# CHARACTERIZING CHESAPEAKE BAY -

# A DOCUMENTATION OF ENVIRONMENTAL CHANGE

Gail B. Mackiernan
Willa Nehlsen[1]
David A. Flemer[2]
Virginia K. Tippie

U.S. Environmental Protection Agency
Chesapeake Bay Program
839 Bestgate Road
Annapolis, MD 21401
U.S.A.

[1]present address:
CREST
P.O. Box 175
Astoria, OR 97103
USA

[2]present address:
ORD, DEPER (RD682)
U.S. EPA
401 M. St. SW
Washington, DC 20400
USA

903R83103

# CHARACTERIZING CHESAPEAKE BAY - A DOCUMENTATION OF ENVIRONMENTAL CHANGE

Gail B. Mackiernan
Willa Nehlsen[1]
David A. Flemer[2]
Virginia K. Tippie

U.S. Environmental Protection Agency
Chesapeake Bay Program
839 Bestgate Road
Annapolis, MD 21401
U.S.A.

[1]present address:
CREST
P.O. Box 175
Astoria, OR 97103
USA

[2]present address:
ORD, DEPER (RD682)
U.S. EPA
401 M. St. SW
Washington, DC 20400
USA

Library
U. S. Environmental Protection Agency
Region III
Central Regional Laboratory
839 Bestgate Road
Annapolis, Maryland 21401

CB 00180

QH 545.W3 C44

# ABSTRACT

This paper is a summary of the U.S. EPA's report, Chesapeake Bay - A Profile of Environmental Change (Flemer, et al. 1983). This document provides an evaluation of the present environmental health of the estuary and how it has changed in recent years. Historical information from past Bay research and monitoring, as well as results of EPA-supported studies, was collected in a comprehensive database. These data were used to assess trends in a number of physical and biological parameters. Potential relationships between observed trends in environmental quality and resources were identified and evaluated.

Major findings of the characterization effort include:

- Increase in concentrations of nitrogen and phosphorus, particularly in the upper Bay and upper reaches of tributaries.
- Increase in volume of low dissolved oxygen water in summer.
- Elevated levels of toxicants in sediments and water, particularly in the upper Bay and near urbanized areas.
- Loss of submerged aquatic vegetation (SAV) in areas of the Bay characterized by increasing levels of nutrient enrichment.
- Significant declines in landings and spawning success of freshwater spawning fish.
- Significant declines in oyster spat set, especially in the upper Bay and western shore.
- Reduced diversity and abundance of benthos in areas impacted by sediment toxicity or low dissolved oxygen.
- Ranking of Bay regions by environmental quality status shows that the upper main Bay, upper reaches of tributaries, and areas near urban sources show similar patterns of toxic and nutrient enrichment.

Although unequivocal "cause-and-effect" between trends in environmental quality and living resources could not be demonstrated, there is a correspondence of observed patterns. Also, a number of analyses support reasonable potential hypotheses as to effects of environmental change. The inference is that at least some trends in SAV, shellfish, and anadromous fish reflect the integrated response to anthropogenic intervention in the Chesapeake Bay ecosystem.

# CHARACTERIZING CHESAPEAKE BAY - A DOCUMENTATION OF ENVIRONMENTAL CHANGE

## INTRODUCTION

The Chesapeake Bay Program (CBP) characterization report, Chesapeake Bay: A Profile of Environmental Change, describes trends in water and sediment quality, and in the living resources of the estuary (Flemer et al. 1983). Historical information from past research and monitoring efforts was used to assess changes as well as present status for a number of physical and biological parameters. In addition, potential relationships between the observed trends in water quality and resources were identified and evaluated. Findings of the CBP's research program were integrated with historical trends data for this assessment.

In part, CBP's characterization of Chesapeake Bay is based on a ranking of specific areas, or segments, of the Bay in regard to selected water quality variables, as well as the diversity and abundance of their living components. The water quality parameters evaluated include nutrients, dissolved oxygen, chlorophyll a, organic chemical compounds, and heavy metals. The living resources which were assessed include phytoplankton, submerged aquatic vegetation, benthic organisms (including shellfish), and finfish. Each segment's relative status was established in accordance with CBP's principal scientific findings, which are as follows:

- Levels of nutrients (primarily nitrogen and phosphorus) show increasing trends in many areas of the Bay. Nutrient enrichment is most severe in the northern and middle Bay and upper reaches of tributaries. Only parts of the Potomac, James, and some smaller areas currently exhibit improving water quality with regard to nutrients. Concentrations of chlorophyll a are also increasing in most regions where sufficient data is available for assessment.

- The amount of Bay water showing low (or no) dissolved oxygen in summer is estimated to have increased 15-fold in the last 30 years. Currently, much of the water deeper than 40 feet is anoxic from early mid-May through September in an area reaching from the Annapolis Bay Bridge to the Rappahannock River.

- Elevated levels of heavy metals and toxic organic compounds are found in Bay water and sediments. Highest concentrations occur near urban or industrialized areas, and in the upper Bay. Some of these toxicants are being bioconcentrated by plankton, shellfish, and finfish.

- Oyster spat set has declined significantly in the past 10 years, particularly in the upper Bay, western tributaries, and some Eastern Shore areas such as the Chester River. Trends in oyster harvest show a similar pattern.

- Landings of freshwater-spawning fish, such as shad, alewife, and striped bass, have decreased in recent years. Spawning success of these and other semi-anadromous or anadromous species has also been fair to poor in most areas sampled. Harvests of marine-spawning fish, such as menhaden, have generally remained stable or increased.

- The recent loss of submerged aquatic vegetation (SAV) appears related to increasing nutrient enrichment: enhanced phytoplankton growth and epiphytic fouling of plants has reduced the light reaching SAV below critical levels. Increased turbidity from sediment loads may also be contributing to light limitation in some areas. Toxicants such as herbicides seem to be a problem primarily in local areas close to sources.

- Reduced diversity and abundance of benthic organisms can be related to toxic contamination of sediments in heavily impacted areas. Low dissolved oxygen in summer is another major factor limiting benthic populations, including shellfish, in the upper and mid-Bay. Low dissolved oxygen also can be expected to reduce available habitat for finfish, particularly demersal species.

- Declining water quality -- nutrient enrichment and increased levels of toxicants -- is occurring in major spawning and nursery areas for freshwater-spawning fish, as well as in areas experiencing reduced oyster spat set.

- Ranking Bay regions based on water and sediment quality status indicates that the upper and mid-Bay mainstem, tidal-fresh and transition reaches of major tributaries, and many smaller tributaries contain moderate to high levels of nutrients. The pattern of toxic substances is generally similar, although high contamination is also found near urban and industrialized areas in the lower Bay.

## CURRENT CONDITIONS AND TRENDS IN WATER AND SEDIMENT QUALITY

The quality of the Bay's water and sediments reflects both its natural physical and chemical characteristics, and the impact of man's activities. Over 150 tributaries - large and small - drain the 64,000 square mile watershed. Along with freshwater, the rivers bring other materials into the Bay: nutrients, sediments, and toxic substances. Although the Bay has the ability to assimilate some of this material, we now know that most remains within the estuary (Bieri et al. 1982, Smullen et al. 1982). Man's activities have greatly

contributed to the inputs of nutrients and sediment into Chesapeake Bay, in addition to the variety of synthetic chemicals, heavy metals, and other potential toxicants from anthropogenic sources.

Chesapeake Bay has changed greatly since the time of the first settlers (Figure 1). For example, in the last 400 years, human population in the upper Bay watershed alone has increased to nearly four million. Forests have been replaced by fields and developed areas. Many of these observed changes, and their consequences, were well underway by the 1850's (Brush and Davis 1982). Sedimentation rate, due primarily to land clearing, has accelerated since the civil war (Brush and Davis 1982). The estuary is also more "flashy" - that is, peak runoff flow is higher and low flow is lower than in the past (i.e., pre-1800) (Biggs 1981). This is due to loss of forest, which tends to adsorb rainfall and release runoff water more slowly than cleared fields, roads, and other modified areas. The delivery of nutrients to the Bay has become greater, reflecting increases in runoff containing suspended sediment and fertilizers, as well as the addition of sewage effluents (Heinle et al. 1980, D'Elia 1982). The amount of toxic materials - heavy metals and organic chemicals - has similarly increased as industrialization has progressed (Helz et al. 1981). Many of these changes occurred before the first scientific surveys of the Bay in the later 1930's. For that reason, it is sometimes difficult to show strong recent trends, as the bulk of the change in the Bay environment had already taken place before any water quality data were collected.

## Nutrient Enrichment

Nutrients, such as nitrogen and phosphorus, are essential for plant growth, and thus for primary productivity in the estuary. However, in excess these nutrients can cause problems, including blooms of undesirable algae, reduction in dissolved oxygen, and decreased water clarity. Based on data collected between 1950 and 1980, the CBP characterization effort determined that most areas of Chesapeake Bay are experiencing increased nutrient concentrations. Figure 2 summarizes the current nutrient status of the estuary: the northern Bay and upper portions of tributaries presently have relatively high nutrient concentrations, the mid-Bay, lower portions of tributaries, and eastern embayments have moderate concentrations of nutrients, while while the lower Bay (where sufficient data exists) appears not enriched. When trends from 1950 to 1980 are analyzed, they indicate that in most areas water quality is degrading - that is, nutrient levels are increasing. Total nitrogen concentrations are declining in the Patapsco, lower Potomac and upper James, while total phosphorus concentrations are

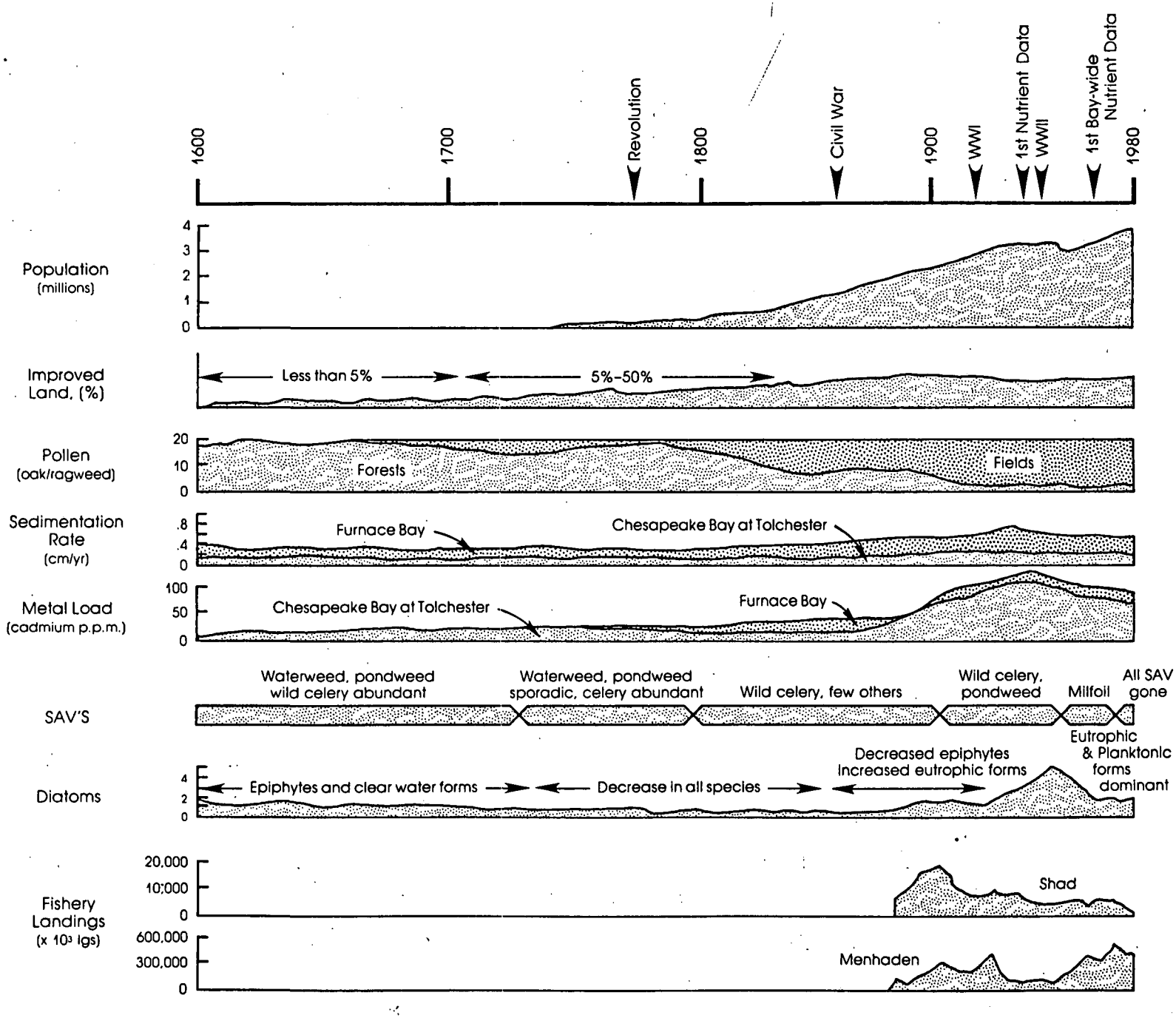


FIGURE 1. TIME HISTORY OF NORTHERN CHESAPEAKE BAY, 1600 to 1980. An important aspect of understanding how Chesapeake Bay will respond to pollution is to examine the Bay's past. In the northern Bay, human activity, beginning at the top of the chart with population growth, has been changing water quality since the time line began (see Appendix A for further discussion).

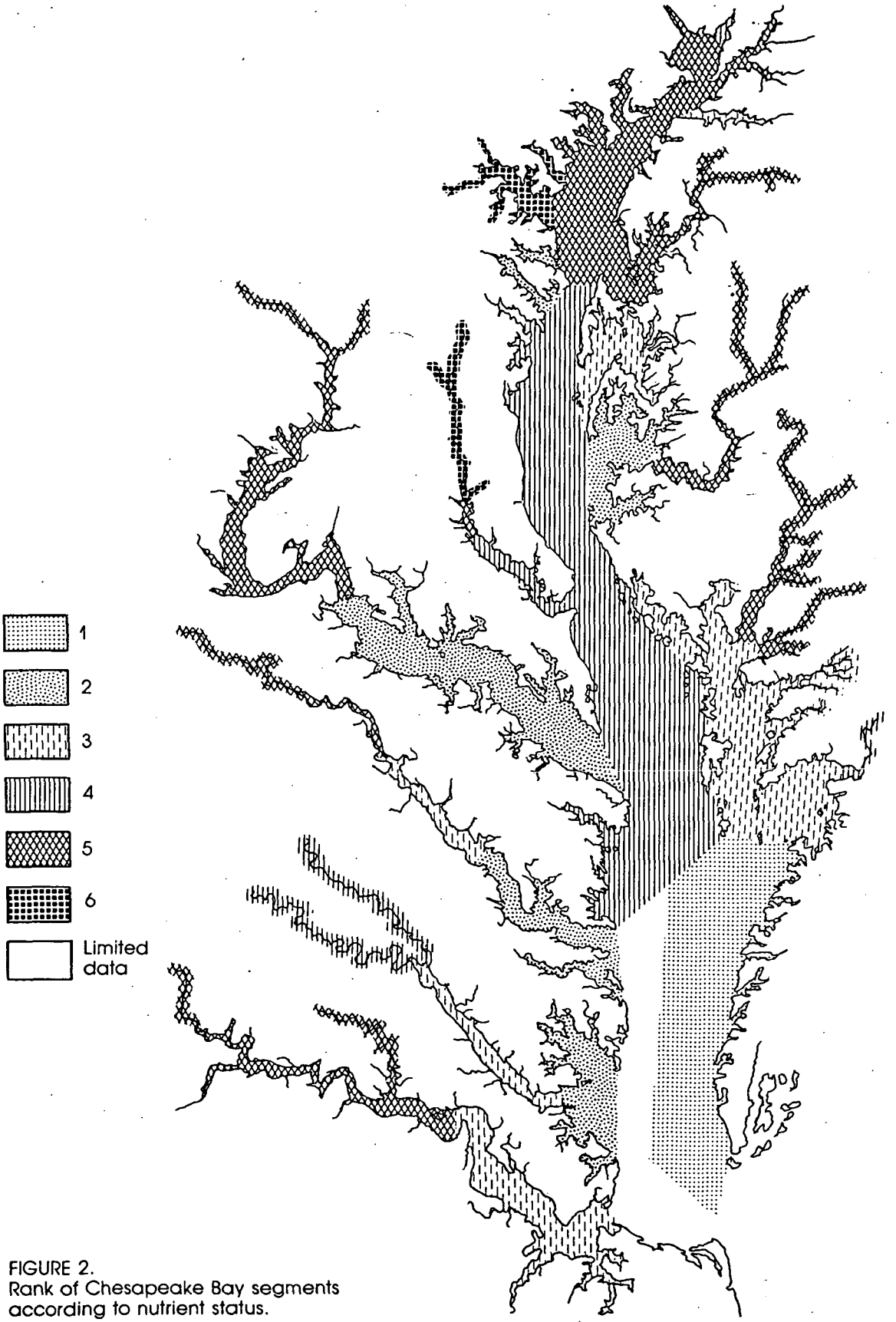


FIGURE 2.
Rank of Chesapeake Bay segments according to nutrient status.

declining in the upper Potomac and throughout the James. Elsewhere, trends are increasing (or stable) for most forms of nutrients, particularly in the mid and upper Bay mainstem and larger tributaries. The improvement in the Potomac is probably due primarily to phosphorus control efforts at the Blue Plains Sewage Treatment Plant. Control efforts appear to be making a difference, but it is apparent from the effects discussed below that additional Bay-wide nutrient controls are needed.

## Dissolved Oxygen and Chlorophyll a Trends

In order to assess the resource management implications of these nutrient trends, it is valuable to examine a related parameter - dissolved oxygen. As nutrient levels increase, phytoplankton (algal) growth is encouraged and more organic matter is produced. Bacterial decomposition of this organic matter consumes oxygen. If more oxygen is used than supplied by reaeration or photosynthesis, as often occurs in deep water, the water becomes near or fully anoxic, and devoid of most forms of life except anaerobic bacteria. This process occurs naturally in some Bay areas during the summertime; however, high nutrient loads can increase its severity.

Both the chlorophyll a trends, as an indication of algal biomass, and the dissolved oxygen trends suggest that the duration and extent of anoxia has been accelerated in the Bay in recent years. As indicated in Figure 3, there were no anoxic waters and only limited areas of low dissolved oxygen in the main stem of the Bay during July of 1950. A general trend towards increased volume of low dissolved oxygen water occurred throughout the 1960's and 1970's. By 1980 a large area of the main stem of the Bay was experiencing anoxic conditions in July, at depths greater than 12-15 meters (Figure 3). It is estimated that the volume of water with dissolved oxygen concentrations equal to or less than 0.7 mg $L^{-1}$ (0.5 mg $L^{-1}$) was 15 times greater in 1980 than in 1950. The duration of oxygen depletion also increased. It was sporadic during the mid-1950's; occurred from mid-June to mid-August during the 1960's; and, in 1980, began during the first week in May and continued into September. This increase in the spatial and temporal extent of low dissolved oxygen levels reduces the area of the Bay that can support normal finfish and shellfish populations.

## Organic Compounds in Water and Sediments

Organic compounds can occur naturally; although the ones of major concern as pollutants are synthetically produced. The distribution of organic compounds, such as hydrocarbons, pesticides, and herbicides, in the bottom sediments and the water column of the main Bay (Figure 4)

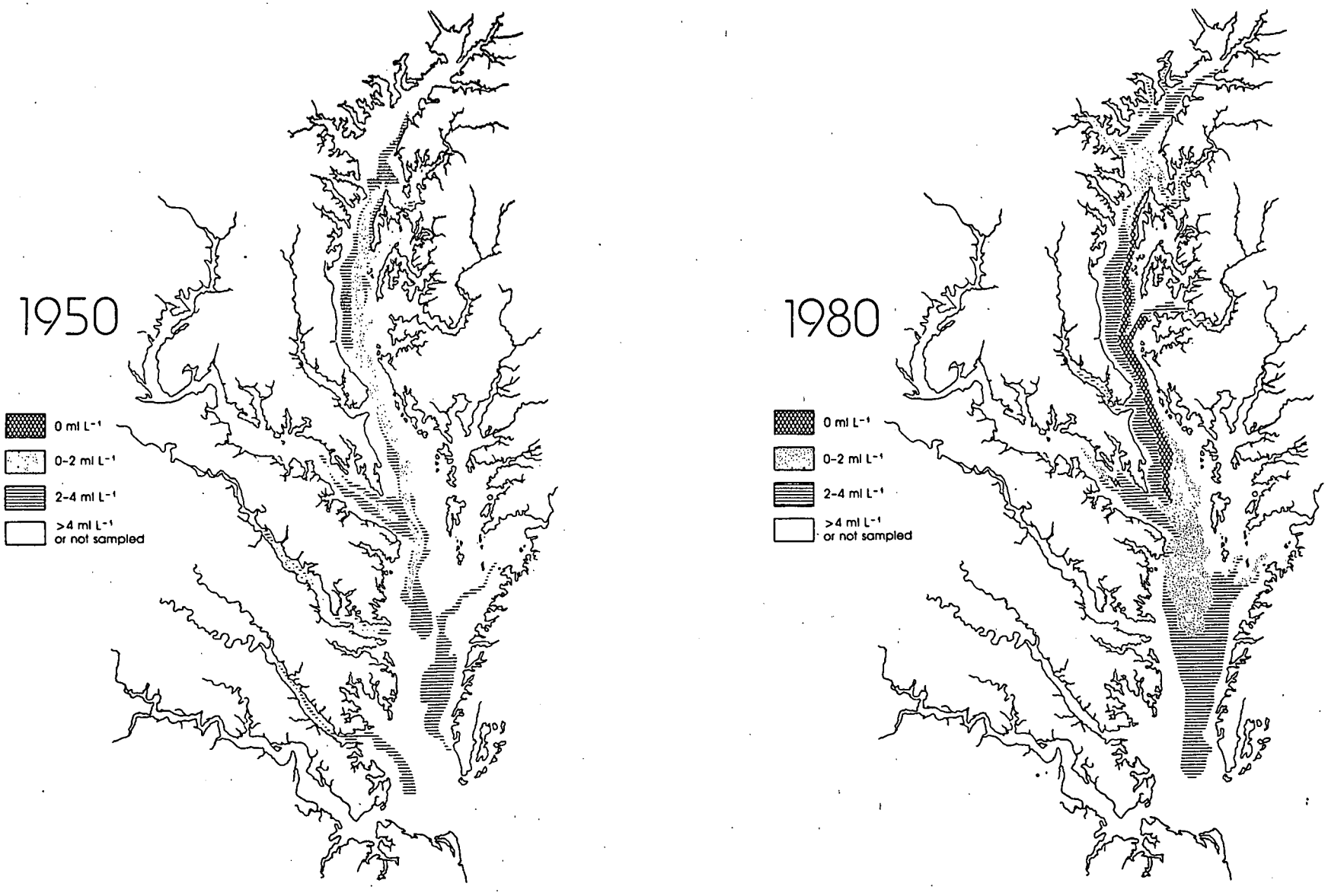


FIGURE 3. Extent of anoxic bottom water in the main stem of Chesapeake Bay in 1950 (left) and 1980 (right).

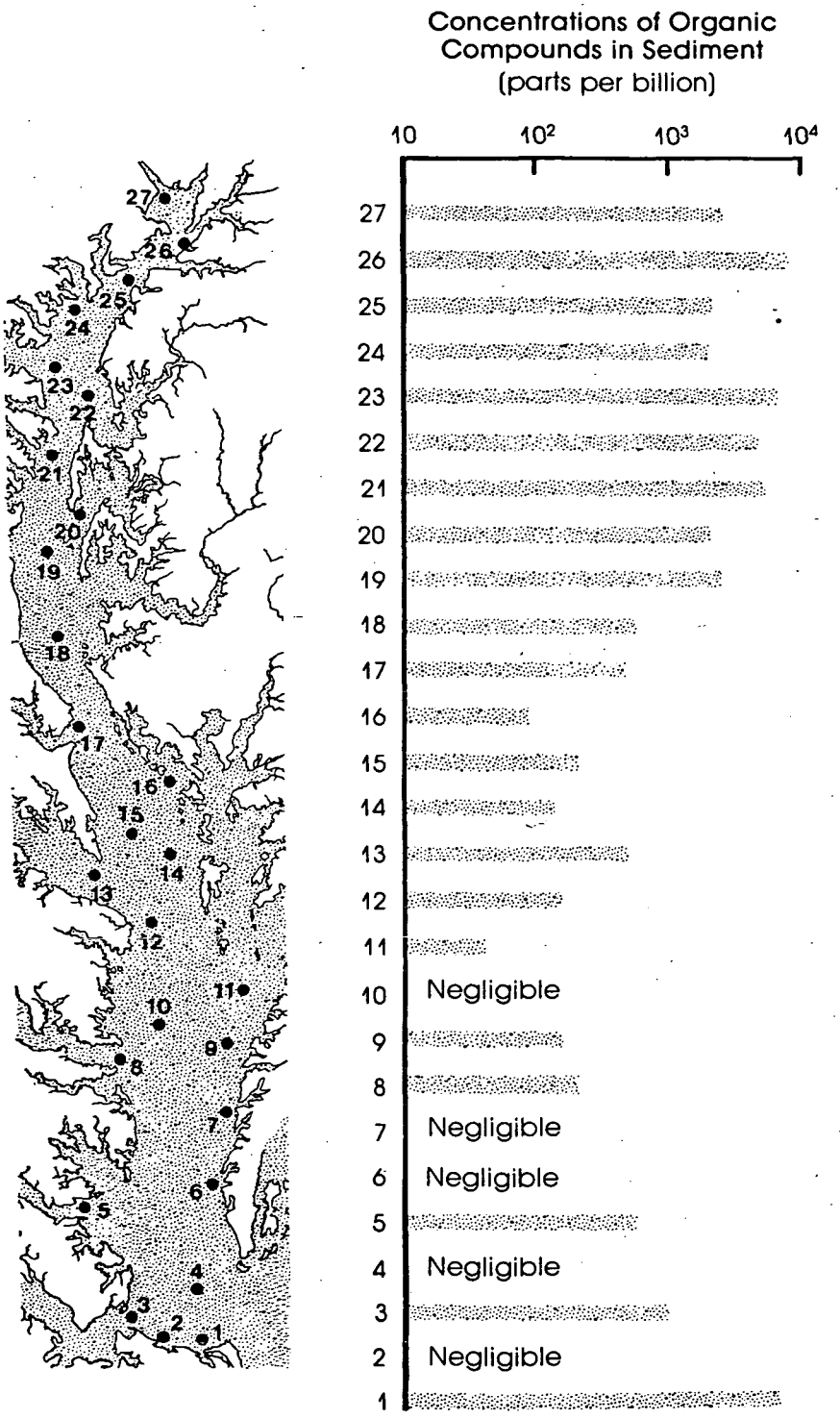


FIGURE 4. Station locations and bar graphs representing concentration sums (ppb) of all recognizable peaks for organic compounds after normalizing for silt and clay content. (From Bieri and Huggett, 1982).

and an analysis of limited tributary data suggest that organic compounds concentrate near sources, at river mouths and in maximum turbidity areas (Bieri et al. 1982a). The highest concentrations of organic chemicals in the sediments were found in the Patapsco and Elizabeth Rivers, exceeding 100 parts per million (ppm) at several locations (Bieri et al. 1982b). In the main Bay, highest concentrations of organic substances occur in the northern half. Most observed sediment concentrations range from 0 to 10 ppm; however, in the upper Bay some stations had levels over 50 ppm total organics (Bieri et al. 1982c).

These general trends suggest that many of the problem organic compounds in the Bay tend to adsorb to suspended sediments, and then accumulate in areas dominated by fine-grained sediments. Benthic organisms located in such areas tend to accumulate the organic compounds in their tissues. Studies of the pesticide Kepone, which was discharged into the James River during the 1970's, have further substantiated these conclusions (Nichols and Cutshall 1981). A major mechanism for accumulation of this persistant pesticide appears to be bioconcentration by plankton; this has implications for transfer of this and similar toxicants through the food web. Some toxic organic compounds, such as the herbicides atrazine and linuron, appear to undergo fairly rapid chemical and physical degradation once they enter the estuary and, therefore, they probably do not pose as serious a problem Bay-wide (Kemp et al. 1982).

Trace Metal Contamination

Metals are chemical elements which occur naturally in the environment, but which, in excess can become toxic to organisms. Many areas of the Bay show trace metal concentrations in bottom sediments that are significantly higher than natural background levels. Figure 5 shows the degree of metal contamination (i.e., enrichment over background) in the surface sediments of Chesapeake Bay. The contamination index ($C_I$) was developed by comparing present concentrations of Cd, Cu, Cr, Ni, Pb, and Zn in the Bay's surface sediment to predicted natural levels from the weathering of rock in the Bay watershed and from measured pre-colonial levels from sediment cores. If the present concentration of a given metal exceeded these natural Chesapeake Bay background levels it was considered to be anthropogenically enriched. The most contaminated sediments are located in the Patapsco and Elizabeth Rivers, both heavily industrialized tributaries. Metal concentrations up to 100 times greater than expected natural background levels were found in these areas. High levels of metal contamination ($C_I \geqslant 14$) were also found in the upper Potomac, upper James, upper mid-Bay and small sections of the Rappahannock and York. Moderate contamination occurs in the Susquehanna flats and off the mouth of the Potomac River. These trends suggest that higher concentrations

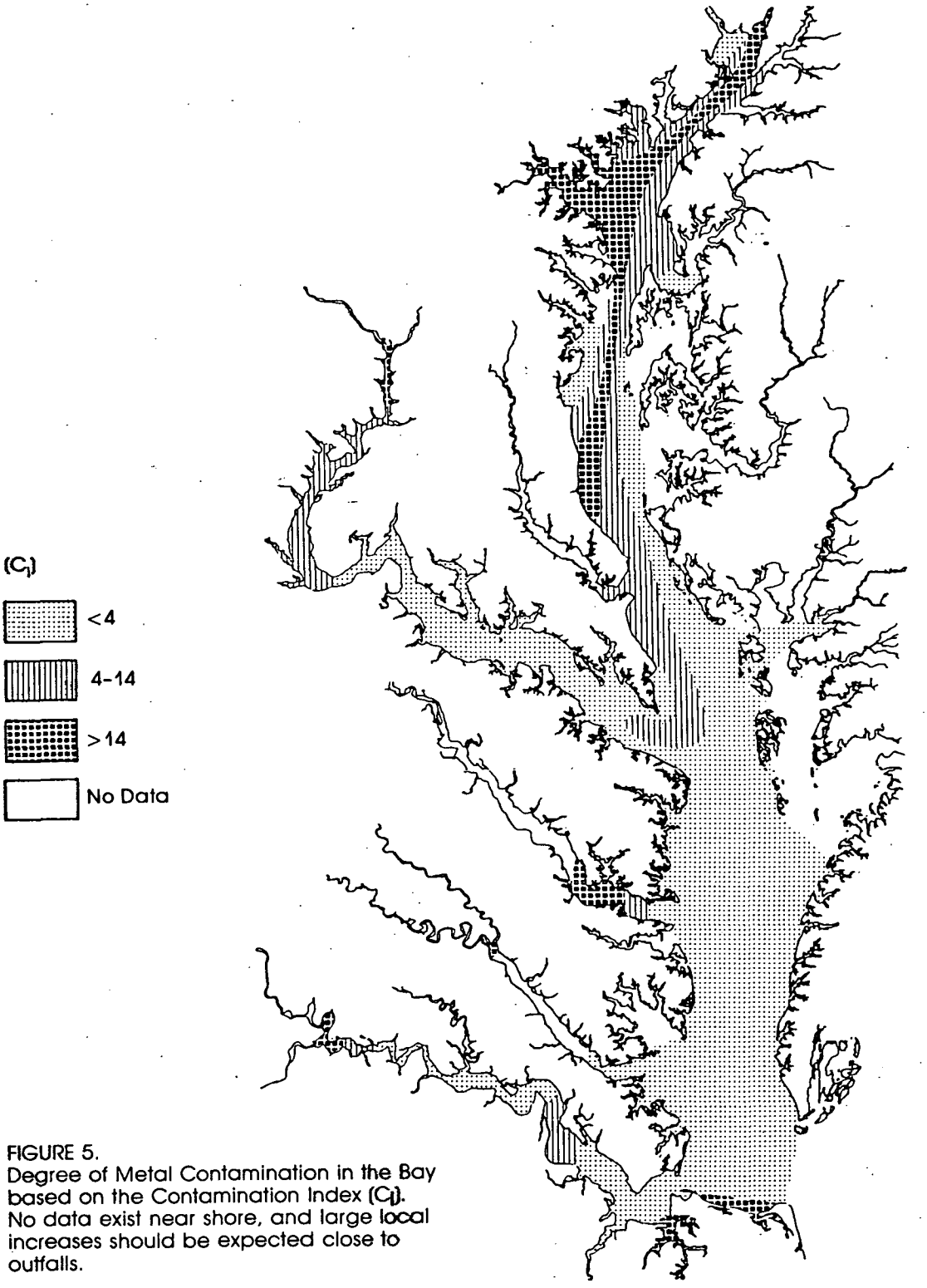


FIGURE 5.
Degree of Metal Contamination in the Bay based on the Contamination Index ($C_i$). No data exist near shore, and large local increases should be expected close to outfalls.

are found near industrial sources and in areas where fine sediments accumulate, such as in the deep shipping channel of the upper Bay. In general, there is little movement of metals out of the most contaminated areas, except when physically transported, as might occur through movement or disposal of contaminated dredge material.

Significant levels of particulate and dissolved metals occur in the water column. Concentrations of particulate Co, Cr, Cu, Ni, and Zn are greatest in the upper Bay and near the turbidity maximum; actual values vary greatly with salinity, tidal cycle, and amount of suspended sediment (Nichols et al. 1981, Kingston et al. 1982). High dissolved values, some exceeding EPA water quality criteria, have been observed, particularly for cadmium, copper, zinc, and nickel. These are most frequent in areas near industrial sources, and upper reaches of the main Bay and western shore tributaries.

## CURRENT CONDITIONS AND TRENDS IN LIVING RESOURCES

Major changes in Bay resources can be identified, which include shifts in relative abundance of species or the types of biological communities found in various areas. The CBP focussed on individual living resource groups (e.g., submerged aquatic vegetation and finfish), described documented trends, and compared present conditions with past or potential status.

### Phytoplankton in Two Well-Documented Areas

The upper Bay (above the Annapolis Bay Bridge) and upper Potomac River (tidal-fresh reach) have shown increased dominance by a single species of phytoplankton and increased algal biomass. Such changes are considered to be indicative of eutrophication, and in fact have paralleled changes in nutrient enrichment in these areas. These two areas are those for which best data are available; similar changes may be occurring elsewhere, or could be expected to occur if nutrient enrichment continues.

The Potomac River's tidal-fresh reach was characterized in the 1960's and 1970's by massive blue-green algal blooms, an indicator of excess nutrients (Pheiffer et al. 1972, Clark et al. 1980). Increased phosphorus control in the watershed in recent years appears to have been beneficial (Champ et al. 1981). In 1979 algal populations were diverse, and blue-greens made up only 25 percent of the total phytoplankton population. Total cell counts for 1979 and 1980 were also considerably lower than previously (Boulukos and Stoelzel 1980).

Trends in nutrient enrichment of the upper Bay tributaries have closely paralleled those of the upper Potomac during the 1960's. Massive algal blooms are frequently reported in the upper main Bay

(above the Annapolis Bay Bridge), with elevated chlorophyll levels due to increasing numbers of blue-green algae (Clark et al. 1973). By comparison, observations of this area in 1965 to 1966 reported only occasional occurrence of blue-green algae (D. A. Flemer, pers. comm.). It is estimated that cell numbers in this area have increased approximately 250-fold since a 1955-1956 study by Whaley and Taylor (1968), even taking into account the proportions of nannoplankton in most recent studies by Allison (1980).

## Submerged Aquatic Vegetation (SAV) Declines

Since the late 1960's, a dramatic, Bay-wide decline has occurred in the distribution and abundance of submerged aquatic vegetation (Orth and Moore 1982). Loss has moved progressively down-estuary affecting the upper and mid-main Bay, most major tributaries, and upstream reaches of many smaller tributaries (Figure 6). SAV now occupies a significantly more restricted habitat in Chesapeake Bay than at any time during the past, according to CBP studies (Brush and Davis 1982, Orth et al. 1983). SAV's role in the Bay ecosystem has been reduced, and its ability to recover from this current status is uncertain (Boynton and Heck 1982). Changes in distribution and abundance of Bay waterfowl, which feed on SAV, have paralleled these vegetation changes (Munro and Perry 1981).

Annual surveys of SAV conducted by the Maryland Department of Natural Resources and the U.S. Fish and Wildlife Service Migratory Bird and Habitat Research Laboratory have shown that the number of vegetated stations in Maryland dropped from 28.5 percent in 1971 to 4.5 percent in 1982. Species diversity also declined significantly. Comparison of the habitat filled in 1978 with the "expected habitat" (based on depth, substrate, and other criteria) shows that areas of greatest loss (upper Bay, western shore tributaries, and upper Eastern shore tributaries) correspond with areas of greatest nutrient enrichment (Figure 7).

## Changes in Benthic Invertebrates

Benthic animals are considered useful indicators of pollution because most are relatively immobile and cannot readily escape unfavorable conditions. Changes in benthic biomass, community structure, and diversity can indicate a variety of stressful conditions (Boesch 1977). Where sufficient data on benthic communities existed comparisons were made of current conditions, particularly in the main Bay and certain tributaries. Trends in diversity, and relative abundance of pollution-tolerant species such as annelids, were investigated and compared to various environmental criteria. In the main Bay, benthic abundance and diversity seems most related to physical aspects of the environment - i.e., salinity and sediment

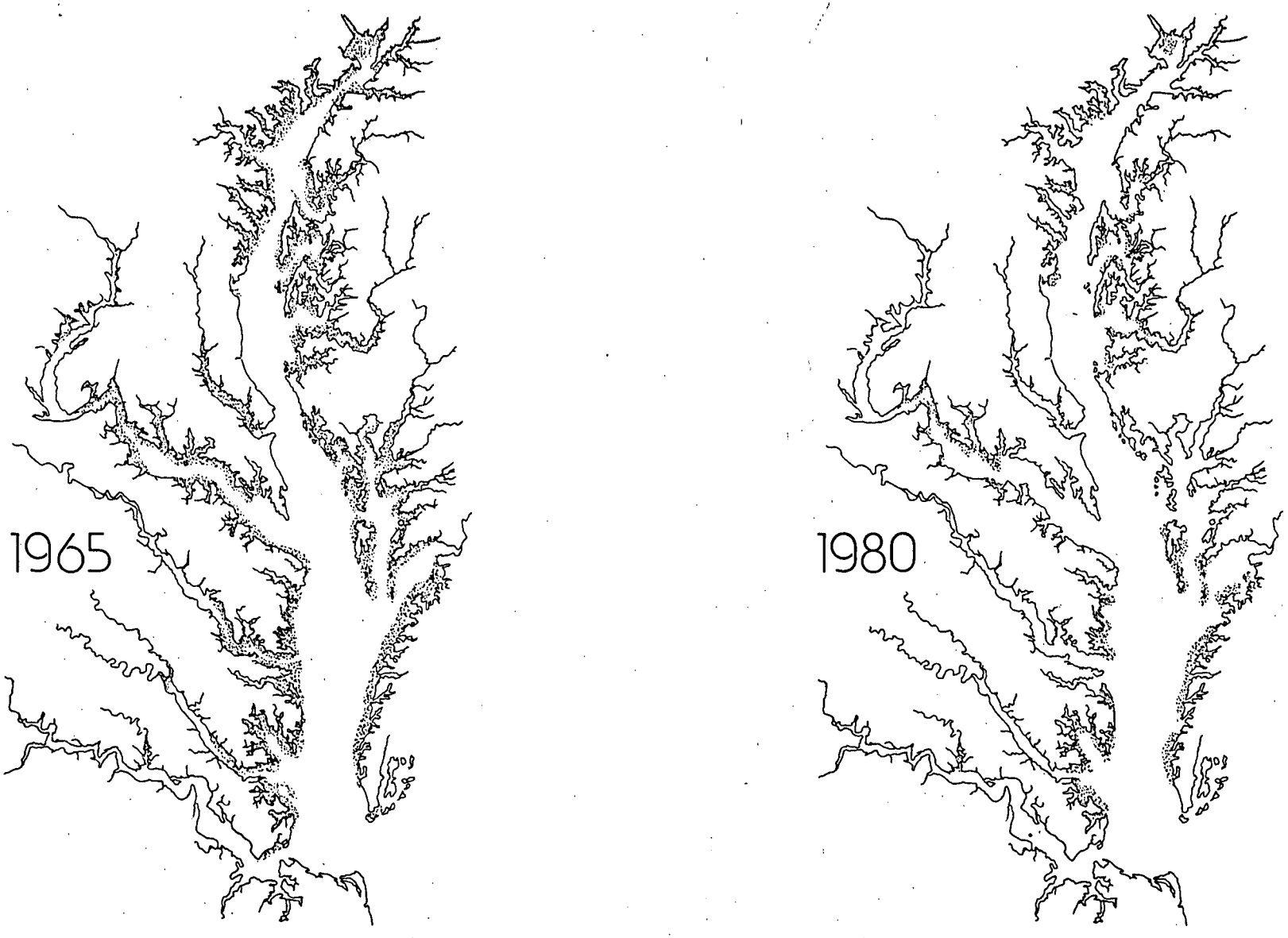


FIGURE 6. General area of SAV distribution in 1965 (left) and 1980 (right).

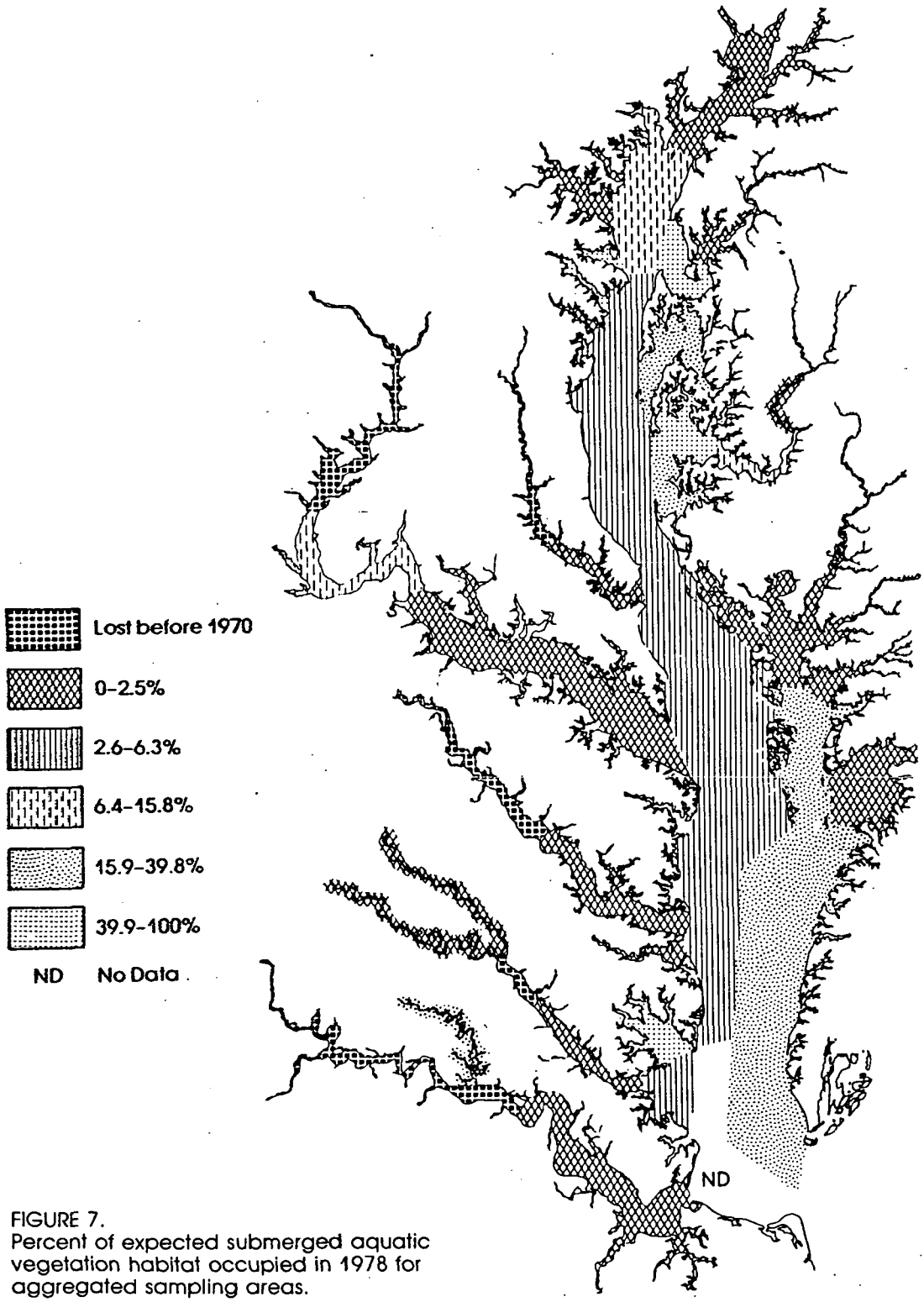


FIGURE 7.
Percent of expected submerged aquatic vegetation habitat occupied in 1978 for aggregated sampling areas.

type, - as well as predation and other biological interactions (Boesch 1977a). Highest community diversity occurs in the lower Bay polyhaline zone. In some polluted tributaries, especially the Patapsco and Elizabeth Rivers, significant declines in species diversity and enhancement of pollution-tolerant annelids, relative to molluscs or crustacea, are observed (Reinharz 1981, Schaffner and Diaz 1982). These changes are characteristic of stressed communities, and have been observed in other impacted areas such as the New York Bight (Wolfe et al. 1982).

Trends in Commercial Shellfish

The density of annual oyster (*Crassostrea virginica*) spat set is a measure of the success of oyster reproduction and recruitment, and is a reasonable predictor of oyster harvest (Ulanowicz et al. 1980). Comparison of the average oyster spat set for the past ten years with the previous ten to thirty years shows significant declines in the upper main Chesapeake Bay and the Chester, James, Nanticoke, Patuxent, Pocomoke, Potomac, Rappahannock, and Wicomico Rivers, Eastern Bay, Fishing Bay, and Pocomoke Sound. In general, 1980 was a good year for spat fall, particularly in Eastern Shore tributaries; this fact is related to high salinities during the spawning period (Davis et al. 1981). However, spat set in the upper Chesapeake and its western tributaries was generally light even in this good year. The trend toward light spat set in upstream reaches has been documented in detail for the Potomac River; while spat set in the lower river has continued to vary in response to salinity, set in the middle and upper Potomac has been suppressed since the late 1960's (Krantz and Carpenter 1981). Changes in water quality and increased sediment loads are implicated (Krantz and Carpenter 1981).

Harvest of oysters for Cheaspeake Bay has declined since 1880, but since 1960-1965 has remained relatively stable (Figure 8). This is in part due to more intensive fishery management practices, such as shell and seed planting. Harvest for the western shore has decreased significantly during the period 1962 to 1980, while harvest for the Eastern Shore has increased significantly. This is consistent with the Eastern Shore's maintaining better spat set. For the Chesapeake Bay as a whole, declines in oyster harvest have been somewhat offset by increased harvest of blue crabs (*Callinectes sapidus*). As a result, the Bay-wide landings of shellfish (in pounds) have not changed greatly from 1962-1970 to 1970-1980. However, overall shellfish harvest for the western shore has decreased significantly during this period.

Shifts in Finfish Harvest

The CBP examined trends in harvest and other indicators (e.g., young-of-the-year surveys) for the major commercial species historically

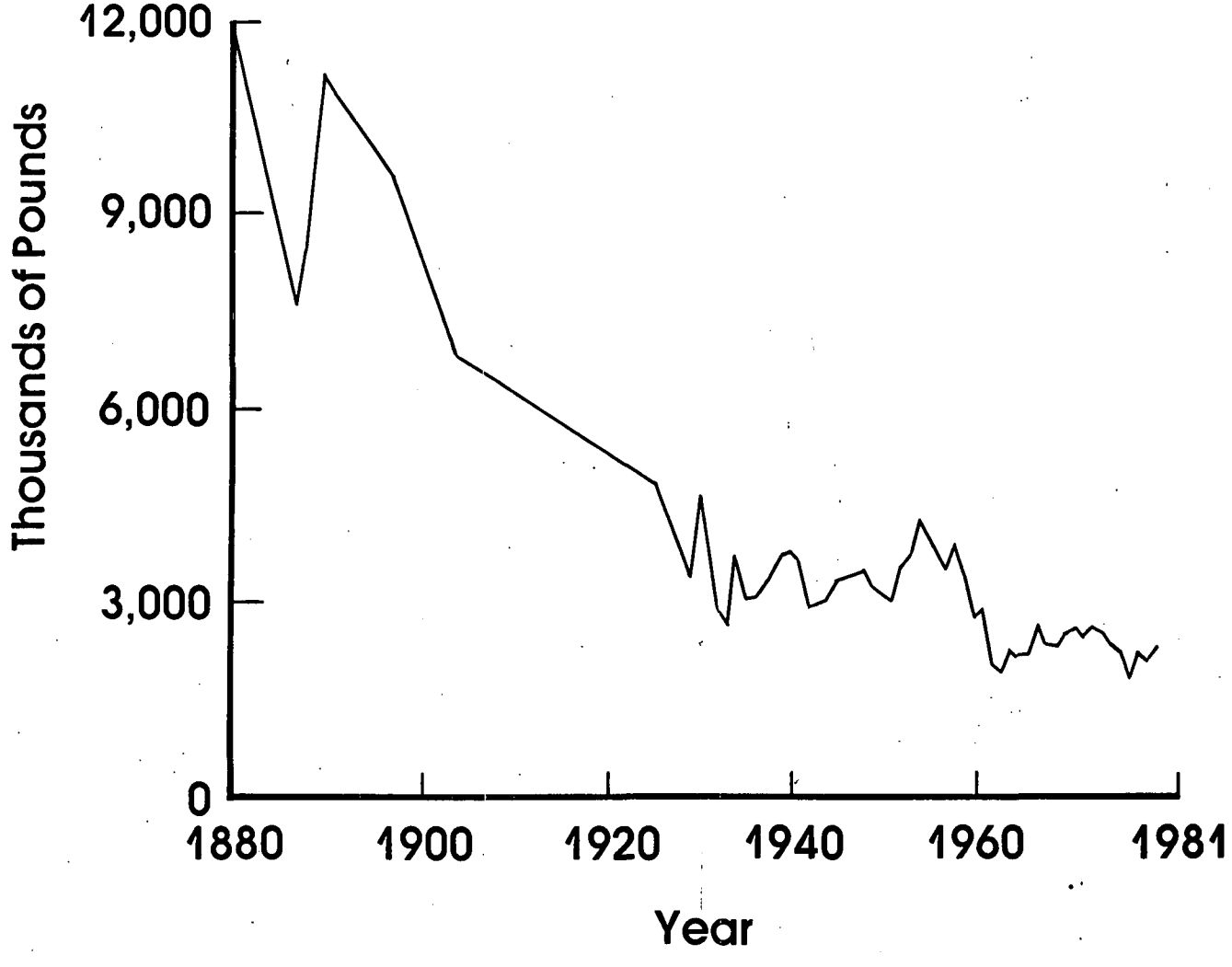


FIGURE 8. Historical pounds of shucked oyster meat for Chesapeake Bay, 1980 to 1981.

landed in Chesapeake Bay. These include freshwater spawners such as striped bass (Morone Saxatilis), white perch (M. americana), yellow perch (Perca flavescens), catfish (Ictalurus spp), shad (Alosa sapidissima), and alewife (Alosa pseudo-harengus), marine spawners such as menhaden (Bevoortia tyrannus), croaker (Micropogonias undulatus), spot (Leistostomus xanthuros), bluefish (Pomatomus saltatrix), and weakfish (Cynoscion regalis) as well as three forage fish, Bay anchovy (Anchoa mitchilli), mummichog (Fundulus heteroclitus), and Atlantic silverside (Menidia menidia).

The Maryland juvenile index provides consistent data since 1958 for the upper Bay, Nanticoke, Choptank, and Potomac Rivers (Boone 1980). Juvenile indices of most anadromous and freshwater species show declines in recent years, with the exception of the Potomac River where white perch and yellow perch have increased. Information for Virginia waters is not directly comparable, due to differences of methodology and target species (sciaenids) (Wojcik and Austin 1982). However, trends in marine-spawning fish were similar in both data sets. Marine spawners show general overall increases in all basins, although some species show declines in the most recent surveys. In Maryland, mummichog shows an increasing pattern similar to that of marine spawners, while the Bay anchovy and Atlantic silverside show declines. However, the anchovy has been increasing in Virginia tributaries surveyed during the same period. This may reflect differences in water quality or habitat (particularly availability of SAV, used as shelter by this species) between the two states.

Fishery statistics maintained by the National Marine Fishery Service indicate that harvests of anadromous and other freshwater-spawning finfish have been declining in Chesapeake Bay (Figure 9). The downward trend in American shad has been continuous since 1900, while declines in river herring, yellow perch, and striped bass landings have been more recent. Landings of alewife, shad, and yellow perch are now at unprecedented low levels. Harvests of marine spawners, on the other hand, have increased in most areas. Menhaden landings have risen steadily since 1955, while the increase in bluefish landings has been more recent. The increased yield of marine spawners and decreased yield of freshwater spawners represent a major shift in the proportion of the finfishery accounted for by each group: during 1881-1890 marine spawners accounted for about 75 percent of the fishery, while during 1971-1980 they accounted for 96 percent. Similarly, an assessment of individual basins for the two periods 1962-1970 and 1971-1980, shows significant declines in freshwater spawners while landings of marine spawners in most basins increased significantly.

The large relative increase in marine spawners and actual decline in freshwater spawners illustrates gradual reduction in the diversity of Chesapeake Bay fisheries. Diversity is not used here in the sense

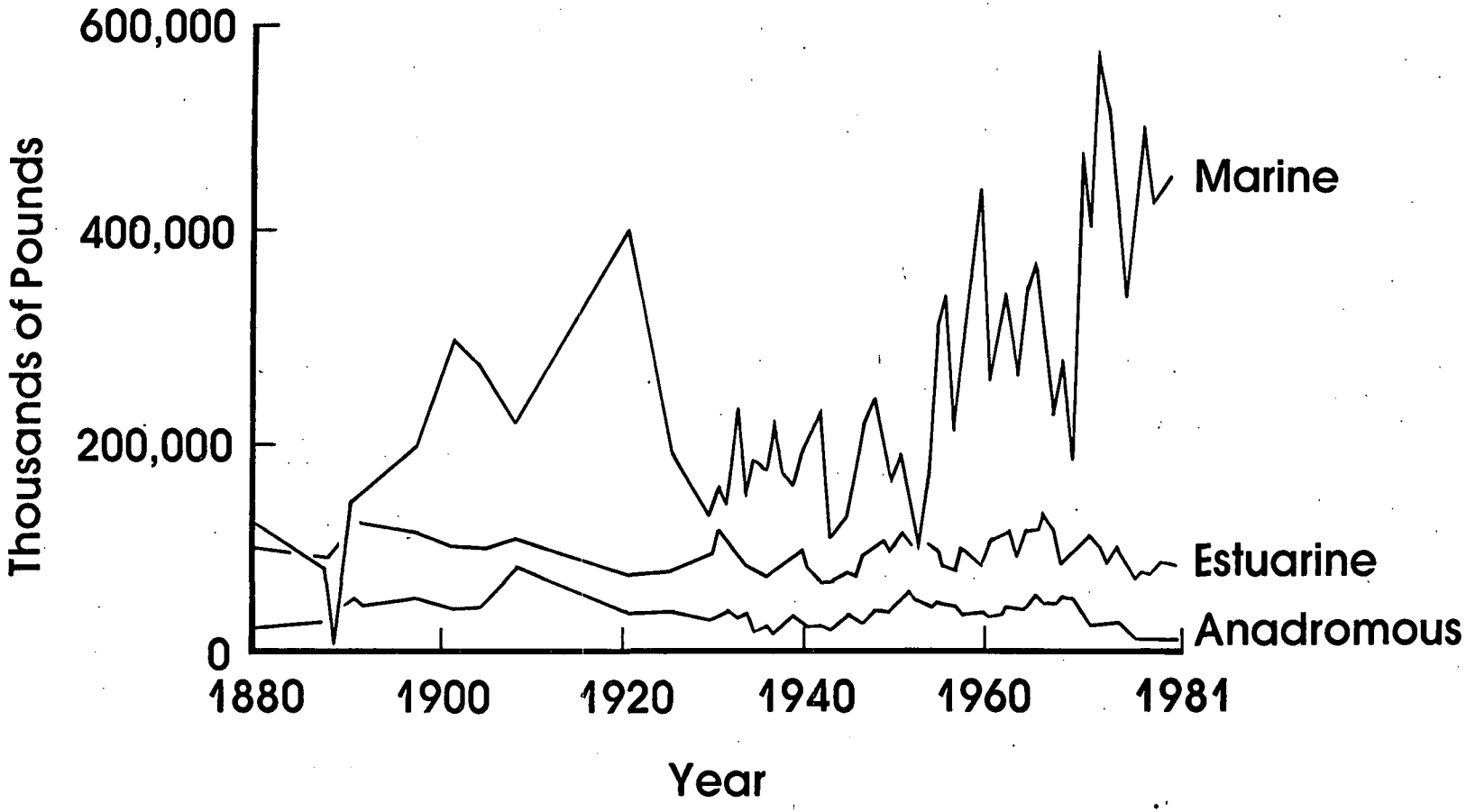


FIGURE 9. Historical landings for the commercial fish species investigated by the Chesapeake Bay Program, separated into freshwater spawners, estuarine spawners (shellfish), and marine spawners.

of number of species alone, but in the sense of number of species and the relative eveness of the contribution of these species towards the total harvest. Such a loss of diversity could be viewed as potentially undesirable because harvests are more vulnerable to year-to-year fluctuations in population size of major commercial and recreational species. There is less resiliency (both economic and ecological) in single-species fisheries. The economic impacts of the failure of the California sardine, the Peruvian anchoveta, or the Delaware Bay menhaden fisheries are prime examples (e.g., Price 1973).

Because freshwater-spawning fish and estuarine-spawning shellfish spend all or most of their sensitive life stages in the Bay, their well-being may be considered as an indication of the health of the estuary. Thus, the declines in most of these species simultaneously is reason for concern.

## RELATIONSHIPS BETWEEN WATER AND SEDIMENT QUALITY AND LIVING RESOURCES

Organisms respond directly to changes in their habitat and changes in food supply, competitors, or predators. Major factors which affect the Bay's living resources include natural variables such as freshwater inflow, temperature, or other organisms, as well as man-induced stress such as nutrient and toxicant enrichment. Distinguishing between effects triggered by anthropogenic, as opposed to natural causes, is often difficult due to the natural variability of organism distribution and abundance. Although the CBP was unable to pinpoint exact causes for specific resource changes, the similarity in patterns and the overlap in the distribution of water or sediment quality and living resource trends in the Bay should be considered as more than a striking coincidence.

### Submerged Aquatic Vegetation

The CBP supported a major research effort to identify the causes of the recent SAV decline. Investigators focussed on two main hypotheses: 1) In recent years use of toxic agricultural materials, particularly herbicides, has increased within the Chesapeake watershed. Runoff of these materials from agricultural areas may be reducing or eliminating aquatic vegetation within the estuary; 2) Reduction in the light available to the plants due to an increase in water column turbidity or increased growth of epiphytes (or both) may be causing the decline. Nutrient enrichment was considered a major factor affecting both turbidity (through increase in phytoplankton biomass) and epiphyte growth. Research supported by the CBP implicated light limitation as the most important factor regulating the SAV loss Bay-wide (Kemp et al. 1983). Herbicides could be important locally, close to sources (although areas affected may represent significant habitat) (Kemp et al. 1983).

The CBP's research conclusions are supported by field observations. Comparison of a map of current SAV status to Bay nutrient conditions reveals that vegetation now occurs primarily in areas that are not enriched or only moderately enriched. Statistical analysis (rank correlation) shows significant correlation between declines in SAV and increased nutrient concentrations in many areas. The major nutrient which appears to correlate with SAV abundance is nitrogen (Fig. 10). A negative response to maximum chlorophyll a values, an analog of both nutrient loading and turbidity, was also found. These analyses support experimental results linking the recent loss of Bay vegetation to increases in nutrient loadings and ultimately to light stress caused by increasing phytoplankton biomass and epiphytic growth (Twilley et al. 1982, Kemp et al. 1983).

Benthic Organisms

Major anthropogenic factors which could adversely affect benthic organisms in Chesapeake Bay are toxic materials, either in bed sediments or in the overlying water column, and nutrients. Toxicants can produce either acute (e.g., elimination of susceptible species) or sublethal (e.g., accumulation in body tissues) effects. Nutrient enrichment can alter the Bay's benthic community structure by stimulating phytoplankton production, and thus increasing organic matter loads to the sediments (Bascom 1982). Excessive production of organic material has been linked to the increased duration and extent of low dissolved oxygen in Chesapeake Bay, which is decreasing available benthic habitat (Taft et al. 1980).

Episodes of low dissolved oxygen have been cited as the major factor limiting benthic distribution in deeper waters of the upper and mid-main Bay (Mountford et al. 1977). The documented increase in extent of anoxic water in the mid-Bay can be related to complete loss of benthic habitat or replacement with emphemeral assemblages. This may have secondary impacts on bottom-feeding predators such as crabs or demersal fish, which can be stressed by food limitation as well as reduction of habitat. Recent changes in the mid-Bay blue crab fishery, especially the necessity to set crab pots in shallower water, may be a direct result of these anoxic episodes.

Changes in benthic diversity, abundance, and community structure could be related to toxic contamination of sediments only in areas recognized as "impacted" (e.g., the Patapsco River and the Elizabeth River)(Figure 11). These areas are characterized by low benthic diversity and abundance, and dominance by pollution-tolerant annelids,

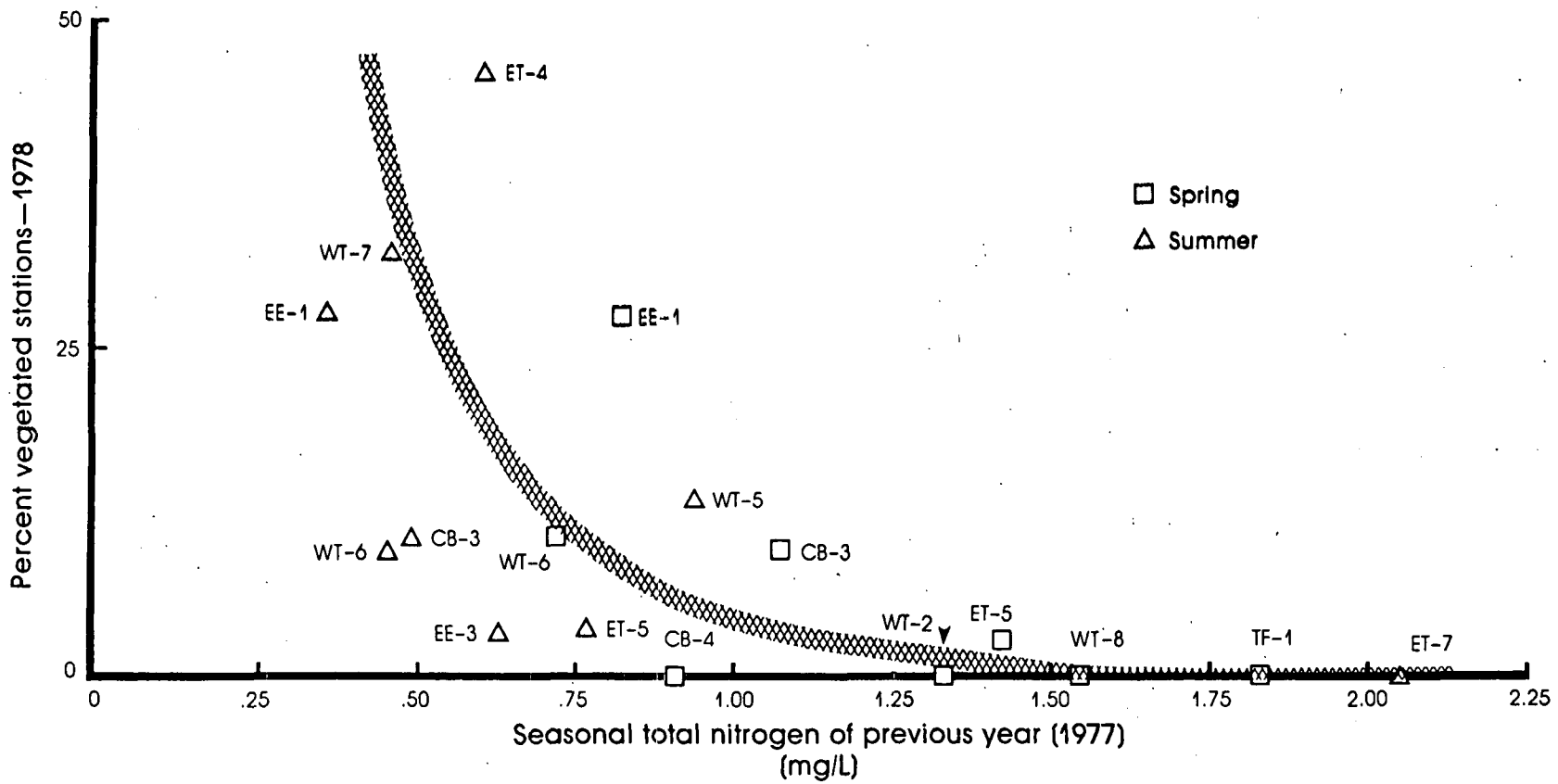


FIGURE 10. Correlation between percent vegetated stations and annual total nitrogen of previous year.

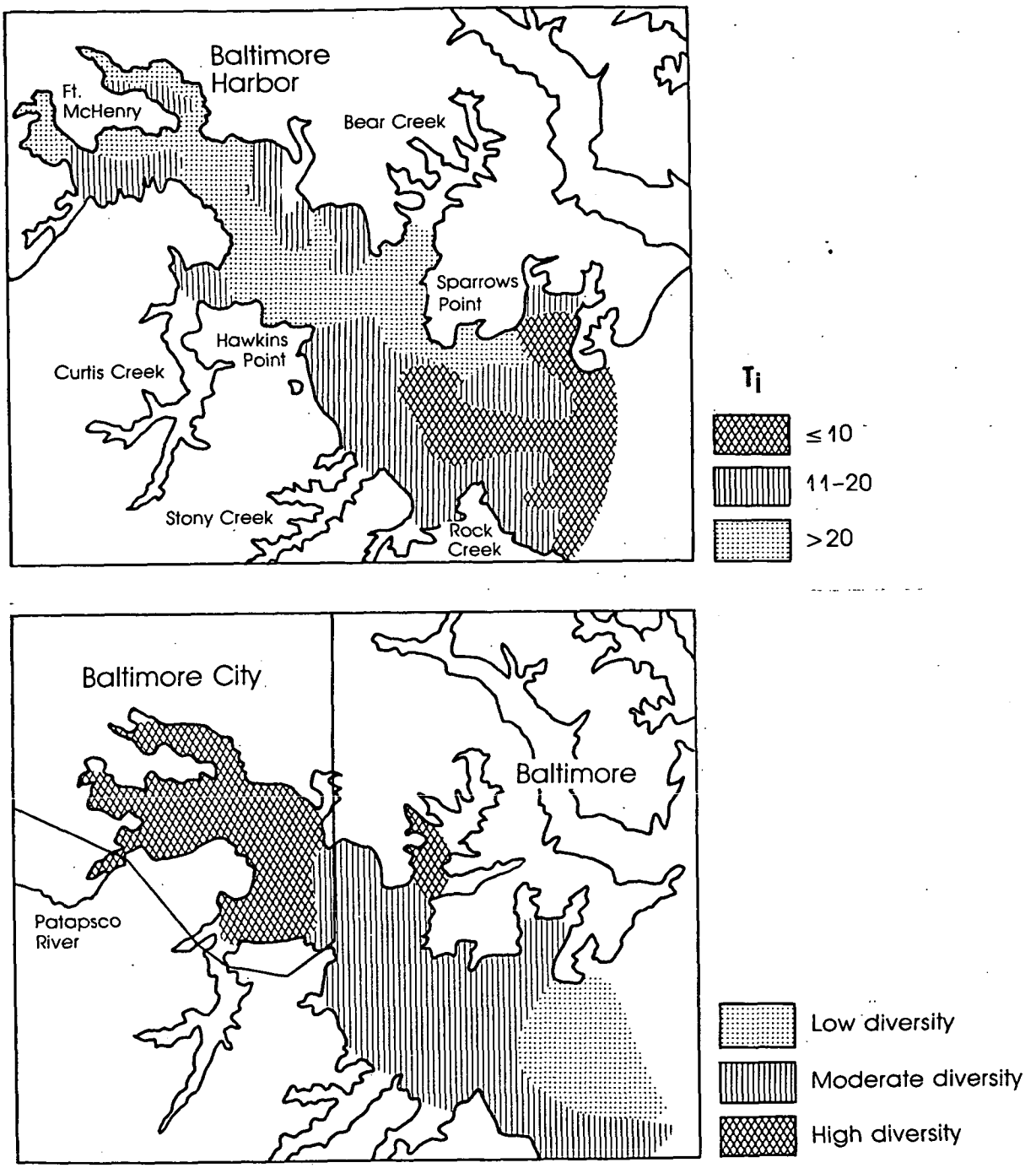


FIGURE 11. Comparison of benthic community diversity to sediment toxicity. (Toxicity Index, $T_I$) in the Patapsco River, Maryland.

in comparison to nonpolluted reference areas (Reinharz 1981, Schaffner and Diaz 1982). Elsewhere, other factors, primarily physical or biological, are apparently controlling benthic distributions. However, bioaccumulation of certain metals in tissues of shellfish could be correlated with enrichment of those metals in the bed sediments, even in the main Bay.

Oysters

Oysters (and other shellfish) are benthic organisms but, because of their commercial importance oysters are treated separately here. Factors affecting benthic communities in general (i.e., low dissolved oxygen water, and toxicants in sediments or water column) will impact oysters as well. In addition, oysters are potentially vulnerable to shifts in phytoplankton species brought about by nutrient enrichment (Ryther 1954). Phytoplankton species usable as food can be replaced by undesirable or inedible forms such as blue-greens or non-motile green algae (Ryther and Officer 1981). Comparison of EPA water quality criteria to measured and estimated concentrations of toxicants in the water column revealed a number of violations in areas of oyster habitat; these were chiefly for heavy metals. Although the duration or extent of high toxicant concentrations is presently unknown, the observations may be significant. Populations stressed by a variety of factors, may be more vulnerable to diseases, such as MSX (*Minchinia nelsoni*) or "Dermo" (*Perkinus marinus*). Impact of these protozoan parasites has increased in recent years due to higher salinities resulting from drought (Krantz and Davis 1983).

In addition, oyster habitat is adversely impacted by the increased rate of sedimentation in Chesapeake Bay. Beds may be buried, or spat set impeded, by deposition of sediment. Loss of once productive oyster bars in the upper Bay is probably due in part to sedimentation over the past 100 years (Alford 1968).

Fishery Landings and Juvenile Index

Although total fishery landings in Chesapeake Bay have increased since 1920, the distribution of landings among species has changed significantly. Anadromous and other freshwater-spawning fish such as shad and striped bass have declined greatly in importance, while marine spawners have remained stable or increased. Finfish juvenile index - a measure of recruitment success - reflects these trends as well.

Several causes of this change in distribution have been suggested: 1) nutrient enrichment may lead to food web shifts (i.e., changes in phytoplankton and zooplankton species) primarily affecting early life stages; 2) the level of toxicants, particularly heavy metals, pesticides, and chlorine, in some major spawning areas are elevated

and, in fact, have exceeded EPA criteria in some spawning or nursery areas used by anadromous fish; 3) habitat is being lost because of increased area of low DO water; 4) adverse climatic conditions (freshwater inflow, temperature, etc.) have reduced the spawning success of anadromous species; 5) overfishing is affecting stock sizes; 6) construction of dams represents a physical obstruction that impedes spawning success of anadromous and semianadromous species; and 7) modifications of upstream spawning and nursery habitat, such as wetlands destruction and stream channelization further stresses fishery stocks. It is possible that all of these factors are contributing to the changes observed in Chesapeake Bay resources.

Concentrations of toxicants exceeding EPA water quality criteria were discussed earlier. Many of these criteria violations occurred in spawning or nursery areas used by anadromous fish. If such high toxicant concentrations prove to be wide-spread or frequent, adverse impacts would be expected, particularly to sensitive larval stages.

The large increase in duration and extent of anoxia in the mid-Bay is certainly reducing available habitat for a number of species, particularly bottom feeders such as spot or croaker. Food limitation could result in reduced growth or other "quality changes" in the condition of fish, even if populations per se are not affected.

Statistical analysis of juvenile indices shows that, although natural variables such as temperature and flow exert a major influence on recruitment success of most freshwater spawning species, factors such as nutrients and dissolved oxygen can also affect year-to-year success (Flemer et al. in press). Major influencing factors vary from river to river, suggesting that management strategies also will have to differ between each of these systems.

Effects of harvest, particularly on already declining populations, may potentially be significant. Unfortunately, information on fishing effort is lacking for most Chesapeake Bay fisheries, so that attempts to relate commercial landings to actual stock abundance have not been successful (Rothschild et al. 1981, Bartone 1982). There is also evidence that recreational catch for some species is significant (Williams et al. 1982).

Finally, impacts of habitat modification on freshwater spawning finfish, or species which use low salinity nursery areas, could be important in many areas of the Bay. Many tributary streams have man-made structures, such as dams, which impede the migration of anadromous fish (O'Dell et al. 1980). Loss of wetlands in the Bay region was extensive prior to passage of protective legislation in the early 1970's; much of this loss was in areas important as finfish nursery habitat (Settle 1969, Metzgar 1973).

## STATE OF THE BAY

CBP developed a numerical ranking system to assess the status of certain water quality and living resource variables to provide a snapshot of the "state of the Bay". Nutrients, trace metals, and submerged aquatic vegetation, were used as the primary classification variables because of their importance and the completeness of data. Variables were ranked numerically by Bay segment.

Ranking of nutrients was based on mean concentrations of total nitrogen and total phosphorus observed in each segment during the period 1977-1980. The potential dissolved oxygen demand of organic matter containing these given nitrogen and phosphorus concentrations was also taken into account, because of the link to biological resources (Table 1). Class 1 and 2 are characteristic of areas with low nutrient enrichment (e.g., lower Bay, Eastern Bay, and lower York River) while class 5 and 6 represent the most impacted systems (e.g., upper reaches of major tributaries, Baltimore Harbor, and the Back River). Rankings of trace metals were based on $C_I$, the Contamination Index. Eastern shore and lower Bay areas show lowest $C_I$ values, while regions close to urbanized or industrial areas have highest $C_I$ values. When nutrient and toxicant ranks are aggregated, the following assessment can be made: poorest water and sediment quality now occurs in the upper Bay, upper reaches of the Potomac and James Rivers, the Patuxent River and some smaller areas such as the Patapsco River, the lower Potomac, James, mid-Bay, and most of the York and Rappahannock, and eastern shore tributaries are moderate in water and sediment quality, the lower Bay mainstem, Mobjack Bay, Pocomoke Sound, lower Choptank, and Eastern Bay currently have the best water and sediment quality (Figure 12).

TABLE 1. CLASSIFICATION OF CHESAPEAKE BAY WATER USING TOTAL NITROGEN (TN) AND TOTAL PHOSPHORUS (TP), AS RELATED TO POTENTIAL OXYGEN DEMAND

| Class | TN mg $L^{-1}$ | TP mg $L^{-1}$ | Potential DO Demand mg |
|---|---|---|---|
| 1 | 0 - 0.40 | 0 - 0.056 | 8 |
| 2 | 0.41 - 0.60 | 0.057 - 0.084 | 12 |
| 3 | 0.61 - 0.80 | 0.085 - 0.112 | 16 |
| 4 | 0.81 - 1.00 | 0.113 - 0.140 | 20 |
| 5 | 1.01 - 1.75 | 0.141 - 0.245 | 35 |
| 6 | 1.76 + | 0.246 + | 36+ |

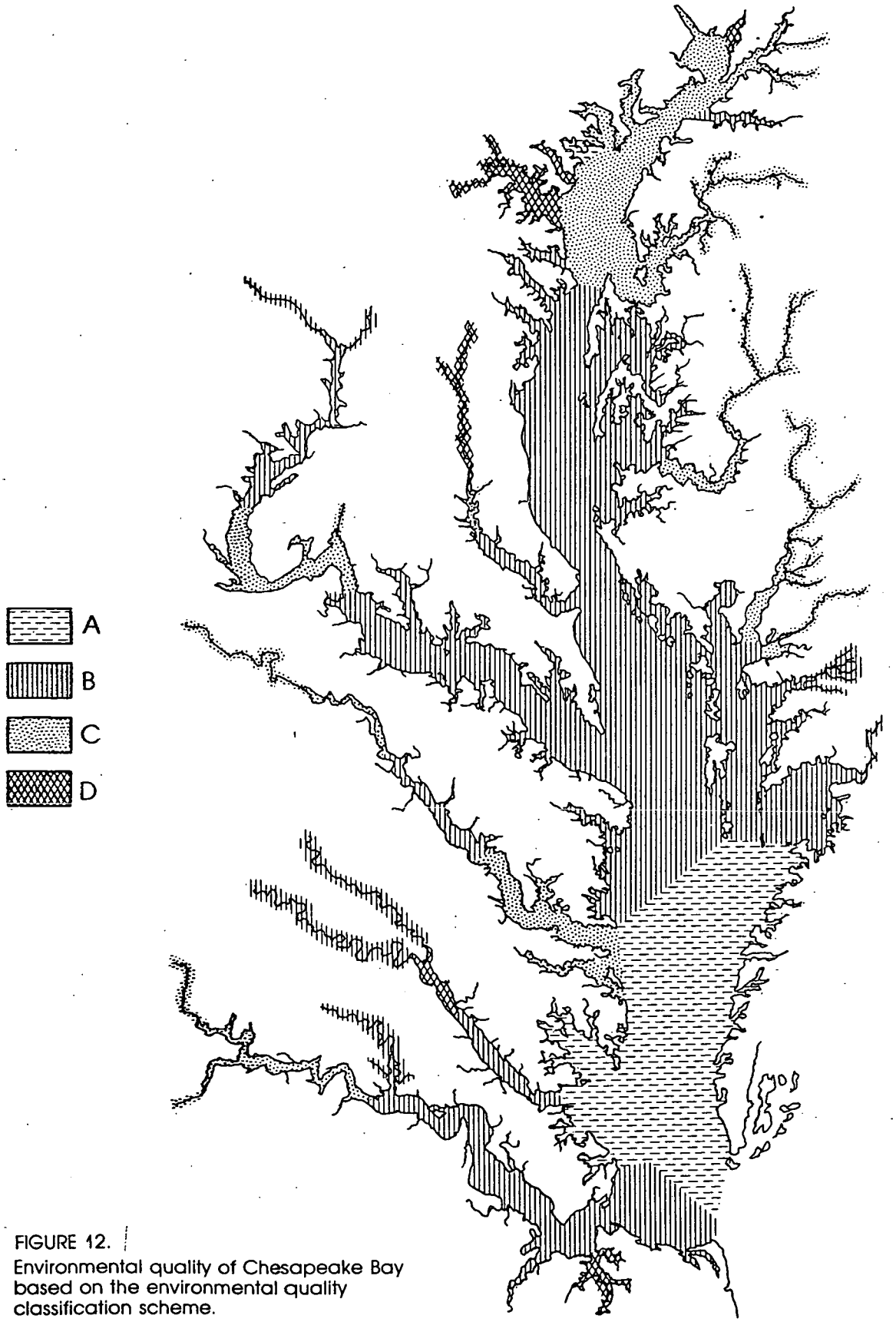


FIGURE 12.
Environmental quality of Chesapeake Bay based on the environmental quality classification scheme.

Submerged aquatic vegetation (SAV) was ranked according to the utilization of potential habitat by the plants. Most favorable are the lower Bay, Eastern Bay, and lower Choptank River, while most other segments were poor in respect to SAV. Oyster spat set (recruitment) and anadromous fish harvest were also assessed, although not ranked numerically because of lack of bay-wide data. When this asessment is combined with SAV ranking, the following evaluation can be made: the upper Bay and western shore shows a general pattern of decline in the three resources, the upper Patuxent, James, and Patapsco and Middle Rivers showed the poorest resource quality, Tangier Sound and the lower and mid-Bay display moderate resource quality, the Eastern Shore generally appears to be the most productive region of the Bay system (this conclusion is supported by the regional comparison where Eastern Bay, and the Choptank and Chester Rivers ranked most favorably).

When the ranks of water quality are compared to the ranks of living resources, it is evident that areas with the best resource quality correspond to areas with the best water and sediment quality (e.g., eastern embayments). This suggests that, to improve the quality of resources in the Chesapeake Bay, water and sediment pollution must be reduced. Achieving this goal will require the concerted effort of both government and the private sector.

## LITERATURE CITED


Alford, J.J. 1968. Changing Oyster Yields in the Major Administrative Units of the Chesapeake Bay Fishery. Ph.D. Thesis. University of KA.

Allison, Jim. 1980. Phytoplankton Sampling Results. Technical Briefs. Maryland Office of Environmental Programs. Annapolis, MD.

Bascom, W. 1982. The Effects of Waste Disposal on the Coastal Waters of Southern California. Environ. Sci. Technol. 16(4):226A-236A.

Bieri, R.H., O. Bricker, R. Byrne, R. Diaz, G. Helz, J. Hill, R. Huggett, R. Kerhin, M. Nichols, E. Reinharz, L. Schaffner, D. Wilding, and C. Strobel. 1982a. Toxic Substances. In: Chesapeake Bay Program Technical Studies: A Synthesis. E.G. Macalaster, D.A. Barker, and M.E. Kasper, eds. U.S. Environmental Protection Agency, Washington, DC. 635 pp.

Bieri, R.H., C. Hein, R.J. Huggett, P. Shou, H. Slone, C. Smith, and C. Wu-Su. 1982b. Toxic Organic Compounds in Surface Sediments from the Elizabeth and Patapsco Rivers and Estuaries. Grant No. R806012. Final Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program. 136 pp. + Appendices.

Bieri, R.H., P. DeFur, R.J. Huggett, W. MacIntyre, P. Shou, C.L.

Smith, and C.W. Su. 1982c. Organic Compounds in Surface Sediments and Oyster Tissues from the Chesapeake Bay. Grant No. R806012. U.S. Environmental Protection Agency's Chesapeake Bay Program. Annapolis, MD. 79 pp.

Biggs, R.B., 1981. Freshwater Inflow to Estuaries, Short and Longterm Perspectives. Proc. Natl. Symp. on Freshwater Inflow to Estuaries. U.S.F.W. #/FWS/OBS-81-04.

Boesch, D.F. 1977a. A New Look at Zonation of Benthos Along the Estuarine Gradient. In: Ecology of Marine Benthos. B.C. Coull, ed. University of South Carolina Press, Columbia, SC.

Boesch, D.F. 1977b. Application of Numerical Classification in Ecological Investigations of Water Pollution. V.I.M.S. Spec. Sci.Rep. 77. 114 pp.

Boone, J.G. 1980. Estuarine Fish Recruitment Survey. Maryland DNR Report F-27-R-6.

Bortone, S. 1982. An Analysis of Possible Relationships Between Fishing Effort and Various NOAA Landing Statistics for Chesapeake Bay Fisheries. Unpublished EPA Manuscript.

Boulukos, K.E. and V.A. Stoelzel. 1980. Phytoplankton Composition and Abundance in the Potomac River Estuary. 197-202 pp. In: Potomac Estuary Study, 1980 Fiscal Year Annual Report. U.S.G.S. Administrative Report. 244 pp.

Boynton, W.R. and K.L. Heck, Jr. 1982. Ecological Role and Value of Submerged Macrophyte Communities: A Scientific Summary. 428-502 pp. In: Chesapeake Bay Program Technical Studies: A Synthesis. E.G. Macalaster, D.A. Barker, and M.E. Kasper, eds. U.S. Environmental Protection Agency, Washington, DC. 635 pp.

Brush, G.S., and F.W. Davis. 1982. Stratigraphic Evidence of Human Disturbance in Chesapeake Bay Tributaries. Final Draft Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program. Annapolis, MD.

Champ, Michael A., O. Villa, and R. Bubeck. 1981. Historical Overview of the Freshwater Inflow and Sewage Treatment Plant Discharges to the Potomac River Estuary with Resultant Nutrient and Water Quality Trends. In: Proceedings of the National Symposium on Freshwater Inflow to Estuaries. Vol. II. R.D. Closs and D.L. Williams, eds. U.S. Dept. of the Interior. Washington, DC. pp.350-373.

Clark, Leo J., Daniel K. Donnelly, and Orterio Villa, Jr. 1973. Nutrient Enrichment and Control Requirements in the Upper Chesapeake Bay. Summary and Conclusions. Tech. Report #56. Environmental Protection Agency, Annapolis, MD.

Clark, Leo. J., Stephen E. Roesch, and Molly M. Bray. 1980. Assessment of 1978 Water Quality Conditions in the Upper Potomac Estuary. Environmental Protection Agency. Annapolis, MD. 91 pp.

Davis, H.E., D.W. Webster, and G.E. Krantz. 1981. Maryland Oyster Spat Survey. Maryland Sea Grant Program Report. UM-SG-TS-81-03. 22 pp.

D'Elia, C.F. 1982. Nutrient Enrichment in Chesapeake Bay: An Historical Perspective. In: Chesapeake Bay Program Technical Studies: A Synthesis. E.G. Macalaster, D.A. Barker, and M.E. Kasper, eds. U.S. Environmental Protection Agency, Washington, DC. pp. 45-102.

Flemer, D.A., J.L. Taft, K.S. Price, G.B. Mackiernan, W. Nehlsen, R.B.Biggs, N.H. Burger, D.A. Blaylock. (In Press). Nutrient Enrichment of Chesapeake Bay Correlated with Decline of Striped

Bass: A Speculative Hypothesis. Presented at the American Fishery Society Annual Meeting, Hilton Head, SC. September 1982.

Flemer, D.A., G.B. Mackiernan, W. Nehlsen, and V.K. Tippie. 1983. Chesapeake Bay: A Profile of Environmental Change. U.S. EPA, Region III, Philadelphia, PA. 200 pp + Appendices.

Heinle, D.R., C.F. D'Elia, J.L. Taft, J.S. Wilson, M. Cole-Jones, A.B. Caplins, and L.E. Cronin. 1980. Historical Review of Water Quality and Climatic Data from Chesapeake Bay with Emphasis on Effects of Enrichment. Grant #R806189. U.S. Environmental Protection Agency's Chesapeake Bay Program Final Report. Chesapeake Research Consortium, Inc. Publication No. 84. Annapolis, MD.

Helz, G.R., S.A. Sinex, G.H. Setlock, and A.Y. Cantillo. 1981. Chesapeake Bay Sediment Trace Elements. University of Maryland. College Park, MD. 202 pp.

Kemp, W.M., W.R. Boynton, R.R. Twilley, J.C. Stevenson, and J.C. Means. 1983. The Decline of Submerged Vascular Plants in Upper Chesapeake Bay: Summary of Results Concerning Possible Causes. Report to U.S. Environmental Protection Agency's Chesapeake Bay Program, University of Maryland Center for Environmental and Estuarine Studies Contribution No. 1431.

Kemp, W.M., R.R. Twilley, W.R. Boynton, J.C. Stevenson, and J.C. Means. 1982. Submerged Aquatic Vegetation in the Upper Chesapeake Bay, I. Investigations Related to Possible Causes of the Decline. Final Report Submitted to the U.S. Environmental Protection Agency's Chesapeake Bay Program.

Kingston, H.M., R.R. Greenberg, E.S. Beary, B.R. Hardas, J.R. Moody, T.C. Rains, and W.S. Liggett. 1982. The Characterization of the Chesapeake Bay: A Systematic Analysis of Toxic Trace Elements. Grant No. EPA 79-D-X-0717. Final Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program.

Krantz, G.E. and H.A. Davis. 1983. Maryland Oyster Spat Survey Fall 1982. Technical Report # UM-SG-TS-83-01, Maryland Sea Grant Program, College Park, MD. 14 pp.

Krantz, G.E., and A.C. Carpenter. 1981. Potomac Estuary Oyster Fishery: Past, Present, and Future. In: Proc. Fifth Annual Meeting, Potomac Chapter Am. Fish. Soc. May 28-29, 1981. pp. 166-192.

Metzgar, R.G. 1973. Wetlands in Maryland. Maryland Dept. State Planning Publ. 157. Baltimore, MD. 15 pp. + Appendices.

Mountford, N.K., A.F. Holland, and J.A. Mihursky. 1977. Identification and Description of Macrobenthic Communities in the Calvert Cliffs Region of the Chesapeake Bay. Ches. Sci. 18(4):360-369.

Munro, R.E. and M.C. Perry. 1981. Distribution and Abundance of Waterfowl and Submerged Aquatic Vegetation in the Chesapeake Bay. Final Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program from U.S. Fish and Wildlife Service, Migratory Bird and Habitat Laboratory, Laurel, MD. 180 pp.

Nichols, M.N., Richard Harris, and Galen Thompson. 1981. Significance of Suspended Trace Metals and Fluid Mud in Chesapeake Bay. EPA Grant #R806002. U.S. Environmental Protection Agency's Chesapeake Bay Program. Annapolis, MD. 129 pp.

Nichols, M., and N. Cutshall. 1981. Tracing Kepone in James Estuary Sediments. Rapp. P.V. Reun. Cons. Int. Explor. Mer. 181:102-110.

O'Dell, J., J. Mowrer, and J. Gabor. 1980. Survey and Inventory of Anadromous Fish Spawning Areas. Md. Dept. Nat. Resources, Tidewater Admin. Completion Report, Project AFC-9. 165 pp. + Appendices.

Orth, R.J. and K.A. Moore. 1982. Distribution and Abundance of Submerged Aquatic Vegetation in the Chesapeake Bay: A Scientific Summary. In: Chesapeake Bay Program Technical Studies: A Synthesis. E.G. Macalaster, D.A. Barker, and M.E. Kasper, eds. U.S.EPA, Washington, DC. pp. 381-427.

Orth, R.J., K.A. Moore, and J. Van Montfrans. 1983. Submerged Aquatic Vegetation: Distribution and Abundance in the Lower Chesapeake Bay and the Interactice Effects of Light, Epiphytes and Grazers. Contract No. X003246. Final Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program. Annapolis, MD. 136 pp.

Pheiffer, Thomas H., Daniel K. Donnelly, and Dorothy A. Possehl. 1972. Water Quality Conditions in the Chesapeake Bay System. Technical Report #55. U.S. Environmental Protection Agency. Annapolis, MD. 313 pp.

Price, K.S. 1973. The Great Menhaden Fishery of Lewes, Delaware. Trans. Del. Acad. Sci. 1971. 2:181-191.

Reinharz, E. 1981. Animal Sediment Relationships: A Case Study of the Patapsco River. Maryland Geological Survey, Baltimore, MD. Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program. 96 pp.

Rothschild, B.J., P.W. Jones, and J.S. Wilson. 1981. Trends in Chesapeake Bay Fisheries. Trans. 46th N.A. Wildf. and Natr. Res. Conf. Wildlife Mgt. Inst., Washington, DC. pp. 284-298.

Ryther, J.H. 1954. The Ecology of Phytoplankton Blooms in Moriches Bay and Great South Bay, Long Island, New York. Biological Bulletin. 106(2):198-209.

Ryther, J.H., and C.B. Officer. 1981. Impact of Nutrient Enrichment on Water Uses. In: Estuaries and Nutrients. B.J. Neilson and L.E. Cronin, eds. Humana Press. Clifton, NJ. 643 pp.

Schaffner, L.C., and R.J. Diaz. 1982. Biogenic Structure and Community Composition of the Elizabeth and Ware Rivers. Draft Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program, January 1982.

Settle, F. 1969. The Survey and Analysis of Changes Affected by Man on Tidal Wetlands of Virginia, 1955-1969. M.S. Thesis, V.P.I., 1969.

Smullen, J.T., J.L. Taft, and J. Macknis. 1982. Nutrient and Sediment Loads to the Tidal Chesapeake Bay System. In: Chesapeake Bay Program Technical Studies: A Synthesis. E.G. Macalaster, D.A. Barker, and M.E. Kasper, eds. U.S. Environmental Protection Agency, Washington, DC. pp. 147-261.

Taft, J.L., W.R. Taylor, E.D. Hartwig, and R. Loftus. 1980. Seasonal Oxygen Depletion in Chesapeake Bay. Estuaries. 3:242-247.

Twilley, R.R., W.M. Kemp, K.W. Staven, W.R. Boynton, and J.C. Stevenson. 1982. Effects of Nutrient Enrichment in Experimental Estuarine Ponds Containing Submerged Vascular Plant Communities. In: Submerged Aquatic Vegetation in Upper Chesapeake Bay. I. Experiments Related to the Possible Causes of Its Decline. W.M. Kemp., ed. Grant No. 805932. Final Draft Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program. Annapolis, MD.

Ulanowicz, R.E., W.C. Caplins, and E.A. Dunnington. 1980. Forecasting of Oyster Harvest in Central Chesapeake Bay. Estuarine Coastal Mar. Sci. 11:101-106.

Whaley, Richard C., and W. Roland Taylor. 1968. A Plankton Survey of the Chesapeake Bay Using a Continuous Underway Sampling System. Tech. Report 36. Chesapeake Bay Institute, Johns Hopkins University, MD. 89 pp.

Williams, J.B., H.J. Speir, S. Early, and T.P. Smith. 1982. 1979 Maryland Saltwater Sportfishing Survey. Tidewater Administration # TA-CRD-82-1. 100 pp.

Wojcik, F.J., and H. Austin. 1982. Estimates of Abundance - VIMS Small Fish Trawl Survey - York and Rappahannock Rivers, 1955 to 1982. VIMS, Gloucester, VA. Report to the U.S. Environmental Protection Agency's Chesapeake Bay Program. 15 pp.

Wolfe, D.A., D.F. Boesch, A. Calabrese, J.F. Lee, C.D. Litchfield, R.J. Livingston, A.D. Michael, J.M. O'Connor, M. Pilson, and L.V. Sick. 1982. Effects of Toxic Substances on Communities and Ecosystems. In: Ecological Stress and the New York Bight: Science and Management. G.F. Mayer, ed. Estuarine Research Foundation, Columbia, SC. 715 pp.