 1985 and 3 September 1985. No corresponding problems in water quality have been identified for the transitional region of the James River.

Periodic hypoxic or anoxic events with resultant high benthic mortalities should have several predictable effects. Longer-lived benthic organisms, which are generally also the deep-dwelling forms, cannot survive long enough to become established in the deeper depth intervals; therefore, the community becomes dominated by short-lived shallow-dwelling species. Estimates of living benthic resources are generally lower because of higher mortality rates. Annual means for total number of individuals may be high at stressed stations because of heavy recruitment in the spring and summer by short-lived opportunists. Variance estimates associated with these means should be very large. Annual biomass estimates should be lower because in most benthic communities biomass estimates are dominated by long-lived species. Species diversity as measured by the average number of species present per sample should be lower because fewer species have the physiological adaptations, behavioral characteristics, or spatio-temporal recruitment patterns necessary to overcome the effects of periodic hypoxic or anoxic stress.

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Distribution and Abundance of Submerged Aquatic Vegetation in 1984 and 1985

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Communities of submerged aquatic vegetation (SAV) are an integral part of the Chesapeake Bay ecosystem. They provide an important habitat for many species, either as a food source or as protection from predators, i.e., as a nursery. By reducing currents and baffling waves, they allow for deposition of suspended material. In addition, they bind sediments with their roots and rhizomes to prevent erosion of the underlying material. They are important in nutrient cycling through both the absorption and release of nitrogen and phosphorus (Thayer et al. 1975; Kemp et al. 1984; Orth and Moore 1984; Ward et al. 1984).

The interest in SAV communities, generated in the 1970s because of their dramatic Bay-wide decline, has continued into the 1980s. A key aspect of the research programs currently being funded by both Maryland and Virginia entails annual monitoring of all SAV beds in the Chesapeake Bay and its tributaries.

The first Bay-wide aerial survey of SAV beds was conducted in 1978 and resulted in two separate reports on the SAV distribution in Virginia and Maryland (Orth et al. 1979; Anderson and Macomber 1980). Between 1979 and 1984, various state agencies conducted a number of field and aerial surveys in sections of the Bay, but there was no Bay-wide effort to monitor SAV distribution.

The first coordinated mapping of all the SAV beds in the Bay was attempted in 1984. In addition to the aerial surveys, 1984 ground survey information was included to provide as much detail as possible on the SAV distribution in that year (Orth et al. 1985). Although some problems were experienced in acquiring the photography (e.g., poor weather, airspace restriction), coverage of almost all areas was obtained. Ground surveys included efforts by the U.S. Geological Survey (USGS) and the Northern Virginia Community College (NVCC) in the Potomac River; Maryland's Department of Natural Resources (MD DNR) SAV station survey of the entire upper Bay; the Virginia Institute of Marine Science (VIMS) surveys in the lower Bay; and several sectional surveys conducted by Harford Community College (HCC) and the University of Maryland's Horn Point Laboratory (HPL).

A coordinated survey for SAV adjacent to the shoreline of the Chesapeake Bay and its tributaries was repeated in 1985. Ground survey information was available from USGS, MD DNR, HPL, HCC, and VIMS. In addition to these scientific surveys, the Chesapeake Bay Foundation (CBF) and the Citizens Program for Chesapeake Bay (CPCB) solicited help from citizen volunteers to help locate SAV beds and provide ground truth for the aerial photography. Maryland's Charter Boats Association also participated in the SAV ground truthing through funding provided by the MD DNR Watermen's Assistance Program.

In 1985 color aerial photography at a scale of 1:12,000 was used to map the Maryland portion of the Bay, while black and white photography at a scale of 1:24,000 was used to map the Virginia portion. Both areas had been photographed with 1:24,000 color photography in 1984. SAV beds detected on the aerial photography were traced onto mylar USGS quadrangles, and areas of each bed were then digitized. Data was reported in square meters for each quadrangle. For ease of reporting, the Bay was divided into 21 sections and three zones (Figure 1), which will be used in further discussions of the data.

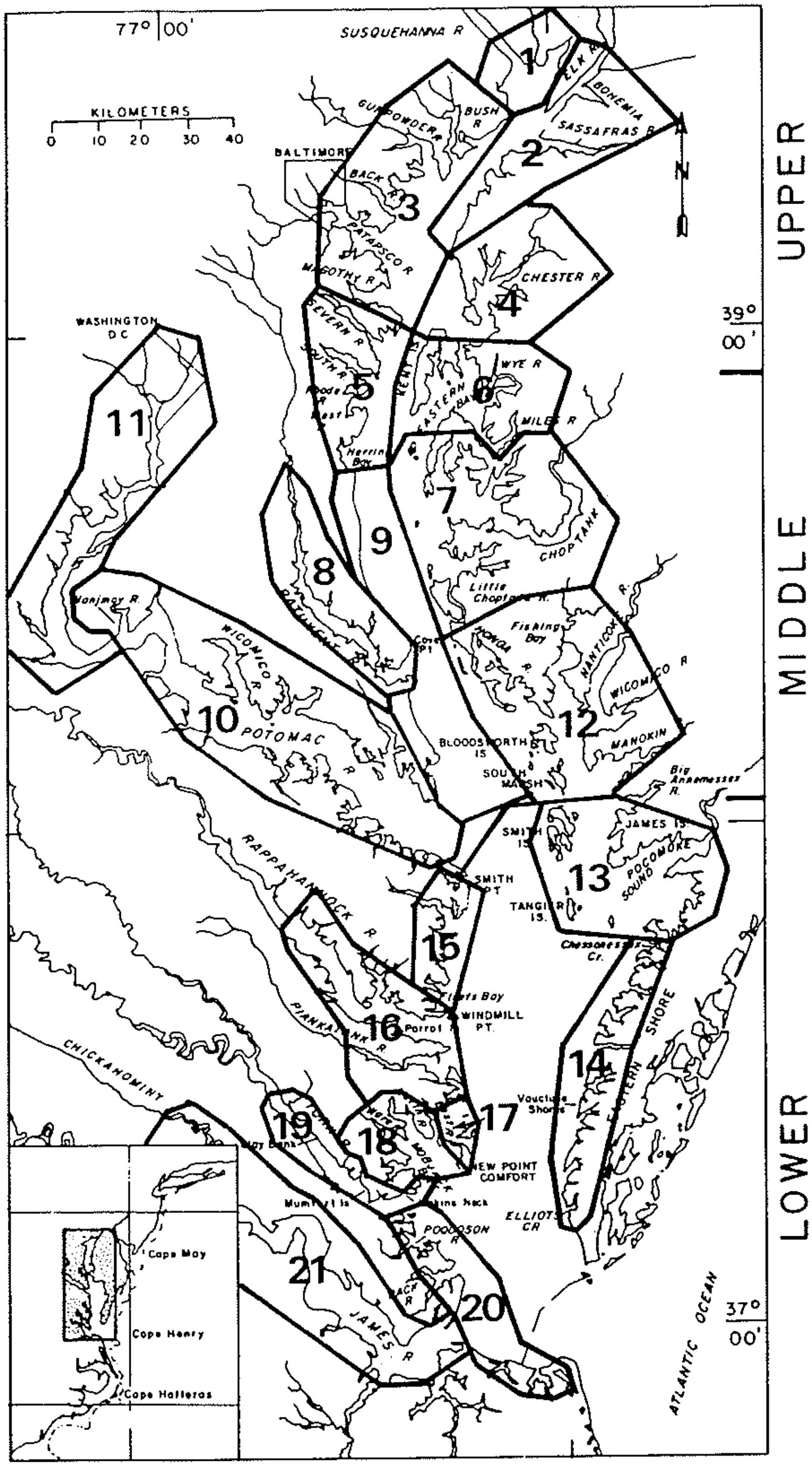

Figure 1. Map of the Chesapeake Bay illustrating 21 sections and 3 zones used for reporting distribution and abundance of submerged aquatic vegetation.

RESULTS

A total of 19,390 hectares (Table 1) of SAV was mapped in the Chesapeake Bay in 1985, a 26% increase over that reported in 1984. The upper zone had 3,025 hectares of SAV in 1985, representing a decrease of 4.5% from that reported in 1984 (3,168 hectares). The middle zone showed an increase of 398%, from 984 hectares in 1984 to 4,912 hectares in 1985. All sections in this zone showed an increase in SAV for 1985. The lower zone increased less than 1%, from 11,248 hectares in 1984 to 11,379 hectares in 1985. The following is a discussion of SAV trends in each of the 21 sections of the Bay (refer to Figure 1 and Table 1).

Upper zone

Section 1: Susquehanna Flats. The distribution of SAV in this section decreased by 6.5% in 1985, from 2,150 hectares in 1984 to 2,011 hectares in 1985. Seven species of SAV were found in 1985, with *Myriophyllum spicatum* the most abundant.

Table 1. Number of hectares of bottom covered with submerged aquatic vegetation (SAV) in 1978, 1984, and 1985 for different sections within the three zones in the Chesapeake Bay (data for 1978 from Orth et al. 1979, and Anderson and Macomber 1980; data for 1984 from Orth et al. 1985).

Section	No. of hectares 1978	1984	1985
Upper Bay zone			
(1) Susquehanna Flats	804*	2150	2011
(2) Upper Eastern Shore	29	43	105
(3) Upper western shore	484	244	238
(4) Chester River	1475	731	671
Total	2792	3168	3025
Middle Bay zone			
(5) Central western shore	241	0	26
(6) Eastern Bay	1800	66	356
(7) Choptank River	1740	82	1528
(8) Patuxent River	34	9	44
(9) Middle western shore	11	0	23
(10) Lower Potomac River	410	194	381
(11) Upper Potomac River	--+	600	1440
(12) Middle Eastern Shore	210	33	1188
Total	4446	984	4986
Lower Bay zone			
(13) Tangier Island complex	3759	5447	5504
(14) Lower Eastern Shore	1991	2232	2227
(15) Reedville	364	264	172
(16) Rappahannock River complex	93	23	20
(17) New Point Comfort region	271	299	332
(18) Mobjack Bay complex	1785	1550	1505
(19) York River	157	238	258
(20) Lower western shore	925	1149	1315
(21) James River	54	46	46
Total	9399	11,248	11,379
Total for all zones	16,637	15,400	19,390

*1978 data for Susquehanna Flats remapped and digitized to allow for greater compatability with 1984 data.

+No aerial photography was taken of this area in 1978; the absence of SAV is based on ground survey observations by the USGS.

Other species of importance were *Heteranthera dubia*, *Vallisneria americana*, and *Hydrilla verticillata*, which appeared to be increasing in abundance along the Susquehanna River and in the Havre de Grace area.

The MD DNR survey found SAV at one of the 37 stations sampled annually in the Susquehanna Flats.

Section 2: Upper Eastern Shore. This section showed a 142% increase in SAV from 1984 (43 hectares) to 1985 (105 hectares). Most of the increase in SAV in 1985 occurred along the Elk, Bohemia, and Sassafras Rivers. Fifteen stations were sampled by MD DNR in the Elk and Bohemia Rivers, with no vegetation recorded at any of those stations. Similarly, no vegetation was found at the 10 stations sampled by the MD DNR survey on the Sassafras River or the five stations on Stillpond Creek. Other field surveys conducted by citizens and charter boat captains, along with observations of drifting SAV by MD DNR field crews, revealed that *M. spicatum* was the most prevalent species in this section. Seven stations sampled by MD DNR in the southern portion of the section, from Howell Point to Swan Point, also had no SAV.

Section 3: Upper western shore. The 1985 aerial survey indicated 238 hectares of SAV in this section, a decrease of 2.4% from that mapped in 1984 (244 hectares). Aerial photos indicated that SAV was present in all river systems (Gunpowder, Bush, Back, Middle, and Magothy) in the section. Generally most of the SAV was present in the lower section of each river. Four of 27 MD DNR stations on the Gunpowder, Bush, Back, and Middle Rivers found rooted SAV in 1985, one more than in 1984. Species present in these samples were *M. spicatum, Chara, V. americana, Potamogeton perfoliatus*, and *Najas guadalupensis*. No rooted SAV was found by MD DNR at the 12 Magothy River stations.

Section 4: Chester River. In 1985, 671 hectares of SAV were mapped in the Chester River section, a decrease of 8.2% from the 731 hectares mapped in 1984. As in 1984, most of the SAV mapped (87%) occurred on the Langford Creek quadrangle. Five species of SAV were reported by citizen and MD DNR field surveys: *Ruppia maritima, Zannichelia palustris, P. perfoliatus, Potamogeton pectinatus*, and *M. spicatum*. *P. perfoliatus* and *Ruppia maritima* were the most prevalent.

The MD DNR survey found eight (22.2%) of their 35 stations in the Chester River vegetated in 1985, as compared with seven (19.4%) in 1984.

Middle zone

Section 5: Central western shore. A total of 26 hectares of SAV was mapped in this section in 1985, where none was seen in 1984. Seventy-two percent of the SAV reported was located in Herring Bay on the North Beach quadrangle. No SAV was mapped in any river system in this section except for a small bed near the mouth of the West River.

The MD DNR survey found no rooted SAV in either the Severn section or the South, West, and Rhode River section.

Section 6: Eastern Bay. In 1985 a total of 356 hectares of SAV were noted on the aerial photography, an increase of 441% over the 66 hectares reported in 1984. *Ruppia maritima* was the most abundant species reported in field surveys by citizens and MD DNR personnel. *Potamogeton pectinatus* and *P. perfoliatus* were also reported, but other species reported in 1978, such as *M. spicatum, Elodea canadensis*, and *Z. palustris*, were not seen.

The MD DNR survey, as in 1984, found no SAV at the stations from Love Point to Kent Point. Of 46 stations in the Eastern Bay section the number vegetated increased from three (6.5%) to eight (17.4%). *Ruppia maritima* was the only species found in the MD DNR survey.

Section 7: Choptank River. In 1985, a total of 1,528 hectares of SAV was noted on the aerial photography, as compared with only 82 hectares in 1984 (a 1,760% increase). Six species were reported in this section, with *R. maritima* the most abundant species reported in field surveys. Other species found were *P. perfoliatus, P. pectinatus, Z. palustris, N.guadalupensis*, and *V. americana*.

The MD DNR survey found rooted SAV at seven of 60 stations on the Choptank River in 1985; none of the 19 stations on the Little Choptank River had SAV. All SAV found was *R. maritima*. Information provided by HPL showed SAV at five of their six monitored areas, as compared with two in 1984. Horn Point was the only station not vegetated, and dramatic increases were seen at all the other stations. Species present were *Z. palustris* in June followed by *R. maritima* in July (Stevenson et al. 1986).

Section 8: Patuxent River. In 1985, 44 hectares of SAV were noted on the aerial photography, as compared with nine in 1984. SAV was noted on four of the five quadrangles in this section.

The MD DNR survey found no SAV at the 43 stations surveyed.

Section 9: Middle western shore. A total of 23 hectares of SAV was noted on the aerial photography in this section in 1985. None had been noted in 1984. Most of the mapped SAV in this section was found in small marsh ponds that drain into the Bay. The MD DNR survey found no SAV at eight sampled stations from Curtis Point to Cove Point. This section is a very exposed region, with little habitat suitable for SAV; thus it would not be expected to support significant stands of SAV.

Section 10: Lower Potomac River. In 1985 there were 381 hectares of SAV in the lower Potomac River, as compared with 194 mapped in 1984. This change represents a 69% increase, of which 9% comprises quadrangles that were not mapped in 1984 because of a lack of photographic coverage.

The MD DNR survey sampled 88 stations in the lower section, and found vegetation at four stations, all at the northern end of the section near Upper Cedar Point and the Nanjemoy River. Species located at these stations were *P. perfoliatus, V. americana, Z. palustris, M. spicatum*, and *N. guadalupensis*.

Section 11: Upper Potomac River. In 1985, 1,440 hectares of SAV were noted on the aerial photography of this section as compared with 600 in 1984, a 140% increase. The vegetation was largely confined to the upper reaches of the section between Alexandria, Virginia and Marshall Hall, Maryland. Since 1984 the vegetation has spread almost 2 km farther downriver. The most abundant and most widely distributed species were *H. verticillata, M. spicatum, Heteranthera dubia, Ceratophyllum demersum, V. americana* and *N. guadalupensis*. Results of the USGS shoreline survey showed that *Hydrilla verticillata* was more abundant than all other species in 25% of the vegetated areas, accounting for 62% of the total dry weight from the fall sampling (Rybicki et al. 1986).

The MD DNR survey sampled 52 stations in this section, of which three yielded SAV. Rooted SAV species found at these stations were *M. spicatum, H. verticillata*, and *C. demersum*.

Section 12: Middle Eastern Shore. In 1985, there were 1,188 hectares of SAV in this section as compared with only 33 hectares in 1984. This 3,504% increase was the largest in any section of the Bay. One of the most significant increases was the 265 hectares, mostly in one large bed, in the Barren Island Gap region, where no SAV was seen in 1984.

The MD DNR survey sampled 169 stations in this section. SAV was found at one station each in the James/Barren Island section, Honga section, and the Bloodsworth Island/South Marsh Island section; at two stations in the Manokin River section; and at three stations in the Big/Little Annemessex River sections. No SAV was found in the Fishing Bay or Nanticoke/Wicomico River sections. *Ruppia maritima* was found at seven of the eight sample points with SAV, and *Z. palustris* was located at the other site.

Lower zone

Section 13: Tangier Island complex. This section contained the greatest amount of SAV in the lower Bay zone, with 5,504 hectares, or 49% of the total for this zone; this amount is similar to that reported for 1984.

SAV beds were concentrated in distinct areas in the section: adjacent to Big Marsh between Chesconessex Creek and Deep Creek; on the west side of Webb and Halfmoon Island; the east side of Great Fox Island; and in the areas between Tangier Island and Smith Island. Dominant species in this section were *Zostera marina* and *R. maritima*. Although this section had significant stands of SAV, and data in Table 1 indicate that the abundance of SAV has increased, a MD DNR survey found SAV in only eight of 57 stations. Contrary to the findings of the aerial survey, the DNR survey indicated that SAV abundance decreased to 23.5% of the surveyed stations in the Smith Island portion and has been continually declining from 47.1% of the stations in 1980.

Section 14: Lower Eastern Shore. This section contained 2,227 hectares of SAV in 1985, in dense to scattered patchy beds from Chesconessex Creek to Elliots Creek. Large beds of *Z. marina* and *R. maritima* were present around Cape Charles, and at the mouths of Cherrystone Inlet and Hungars, Mattawoman, Occahannock, Craddock, Pungoteague, and Onancock Creeks.

SAV in the Vaucluse Shore "historical" areas was reduced slightly (6%) from 1984. This is one of six sites where historical aerial photography from various years since 1937 was used to map SAV distribution (see Orth et al. 1979 for more detail). The SAV at the site has been declining gradually in the last 50 years, principally because of the migrating nature of the sand bars and spits that cover existing SAV and prevent potential SAV growth.

Section 15: Reedville. The Reedville section contained 172 hectares in 1985, a decrease of 35% from 1984 (264 hectares). This reduction was evident in the Fleets Bay historical area, which declined in spatial coverage by 15%. Most of the SAV beds in this section are small and sparse, are susceptible to disturbance, and can undergo rapid changes.

Section 16: Rappahannock River complex. Only 20 hectares of SAV were found in this section in 1986, an area similar to that found in 1984 (23 hectares). The dense SAV stands found in the Milford Haven area consisted predominantly of *Z. marina*. There were no SAV beds in the Parrott Island historical area.

Section 17: New Point Comfort. SAV beds in this section were concentrated in the area between New Point Comfort Lighthouse and Horn Harbor. This section contained 332 hectares of SAV in 1985, consisting of *Z. marina* and *R. maritima*. This figure represents an 11% increase in spatial coverage from 1984.

Section 18: Mobjack Bay complex. This section contained the greatest amount of SAV along the entire western shore, with 1,505 hectares in 1985, a 3%

decrease from 1984. SAV beds consisting of *Z. marina* and *R. maritima* were present along the shoreline of the entire Mobjack Bay and three of four tributaries: the Severn, Ware, and North Rivers. Little SAV appeared in the East River; SAV in the East River historical area decreased 32% from 1984.

Section 19: York River. This section contained 258 hectares of SAV in 1985, an increase of 8% over that found in 1984. SAV beds (*Z. marina* and *R. maritima*) were found from Gloucester Point to the mouth of the river, principally along the north shore. Transplanted SAV beds (*Z. marina* only) at Gloucester Point were thriving, and individual planted units were rapidly expanding. Transplanted *Zostera* at Mumfort Island has been much less successful than at Gloucester Point. *Zostera* transplanted to Clay Bank, the upriver limits of the species in the past, has never survived through the summer.

SAV in the Jenkins Neck historical area increased 17% from 1984, but was still 150 hectares below levels found during the years when SAV was very abundant. SAV continued to be absent from the Mumfort Island historical area.

Section 20: Lower western shore. There were 1,315 hectares of SAV in this section in 1985, an increase of 14% from 1984. These beds, consisting of both *Z. marina* and *R. maritima*, were still concentrated in Broad Bay, Back River, Drum Island Flats adjacent to Plumtree Island, and on the south side of Goodwin Island. The beds found on Drum Island Flats represented one of the more extensive and densely vegetated areas along the western shore.

Section 21: James River. No SAV beds were identified in the James River from the aerial photography or ground surveys. The concentration of SAV in the Chickahominy River still persisted (46 hectares); these were the only beds found in the entire section. The species found in these upriver and marsh creek areas were fresh-to-brackish water species such as *C. demersum*, *E. canadensis*, and *Najas* spp.

SUMMARY

The distribution and abundance of SAV was mapped for the entire Chesapeake Bay in 1985. The entire Chesapeake Bay exhibited 19,390 hectares of SAV in 1985, compared with 15,400 hectares in 1984, a 26% increase.

The upper Bay zone had 3,025 hectares of SAV in 1985 (15.6% of the total SAV in the Bay), which was a decrease of 4.5% from that reported in 1984. The Susquehanna Flats section contained 66% of the SAV in this zone. Three of the four sections in this zone showed a slight decrease in SAV abundance, whereas a 142% increase was seen in the sparsely vegetated upper Eastern Shore section, principally along the Elk, Bohemia, and Sassafras Rivers. SAV beds in the upper Bay zone consisted of 13 species. Dominant species in Susquehanna Flats were *M. spicatum*, *H. verticillata*, and *V. americana*, whereas the Chester River was dominated by *P. perfoliatus* and *R. maritima*.

The middle Bay zone had 4,986 hectares of SAV in 1985 (25.7% of the total SAV in the bay), which represents a 389% increase from 1984. All sections in the zone showed an increase in SAV, with most (3,072 hectares) of the SAV and the greatest percentage changes occurring in the Eastern Bay (441%), Choptank River (1,760%), and middle Eastern Shore (3,504%) sections on the Eastern Shore of the mainstem of the Bay. The Patuxent River, although sparsely vegetated, showed a 401% increase in SAV, from 9 hectares in 1984 to 44 in 1985. Both Potomac River sections increased in SAV in 1985, with the largest increase (104%) in the upper Potomac River section.

SAV beds in the mainstem of the Middle Bay Zone consisted principally of *R. maritima*. The Potomac River SAV beds consisted of 14 different species, with the most prevalent being *M. spicatum* and *H. verticillata*.

The return of SAV to the upper Potomac River continues to be significant because of its rapidity. In less than five years, the vegetated area has increased from almost nothing to 1,440 hectares. Although *Hydrilla* is one of the dominant species, 13 other species coexist and, in some areas, share the dominant role with *Hydrilla*.

The lower Bay zone had 11,379 hectares of SAV in 1985 (58.7% of the total SAV in the bay). This amount was similar to that reported for 1984. Most (68%) of the SAV in this zone was found along the eastern shore, with the major beds being located on the broad, shallow flats on and near Tangier and Smith Islands. SAV beds were concentrated at the mouths of the major bayside creeks, principally Cherrystone Inlet, and Hungars, Mattawoman, Occahannock, Craddock, Pungoteague, and Onancock Creeks. Along the western shore of the zone, SAV beds were found in Back River, at Drum Island Flats adjacent to Plumtree Island, at the mouth of the York River adjacent to the Guinea Marshes, along the shoreline of the Mobjack Bay, and in a small band from New Point Comfort to Horn Harbor. There were no major changes in SAV distribution in the nine sections in this zone. The largest change was in the Reedville section, where SAV distribution decreased 34% from 1984.

SAV beds in the lower zone consisted principally of two species, *Z. marina* and *R. maritima*.

Zannichelia palustris has also been found in small isolated patches, but is not considered a dominant species here.

SAV was still absent in two of the six historical areas from the lower Bay zone (Mumfort Island and Parrott Island). SAV increased in the Jenkins Neck area (17%) but decreased in the East River (33%), Fleets Bay (150%), and Vaucluse Shore (6%) areas from 1984. Changes in the Vaucluse Shore area were related to the dynamic nature of the sand bars and sand spits that continually alter the area available for SAV growth. Changes in the East River and Fleets Bay distribution occurred in very patchy beds. These beds are more susceptible to physical damage from storms and can easily change in less than a year.

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Abundance of Maryland Shellfish and Finfish

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SHELLFISH

Oyster

Maryland's annual harvests of American oyster (*Crassostrea virginica*) have declined dramatically, from >50 x 10^6 pounds before 1900, to 20 x 10^6 pounds in 1939 and <10 x 10^6 pounds today. Figure 1 shows commercial oyster landings and the amount of spat set annually on natural oyster bars from 1939 through 1985 (note that spatfall is expressed as spat per tenth-bushel of oysters). Spatfall data for years before 1975 represented averages for all oyster bars sampled throughout the Maryland portion of the bay in a given year. The number and location of bars sampled varied from year to year. Since 1975 the spatfall data has been standardized by use of 55 key bars that are equally distributed throughout the Maryland portion of the Bay.

Figure 1 shows that while spat set fluctuated greatly between 1939 and the early 1950s, it never fell below 20 spat/bushel, and adult oyster harvests were >14 x 10^6 pounds per year. Annual oyster landings fell to <10 x 10^6 pounds annually during the early 1960s, probably because of downward trend in spatfall

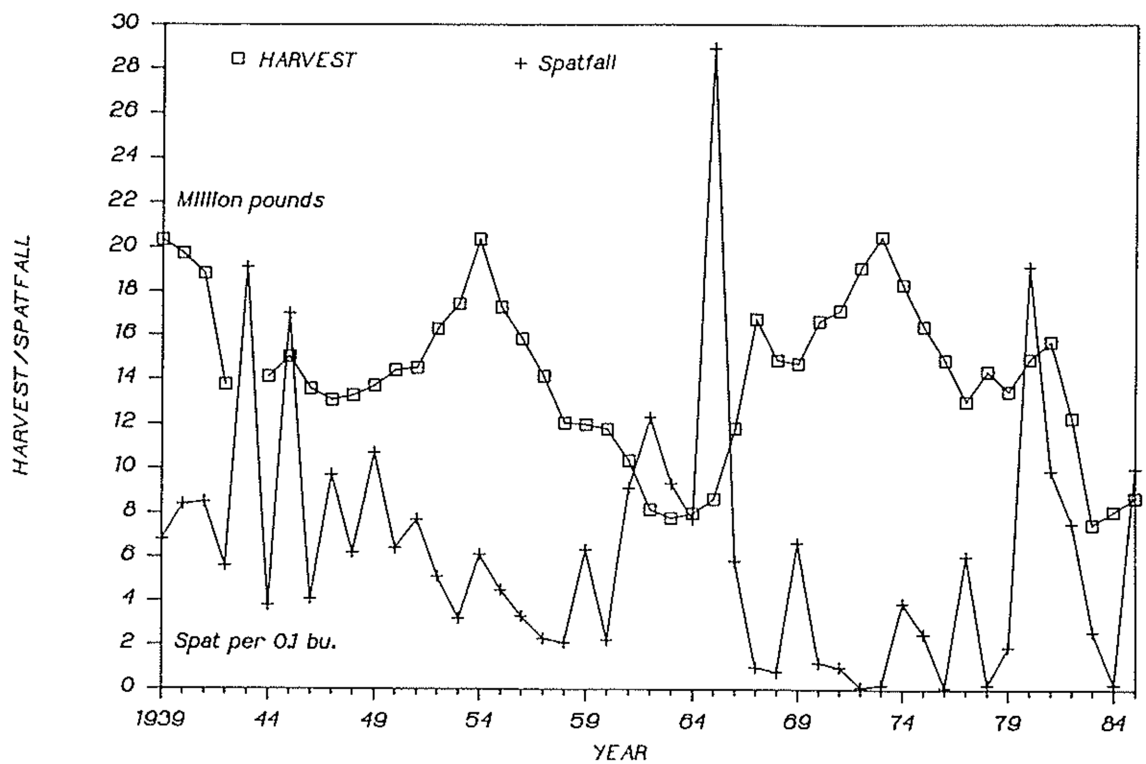

Figure 1. Commercial oyster landings and average spatfall in Maryland, 1939-1985.

Table 1. Oyster mortality and prevalence of MSX (disease due to *Haplosporidium nelsoni*) and Dermo (due to *Perkinsus marinus*) on 20 Maryland bars in fall 1985 and summer 1986.

Location	Total oyster mortality (%)		Prevalence (%) of Dermo		Prevalence (%) of MSX,
	Nov. 85	Aug. 85	Nov. 85	Aug. 86	Nov. 85
Eastern shore					
Pocomoke River, Marumsco	8	26	28	23	14
Tangier Sound, Old Woman's Leg	12	30	4	46	32
Manokin River, Georges	9	23	14	46	0
Nanticoke River, Middle Ground	64	86	100	86	36
Tangier Sound, Sharkfin Shoal	28	56	74	60	8
Holland Straits, Spring Island	17	40	-	63	-
Fishing Bay, Clay Island	11	50	94	56	6
Honga River, Norman	16	22	14	13	16
Little Choptank River, Ragged Point	6	34	36	13	0
Choptank River, Cook Point	43	44	4	13	4
Choptank River, Light House	3	19	2	20	4
Broad Creek, Deep Neck	2	13	2	36	0
Eastern Bay, Hollicutt Noose	3	4	4	13	0
Eastern Bay, Bugby	4	8	10	20	2
Chester River, Buoy Rock	14	4	6	13	0
Western Shore					
Upper Bay, Flag Pond	9	29	4	26	0
Patuxent River, Broome Island	8	39	16	26	2
Patuxent River, Hog Island	12	46	8	6	10
Potomac River, Cornfield Harbor	33	54	88	93	12
St. Mary's River, Chickencock	18	53	70	83	16

in the 1950s and an outbreak of MSX (disease due to *Haplosporidium nelsoni*) from 1960 to 1964 in the Tangier Sound area. Spat settlement increased during the early 1960s, leading to another period of high average harvests from the late 1960s through the mid- to late-1970s, when annual landings were >16 x 10^6 pounds. During this period of high harvest pressure, however, recruitment was at an all-time low: between 1967 and 1979 average annual spat set ranged from 1 to 66 spat/bushel, and during 9 of the 13 years it fell to <20 spat/bushel. Although spat set was good in some areas of the Bay in the early 1980s, the extended period of poor recruitment in the 1970s and a widespread and severe outbreak of MSX disease from 1980 through 1983 caused declines in oyster harvests and recruitment in the 1980s.

Figure 1 illustrates changes in oyster landings and recruitment, but it cannot show the dramatic decline in harvest area or the geographical distribution of spat set. Whereas oysters were once prevalent throughout the Maryland portion of the Chesapeake Bay, natural spat set is now limited largely to tributaries of the lower Eastern Shore and to the mouth of the Potomac River.

Weather conditions may have a marked effect upon oyster spatfall. Periods of low rainfall, leading to high salinities, appear to favor recruitment. The early 1980s were dry years; average spat set in 1980 on the key bars was 191 spat/bushel, one of the highest values ever recorded. Average spat set declined from this high to 2.4 spat/bushel in 1984, after two wet years in 1983 and 1984. Only the summer after tropical storm Agnes (1972) produced a spatfall lower than in 1984. After this dismal showing, spat set in 1985 looked very good; an average of >100 spat/bushel was recorded, after a dry spring. The high spatfall in 1985 followed the pattern of the successful early 1980s; the spatial extent was greatly reduced in comparison with the locations of historical (1938-1965) high spat set.

Success of the oyster fishery depends on more than one year of high spatfall. The number of consecutive years of above-average spat set is important, as well as the harvest pressure, occurrence of anoxic waters, and presence of disease. Unfortunately, the same high salinities favorable to oyster reproduction are conducive to the spread of parasite-caused oyster diseases, Dermo (caused by

Perkinsus marinus) and MSX. Table 1 shows that total oyster mortality rates increased from November 1985 to August 1986 on 19 of 20 bars sampled. During the same time, the prevalence of Dermo increased on 12 and decreased on 7 of the 20 bars sampled. Results of histological examination of 1985 oysters for MSX are incomplete. Incidences of MSX appear to be low in the Choptank River-Eastern Bay-Chester River area, but higher on the lower Eastern Shore (32%-36% in Tangier Sound/Nanticoke River) and lower Potomac River (6%-8%).

Other Shellfish

Commercial harvesting of the soft-shell clam (*Mya arenaria*) began in 1951, after the development of the hydraulic clam harvester. Total landings (pounds) and value (dollars) of the Maryland soft clam harvest, from 1962 through 1985, are shown in Figure 2. The average harvest before 1971 was <4.5 x 10^6 pounds; from 1962 through 1971 it was 6.7 x 10^6 pounds. In 1972 the industry was shut down because of the effects of tropical storm Agnes. It was closed again in 1973, by the Department of Health and Mental Hygiene, because of poor bacterial quality of the clams. After 1973 the average yearly harvest was 2.1 x 10^6 pounds, less than half the average pre-1972 catch. Current stocks of the soft-shell clam remain low; the average of annual landings 1981-1985 was 1.5 x 10^6 pounds. Landings in 1985 of 1,314,851 pounds showed a slight increase over the 1984 figure of 938,123, which was the lowest in this five-year period.

Although large annual fluctuations in the abundance of the blue crab (*Callinectes sapidus*) are common, over the long term crab harvests have remained strong. From 1929 through 1980 total crab landings (hard and soft) have ranged from 10.2 x 10^6 pounds (1968) to 36.9 x 10^6 pounds (1930), with an average value of 24.5 x 10^6 pounds. For 1981 through 1985 blue crab landings averaged 52.6 x 10^6 pounds, with a low of 43.6 x 10^6 in 1982 and a high of 59.7 x 10^6 in 1981. A new reporting system was initiated in Maryland in 1981; the apparently large increase in landings in the 1980s is an artifact of the reporting system. Total landings of 58.7 x 10^6 pounds in 1985 were an increase over the 1984 landings of 48.7 x 10^6 pounds, the lowest value in the last five years.

FINFISH

Commercial landings of Maryland finfish from 1981 through 1985 are presented (Figure 3) in four categories: anadromous, including striped bass, shad, alewives, and blueback herring; marine, including bluefish, spot, and sea trout; estuarine, including white perch and croaker; and other, including catfish and yellow perch. Menhaden, the most important marine species, has not been included in this figure because

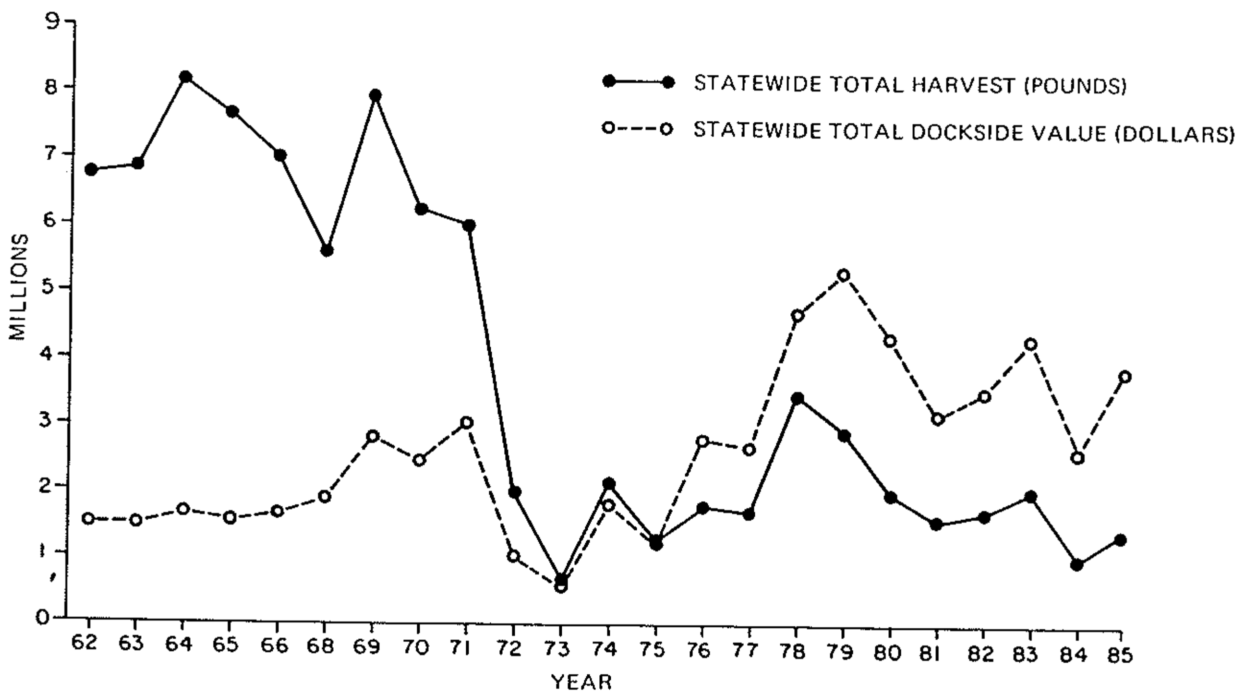

Figure 2. Commercial soft-shell clam landings and value in Maryland, 1962-1985.

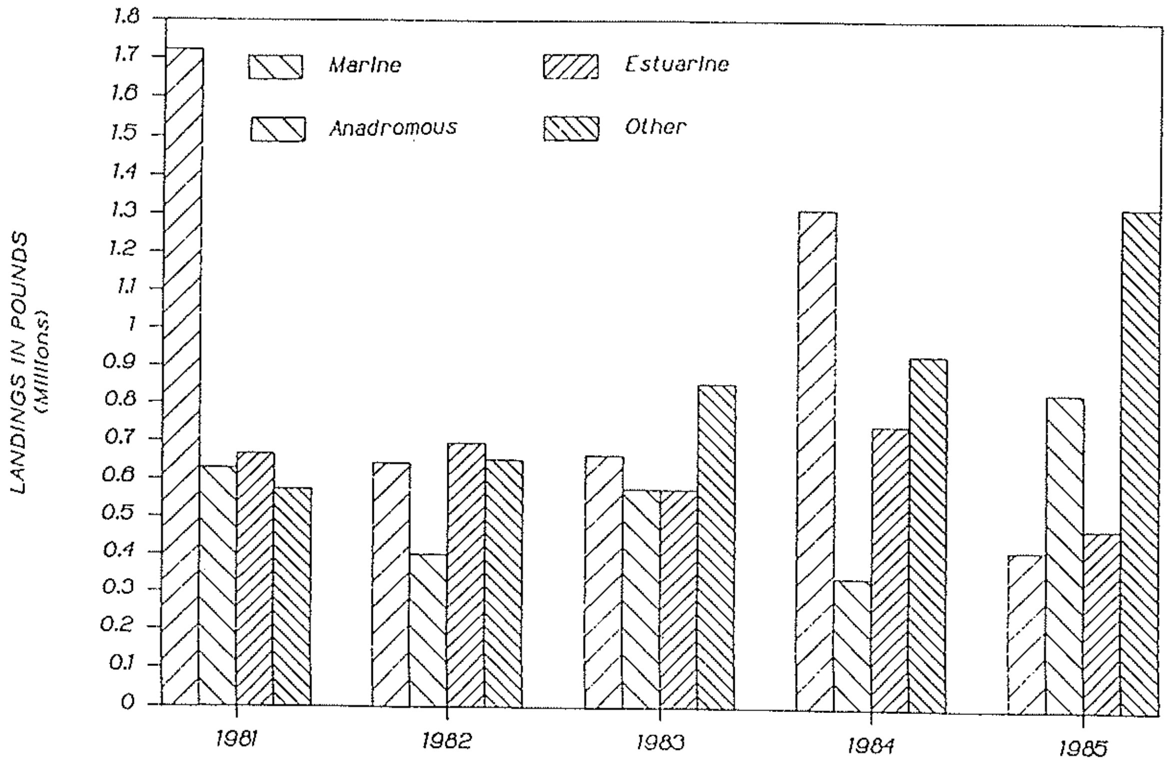

Figure 3. Commercial finfish landings in Maryland, 1981-1985.

landings are so high that the scale would have to be greatly distorted. Figure 4 compares menhaden landings to the total of other finfish.

Anadromous Fish

Striped Bass. No clear trend emerges for the anadromous group. This category is dominated by landings of striped bass (*Morone saxatilus*), which have fluctuated over the period. Striped bass landings for Maryland, including the Potomac River catch, fell from 1.6 x 10^6 pounds in 1981 to 0.5 x 10^6 pounds in 1982 and 1983, then increased to 1.4 x 10^6 pounds in 1984. The moratorium on taking striped bass in Maryland waters became effective 1 January 1985, so the low 1985 landings of 41,000 pounds represented only the Potomac River catch.

Commercial striped bass landings and the juvenile index from 1954 to 1985 are plotted in Figure 5. Although the juvenile index (JI) frequently varied before 1975, ranging from 1.6 in 1959 to 30.4 in 1970, a sufficient number of strong year-classes were produced to maintain a commercial fishery in excess of 2 x 10^6 pounds per year. Since the early 1970s both recruitment and commercial landings of striped bass have declined. Only two years since 1975 have produced a near-average year-class, and commercial landings have been <2 x 10^6 pounds (with the exception of 1980, which produced 2.1 x 10^6). Because of the declining commercial landings and consistently poor recruitment, a moratorium on the commercial and recreational catch of striped bass was implemented in January 1985. The objective of the moratorium is to protect the "average" 1982 year-class (JI=8.4), and subsequent year-classes, because the 1982 year-class offers considerable potential for increasing spawning stock.

Stock assessment studies allow managers to estimate relative population size more accurately than is possible with data on commercial or recreational landings. These studies also provide information to characterize the population, including age and sex distributions. The Estuarine Fisheries program of the Maryland Department of Natural Resources has been conducting assessments of the striped bass spawning stock since the spring of 1982. Relative spawning stock size was lowest in 1982 and 1983 and highest in 1985. The increase in 1985 is due to the presence of males from the relatively successful 1982 year-class, which has been protected by the moratorium. Females, which reach sexual maturity later than males, are presently much less abundant than males in the spawning population. Until the 1982 females become

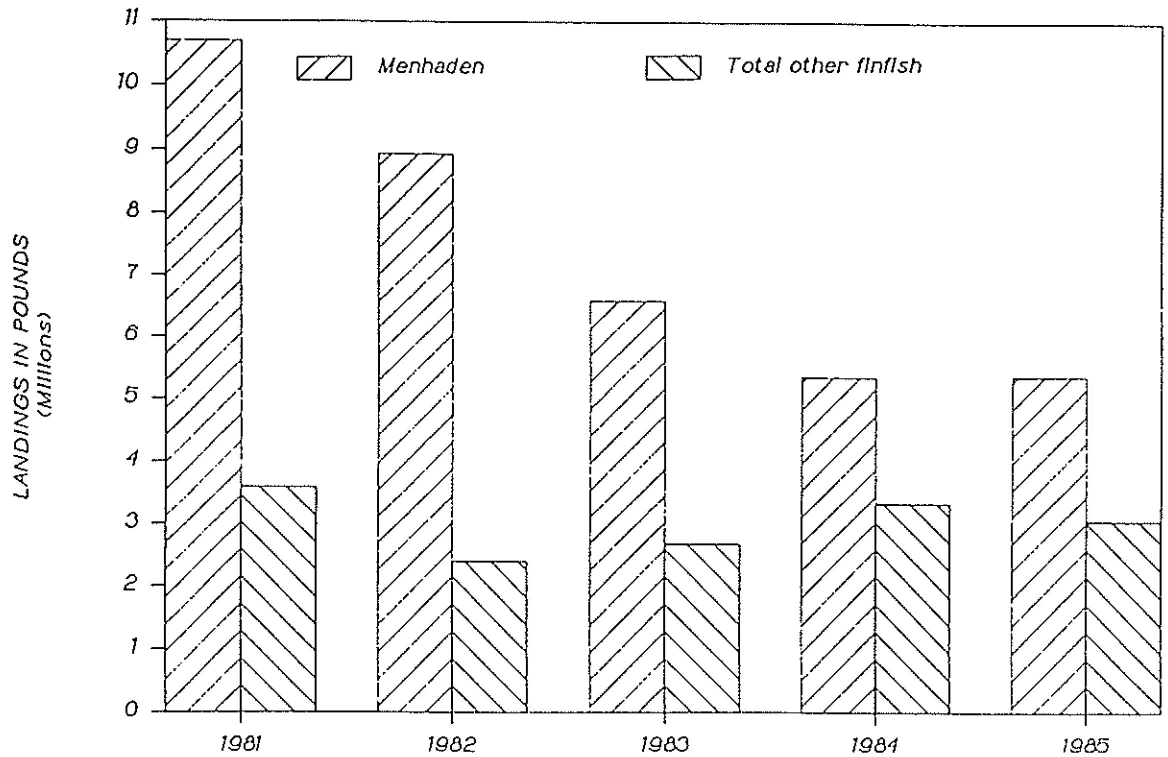

Figure 4. Commercial menhaden landings compared with total landings of other finfish, 1981-1985.

sexually mature, it appears that very old females, which are greatly reduced in number, are the most important component of the spawning stock.

Shad and herring. The anadromous category also includes American shad (*Alosa sapidissima*) and the herrings: alewives (*Alosa pseudoharengus*) and blue-back herring (*Alosa aestivalis*). Landings of herrings generally increased over the five-year period, rising from a low of 82,158 pounds in 1981 to the high of 185,442 pounds in 1985. The 1985 landings were greater than the 1984 catch of 134,199 pounds, which had dropped slightly from 1983 (158,546 pounds).

Shad landings also increased over this period, rising from a low of 573 pounds in 1981 to 62,373 pounds in 1983. Landings in 1984 increased slightly to 70,045 pounds and in 1985 reached their highest value of 189,487 pounds. However, the shad fishery has been closed in the Maryland portion of Chesapeake Bay since 1980, so these figures represent only the commercial landings in the intracoastal waters and the 2% by-catch in the Potomac.

The Tidal Fisheries Division has been conducting an investigation of American shad in the upper Chesapeake Bay since 1980. The program consists of five parts: a springtime tagging and size estimate of the adult spawning population; adult population characterization; springtime sport-fishing survey; a summer/fall juvenile recruitment survey; and a literature search and review.

Population estimates of adult American shad returning to the upper Chesapeake Bay in the spring of each year are calculated using the Petersen and Schaefer statistics. Table 2 indicates a generally increasing

Table 2. Population estimates of American shad, 1980-1986.

Year	Peterson estimate	Schaefer estimate
1980	2,675	NC*
1981	5,477	6,912
1982	31,960	33,742
1983	7,727	8,031
1984	3,814	3,537
1985	11,093	12,903
1986	20,860	20,012

*NC = not calculated this year

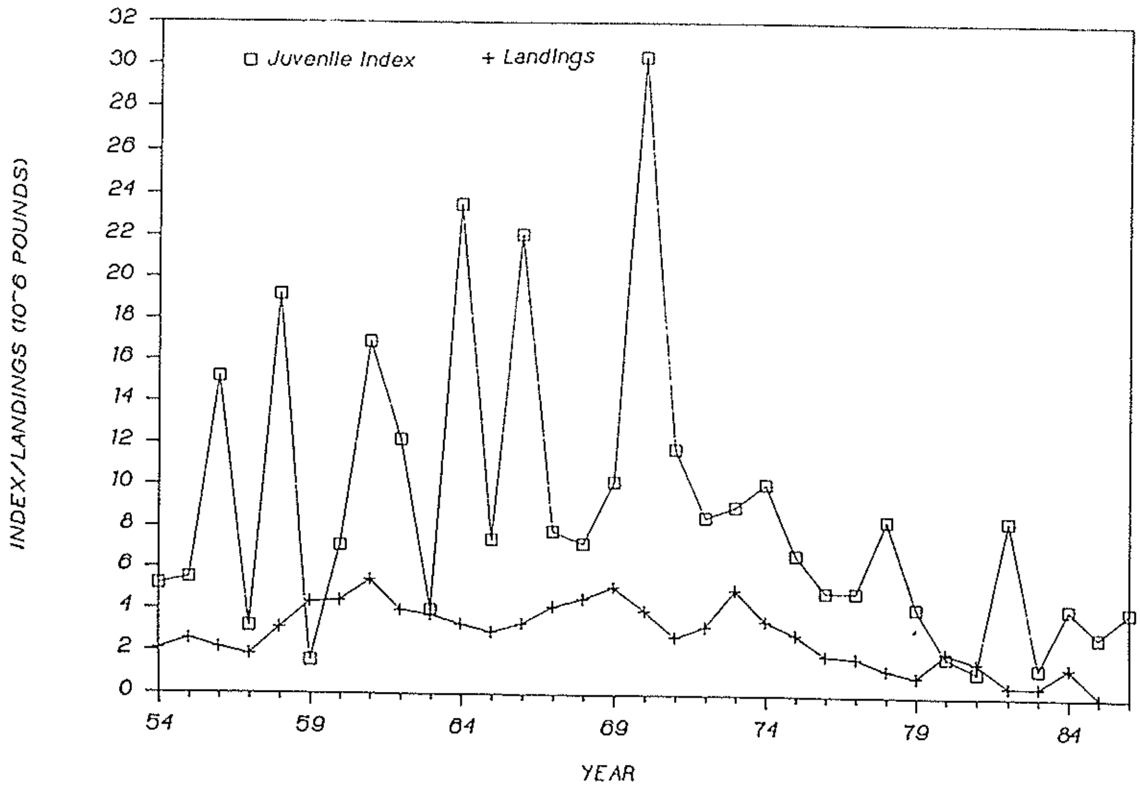

Figure 5. Commercial striped bass landings and juvenile index in Maryland, 1954-1985.

trend, from 1980 through 1986, although most estimates were not statistically different. Estimates for 1982 must be considered too high because of major operational changes in the Conowingo Dam Fish Lift Facility this year. Low estimates for 1984 may be due to high river flows during the spring of 1984.

Unfortunately, results of the juvenile survey are less encouraging than adult stock estimates. A single young-of-the-year shad was collected during the 1982 survey and the 1985 survey. No juvenile shad were found in the other four years of this study.

Marine

Menhaden (*Brevoortia tyrannus*) accounts for the largest portion (by weight) of marine species landed. Figure 4 compares the menhaden landings to the total landings for all other species considered here. Although there was little difference between the 1984 and 1985 catches, the commercial landings of menhaden have decreased from 10.7 x 10^6 pounds in 1981 to 5.4 x 10^6 pounds in 1985. Despite this recent decline, the long-term trend for menhaden landings is an increase. The average catch for 1950-1965 was 2.9 x 10^6; for 1966-1976, it was 5.4 x 10^6 pounds; and for 1981-1985, it was 7.4 x 10^6.

Landings for other marine species fluctuated, showing no clear trend over this five-year period (Figure 3). Bluefish (*Pomatomus saltatrix*) landings ranged from 184,848 pounds to 509,226 pounds during the period, with the lowest in 1984 and the highest in 1985. Sea trout (*Cynoscion regalis* and *Cynoscion nebulosus*) varied from a low of 104,756 pounds in 1982 to a high of 316,372 pounds in 1985. The 1985 landings were an increase over the low 1984 value of 112,489 pounds. Compared with other marine species, recent landings of spot (*Leiostomus xanthurus*) are low, ranging from 6,154 pounds in 1984 to 129,377 pounds in 1983. Landings decreased from 43,318 pounds in 1984 to 7,655 pounds in 1985. It appears that 1984 was a poor year for bluefish and sea trout, but moderately successful for spot, whereas 1985 was very good for bluefish and sea trout, but poor for spot. One must keep in mind, however, that commercial landings data do not provide information on catch per unit effort.

Estuarine

The estuarine component (Figure 3) appears relatively stable, fluctuating over 1981-1985 without great differences. The largest change occurred between

1984 and 1985 when landings of white perch (*Morone americana*), which dominate this category, fell from a high of 718,015 pounds to a low of 462,793 pounds. Croaker (*Micropogonias undulatus*) landings also declined from a high of 27,072 pounds in 1984 to 9,514 pounds in 1985. The poorest year for croaker was 1983, when landings totalled 417 pounds.

Other

The component designated as "other" in Figure 3 shows a clear rising trend from 1981 through 1985, mainly because catfish (*Ictalurus* spp.) landings increased steadily, from 559,600 pounds in 1981 to 1,274,070 pounds in 1985. Landings of yellow perch (*Perca flavescens*), the other species included in this category, also increased from 15,145 pounds in 1981 to 48,081 pounds in 1984. There was a small decrease, to 44,019 pounds, in 1985.

Abundance of Virginia Shellfish and Finfish

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CLIMATE

Water temperature, which has been measured from the pier at the Virginia Institute of Marine Science (VIMS) since 1946, has shown a steady upward trend since 1975-1976. This trend has been most dramatic during the fall-winter period, with October and November of 1984 and 1985 being two of the warmest periods in the 30-year record. The fall of 1985 was the warmest in 30 years. Winter (January-March) temperatures have also shown a steady rise since the record cold January-February of 1977-1978.

Streamflow during 1984 was similar to the "wet" period of 1972-1980, whereas 1985 was similar to the drought of the mid-1960s. The spring of 1985 was particularly dry, with the normal peak period of spring run-off absent. Annual rainfall averages can be misleading, as an "average year" may be the result of significant rainfall during only one season, the other three being bound in a drought. Such was the case in 1985 when hurricanes Gloria and Juan and the subsequent November northeaster produced heavy autumn run-off that raised the annual total during an otherwise drought year. Furthermore, the fall rains and subsequent run-off did not occur during biologically significant times.

Winds and resultant surface transport at the Bay mouth during 1985 were generally not favorable for larval recruitment during May-July, as southwest winds produced extended periods of offshore transport. Late summer winds were variable and provided no significant transport onshore or offshore. Fall winds and resultant surface transport on the shelf were favorable during both 1984 and 1985 for recruitment to the Bay by shelf-spawned fish including spot, croaker, and flounder. Conditions are favorable when northerly winds produce a southwesterly flow of coastal waters capable of transporting the larvae of the shelf-spawning species to the mouth of the Bay.

RESOURCES

Oyster

The warm fall of 1984 and the warmer fall of 1985 held the oyster in spawning condition through the end of October. Spatfall continued through October, particularly in 1985, and the early-season harvests of market oyster were poor, as most oyster were in a recently spent condition. Virginia oyster landings have been generally stable since 1972, fluctuating between 4.0×10^6 and 6.0×10^6 pounds of shucked meat ($0.65\text{-}1.00 \times 10^6$ bushels), except for 1978-1980 when landings jumped to $8.1\text{-}8.4 \times 10^6$ pounds as a result of unrestricted dredging in the Pocomoke-Tangier Sounds. Landings totalled 4.3×10^6 pounds (0.70×10^6 bushels) in 1984 and 4.7×10^6 pounds (0.76×10^6 bushels) in 1985 (Figure 1 top).

Oyster spat. Since 1946 spatfall has been monitored at VIMS during the fall on oyster shell dredged from the public oyster bars, and the data set provides documentation of the catastrophic decline in recruitment after the introduction of MSX during the late 1950s. A summer shellstring survey was initiated in 1963. These data also show the degree of interannual variation in recruitment potential. During the 1940s and 1950s a rate of 1000-2000 spat/shell from the fall survey was normal. This rate dropped to 0-100 during the late 1960s and 1970s. From 1981 through 1983 the "strike" improved to 400-800 spat/shell. Some oyster bars even showed levels exceeding the pre-1960s decline. This heavy set, in spite of smaller brood stock, demonstrates the lack of parent-progeny dependence (density-dependent) and the importance of local environmental variability (density-independent) in the determination of year-class strength. Note, however (Figure 1 bottom), in 1968-1971 the summer shellstring count was up, but the fall shell bag count was down. This suggests that despite a good initial set, subsequent survival was poor.

Virginia has generally experienced unusually dry summers since 1980, and these conditions, which have raised the salinities over the James River seed beds, may in part be the cause of the improved summer set on the shellstrings.

The summer spatfall on shellstring averaged over the season for 1984 and 1985 was moderate to heavy in most of Virginia's rivers (1-20 spat/shell is considered poor; 20-200 moderate; and 200-2000, heavy). However, there was considerable variability both temporally and spatially (Figure 1 bottom). Wreck Shoal in the James River is considered a "typical" oyster bar and so is presented here as an example of setting patterns. Generally, 1985 was better than 1984, with 1984 being more representative of the low recruitment of the 1970s. The James River seed beds received a heavy but variable set during 1985, possibly because of the higher salinities.

Although summer shellstring spatfall counts are a good index of potential recruitment, survival through the first season is generally poor, and subsequent fall or spring counts of spat on shell on the bottom, which indicate the degree of survival, are more realistic. Survival of the spat through the first summer was excellent in 1981-1983, but was low in 1984 and 1985. Current research on the effects of fouling and predation on the James River seed beds suggests that predation, particularly by blue crabs, may be a contributing factor, but it probably does not account for the state-wide poor survival.

MSX. During the drought of 1980-81 there was no appreciable intrusion of MSX (*Haplosporidium nelsoni)* or other oyster pathogens upriver in Virginia. Normally May-June is the peak period of MSX infection, with the pathogen appearing in samples during July. Oyster become most susceptible during

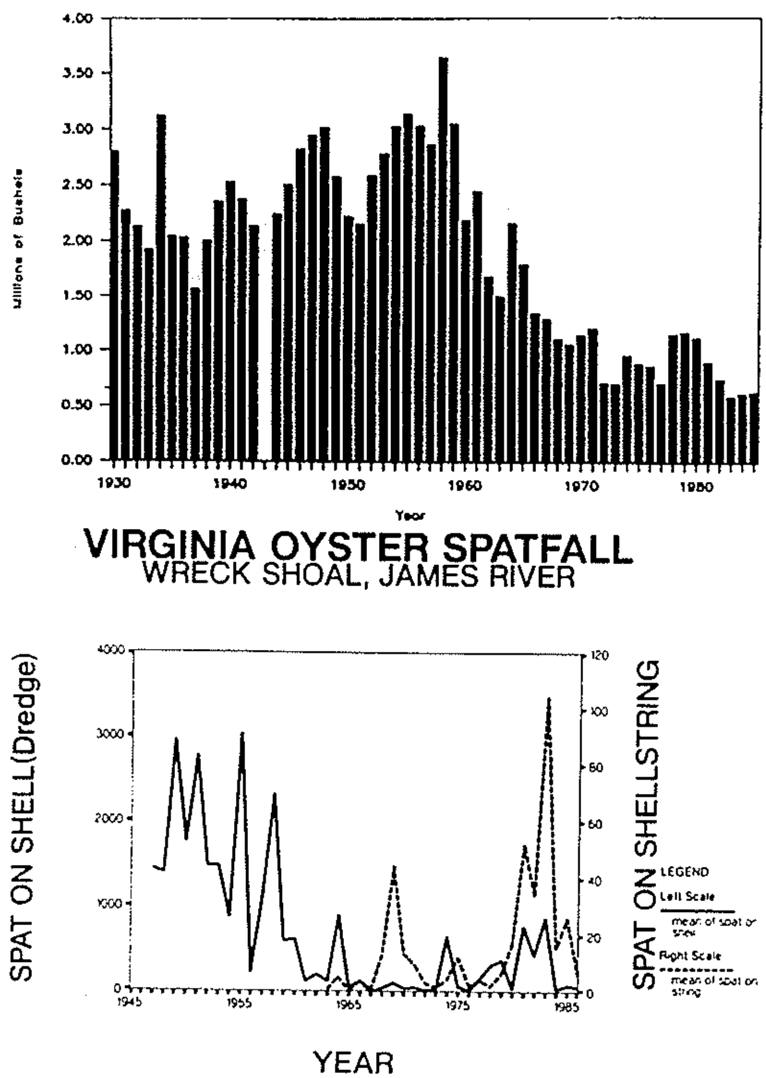


Figure 1. Virginia landings of market oysters, 1930-1985 (top); and spat set of James River oyster on shellstrings (bottom).

years with a dry spring, as the low salinities that normally prevent the spread are not present. Dry conditions early in spring 1985 were conducive to the upriver spread of pathogens.

Striped Bass

Young-of-the-year striped bass are taken in the VIMS river trawl survey, usually during the winter when the juveniles are eight to nine months old. The

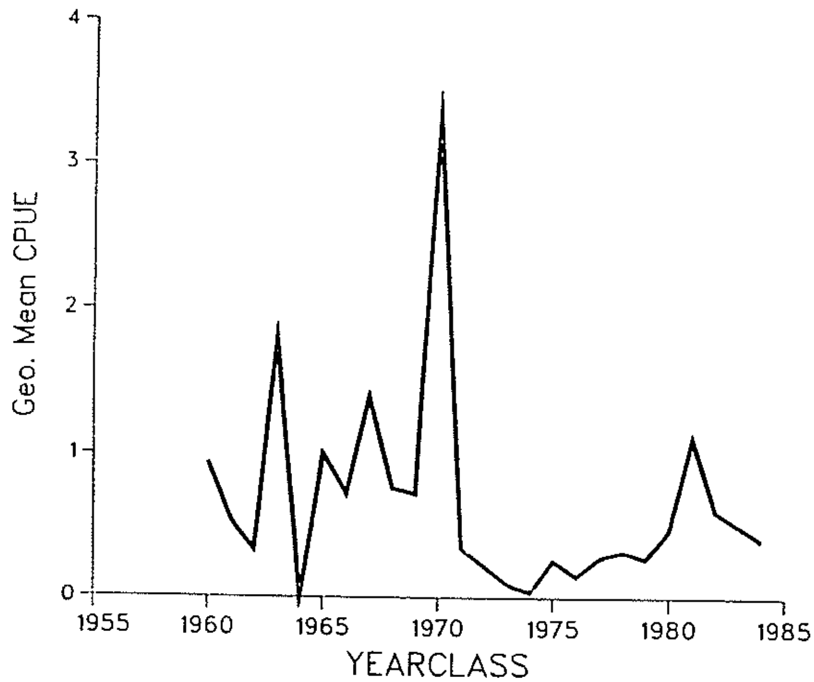
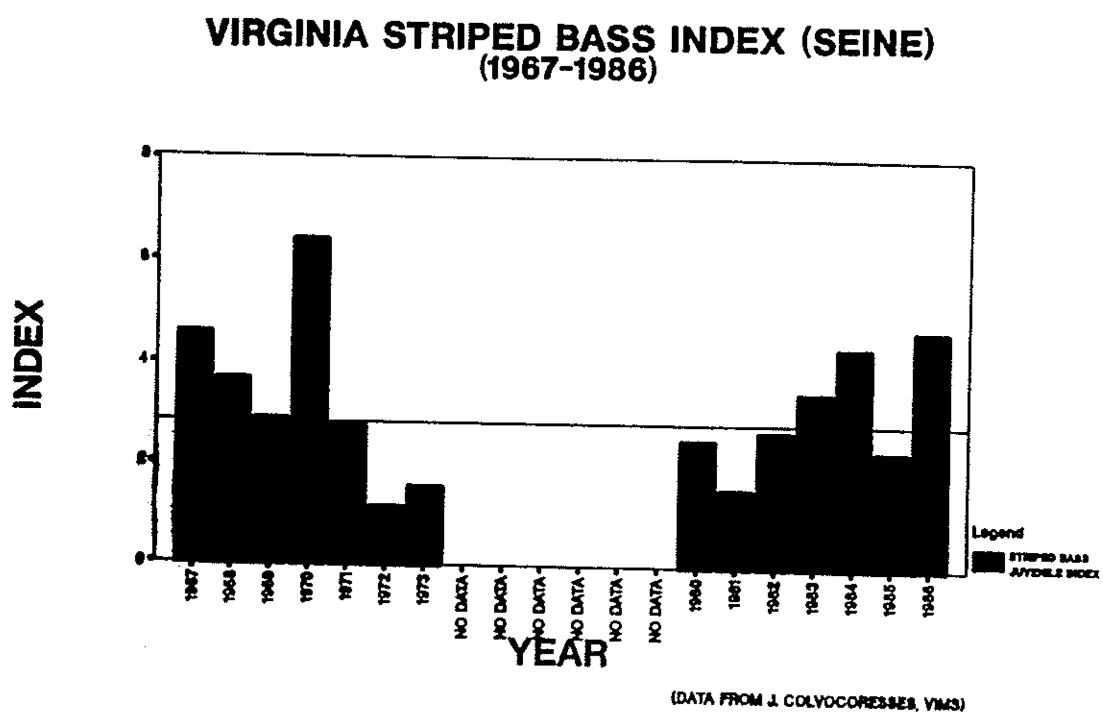


Figure 2. York River index and commercial landings for striped bass as determined by the VIMS trawl survey (top); and adjusted mean catch per haul as determined by beach seine (bottom).



trawl data have shown that over the years both dominant and failure year-classes can be monitored, and that success or failure of recruitment in one river is not necessarily reflected in the other rivers (Figure 2 top). Winter trawl catches are very sensitive to temperatures, with more fish being taken during colder years, often regardless of year-class strength. The beach seine data (Figure 2 bottom) are a better index of year-class strength. From 1967 through 1973 and from 1980 to the present, beach seine surveys have also been conducted in the summer, coinciding with the first appearance of the young-of-the-year.

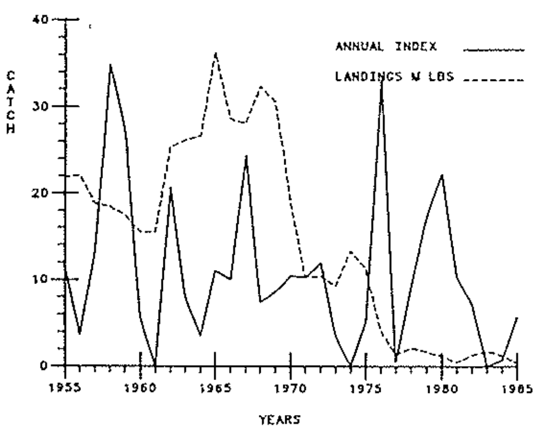
The beach seine index has shown a positive trend since 1981, with 1984 the highest since the record 1970 year-class was produced (Figure 2 bottom). The 1985 year-class was considered average, as was the 1982 year-class. Monitoring during 1985-1986 of commercial (>18") and sub-legal catches suggests that these strong year-classes (1982-1984) have survived. Although the 1985 index was only average, the numbers may have been biased downward, as the higher salinities from the drought displaced the juveniles further upriver than normal, where the sampling sites were not conducive to seining.

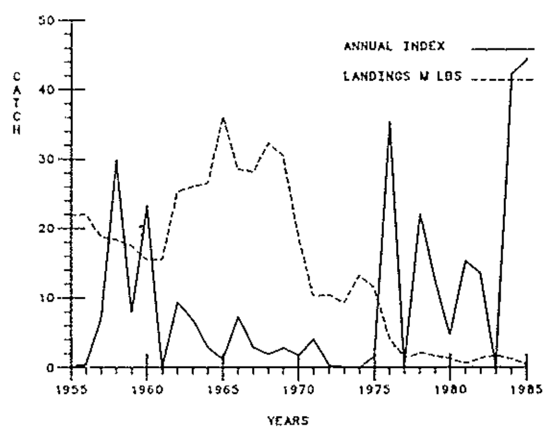
Initial surveys for 1986 young-of-the-year show a very wide range in sizes (20-80 mm) with an estimated modal size around 50 mm. Normally the range is around 30-50 mm with a 40 mm mode. Estimates made on the spawning ground during April and May suggest that the fish spawned earlier, more briefly, farther upstream, and in a more compressed area than usual. Preliminary indications are that the 1986 year-class will be strong.

Alosines

During 1985 the spring spawning run was interrupted by a cold freshet. Juvenile indices from a pushnet survey in the Mattaponi and Pamunkey, however, did not seem to be affected, as the indices for American shad, blueback, and alewife were generally higher in 1985 than in 1984. The trawl survey indices show poor recruitment for shad and alewife, but excellent recruitment during 1984 and 1985 for the blueback herring (Figure 3).

Commercial landings were lower in 1985 than 1984 for all three species. Alewife and blueback herring stocks show no signs of recovery as indicated by commercial landings. American shad shows some





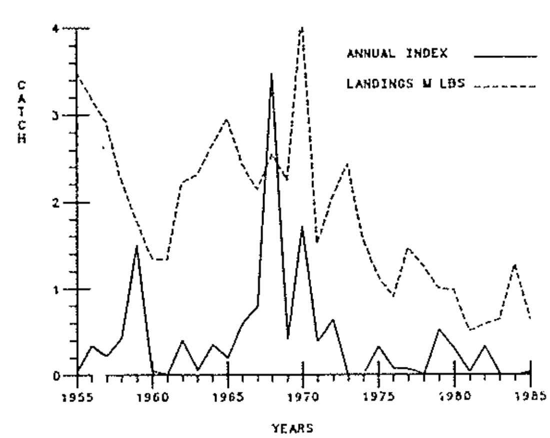


Figure 3. York River index and commercial landings for alewife (upper left), blueback herring (upper right), and American shad (lower left), as determined by the VIMS trawl survey.

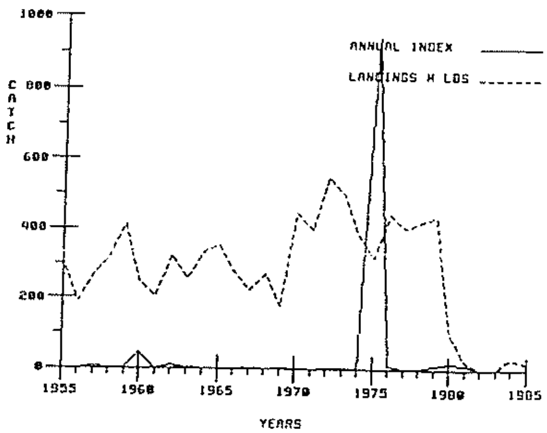


Figure 4. York River index and commercial landings for menhaden, as determined by the VIMS trawl survey.

signs of recovery, as catch has shown an upward trend since 1981.

Menhaden

Observations suggest that the number of small menhaden in the Bay has increased in recent years. Neither the beach seine nor trawl surveys sample the young-of-the-year menhaden.

Virginia menhaden landings, which have averaged over 300 x 10^6 pounds annually since 1950, dropped abruptly from 501 x 10^6 pounds in 1977 to 34 x 10^6 pounds in 1978, and have averaged 25-35 x 10^6 pounds since (Figure 4). This drop was the result of a combination of reduced biomass, interstate fishery regulations, and a reduction in effort (number of vessels) in the mid-Atlantic fishery that landed fish in Virginia. Most significant was the reduction in Chesapeake Bay landings, from 439.3 x 10^6 pounds in 1977 to 9.3 x 10^6 pounds in 1978.

Total Virginia landings were 31.6 x 10^6 pounds in 1984, and 17.3 x 10^6 pounds in 1985, the lowest year on record. This reduction is due to all three factors mentioned above. Landings in 1986 probably will be even lower, as Standard Products, the largest Virginia harvester, will not fish. The number of fish is increasing, although the biomass remains low, as these fish are still juveniles.

Currently, the most significant menhaden fishery in the bay is the pound-net fishery for crab bait.

The incidence of the fungal disease (ulcerative mycosis) in menhaden in the Chesapeake Bay has been increasing over the last two years. Very high incidences have been reported from Pamlico Sound already this summer (1986), and biologists are alert for evidence this summer in the Bay.

Flounder

Juvenile flounder are normally very scarce in samples taken by the VIMS trawling survey from the Bay and tributaries. Juveniles were collected during the period 1979-1983 when flounder landings reached record highs (Figure 5). Current understanding of flounder stocks suggests that fish >12" in the Bay are from the "southern stock", those spawned in North Carolina waters; and that the juveniles in the Bay (the "Virginia stock") upon reaching 12" migrate north into the Mid-Atlantic Bight, and are generally not taken by Virginian fishermen. A new survey, starting in the summer of 1986 and combining seine and a small trawl, has shown the Virginian Eastern Shore creeks and sounds to be a productive post-larval nursery ground. Recent concerns about the "demise" of the flounder stock are due in part to its return to average conditions. Although 1984 landings were 9.7 x 10^6 pounds, and 1985 only 5.0 x 10^6 pounds, these figures are still well above the 1.5-3.5 x 10^6 pounds per year taken during 1955-1975. A very significant fraction of the Virginia landings is taken in the territorial sea, and much of the increase since the mid-1970s results from the development of the territorial ocean trawl fishery.

Croaker

Croaker have been abundant in the Bay and tributaries since 1984, a result of the excellent 1982-1985 recruitment. Commercial landings have reflected this abundance, climbing from 0.1 x 10^6 pounds in 1983 to 2.1 x 10^6 pounds in 1985 (Figure 6). The 1985 index of 18 is the highest in the 30-year period of the survey. This abundance reflects the favorable fall winds on the shelf and good over-winter survival

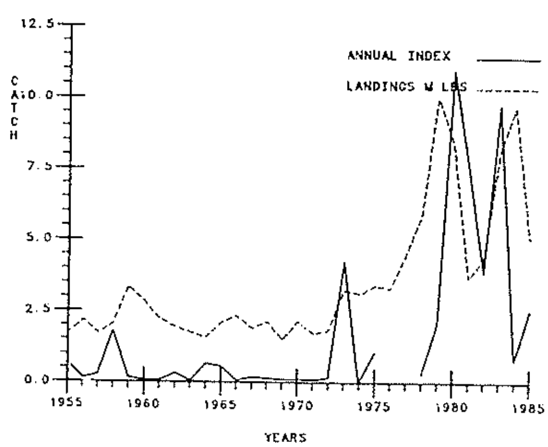


Figure 5. York River index and commercial landings for flounder, as determined by the VIMS trawl survey.

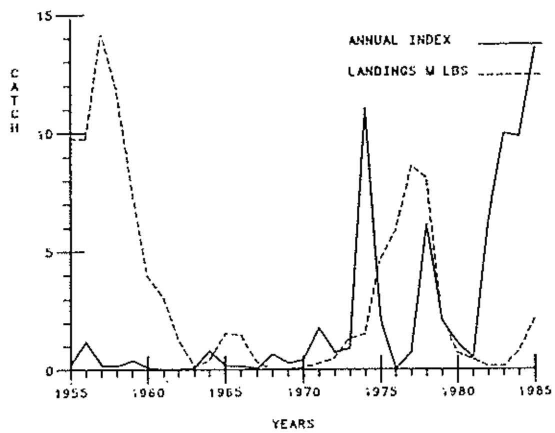


Figure 6. York River index and commercial landings for Atlantic croaker, as determined by the VIMS trawl survey.

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of juvenile croaker in the Bay due to the warmer winters.

Blue crab

Spring and summer weather patterns often have a greater impact on crab catches in pots than does their relative abundance. When the rivers are cool and fresher in the spring, or particularly hot in the summer, crabs seek deeper water, where they are less available to pots. Furthermore, extended periods of southwest winds during summer can produce localized upwelling along the southern shores of the major Virginia tributaries such as the Rappahannock. When these conditions coincide with a stratified water column and low dissolved oxygen below the thermocline, the upwelling sometimes brings the low-oxygen waters closer to shore and kills crabs caught in pots and subsequently reduces the area available for fishing.

Virginia hard crab landings have been 36-40.4 x 10^6 pounds in 1977-1985, with a slight upward trend through 1984. Landings in 1984 were 49.4 x 10^6 pounds; in 1985, 37.7 x 10^6 pounds (Figure 7).

Estimates of megalopae (post-late-larval stage blue crabs) during the summer of 1985 suggested a very small year-class; however, catches of juveniles in the fall trawl survey were average. Subsequent peeler catches during the spring and summer of 1986 (1985 year-class) were good during May, but dropped off during June and July, a normal pattern.

Warmer winters delay the date when temperatures drop to 8.3° C (47° F), the temperature at which crabs bury in the mud and become susceptible to the Virginia winter crab-dredge fishery. The current trend toward warmer Decembers may result in reductions in the winter dredge fishery; However, many of the female crabs migrate out of the Bay during warm winters and become susceptible to ocean trawlers along the Virginia Capes.

Considerable concern has been generated in Virginia during the 1985 fishing season as Maryland watermen, fishing for the first time in Virginia's waters, raised the overall catch, but because of problems documenting where the landings were reported, the size of the increase is not known. Efforts are currently under way in both states to document the level of catch and effort in the blue crab fishery.

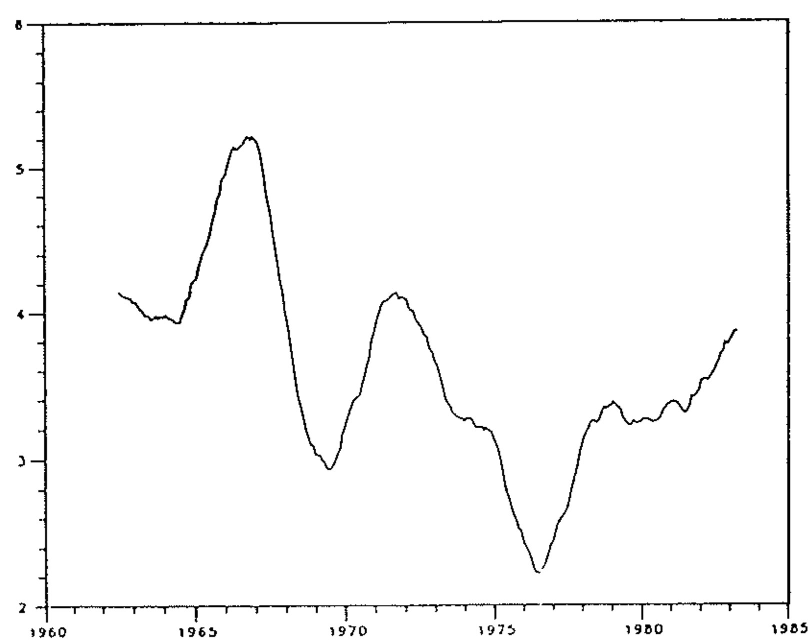

Figure 7. Virginia crab landings (millions of pounds), 1960-1985.

Cooperative Program for Tagging of Striped Bass with Binary-Coded Wire Tags in the Chesapeake Bay in 1985

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In June 1985 the United States Fish and Wildlife Services (USFWS) and the Maryland Department of Natural Resources (MDNR) signed a cooperative agreement to implement a program for striped bass tagging and stocking in the Chesapeake Bay. The goal of the experimental program is to document the effectiveness of stocking efforts in the Bay and along the Atlantic Coast. The long-term objectives (five years or more) are to determine the contribution of hatchery fish to the spawning population and to study the migratory patterns and survival of stocked fish.

Under the agreement, USFWS designated and committed six Federal hatcheries and a program coordinator. MDNR provided striped bass fry (approximately 10 days old) and the use of the Manning State Hatchery for both hatching and tagging the bass. The Atlantic States Marine Fishery Commission, Striped Bass Stocking Committee reviewed the program for biological feasibility. They recommended using binary-coded wire tags and also suggested certain biological and fishery management procedures to assure program success.

The binary-coded wire tag was chosen because of its excellent retention and because it allowed identification of groups of fish raised in various hatcheries and released in different locations within the Bay tributaries. In addition to the binary-coded tags, 4,000 fish were tagged with a Floy internal-anchor streamer tag to provide information on tag retention, angler return, and fish distribution.

METHODS

EA Science and Technology, Inc. of Middletown, NY, provided six binary-coded wire-tagging machines, quality-control devices (QCDs), a large tagging trailer, and technical assistance in set-up and operations. Stainless steel wire tags were obtained from Northwest Marine Technology, Inc. of Shaw Island, WA. All tags were coded as to agency, hatchery, stocking location, and year of tagging. The six federal hatcheries at Harrison Lake, VA, Edenton and McKinney Lake, NC, Frankfort, KY, Bowden, WV, and Orangeburg, SC, Maryland's Manning Hatchery, Horn Point, and Baltimore Gas and Electric's Crane Aquaculture Hatchery provided the 4-10-inch striped bass.

During tagging, fish were anesthetized and were handled in a 1-2% salt solution. Fish were usually in the anesthetic-saltwater solution for an average of 10-15 minutes before they were tagged. The QCDs magnetized the tags, which were implanted perpendicular to the fish's body in the adductor muscle.

Quality control was performed in several ways. On a daily basis, a small subsample of tagged striped bass were placed back in the QCDs to insure short-term retention and magnetization of the tag. Additional subsamples were held for periods of 2-10 days in saltwater tanks in a continuing check for short-term tag retention and magnetization. After release magnetization checks will continue with field portable tag detectors.

MDNR biologists are equipped with tag detection machines; during striped bass survey work they will be examining all striped bass captured for binary-coded wire tags and internal-anchor tags.

RESULTS AND DISCUSSION

Tagging of striped bass began 14 November 1985 and continued until 18 December 1985. Almost 187,000 striped bass were tagged with binary-coded wire tags (Table 1), and 4,000 of these were double-tagged with internal-anchor tags (Table 2). Fish were released into the Nanticoke and Patuxent Rivers and Turners Creek off the Chesapeake and Delaware (C&D) Canal. Tagging was terminated on 18 December because low air and water temperatures caused extreme stress in the striped bass being handled and tagged, with an excessive mortality rate (>50%). In order to avoid additional stress tagging was stopped. At that point approximately 42,000 fish that were at or in transit to Manning, or in holding houses at federal hatcheries being prepared for the trip to Maryland, had to be released untagged. USFWS and MDNR hope to tag 500,000 striped bass in 1986.

Table 1. Number, size, destination, and source of 186,926 tagged striped bass stocked from Manning Hatchery, 14 November-18 December 1985.

Date	No. of fish	Size	Stocking area	Source
11/14	4,723	25/lb	Patuxent @ Benedict	Manning
11/15	5,418	9.4/lb	Turners Creek	BG&E*
11/18	3,649	3-6"	Patuxent @ McGruders	Harrison Lake
11/18	4,628	10.3/lb	Turners Creek	BG&E
11/19	4,924	3-6"	Patuxent @ Solomons	Harrison Lake
11/19	5,116	7.6/lb	Nanticoke @ Vienna	BG&E
11/20	5,092	60/lb	Nanticoke @ Vienna	Frankfort, KY
11/20	4,117	3-6"	Patuxent @ Benedict	Harrison Lake
11/21	2,401	3-6"	Patuxent @ McGruders	Harrison Lake
11/21	6,250	3-6"	Patuxent @ Benedict	Harrison Lake
11/22	5,835	3-6"	Patuxent @ Benedict	Harrison Lake
11/25	4,145	3-6"	Patuxent @ Benedict	Harrison Lake
11/25	5,162	6.7/lb	Nanticoke @ Vienna	BG&E
11/26	7,581	9.4/lb	Nanticoke @ Vienna	BG&E
11/26	7,562	3-6"	Patuxent @ Benedict	Harrison Lake
11/27	2,039	4-7"	Patuxent @ Benedict	Harrison Lake
11/27	3,533	3.7/lb	Nanticoke @ Vienna	BG&E
12/2	4,416	4.2/lb	Nanticoke @ Vienna	BG&E
12/3	6,685	3-6"	Turners Creek	Harrison Lake
12/4	3,946	4.2/lb	Nanticoke @ Vienna	BG&E
12/5	14,233	2-6"	Turners Creek	Harrison Lake
12/10	7,625	3-6"	Patuxent @ Benedict	Edenton NFH
12/11	872	3/lb	Nanticoke @ Vienna	BG&E
12/12	1,874	3-6"	Patuxent @ Benedict	McKinney Lake
12/13	2,327	4-7"	Patuxent @ Benedict	Edenton
12/13	12,336	4-7"	Patuxent @ Benedict	Edenton
12/16	6,405	3-6"	Nanticoke @ Vienna	Horn Point
12/16	12,350	5-7"	Patuxent @ Benedict	Edenton
12/17	5,105	3-6"	Patuxent @ Benedict	Edenton
12/17	10,133	3-6"	Nanticoke @ Vienna	Edenton
12/18	5,530	3-6"	Patuxent @ McGruders	McKinney
12/18	3,939	3-6"	Turners Creek	Orangeburg
Total	186,926			

*BG&E = Baltimore Gas and Electric Company.

Table 2. Number, source, and destination of striped bass tagged with Floy (internal-anchor) external tags as well as binary-coded wire tags, 19 November 1985-6 February 1986.

Tag numbers	Source	Stocking location	Date
1000-1199	Harrison Lake	Patuxent River	11/19/85
1200-1599	BG&E*	Nanticoke River	11/19/85
1600-1999	Harrison Lake	Patuxent River	11/20/85
2000-2249	Harrison Lake	Patuxent River	11/21/85
2250-2499	BG&E	Nanticoke River	11/25/85
2750-3249	BG&E	Nanticoke River	11/26/85
3250-3499	Harrison Lake	Patuxent River	11/27/85
3500-3749	BG&E	Nanticoke River	11/27/85
3750-3999	BG&E	Nanticoke River	12/04/85
4000-4199	Edenton	Patuxent River	12/11/85
4200-4249	BG&E	Nanticoke River	12/11/85
4250-4449	McKinney Lake	Patuxent River	12/12/85
4450-4499	Edenton	Patuxent River	12/13/85
4500-4699	Edenton	Patuxent River	12/17/85
4700-4799	Edenton	Nanticoke River	12/17/85
4800-4999	Bowden	Patuxent River	2/06/86

*BG&E = Baltimore Gas and Electric Company.

The mortality rate for fish during shipping and up to 12 hours afterward averaged around 6%. Deaths were primarily due to low oxygen levels during transportation, stress, and physical damage incurred during transportation and handling. The mortality rate after tagging (excluding December 18) was <1%. If fish were received at Manning Hatchery in good condition and handled in highly oxygenated water with salt and an anesthetic, tagging would cause almost no deaths.

As of September 1986, 65 tagged fish have been returned from the Nanticoke and Patuxent–all of them double-tagged.

Retention of the binary-coded wire tag was excellent immediately after tagging: 98% of all fish sampled were tagged and magnetized correctly. Post-tagging retention and magnetization data have not been analyzed, as only 65 tagged fish have returned to date.

Long-term Trends (1948-1986) of Wintering Waterfowl in the Chesapeake Bay

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Few areas in the world have been as historically famous as the Chesapeake Bay for wintering waterfowl. This 180-mile long bay, with 4,000 miles of shoreline and extensive shoal water areas, has provided optimal foraging habitat for millions of waterfowl during the winter. From approximately 1880 to 1910 waterfowl wintering on the Chesapeake Bay sustained the largest market-hunting business known to man (Kimball 1969; Walsh 1971). Accounts by sportsmen and naturalists relate how the water areas were covered with ducks (Herbert 1873; Grinnell 1901; Sanford et al. 1903). Waterfowl were killed by the thousands and stuffed into barrels for transport by train to the major cities in the East.

The decrease in number of waterfowl in the Chesapeake Bay early in the 20th century aroused concern among Americans, and in 1918 market hunting was outlawed with a treaty between the United States and Great Britain (for Canada). Waterfowl populations began to increase slowly in North America, until the drought of the 1930s. Coupled with excessive drainage of northern breeding areas, the drought resulted in population declines that again aroused public concern. New hunting regulations in 1935 outlawed the use of live decoys and bait while hunting. The "duck stamp" program was initiated in 1935 to provide funds to establish more waterfowl refuges in the United States.

Over the past three decades the public has become concerned about the impact of environmental pollution on waterfowl habitats. The Chesapeake Bay, with large metropolitan areas on the western shore, bore the brunt of this abuse, with continued degradation of habitat. During this period biologists became aware that submerged aquatic vegetation (SAV) was disappearing in many areas of the Bay (Bayley et al. 1978). Parts of some rivers, especially in the upper Bay region, became totally devoid of plants.

The objective of this report is to discuss the present status of the major waterfowl species in the Chesapeake Bay on the basis of 39 years (1948-1986) of winter survey data. Populations of each species are compared to populations in the Atlantic Flyway and North America to determine if changes detected in the Chesapeake Bay are due to conditions in the Bay or to Flyway or continental population levels.

METHODS

All survey data used in this report were obtained from unpublished data in files of the Office of Migratory Bird Management, U.S. Fish and Wildlife Service (USFWS), Laurel, Maryland. Chesapeake Bay counts represent combined counts for Maryland and Virginia. Surveys were flown at low levels (25-100 m) with single-engine aircraft of the USFWS and various state wildlife agencies. Surveys in the Chesapeake Bay have been conducted since 1948 in early January, when waterfowl populations are more stable and concentrated than at other times during the winter.

Comparison of the average number of waterfowl during the 1980s with the average number during earlier periods indicates the present status of waterfowl. Survey data in graphs are presented as five-year averages (except for the four-year period 1983-1986) to minimize annual fluctuations and emphasize long-term trends. Survey techniques and data analysis are further discussed in Perry et al. (1981).

RESULTS AND DISCUSSION

Tundra Swans

Populations of tundra swans (*Cygnus columbianus*) in the Chesapeake Bay have been

Table 1. High, low, and mean populations of 13 waterfowl species in the Chesapeake Bay, 1948-1986, as determined by aerial winter surveys.

Species	High count (year)	Low count (year)	39-year mean	1980s mean
Tundra swan	75,854 (1955)	18,216 (1948)	36,710	35,065
Canada goose	701,470 (1981)	62,130 (1948)	382,760	590,335
Black duck	281,485 (1955)	28,820 (1979)	84,197	51,365
Mallard	182,195 (1956)	8,235 (1949)	51,212	57,553
Wigeon	144,350 (1955)	900 (1984)	29,246	5,226
Pintail	78,211 (1956)	400 (1970)	16,282	3,935
Canvasback	399,320 (1954)	34,300 (1986)	104,012	52,931
Redhead	118,800 (1956)	800 (1983)	35,288	3,506
Scaup	403,658 (1954)	10,700 (1982)	65,909	29,973
Goldeneye	40,518 (1956)	2,445 (1976)	19,659	17,513
Bufflehead	36,023 (1977)	2,502 (1959)	14,813	16,840
Ruddy duck	124,740 (1953)	4,703 (1976)	33,642	15,729
Scoter	130,900 (1971)	1,551 (1981)	16,760	6,565

variable during the 39-year period of aerial surveys (Table 1, Figure 1). Numbers were lowest at the beginning of the surveys in 1948 (18,216) and then peaked in 1955 (75,854). The long-term average population was 36,710. The average recorded in the 1980s was 35,065, which was only 5% less than the pre-1980s average of 37,070.

In the early years of the surveys, swans in the Chesapeake Bay were found mostly in the lush beds of aquatic vegetation on the central portions of the Eastern Shore. In the late 1960s and early 1970s, however, tundra swans began to feed in agricultural fields on waste corn and winter cover crops. Although most of this feeding occurred on the Eastern Shore, one large flock of approximately 1,000 was seen regularly in farm fields near Benedict, Maryland, near the Patuxent River. The use of fields for feeding areas began in the Bay area (Munro 1980) as SAV beds in the Bay were disappearing. Stewart (1962) did not mention field feeding by swans. The swans apparently adapted to an alternate feeding pattern that appears to be to their advantage.

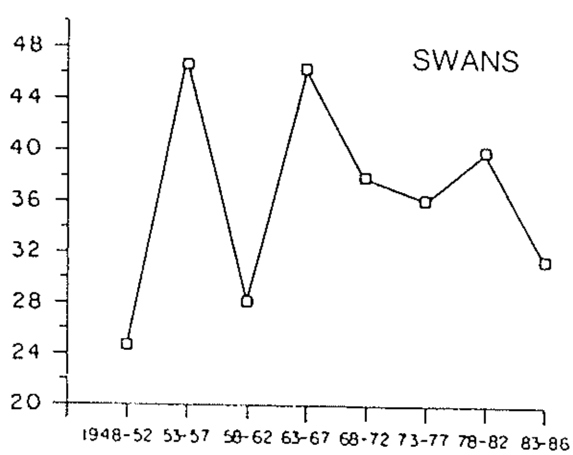

Figure 1. Long-term trends in populations (x1000) of tundra swans in the Chesapeake Bay during eight periods from 1948 through 1986.

The Chesapeake Bay historically has been the most important wintering area for tundra swans in North America, and in the early years of the survey population trends in the Chesapeake Bay, Atlantic Flyway, and North America were similar. During the 1970s and 1980s, however, the number of tundra swans in North Carolina has increased to include more than half of the Atlantic Flyway population. This change in distribution is most likely due an to increased number of agricultural areas in North Carolina and overall less human disturbance in these feeding areas. Agricultural fields in North Carolina, which tend to be larger than in other areas, also may favor the large swans during take-off. The increased population and purported damage to agricultural areas by the swans were two reasons for establishing special hunting regulations for tundra swans in North Carolina during the 1984-1985 and 1985-1986 hunting seasons.

Canada Geese

Populations of Canada geese (*Branta canadensis*) in the Chesapeake Bay have undergone phenomenal

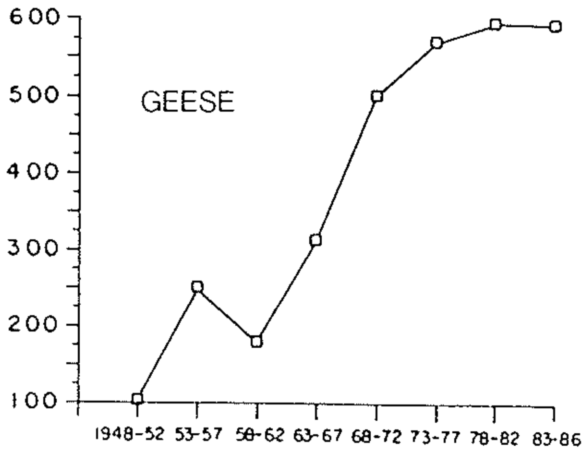

Figure 2. Long-term trends in populations (x1000) of Canada geese in the Chesapeake Bay during eight periods from 1948 through 1986.

changes during the 39 years of winter surveys (Table 1, Figure 2). As was the case with tundra swans, numbers were lowest (62,130) at the beginning of the survey. The population steadily increased and peaked in 1981 at 701,470. The long-term average was 382,760. The average during the 1980s has been 590,335 geese, which was 75% higher than the pre-1980s average (337,352). Overall, population trends in the Chesapeake Bay during the 39-year period were not similar to trends in the Atlantic Flyway and North America. Populations south of the Chesapeake Bay (mainly in North Carolina) declined over this period, whereas continental trends have been variable.

This dramatic increase in populations of Canada geese appears to be directly related to their ability to capitalize on abundant food in the agricultural areas of the Eastern Shore. Waste corn available to geese after harvest provided the necessary high-energy food for geese at the same time their traditional foods of emergent and submergent plants were declining throughout the Bay. Goose populations continued to increase during the 1970s and 1980s despite liberal hunting regulations for this species. The high-energy food enabled the geese to feed less frequently; thus they were less exposed to hunting pressure than were species constantly searching for food. By maintaining excellent body condition throughout the winter, geese reached nesting areas in northern Canada in good breeding condition. Geese usually improve their breeding condition by feeding at James Bay, Canada, before the final flight north.

Some people are now concerned that increased hunting pressure on the Eastern Shore and abundant food resources in Pennsylvania and New York may result in fewer geese migrating to the Delmarva peninsula. This "shortstopping" phenomenon began during the 1960s and caused reductions in historically large goose populations in the Southeast, especially North Carolina. As long as snow-free corn fields and ice-free water are abundant in northern areas, Canada geese will minimize their southward migration, especially to areas that are heavily hunted.

American Black Duck

The black duck (*Anas rubripes*) has traditionally frequented the eastern coast, and large numbers have been recorded in the Chesapeake Bay (Table 1, Figure 3). The highest number (281,485) of black ducks in the Bay was recorded in 1955 and the lowest (28,820) in 1979. The long-term average population was 84,197 ducks. During the 1980s the population averaged only 51,365 ducks, which was 44% lower than the pre-1980s average of 91,379.

During the 1950s approximately half of the Atlantic Flyway black ducks were recorded in the Chesapeake Bay. During the 1960s and 1970s only one-third were recorded in the Bay, and during the 1980s less than one-fourth of the Atlantic Flyway black ducks wintered in the Chesapeake Bay. Although black duck populations have declined most dramatically in the Chesapeake Bay, declines have been noted in all wintering areas of the Flyway. Surveys now record black ducks most frequently in coastal areas of New Jersey.

During the 1950s, approximately 85% of the Maryland black ducks were recorded in sections of the eastern shore of the Bay, especially the Chester River (Stewart 1962). With the demise of the SAV, black ducks did not have an alternate food source readily available. Most black ducks in the Chesapeake Bay during recent years have been found on freshwater areas

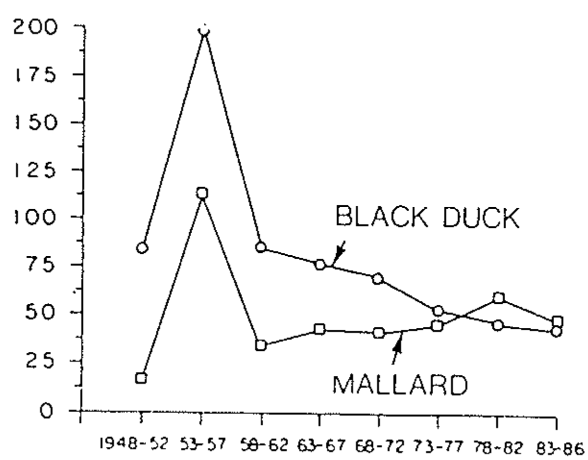

Figure 3. Long-term trends in populations (x1000) of black ducks and mallards in the Chesapeake Bay during eight periods from 1948 through 1986.

of the Patuxent River and tributaries of the York and James Rivers. In these areas, black ducks feed on seeds of smartweeds (*Polygonum* spp.), rice cutgrass (*Leersia oryzoides*), and other marsh plants (Perry and Uhler 1981). Small flocks of black ducks are also recorded throughout the cordgrass (*Spartina alterniflora*) marshes in the brackish areas of the Bay. The salt marsh snail (*Melampus bidentatus*) is their predominant food. Black ducks have also been observed feeding on corn in agricultural areas near the Chester River (V.D. Stotts, pers. comm.).

Mallard

The mallard (*Anas platyrhynchos*) has traditionally been mainly a Mississippi Flyway duck, but populations tend to spill over to other flyways. Mallard population trends in the Bay are similar to those of the black duck (Table 1, Figure 3). Mallard populations in the Chesapeake Bay were lowest in the late 1940s and early 1950s, with a low count (8,235) in 1949. Excellent breeding conditions in the prairie provinces of Canada in the mid-1950s caused populations to rise, and the wintering population in Chesapeake Bay peaked at 182,195 in 1956. Drought conditions in the late 1950s and early 1960s caused populations to decrease and to remain relatively low and stable throughout the 1970s.

In the mid-1970s large numbers of game-farm mallards were released in the Chesapeake Bay, with releases continuing throughout the 1980s. The release program is probably a major reason that mallard numbers in the Chesapeake Bay were 16% higher (57,533) during the 1980s than the pre-1980s average (49,826). Many of these game-farm mallards are found in close association with human activity, and this species appears to adapt to changing environmental conditions more readily than the closely related black duck. Mallards were more numerous than black ducks in the Chesapeake Bay during eight of the last 10 years (1977-1986). The long-term average population of mallards in the Bay was 51,212.

Stewart (1962) found that seeds of smartweeds, bulrushes (*Scirpus* spp.), and burreed (*Sparganium americana*) predominated in the mallard diet in freshwater areas. In brackish areas seeds, leaves, and stems of SAV were more important as food sources. Rawls (1978) found SAV as the predominant food during the 1960s. In the 1970s, however, SAV comprised only 5% of the mallards' diet (Munro and Perry 1981); they relied predominantly on the seeds of over 100 species of marsh plants.

Wigeon

Populations of wigeon (*Anas americana*) in the Chesapeake Bay declined during the years of aerial surveys (Table 1, Figure 4). Populations peaked (144,350) in 1955, most likely because of excellent production in the breeding provinces of Canada. Wigeon numbers declined to a low of only 900 ducks in 1984. The long-term average winter population was 29,246. During the 1980s the winter population has averaged only 5,226 ducks, a figure 85% lower than the pre-1980s average of 34,500. Populations of wigeon have declined faster in the Chesapeake Bay than in the Atlantic Flyway and in North America.

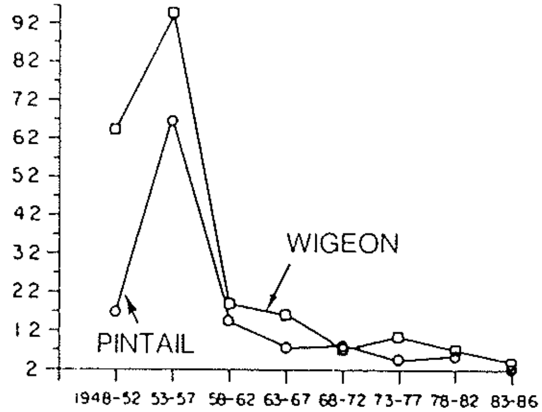

Figure 4. Long-term trends in populations (x1000) of wigeon and pintail in the Chesapeake Bay during eight periods from 1948 through 1986.

Wigeon in the Chesapeake Bay have traditionally been associated with canvasbacks and tundra swans, and usually fed in vegetated areas. During the 1950s, over 80% were recorded along the eastern shore of the Bay (Stewart 1962). Wigeon typically ate the upper vegetated parts of plants that were discarded or dislodged by canvasbacks or other waterfowl, although they also fed on winter buds of wild celery (*Vallisneria americana*) (Stewart 1962). During the 1960s, wigeon fed on the exotic plant eurasian watermilfoil (*Myriophyllum spicatum*) more than any other duck species (Rawls 1978). Because the wigeon was unable to change to alternate food sources as some other species did, wigeon numbers in the Bay declined as the amount of vegetation decreased.

Northern Pintail

The pintail (*Anas acuta*) is mainly a Pacific Flyway duck, although large numbers have been observed in the Chesapeake Bay (Table 1, Figure 4). Population peaked in 1956 at 78,211 but declined to a low of only 400 in 1970. The long-term average number of pintail in the Bay was 16,282. The 1980s average of only 3,935 ducks was 79% lower than the pre-1980s average of 18,982. The average number of pintail in the Atlantic Flyway during the 1980s has been 52,657, and most have been recorded in the Carolinas. Continental pintail populations reached an all-time low in 1986.

The pintail, like the wigeon, was most common in the Bay during periods of good breeding conditions in Canada and excellent winter habitat in the Bay. With the loss of SAV in the Bay, pintail populations have decreased, and it seems that this species has been unable to take advantage of alternate food sources, with one notable exception. Perry and Uhler (1981) found that pintail from the James River had fed on the Asiatic freshwater clam (*Corbicula manilensis*) more than any of the other duck species examined; however, umbrella sedges (*Cyperus* spp.), rice cutgrass, and smartweeds were predominant foods.

Canvasback

The canvasback (*Aythya valisineria*) has traditionally been symbolic of the Chesapeake Bay, and large numbers have wintered in the Bay (Table 1, Figure 5), especially in the Susquehanna Flats area. During the heyday of market hunting the canvasback commanded top price among ducks in the market. It is not known how many canvasbacks once frequented the Bay, but aerial surveys since 1948 showed peak numbers (399,320) in 1954. But canvasback populations plummeted shortly afterwards to a low of 48,120 in 1958.

Populations increased in the mid 1960s as a result of better conditions on the breeding grounds and restrictive hunting regulations (Perry et al. 1981). Canvasback numbers, however, decreased again in the late 1960s, and in 1972 the hunting season on canvasbacks was closed. The long-term average population of canvasbacks in the Chesapeake Bay was

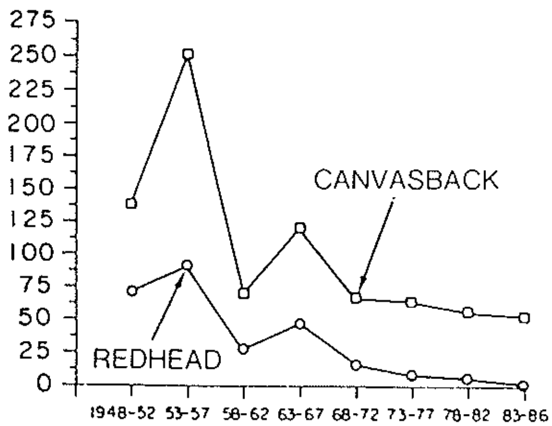

Figure 5. Long-term trends in populations (x1000) of canvasback and redhead in the Chesapeake Bay during eight periods from 1948 through 1986.

104,012; in the 1980s the population has averaged 52,931, or 54% lower than the pre-1980s average of 115,811. In 1986, canvasbacks in the Bay were at an all-time low of 34,300. Canvasback populations in the Bay during the 1970s and 1980s have been relatively stable despite increasing populations in the Atlantic Flyway and North America. This phenomenon led Perry et al. (1981) to speculate that habitat degradation in the Bay was adversely affecting populations of wintering ducks.

When SAV beds in the Bay declined, the canvasback was more successful in seeking alternate food sources than were other duck species. Now Chesapeake Bay canvasbacks feed predominantly on molluscs (Perry et al. 1981); however, these are not considered to be as nutritionally sound as the high-energy plant tubers they formerly ate (Perry et al. 1986).

Redhead

Populations of redheads (*Aythya americana*) in the Chesapeake Bay are on a long-term downward trend (Table 1, Figure 5). Since a peak of 118,800 in 1956, this population has steadily declined to a low of only 800 ducks in 1983. The long-term average was 35,288, but during the 1980s an average of only 3,506 have been recorded in the Bay. This figure is 92% lower than the pre-1980s average of 42,240. Most of these ducks are seen in the Tangier Island area. The Atlantic Flyway's average of 97,914 during the 1980s indicates that population declines in the Chesapeake Bay have been more drastic than in other areas.

Unlike the canvasback, the redhead did not change its food habits as habitat conditions changed. It still feeds on the upper vegetative parts of SAV (Perry et al. 1981). With the loss of SAV in the Bay, redhead populations in the Bay declined, and now redheads are most abundant in North Carolina, Florida, and Texas, where SAV is abundant (Perry and Uhler 1982). Because the redhead is now wintering in different areas than the canvasback, hunting regulations are no longer the same for the two species, as they were historically; they are usually more liberal for the redhead.

Scaup

Scaup populations in the Chesapeake Bay represent two species, the greater (*Aythya marila*) and lesser (*Aythya affinis*) scaup. Populations of scaup (Table 1, Figure 6) in the Bay peaked in 1954 at 403,658 and then declined in the late 1950s. Populations increased in the 1960s and then declined steadily to a low of 10,700 in 1982. The long-term average population was 65,909; in the 1980s, the population has been 61% lower than this level,

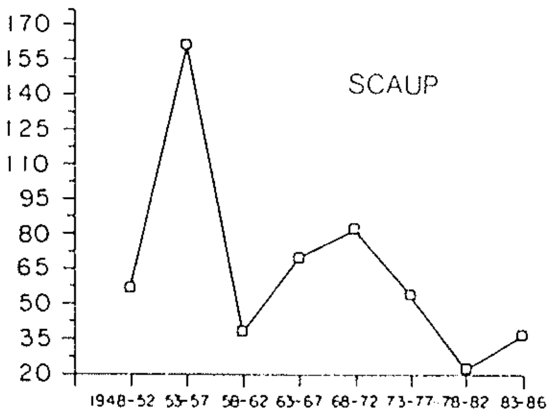

Figure 6. Long-term trends in populations (x1000) of scaup in the Chesapeake Bay during eight periods from 1948 through 1986.

averaging 28,973 ducks. Trends of scaup populations in the Bay have diverged from those in North America and the Atlantic Flyway. For unknown reasons scaup populations in the Bay in the early 1960s did not reflect the record 2.6 million recorded throughout North America.

Historically, scaup have fed on molluscs and crustaceans (Stewart 1962; Munro and Perry 1981), and current food habits indicate similar food preferences. Although the diversity and number of invertebrate food organisms have probably declined because of the loss of SAV in the Bay, it is doubtful that this loss has significantly affected the distribution or abundance of scaup (Perry et al. 1981).

Common Goldeneye

The goldeneye (*Bucephala clangula*) is a hole-nesting duck that breeds in the forested wetlands of southern Canada. Wintering populations in the Chesapeake Bay peaked in 1956 at 40,518 and reached a low in 1976 at 2,445 (Table 1, Figure 7). The long-term average population in the Bay has been 19,658, and in the 1980s the average population in the Bay has been 17,513, which is 13% lower than the pre-1980s average of 20,128. Trends of goldeneye populations in North America and the Atlantic Flyway have been similar during survey years.

Goldeneye feed mainly on invertebrates (Stewart 1962; Munro and Perry 1981); they feed in deep water and usually not in shallow areas where SAV occurs. Thus changes in the distribution and abundance of SAV have probably not affected goldeneye populations. The amount of vegetation eaten by goldeneye has declined, however, during the hundred years in which food habits analyses have been conducted.

Bufflehead

Although the bufflehead (*Bucephala albeola*) and goldeneye both breed and winter in similar habitat, their wintering population trends are different (Table 1, Figure 7). Bufflehead numbers have been steadily increasing from a low of 2,502 in 1959 to a peak of 36,023 in 1977. The long-term average population was 14,813. During the 1980s the average population has been 16,840 ducks, which was 17% higher than the pre-1980s average of 14,444. Population trends in the Chesapeake Bay have been similar to those in the Atlantic Flyway and in North America for the bufflehead.

The bufflehead has traditionally fed on invertebrates, although vegetation has formed a more important part of its diet in the past than it does now. During the 1970s the predominant food of buffleheads was the duck clam, *Mulina lateralis* (Munro and Perry 1981).

Ruddy Duck

The ruddy duck (*Oxyura jamaicensis*) has shown a significant decline in numbers in the Chesapeake Bay during years of aerial surveys (Table 1, Figure 8). Populations peaked at 124,740 in 1953 and declined to a low of 4,703 in 1976. The long-term population average for the Bay was 33,642. The 1980s average of 15,729 was 58% less than the pre-1980s average of 37,560. Trends of ruddy duck populations in the Bay have differed from those in the Atlantic Flyway and North America. Highest numbers of ruddy ducks in the Atlantic Flyway are recorded in North Carolina.

Although the ruddy duck was traditionally a vegetative feeder (Cottam 1939), it now feeds to a greater extent on invertebrates (Perry et al. 1981). Increasing numbers of ruddy ducks are recorded around

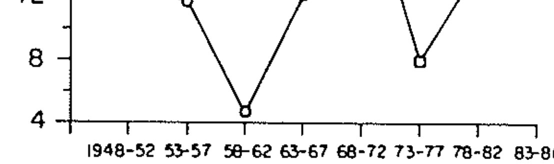

Figure 7. Long-term trends in populations (x1000) of goldeneye and bufflehead in the Chesapeake Bay during eight periods from 1948 through 1986.

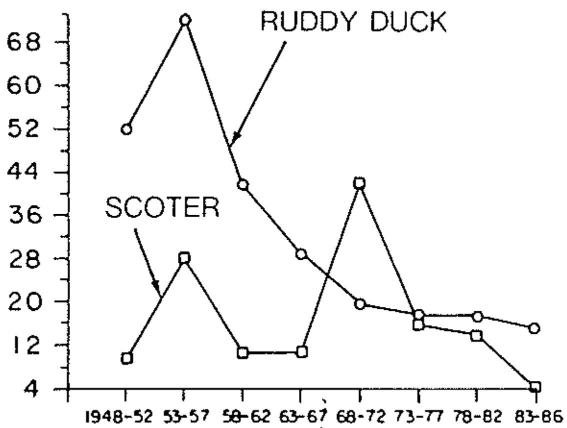

Figure 8. Long-term trends in population (x1000) of ruddy duck and scoter in the Chesapeake Bay during eight periods from 1948 through 1986.

cities like Baltimore and Washington, D.C. (Wilds 1979), where they are probably feeding on tubificid worms (Tubificidae) (Stark 1978).

Scoter

Populations of scoter (*Melanitta* spp.) in the Chesapeake Bay have been variable (Table 1, Figure 8). Populations peaked in 1971 at 130,900 and then reached a low of 1,551 in 1981. The long-term average was 16,760, and the average in the 1980s has been 6,565, or 65% lower than the pre-1980s average of 18,990. The average Atlantic Flyway scoter population during the 1980s was 57,386.

Scoters are traditionally invertebrate feeders (Cottam 1939; Martin et al. 1951), although no record of their food habits in the bay has been made by Stewart (1962), Rawls (1978), or Munro and Perry (1981). Changes in their distribution within the Bay may be due to changing food resources, and should be investigated.

SUMMARY

Overall the long-term average of Chesapeake Bay waterfowl during January has been 1 million birds. During the 1980s, despite a stable average of 1 million, there were major changes in species composition. For example, Canada goose populations during the 1980s were 75% higher than the average population before 1980. This increase is directly related to their ability to utilize the abundant field crop resources (mainly corn) on the Eastern Shore.

Among the ducks, only the mallard and bufflehead populations during the 1980s were higher than their average populations during the 32-year period of 1948-1979. All other species of ducks have shown significant declines, which seem to be directly related to the degradation of waterfowl habitat in the Chesapeake Bay. Duck populations in the Bay can be expected to remain at low levels until SAV beds recover in the Bay and production improves on the breeding areas.

ACKNOWLEDGEMENTS

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Status and Trends of the Patuxent River

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BASIN CHARACTERISTICS

The Patuxent (Figure 1) is the largest intrastate river in Maryland (Maryland Environmental Service 1974). It originates on Paris Ridge at the junction of Howard, Montgomery, and Carroll Counties and flows south-southeasterly for 175 km (110 miles) to its confluence with the Chesapeake Bay at Solomons. The mainstream of the Patuxent River forms a boundary between Howard, Anne Arundel, and Calvert Counties on the north and east and Montgomery, Prince George's, Charles, and St. Mary's Counties on the south and west.

The area of the Patuxent watershed is approximately 2,230 km^2 (900 square miles). The largest tributary in the basin is the Little Patuxent River, which joins the mainstream at Bowie. Approximately 27% of the land is agricultural, 29% urban, and 44% forested. Land-use trends from 1930 to 1980 are summarized in Table 1. In general, there has been a decrease in agricultural land (which has been characteristic of the state), an increase in urban and residential lands, and almost no change in the percentage of forested areas.

In concert with land-use changes in the basin there have been substantial population changes as well. Population grew slowly from 1900 (pop. 27,000) through 1940 (pop. 37,000); however, population reached 134,000 in 1960 and 260,000 in 1970 (Water Resources Administration 1977; Wolman et al. 1961).

The climate of the Patuxent River watershed is predominantly continental, with short cold winters and long warm summers. There are approximately 180 frost-free days per year. The median annual precipitation in the Basin is about 110 cm per year (Water Resources Administration 1977). Rainfall is higher and more intense in the summer than in other seasons because of frequent local thunderstorms.

Approximately 30% of the precipitation is discharged from the basin as streamflow. Although some of the sub-basins of the Patuxent are in predominantly piedmont areas while others are in the coastal plain, the percentage of rainfall discharged as runoff is fairly constant, averaging about 30% for each sub-basin. Average riverflow above tidal influence, at Hardesty (river mile 52) is about 238 cubic feet/second (USGS 1976). On the mainstem of the river at Laurel, there are two reservoirs (Tridelphia and T. H. Duckett Reservoirs) with a combined capacity of 13.4 billion gallons and a yield of about 65 million gallons per day. Some of this water is exported from the basin for use by the Washington Suburban Sanitary Commission, which serves approximately 1.3 million people in the metropolitan Washington area (Water Resources Administration 1977). The WSSC withdrawal represents about 10% of the total freshwater runoff in the basin if an average runoff rate of 0.85 cubic foot/second per square mile is assumed.

The Patuxent watershed spans two distinct physiographic regions. The upper 25% (or the headwater region) lies in the piedmont plateau entirely within Howard and Montgomery Counties. It extends from the Frederick County line to the fall line that crosses the mainstem of the Patuxent River at Laurel and the Little Patuxent River at Savage. In this headwater area the land is primarily used for urban and agricultural purposes. The two reservoirs (Tridelphia and T. H. Duckett) are located in the headwater region

NOTE. This report is University of Maryland UMCEES reference no. 87-25.

and, for water-quality reasons, are protected from point-source dumping of wastewater from the suburban regions. Most of the wastewater generated in this region is intercepted and carried downstream to plants located in the central region. Consequently, point sources of sewage pollution are not a major problem in the headwater region. Non-point sources of pollution, mostly due to urban expansion, agricultural operations, and highway and sewer development (often in the flood plain) have led to problems with sedimentation and storm-water runoff. One of the major reasons for the severity of the sediment problem is that the main soil association in the region is highly erodible when cleared for agricultural and urban usage (Maryland Environmental Service 1974). The direct effect of this runoff in the early 1970s was documented by Roberts and Pierce (1976).

The middle region of the watershed, starting from the Laurel-Savage areas, is located in the coastal plain and extends to the mouth of the Patuxent at Solomons. This reach of the river is characterized by broad, flat, low-lying, swampy flood plains of the river and its tributaries. The flood plain provides a continuous corridor of swamps and marshes, usually bordered by upland forests. A segment of this area is relatively inaccessible and has been designated as a state scenic river area. The river here is slow and sluggish, relatively narrow (50-75 ft), and shallow. Because of the reduced flow of the Patuxent River below T. H. Duckett Reservoir and the wastewater effluents discharged in this area, water quality has declined (Tsai 1968, 1970).

The lower part of the watershed drains into a tidal estuary. Beginning in the vicinity of Spy Glass Island, 3.2 km above Wayson's Corner, the Patuxent enters an area of unforested marshes that appear to be the result of extensive siltation from upstream agricultural operations and urban development. The

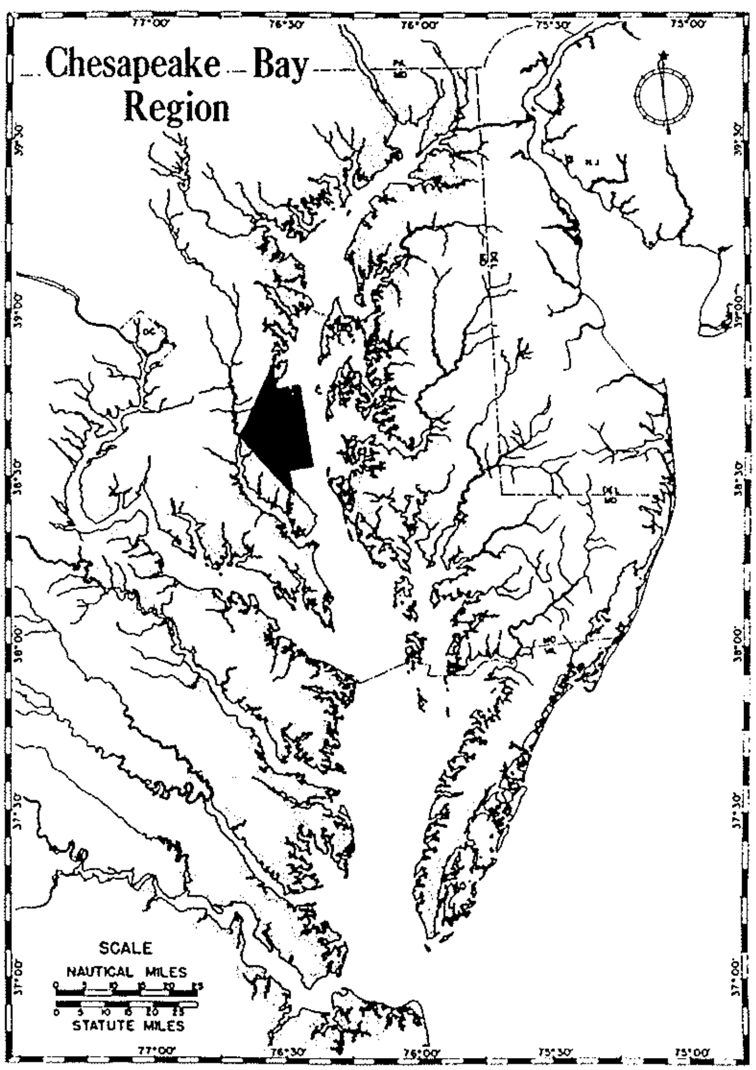

Figure 1. Location (arrow) of Patuxent watershed.

Table 1. Estimated land use in the Patuxent River Basin.

Type of area	Percentage in use				
	1930	1953	1969	1973*	1980+
Forests	40	42	40	41	44
Fields and meadows	50	43	37	36.5	27
Urban and residential	10	15	23	15.8	29
Water	--	--	--	5.7	--
Marshes	--	--	--	1.0	--

NOTE. Estimates for 1930, 1953, and 1969 from Roberts and Pierce (1976); original data for 1930 and 1953 from Federal Water Pollution Control Administration (1967, p. III-2); estimates for 1973 from Unger et al. (1978).

*There was not an actual reduction in urban and residential acreages between 1969 and 1973. Because of different measurement systems, 1973 data are not directly comparable with earlier data. We currently believe that the differences between these estimates are based more on measurement technique than on reality (Mihursky and Boynton 1978).

+Estimated land use patterns projected by The Johns Hopkins University (1966).

marshes provide an ideal habitat for nesting, feeding, and reproduction of waterfowl. Eagles, ospreys, king-rails, sora, mink, muskrat, and otter are also found here.

Beginning at Deep Landing (river mile 24) the Patuxent estuary gradually widens and deepens into a saline arm of the Chesapeake Bay. The marshes are replaced by bluffs, often over 20 ft high, with sandy shores and rolling hinterlands. The estuary has long supported a commercial harvest of oysters, crabs, clams, and finfish (including shad, herring, white perch, spot, and striped bass). Below the Benedict Bridge (river mile 20) the estuary continues to broaden and is characterized by a two-layer circulation pattern; however, at times the mouth of the estuary in the Solomons vicinity exhibits a three-layered circulation pattern (Owens 1969). In this lower area of the estuary, the water is generally much clearer than above the Benedict Bridge and is affected by water-quality parameters characteristic of the mainstem of Chesapeake Bay.

The Patuxent estuary ranks sixth in volume (7.57×10^8 m^3), second in mean depth (5.37 m), and seventh in surface area (1.41×10^8 m^2) among the 12 primary tributaries to the Chesapeake Bay.

WATER QUALITY TRENDS

In 1964 the U. S. Congress passed the Federal Water Pollution Control Act, requiring that states establish water-quality standards for interstate waters in order to qualify for federal financial aid in the construction of wastewater treatment facilities. This action accelerated activity in Maryland and focused attention on the Patuxent system.

The fortuitous establishment of the Chesapeake Biological Laboratory at the mouth of the Patuxent estuary in 1925 resulted in the establishment of a relatively long-term data base on the estuarine system. Water-quality parameters have been the most studied aspect of the Patuxent system, with data published from periodic investigations since the 1930s.

The spatial coverage of measurements extends, for some parameters, from the headwaters to the mouth of the estuary. Occasionally, vertical measurements have been made in the estuarine portion of the system. To date, more than 30 in-depth studies have been identified.

As with most aspects of the Patuxent system, comparison between studies has been difficult because station locations, sampling intensity, techniques, parameters measured, etc., have varied depending on the goals of the individual studies. Considerable year-to-year variations in concentrations have further restricted comparisons.

However, over the years certain trends in key water-quality characteristics began to emerge. Realization of these trends and their implications for estuarine living resources, aesthetics, and recreation resulted in substantial public, media, and legislative involvement. Court suits called attention especially to expanding sewage treatment capacity in the watershed and the problem of over-enrichment (eutrophication) from excess nutrients (nitrogen and phosphorus) due to discharge of treated sewage water.

D'Elia and Boynton (1982) provided a summary of annual river flow and total annual nitrogen and

Table 2. Summary of annual average river flow (cubic feet/second) and total annual nitrogen and phosphorus loading (10^3 kg/year) to the Patuxent River estuary.

		Nutrient loading*	
Year	River flow	Total nitrogen	Total phosphorus
1964	-	-	-
1965	70.6	231	82
1966	25.6	107	43
1967	135.6	388	127
1969	45.2	164	61
1970	192.4	516	155
1971	531.3	1215	294
1972	772.2	1682	372
1973	442.2	1038	262
1974	199.3	531	157
1975	481.8	1117	276
1976	279.8	704	196
1977	122.1	357	115
1978	453.0	1059	264
1979	745.0	1630	364

NOTE. Average annual river flow data from U.S. Geological Survey (1966-1981) gaging station at Laurel, Md., adjusted to Bowie, Md.

*Nutrient loading calculated from Guide and Villa (1972) on the basis of statistical relationships between river flow and nutrient concentration. These data represent fluxes past Bowie, Md. (river mile 60).

phosphorus loadings to the Patuxent estuary for 1965 through 1979 (Table 2). The values reflected nutrient increases from increased discharge of treated wastewater as well as non-point contributions from changed land-use patterns. Differences between wet and dry years were also apparent. In general the trends reflected increasing discharges of nutrients to the estuary coincident with urbanization in the non-tidal segment of the watershed.

Gradually, the Patuxent became recognized as a model subsystem of the Chesapeake as a whole, eventually serving to reinforce EPA's findings and recommendations on the Bay.

The following discussions and graphics, extracted from a large body of information, focus on some long-term data bases and trends that relate to water-quality parameters of most concern because of their linkage to ecologically damaging consequences.

Phosphorus

Two phosphorus fractions are commonly reported: dissolved inorganic phosphorus (DIP) and total phosphorus (TP). Since the earliest and longest record exists for DIP, we trace only this nutrient value over time. Figure 2 (top) provides data from the Solomons-Broomes Island area from 1939 (Newcombe and Brust 1940); from 1963-1964 (Herman, Mihursky, and McErlean 1968); and from 1969 (Flemer et al. 1970). This station is near the estuary mouth and, as is typical of other estuary reaches, has shown increasing levels of DIP over the years.

Nitrogen

Of the nitrogen fractions (nitrate, nitrite, ammonia, dissolved organic nitrogen, total Kjeldahl nitrogen, and particulate nitrogen) that are currently routinely measured, only nitrate was measured in the Patuxent before the initiation of major sewage-treatment plant operations (Nash 1947). Figure 2 (bottom) shows dissolved inorganic nitrogen values for Lower Marlboro, a station in the oligohaline (low-salinity) reach of the Patuxent. Data are from the same sources as for phosphorus. There is a clear seasonal pattern of nitrate concentrations, with high values throughout the estuary in winter and low values in summer and fall. Nitrate patterns tend to be strongly correlated with river flows. There appears to have been a major increase in nitrate levels after 1936 and after 1963, especially in winter periods. At Lower Marlboro winter values in 1970 were 8 times those reported in 1963 and 20 times greater than those reported in 1936.

Chlorophyll

Chlorophyll values, which are a measurement of the standing stock of microscopic plant life (phytoplankton) in the estuary, have increased over the years of study. Figure 3 shows chlorophyll levels at the Benedict Bridge station, at the lower end of the turbidity maximum region and in the mesohaline segment of the estuary. "Greening" of the estuary became apparent in the 1970s; this phenomenon results when phytoplankton growth is stimulated by increased levels of plant fertilizers (nitrates and phosphates).

Water Clarity

Sediment due to development practices and farming activity is deposited in all tidal estuaries of the Bay. Sedimentation rates for the Patuxent have been published by numerous authors (Table 3).

Discharge values can vary because of differences in rainfall and runoff from year to year as well as changes in land use. Accumulation rates can also vary with the same factors. The difference between 1969 values reported by Roberts and Pierce (1976) and those reported by Keefe et al. (1976) undoubtedly reflects a difference of methodology.

The importance of these values is that when soil is lost from land to the estuary, it is deposited and resuspended by hydraulic and atmospheric conditions such as tides and winds, causing a so-called "browning" of the estuary.

The browning and greening of the Patuxent results in reduced light penetration into the water column and decreased water clarity. This phenomenon is reflected in Figure 4. Secchi-disk values indicate the water depth at which a lowered white disk disappears. Comparisons of Secchi-disk depths from 1936-1939 with those from 1968-1970 suggest a decrease in water clarity over time.

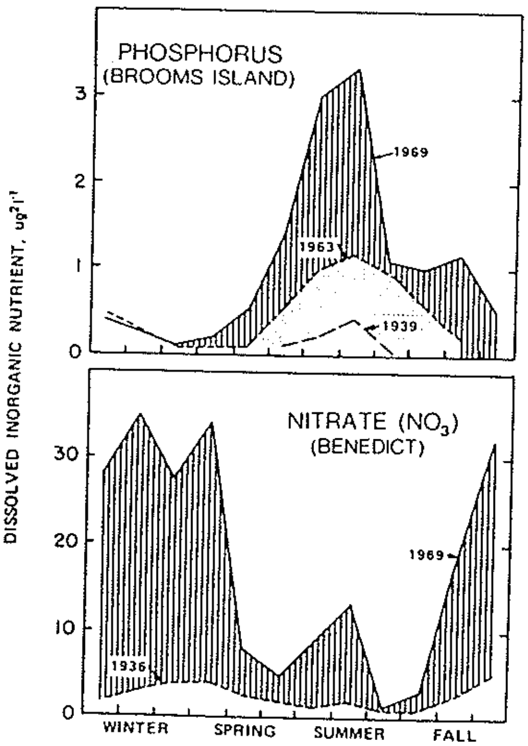

Figure 2. Historical trends in Patuxent River concentrations of phosphorus (top) and nitrate (bottom).

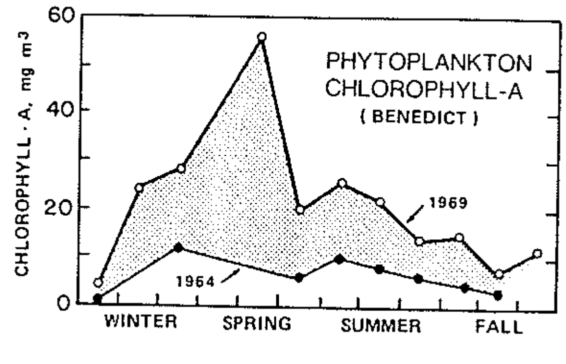

Figure 3. Chlorophyll values at Benedict Bridge station in 1964 and 1969.

Dissolved Oxygen

Nash (1947) reported seasonal dissolved oxygen (DO) concentrations for the Solomons area in the late

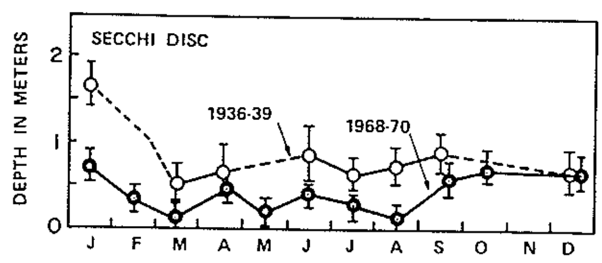

Figure 4. Secchi disk values in the turbidity maxium zone (25-65 km) of the Patuxent estuary for 1936-1939 and 1968-1970.

Table 3. Estimates of sedimentation rates in the Patuxent River estuary.

Period	Discharge (metric tons)	Accumulation rate (mm/yr)	Reference
1859-1944	2800 x 10^5	27	John Hopkins Univ. 1966
1860-1960	---	5-10	Roberts and Pierce 1976
1966	1.7 x 10^5	1.2	Johns Hopkins Univ. 1966
1972*	5.1 x 10^5	36	Fox 1975
1969	2.2 x 10^5	37	Roberts and Pierce 1976
1969	0.2 x 10^5	--	Keefe et al. 1976
1970	0.3 x 10	--	Keefe et al. 1976

*Estimates for 1972 after tropical storm Agnes.

1930s and mid-1940s. Surface and bottom (17 m) oxygen concentration were similar from January through March and from October through December, ranging between 8.5 and 12.2 mg/liter. During the remainder of the year, surface and bottom DO concentrations were quite different, with bottom DO concentrations being considerably lower (Figure 5). DO concentration in surface waters ranged between 90% and 110% saturation throughout the study period, but DO concentrations in the bottom water did not exceed 100% saturation except briefly in October. Summer values were low and reached a minimum (35%) in June. Nash (1947) suggested that the oxygen minima may have occurred in June rather than at the temperature maxima (August) because vertical stability was greater in June than in August. Data organized by D. Heinle (pers. comm.)[1] indicated that deep waters near the mouth of the Patuxent were occasionally hypoxic or anoxic in the period 1938-1948. However, except for two measurements, DO concentrations in deep waters above Broomes Island were >3 ppm. Thus, early records suggest generally saturated conditions in the surface and bottom waters through fall and winter. Surface waters in the summer were also near saturation. Low DO concentrations were characteristic of deep waters near the mouth of the estuary, probably because of inflows of oxygen-poor water from Chesapeake Bay. Deep waters in the middle reaches of the estuary generally had DO concentrations >3 ppm.

Seasonally, DO was highest (15 ppm) in the late winter and lowest (4 ppm) in the summer. Weekly average percentage saturation was lowest (60%) in August and September. The annual range in percentage saturation varied from 53%-114% in 1964 and 1965 to 55%-152% in 1966 and 1967. There was considerably less annual variation in percentage saturation of surface waters in the Solomons area (Nash 1947).

Cory (1974) also reported DO data for the period 1964 and 1969 at the Benedict Bridge station. DO ranged from 3.6 to 15 mg/liter in 1964 and from 2.3 to 16.5 mg/liter in 1969. Percentage saturation varied from 60% to 130% and from 30% to 184% in 1964 and 1969, respectively. Finally, the magnitude of the diel oxygen variation in the summer changed from about 3 mg/liter-day in 1964 to 7 mg/liter-day in 1969. Cory suggested that the increased seasonal and

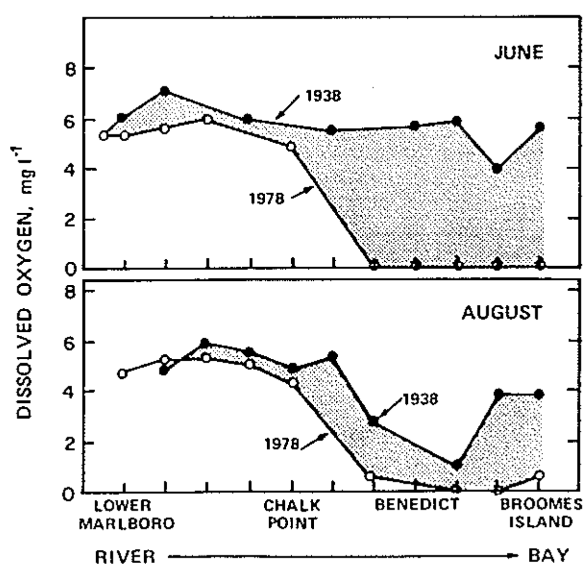

Figure 5. Minimum dissolved oxygen values (bottom waters) in June and August of 1938 and 1978.

[1] Unreported data originally collected by C. L. Newcombe; part of CBL files.

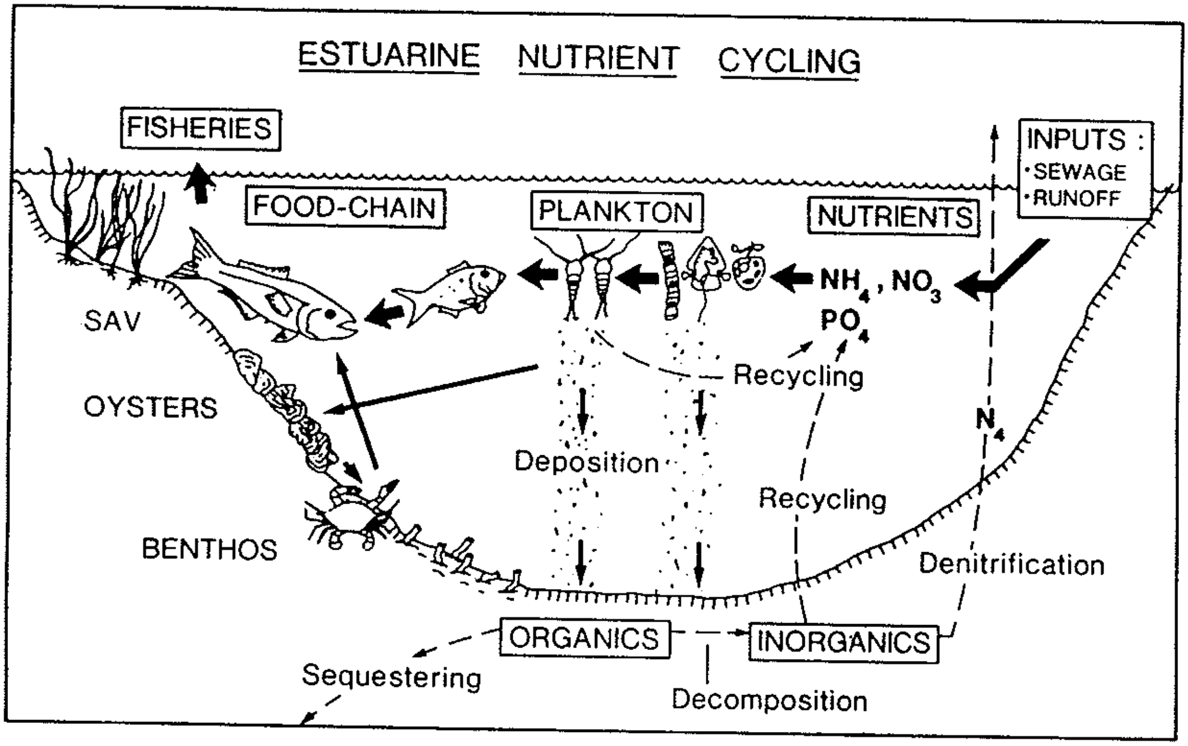

Figure 6. Schematic of estuarine nutrient cycling.

diel ranges in DO were due to increased upstream loading of domestic waste.

Flemer et al. (1970) summarized several annual cycles of dissolved oxygen data (expressed as percentage saturation) for Patuxent surface waters. In general, surface waters in 1968-1970 were supersaturated at Queentree Landing (river mile 13). Above Lower Marlboro (river mile 28) saturation values were generally <100%, with the lowest values in the late summer. At stations upriver of Jug Bay (river mile 37), saturation values >75% were observed only during the winter months. The low values observed as far downstream as Trueman Point in July 1969 were associated with heavy rainfall.

The emerging patterns of dissolved oxygen values (see Figure 5) in the Patuxent tend to support two conclusions. First, differences in day and night oxygen values over time reveal greater values of supersaturation in the daylight hours and increasingly lower saturation values at night. Such values reflect a classic pattern of increased phytoplankton growth and daytime photosynthesis and night-time respiration due to nutrient enrichment.

Second, the apparent increase in extent of hypoxia and anoxia in the lower and deeper portions of the estuary over time suggests a probable process of increased nutrients stimulating increased production of algal biomass that is unused by filter-feeding organisms (zooplankton, shellfish, and fish grazers). This unused plant biomass is decomposed eventually by microbial activity, which in turn consumes and helps deplete oxygen. This sequence of biological events also results in production of remineralized nutrients, with subsequent or sporadic release of nitrogen and phosphorus into the water column. This remineralization in turn can stimulate algal growth, restarting a cycle that has been termed a positive-feedback loop, which is believed typical of the entire Bay ecosystem (Figure 6).

FUTURE DIRECTIONS

As a result of the Governor's conference and signed state and federal agreements of 1983, a Bay clean-up and monitoring program has been put in place. The Patuxent has been singled out by Governor Harold Hughes as a model subecosystem of the Bay and is scheduled for special research, management, and monitoring.

The Patuxent was chosen for this effort because it has a long-term data base, it is wholly within Maryland and therefore easily regulated by the state, and in a fair measure it reflects the Bay system as a whole. Thus learning, successful regulation, management, and experimentation on the Patuxent are cost-effective and transferable to the main body of the Bay.

Major plans include a commitment to nitrogen control as well as the traditional nutrient, phosphorus. Also, a long-term research program is aimed at developing a usable physical, three-dimensional time-variable hydrodynamic model of the estuary. This physical model in turn is to be linked to an ongoing effort in water-quality modeling. It is hoped that these physical and water quality models can be used to help explain the activities, cycles, and dynamics of biological systems of the estuary. Once the operant techniques are successfully mastered, the models can be run to predict outcomes of proposed management strategies and specific actions.

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