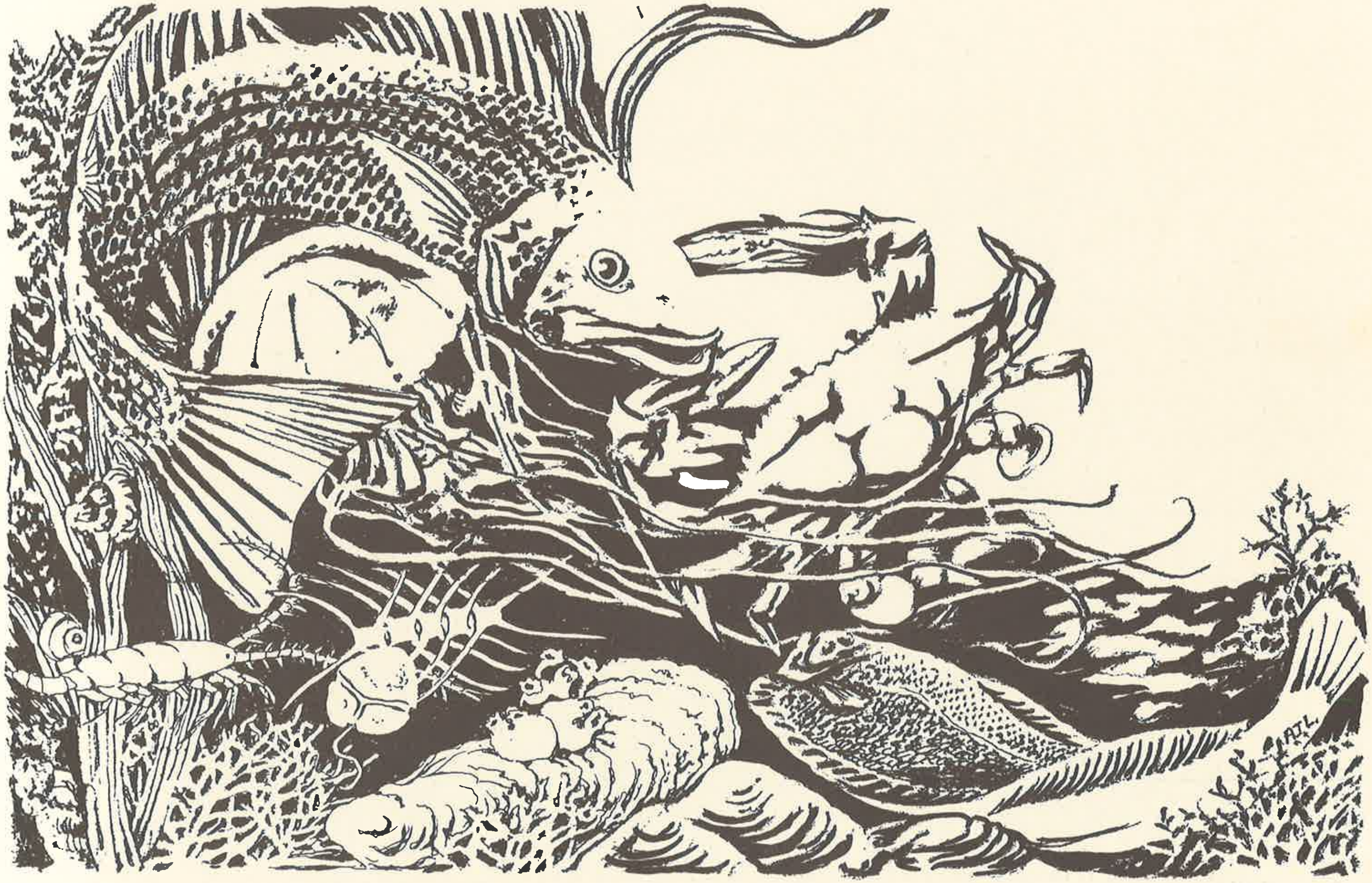
office of environmental programs
maryland department of health and mental hygiene

monitoring for management actions

chesapeake bay water quality monitoring program - first biennial report



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monitoring for management actions

The Maryland Office of Environmental Programs
Chesapeake Bay
Water Quality Monitoring Program
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preface

Maryland's concern with the health of the Chesapeake Bay began long before the Environmental Protection Agency undertook its intensive five-year study of the environmental quality and management of the Bay and its resources. Marylanders have always demonstrated a pride in and a concern for the Chesapeake. Perhaps this affection results from the valuable economic and recreational resource the Bay has been to the State for more than three centuries. But the origin of this pride and concern goes beyond the obvious. To many, the Bay is an integral part of Maryland's heritage, and represents our link to a proud and historic past. Its restoration and protection also presents a serious challenge to every Marylander. The effort to revive this precious resource will require a commitment far greater than that undertaken in previous decades. It is a commitment stretching beyond our lifetime. If we are to be truly successful in restoring the Chesapeake Bay to its former vitality, the commitment must be passed from one generation to the next. Our stewardship of the Bay will never end.

In order to successfully confront the challenge to restore the Bay, and to insure that our legacy to future generations is an ecologically balanced and bountiful Bay, we must continue to institute a broad spectrum of pollution abatement and resource restoration programs. In the last several years we have intensified efforts to reduce the direct discharge of undesirable materials into the Bay. We have passed landmark legislation to restrict development along the Bay's fragile shoreline and to protect key biological resources from continuing exploitation. While we are confident that these types of actions will eventually contribute to improving the health of the Bay, we don't fully understand how the system will respond to the wide range of available management options. Will we see results in 2-5 years, or will the Bay require a decade or more to purge itself of the nutrients and toxicants stored in its sediments? We do know that the Bay is an extremely complex and changing system, dominated by a myriad of physical, chemical, and biological forces. We also know that the Bay has historically demonstrated a remarkable resilience to many natural or man-induced perturbations. It has endured centuries of storms, droughts, urbanization, shipping, and fishing. But the Chesapeake Bay of today is a more fragile system, increasingly vulnerable to man's actions. The ever growing stress from point and nonpoint sources of nutrients and toxics is approaching a critical threshold which threatens to alter vital links of the aquatic food chain so important to sustaining viable populations of finfish and shellfish in the Bay.

Without a more thorough knowledge of the sources of pollutants entering the Bay, an understanding of the transport and deposition processes in the mainstem and tributaries, and a quantitative characterization of the present biological resources, we cannot confidently predict the Bay's response to current efforts and future management actions. Unfortunately, much of the required data on a Bay-wide basis do not exist. We simply do not have adequate spatial and temporal information about fundamental physical, chemical and biological processes. In an effort to address this situation, the Office of Environmental Programs (OEP) initiated a multi-faceted monitoring program in the summer of 1984. In addition to significantly enhancing the scale of the existing water chemistry sampling effort, the OEP program also supports data collection of other key ecological indicators of the Bay's health. Many scientists in the Bay community collaborated with OEP scientists in the development and implementation of the current program. Those most intimately involved with the current program are contributing authors on this report.

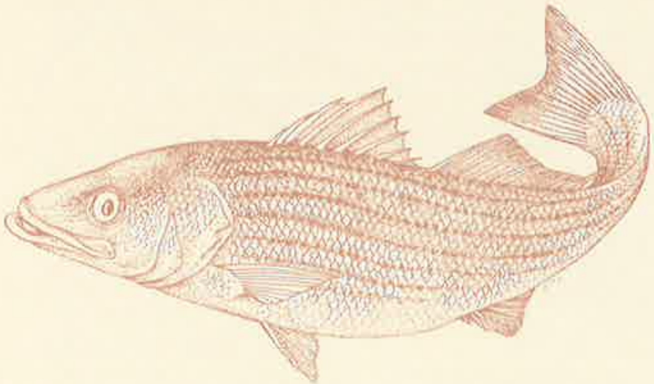
Regardless of our degree of commitment to saving the Bay, we must also recognize that we are working with limited fiscal resources. Most of our potential management actions will be extremely costly. But the cost of not being successful is much greater. We must assess the effectiveness of ongoing management programs, and continue to develop and implement new and enhanced strategies. The data from the OEP monitoring program will play a key role in the success of these plans, and thereby the success of our efforts to restore the Chesapeake.

This first biennial report describes the development of the current OEP Chesapeake Bay water quality monitoring program, and presents the findings of the first two years of operation. We are optimistic that future reports will chronicle the improvements we all strive to see.

William M. Eichbaum
Assistant Secretary for Environmental Programs

contents

1. introduction



The State of Maryland is actively pursuing a management policy to protect and restore the economic and recreational value of Chesapeake Bay. To assist in this goal, the Maryland Office of Environmental Programs (OEP) has designed and implemented a Chesapeake Bay Water Quality Monitoring Program. The purpose of this program is to provide State managers and policy makers with accurate, timely and comprehensive information about the Bay's existing condition and how it is responding to management initiatives. This information is required to evaluate current management policies and to formulate new goals and policies in the future. Perhaps most importantly, the results of the monitoring effort will provide a yardstick with which to measure progress towards the ultimate goal of protecting and restoring Chesapeake Bay.

The information by itself, however, will not clean up the Bay. Measurable progress can be expected only when this information is used in the development, implementation and evaluation of management actions. Furthermore, the struggle toward progress will be difficult in the face of mounting population pressures. A long-term commitment to develop and maintain technically sound management plans is the only real hope for success in restoring vitality to Chesapeake Bay.

Presented here are the results of the first two years of the monitoring program. During this period (summer 1984 through summer 1986) a major campaign has been initiated to reveal the present condition of the Bay in quantitative terms, to assess how the Bay is changing in response to management decisions, and to determine the causes of the current decline. At this early stage in the program, an unprecedented understanding of the Bay's current condition has already been achieved. It is this developing understanding of current conditions that will be the focus of this report. Future reports will examine in more detail the Bay's response to management actions and some of the underlying causes of the Bay's problems.

PROGRAM FORMULATION

In order to insure that the OEP effort is capable of supporting effective management actions, it is imperative that the program be logically formulated. Past experiences indicate that the probability of success in satisfying this program's objectives will be enhanced because the following elements were considered during the initial program design:

- A clear statement of the relevant **management issues** to be addressed,
- The development of specific **management questions** that define the information needed for management actions,
- The **design** of a technically sound and practical sampling program,
- A timely **analysis, interpretation** and presentation of **results,** and
- The development of **management policies** and **actions.**

The remainder of this chapter will present a discussion of each of these five elements using examples to demonstrate the actual processes that were followed. A further discusssion of the last step, development of management actions and policies, will be presented in the final chapter.

MANAGEMENT ISSUES

The first task that managers and scientists face before they can initiate efforts to restore the health of the Chesapeake Bay and its major tributaries is to clearly define what the major management issues are. Success in restoring the Bay will logically depend on a clear conceptualization of the problems we are trying to correct. This conceptualization of the management issues will then lead to specific actions that are perceived as necessary to bring about a recovery. Of course, the definition of management issues and management actions will significantly impact the design of the monitoring program and the ultimate application and utility of the monitoring results.

In 1983, the Environmental Protection Agency and the States of Maryland and Virginia completed a seven year, $27 million program to characterize the existing state of the Bay, to study the causes of the observed declines in the Bay, and to propose strategies needed to begin corrective measures. Relying on available historical data and supplemental information collected by the EPA/States program, the major management issues were identified as:

- Declining levels of oxygen in Bay waters,
- Increasing levels of phytoplankton (microscopic plants) due to nutrient enrichment,
- The presence of toxic materials, and
- Declines in living resources.

Once the broad management issues were defined, there was a need to develop more specific questions that would guide future management actions and serve as a focus for evaluating their success or failure. Answers to these management questions are the pieces of information necessary to develop technically sound actions and policies.

MANAGEMENT QUESTIONS

Management questions were formulated for each of the major management issues presented above. Consideration was given to the information already available from existing monitoring and research programs. Some of the management questions were relatively well studied by the State, and sufficient information was available to continue existing management plans. For several of the management questions, the available data was determined to be insufficient to develop revised or new management strategies.

To illustrate the concept, examples of management questions formulated for each of the management issues are given below:

Decreasing Oxygen Levels:

Where are the major areas of low dissolved oxygen waters in the Chesapeake Bay System?

Is the areal extent of low dissolved oxygen waters expanding over time?

Which pollutant inputs are most responsible for the low oxygen conditions?

Increasing Phytoplankton Levels:

Where are phytoplankton blooms a major problem?

Has the severity of phytoplankton blooms in impacted areas, such as the Potomac and Patuxent Rivers, decreased since 1980 when management initiatives were being implemented?

What is the relationship between nutrient levels and phytoplankton biomass?

Toxicants:

Where are the major concentrations of heavy metals in the sediments of the Bay?

Are toxicant levels in the sediments of historically impacted areas, such as Baltimore Harbor, decreasing?

Are toxicants that are accumulating in the sediments also entering the food chain?

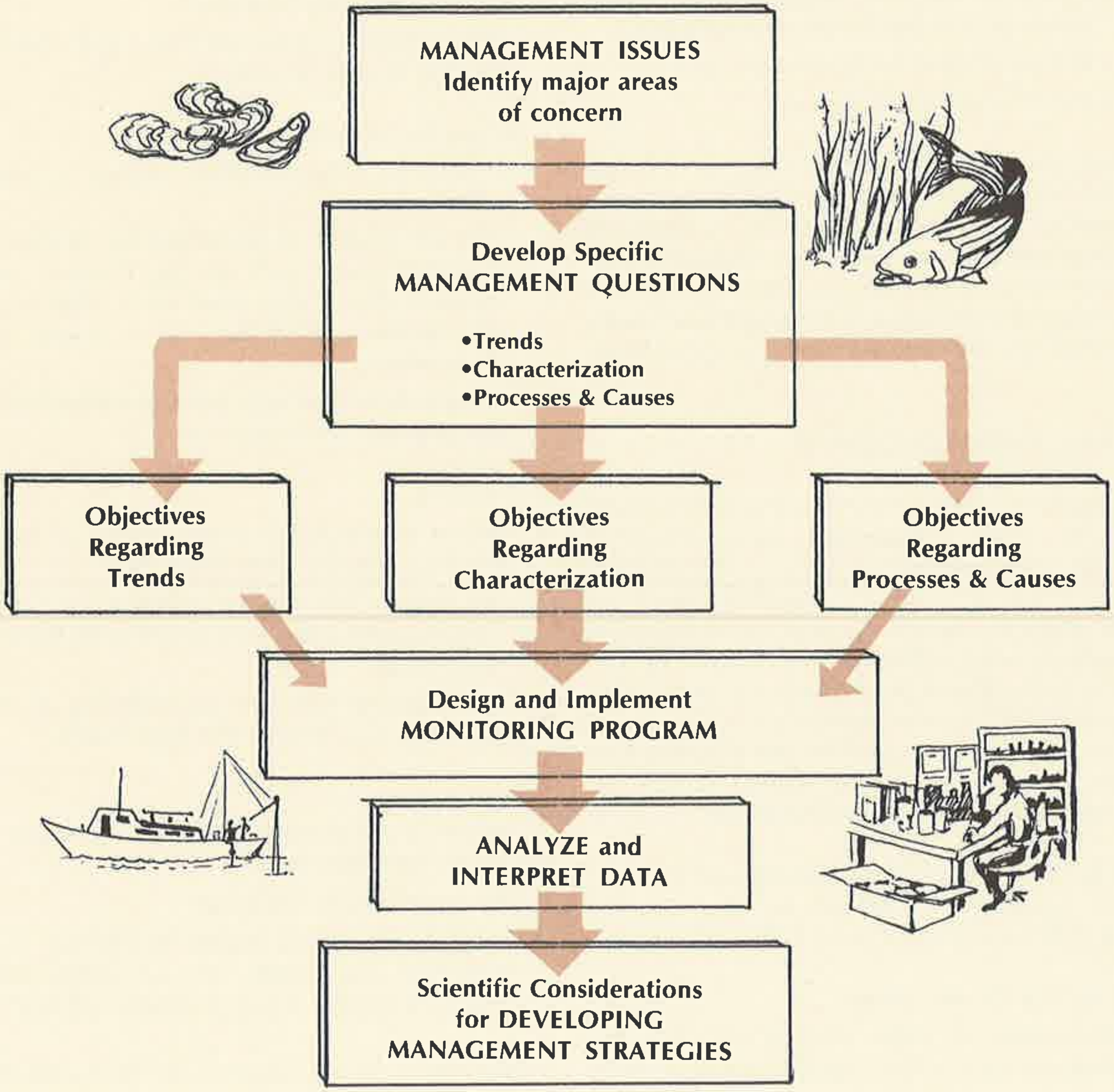
Resources:

Where is striped bass spawning succeeding or failing in the Bay system?

Are oyster stocks declining?

What environmental factors, for example food resources and acidity, are correlated with spawning success of fish in nursery regions?

Examination of the spectrum of major manage-



MONITORING PROGRAM FORMULATION

ment questions revealed that they could be separated into 3 major categories:

- Questions about the spatial and temporal characterization of each problem
- Questions about observed trends in time
- Questions about processes and causes relating to the major management issues

These three categories of management questions thus became the guiding objectives for designing the monitoring program. The specific physical, chemical and biological components of Bay water quality that were chosen for monitoring were those considered necessary to adequately address the major management issues.

The first two objectives of the monitoring program – characterization and trend - were considered to be goals that were fully-achievable by the monitoring program. At this time an initial characterization using the monitoring results is possible, although we will achieve greater confidence and reliability in this assessment with several years of data. The initial characterization is the subject of this report. The identification of trends will be an ongoing objective as management actions are continually being evaluated. The third objective – processes and causes - requires a synthesis of monitoring data with research and modeling programs to achieve definitive answers to most management questions in this category. There are also management questions that are not fully covered under the water quality program such as those related to living resources; these questions are being addressed by other State programs specific to this problem. Nonetheless, there are important questions relating to living resources that cannot be answered without the comprehensive perspective of the current water quality monitoring program.

DESIGN OF SAMPLING PROGRAM

The design of the present monitoring program is predicated upon the management issues and questions discussed above. The program will only be successful to the degree that it can ultimately respond with sound answers to the management questions being posed. Thus, in assembling the program details, the attainment of these answers was always the foremost consideration.

To reach its stated goals, it is essential that the program be technically sound. State-of-the-art scientific knowledge was incorporated into all phases of the monitoring design to assure technically defensible results. For each discipline contained in the monitoring program, OEP scientists solicited technical reviews from recognized experts.

To be implemented effectively and sustained for the time necessary to yield results, the monitoring program also needs to be logistically and economically practical. This means that the program is scaled properly, is efficient, measures the minimum number of the meaningful variables, and is flexible enough to change when necessary.

Finally, the complex physical, chemical and biological processes characteristic of estuarine systems must be considered in the design of an effective monitoring program. Without a solid understanding of how these processes influence the selection of variables to be measured, sampling frequencies, measurement methods, and data analyses techniques, the results will have limited application to management policy formulations. A description of these important processes and how they influence the problems facing Chesapeake Bay is contained in the next chapter.

A brief description of the overall program design is presented in chapter 3. In each subsequent chapter that addresses elements of the monitoring program, more specific aspects of the program design are discussed prior to the presentation of results.

ANALYSIS, INTERPRETATION, AND RESULTS

A critical step that determines the usefulness of the monitoring program is the analysis of data, interpretation of the findings and presentation of results. This final link is necessary to bring the wealth of information collected under the monitoring program into coherent and usable products. These products complete the sequence of events that allow the program to fulfill its objective of providing management with a valuable planning and assessment tool. Too often, ambitious and well-intentioned programs have floundered at this crucial final stage.

In order for the monitoring data to be used in the decision making process, it must first be meaningfully analyzed by one or more objective techniques. For some applications, a simple graphical analysis may suffice because the patterns are obvious or the analysis is exploratory in nature such as examining potential cause and effect relationships. Graphical analysis is also valuable for the preliminary phases of data analysis when, in many cases, insufficient data is available to warrant specific statistical tests. Graphical representations of the data are the principal products in this report because we are presently in the preliminary phases of data analysis.

In more rigorous levels of data analysis, objective statistical techniques are applied to evaluate hypotheses. Hypotheses, in the context of the monitoring program, are simply a formulation of the management questions into a statistically testable statement. For example, one of the management questions stated above concerning increased phytoplankton levels and the effectiveness of management inititives since 1980 could be formulated into the following specific hypothesis: Phytoplankton levels in the tidal fresh area of the Potomac River during summer have not changed since 1980. An appropriate statistical test could then be applied to either accept or reject this hypothesis. If the hypothesis was rejected and levels actually were shown to decline since 1980, the management question concerning trends in phytoplankton for this region would be answered. The use of statistics must be very carefully applied, however, paying particular attention to the assumptions of each technique in relation to the data that is available from the monitoring program. In fact, the requirements of statistical testing was one of the critical factors considered in the program's design to insure that appropriate data would be collected.

Once the monitoring data has been analyzed, the results must be interpreted in the context of the management decisions that will depend upon this information. Often, there will be numerous specific results from several different monitoring elements that must be synthesized into a unified finding about a particular management issue. It is also important that the results from the monitoring data be accompanied by some statement of the confidence, or scientific uncertainty, that should be associated with a particular finding. Confidence in the findings could include limits on the estimates of particular measurements of the Bay's condition or limits on the geographical locations to which a result may apply.

Finally, the interpretation of results should conclude with recommendations for management policies. This is the culmination of the sequence of events upon which that entire program is based. It presents managers with a suggested course of action based upon the careful evaluation of monitoring results. Of course, there are other considerations, as will be discussed in the following paragraphs, that also influence the final decisions on management policies and actions.

MANAGEMENT POLICIES AND ACTIONS

The degree to which OEP's monitoring program results are incorporated into the formulation of management policy and actions directed towards Bay restoration will determine the true efficacy of the program.

In almost all management decisions aimed at restoring the Bay, several issues must be considered. First, there is the technical foundation for the decision. This is where the monitoring program is expected to be a powerful tool. Sometimes the monitoring data will be used in conjunction with computer models to provide an added dimension of forecasting the outcome of a variety of potential management strategies. Results from research studies may also provide technical input in the area of cause-and-effect relationships.

Other important considerations that will bear upon a final management policy are the priorities of citizens who would be affected by the decision, the economics of the decision and the available technology to support the implementation of a particular management policy.

In the end, however, it is the monitoring program that will provide the verdict on the success of individual or collective management decisions. These evaluations will either lead to a strengthening of our original management positions or to a reformulation of strategies to provide more effective measures aimed at restoring the Bay's health.

A more detailed description of the strategies that will be used in the development of policies and management actions will be the subject of the final chapter.

2. understanding the bay's problems

An understanding of the problems that confront today's Chesapeake Bay is central to a strategy to restore and protect this valuable resource. Without an understanding of how this complex system responds to pollutants, it will be difficult to target effective management actions. Likewise, an understanding of the physical, chemical and biological processes in Chesapeake Bay played a central role in the formulation of the water quality monitoring program. Since the program is directed at specific management issues, there is a logical basis for including particular elements in the design. While it is necessary to monitor the obvious problem, for example low dissolved oxygen, it is also necessary to monitor the principal causes such as nutrient enrichment, phytoplankton growth and deposition, and water stratification which prevents oxygen from mixing into the bottom waters. Usually, the underlying causes, such as nutrient enrichment in the example just presented, are more directly under our control than are the impacts that develop as the Bay responds to pollutants. There are also natural processes, such as water stratification, which must be examined to place an evaluation of pollutant impacts in the proper perspective.

In this chapter, some of the major problems confronting Chesapeake Bay will be examined within the ecological context of natural physical, chemical and biological processes. This information is intended to assist in an understanding of why the monitoring program is designed as it is and to provide background information that may be helpful in the comprehension of subsequent chapters.

PROBLEMS CONFRONTING THE BAY

Most of the problems currently perceived as causing declines in the Bay's health have a common denominator—man. Man has acted directly by adding "wastes" to the Bay and its tributaries and by withdrawing its resources. Man has acted indirectly by changing the character of the land and air that surround and interact with the Bay.

The most profound Bay-wide impacts have resulted from large inputs of nutrients and other chemicals from sewage treatment plants or industrial operations, referred to as point sources, and from stormwater running off urban or rural land, referred to as nonpoint sources. These inputs are primarily composed of natural elements which are entering the Bay in excessive quantities. These are elements that normally recycle in the environment between plant and animal or between land, water and air. Problems have been created because of major perturbations in the balance of these recycling processes due largely to high populations along the shores of Chesapeake Bay. This imbalance results in an abnormal shift of recycled products, such as nutrients, so that they now enter and accumulate in Bay waters. When the shift in the balance of recycling is considerable, as it is in some regions of Chesapeake Bay, these natural products can cause severe problems. The nature of these impacts will be discussed later.

Another type of problem confronting the Bay comes from toxic compounds, unnatural products created by man or naturally-occurring chemicals that are concentrated to levels far exceeding the trace quantities normally found in the environment. These compounds are usually discharged during the manufacture, application or disposal of various products. These toxicant problems tend to be most severe in regions of the Bay where manufacturing industries or waste disposal sites are concentrated. The problems caused by toxic compounds are difficult to predict or understand because of their extremely complex chemical properties. It is known, however, that serious human and environmental health impacts may result when these compounds enter the Bay.

THE BAY ECOSYSTEM

Chesapeake Bay—the mainstem and tidal tributaries—constitutes an ecosystem. An ecosystem is a unit within which there is close linkage of many physical, chemical and biological processes such as water circulation, nutrient recycling and food chains. Ecosystems interact with adjacent ecosystems, making their boundaries sometimes difficult to distinguish. Chesapeake Bay is an **estuarine** ecosystem.

As an estuarine system, Chesapeake Bay is one of the most complex ecosystems. Within its boundaries exist a range of aquatic environments, from fresh to nearly full-strength seawater, allowing a broad spectrum of organisms to flourish and chemical reactions to proceed. It has complex physical circulation patterns that vary with season, tide and weather. Outside of its boundaries, adjacent or sometimes remote ecosystems influence Chesapeake Bay, thereby contributing additional complexity (Figure 1). Many of these

Figure 1. *Influence of adjacent ecosystems on the Chesapeake Bay ecosystem.*

external effects are mediated through the atmosphere such as rainfall which affects freshwater, nutrient and sediment inputs to the Bay and wind patterns which exert strong influences on water circulation within the Bay. Acidic precipitation, originating from distances of hundreds of miles surrounding the Bay, is also transported by the atmosphere. Other external effects arise because several key living resources such as blue crabs and striped bass migrate to spend part of their lives outside of the Bay. Unfavorable currents in coastal waters off the mouth of the Bay and successful fishermen off the New England coast can have appreciable impacts on the abundance within the Bay of blue crabs and striped bass, respectively.

POLLUTANT IMPACTS IN THE CONTEXT OF NATURAL PROCESSES

Estuaries, like many ecosystems, are resilient in response to natural perturbations of the environment such as large storms and droughts. The system may be knocked out of balance by these unusual events, as Chesapeake Bay was during and after tropical storm Agnes in 1972. Nevertheless, the Bay gradually returns to a state similar to that existed prior to the disturbance. Similarly, most systems can remain relatively unchanged when confronted with a modest level of anthropogenic (of human origin) influences. However, there are often thresholds beyond which resilience or assimilative capacity for a given system can be exceeded, resulting in significant changes in the balance of the ecosystem. When these thresholds are exceeded, as they appear to be in parts of Chesapeake Bay, the system responds with perceptible changes or **impacts**. In the Bay, these impacts can take the form of low dissolved oxygen concentrations, turbid waters and lowered abundances of fish and shellfish. Because these impacts are usually the result of substantial historical as well as ongoing anthropogenic influences that have finally overwhelmed the Bay's assimilative capacity, responses to measures taken to rectify the problems may not become apparent for many years. Thus, the effort to improve conditions in Chesapeake Bay and to monitor the progress of management actions will need to be sustained for many years before the goal of improving the Bay's health can be realized.

To develop and evaluate plans for protecting and restoring the Bay, one must have an appreciation for the complex interactions that mediate between anthropogenic influences, such as sewage treatment plant discharges or urban runoff, and measurable ecosystem impacts. The measurable impact, such as low dissolved oxygen or reduced fisheries yield, often results from a convoluted series of physical, chemical and biological events that may make the impact seem unrelated to the cause in character, time or place. For example, land use changes in Pennsylvania could cause appreciable increases in the amount of nitrogen and phosphorus entering the Susquehanna River and ultimately transported by spring runoff into Chesapeake Bay. An increase in nitrogen and phosphorus may fuel excessive summer algal growth in the upper Bay. Much of this algal production may then settle in the deep waters of the Bay in Maryland resulting in oxygen deficient waters as this algal material is metabolized by bacteria. Thus, the observed impact, which is low dissolved oxygen, is much different than the cause, which is land use practice. The impact occurs far away from the cause of the problem and it may be several months before the pollutant input is manifest as an impact.

Physical Circulation Patterns are one of the most important characteristics of the Chesapeake Bay estuary. Although quite variable, most of the mainstem and the lower reaches of the tributaries generally have a two-layer flow pattern with lighter, fresher surface waters showing a net flow seaward and heavier, saltier bottom waters showing a net flow landward (Figure 2). This circulation pattern has profound influences on both natural processes and man's disturbances. Many small but important organisms such as oyster larvae and phytoplankton (microscopic plants suspended in the water column) depend upon the deeper, landward moving waters to reach favorable areas of the Bay and complete their life cycle. At the same time, this two-layer flow tends to trap material that enters the Bay either naturally or through man's activities. Inputs to the Bay generally enter the system in surface layers, far from the mouth of the Bay. During seaward transport, much of this material tends to settle to deeper waters. Once it reaches these bottom layers, the settling material starts travelling back up the Bay or is deposited in the sediments. Whether in the lower portion of the water column or in bottom sediments, the material can undergo chemical and biological transformations and continue through additional transport cycles

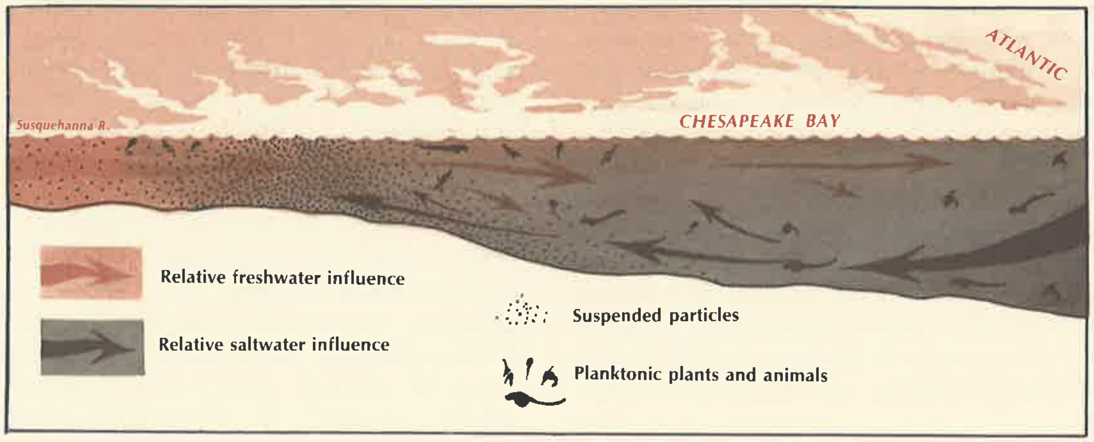


Figure 2. *Two-layered flow patterns of Chesapeake Bay waters showing net down-Bay movement of surface waters and net up-Bay movement of bottom waters.*

between surface and bottom waters. Ultimately, however, little of the material that enters the Bay ever exits from its mouth. This concept is particularly important to understanding the effects of pollutants which are not "flushed away" as in free-flowing rivers but are "trapped" in the estuary. The "trapping" of pollutants is another reason why the restoration of Chesapeake Bay will require a long-term commitment; it will take some time to dissipate the accumulation of inputs that have entered over the past decades.

Chemistry plays a large role in both the natural processes and anthropogenic disturbances of an estuary. All life is dependent upon numerous chemical reactions which are ultimately driven by the energy of sunlight. This energy is captured by plants during a process known as photosynthesis. This captured energy is stored in chemical bonds between elements such as carbon, oxygen, hydrogen, nitrogen and phosphorus which serve as building blocks for the complex molecules synthesized by the photosynthetic chemcial reactions within plants. In turn, animals and bacteria, as they digest their food, break down the complex molecules to capture energy stored in their chemical bonds. In this breakdown process, the building block elements are released back into the water. This continuing process of synthesis and degradation is known as recycling. As noted earlier, it is often the imbalance of these normal recycling processes that have impacted the Bay's health.

In most natural systems, chemical recycling is reasonably "tight", meaning that chemical synthesis from building block elements roughly balances their release by degradation processes. In Chesapeake Bay. However, the balance of recycling processes in the Bay has been affected by the unusually high import of building block elements such as nitrogen and phosphorus generated from human biological waste and runoff from altered land surfaces. One of the outcomes of this chemical imbalance is a condition known as eutrophication which will be elaborated upon below.

Biological Processes in Chesapeake Bay are the most visible and relevant to most people. The crabs and oysters on your plate or an algal bloom on the Potomac River that looks like green paint are vivid examples of the Bay's biological activity. Often it is the abundance of biological resources that are used to judge the "health" of the Bay.

Biological processes are governed by the chemical and physical environment discussed above and by biological interactions such as those occurring in the food chain (more correctly labeled the **food web** to indicate complex linkages). In aquatic ecosystems such as Chesapeake Bay, most biological processes are fueled by the growth of phytoplankton, the principal photosynthetic organisms. The growth, or production, of phytoplankton requires light, water and the presence of several essential elements. In Chesapeake Bay, as in other aquatic systems, levels of nitrogen, phosphorus, light and temperature appear to be the major determinants of phytoplankton production. Much of the phytoplankton production is utilized to sustain the growth of higher organisms such as zooplankton (microscopic animals in the water column) and benthic organisms living within or on the bottom sediments. These consumers in turn fall prey to larger and larger animals, ultimately leading up to predatory fishes such as the striped bass and other high-level predators such as birds and humans who remove biological resources from the Bay.

At the same time that biological production is passing up the food web to higher predators, some of that production, in the form of biological wastes or dead organisms, is shunted to pathways that lead to decomposition of this matter into its basic elements. This decomposition is usually mediated by digestive enzymes in the guts of animals and by bacteria, either free-living in the environment or harbored within organisms. In the Bay these decompositional processes are actively occurring both in the water column and in the sediments. The basic elements regenerated by decomposition can then be utilized once again by phytoplankton populations and the circular pathway describing the recycling of chemical elements is completed. Many of the biological, chemical and physical interactions important to the Bay ecosystem are diagrammed in Figure 3.

The preceding discussion has emphasized the need to understand physical, chemical and biological factors and their interactions when confronted with the task of protecting and restoring the Bay. One of the most profound conditions affecting the Bay – **eutrophication** – is a typical example of how physical, chemical and biological processes interact in response to anthropogenic inputs to produce a significant impact on the Bay (Figure 4). It also points out the need for a monitoring program that is comprehensive in its approach so it can yield the information necessary to guide management actions.

Eutrophication is a term used to describe the overenrichment of aquatic systems by excessive inputs of phytoplankton nutrients, typically phosphorus and/or nitrogen. In unimpacted systems, nutrients are present in such low quantities that algal growth is controlled. In systems with an oversupply of these nutrients, the growth of phytoplankton is stimulated, initiating a chain of events that leads to the symptoms of eutrophication. Usually, a major fraction of the enhanced phytoplankton growth cannot be assimilated through the normal food web. This situation occurs because there simply is too much phytoplankton being produced or because certain phytoplankton species, which are unpalatable and thus not eaten by the important small animal consumers, start to flourish under these conditions.

Sometimes, the excessive algal growth of eutrophic waters is readily visible as algal "blooms" or "scums" that form near the surface. More typically, much of the activity associated with eutro-

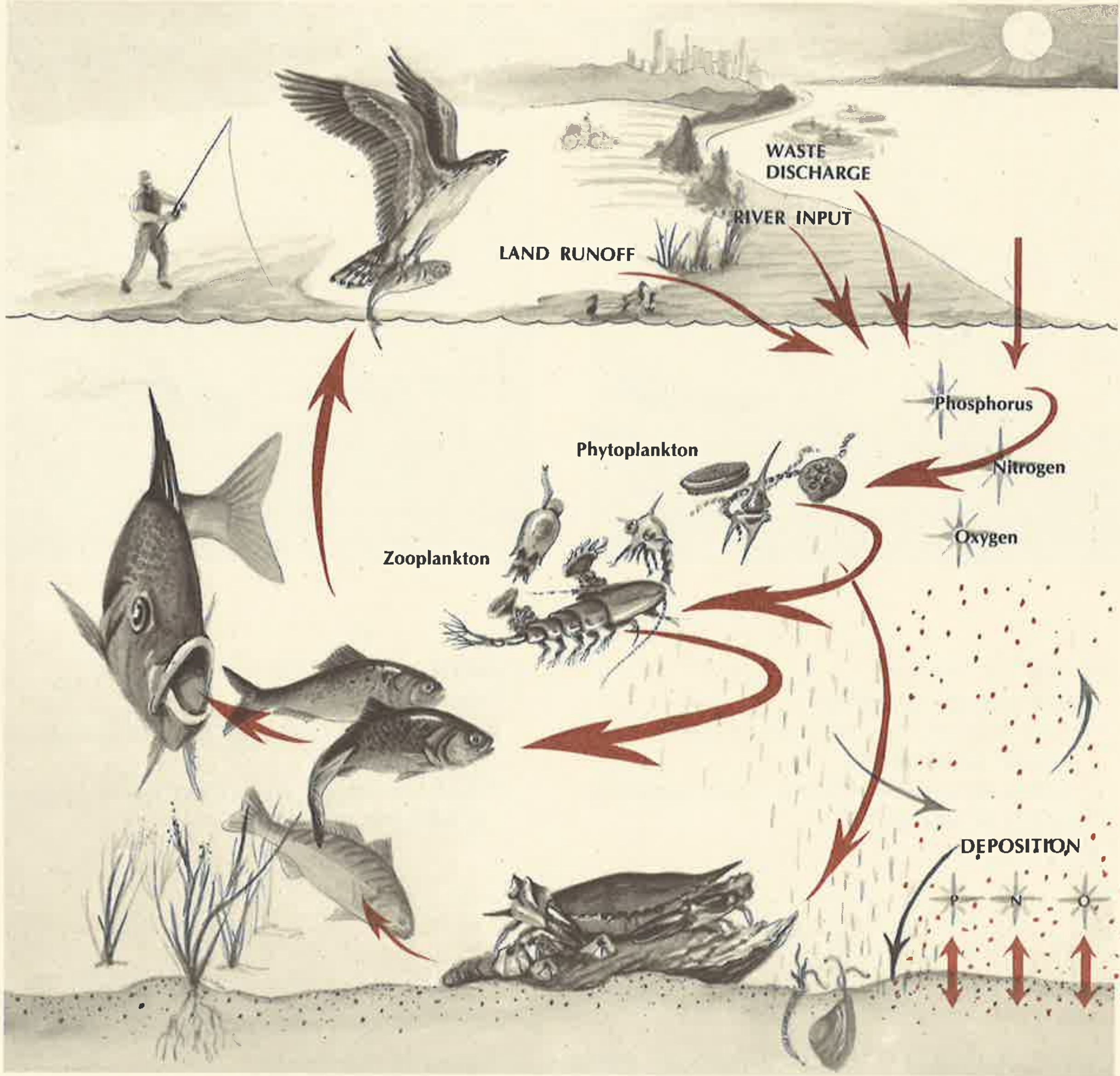


Figure 3. *Major ecological relationships in Chesapeake Bay.*

phication is hidden below the surface. The large mass of algal growth that does not enter the food web pathways leading to larger animals, enters the decomposer pathways as it sinks to bottom waters and sediments. The decomposition of this algal matter by bacteria requires large amounts of oxygen which quickly depletes dissolved oxygen from bottom waters. Physical circulation patterns in many parts of the Bay during spring and summer exacerbate the problem by restricting the mixing of oxygen-rich surface waters with bottom waters. Furthermore, there are some complex chemical conditions produced by eutrophication which cause additional phosphorus and nitrogen to be released from sediments. These additional inputs of nutrients tend to further accelerate the eutrophication process by prolonging or stimulating additional algal growth.

Low oxygen conditions produced by eutrophication result in major losses of habitat for fish and shellfish that cannot survive in these stressed environments. Eutrophication also causes much of the turbidity that affects the aesthetic appeal of Bay waters in many areas. Thus, a complex series of underlying physical, chemical and biological processes has transformed an anthropogenic influence into a wide-ranging impact. As this example demonstrates, if we are to make progress in the effort to protect and restore Chesapeake Bay, the underlying causes of each problem must continue to be monitored, understood and **acted** upon so that the damaging impacts can be mitigated.

BALANCED SYSTEM
- **algal growth controlled**
- **water transparency high, encouraging aquatic plant growth**
- **sufficient oxygen in bottom waters support a variety of aquatic life**

EUTROPHIC SYSTEM
- **algal growth excessive**
- **water transparency reduced, limiting aquatic plant growth**
- **depleted oxygen in bottom waters reduces habitat for aquatic life**

Figure 4. *Comparison of balanced and eutrophic conditions in an estuarine environment.*

3. program description

The OEP Chesapeake Bay Water Quality Monitoring Program is a carefully assembled group of monitoring components all guided by the same philosophy and integrated into a unified study. This integration was incorporated in the study design phase, it is in place during implementation (for example, the coordination of sampling activities), and it is a key aspect in the analysis of results. The objectives followed consistently for all components, reflecting the major management questions as described in Chapter 1, are:

- **Characterization** of the existing baseline water quality conditions.
- Detection of **trends** in water quality indicators.
- Increasing the understanding of **processes and causes** affecting Bay water quality and the linkage between water quality and living resources.

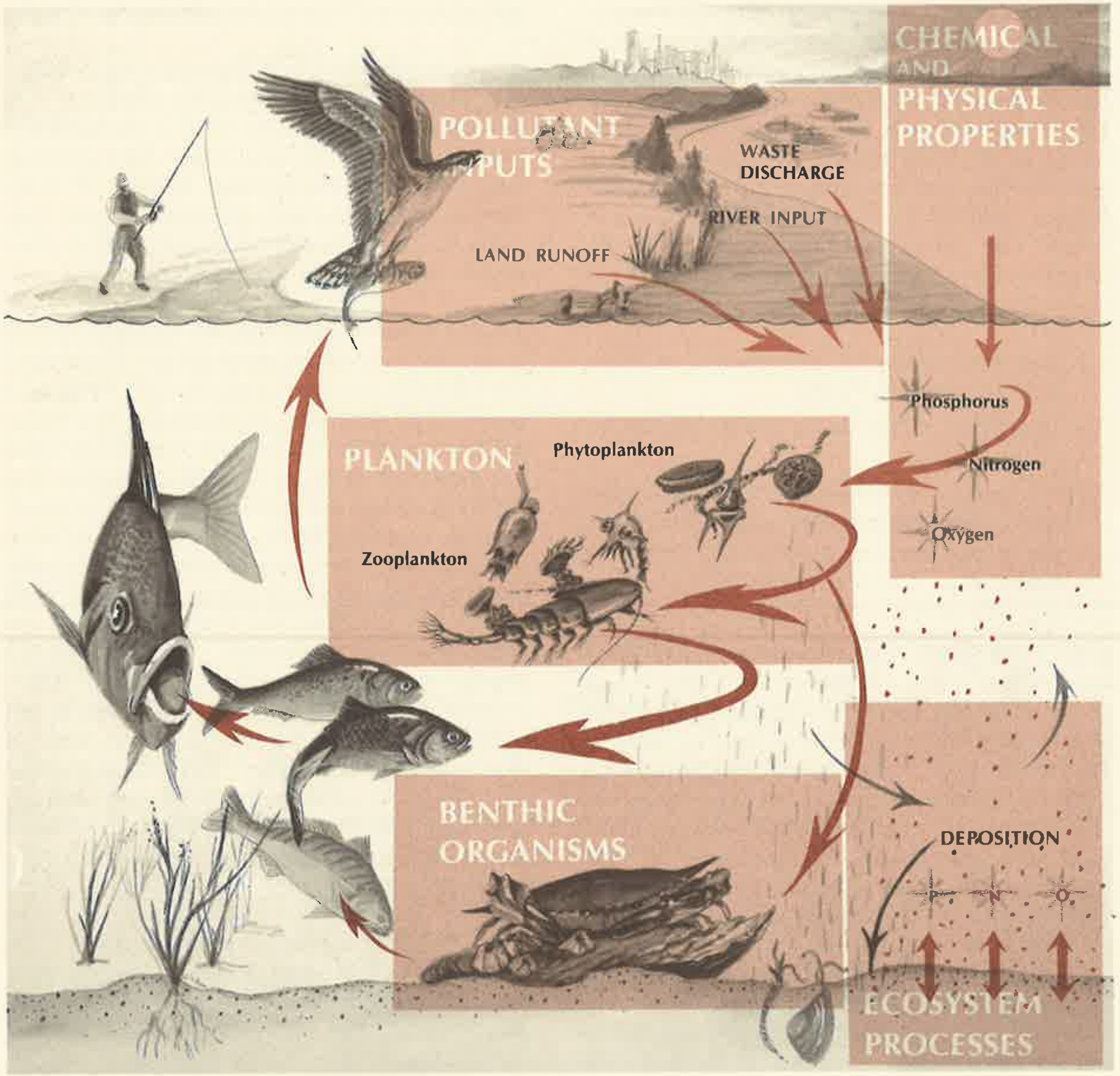
Before the State's recent monitoring initiatives commenced in the Summer of 1984, certain segments of the Bay had been studied intensively for only brief periods of time and often only in selected seasons. In one area, chemical and physical measurements may have been taken. In other areas or times, biological measurements may have been taken. This level of effort may have been sufficient for the objectives of each of these studies but it left many gaps in our understanding of the Bay.

The newly initiated OEP water quality monitoring program closes the previously existing gaps by being **comprehensive**, maintaining a **Bay-wide** perspective and having a **long-term** commitment.

It is **comprehensive** in its approach by including the most important physical, chemical and biological measurements from a management and scientific perspective. These measurements take place in a coordinated fashion, in many cases at exactly the same times and places; data collected in this way enhances our ability to interpret linkage between monitored parameters.

Second, a **Bay-wide** perspective has been applied to the location of sampling stations throughout the tidal tributaries and mainstem of Chesapeake Bay. Existing programs, such as that in the Patuxent River, were enhanced and incorporated into the expanded program while those regions that lacked coverage are now included. As a result, every major tidal tributary in the State is included in the present monitoring network, as well as the mainstem from Havre de Grace at the head of the Bay to the mouth of the Potomac River at the State line. The Bay-wide coverage reaches beyond our state boundaries with similar efforts in Virginia and Pennsylvania, coordinated by the three states and EPA. Bay-wide coverage is necessary in order to effectively evaluate where and how pollution control measures are working, to identify regions in need of additional remedies and to better understand the fate and effect of pollutant inputs.

Third, this monitoring program has been constructed with a **long-term** perspective, as mandated by a bill passed in the 1985 State legislature which directs Maryland's OEP and Department of Natural Resources to initiate and continue moni-



toring of the Bay's water quality and living resources. In a system as large and complex as Chesapeake Bay, where natural year-to-year variability can make trends difficult to discern, several years of record are required to make reliable assessments from monitoring programs. Furthermore, the challenge of cleaning up Chesapeake Bay is likely to continue well into the future, requiring continued vigilance as added pressures impinge upon its shores.

Each component within the overall Water Quality Monitoring Program was chosen with an ecological perspective to provide a comprehensive set of important water quality indicators. While each component individually is capable of providing an indication of Chesapeake Bay water quality, the synthesis of information from all of these elements permits much more precise and meaningful assessments to be made. Each of these components is portrayed in Figure 5 and explained briefly below.

Figure 5. *Components of the OEP Water Quality Monitoring Program in the perspective of major ecological relationships in Chesapeake Bay.*

Chemical and Physical Properties - The measurement of chemical and physical variables such as salinity, dissolved oxygen, suspended sediment and nutrients, provides baseline data to characterize physical properties of the system such as stratification and provide knowledge of the levels and distributions of important pollutants. This element has the most intensive spatial and temporal coverage and forms the foundation for interpreting measurements from all other components.

Toxicants - Toxic pollutants, both metals and organic compounds, are measured in the sediments where they tend to accumulate after being discharged into the estuary. Levels in the tissues of benthic organisms are also monitored as an indicator of accumulation in the food chain.

Plankton - Plankton include the microscopic plants and animals suspended in the water column that form the base of the estuarine food web. Thus, they are directly or indirectly crucial to the success of important Bay resources such as fish and shellfish. These organisms are also responsible for the symptoms of eutrophication, such as low dissolved oxygen and decreased water clarity, that result from excessive nutrient inputs.

Benthic Organisms - Benthic organisms, which live in or on the bottom sediments of Chesapeake Bay, have a prominent role in the food web as important components of fish and crab diets. They also mediate in many processes occurring where bottom sediments interface with the overlying water column. They are good indicators of Bay water quality, especially local conditions, since they occupy a relatively fixed position on the Bay bottom and respond to changes over both long and short time intervals.

Ecosystem Processes - Many of the important water quality indicators are not static measures, but rather processes or rates that reflect the dynamic nature of water quality in Chesapeake Bay. Several of these processes were chosen as a separate element of the OEP program such as sediment-water column exchanges of nutrients, oxygen and particulate matter. Other important processes such as phytoplankton growth rates and river inputs are included as part of other program elements.

Pollutant Inputs - The input of freshwater, sediment and nutrients from the major rivers and point sources control water quality to a large extent in the Bay and its tributaries. This component therefore becomes crucial to an interpretation of Bay water quality and to track the progress of management actions throughout the Chesapeake Bay basin. River input monitoring is the major new initiative in the OEP program.

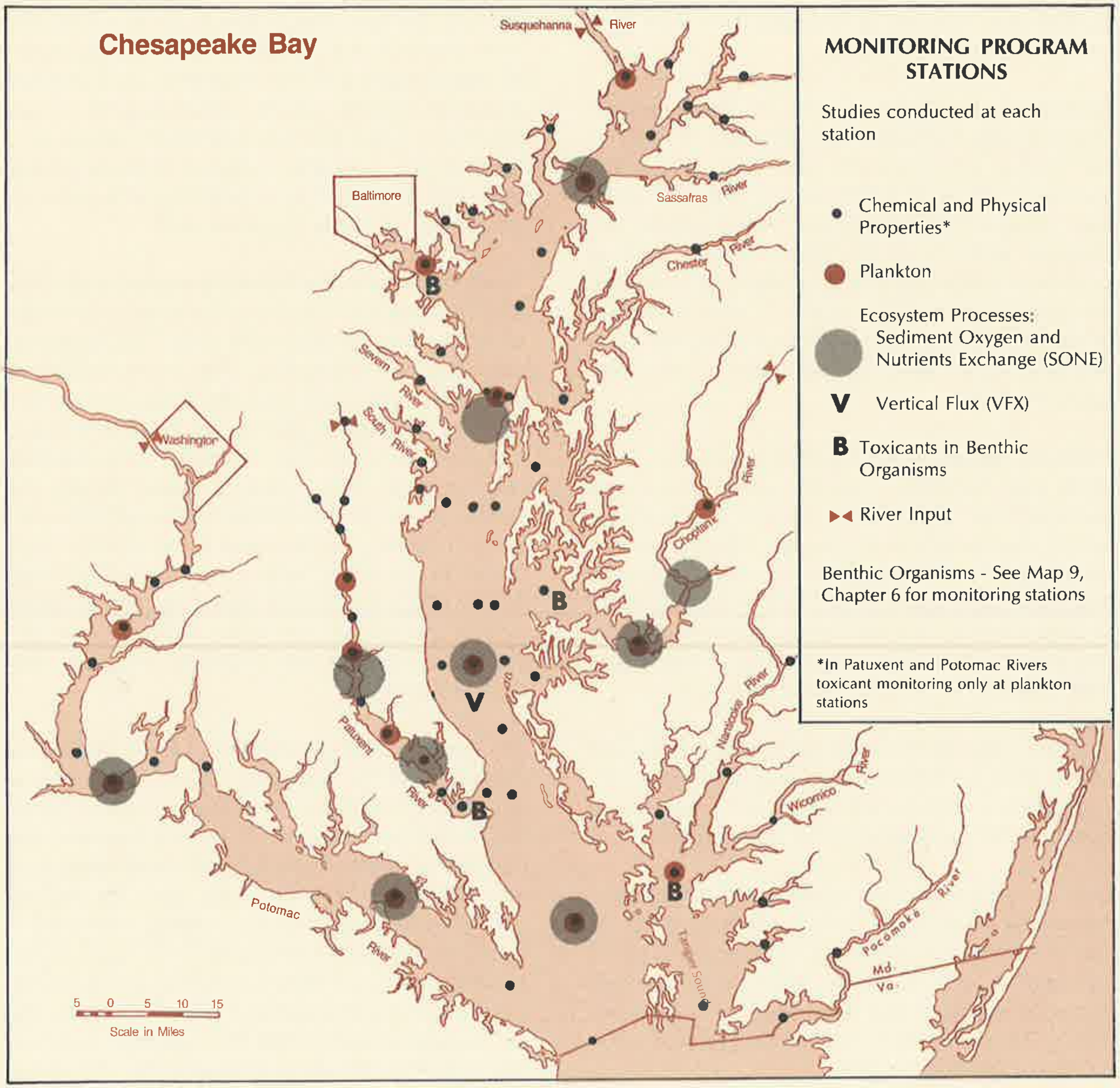
In assembling the monitoring elements described above into a unified study, several design considerations were applied uniformly to insure success in achieving the program's objectives.

First, no elements were considered for monitoring unless there was a sound scientific basis for measuring the parameters that comprise a given component. Where some uncertainty existed, literature reviews and pilot studies were conducted before implementation to evaluate alternative monitoring designs.

Second, the selection of sites to be monitored for each element was designed to be representative of major regions in the mainstem and tributary estuarine system. Other considerations in site selection, once the representative nature of a location was satisfied, included important habitats, such as striped bass spawning areas, and the availability of useful historical data.

Third, frequency of monitoring was tailored to the known temporal variability for given parameters to efficiently and effectively utilize the resources available for monitoring. The more variable a parameter is through time, the more frequently it must be sampled to provide an accurate and precise measurement. For example, river loadings can undergo very rapid changes during the course of a storm and therefore conditions must be monitored several times a day during these events to provide an accurate picture of loadings. At the other end of the spectrum are sediment measurements that are more stable in character through time and are therefore sampled only once per year.

The management of information generated by the program and the reporting of results is a critical final step in the program design. Much of the effort to date in this aspect of the program has been devoted to constructing a reliable and responsive data base from which to draw upon for analysis and interpretation. All data being collected is stored on computer-based media for rapid access and manipulation. Rigorous quality assurance insures that the data collected in the field and in the lab is reliable and meets the intended needs of the program. Reporting of results from the moni-



MONITORING PROGRAM STATIONS

Studies conducted at each station

● Chemical and Physical Properties*

● Plankton

● Ecosystem Processes:
Sediment Oxygen and Nutrients Exchange (SONE)

V Vertical Flux (VFX)

B Toxicants in Benthic Organisms

▶◀ River Input

Benthic Organisms - See Map 9, Chapter 6 for monitoring stations

*In Patuxent and Potomac Rivers toxicant monitoring only at plankton stations

Map 1.

MONITORING COMPONENTS

Yearly frequency of sampling for parameters measured by the monitoring program

	MEASURED PARAMETER	Chemical and Physical Properties	¹Plankton	Benthic Organisms	Ecosystem Processes		²River Input
					SONE	VFX	
WATER COLUMN	Salinity	12-20		10	4	17	12+
	Conductivity	12-20		10	4	17	365
	Temperature	12-20		10	4	17	365
	Dissolved Oxygen	12-20		10	4	17	12+
	pH	12-20		10			12+
	Secchi Depth	12-20					
	Nitrogen	12-20			4	17	12+
	Phosphorus	12-20			4	17	12+
	Carbon	12-20			4	17	12+
	Silicon	12-20			4		12+
	Total Suspended Solids	12-20			4	17	365
	Chlorophyll a	12-20	18		4		12+
	Pheophytin a	12-20	18		4		12+
	Phytoplankton Productivity		18				
	Species Composition, Abundance and Biomass		12-18	10			
	Freshwater Discharge						365
SEDIMENTS	Oxygen Demand				4		
	Nitrogen Content and Flux				4	17	
	Phosphorus Content and Flux				4	17	
	Carbon Content or Flux	1		10	4	17	
	Silicon Flux				4		
	Chlorophyll a					17	
	Phytoplankton species composition and abundance					17	
	Particle Size Distribution	1		10			
	Moisture Content	1		10			
	³Organic Toxicants	1					
	³Metal Toxicants	1					

[1] *Sampled in coincidence with chemical and physical properties; includes phytoplankton, microzooplankton and mesozooplankton.*

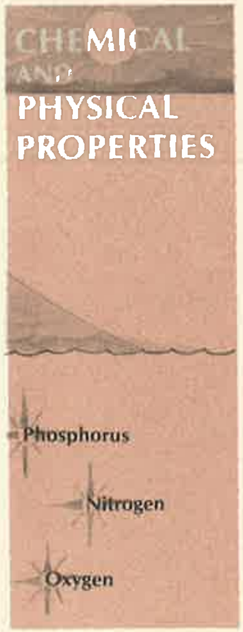
[2] *12+ indicates that frequency of sampling includes monthly measurements plus intensive sampling during storm events.*

[3] *These parameters were also measured in benthic organisms from 1 to 3 times per year.*

toring program is also proceeding as planned. Yearly data reports have been and will continue to be forthcoming from each of the individual monitoring components in a common format; these individual reports can be viewed as the building blocks for subsequent, more synthetic data analysis efforts. In future stages of the program, when the data base is sufficient to achieve this more synthetic level of analysis, the results of individual monitoring elements will be brought together to form a comprehensive interpretation of Chesapeake Bay water quality. This synthesis of information from all the interrelated indicators of water quality, is the strength of the State's program. Following this report, at two year intervals starting in the fall of 1988, there will be a technical synthesis report of information from the monitoring program. A concise summary, distilled from this technical synthesis, will be produced by the spring of the following year. The yearly data reports from each monitoring element, and the two levels of synthesis every other year, will insure that all citizens, legislators, managers and scientists can profit from the State's assessment of Chesapeake Bay water quality.

The present suite of program components, sampling locations (Map 1) and sampling frequencies represents an efficient and cost-effective design. One could always point, however, to areas in the Bay without sampling sites for certain variables or the additional information that could be gained with more sampling trips. But, this thinking must be balanced by the benefit that such additional information would yield for the expense involved. This cost-benefit analysis was also a major factor in the selection of the monitoring program design. The current design yields a practical and technically sound program capable of reaching its objectives on a Bay-wide scale and capable of being sustained for the time necessary to reach its major objectives.

4. chemical and physical properties



The chemical and physical properties of an estuary provide many of the fundamental indicators of water quality. Chemicals such as nutrients and toxicants reflect most directly the impacts of man's activities on the Bay. Once in the Bay ecosystem, these chemicals can undergo a variety of transformations and exert a strong controlling influence on living resources and the biological food web. Physical properties such as water transparency, temperature and density stratification show both human impacts and natural processes. An understanding of these physical properties is often crucial to the interpretation of chemical and biological elements of the monitoring program.

The success or failure of efforts to restore the Bay will first be evident in the chemical and physical data from this monitoring program. Indicators such as nutrient and dissolved oxygen concentrations will signal important changes in the Bay. The response of other biological indicators and living resources will require more time as the perturbed food web readjusts and pollutants stored in the system are dissipated. This rapid and interpretable response in chemical and physical indicators is vital to the success of management strategies. These strategies must be evaluated as quickly as possible to insure that they are properly targeted and cost-effective.

DESIGN CONSIDERATIONS

Because chemical and physical measures provide the most fundamental and interpretable indicators of water quality, they were given the broadest spatial and temporal coverage within the overall program. The chemical and physical indicators also provide a baseline of information for the interpretation and extrapolation of biological and process measurements made at a subset of stations.

In order to characterize water quality in the Chesapeake Bay system, virtually every significant tributary to the Bay as well as the mainstem has been included in the sampling design (see Map 1). All stations are located in tidal waters with salinity regimes ranging from completely freshwater in the upper tributaries and mainstem to over 20 parts per thousand (60% seawater) in bottom waters of the mainstem near the mouth of the Potomac.

In smaller tributaries, where only one site was sampled, stations were located near the upper extent of the main channel regions. These areas are generally representative of local water quality conditions in each of the basins and avoid the often overwhelming influence of mainstem waters near river mouths.

In larger tributaries and the mainstem, multiple stations were sited along their length to characterize the strong spatial gradients that usually occur from upper, freshwater reaches, to lower, high salinity estuarine reaches. In the Potomac and Patuxent Rivers, two of the largest tributaries in Maryland, ongoing intensive sampling networks were incorporated into the present program design. In the deep-trough region of the mainstem, where low oxygen problems are most severe, four lateral transects were established to characterize west to east differences in water quality.

In the siting of station locations within representative regions, other considerations such as important habitats (for example striped bass spawning reaches), historical records and local influences such as sewage treatment plants, basin morphometry, and hydrodynamics, were incorporated into station siting decisions.

At each station, measurements of salinity, dissolved oxygen, temperature, pH and water transparency, are made. Water samples are collected at one or two depths in both surface and bottom waters to provide representative samples from the water column. These water samples are then chemically analyzed for nitrogen, phosphorus, carbon and silica constituents, total suspended solids and chlorophyll, which is a measure of phytoplankton biomass.

The frequency of water column sampling is up to 20 times per year - 2 times per month from March through October and once per month from November through February. In smaller tributaries, the frequency of sampling is once per month year-round. This frequency of sampling is intended to provide reliable estimates of seasonal changes in water quality and provide a measure of variability within seasonal time frames.

Monitoring for toxicants is focused primarily on the analysis of sediments. This strategy is followed because most toxicants that are released into the water become associated with particulate material, settle and thus become concentrated in bottom sediments. Higher concentration of toxicants in sediments aid in the detection and quantification of these compounds. Toxicants deposited in the sediments also provide an integration of exposure over time within a region.

Sediment samples are collected once-yearly at most of the water quality stations for the analysis of organic compounds and heavy metals. These compounds represent likely contaminant inputs from point and nonpoint sources such as industries, croplands and sewage treatment facilities. Associated measurements such as sediment grain size and organic matter content are made to aid in the interpretation of toxicant concentrations. In addition, at selected sites, the same compounds measured in sediments are also measured in the tissues of benthic organisms that are abundant in these locations. These tissue levels provide an assessment of contaminant levels entering the food chain and the relationships between contaminants in the sediments and in organisms living on or in those sediments.

RESULTS

Physical Characteristics

During the initial two years of the program, the Bay exhibited very different physical characteristics resulting from large differences in freshwater flows. These contrasting years provide an indication of how much natural variability we might expect to encounter on a year-to-year basis. In 1984, most basins draining into Chesapeake Bay experienced flows 30% to 100% above normal during the summer while flows in the summer of 1985 were 20% to 50% below normal. These differences in freshwater flow produced noticeable differences in the physical structure of Bay waters. For example, in the deep waters of the mainstem, high flows in the summer of 1984 reduced surface and bottom salinities by approximately 6 parts per thousand (ppt) and 3 ppt, respectively, relative to 1985 (Figure 6, A and B). This resulted in a larger salinity difference from surface to bottom in 1984. These surface to bottom changes in salinity restrict the mixing of surface and bottom waters and therefore mixing was more restricted in the summer of 1984. The strength of this barrier to mixing can have important implications for water quality conditions; its effect on dissolved oxygen concentrations will be discussed below.

Suspended solids concentration in the water column is an important water quality indicator beacause of its effect on water transparency. These suspended solids consist of inorganic material such as clays and organic material such as living phytoplankton. Suspended solids reduce the depth to which sunlight can penetrate, thereby reducing the habitable zones for phytoplankton and submerged aquatic vegetation which depend upon light to grow. Water transparency, or turbidity, is considered the primary limiting factor to phytoplankton growth in some regions of the Bay. Reduction in light penetration has also been implicated as a major cause of declines in submerged aquatic vegetation in recent decades.

As with many other water quality constituents, suspended solids in the Bay's tidal waters are influenced by river inputs. Management actions in the Bay's watersheds that stabilize soil and shoreline erosion will help to reduce the river

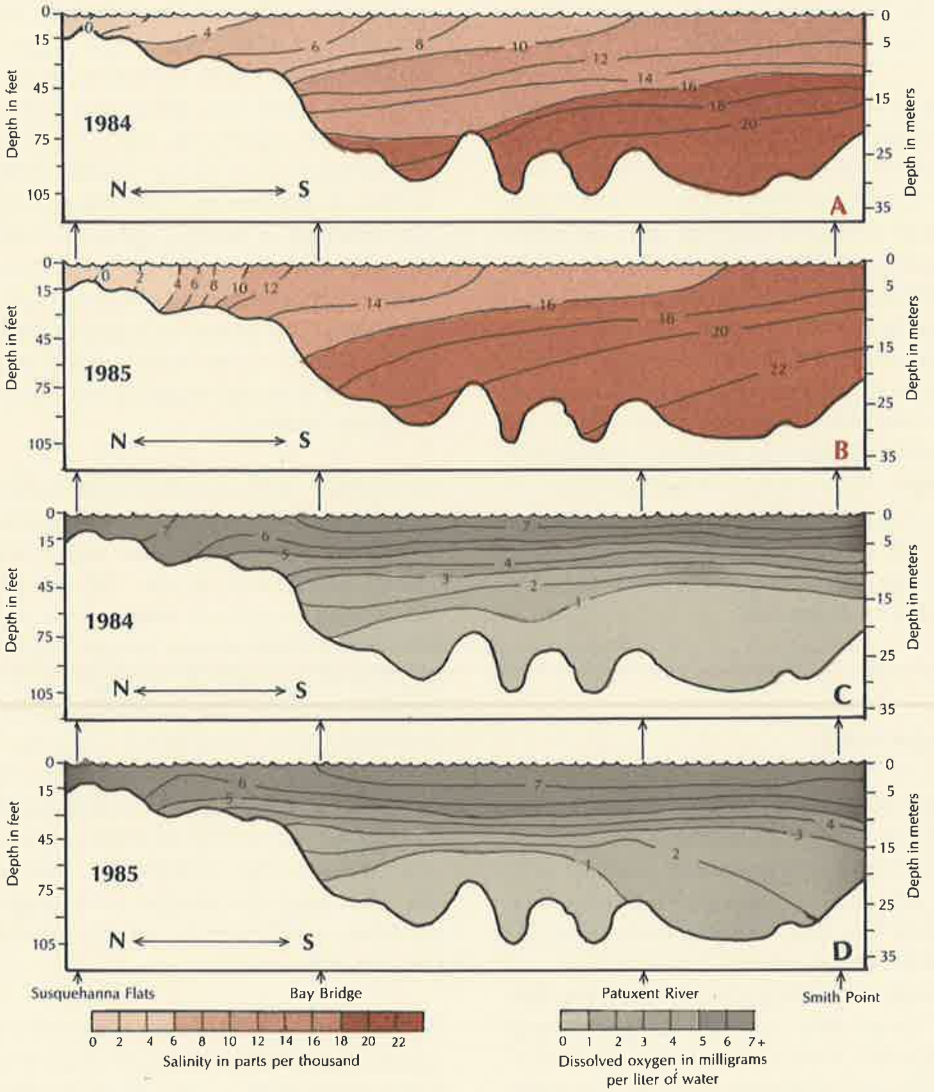


Figure 6. *Longitudinal profiles for average salinity and dissolved oxygen in the Chesapeake Bay mainstem during the summers of 1984 and 1985.*

loadings of suspended sediments and in turn increase water transparency. Natural processes also contribute to the amount of suspended solids in the water column. In areas of high mixing such as near the upstream extent of salinity intrusion in the mainstem and tributaries, there is usually a peak in suspended solids called the "turbidity maximum". In this region, trapping of river-derived inputs and resuspension of bottom sediments contributes to high levels of suspended solids. This turbidity maximum region occurs between Pooles Is. and Turkey Pt. in the mainstem of Chesapeake Bay. Here, turbidity is highest and total suspended solids are generally 15-25 mg/l (mg = milligrams of mass and l = liters of volume) in surface waters.

Below the influence of river-borne inorganic sediment loads and the turbidity maximum region, turbidity generally declines and phytoplankton populations become a more important factor affecting water clarity. These areas are expected to show decreases in turbidity in response to nutrient control measures which limit phytoplankton growth. In the lower Maryland Bay, turbidity declines and total suspended solids decrease to about 5-10 mg/l. Turbidity in the mainstem is shown in Figure 7. This relative measure of turbidity was derived from Secchi disc readings which measure water transparency. The up-Bay to down-Bay gradient from high to low turbidity is evident at all times of year.

Dissolved Oxygen

Depletion of oxygen in bottom waters is one of the more devastating symptoms of the stresses

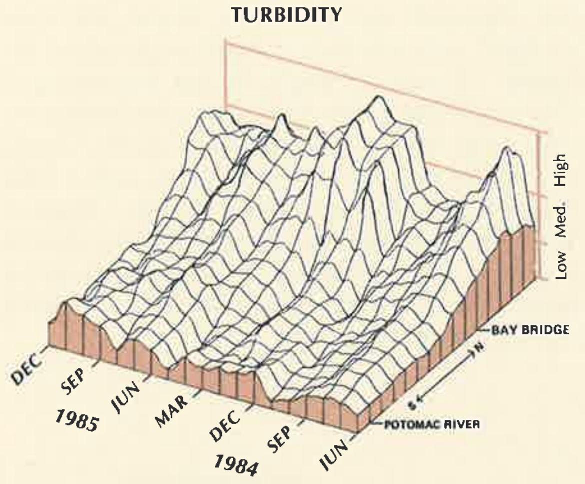


Figure 7. *Turbidity levels in the Chesapeake Bay mainstem from June, 1984 through December, 1985.*

being placed on Chesapeake Bay. The increased severity of dissolved oxygen depletion in Chesapeake Bay has caused declines in habitat for living resources as well as causing direct mortalities of fish and shellfish. It is therefore very important that we monitor dissolved oxygen conditions to determine with better certainty where problem areas occur and how they might respond to management initiatives. It is also important to understand both the natural and anthropogenic contribution to this problem so that these two factors can be differentiated in our analysis of the data. The importance of natural processes is evident when comparing the summers of 1984 and 1985.

Low dissolved oxygen develops in bottom waters as a result of the interplay between two opposing processes. High levels of organic material in Bay bottom waters and sediments decompose and in the process consume large amounts of oxygen. At the same time, oxygen from the atmosphere and from phytoplankton photosynthesis in surface waters is mixing downward to replenish oxygen levels in bottom waters. In the spring and summer, due to high levels of organic material (largely derived from algal growth) and high temperatures which enhance decompositional processes, the oxygen in bottom waters is consumed at very rapid rates. This is also a time of year when mixing of surface and bottom waters is inhibited by large differences in surface to bottom salinity. Thus, it is in the spring-summer period when the interplay between consumption and re-oxygenation causes oxygen levels in bottom waters to reach a yearly minimum.

As mentioned previously, (and shown in Figure 6, A and B) the higher flows from the Susquehanna River in the summer of 1984 caused stronger vertical salinity gradients in the mainstem when compared to the summer of 1985. The average dissolved oxygen profiles, as shown in Figure 6, C and D, for the 1984 and 1985 summer periods illustrate the influence of restricted mixing of surface and bottom waters brought about by the higher salinity gradients in 1984. There were several differences between average conditions in the two years, especially in the areal extent of hypoxic waters (here defined as waters with dissolved oxygen levels of less than 1.0 mg/l). In 1984, hypoxic water extended to well below the mouth of the Potomac River and into Virginia waters while in 1985, hypoxic waters did not reach past the mouth of the Patuxent River. Periodic reoxygenation events, brought about by mixing of surface and bottom waters, were more frequent in 1985 due to the lower salinity gradients. The identification of these periodic reoxygenation events and the dynamic nature of bottom water dissolved oxygen concentrations with the present monitoring program has greatly expanded our knowledge of this phenomenon and will permit a much more reliable assessment of its year to year changes than was ever possible before.

In general, the lower reaches of many larger Bay tributaries have deep water dissolved oxygen concentrations that follow a pattern similar to the mainstem. However, in the lower Patuxent River, where surface to bottom salinity gradients were also more pronounced in 1984 than in 1985, the differences in dissolved oxygen levels between the two summers were not as obvious as in the mainstem. The observed discrepancy between the dissolved oxygen conditions in the Patuxent and the Bay during the summers of 1984 and 1985 is indicative of the influence of factors other than stratification. System specific characteristics such as river bottom topography, localized storm events and periodic exchanges with mainstem waters also affect dissolved oxygen conditions.

An indication of the influence of mainstem dissolved oxygen conditions on dissolved oxygen in the lower Patuxent can be seen in Figure 8. The 1984 mean summer profile suggests that deeper Bay waters with low dissolved oxygen concentrations may be intruding into the lower Patuxent and producing an area of low oxygen concentrations just inside the mouth. However, in the 1985 mean summer profile, this phenomenon is not apparent. Because of the shallow sill separating

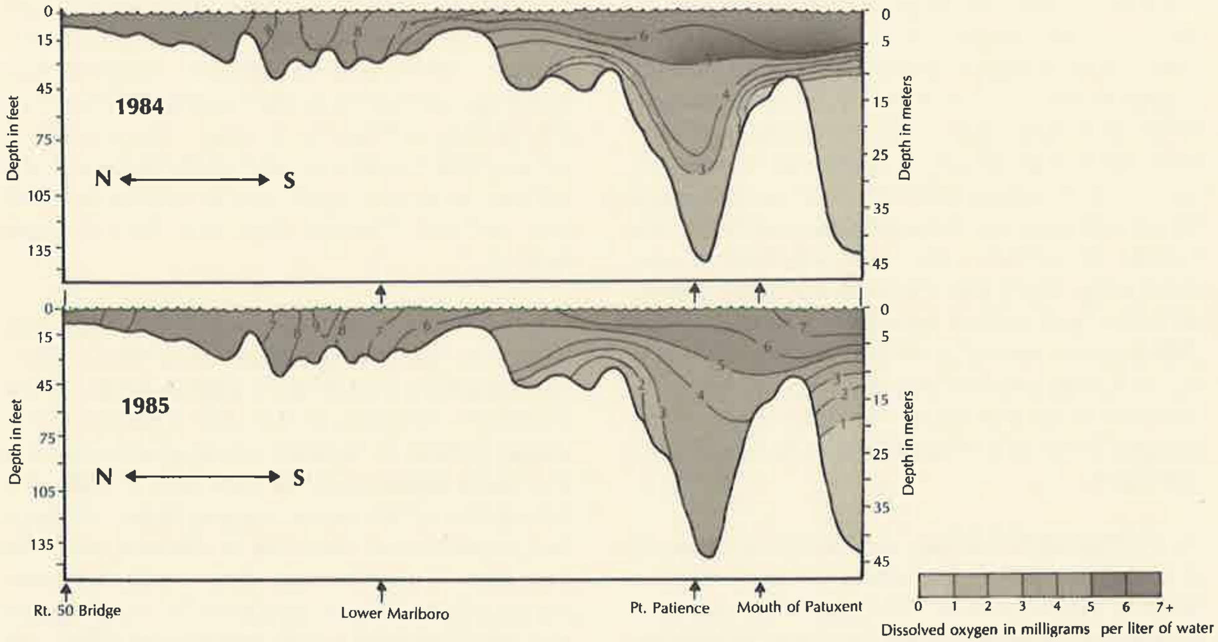


Figure 8. *Longitudinal profiles for average dissolved oxygen in the Patuxent River during the summers of 1984 and 1985.*

deeper Bay waters from deeper Patuxent waters, the exchange appears to be restricted much of the time. The intermittent nature of the deep water exchange makes it difficult to quantify its effect. This exchange phenomenon and related issues in the Patuxent estuary are the subject of a detailed monitoring and modeling study by OEP.

Nutrients

Concentrations of nutrients are critical to defining the "health" of Chesapeake Bay waters and the degree of impact imposed by man's activities. Nutrients, primarily nitrogen and phosphorus, are necessary for algal growth and their excessive inputs into Bay waters are the primary cause of eutrophication problems. The nutrient status of Chesapeake Bay will be a key determinant in the targeting of management actions and the evaluation of their success.

Nitrogen: Levels in Chesapeake Bay are generally elevated in the upper reaches of the mainstem and tributaries, exhibiting the influence of inputs of this nutrient from rivers and point sources (Map 2). In tidal fresh areas of the mainstem and Patuxent, Potomac and Choptank Rivers, the total nitrogen concentration is high, with values between 1.5 and 2.5 mg/1. In the Patuxent and Potomac Rivers, sites with high point source inputs which do not vary much on a seasonal basis, the total nitrogen values do not show appreciable seasonal changes. However, in the Choptank River where nonpoint sources dominate, there is a distinct nitrogen peak in winter and spring when high freshwater flows increase nonpoint source inputs.

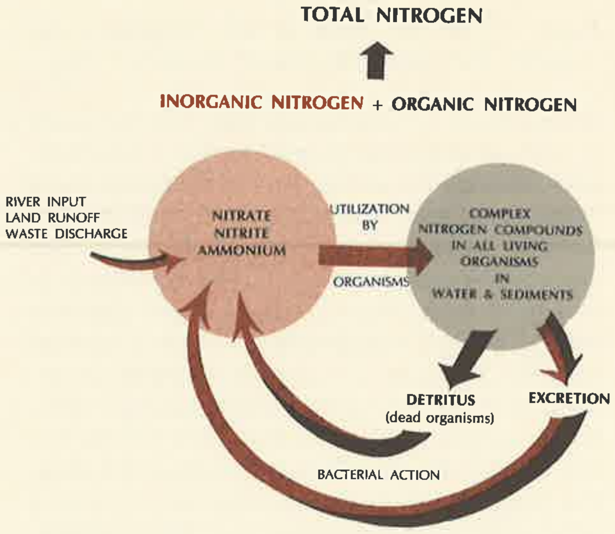
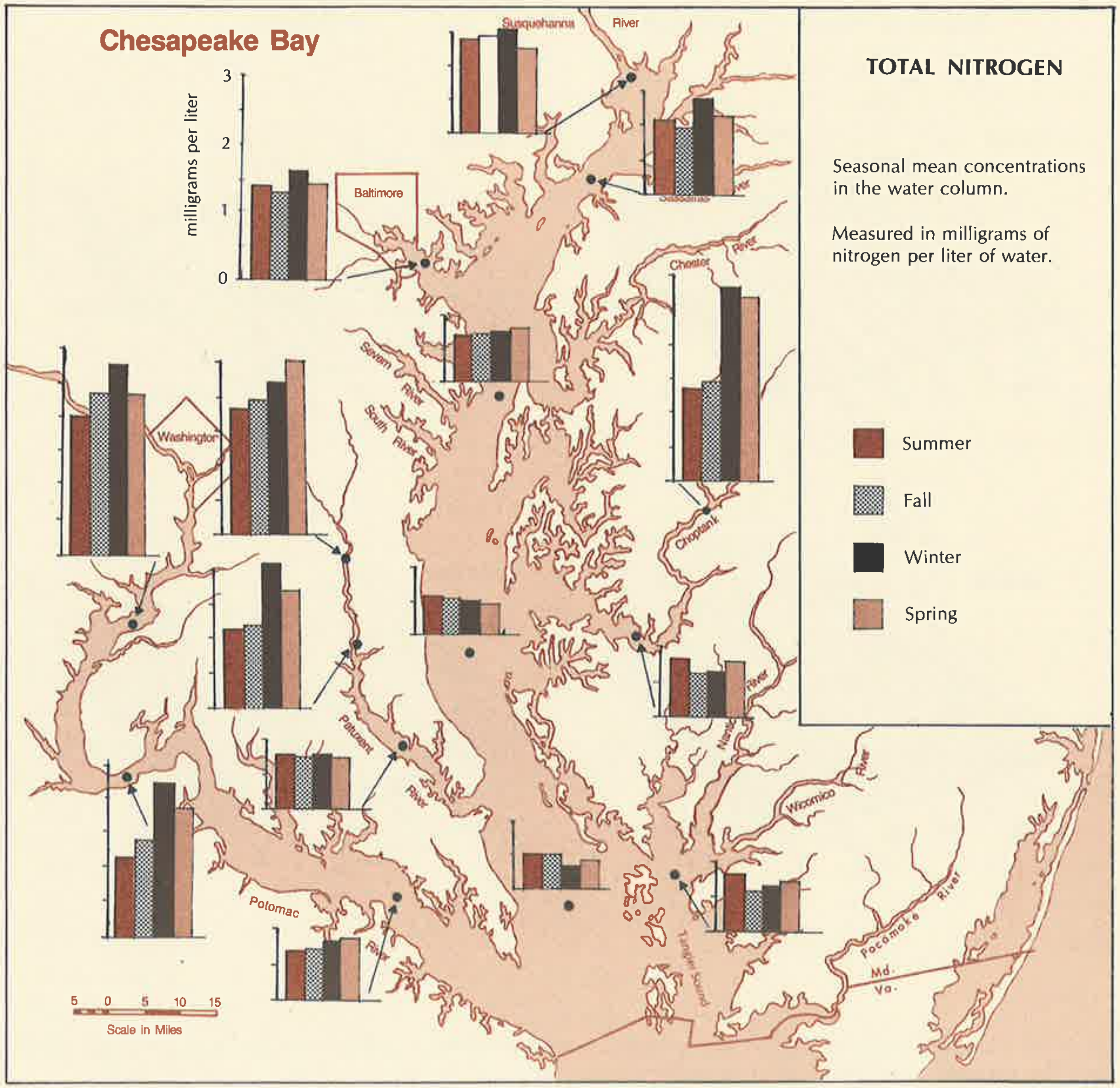


Figure 9. *Simplified cycle of inorganic and organic forms of nitrogen in Chesapeake Bay. Total nitrogen is the sum of inorganic and organic forms. Phosphorus is similarly recycled through inorganic and organic forms.*

Total nitrogen declines downstream in the mainstem and each of the tributaries as high nutrient inputs at the head of the estuaries are diluted. The Patuxent, Potomac and Choptank Rivers all exhibit lower total nitrogen levels in their downstream, high-salinity reaches relative to upstream locations. These levels are similar between the three systems, ranging between 0.6 and 0.9 mg/l. The Baltimore Harbor (lower Patapsco River) station, which has a salinity regime comparable to the lower stations in the three tributaries just discussed, exhibits nitrogen concentrations almost twice what is found in those systems. The mainstem, on the other hand, exhibits the lowest concentrations, about 0.5 mg/l, in its saltier reaches.

Tangier Sound, an area generally considered more pristine than most in Maryland's Bay, also shows the influence of nutrients transported by several rivers draining the lower Eastern Shore. Total nitrogen is approximately 50% higher than comparable areas in the adjacent mainstem.

A closer examination of nitrogen in the mainstem reveals distinct spatial patterns in the different forms of nitrogen. Figure 9 shows a simplified diagram of the major relationships between the different forms of nitrogen. The strong gradient of declining total nitrogen from the head of the Bay can be seen to be driven principally by changes in dissolved inorganic nitrogen (nitrate, nitrite, ammonium), which ranges from around 1 mg/l in the upper Bay to less than 0.25 mg/l in the lower Bay (Figure 10, A and B). Most of this dissolved inorganic nitrogen is in the form of nitrate delivered by the Susquehanna River.



TOTAL NITROGEN

Seasonal mean concentrations in the water column.

Measured in milligrams of nitrogen per liter of water.

Map 2.

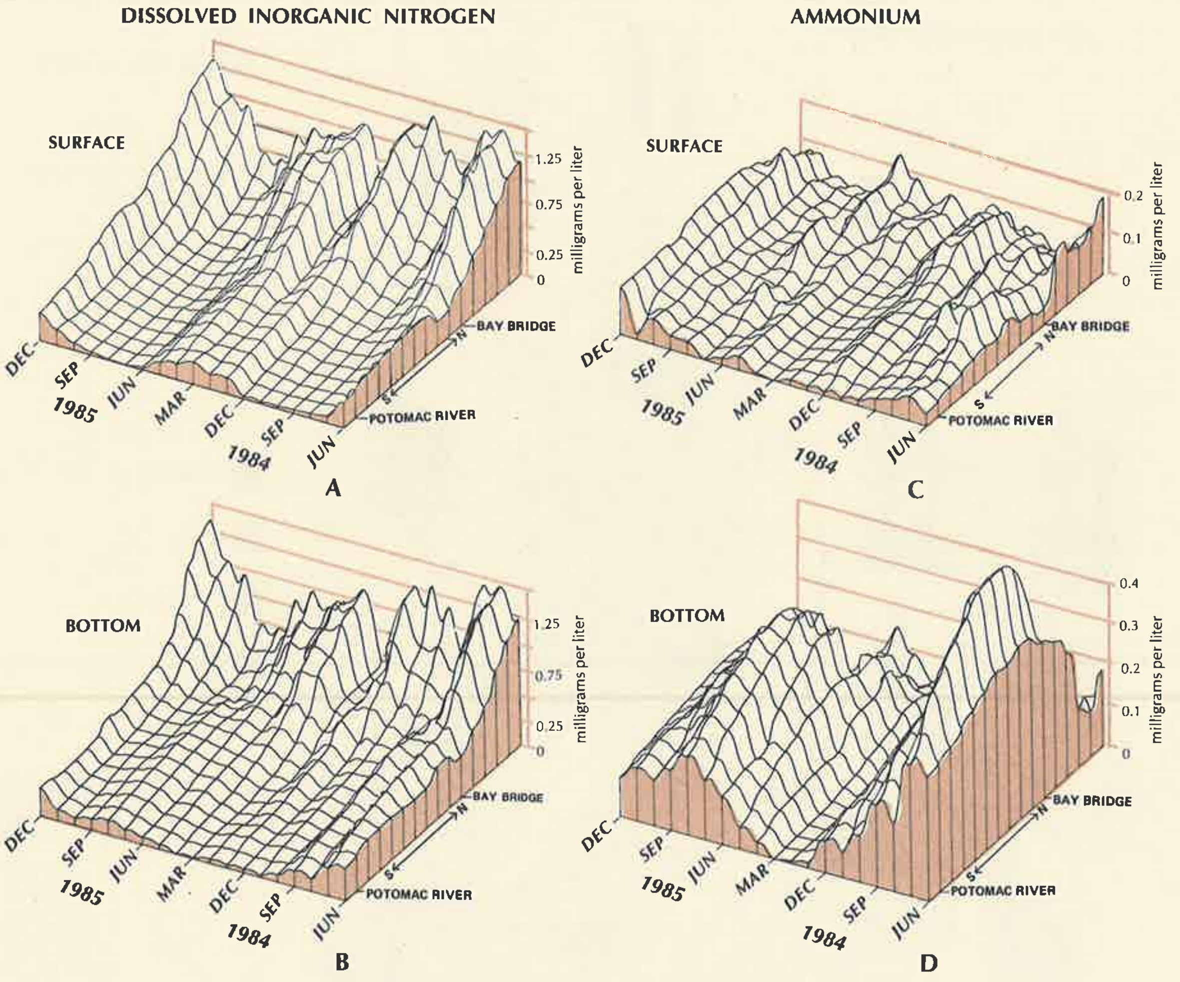


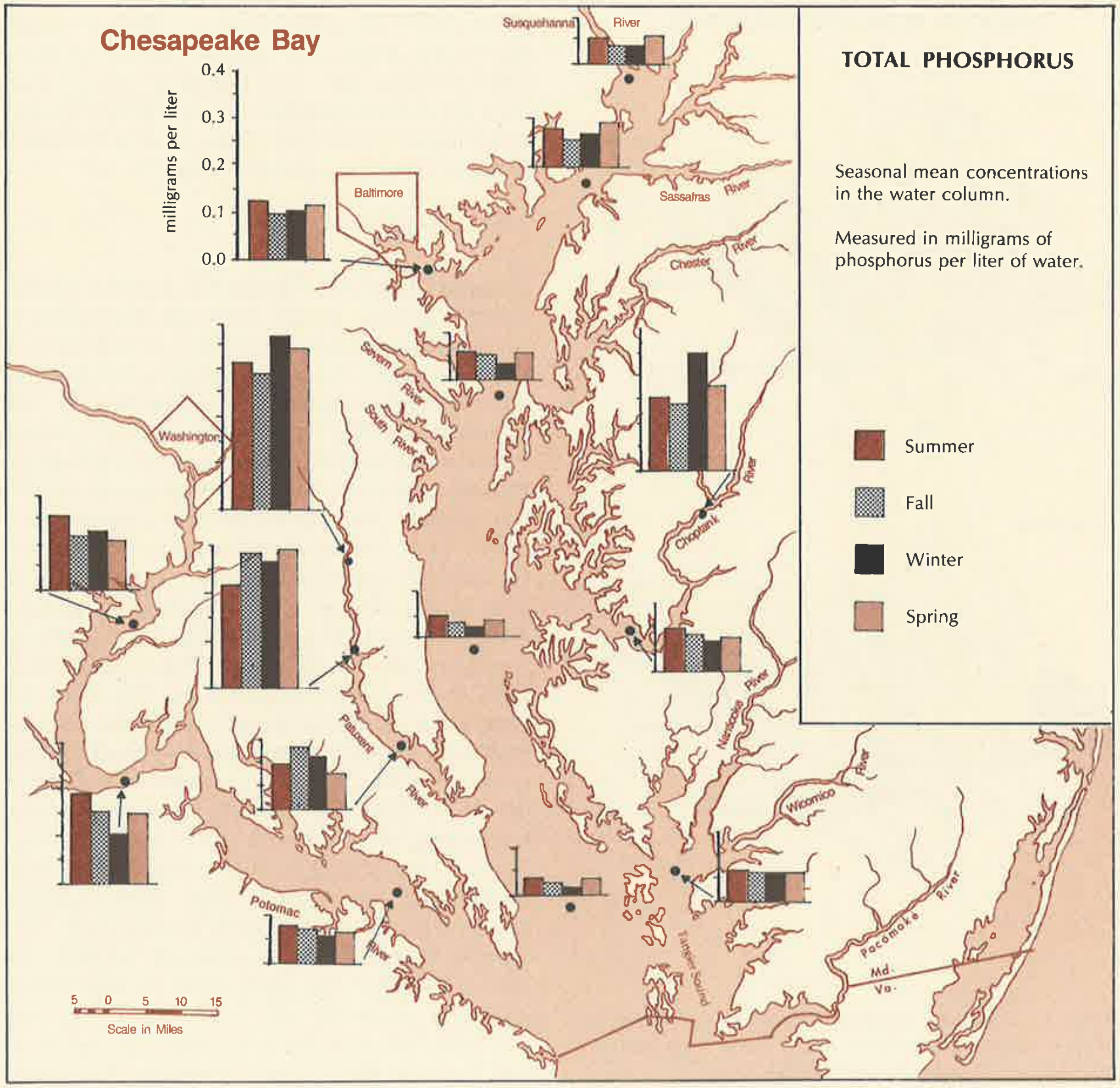
Figure 10. *Dissolved inorganic nitrogen and ammonium concentrations in surface and bottom waters of the Chesapeake Bay mainstem from June, 1984 through December, 1985.*

Another dramatic pattern is brought about by the recycling of nitrogen by the Bay's microorganisms. During the summer, recycling rates of nitrogen from biological activity in the sediments and the water column are high. This nitrogen recycling produces ammonium, an inorganic form of this nutrient. In the upper mixed layers of the water column this recycled form of nitrogen is actively consumed by growing phytoplankton and thus the ammonium does not accumulate (Figure 10, C). In bottom waters, where the utilization by organisms is relatively low, this form of nitrogen does accumulate during summer months (Figure 10, D). This high concentration of ammonium in bottom waters can serve as a source of nitrogen for summer algal growth as it mixes upward into surface waters. The nitrogen patterns observed in mainstem waters are also found in the major tributaries which generally function as smaller-scale analogues of the Bay itself.

Phosphorus: Similar to patterns observed for nitrogen, total phosphorus concentrations are highest in the upper reaches of the Bay and its tributaries (Map 3). Unlike nitrogen, however, concentrations in the tributaries are generally significantly higher than in the mainstem and point to some appreciable differences among rivers. The Patuxent River has the highest total phosphorus concentrations, reaching 0.35 mg/l, in its upper tidal reaches when compared to similar areas of the Potomac and Choptank Rivers which usually exhibit concentrations below 0.2 mg/l. The highest total phosphorus concentrations in the mainstem are about 0.1 mg/l. Anthropogenic loadings, from point and nonpoint sources, lead to the high phosphorus concentrations observed in the tributaries. Differences in point source loadings of phosphorus among tributaries, relative to river volume and flushing, probably accounts for much of the differences in phosphorus concentrations among the rivers.

Total phosphorus in the high salinity, lower estuarine zones of the Patuxent, Potomac and Choptank Rivers show declines from upstream locations. However, these tributary concentrations remain appreciably higher, about 0.1 mg/l, than comparable areas of the mainstem at less than 0.05 mg/l. Baltimore Harbor exhibits one of the highest concentrations of phosphorus in the Bay's higher salinity zones, being similar to levels found in the lower Patuxent. Tangier Sound exhibits total phosphorus concentrations approximately twice that found in adjacent regions of the mainstem. As with nitrogen, inputs from the watersheds surrounding Tangier Sound are the likely explanation for this finding.

Recycling of phosphorus is also evident in the monitoring data from the mainstem. Like nitrogen, phosphorus is recycled actively during summer months in both the water column and sediments. Sediment release of phosphorus into the overlying water column is especially strong when oxygen levels are low, as they are in summer. This phosphorus from the sediments and lower water column, recycled as dissolved inorganic phosphorus, builds to high concentrations in bottom waters during spring and summer months (Figure 11, B) because of restricted mixing between surface and bottom waters at this time of year. Furthermore, phytoplankton, which would typically consume this form of phosphorus, cannot grow at



TOTAL PHOSPHORUS

Seasonal mean concentrations in the water column.

Measured in milligrams of phosphorus per liter of water.

Map 3.

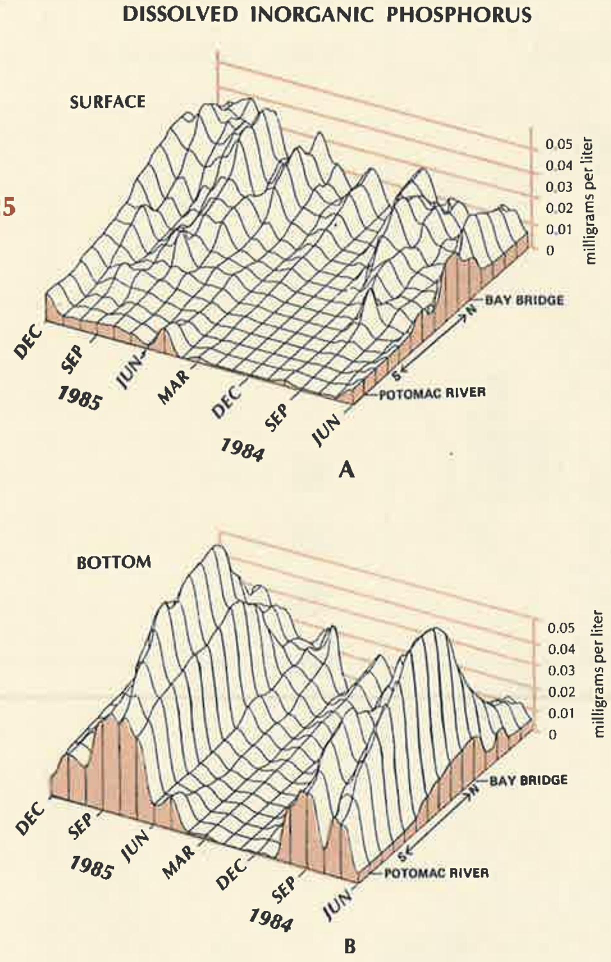


Figure 11. *Dissolved inorganic phosphorus concentrations in surface and bottom waters of the Chesapeake Bay mainstem from June, 1984 through December 1985.*

these depths because insufficient light penetrates the turbid waters. In surface waters, growing phytoplankton consume inorganic phosphorus. This uptake keeps inorganic phosphorus concentrations lower in surface waters relative to bottom waters during the summer (Figure 11, A).

Toxic Chemicals

Organic Chemicals: Polynuclear aromatic hydrocarbons (PAH's) are the most abundant class of organic toxicants detected in bottom sediments in the Chesapeake Bay. Detectable concentrations were found at every station sampled (Map 4). The occurrence of PAH's in sediments is of concern because several PAH compounds have proven to be potent carcinogens in mammalian and aquatic test animals. PAH contamination originates primarily from the atmospheric deposition of particles formed from the combustion of all forms of fossil fuels, and from the leaching of organic material from coal particles that are commonly found in upper Bay sediments. The upper Bay stations in the mainstem and at the mouth of the Patapsco River are the most heavily contaminated with PAH's, with concentrations approaching 10 parts per million (ppm). It appears that much of the PAH's that enter the Bay from the Susquehanna and Patapsco Rivers remain in that vicinity. Not all PAH's in sediments are hazardous, since background or natural PAH concentrations always occur in the estuarine environment. The Tangier Sound station, a relatively unimpacted site, exemplifies low-level PAH concentrations and is a reference site with which the contaminated areas can be compared. The mouth of the Patuxent River shows unusually high sediment PAH concentrations which can be attributed to the occurrence of coal particles on the river bed in this area.

PAH concentrations in the tissues of the Macoma clams (Map 4), showed that the tissue levels were directly related to the degree of sediment contamination (Figure 12). PAH concentrations in the tissues of clam worms (*Nereis* species) were also related to sediment PAH concentrations (Figure 12). It appears that the relationship between sediment and tissue levels might be different for the two organisms, probably due to differences in feeding and metabolism. The natural organic carbon content of sediments also appears to play an

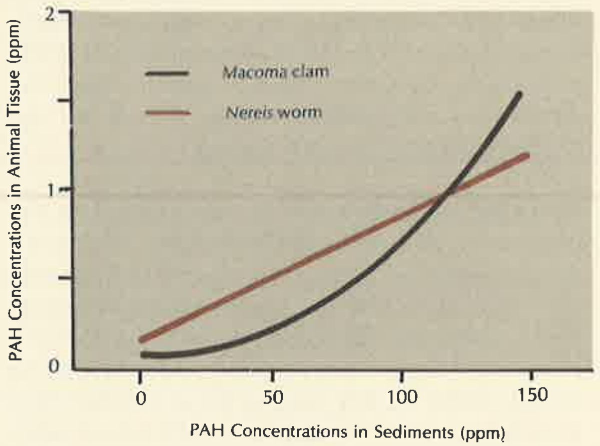
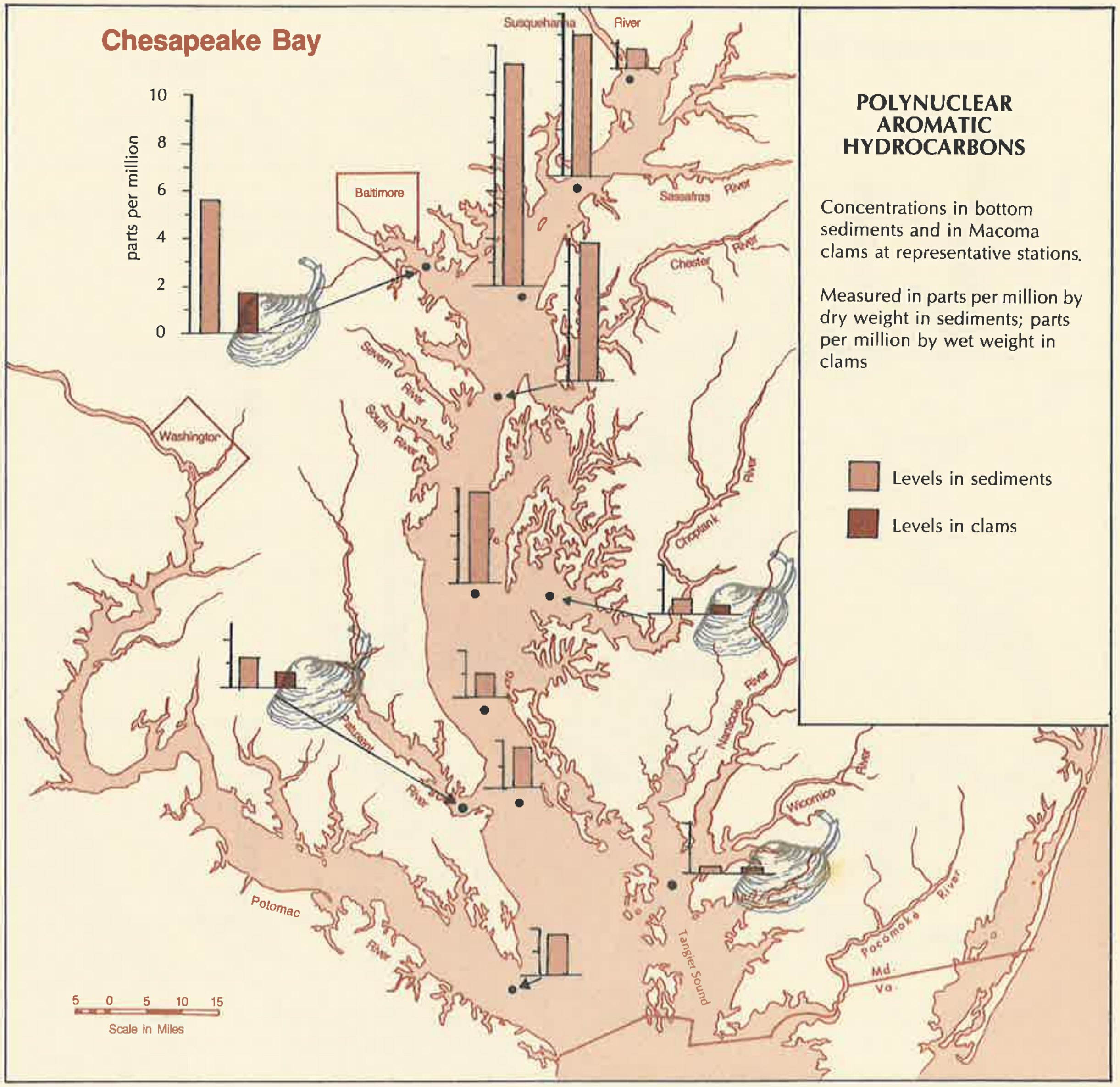


Figure 12. *Relationship between polynuclear aromatic hydrocarbon (PAH) concentrations in sediments and in tissues of Macoma clams,* Macoma balthica, *and polychaete worms,* Nereis sp. *Concentrations in sediments are in parts per million (ppm) based on weight of sediment organic carbon. Concentrations in organisms are in ppm based on total wet weight.*

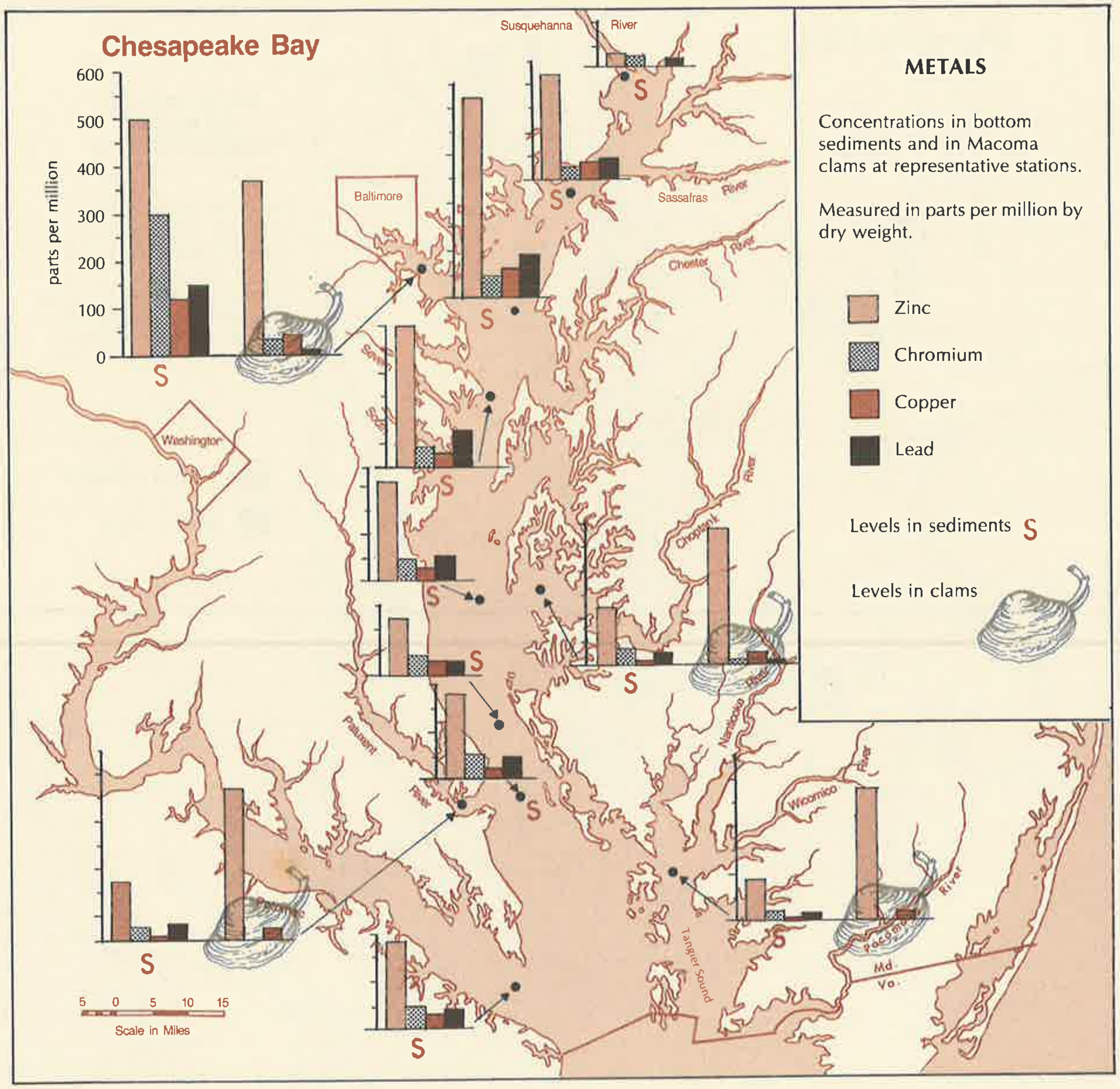
extremely important role in the retention of toxicants, such as PAH, in sediments and in the amount of sediment-associated PAH that accumulates in sediment-dwelling organisms. While the relationships presented here are still preliminary, they point to the link between sediments and organisms dwelling there. These relationships and others throughout the food chain will help us to assess and understand the potential threat posed by toxicants in the Bay.

Metals: Metal concentrations in sediments and biota were determined at the same sites where analysis was performed for the organic toxicants discussed above. The concentrations of four metals - zinc, copper, chromium and lead - are presented in Map 5. Clearly, higher sediment concentrations of trace metals are associated with heavily industrialized areas such as Baltimore Harbor. Additionally, broader spatial trends exist, such as a high to low gradient north to south due in part to input from the Susquehanna river and atmospheric input of such metals as lead from industrial areas to the north.

From both an ecological and human health standpoint, it is particularly important, as with organic toxicants, to assess the degree to which metals are accumulating in organisms. Although in general terms one can see that the highest metal concentrations in Macoma clams are associated with the most contaminated sediments, the relationship between metals in the biota and sediments is apparently complex. Factors affecting this relationship probably include the sediment characteristics as well as the organisms' physiology and feeding habits. The concentrations of metals in



Map 4.



Map 5.

Macoma clams vary less than the levels in associated sediment samples and there appears to be different proportions of the 4 metals in sediments as compared to the clams (Map 5).

CONCLUSIONS

- The areal extent of low dissolved oxygen in bottom waters of the mainstem was much greater in 1984 than in 1985. This difference was due to natural physical factors which can be accounted for in the present program relative to pollutant impacts.
- Elevated nitrogen levels of over 1 mg/l are consistently found in the upper mainstem and tributaries of Chesapeake Bay and in Baltimore Harbor due to the proximity of high point and nonpoint loads of this nutrient.
- Phosphorus concentrations, like those for nitrogen, are highest in the upper reaches of the mainstem and tributaries. There are, however, major differences between the mainstem and the different tributaries, indicating large differences in the proportions of phosphorus loadings between systems; much of this difference appears to be related to point source inputs.
- Spatial distributions of organic and metal toxicants in sediments and biota show the effects of high industrial activity in the upper Bay.
- Results from the first two years indicate that with the spatial and temporal resolution presently incorporated in the monitoring program, the objectives of characterization, trend and understanding water quality processes as they relate to chemical and physical conditions are achievable.

5. plankton

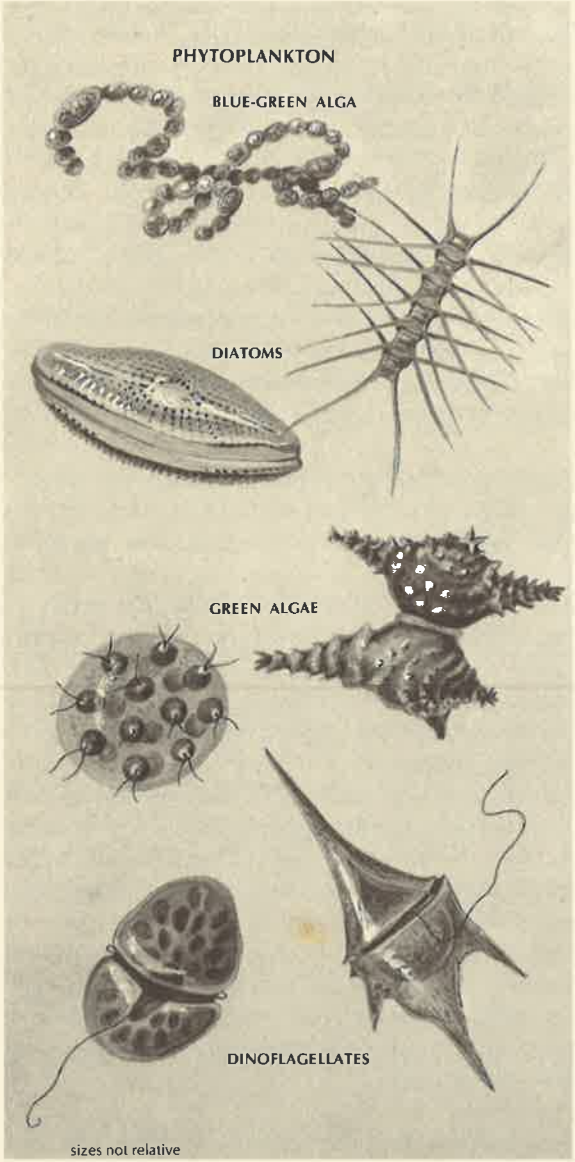
Plankton, the microscopic plants and animals suspended in the water column, are the foundation of the food web in aquatic ecosystems such as Chesapeake Bay. The plankton also represent one of the most direct and profound responses to pollution entering the Bay. In fact, the degree of euthrophication or nutrient enrichment is often gauged by the amount of plankton growth in an aquatic environment. Because of their critical position at the foundation of the food web, the plankton response to pollution has many ramifications. For example, the increased growth of plankton in response to excessive nutrient additions initiates a chain of events that leads to the adverse symptoms of eutrophication, such as low dissolved oxygen concentrations and consequently the loss of habitats for living resources.

Because of plankton's fundamental importance to the eutrophication process, limitation of their growth, or production, is often one of the direct targets of management actions. These actions are typically directed at reducing nutrient inputs as a means of limiting plankton growth. The limitation of plankton growth is in turn expected to improve some of the impacts that result from excessive growth. Thus, an assessment of water quality to guide and evaluate management actions logically includes the measurement of plankton communities and their growth rates.

Plankton assessments in the water quality monitoring program are targeted at three functional groups - phytoplankton, microzooplankton and mesozooplankton. All of these groups are microscopic in size. Phytoplankton represent a diverse group of organisms that, as plants, capture the sun's energy, convert it into living tissue and thus support all life in Chesapeake Bay. A wide variety of phytoplankton species exists, some living as single cells and some as colonies. A knowledge of the types of species occurring in the Bay is important to an understanding of how these organisms are utilized in the system. For example, certain species can be easily consumed by zooplankton grazers to support higher life forms. Other species, often indicative of eutrophic conditions, are resistant to normal phytoplankton predators and may therefore be more prone to enter the decomposition pathways which contribute to low dissolved oxygen problems.

Zooplankton are the primary consumers of phytoplankton and bacteria, funneling food energy from phytoplankton production and bacterial decomposition up to higher organisms such as fish. Larval fish survival in spawning areas is dependant upon sufficient densities of appropriate zooplankton species to feed upon. The zooplankton food supply in spawning grounds during spring is one of the critical factors currently being examined in relation to the success or failure of striped bass reproduction. Certain fish such as bay anchovy and silversides remain zooplankton feeders throughout their lives. Still other species, such as menhaden, consume zooplankton as larvae and juveniles and then switch to feeding exclusively on phytoplankton as adults. Thus, a knowledge of the species composition and abundance of zooplankton communities is required to assess the food supply for the Bay's fisheries resources.

Zooplankton consumption of phytoplankton and



bacteria can be a regulating force over these communities; in turn, excretion by zooplankton is one of the most significant recycling mechanisms that supplies phytoplankton with nitrogen and phosphorus for growth. Therefore, an evaluation of the zooplankton community is critical to understanding both the fate of phytoplankton production and nutrient recycling.

Microzooplankton are organisms less than about 2 hundredths of an inch and are comprised for the most part by protozoans such as tintinnids, rotifers and juvenile stages of mesozooplankton. Mesozooplankton are defined in this program as those animals larger than about 1 hundredth of an inch and include organisms such as tiny crustaceans and larvae of bottom-dwelling organisms such as oysters, crabs and worms. Large, visible plankton organisms such as sea nettles and comb jellies, that are important in Chesapeake Bay, are enumerated in samples collected for the mesozooplankton program; results for these organisms, however, are not presented in this report.

DESIGN CONSIDERATIONS

Plankton measurements are conducted at a subset of stations sampled for chemical and physical conditions (see Map 1) that are representative of the tidal-fresh, salinity-transition and lower-estuarine zones in both the mainstem and major tributaries. Samples are taken at the same time as physical and chemical measurements to allow for direct linkage between these two programs.

Phytoplankton: The Bay's phytoplankton biomass, species composition and productivity is assessed 18 times per year. Phytoplankton biomass is determined indirectly by measuring chlorophyll concentrations in water samples as part of the chemical/physical program. Chlorophylls are complex molecules contained within plant cells that help to capture the sun's light energy. Because chlorophyll molecules are only found in photosynthetic organisms such as phytoplankton, their concentration in water samples can be used as a reliable indicator of phytoplankton biomass. Because the Bay's phytoplankton are not distributed evenly in the water column, either vertically or horizontally, special techniques are required to provide reliable estimates of average chlorophyll concentrations. At all plankton stations, all 22 mainstem stations and 10 stations in the Patuxent estuary, a surface-to-bottom depth profile of chlorophyll is determined to provide better vertical resolution. As the sampling vessel cruises between stations on the Patuxent River and the mainstem, additional horizontal resolution of chlorophyll is obtained by continuous monitoring of surface water concentrations. At all plankton stations, phytoplankton species composition and abundance are determined in waters both above and below the pycnocline (the density gradient separating surface and bottom waters). Samples for this enumeration are composited from several depths to produce a large, well-mixed sample.

A final, but critical, estimate of the phytoplankton community is the measurement of phytoplankton primary production, or growth rate. This measurement complements the "standing stock" assessment of biomass and species composition described above and may be a more sensitive indicator of trends. It is quite conceivable that management actions may severely limit algal growth rates while at the same time standing stocks may not change appreciably. This would be a significant achievement that could go unnoticed without primary productivity estimates. The primary production estimates also provide valuable information for interpreting and synthesizing information from other monitoring components such as vertical flux rates of organic matter, nutrient fluxes between the sediments and water column, dissolved oxygen deficits, zooplankton communities, benthic communities and nutrient inputs from point and nonpoint sources.

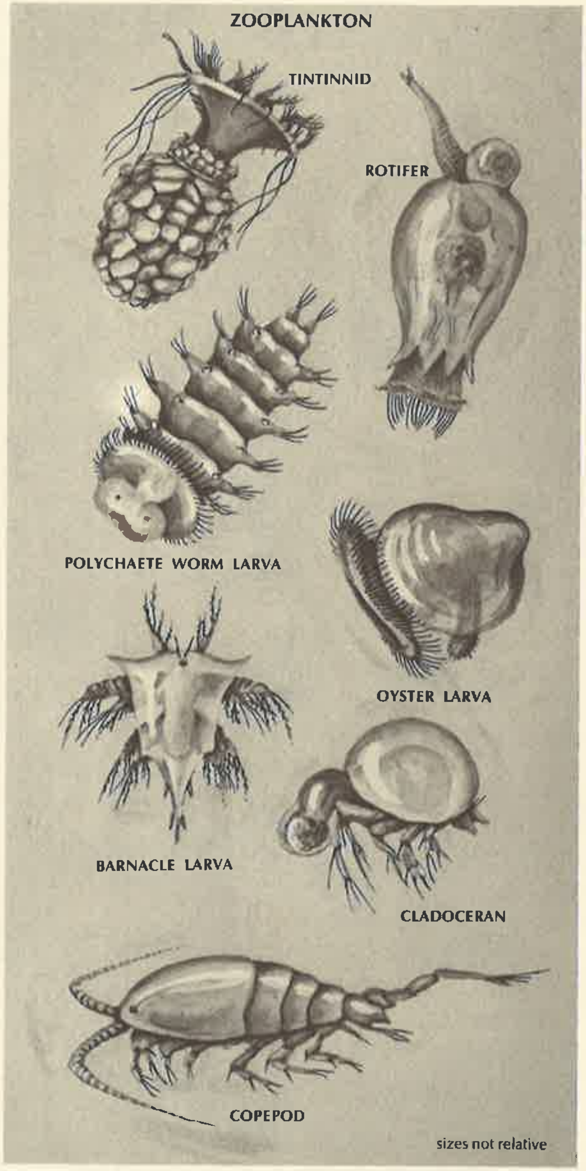
Zooplankton: The zooplankton community is sampled at the same set of stations and at the same times as those used for the phytoplankton community. Because zooplankton usually have longer generation times than phytoplankton, the zooplankton community generally changes at a slower rate than the phytoplankton community. Thus, the once-monthly sampling frequency for zooplankton provides temporal resolution comparable to the phytoplankton sampling program. Large volume samples are composited and concentrated separately from above and below the pycnocline for microzooplankton and from the entire water column for the larger mesozooplankton. Zooplankton biomass as well as species composition and abundance are determined. Separate biomass estimates are made for the contribution from large jellyfishes, such as sea nettles, and comb jellies.

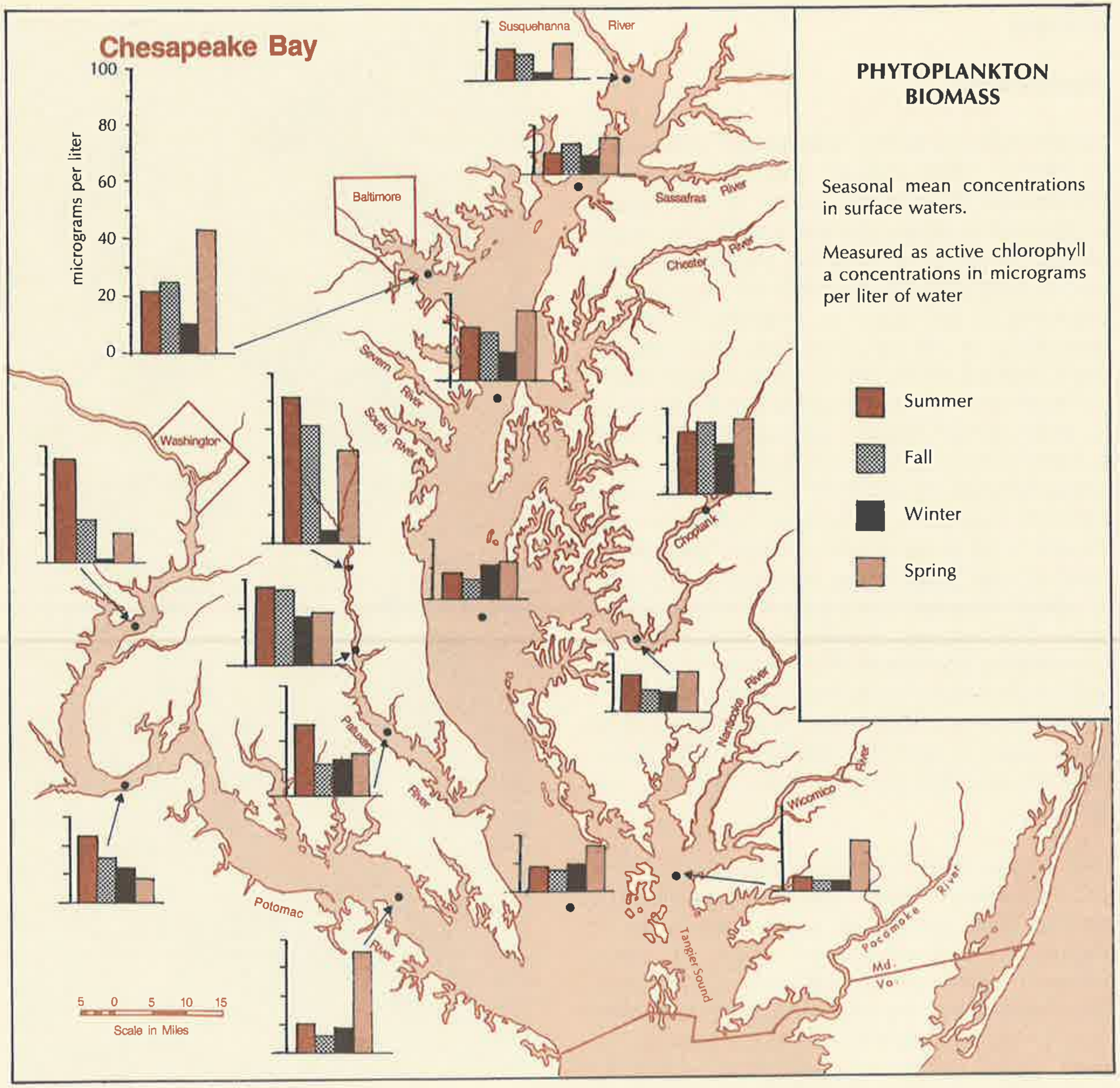
RESULTS

Phytoplankton

Results from the OEP phytoplankton component in 1984 - 1985 indicate that the waters of Chesapeake Bay sustain some of the highest phytoplankton biomasses and growth rates found among estuaries world-wide. Average surface-water chlorophyll concentrations in most seasons exceeded 20 μg/1 (μg = micrograms of mass) in large areas of the Patuxent, Potomac, Patapsco and Choptank Rivers and in the mainstem region centered around the Annapolis Bay Bridge (Map 6). Peaks of over 50 μg/1, although hidden in the seasonal averages, were common in these same areas. Average chlorophyll levels in the upper Patuxent River were particularly high, exceeding 35 μg/1 in all seasons except winter, and several peaks of over 90 μg/1 were observed in all 3 salinity zones sampled (see Figure 15 for tidal-fresh zone). The summers of 1984 and 1985 in the upper Potomac River were characterized by average surface chlorophyll concentrations of 35-40 μg/1. In mid-August, 1985, nuisance species of blue-green algae, a recurring problem in the upper Potomac, reached bloom levels of around 100 μg/1.

One of the most significant findings from the phytoplankton program was the relatively high biomass observed during winter and spring in bottom as well as surface waters in lower estuarine regions of the mainstem and tributaries. This contrasts with summer months when bottom water chlorophyll concentrations are quite low in these areas. An example of these seasonally





PHYTOPLANKTON BIOMASS

Seasonal mean concentrations in surface waters.

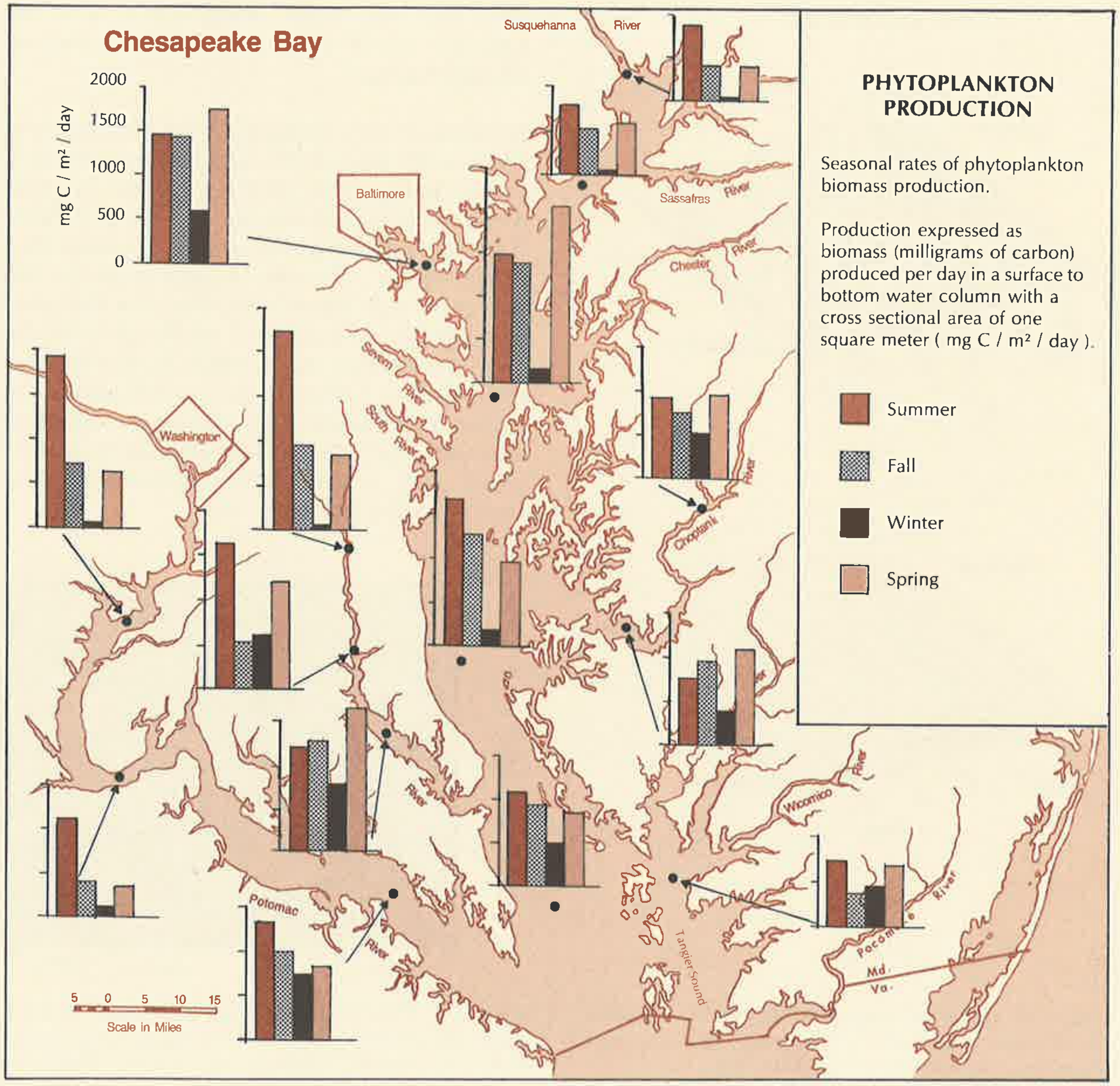
Measured as active chlorophyll a concentrations in micrograms per liter of water

Map 6.

changing surface and bottom-water concentrations is shown for the mainstem in Figure 13. The high bottom concentrations result from the settling of cells growing in surface waters and from transport up-Bay in bottom waters. During these colder winter and spring months, unlike at other times of year, phytoplankton are apparently able to survive longer in bottom waters that do not have sufficient light for growth. This is probably due to their lower metabolic rates at low temperatures and the fact that oxygen concentrations are relatively high in bottom waters at this time. This large pool of living phytoplankton that builds through winter and spring disappears rapidly with the onset of increasing temperatures in late spring, presumably as a result of rapid decomposition. The decomposition of this phytoplankton biomass is probably a major factor contributing to the development of low oxygen conditions in the stratified portions of tributaries and the mainstem. The management implication is that we cannot ignore the growth of phytoplankton that occurs during colder months since it may result in water quality impacts during warmer seasons.

Primary productivity, or the growth of phytoplankton, is measured as the photosynthesis of new cellular material and can be measured in terms of carbon. Rates are then expressed as the amount of carbon produced per day within a surface to bottom column of Bay water with a cross-section of 1 square meter. Primary productivity in the Bay is highest in spring, summer and fall when temperatures are warmer and days are longer (Map 7). Thus, winter is consistently the time of lowest productivity, even though the biomass of phytoplankton (see Map 6) may not decline as precipitously during the colder months. This point is well illustrated by seasonal patterns in the mainstem data as shown on the maps. The winter decline in productivity is less pronounced in high salinity areas where water temperatures remain warmer than in freshwater areas. Again, the mainstem transect from the freshwater head of the Bay to the State line, where higher salinities occur, illustrates this point.

Two of the highest seasonal phytoplankton productivity rates were recorded during summer in the tidal fresh areas of the Patuxent and Potomac Rivers with values of 2 grams of carbon produced per square meter per day; the rates in these areas during other seasons, however, dropped to less than half of the summer values. Summer productivity in the lower Patuxent, Potomac, Choptank and Patapsco Rivers, and in the mainstem, was less than in the upper Patuxent and Potomac, but rates in these higher salinity zones generally remained substantial during spring and fall as well. Overall, the mainstem productivity rates were comparable to those found in most areas of the tributaries. This contrasts with the finding of substantially higher phytoplankton biomass concentrations in most of the upper tributaries relative to the mainstem. This apparent contradiction leads to the conclusion that phytoplankton growth rates on a per unit biomass basis are lower in the upper tributaries than in the mainstem. Light limitation of phytoplankton growth in the tributaries is a likely explanation for these lower growth rates since nutrients, another potentially limiting factor, are actually more abundant in the upper tributary regions. This explanation is supported by high inorganic sediment concentra-



PHYTOPLANKTON PRODUCTION

Seasonal rates of phytoplankton biomass production.

Production expressed as biomass (milligrams of carbon) produced per day in a surface to bottom water column with a cross sectional area of one square meter (mg C / m² / day).

Map 7.

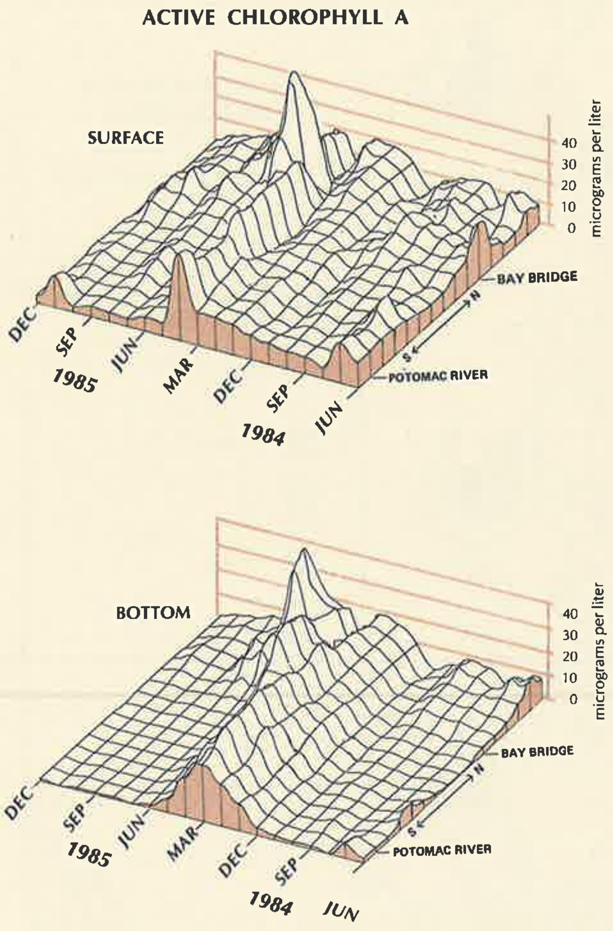


Figure 13. *Active chlorophyll a concentration in surface and bottom waters of the Chesapeake Bay mainstem from June, 1984 through December, 1985.*

tions and low water transparencies that are typically found in the upper tributaries to Chesapeake Bay.

Productivity rates measured in the mid-portion of Chesapeake Bay, off the mouth of the Choptank River, during 1984-1985 are similar to rates measured in the same region between 1974-1977 (Fig. 14) suggesting that annual phytoplankton production is relatively constant over the last decade for this region of the Bay. The high summer peaks in 1972 and 1973 are thought to be the result of Hurricane Agnes which brought tremendous loads of nutrients into the Chesapeake Bay system. This decade of information is a model for what we expect the present program to yield in future years at many other representative sites within the Bay system.

Zooplankton

Zooplankton biomass was found to be highest in the tidal freshwater areas of the Patuxent, Potomac and Choptank Rivers (Map 8). Biomass was also relatively high in downstream areas of the Patuxent and Choptank Rivers. By contrast, in the tidal fresh portion of the mainstem at the mouth of the Susquehanna, zooplankton biomass was low except in the fall. Other mainstem areas also had relatively low biomass levels when compared to the tributaries.

Seasonally, the greatest variations in zooplankton biomass occurred in the upstream regions of tributaries, although the response differed between rivers. In the upper Patuxent and Potomac Rivers, peaks occurred in the warmer months and

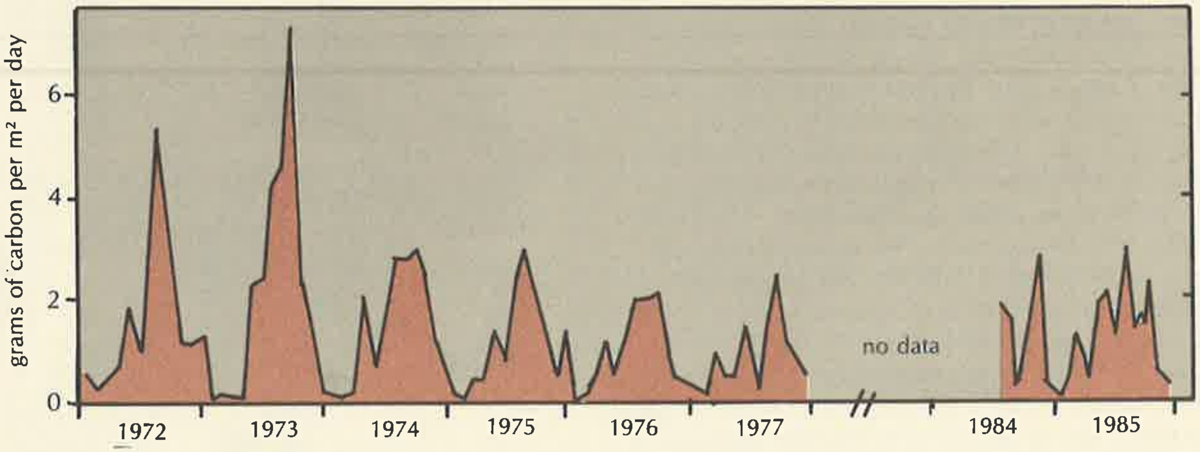
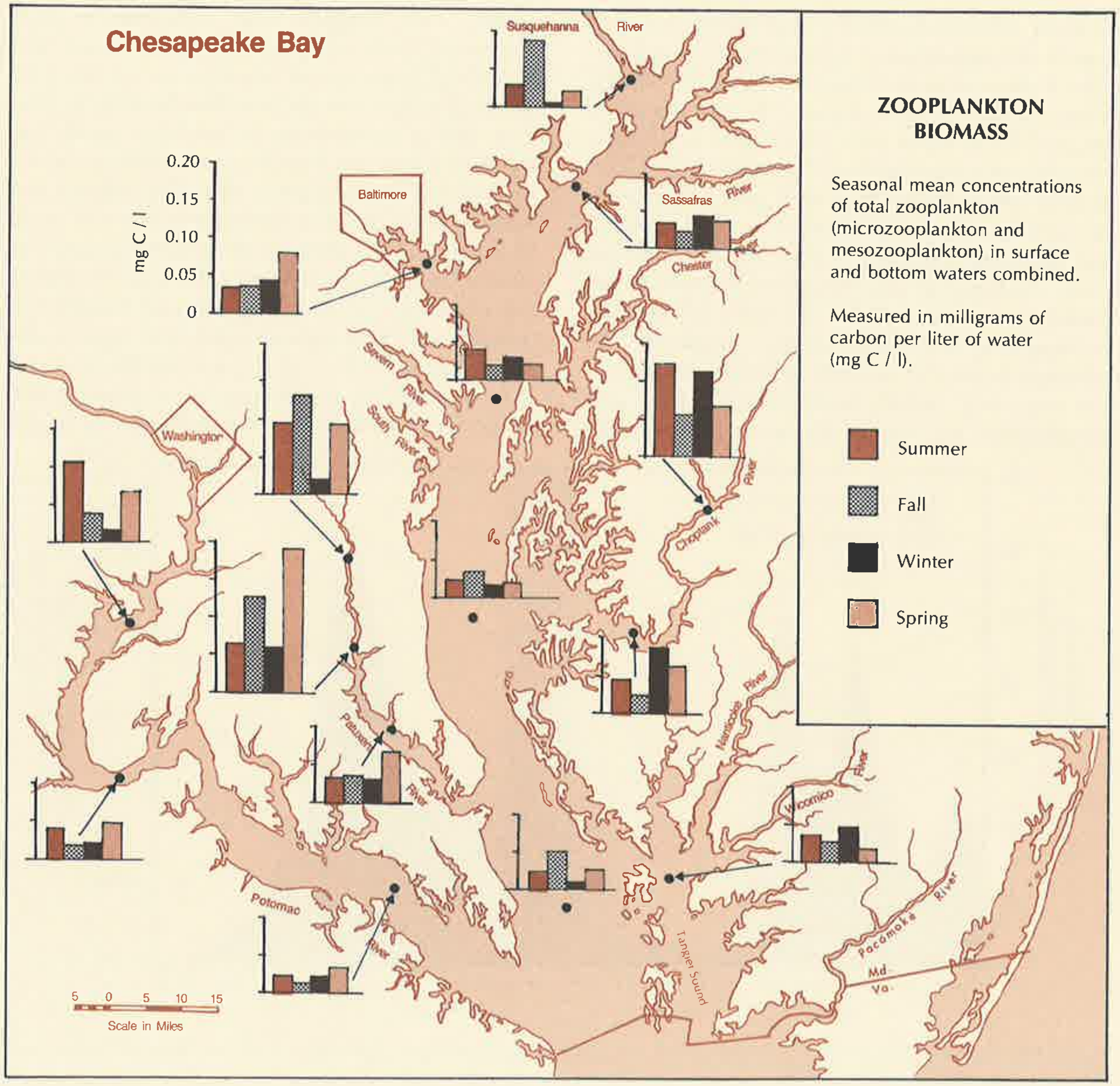


Figure 14. *Historical record of phytoplankton primary productivity (grams of carbon/meter squared/day) at the Chesapeake Bay mainstem station off the mouth of the Choptank River.* *(Data from 1972 through 1977 is from Mihursky, J. A., D. R. Heinle and W. R. Boynton. 1977. Ecological Effects of Nuclear Steam Electric Station Operations on Estuarine Systems. Univ. of Md. Chesapeake Biol. Lab. Ref. No. 77-28-CBL).*

winter levels were low. In the upper Choptank, however, peaks occurred in both summer and winter. During spring, the spawning period for striped bass and other fishes in the upper tributaries, zooplankton food resources for the developing larvae were abundant in the upper Patuxent, Potomac and Choptank. In the historically important striped bass spawning grounds at the head of the Bay, however, zooplankton biomass was relatively low. This may be an important factor to examine as an explanation for declines in striped bass recruitment observed for this region in recent years.

Phytoplankton and Zooplankton Relationships

Many of the patterns observed for zooplankton (Map 8) can be explained by looking at their food supply, the phytoplankton (Map 6). The high levels of zooplankton in the upper Patuxent, Potomac and Choptank Rivers correspond to high levels of phytoplankton in these regions. The seasonal patterns also show close correspondence between these two monitoring components. Low phytoplankton concentrations during winter in the upper Patuxent and Potomac Rivers correspond to low zooplankton concentrations at this time of year. The upper Choptank station, when contrasted with the other two tributaries, exhibited relatively high zooplankton densities during winter. It also maintained much higher phytoplankton biomass levels than the Patuxent and Potomac during winter. The station at the head of the Bay also demonstrated a correspondence between relatively low phytoplankton levels and relatively low zooplankton densities.



Seasonal mean concentrations of total zooplankton (microzooplankton and mesozooplankton) in surface and bottom waters combined.

Measured in milligrams of carbon per liter of water (mg C / l).

Map 8.

A more detailed example of the relationship between phytoplankton and zooplankton communities is presented in a time series for the upper Patuxent River station (Figure 15). This station is located in the lower tidal fresh region and is in a striped bass spawning area. The spawning period, during which striped bass eggs and larvae were actually collected at this station by the zooplankton sampling program, is denoted by a shaded area. The figure clearly depicts late summer to fall peaks of phytoplankton in both years followed by increases in the zooplankton community. In spring through mid summer, which encompasses the spawning period, both phytoplankton and zooplankton are maintained at moderately high levels. This suggests that zooplankton food resources were adequate for the survival and growth of larval fish in this area. In winter, both phytoplankton and zooplankton biomass is low. The strong correlations in seasonal cycles between the two communities at this station, as well as the spatial correlation discussed above, are evidence for the link between these two communities and the ability of the present program to define those linkages. With this ability to define relationships, the plankton program should add considerably to our understanding of water quality problems such as phytoplankton blooms and low dissolved oxygen waters. In addition, it will be a valuable water quality indicator for evaluating the response of the Bay to management actions and assessing the linkage between water quality and living resources.

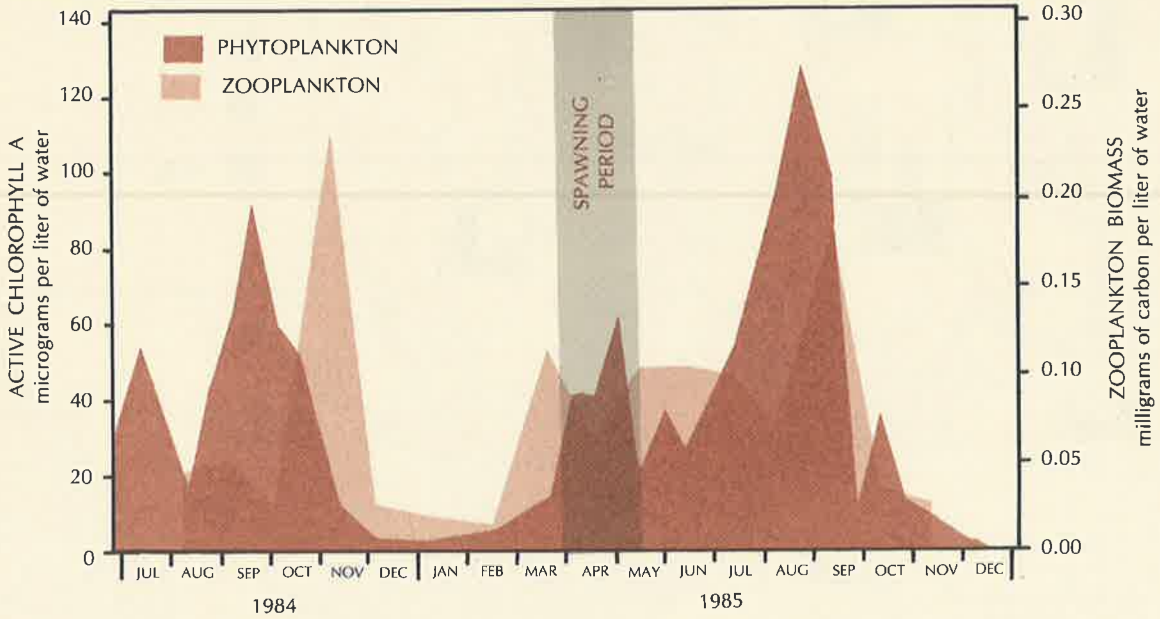


Figure 15. *Seasonal phytoplankton, zooplankton and fisheries relationships in the upper Patuxent River at Nottingham between July, 1984 and Dec., 1985.*

CONCLUSIONS

- Phytoplankton biomass is high throughout the Bay system but especially so in the tributaries where seasonal chlorophyll averages typically exceed 20 µg/1. Blooms of over 50 µg/1 are common throughout the Bay and its tributaries.
- Phytoplankton biomass builds to considerable levels in both surface and bottom waters of high salinity areas during winter and spring. This is probably an important factor in the development of hypoxic waters during warmer months.
- Phytoplankton productivity is more evenly balanced spatially than biomass throughout different regions of the mainstem and tributaries; winter levels are low, with the seasonal patterns most pronounced in lower salinity areas.
- A comparison of spatial patterns in phytoplankton productivity with phytoplankton biomass and nutrient concentrations suggests that light may be an important factor limiting phytoplankton growth in the upper tributary regions.
- Zooplankton biomass shows strong correlations in space and time with phytoplankton biomass. The demonstration of relationships between these two communities with the current monitoring program indicates that important program objectives, including the evaluation of water quality processes and the impact of water quality conditions on living resources are achievable.

6. benthic organisms

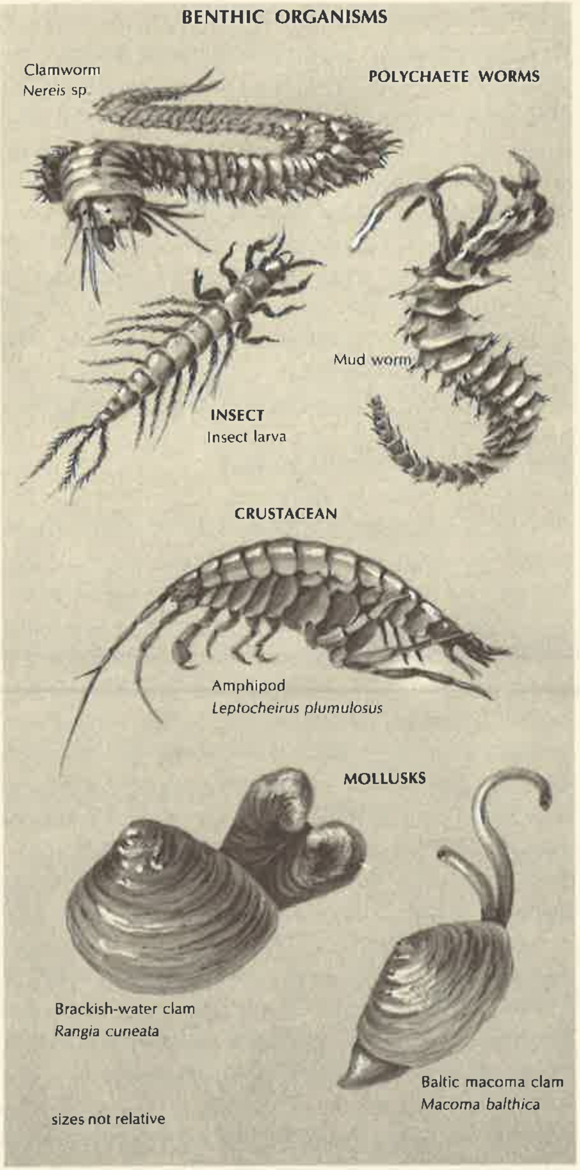
The Chesapeake Bay is home to an active community of organisms which live in association with bottom sediments. This assemblage, collectively known as the benthos, includes familiar organisms such as oysters, clams and crabs, as well as less familiar forms, including segmented and unsegmented worms, small crustaceans, snails, and anemones. A large portion of the living and dead organic material in the water, including the plankton discussed in the previous chapter and plant material washed in from the watershed, settles to the sediment surface and decays. This decaying material is a food source for benthic organisms. As benthic organisms burrow through the sediments and digest this food, a portion of the nutrients and other chemicals buried in the sediments are returned to the overlying water. These recycled nutrients frequently contribute to excess phytoplankton production and eutrophication. The Chesapeake Bay is a nursery ground for many commercially and recreationally important fish. While on their nursery grounds many of these fish feed on the benthos. Benthic organisms thus form important links between primary producers and higher levels of the Bay food web.

The benthic component of the OEP water quality monitoring program is designed around the concept that the composition of benthic communities is determined by ambient sediment and water quality. Therefore, the variety and abundance of organisms composing these communities are likely to respond to improvement in water and sediment quality resulting from pollution abatement programs. Because many benthic organisms live for 1-2 years, changes in their populations are an integration of changes in environmental conditions occurring over their life span. In addition, because benthic organisms are relatively immobile, they complete their life cycle within the Bay and often within specific regions of the Bay. Thus, benthic responses to changes in water quality resulting from Bay-wide cleanup programs are likely to be region specific and thus more easily interpreted. Finally, as important intermediate links in the Bay food web, benthic responses to cleanup actions are likely to be representative of the responses of other living resources. The benthos are, therefore, potentially good indicators of the effectiveness of cleanup efforts.

DESIGN CONSIDERATIONS

The benthic program component is jointly sponsored by OEP and the Maryland Power Plant Research Program (PPRP) and includes historical PPRP long-term benthic monitoring stations. PPRP stations along the mainstem of the Bay have been sampled regularly since 1971. PPRP stations in the Potomac and Patuxent Rivers have been sampled regularly since 1979-1980. Building the current OEP benthic monitoring element around the PPRP long-term benthic monitoring program provides a data record that can be used to interpret responses due to cleanup programs in the context of long-term fluctuations associated with natural phenomena. This separation of changes caused by natural phenomena from improvements brought about by cleanup programs will continue to be an important consideration in future analyses of the benthic program.

Benthic sampling is conducted ten times per year throughout the mainstem Bay and in all the major



Bay tributaries. Station locations (Map 9) encompass the range of salinity and sediment types that occur in the Maryland Bay. Physical and chemical properties of the water (e.g., salinity, temperature, and dissolved oxygen concentration) and sediments (e.g., particle size, and carbon content) that are known to affect benthic organisms are measured at each sampling location.

RESULTS

Salinity is the major natural environmental factor controlling regional distributional patterns for the Bay benthos. Differences in sediment characteristics and in the levels of bottom dissolved oxygen concentrations that occur from shallow to deep habitats control local benthic distributions. Five major assemblages of benthic populations occur along the salinity and sediment gradients (Map 9). These are: (1) a tidal freshwater assemblage, (2) a trace salinity assemblage, (3) a low salinity estuarine assemblage, (4) a high salinity estuarine sand assemblage, and (5) a high salinity estuarine mud assemblage. Salinity increases with bottom depth throughout the Bay. Thus, high salinity assemblages located in deep habitats can be adjacent to low salinity shallow water assemblages.

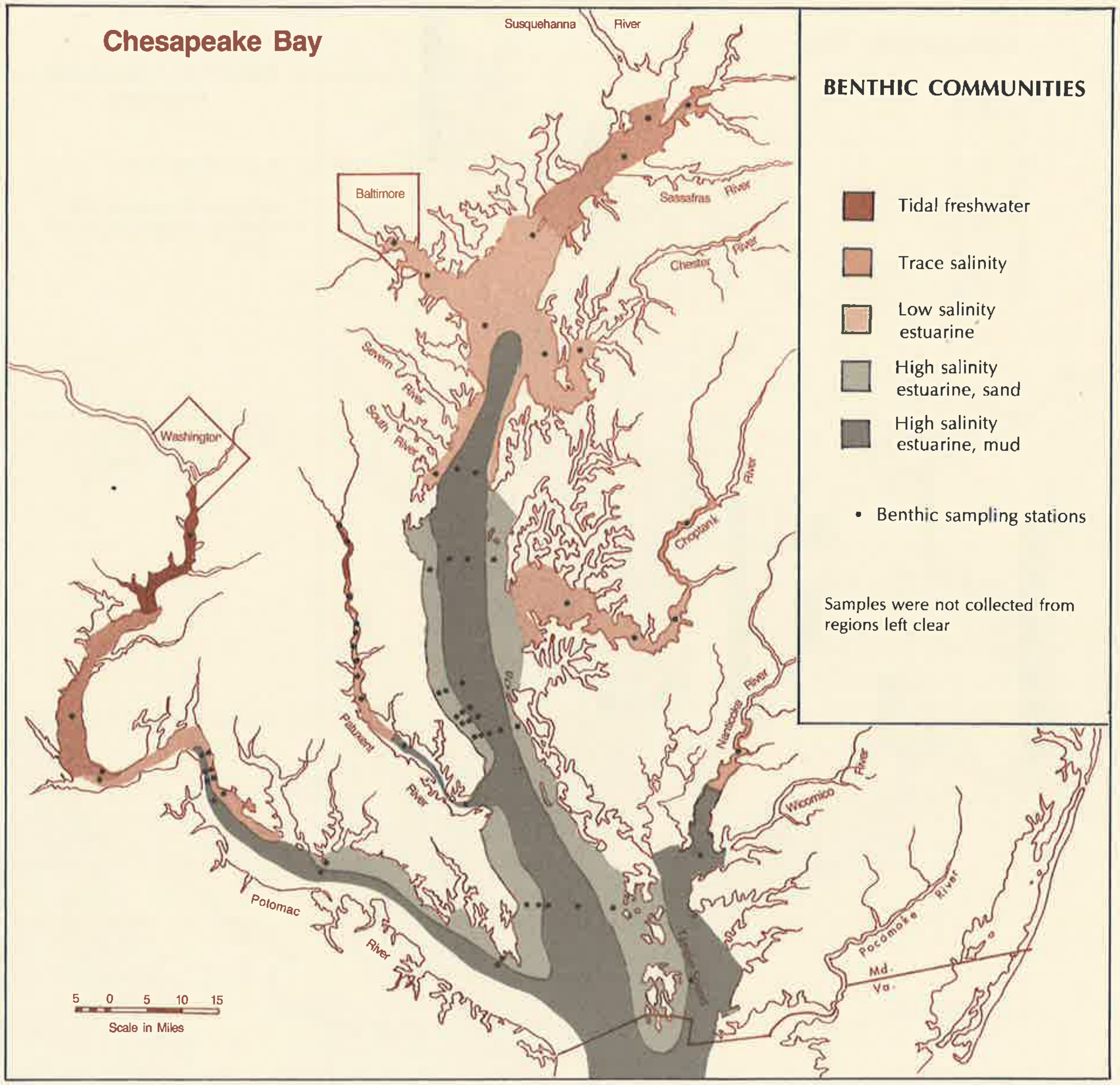
The tidal freshwater assemblage is limited to the upstream portions of Bay tributaries. Aquatic earthworms, called oligochaetes, and larval insects are numerically dominant in this habitat. The trace salinity assemblage occurs in the transition zone between tidal freshwater and estuarine habitats. Its greatest extent occurs in the upper portions of the mainstem Bay and the Potomac River, and is of limited extent in smaller tributaries. A mix of freshwater organisms which tolerate exposure to low salinity, and estuarine species which tolerate exposure to freshwater are abundant in the trace salinity habitat. The low salinity estuarine assemblage is dominated by estuarine species. A few marine species that tolerate exposure to low salinity also occur in this assemblage. The high salinity estuarine sand and mud assemblages are distinct benthic groups, each dominated by marine species that tolerate exposure to low salinity. These asemblages are distinguished from each other by groupings of species that associate with particular types of bottom sediments. It is apparent from Map 9 that most of the Maryland portion of the Bay is inhabited by estuarine assemblages.

The spatial distribution of benthic organism biomass is summarized in Map 10. Biomass is the total dry weight of all benthic animals collected. 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. Low benthic biomass also occurs 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 associated with oxygen-depleted (i.e., anoxic) bottom waters that occur during 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.

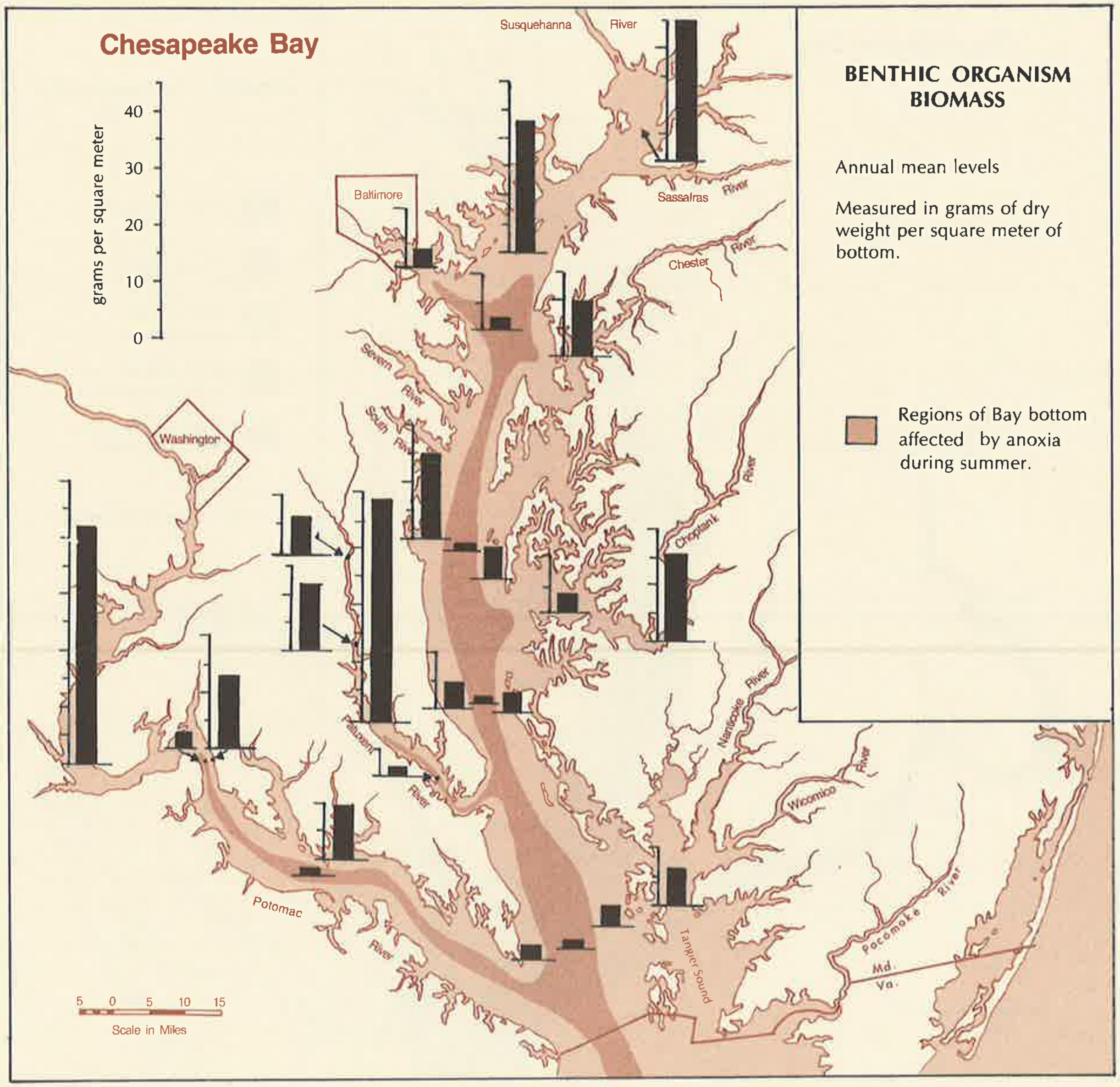
Shallow habitats along the margins of the mainstem Bay and the lower half of the Potomac River do not experience summer anoxia. These regions are characterized by much greater benthic biomass than the adjacent deeper habitats that do experience summer anoxia (Map 10). A variety of benthic organisms are abundant in shallow habitats including small, rapid-growing polychaetes and larger, slower-growing crustaceans and mollusks.

The greatest biomass of benthos, represented by the tallest bars in Map 10, occurs in trace salinity and low salinity estuarine habitats. Much of the suspended sediment and organic inputs to the Bay are deposited in this habitat, the zone of maximum turbidity, and become an available food source for the benthos. The Macoma clam, *Macoma balthica*, and the brackish water clam, *Rangia cuneata*, comprise most of the benthic biomass in the zone of maximum turbidity. These clams are particularly well adapted to feeding on microorganisms associated with organically rich, frequently resuspended sediments.

The biomass of benthic organisms at any one place in the Bay fluctuates as much or more over an annual cycle as it does from place to place. Figure 16 summarizes month-to-month variation for the benthos of typical Bay habitats. In all habitats, peak benthic biomass occurs in the spring. Factors influencing within-year variation in benthic biomass vary among habitats. Essentially no benthic organisms survive anoxic conditions that occur in deep habitats during summer (Figure 16, A). When anoxic conditions dissipate in early fall, deep habitats are repopulated within weeks



Map 9.



Map 10.

by small, rapidly-growing polychaetes. Benthic biomass is also low during summer in shallow habitats along the margins of the Bay and its tributaries (Figure 16, B). Summer low biomass values in shallow habitats are, however, larger than peak biomass values in deep habitats that experience anoxia (Figure 16, A and B). Annual biomass cycles for shallow habitats appear to be associated with the annual phytoplankton cycle suggesting a direct linkage between shallow water benthic biomass and phytoplankton. A variety of species contributes to biomass peaks in shallow habitats, including polychaetes, crustaceans, and mollusks. Seasonal variation in benthic biomass is reduced in the trace salinity habitat (Figure 16, C); however, biomass levels in this habitat are always an order of magnitude higher than those in other habitats.

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 17). As discussed above, *Macoma* biomass is closely linked to the amount of organic material that is produced within or input to the system. Patuxent *Macoma* populations have declined since 1980 as suspended sediment loadings have declined and as sewage treatment facilities have been upgraded. Declining *Macoma* biomass may indicate that the amount of organic material accumulating in Patuxent sediments is decreasing and water quality is improving. These data suggest that pollution abatement and cleanup programs for the Patuxent River are improving water and sediment quality by limiting inputs and pro-

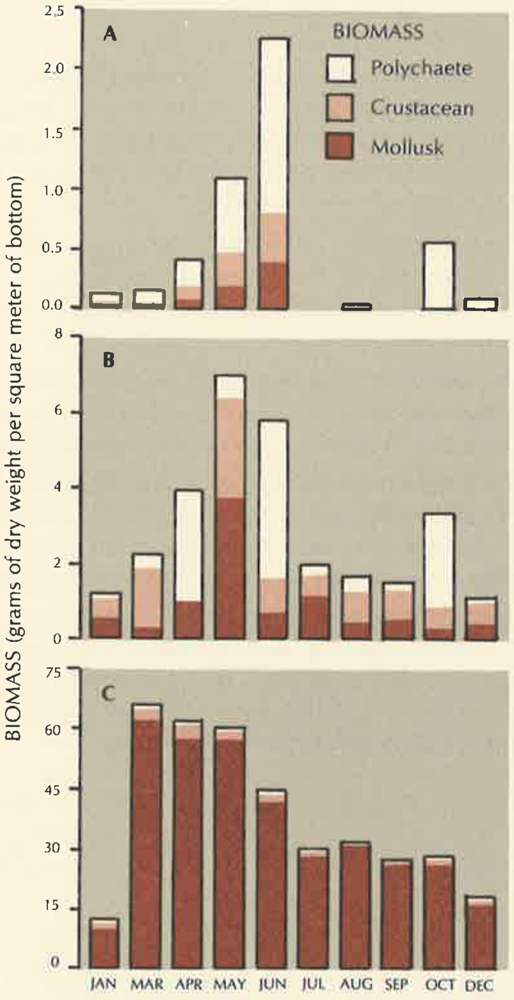


Figure 16. *Annual cycle of benthic organism biomass in three representative habitats found in Chesapeake Bay. These three habitats are high salinity, deep mud (A), high salinity, shallow sand (B) and trace salinity (C). (Note: Biomass scale is different on each graph).*

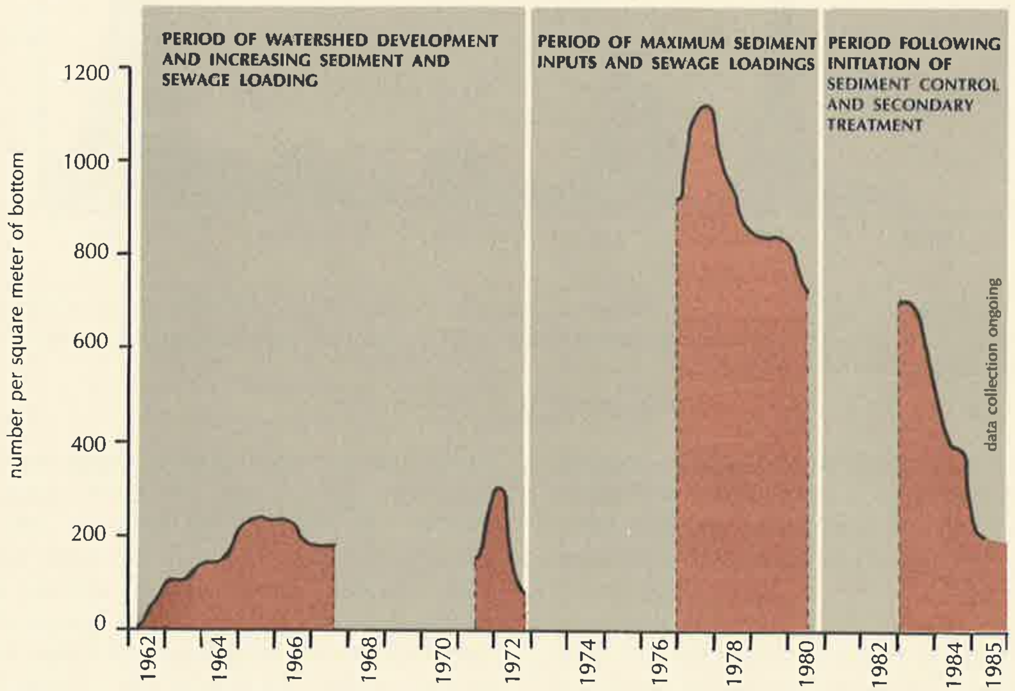


Figure 17. *Historical abundance of adult Macoma clams, Macoma balthica, in the turbidity maximum region of the Patuxent River. Gaps between years indicate periods during which no data were collected.*

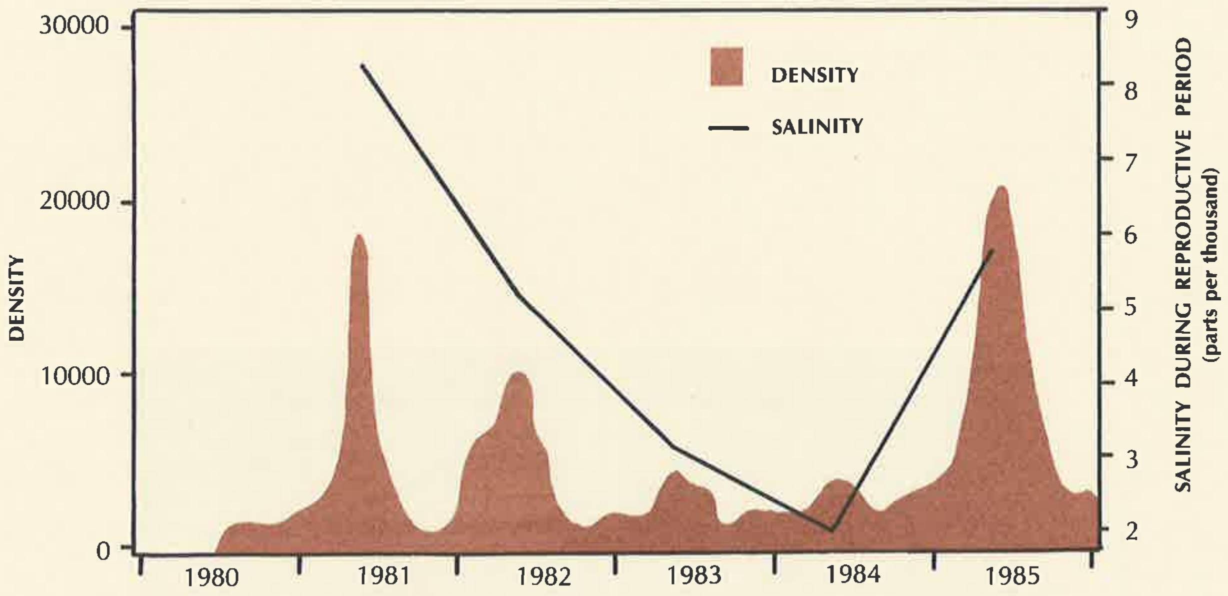


Figure 18. *Historical abundance of the small crustacean,* Leptocheirus plumulosus, *in the low salinity estuarine habitat of the Potomac River. River salinity during the spring of each year is plotted to show its relationship with the annual spring reproductive peak in abundance.*

duction of organic material. The benthos appears to be responding in a measurable and interpretable way and therefore this biological community may be an early indicator of system-wide improvements.

Natural effects of salinity fluctuations on long-term benthic abundance trends are shown in Figure 18 for the low salinity estuarine assemblage in 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 18 is representative of most of the Chesapeake Bay. Long-term benthic responses to salinity and other sources of natural variation can and must be determined before responses to Bay-wide management actions can be assessed.

CONCLUSIONS

- Benthic organisms are an important component of the Bay ecosystem, serving as food for fish and crabs and mediating exchange processes between bottom sediments and the overlying water column.
- Benthic organisms provide a sensitive indicator of water quality that integrates within the food web, over time, and over a number of environmental variables.
- The impact of low dissolved oxygen waters on bottom habitats is difficult to measure directly but is clearly evident in benthic communities.
- The long-term response of benthic organisms to reductions in organic inputs and initial pollution abatement programs in the Patuxent River has been documented and appears to be favorable.
- Benthic responses to pollution controls can be accurately tracked because natural sources of variation are known and can be partitioned from responses associated with pollution abatement and cleanup programs.

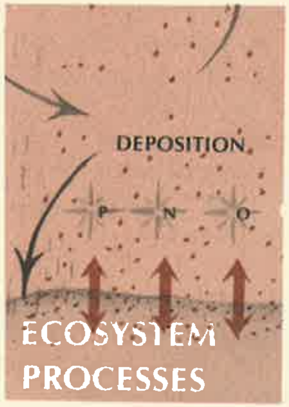
7. ecosystem processes

The Ecosystems Processes Component (EPC) of the water quality monitoring program focuses on the exchange of organic matter, oxygen, and nutrients between Bay waters and sediments. The importance of these exchanges in regulating the productivity and water quality of estuaries has become increasingly clear over the last decade. For example, we know that many bottom sediment (benthic) communities, including commercially important shellfish and finfish, are nourished by organic matter produced in the overlying water. At the same time, the phytoplankton production of many estuaries, including portions of the Chesapeake Bay, depends on the release of fertilizing nutrients—dissolved inorganic forms of nitrogen (N), phosphorus (P), and silicon (Si)—from bay sediments. In addition, oxygen consumption by organisms in sediments is an important factor in the depletion of oxygen from bottom waters.

Interaction between bottom sediments and the water column in the Chesapeake Bay ecosystem involves exchanges of oxygen, nutrients and organic matter. Dissolved N, P and Si are introduced into Bay waters from surface and groundwater runoff, sewage and industrial effluents, and rainfall. As discussed in previous chapters, these nutrients may then be taken out of solution and incorporated into growing phytoplankton. A significant portion of this phytoplankton biomass sinks, either as intact cells or in various stages of decay, and eventually reaches the Bay bottom. On the Bay bottom, much of this rich organic matter is eaten by benthic organisms ranging from microscopic bacteria to large shellfish. This feeding is accompanied by the consumption of oxygen and the formation of "remineralized" inorganic nutrients. The remineralized nutrients in Bay sediments are released back to the overlying water where they may then mixed upwards into the sunlit portions of the water column to support additional phytoplankton production.

Thus, many of the linkages between benthic and water column systems can be characterized as having "positive feed-backs". For example, enhanced phytoplankton production in the upper water column leads to even greater deposition of organic matter to deeper waters and sediments. This, in turn, can fuel greater oxygen-consuming and nutrient-releasing activities by organisms living in the sediments. Unchecked, the cycle of production, deposition, consumption, and remineralization contributes to the lack of oxygen in both sediments and bottom waters. This eventually leads to the deterioration of aquatic habitats for important living resources, a symptom which is characteristic of overly fertilized, or eutrophic, estuarine systems.

The conceptual model of sediment-water column coupling outlined above predicts the following relationships. 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 from sediments will also decrease. Sediment processes, therefore, not only contribute to changes in water quality, they 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 plus changes in the rates of metabolic activities in sediment communities. It is because of these links between nutrient loading, sediment nutrient exchange dynamics, and water quality that long-term trends of deposition of organic matter and sediment-water exchanges of oxygen and nutrients need to be monitored.

DESIGN CONSIDERATIONS

The primary objective of the Ecosystem Processes Component of the OEP Chesapeake Bay Water Quality Monitoring Program is to determine current conditions in the exchange of organic matter, oxygen, and dissolved inorganic nutrients between waters and sediments of Chesapeake Bay and to provide data needed to identify long-term trends in these same exchanges. Additionally, the data collected in this component are to be integrated with those from other monitoring components to produce information needed to develop and evaluate water quality management programs.

To meet these objectives, the EPC project is divided into two complementary parts: (1) determinations of exchanges of oxygen and nutrients across the sediment-water boundary (Sediment Oxygen and Nutrient Exchange - SONE) and (2) measurements of the rate of downward transport of particulate organic matter through the Bay's water column (Vertical Flux - VFX).

Sediment Oxygen and Nutrient Exchange (SONE): Previous studies in Chesapeake Bay have shown that sediment communities undergo seasonal cycles, reflected in the predictable seasonal variations in sediment oxygen demand (SOD) and sediment-water nutrient exchanges. Earlier work has also shown that short-term (daily to monthly) variability in these exchanges at any one location is small compared with seasonal variability at a particular location and variability between stations.

This information indicated that a regional view of these processes could be achieved with quarterly measurements at ten stations located within the Maryland portion of the Bay (see Map 1, Chapter 3). Four stations were identified to cover the salinity gradient along the Bay's mainstem. Within the major tributaries themselves, spatial patterns are examined with an upriver and a downriver SONE station in the Potomac, Patuxent and Choptank rivers.

The net exchanges of oxygen and nutrients across the sediment-water boundary are determined on board ship using intact sediment samples. Triplicate cores from each station are placed in a darkened water bath to maintain normal water temperature. The cores are sealed from the atmosphere and held in the dark for two to five hours. Concentrations of dissolved oxygen and nutrients are measured over time in the water overlying each core and in a control core without sediment. Using these data, exchanges of oxygen and various nutrients can then be calculated to provide a direct indication of the influence of Bay sediments on water quality.

Vertical Flux (VFX): The design of VFX monitoring is governed by constraints somewhat different from those applying to SONE monitoring. Unlike sediment-water exchanges, daily to monthly variability in vertical flux was expected to be large, particularly during the summer. This variability is attributable to the unpredictable and patchy distribution of plankton blooms, variations in zooplankton grazing rates, freshwater flow, and other factors. Obtaining an accurate estimate of annual and seasonal organic matter deposition therefore requires intense sampling during the spring, summer, and fall, with less frequent sampling during the colder months. A station was established at a deep-water, mid-bay location that is representative of areas in the Bay that suffer from low dissolved oxygen in bottom waters (see Map 1, Chapter 3).

The downward flux of particulate material is determined using cup-like traps fixed at 3 distinct depths. The uppermost trap estimates the vertical flux of particles from surface waters to the level of the pycnocline, the middle trap allows estimates of particle fluxes across the pycnocline to deeper waters, and the near-bottom trap collects "new" material reaching the Bay bottom as well as "old" sediment resuspended by tidal currents and waves. Traps are routinely deployed for periods of one to two weeks. Analyses of collected material, which are used to calculate rates of deposition, include particulate N, P, and C, total dry weight, organic fraction and phytoplankton species composition.

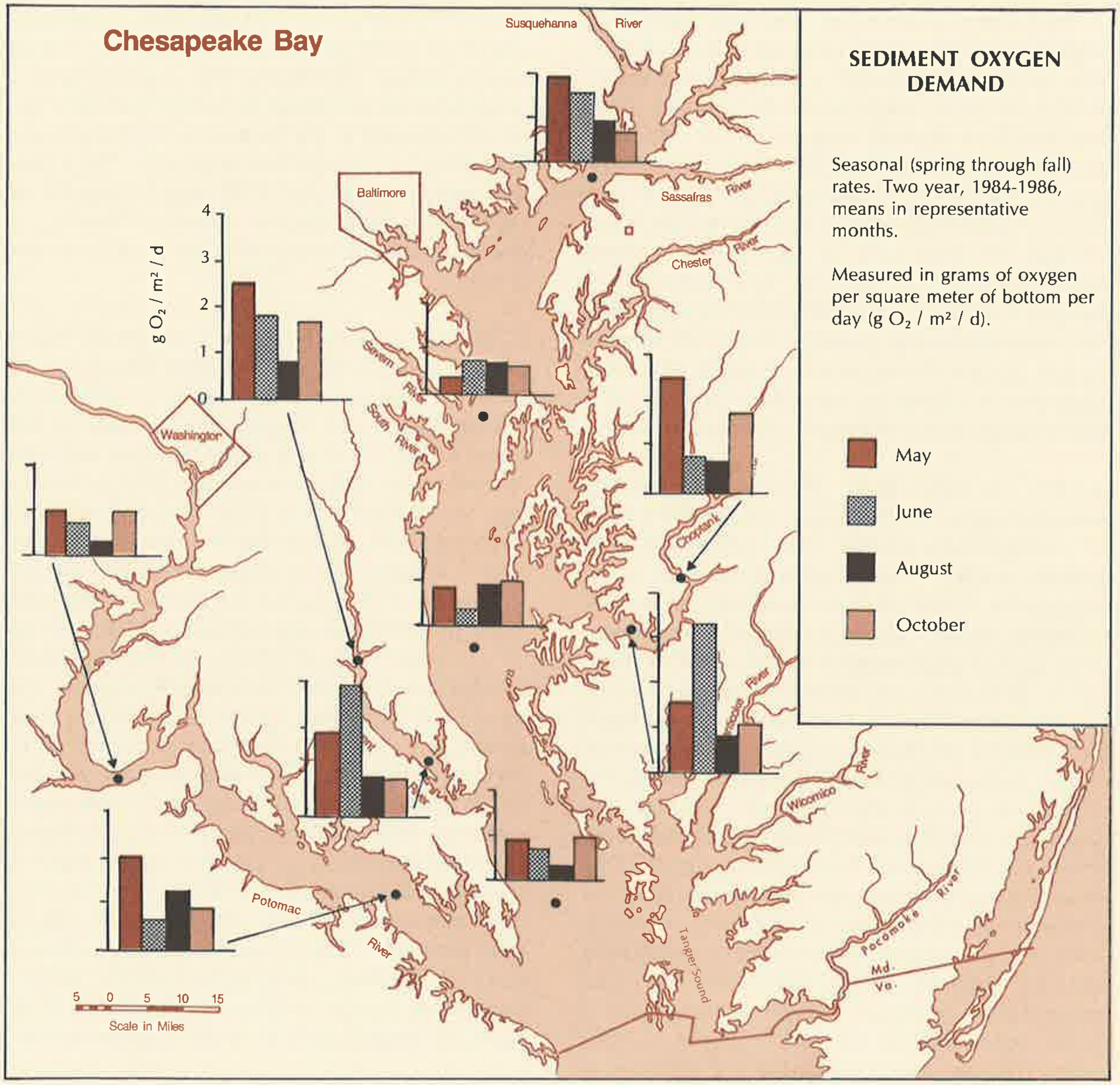
Supporting Data: Additional water column and sediment analyses are routinely carried out as part of the EPC effort. These supporting data are used to assist in the interpretation of ecological events at each station and add to the temporal coverage of monitoring data being collected in other components of the program. For example, profiles of temperature, salinity, and dissolved oxygen conditions are determined through the water column whenever a SONE or VFX station is occupied. Particulate matter concentrations in the water and sediments are also routinely collected. Most importantly, EPC monitoring locations and sampling schedules are coordinated with those of other program elements. Because of this, there is a rich source of additional complementary data with which to interpret EPC trends as well as to enhance the information base developed from other monitoring components.

RESULTS

Sediment Oxygen Exchange

Sediment oxygen demand rates determined during the first two years of SONE monitoring ranged between 0.1 - 3.9 grams of oxygen consumed per square meter of Bay bottom per day (g $O_2/m^2/d$). These values are comparable to rates found in other productive estuarine systems. Seasonal measurements of SOD (Map 11) revealed that oxygen consumption in tributaries was generally greater than along the mainstem and that sediments from the upper Bay had greater SOD rates than those in mid-bay regions. Some of the highest rates were found in the lower Patuxent and lower Choptank Rivers.

SOD rates were often highest in the warmer sampling periods. This is due to the higher rates of oxygen demanding processes, such as biological



Map 11.

metabolism and chemical reactions, caused by higher temperatures. In addition to temperature, the spatial and seasonal patterns in measured SOD rates can be attributed to factors such as the deposition of organic material to the sediments and the availability of oxygen in the water overlying sediments. For example, SOD was low – less than 0.7 g O_2/m^2/d – even in warmer months when oxygen concentrations in the overlying water were less than 2.5 mg/l. The low bottom-water oxygen levels help explain why the two stations in the lower mainstem exhibited low SOD rates in August despite the warm temperatures. It is now clear that SOD rates are ultimately regulated by a combination of interacting environmental factors.

It has recently been learned that certain meteorological conditions can lead to the mixing of surface-water oxygen into oxygen-depleted bottom waters. These events appear to occur repeatedly during the summer and have considerable impact on water quality conditions. One such impact appears to be on SOD rates. While SOD rates are known to be small when oxygen concentrations are very low, the response to suddenly increasing oxygen concentrations due to a mixing event was not known. Would the SOD rate remain low because most of the organisms living in sediments had already died from lack of oxygen? Alternatively, would SOD rates increase greatly due to the accumulation of compounds which quickly react and combine with oxygen. Recent measurements made during the OEP program strongly suggest that the initial response to increased oxygen availability is a large, approximately ten fold, increase in SOD rates. This response is likely due to the chemical reaction of oxygen-consuming sulfur compounds which are generated by bacteria and accumulate during anoxic conditions. The rapid growth of oxygen-consuming bacteria is also a probable factor contributing to the increased oxygen demand following the introduction of oxygen. The important point here is that SOD may be capable of rapidly returning bottom waters to hypoxic or anoxic conditions even following summer mixing events.

SOD at the station in the mainstem off the mouth of the Choptank River (see Map 1, Chapter 3) exhibits a typical seasonal cycle for this area, marked by lowest oxygen uptake rates in late summer when oxygen concentrations are low. Assuming that the yearly average SOD at this station was about 0.8 g O_2/m^2/d and that yearly phytoplankton production in that region (see Map 7, Chapter 5) was about 450 g C/m^2, carbon consumption by mid-bay sediment communities in the presence of oxygen accounts for the utilization of about 25% of primary production of the overlying waters. Recent research suggests that significant additional amounts of carbon consumption by the sediments are occurring when the overlying water is devoid of oxygen, although this is not measured routinely in the monitoring program. This additional amount of carbon consumption would increase the percentage of primary production being utilized by the sediment community. Similar values have been found from a variety of other coastal marine systems and serve to illustrate once again that the bottom community can be a significant consumer of oxygen and organic carbon in the Bay ecosystem.

Sediment Nutrient Exchange

Ammonium, perhaps the most important form of nitrogen for phytoplankton growth, is the dominant form of nitrogen released from estuarine sediments. Consistent with the findings from other estuaries, the fluxes of ammonium found in the OEP program (Map 12) were always directed from the sediments into the overlying water and were as high as 6.5 milligrams of nitrogen released per square meter of Bay bottom per hour (mg N/m^2/h). The spatial patterns of ammonium release differed from that found for SOD measurements. Ammonium release was highest in the lower reaches of the mainstem and the lower Potomac and Choptank Rivers and generally declined toward the upper Bay and the upper tributaries. On a seasonal basis, ammonium flux rates were generally highest in summer and lowest in spring or fall.

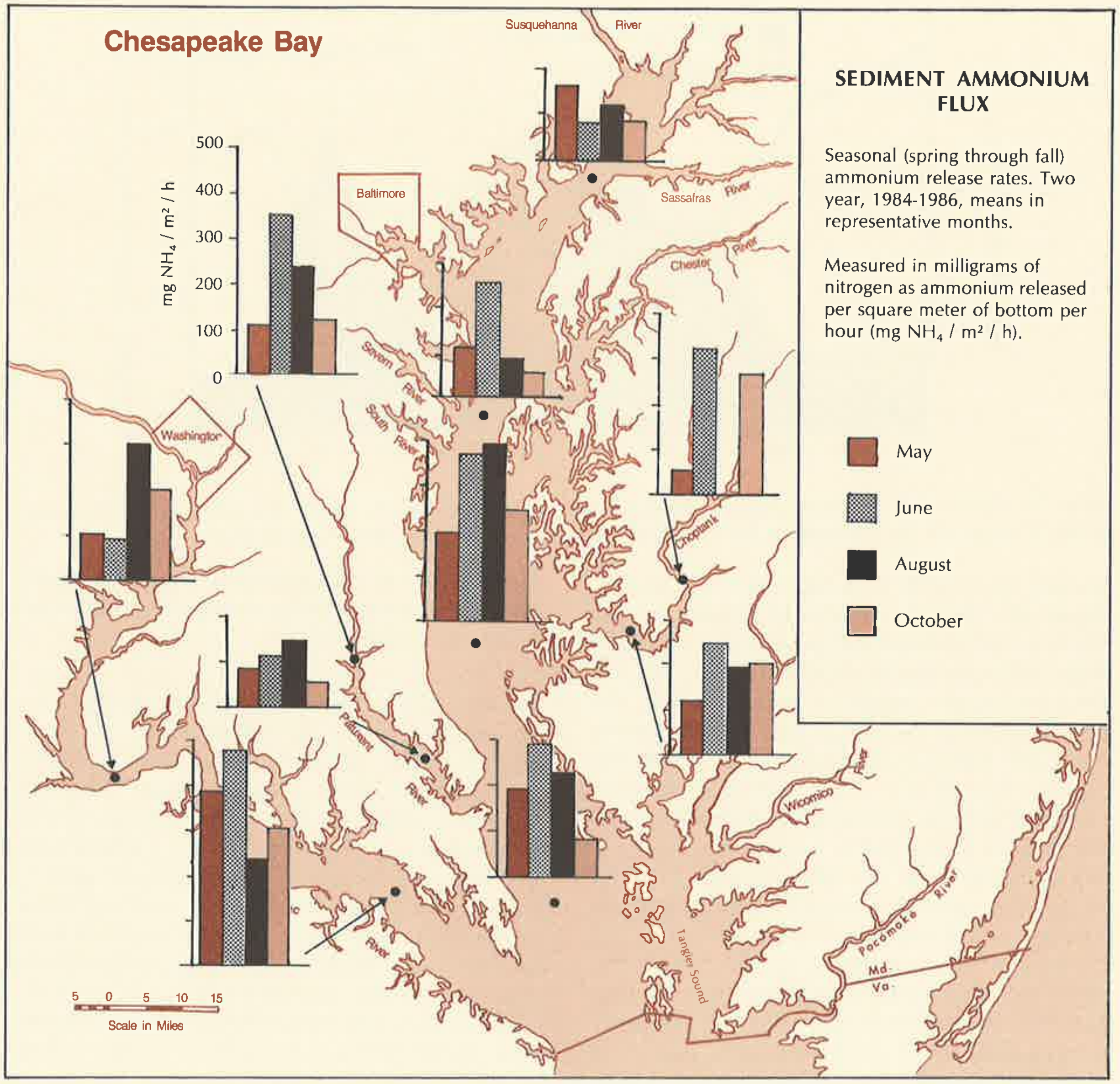
Three other important nutrient fluxes were measured in the SONE program - nitrate, silica, and dissolved inorganic phosphate. Although the results for these nutrients are not presented in detail here, some general findings are summarized below. Nitrate fluxes ranged from -1.4 to +2.1 mg N/m^2/h, the negative and positive signs indicating that nutrient were entering or leaving the sediments, respectively. Fluxes were always positive in upper mainstem and Patuxent sediments and, in October, nearly all stations exhibited positive nitrate fluxes. These observations offer evidence that the early fall, when large amounts of oxygen are introduced into summer-depleted bottom waters, may be notable for active sediment nitrification. Nitrification is a bacterially-mediated chemical reaction between certain nitrogen compounds and oxygen which yields nitrate.

Dissolved inorganic phosphate fluxes ranged from 0.15 - 0.77 mg P/m²/h and tended to be highest in the upper portion of tributary rivers and at stations in the Bay experiencing summer anoxia. Again, the magnitude of the dissolved inorganic phosphate fluxes were such that they could have considerable influence on water quality conditions. This effect can clearly be seen in mainstem bottom waters during summer when dissolved inorganic phosphate builds to high concentrations (see Figure 11, Chapter 4).

Silica, an essential nutrient for diatom growth, was always released from sediments to overlying waters. Diatoms are important species of phytoplankton in Chesapeake Bay, especially prominent in the fall through spring period. Average fluxes ranged from about 12 - 36 mg Si/m²/h and tended to be somewhat higher at the down-Bay mainstem stations than in the upper mainstem and tributary rivers. The observed fluxes appeared sufficient to have substantial impacts on water column concentrations.

Vertical Flux

Vertical flux rates from surface waters to bottom waters of the Bay are expressed as the mass of organic matter, presented here as carbon, passing through an imaginary plane of given area during a day. Average monthly values for two full years at the central bay station ranged from a low of about 0.5 grams of carbon deposited per square meter



SEDIMENT AMMONIUM FLUX

Seasonal (spring through fall) ammonium release rates. Two year, 1984-1986, means in representative months.

Measured in milligrams of nitrogen as ammonium released per square meter of bottom per hour (mg NH_4 / m² / h).

Map 12.

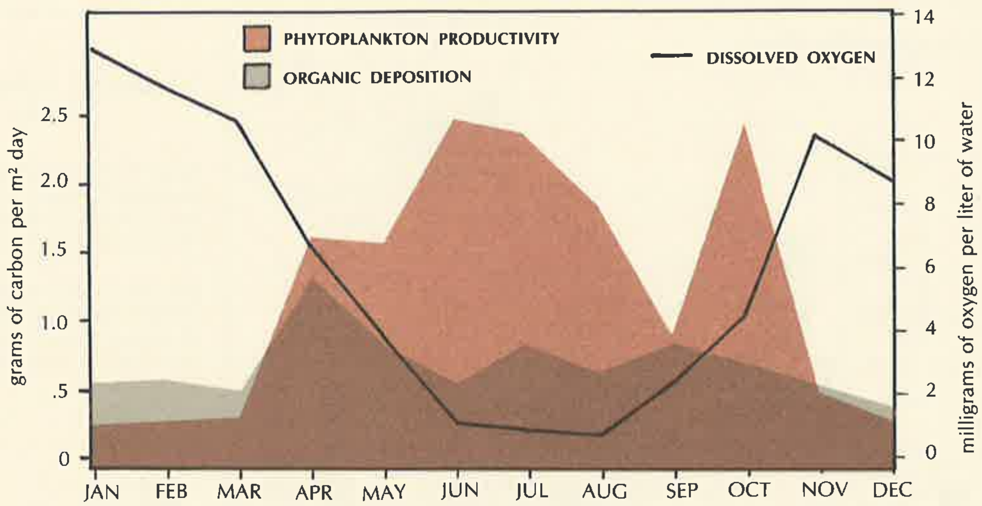


Figure 19. *Relationships between seasonal phytoplankton productivity, organic matter deposition and bottom water dissolved oxygen for the Chesapeake Bay mainstem station off the mouth of the Choptank River.*

per day (g $C/m^2/d$) to a high of 1.3 g $C/m^2/d$ (Figure 19). These are substantial deposition rates which would be expected to have a considerable impact on water quality conditions, especially the dissolved oxygen regime in bottom waters. The general seasonal cycle indicated that deposition of organic material was sustained at a relatively constant level of 0.5 - 0.6 g $C/m^2/d$ in the cold months of January, February and March and then rose sharply to the yearly peak of around 1.3 g $C/m^2/d$ in April. In the May through October period, the monthly-averaged rates varied between about 0.6 and 0.9 g $C/m^2/d$. It is interesting to note that organic matter deposition rates in the colder months are only slightly lower than in summer. The result of this sustained winter and early spring deposition of phytoplankton is a growing accumulation of phytoplankton in bottom waters through the winter with a peak in the spring (see Figure 13, Chapter 5).

The relationship between seasonal phytoplankton productivity in the upper water column, organic matter deposition and bottom water dissolved oxygen is displayed in Figure 19 for the mainstem station located off the mouth of the Choptank River. This relationship is a critical one to understand for assessing management actions aimed at reducing phytoplankton productivity to improve bottom water oxygen problems. Several patterns are evident in this relationship which suggest seasonally varying levels of coupling between surface and bottom waters. In the period from winter through the middle of the spring phytoplankton bloom in April, most of the phytoplankton production appears to enter bottom waters. The period from May through August is characterized by a much lower fraction, generally about ⅓ to ½ of phytoplankton production, reaching bottom waters. In September, when the Bay destratifies and phytoplankton productivity declines from its summer peaks, most of the productivity again reaches bottom waters. An October peak in phytoplankton production is not reflected in the deposition rate although the lack of a correlation may be due to the fact that deposition was only monitored during the first half of October.

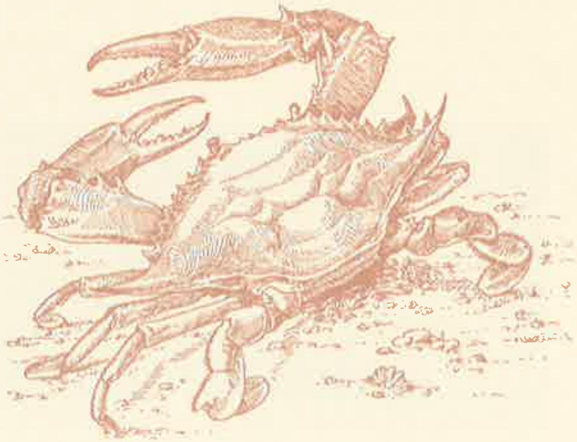
There are some probable explanations for the observed relationships between phytoplankton productivity and organic matter deposition. From January through April and again in September, the plankton component of OEP's monitoring program has found that much of the phytoplankton community is composed of species, such as diatoms, that tend to sink at relatively rapid rates. This is a likely cause for the apparently high fraction of phytoplankton productivity that is being deposited to bottom waters. During the summer, more buoyant phytoplankton cells and a strong density barrier between surface and bottom layers may serve to inhibit the downward transport of organic material.

Another interesting aspect of these data concerns some of the weekly variability in carbon deposition that was observed during summer months. For example, rates varied between 0.25 and 0.8 g $C/m^2/d$ over a two week period during the summer of 1984. The reason for this variability appears to be periodic, short-term blooming and subsequent death and sinking of phytoplankton communities.

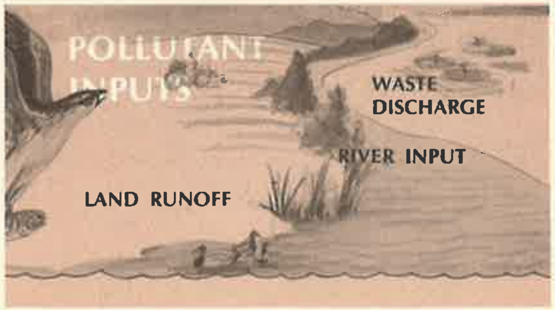
The seasonal cycle of oxygen in bottom waters at the mid-Bay station is typical of this region (Figure 19). During spring, as strong density stratification develops, levels of oxygen decline rapidly and then remain low during summer. In the fall there is a rapid return to the higher oxygen levels observed during colder months. The organic matter that deposits gradually over the colder months and in a large spring pulse is probably responsible for much of the oxygen consumption in bottom waters and sediments that occurs between March and June. This spring period encompasses a decline in average monthly oxygen concentrations near the bottom of about 9 mg/1. During summer, continued substantial deposition of organic matter, coupled with limited reaeration, appears to be sufficient to maintain average dissolved oxygen levels below 1 mg/l. In fall, the enhanced reaeration of Bay waters due to lower density stratification overwhelms oxygen-consuming processes which are declining, in part because of falling temperatures. This leads to a rapid increase in bottom-water oxygen concentrations. The physical ability of water to hold more oxygen at colder temperatures reinforces and partially contributes to the seasonal patterns just described.

CONCLUSIONS

- The rates of oxygen consumption by Bay bottom sediments contribute significantly to bottom-water oxygen depletion which is a major problem in Chesapeake Bay.
- The release of recycled nitrogen, phosphorus and silicon by Bay bottom sediments exert a substantial impact on water column levels of nutrients, phytoplankton production and other water quality indicators.
- The deposition of organic matter, produced by phytoplankton in surface waters, is substantial year-round, ranging in the mid-Bay from 0.5 to 1.3 grams of carbon deposited on a square meter of Bay bottom each day. Highest rates occur during the Bay's annual spring bloom. These high deposition rates are a major factor causing low dissolved oxygen levels to occur in bottom waters.
- The relationship of the Bay's phytoplankton production with organic matter deposition is now becoming clear with data collected under the OEP program. This relationship varies seasonally, with most of the water column production being deposited to Bay bottom waters in colder months and about ⅓ to ½ being deposited during summer. An understanding of this relationship between production and deposition is important to fomulating management actions to improve bottom-water oxygen levels.



8. pollutant inputs



Nutrients, organic material, sediment and other pollutants are introduced to the Chesapeake Bay from a variety of sources. These are generally separated into two broad classes, point and nonpoint sources. Point sources, as the name implies, are inputs with a specific point of entry into the system. Municipal sewage and industrial discharges are examples of the major point sources of pollutants to the Bay. Nonpoint sources do not have a readily identifiable point of entry to the system or they may have many, diffuse points of entry to the system. Rain water runoff and ground water discharges are examples of the major nonpoint sources of pollutants to the Bay.

All of these inputs must be effectively monitored in order to document the present pollutant loadings to the Bay and to track the progress of cleanup efforts. In addition, the point of entry, chemical form, magnitude and timing of the inputs are important information required to understand and evaluate the impact of the pollutants on water quality.

Maryland has been monitoring the major point sources of pollutants to the waters of the state for many years. The severity of the water quality impacts of many point source discharges warranted immediate attention to regulate and control the discharges. Over the years, these regulatory and monitoring efforts have been steadily upgraded. Under the recent Chesapeake Bay initiatives, point source monitoring efforts are being further improved.

Nonpoint sources present a different sort of regulatory and monitoring problem due to the diffuse and unpredictable nature of the inputs. The situation is further complicated by the critical role that largely uncontrollable natural weather patterns play in determining nonpoint source pollution. As many point sources have been brought under control, the importance of nonpoint sources has become more evident and efforts to control and monitor nonpoint sources have been significantly increased.

DESIGN CONSIDERATIONS

The pollutant input monitoring program described here is divided into three major components: 1) municipal point sources, primarily sewage treatment facilities; 2) industrial point source discharges, of a variety of types; and 3) river inputs, the combined result of many upstream, point and nonpoint source pollutant inputs.

Municipal Point Source Monitoring Program

Point source discharges are regulated in Maryland by the Office of Environmental Programs as part of the federally mandated National Pollutant Discharge Elimination System (NPDES) which is administered by the U.S. Environmental Protection Agency (EPA). The OEP monitoring program for point source discharges was developed to meet the specific requirements of NPDES and EPA. The entire program is based on establishing and enforcing specific discharge permits. As part of its regulatory responsibility, OEP issues discharge permits and reviews monitoring data to assure compliance with the permits.

Several types of monitoring approaches are taken for municipal sewage discharges. The most comprehensive monitoring is carried out by the dischargers themselves. Daily sampling and records of effluent parameters and operational indices are generally required. To verify this self monitoring, OEP personnel conduct periodic compliance monitoring at varying frequencies depending on permit conditions, discharge volume and type of treatment process used. Onsite reviews of plant operation are also conducted regularly by OEP engineers.

The new Maryland Chesapeake Bay initiatives affecting municipal point sources are directed toward improving the operation of municipal sewage treatment plants through improved financial management and operator training, improved regulation and monitoring of industrial discharges which go into the municipal waste stream to be treated at sewage treatment facilities, and enhanced compliance enforcement efforts. However, the major focus of the existing point source monitoring efforts, that is, to verify the individual discharger's compliance with permit conditions, did not change.

In the evaluation of water quality impacts of point source pollution the compliance monitoring data dealing with effluent flows and concentrations of associated nutrients are of primary concern. The bulk of the effluent monitoring data is collected by the plant operators. These data are periodically verified by comparison with State monitoring data. In the past, the effluent data for groups of plants have been compiled only periodically to provide Bay or watershed point source loading estimates for specific planning purposes. In conjunction with the enhanced water quality monitoring activities in the Bay and its tidal tributaries, the data are now being compiled on an annual basis.

Industrial Point Source Monitoring Program

In contrast to municipal sewage discharges, the nature of industrial discharges is much more variable. As a result, a more individually tailored discharge monitoring program is required based on the permit requirements for the individual discharger. In general terms, however, the industrial point source monitoring takes the same combination of approaches as used for municipal monitoring. Compliance evaluation inspections are done by OEP engineers to review records and plant operating procedures. Performance audit inspections are conducted to provide quality assurance and to review the discharger's self monitoring activities. Compliance sampling inspections are done to independently analyze the effluent and verify the results of self monitoring data.

As in the case of the municipal point source monitoring, Chesapeake Bay initiatives for the industrial program are focused on improving discharge permit compliance. In addition, biological evaluation of toxic waste discharges using bioassay techniques is being tested as an added regulatory tool for managing industrial discharges into Maryland's streams. The emphasis is on permit compliance for the individual discharger. The data are generally sufficient for Bay-wide, water quality evaluation needs. However, efforts are currently underway to enhance the monitoring where necessary to provide additional information on discharges.

River Input Monitoring Program

As a result of Maryland's Chesapeake Bay initiatives, the river input monitoring program has been enhanced considerably to provide more accurate data for evaluating sediment and nutrient loading to the Bay from its surrounding watersheds. Prior to the start of the new monitoring program in July 1984, routine water quality monitoring of streams in Maryland by OEP was primarily limited to monthly grab samples. With the new monitoring program, regular storm runoff sampling efforts are now being conducted on four major rivers in Maryland.

River inputs present a difficult monitoring problem because of the number of streams and rivers discharging to the Bay and the unpredictable nature of storm events and associated river flows. There are too many streams and rivers discharging to the Bay for it to be practical to monitor them all. In addition, the characteristics of water flowing in a river are constantly changing in response to rainfall in the watershed. Just as it is not practical to monitor every river flowing into the Bay, it is not practical to continuously monitor all water quality characteristics over time.

River flows can generally be divided into two basic categories, base flow and storm events. Under base flow 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 base flow 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. Thus, it is necessary to take numerous samples during the course of the storm to get an accurate estimate of the pollutant load from a particular 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 base flow.

With careful selection of sampling locations and time of sampling it is possible to characterize a number of rivers for a range of conditions and then extrapolate the data to fill in the gaps in sampling coverage. The rivers that are being monitored have been selected to capture runoff from as much of the Bay watershed as possible and to obtain the maximum coverage of the range of different sources of runoff to the Bay and its tributary estuaries. Sampling times are chosen to emphasize storm events, when the majority of the river input loads are delivered to the Bay.

Four tributaries, the Susquehanna, Choptank, Patuxent and Potomac, are being monitored. Together, these rivers represent over 80% of the freshwater flow discharged into the Maryland portion of the Bay. The percentage of the total nutrient and sediment loads associated with these river flows is not as easily determined.

Each watershed has unique characteristics that may significantly influence the loads delivered by each river. In order to accurately extrapolate the monitoring data to cover unmonitored tributaries to the Bay, various approaches can be taken. Approaches range from simple flow based extrapolation of loading data (e.g. 80% of the flow delivers 80% of the load) to sophisticated watershed computer models. All of these involve assumptions about the transferability of water quality data from one watershed to another and are thus subject to considerable interpretation and debate.

RESULTS

In order to facilitate a comparison of the Chesapeake Bay river input monitoring program with the point source monitoring program, the results are presented together. It must be clearly understood that the loading estimates discussed below are not to be taken as a complete inventory of the nutrient inputs to the Bay. What is represented are the river input loads (point and nonpoint sources) for four rivers, representing 80% of the fresh surface water flow into Maryland's portion of the Chesapeake Bay, and the point source loads discharging into the Bay drainage area that are not measured by the river input monitoring program. The nonpoint source nutrient loads from the unmonitored 20% of the flow, the atmosphere, ground water, sediments and other potentially significant sources of nutrients have not been presented here.

In addition, the results shown for both river inputs and point sources indicate the amounts discharged at the location, or in the region indicated. The loads do not necessarily reach the mainstem of the Bay itself. For example, the impact on the Chesapeake Bay of the nutrient loads at the head of the Potomac estuary are substantially moderated by the natural processing which occurs in the Potomac estuary before any of that load reaches the Bay. In order to assess the relative impact of the these loads on various regions of the Chesapeake Bay, so many factors must be taken into account that the problem is best addressed using complex mathematical models. Modeling efforts are presently underway in the Bay and a number of its tributary estuaries in order to carefully address these problems.

Maps 13 and 14 show the major river and point source nitrogen and phosphorus inputs to the Chesapeake Bay in Maryland for the period 1978 through 1985. River inputs include both point and nonpoint source pollutants discharged upstream of the monitoring stations. Point source inputs shown include only those point sources not captured by the river input monitoring stations.

Point source nutrient load estimates have been compiled from a number of sources including the EPA Chesapeake Bay Program, Metropolitan Washington Council of Governments and OEP compliance monitoring data. Historical point source load estimates were only available for certain years. However, since point source loads are fairly stable for extended periods, the gaps in the data presented here do not prevent a meaningful comparison with the river input data.

Even though population and associated sewage flows have increased since 1980, dramatic reductions in point source phosphorus loads have been achieved in the upper Bay western shore and Potomac regions where phosphorus loads have been reduced by 46 and 89 percent respectively. This has been accomplished largely through the installation of improved treatment processes directed at removing phosphorus from the effluent of the major municipal sewage treatment plants. Over the same period, point source nitrogen loads did not change appreciably. Improved treatment processes, although they are not directed at nitrogen removal, have provided some removal and have permitted the nitrogen loads to be relatively stable in the face of increasing flows.

The 1984 and 1985 river input load estimates shown here are reasonably accurate since they result from the analysis of the expanded monitoring data base. However, because of the lack of a comprehensive historical data base, river input annual estimates for the years prior to the initiation of this monitoring program are not as accurate. In particular, estimates for high flow years are less accurate because of the greater uncertainty in predicting storm flow pollutant concentrations as opposed to low flow pollutant concentrations. Estimates for the Potomac, and 1979 and 1980 estimates for the Susquehanna are an exception. These are based on more complete data and are more accurate than other historical load estimates.

The annual variation of the river input data is clear, but there is significant seasonal variability as well. Based on the results of the river input monitoring program, the total nitrogen and total phosphorus loads have been estimated on a seasonal basis for 1984-85. Figure 20 is a set of bar charts showing the flow, total nitrogen and total phosphorus loads contributed by the four rivers during winter (Jan-Mar), spring (Apr-Jun), summer (Jul-Sep) and fall (Oct-Dec) of 1984 and 1985 (note: the loading scale for the Patuxent and Choptank is 100 times smaller than the Susquehanna and Potomac).

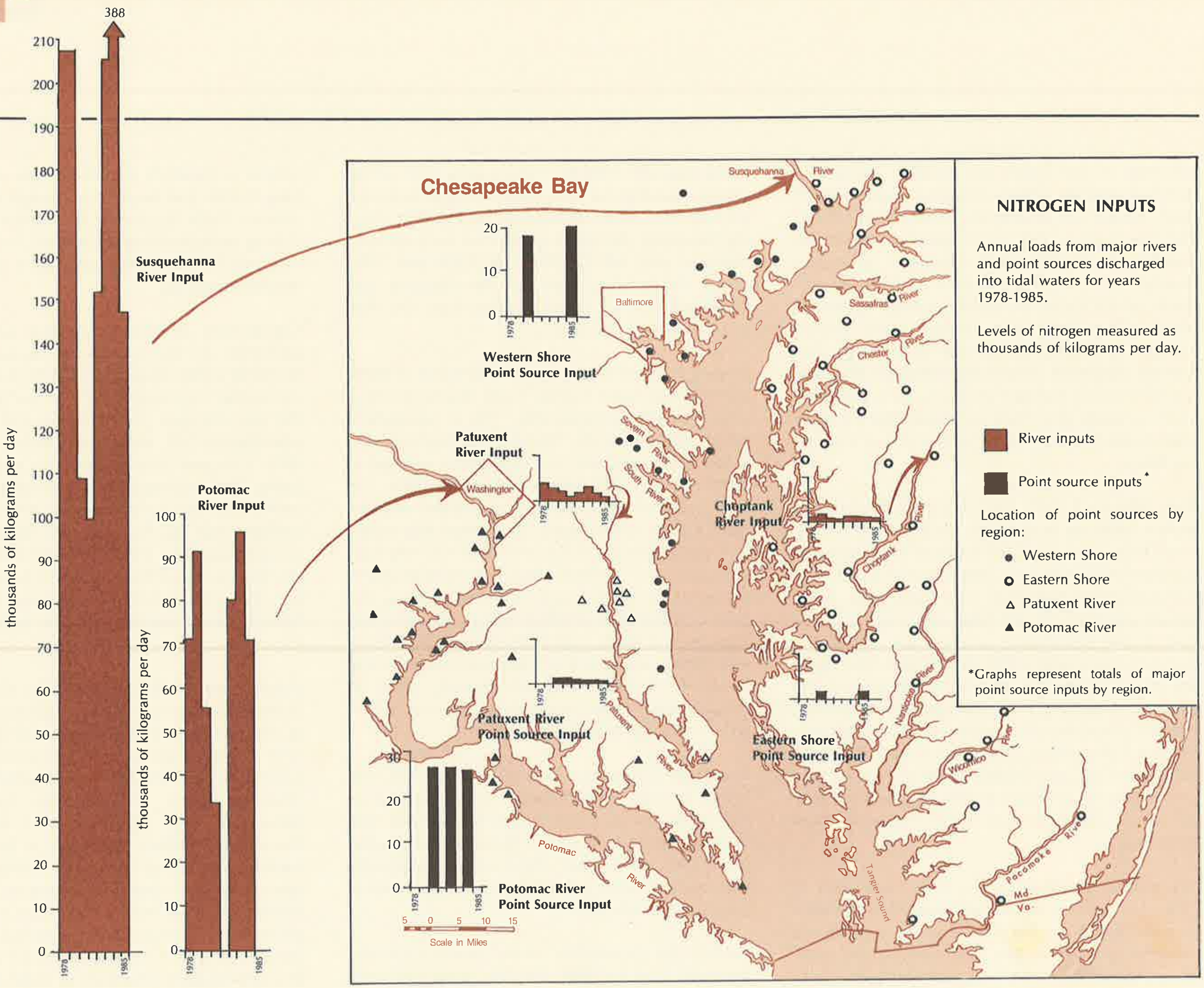
During the course of a year the amount of water and the associated nutrient loads discharged by a river can vary considerably. This is particularly noticeable during the 1984-85 monitoring period when flows averaged 10 - 30% above average in 1984 and 10 - 50% below average in 1985. The seasonality of the flow and associated nutrient loads can be clearly seen. In general, the winter and spring flows and nutrient loads are very high compared to summer and fall contributions. However, as noted earlier, from one year to the next, considerable variation occurs. For example, summer and fall of 1984 had relatively high flows and winter and spring of 1985 had relatively low flows. As a result the winter/spring peak in nutrient loads is not nearly as dramatic as occurred in calendar year 1984.

River flow during the summer of 1985 was well below average (40-50%) and nutrient loads were extremely low as a result. The fall of 1985 was unique, particularly on the Potomac, where the occurrence of a major flood caused unusually high nutrient loads to be delivered to the head of the Potomac estuary.

Despite the uncertainty in the annual estimates for years prior to 1984, the data presented here serves to illustrate the magnitude and extreme year to year and seasonal variability in river input nutrient loads. In general, the highest loads occur during periods of higher rainfall, but flow alone can not be accurately used as a surrogate for nutrient loadings.

Comparison of the flows and nutrient loads delivered by the four rivers reveals some interesting points. Over the 1984-85 period the Susquehanna contributed 73% of the flow, 76% of the total nitrogen (TN) and only 66% of the total phosphorus (TP), while the Potomac contributed 26%, 23% and 32% for flow, TN and TP respectively. This indicates that on average during this period the Susquehanna was relatively rich in nitrogen and the Potomac was relatively rich in phosphorus. The Patuxent contributed 0.6% of the flow, 0.9% of the TN and 1.9% of the TP and was thus rich in both nitrogen and phosphorus. The Choptank contributed 0.2% for flow, TN and TP.

These observed differences in the characteristics of the discharge from the four basins are the result of the interaction of a number of factors. Each river is unique because of the variability of both natural and anthropogenic characteristics of the drainage basins. Physiographic (land surface slope, soil type, geology) and meteorologic characteristics differ from basin to basin and are basically unaffected by human activity. Other important factors—land use practices, population density and point source discharges are definitely attributed to people. More detailed analysis of these factors and the characteristics of the river flow produced is necessary to begin to deal with



NITROGEN INPUTS

Annual loads from major rivers and point sources discharged into tidal waters for years 1978-1985.

Levels of nitrogen measured as thousands of kilograms per day.

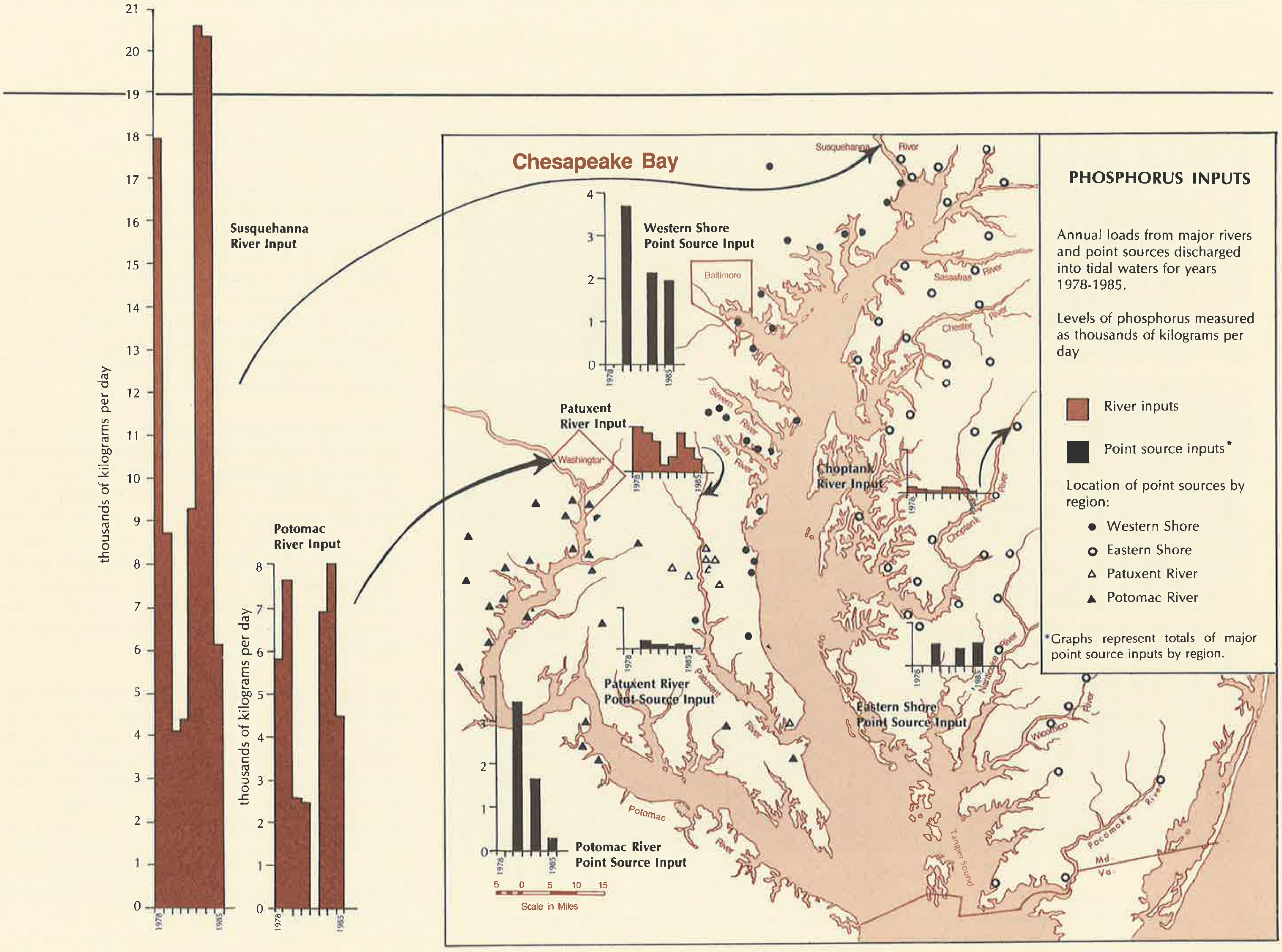
- ▨ River inputs
- ■ Point source inputs*

Location of point sources by region:

- ● Western Shore
- ○ Eastern Shore
- △ Patuxent River
- ▲ Potomac River

*Graphs represent totals of major point source inputs by region.

Map 13.



PHOSPHORUS INPUTS

Annual loads from major rivers and point sources discharged into tidal waters for years 1978-1985.

Levels of phosphorus measured as thousands of kilograms per day

- ▨ River inputs
- ■ Point source inputs*

Location of point sources by region:

- ● Western Shore
- ○ Eastern Shore
- △ Patuxent River
- ▲ Potomac River

*Graphs represent totals of major point source inputs by region.

Map 14.

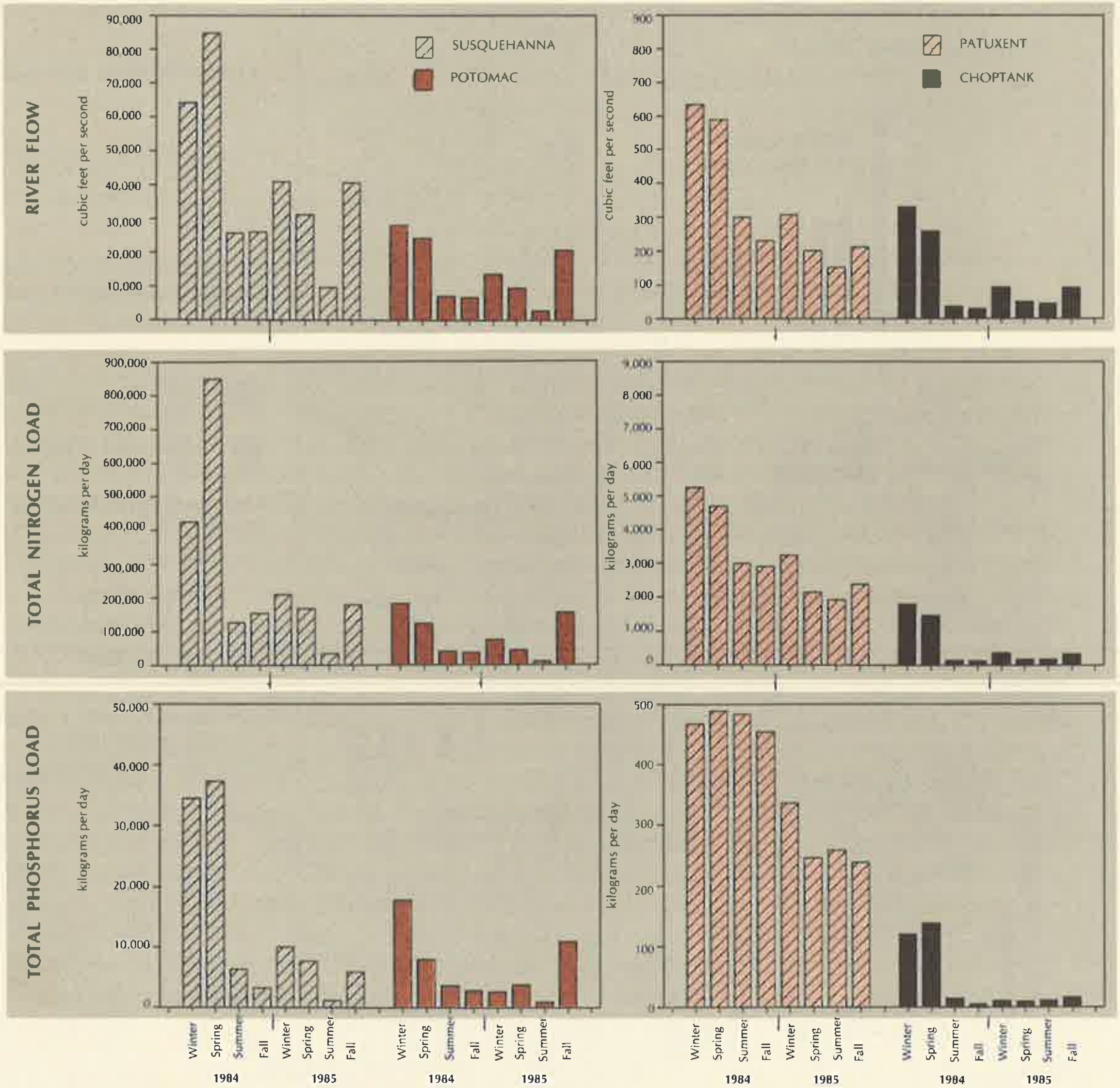


Figure 20. *Seasonal inputs of flow, total nitrogen and total phosphorus for the river input monitoring stations on the Susquehanna, Potomac, Patuxent and Choptank Rivers.*

the unique problems facing each river.

The presentation given above also permits a simple comparison of the river input and point source loads discharging directly to tidal waters of the Chesapeake Bay. Without taking into account all of the other sources of nutrients to the system, the chemical form of the nutrient input and the location of the discharge, it is not realistic to attempt to quantitatively evaluate the relative importance of these inputs. Nevertheless, some general observations can be made.

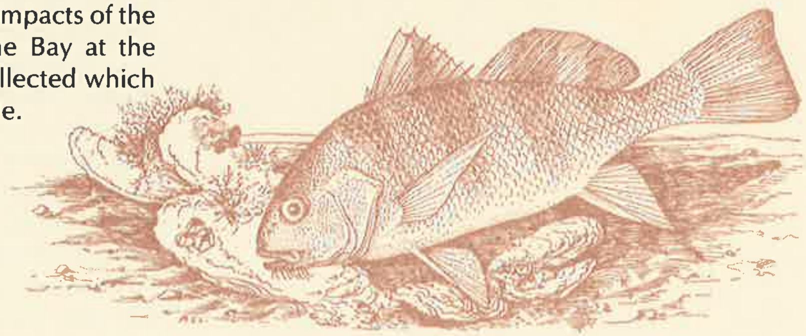
River input and point source data are shown with a standard scale on Maps 13 and 14 to emphasize the realtive magnitude of the loads. It is clear that for both nitrogen and phosphorus the river inputs from the Susquehanna and Potomac are the major source of nutrients to the system. However, because the magnitude of the river input varies considerably from year to year depending on rainfall, the river inputs are of variable significance in the annual nutrient loading budget of the Bay.

For example, the major nutrient inputs to the upper Bay above its confluence with the Patuxent, are the Susquehanna River and point sources from the Western and most of the Eastern shore. For this part of the Bay in 1984, a high runoff year, the Susquehanna River inputs of nitrogen and phosphorus were respectively 20 and 8 times the combined Western and Eastern Shore point source inputs. In 1985, a low runoff year, the nitrogen and phosphorus inputs were 7.5 and 2.5 times the point source inputs.

Comparison of the point and nonpoint loading on a seasonal basis further illustrates the importance of runoff in affecting the balance of nutrient inputs to the Bay. In the upper Bay, river inputs from the Susquehanna reached a minimum in the summer of 1985. During this period, point source loads of nitrogen and phosphorus were comparable to Susquehanna River inputs.

CONCLUSIONS

- Since 1980 dramatic reductions in phosphorus loadings from point sources discharging into the tidal waters of Chesapeake Bay have been achieved in spite of increasing population and associated sewage flows.
- Nitrogen loads from the same point sources have been held fairly stable in the face of increasing sewage flows.
- River inputs of nutrients vary tremendously from year to year and seasonally, generally in correspondence to changes in river flow.
- River flow by itself does not completely determine nutrient load. Each watershed has unique characteristics which affect the exact proportions of nutrient loads and make simple extrapolations of the data inaccurate.
- On an annual average load basis, river inputs far exceed point source inputs to tidal waters. In low flow years this dominance of river input loads is less pronounced and in low flow seasons the river inputs and point source inputs may be comparable.
- Although it is not possible to quantitatively evaluate the relative water quality impacts of the various sources of nutrients to the Bay at the present time, data is now being collected which will permit this analysis to be made.



9. management strategies and the role of monitoring

The primary goal of the OEP monitoring program is to provide State managers and policy-makers with accurate and timely environmental data to be used in the development, implementation and assessment of strategies to control and improve water quality in the Bay. Components of the present OEP monitoring program are structured so that data required to address particular water quality management issues and questions (see Chapter 1) are readily available to decision-makers. However, measurable progress in resolving specific environmental problems can be expected only when this information is used to develop and implement effective management strategies, policies and standards. In the following sections, the process by which numerous, and sometimes conflicting, variables are incorporated into the environmental decision-making process is examined.

MONITORING DATA AND THE ENVIRONMENTAL DECISION-MAKING PROCESS

There are basically two ways in which monitoring data can be used in developing a management action. In a limited number of situations, environmental decisions can be made based directly on an inspection of the available monitoring results. These situations generally occur when desired uses or public health objectives have already been identified, or specific water quality criteria have been established. For example, managers can rapidly assesss the significance of concentrations of heavy metals and organic compounds within the tissues of organisms living in the Bay since federal standards have been established for many of these compounds. Likewise, the major areas in the Chesapeake Bay exhibiting low dissolved oxygen problems can quickly be identified because the State has a standard in effect for this measurement. The rapid identification of environmentally stressed regions within the Bay and its tributaries may be used by managers to initiate water body closures, enforcement actions or special studies.

More typically, the use of monitoring data in making a management decision is less direct. A simple inspection of the data by itself is not sufficient to address cause and effect relationships, to understand the interaction of complex processes or to suggest direct management responses such as the establishment of a water quality standard. In most situations, the data are used in conjunction with the results of research efforts to support various analytical procedures intended to address specific management issues.

The application of both simple and sophisticated statistical techniques can provide significant insights into such issues as characterizing the present status of the Bay's key water quality indicators, detecting trends in water quality over time and providing managers with a "barometer" for assessing the response of the Bay system to management actions. Additionally, a statistical assessment of the available data can aid managers in determining criteria (numerical or descriptive limits) for water constituents which are designed to protect designated uses.

Another example is the use of physical, chemical and biological monitoring data in the development of a water quality computer model. This analytical tool allows managers to forecast the response of a water body to alternative point and nonpoint source control scenarios. The array of management options, such as the water quality response to various levels of nutrient or toxicant removal at point sources, can be evaluated using the model and then the most appropriate control measures can be selected and implemented.

But how is the most appropriate scheme selected? Is it simply the forecasted control option that produces the most desirable environmental outcome? How are other considerations factored into the final recommended strategy? Sound environmental management and policy decisions result from an in-depth assessment of the intended uses, scientific considerations, and economic impacts. The extent to which any one of these three variables dominates the formulation of a management policy or standard is determined by the degree of certainty associated with the variable.

Intended Uses

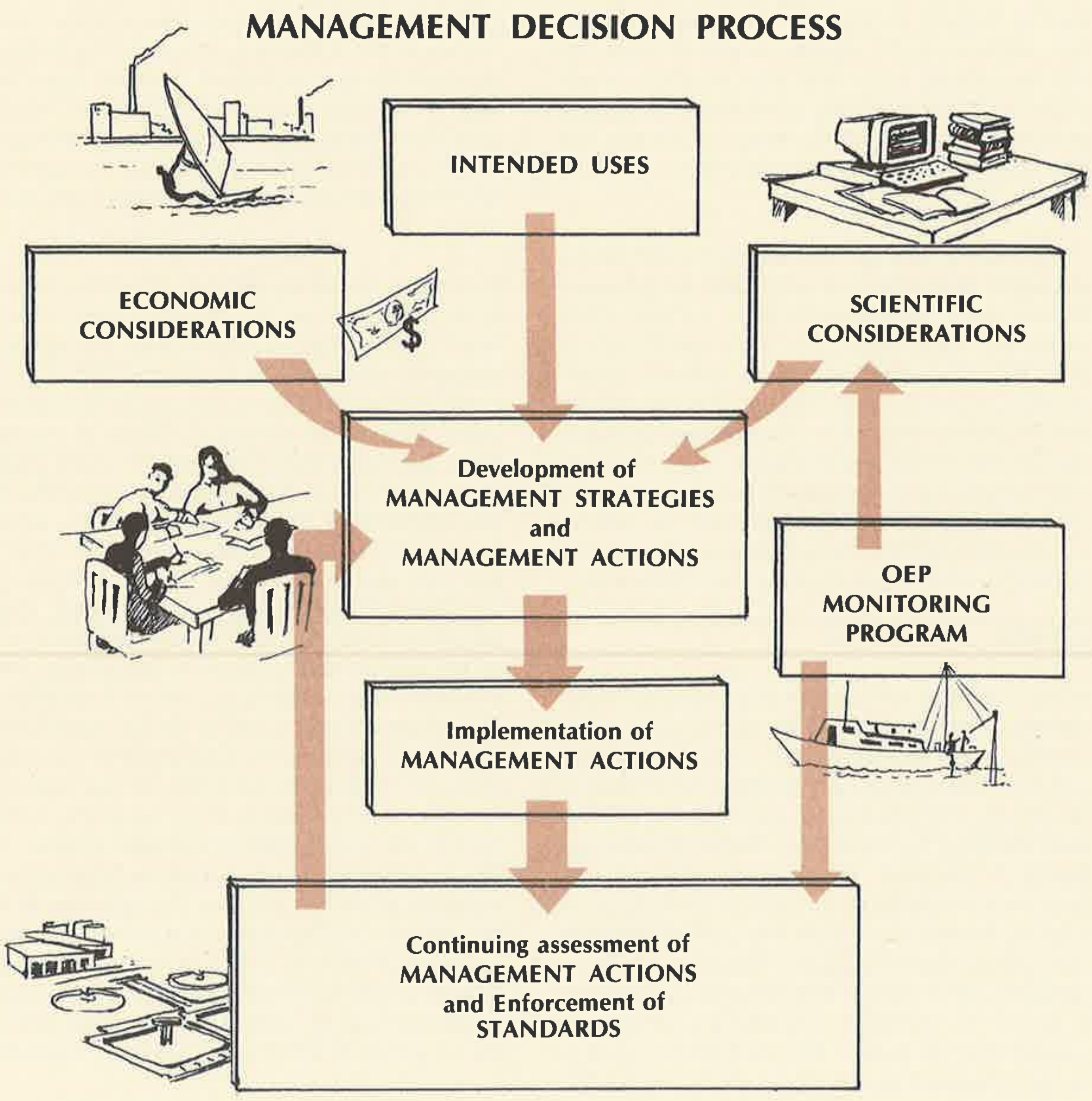
Probably the most difficult and yet important task, is the proper treatment of the diverse and complex political/public factors considered in the development of environmental control programs. Without an accurate and complete understanding of what the objectives are, a successful management program can never be designed and implemented. Managers must be confident that they understand the often conflicting uses the public holds important for a body of water such as the Chesapeake Bay and its tributaries. Examples include recreation, propagation of fish and shellfish, water supply, waste disposal, industrial cooling water, and transportation. In addition to accommodating this diverse list of uses, the public expects that the waters of the Bay will also maintain a reasonable degree of aesthetic quality.

The greatest challenge confronting environmental managers is to meet the needs and expectations of the Bay's user communities without compromising the present and future health of the Bay. This challenge requires an in-depth understanding of the present health of the Bay system and an assessment of the management strategies required to meet these demands. The collection, interpretation and synthesis of data from a sound monitoring program, supplemented by special studies and selected research efforts, provides the necessary information to make this assessment.

Scientific Considerations

When a management action or standard is implemented, managers should be at least reasonably confident that the imposition of such an action will have the anticipated beneficial environmental impact, and will thereby maintain the desired uses identified by the public. However, the complexity of physical, chemical and biological interactions occurring in a system as dynamic as an estuary, prevents managers from having absolute confidence in predicting the outcome of a management action before they develop and impose a policy or standard. Nevertheless, managers should strive to reduce the scientific uncertainty of their decision to a level at which substantive, although perhaps interim, decisions can be made. As long as the limitations of the resulting policy or standard are acknowledged, and the restrictiveness of the policy accurately reflects the level of scientific uncertainty, managers must continue to develop and implement appropriate environmental controls aimed at achieving the desired conditions.

This decision-making process should be viewed as an iterative excercise, in which new information is continually utilized to update management decisions. A monitoring program is critical in this iterative process because it provides an objective assessment of the success or failure of management decisions that have already been implemented. Since our knowledge is incomplete and the environment is continually changing, adjustments will always be necessary. As more information becomes available, the original decision can be changed, refined or even rescinded. These adjustments depend on a number of factors such as the quality and quantity of knowledge available when the standard was set, an evaluation of the environmental response to the implementation of the standard, an assessment of the public response, and a re-evaluation of the uses and benefits. When a policy is formulated or a standard is set, the regulatory authority implies that this decision has been based on the best evidence currently available, and that the response of the environment will be carefully reviewed. It is quite apparent, therefore, that this iterative approach to policy-making will work only if managers make a commitment to continue monitoring and research aimed at "fine-tuning" the initial decisions.



MANAGEMENT DECISION PROCESS

The purpose of any management action is to achieve a desired environmental response. When a management action such as the Upper Bay Phosphorus Control Policy is implemented (see example below), we should expect to see improvements in the problems that were addressed. For this example, the problems were low dissolved oxygen levels and frequent phytoplankton blooms. Traditionally, the most common approach to controlling eutrophication has been to remove nutrients at the point of discharge. Prior to implementing point source controls, and incurring the associated expense, there should be evidence that this control strategy will be effective. Effective management decisions must consider all other feasible control options. How certain are we that the observed water quality problem is reversible or controllable? Has the "problem" existed for centuries, and should the condition therefore be considered "natural"? The establishment of a nutrient control policy or standard implies that such an evaluation has been made and that the best evidence is that implementation of the standard or policy—as applied to point and nonpoint sources—will achieve the desired results.

The current OEP monitoring program, in conjunction with modeling studies and data from waste treatment plants, is capable of quantifying the contributions of nutrients emanating from nonpoint as well as point sources. This information can be used by decision-makers to determine the extent of control to be imposed on both sources. Furthermore, as a result of the initiation of the OEP monitoring program, it should be possible to more accurately ascertain what environmental conditions are controllable or "fixable", as well as identify those problems which may be beyond the reach of any management action.

Economic Considerations

Of the many different approaches that can be taken to improve water quality, almost all impose some costs on the public. These approaches include sewage treatment plant controls, industrial pre-treatment, detergent phosphate ban, land use restrictions and agricultural best management practices. For example, the public has already been asked to absorb the expense of primary and secondary levels of waste removal before effluents are discharged into the Bay system. According to surveys of citizen attitudes toward the environment, however, improvements to the Chesapeake in response to this current level of treatment have not been satisfactory in maintaining or restoring desired water quality conditions. Progress toward restoring the health of the Bay in the face of continued population growth, expanding industrial activities and changing land use will necessarily demand additional fiscal resources in the future.

Conventional biological waste treatment processes are often hard-pressed to hold constant or reduce pollutants entering the Bay and water quality managers frequently have to evaluate the possibility of requiring advanced treatment aimed at further removal of nutrients and toxicants. However, the costs associated with the implementation of advanced methods of waste treatment will impose an even greater economic burden on the public. Will the taxpayers agree to pay? If so, what level of assurance of a water quality response will they demand? The more we understand the Bay system, the more confidently we can predict the benefit associated with the cost of a given level of treatment.

A Specific Example -
The Upper Bay Phosphorus Control Strategy

In the mid-70's, a major concern arose about the apparent trend of the Upper Chesapeake Bay towards eutrophication. Many individuals reported elevated water column phytoplankton levels which precluded or diminished certain desired uses of the Upper Chesapeake. These concerns were raised by people who had spent their entire lives on the Bay – observing it, studying it, or deriving their livelihood from it.

In general, it appeared that the ecology of the Upper Bay was changing from a system with a balance between phytoplankton and rooted aquatic plants, to one dominated by phytoplankton. In an attempt to quantify these qualitative statements, an assessment was made of the existing water quality monitoring data. This analysis confirmed the presence of very high phytoplankton levels in summer and an increasing trend since the 1950's. In addition, preliminary analysis indicated that the nutrient phosphorus, rather than nitrogen, appeared to be limiting phytoplankton growth during the critical summer period in the regions exhibiting a problem.

In order to provide managers with a basis for determining the causes of the phytoplankton problems in the Upper Bay, and to evaluate possible management actions to achieve desired water quality objectives, a mathematical water quality model was developed. The model was formulated in such a way that it was capable of addressing the interactions between nitrogen, phosphorus and phytoplankton biomass. At the conclusion of the development and testing process, which required water quality monitoring data, the model was utilized to project phytoplankton chlorophyll levels in the Chesapeake Bay based on various combinations of nutrient inputs to the Chesapeake Bay. The modeling results determined that the most significant sources of nutrients to the Bay were from the Baltimore Metropolitan Area and the Susquehanna River. This latter source, under high flow conditions, may completely dominate the nutrient distribution in the Upper Bay. The modeling exercise also confirmed that phosphorus is the primary nutrient that limits phytoplankton growth in the upper Chesapeake. If reductions in peak summer phytoplankton populations to levels observed in the 1950's were desired, significant reductions in phosphorus from major point sources in Maryland and the Susquehanna River would be necessary.

Using the results of the modeling and the assessment of monitoring data to provide an initial technical base, and capitalizing on the availability of federal and state funding, Maryland water quality managers developed the Upper Bay Nutrient Control Policy. This policy imposed a 2 mg/l total phosphorus effluent limitation on all large wastewater treatment facilities (greater than 0.5 million gallons per day (MGD) above Baltimore Harbor, and greater than 10 MGD between Baltimore Harbor and the Chesapeake Bay Bridge) discharging into the upper Bay. In addition, the policy provided for the imposition of even more stringent phosphorus requirements for the Bay tributaries where water quality deterioration was generally more severe than in the mainstem.

As with all major disciplines, water quality modeling is a continuously evolving process. To say that the water quality model developed in the Upper Bay study is the final technical answer to our Bay pollution problems is naive. However, the model did provide managers with the technical guidance required to develop a rational environmental policy. In the last few years, OEP has taken part in the development of a comprehensive water quality monitoring, research and modeling program in the Bay and its tributaries. The monitoring component of the program quantifies river inputs, characterizes ambient water column and sediment conditions, evaluates the significance of key processes and quantifies resident plankton and benthic assemblages. The research component addresses sediment/water column interactions, animal/toxicant interactions and plankton dynamics. More advanced mathematical models are being developed to predict with greater confidence the biological and chemical response of the Bay to nutrient loadings. As our understanding of the Bay's natural processes are enhanced by incorporating the results of the monitoring, modeling and research programs, the existing upper Bay policy can be reviewed and appropriate adjustments and refinements made accordingly.

CONCLUSION

The information presented in this report demonstrates that the OEP Chesapeake Bay Water Quality Monitoring Program is producing an important body of information to guide the management and restoration of Chesapeake Bay. The monitoring program has already established some important facts about the present state of water quality in the Bay and its tributaries where a high degree of uncertainty previously existed. Using the monitoring data in conjunction with research and modeling will provide a sound technical base to permit water quality managers to move forward with greater certainty in formulating management strategies. This enhanced technical base will greatly increase the probability that our actions will yield the desired results-a healthy Chesapeake Bay for the citizens of Maryland.

glossary

Algal Bloom - high concentrations of phytoplankton (algae) that occur when conditions, such as light and nutrients, are sufficient to support rapid growth.

Anoxic - a condition where no oxygen is present.

Anthropogenic - of human origin.

Benthic Organisms - organisms living in or on bottom sediments in aquatic habitats.

Biomass - the quantity of living matter, expressed as a concentration or weight per unit area in aquatic systems.

Chlorophyll - the green pigments in plant cells, such as phytoplankton, that are active in photosynthetic reactions; chlorophyll concentration is often used as a measure of phytoplankton biomass.

Deep Trough Region - the deepest portion of the Chesapeake Bay mainstem which is located from the Annapolis Bay Bridge to just below the confluence of the Potomac River. This area experiences severe oxygen depletion of bottom waters during summer.

Detritus - particulate organic matter that is freshly dead or partially decomposed.

Ecosystem - an interactive system which includes the organisms of a natural community together with their physical and chemical environment.

Estuary - a semi-enclosed, tidal, coastal body of saline water with a free connection to the sea and within which sea water is measurably diluted with fresh water derived from land drainage; commonly the lower end of a river.

Euphotic Zone - the surface layer of a body of water which receives sufficient sunlight to support photosynthesis by phytoplankton or rooted aquatic vegetation.

Eutrophication - a complex response by aquatic systems to the excess input of nutrients that stimulate phytoplankton growth. The increased phytoplankton growth leads to other problems such as low dissolved oxygen and shading of submerged aquatic vegetation.

Food Web - the network of pathways within an ecosystem that link organisms to their prey and to their predators.

Hypoxic - a condition where only very low levels of oxygen are present.

Inorganic Compounds - chemical compounds generally not containing carbon and thus not classified as organic compounds; in aquatic systems, inorganic forms of nutrients such as nitrogen and phosphorus are most readily utilized by growing phytoplankton.

Metabolism - the chemical and physical processes occurring in living organisms.

Microgram (μg) - a unit of mass equal to one millionth of a gram.

Milligram (mg) - a unit of mass equal to one thousandth of a gram.

Nutrients - chemicals, primarily nitrogen and phosphorus, that are required for growth, development and reproduction of plants.

Organic Compounds - chemical compounds containing the element carbon; these compounds are the primary constituents of living matter.

Photosynthesis - the synthesis of organic compounds from water and carbon dioxide using light energy in the presence of chlorophyll.

Phytoplankton - microscopic plants (algae) suspended in the water column.

Phytoplankton Productivity - the rate at which a phytoplankton community is growing, often expressed as the generation of biomass in terms of carbon; also known as primary productivity.

Plankton - aquatic organisms, either plants or animals, that are found drifting passively or swimming weakly in the water column.

Pycnocline - the region in a water column where water density changes rapidly, usually due to changes in salinity and temperature; in the Chesapeake Bay, the pycnocline region separates fresher, surface waters with a net flow down-Bay from saltier, bottom water with a net flow up-Bay.

Recycling - as applied to aquatic nutrients, these are the cyclical pathways travelled by elements that result in chemical changes between organic and inorganic forms; these changes are often mediated by biological activity.

Sediment Oxygen Demand (SOD) - the rate at which biological and chemical reactions taking place in bottom sediments consume oxygen from the overlying water column.

Turbidity - decreased clarity of water caused by the presence of dissolved or suspended matter.

Water Column - term used to refer to a water body in its vertical extent.

Zooplankton - small, often microscopic, animals suspended in the water column.

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