How Should Research And Monitoring Be Integrated?

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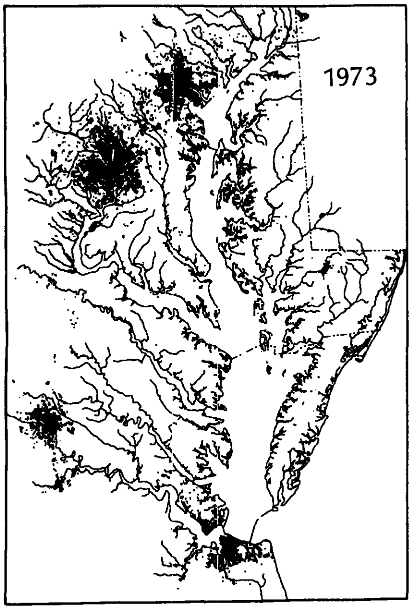
TEN CRITICAL QUESTIONS FOR CHESAPEAKE BAY

IN RESEARCH AND RELATED MATTERS

PEOPLE AND INDUSTRY



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2. WHAT ARE THE EFFECTS OF ENVIRONMENTAL CHANGES?
3. HOW SHOULD DREDGING BE DONE?
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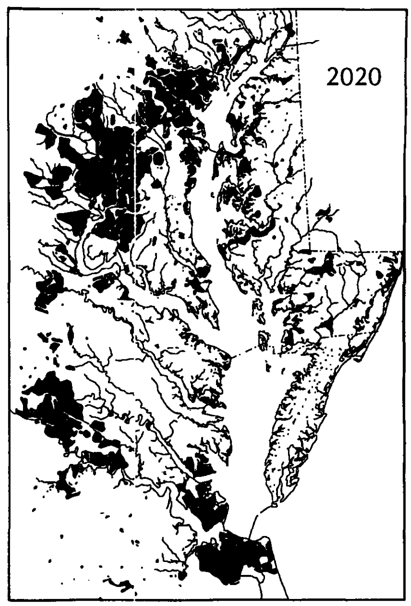

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CHESAPEAKE RESEARCH CONSORTIUM

OCTOBER 1983

CRC

TEN CRITICAL QUESTIONS FOR CHESAPEAKE BAY IN RESEARCH AND RELATED MATTERS

L. Eugene Cronin, Editor

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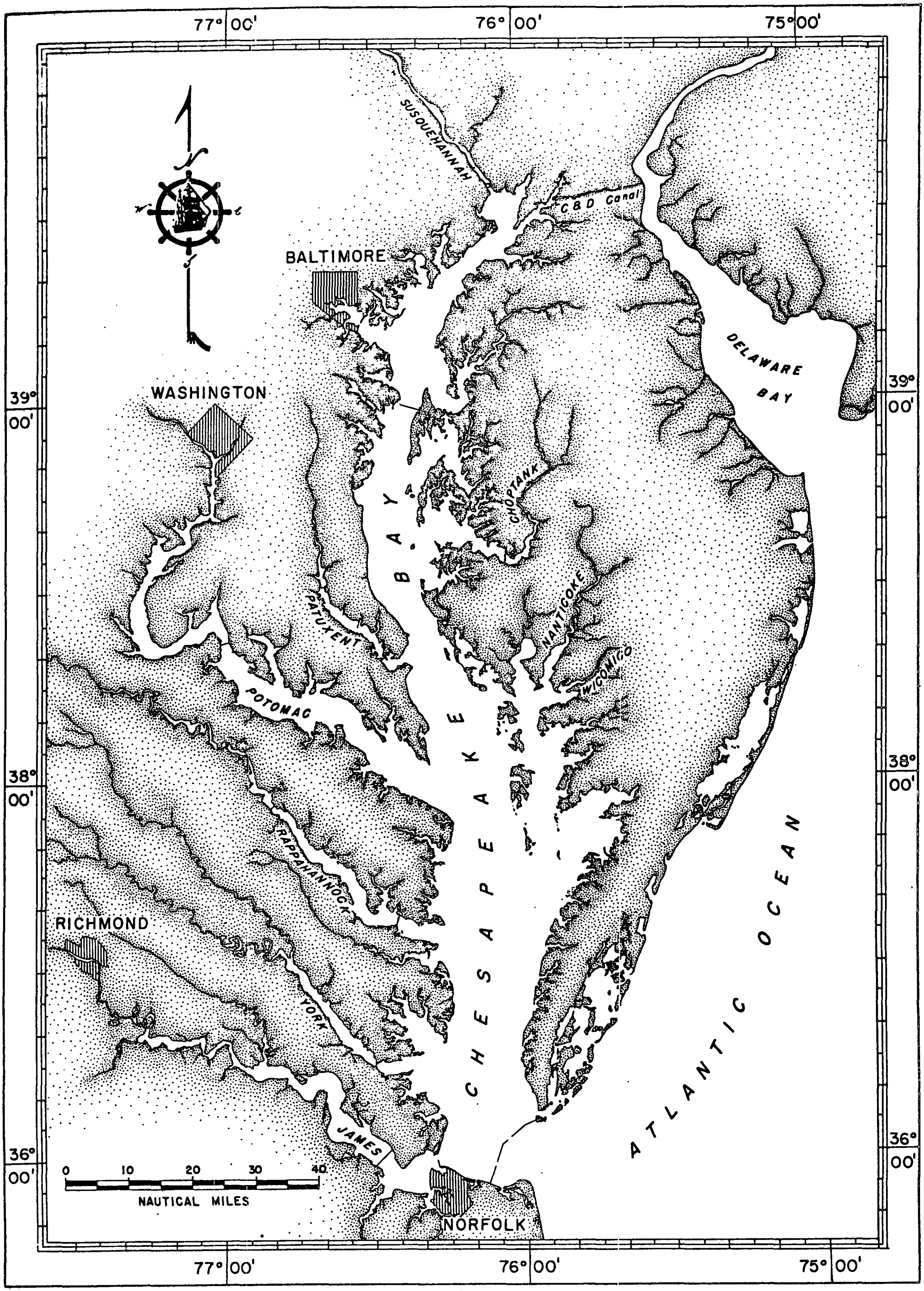

Frontispiece - The Chesapeake Bay System

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PREFACE

Scientific knowledge of Chesapeake Bay and tidal tributaries has accumulated over many years beginning mostly with descriptive surveys prior to the 1960's and 1970's and evolving towards a coupling of monitoring and research in recent years.

This essay discusses the need to more fully couple monitoring and research efforts in the Bay system because such a union of efforts is argued to be the most effective way to assess gross trends in the "health" of the system (monitoring) and to understand the basic forces causing these trends (research). We argue that together they provide part of the framework necessary for effective management of the living resources of the bay region.

Though monitoring and research share some characteristics, they have fundamental differences which yield different levels of understanding and prediction.

We suggest that past confusion between these terms has led to public announcements that the Bay has been "studied to death." This essay challenges this myth and considers the effective interactions between these important activities in detecting changes and establishing cause-effect relationships in a complex estuarine ecosystem such as Chesapeake Bay.

INTRODUCTION

The system including the Chesapeake Bay and its tidal tributaries is acknowledged as a national resource and recognized for its fishery yields, recreational potential, and water courses that provide for commercial shipping and large volumes of water for industry (see Frontispiece). In recent years, many reports and publications have indicated that serious and growing problems exist with the "health" of the Chesapeake Bay system (Cronin 1967, U.S. Army Corps of Engineers 1974 and 1977, Cronin et al. 1977, Heinle et al. 1980, Orth and Moore 1981, Rothschild et al. 1981, Cronin 1982, U.S. EPA 1982 a, U.S. EPA 1983 a).

Concern has been expressed over the large decline in Bay grasses, landings of freshwater spawning fish and dabbling ducks; decreased recreational attractiveness (turbidity and algae), enlargement and intensification of areas of low dissolved oxygen; increases in algal blooms and the threats of toxic substances. Some trends are clear but others are characterized by considerable uncertainty. Confusion over the clarity of trends and their significance is due in part to the limited coupling between monitoring and research. The weaknesses in monitoring are manifold, including: there was frequent lack of appropriate consideration of time and space in sampling, analytical and observational techniques were limited or uncertain in the record, limited statistical analysis and comparison was possible because of sampling design and data were either lost or provided in an inconvenient manner for analysis.

We wish but to emphasize that catch-as-catch-can observations have been grossly inadequate for detection and explanation of changes which have occurred. A continuing record of monitoring and research, based on rational design, is essential for effective and efficient learning and management.

In response to recent emphasis on the need, a major monitoring and research strategy has been developed by the Chesapeake Bay Program of the U.S. Environmental Protection Agency, in cooperation with appropriate agencies in the Commonwealth of Virginia and State of Maryland. It presents "assumptions", a conceptual framework, outlines possible elements in a master monitoring plan, develops proposed strategies in view of existing programs, comments on volunteer monitoring and stresses the necessity of an adequate data management plan including an effective quality assurance plan. Monitoring and research were, also, identified as an important need at the Windmill Point Workshop by those concerned with several areas of Bay usage (CRC 1983). In addition, monitoring has been identified as a major topic for the Governor's conference on Chesapeake Bay scheduled for December, 1983. The work group for this topic at the conference is stressing the need to link monitoring and research.

In this discussion, we wish to examine the relationships between research and monitoring, how research can be used in the design of monitoring programs and how monitoring can be used in the design and interpretation of research. For present purposes, we assume that research, per se, will be justified, as the need arises, in other forums. We recognize that managers have a need to know the "State of the Bay" and that monitoring and research are the principal tools to acquire knowledge about the Bay's well-being and best management.

DEFINITION OF TERMS

Monitoring

Monitoring, in this context, is the systematic sampling and measurement over time of variables which describe the abundance and distribution of biological resources, the distribution and concentrations of physical, geological and chemical properties in the Bay or the location and rates of significant processes. These variables include such properties as temperature, salinity, nutrients, dissolved oxygen, suspended sediments, toxins, biomass and biological species; and such processes as current velocity, circulation of water, freshwater flow, sedimentation rate, photosynthesis, decomposition and waste discharges. Biological resources include fin-and shell-fisheries, wildlife and species which are important in the food web and ecological processes.

Monitoring programs should be designed to accomplish one or more of the following:

(1) determine the time and/or space scales of natural variability which characterize the properties or processes of the system,

(2) describe significant changes over time and space in components and processes,

(3) detect and measure changes in properties and processes that may be caused by human activities,

(4) determine when such changes are in violation of environmental laws and regulations.

This discussion is primarily concerned with characteristic scales of variation and observation of trends and will not directly consider the third purpose involving the enforcement of regulations. Characteristic time and space scales and their associated averages and patterns of statistical variance must be known in order (1) to distinguish natural variations from human effects, (2) to articulate specific questions so that research programs can be designed to solve the particular problems or explain particular phenomena, (3) to provide a rationale for the establishment of environmental regulations that are appropriate for the systems of interest and (4) to evaluate the effectiveness of management controls.

Research

Research is the systematic collection and analysis of experimental and/or field observational data that produces knowledge. Generally an hypothesis, an idea, or an assumption developed from preliminary work is tested and either validated or rejected.

Research programs utilize this scientific approach to solve a problem or explain an observed phenomenon, e.g., the problem of how nutrients from sewage and fertilizers affect living resources or the phenomenon of annual oxygen depletion. Research programs generally require rigorous and complex sampling, measurement, and/or experimental schemes that are not (and should not be) employed in monitoring programs. Observations generated by monitoring have frequently been the basis for an hypothesis and are often required to formulate research programs, and the results of research are often used to modify existing monitoring programs (i.e., change the variables measured, their time and space scales and their precision) or to initiate new ones. Thus, monitoring and research form a loop, each feeding or reinforcing the other to achieve better understanding of the Bay ecosystem. An improved understanding of the system is the basis for informed management.

A key feature that differentiates monitoring from research is the ability of the latter to structure observations in a way that identifies and frequently quantifies the probable cause of an observation. Hypothesis (question) framing and testing is the essential difference. Experimental design, whether field or laboratory (including micro- and mesocosms) studies, must address through use of an analytical control the explanation of that part of a measurement associated with the cause of an effect. An example of coupling field monitoring and research that integrated field and laboratory experiments through hypothesis testing is provided by a hierarchical research design used to examine the effects of herbicides on Bay grasses (Kemp et al., 1983) (Figure 1). The hierarchical design will be shown to be a useful construct to examine the coupling of spatial and temporal scales characteristic of various ecological mechanisms. Relationships are complicated in ecosystems because an effect may be associated with one or more causes and vice versa.

Management

We borrow from the U.S. Environmental Protection Agency's Chesapeake Bay Program design for the coupling of monitoring, research and management (Figure 2). This design provides a pattern for acquisition of knowledge about the Bay's well being and for communication to support best management. The first consideration

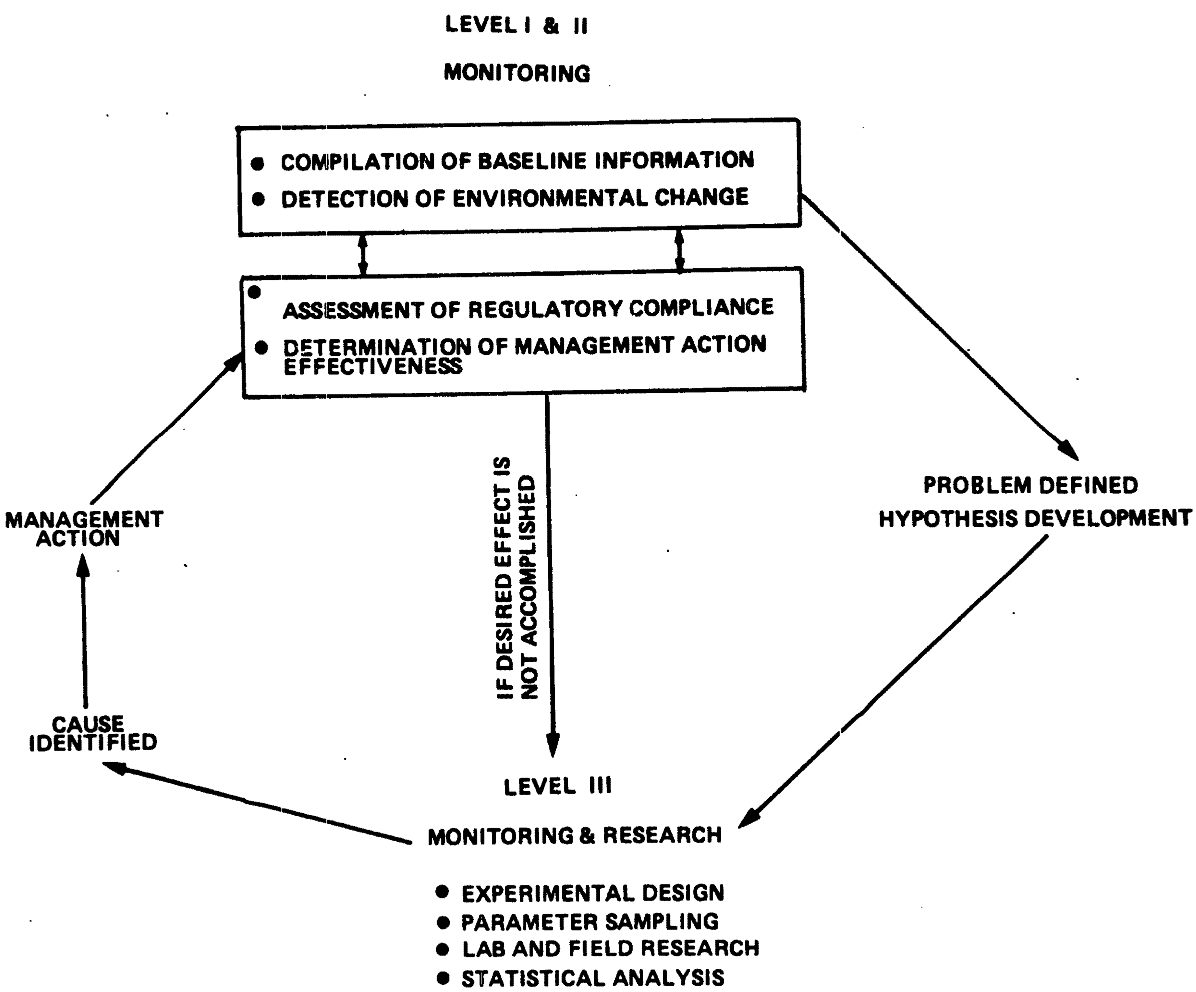


Figure 2. Diagram showing the relationship between Monitoring, Research and Management (from U.S. EPA 1983b).

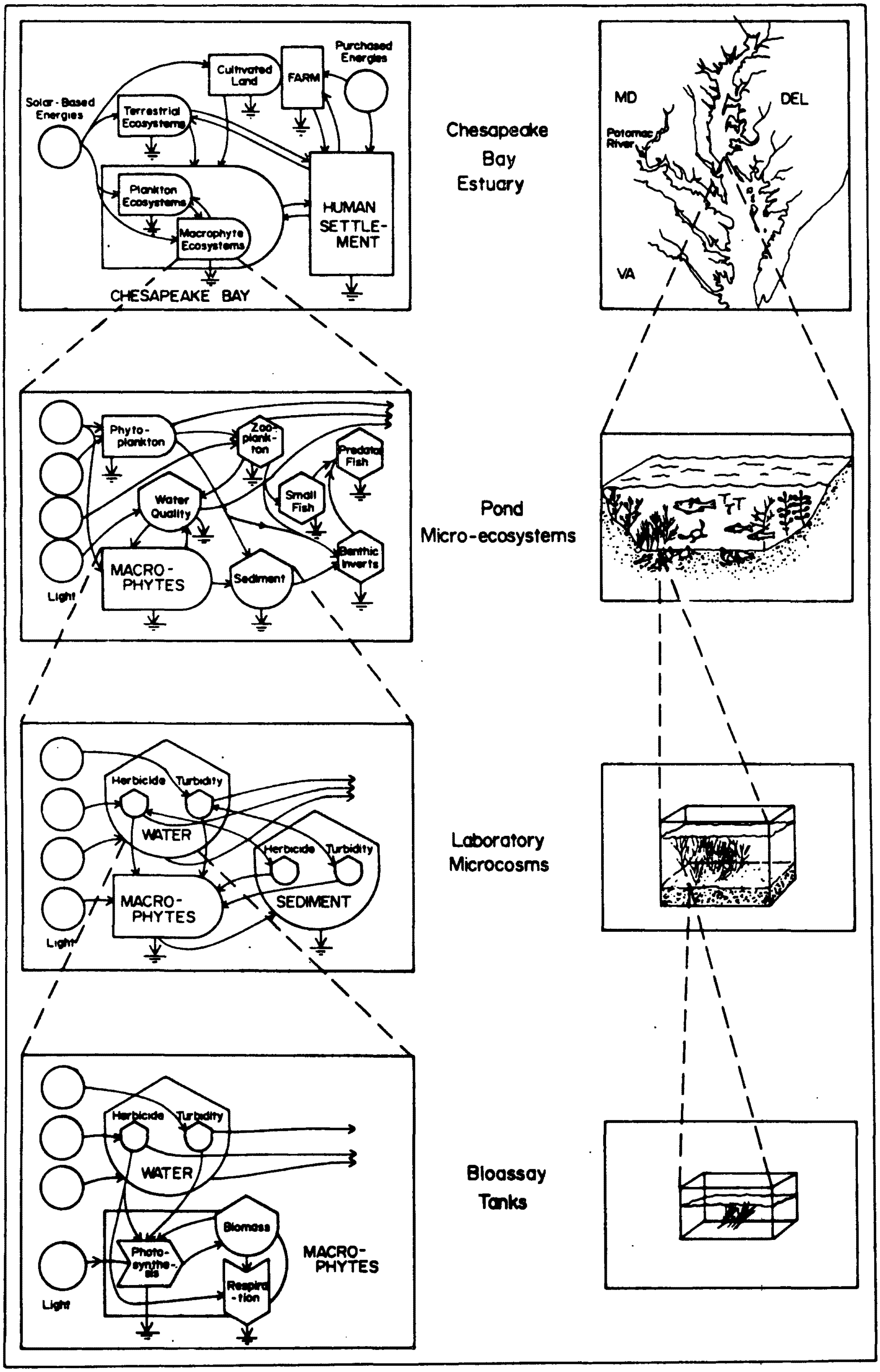


Figure 1. Conceptual scheme illustrating the hierarchical design of research on submerged aquatic vegetation and associated Chesapeake Bay ecosystems. The illustrations on the right show various scales of research focus, and model diagrams on the left represent principal parts and processes of systems which correspond with the hierarchical level being studied. Graphic symbols are those of H.T. Odum 1971. (from Kemp et al. 1980).

is whether or not there is a significant environmental problem in the Bay system. Descriptive monitoring can provide signals through baseline or trend information for the detection of environmental change. Statistical correlations among variables can help identify the properties of the ecosystem apparently associated with a problem and provide initial information for hypothesis framing and testing. This activity feeds into a meaningful coupling of monitoring and research. Research will aid in the identification and evaluation of probable causes so that appropriate management action can be made. By closing the loop in the diagram, we see that further and perhaps refocused monitoring can determine if regulatory compliance is being met or a management control action is effective. If not, then we move to additional monitoring and research. In reality, there are times when it is prudent for managers to act with a higher level of uncertainty than desired because human activity may impact the Bay faster than monitoring and research can keep pace. This dynamic feature of management of the Bay's resources must be acknowledged fully by both scientists and managers. Decisions based on such high uncertainty should be acknowledged as such so they do not inhibit further research and monitoring.

THE INTERDEPENDENCE OF RESEARCH AND MONITORING

Scales of Variation and Correlation

In this section we will examine the importance of understanding the space-related and time-related characteristics of ecological processes in the estuary. Monitoring and research must contend with these fundamental patterns. For example, increases in the magnitude, extent and duration of low levels of dissolved oxygen in the deeper waters of the main Bay and tributaries result from the net effects of processes that contribute oxygen to the waters and those processes which remove dissolved oxygen. These include, but are not limited to, photosynthesis, rate of biological community respiration, surface reaeration, mixing of the waters and solubility of dissolved oxygen as affected by salinity and temperature. These processes typically have spatial and temporal scales that range from centimeters and minutes (e.g., micro-patches of phytoplankton) to tens of kilometers and months (e.g., transport of dinoflagellates up the Bay in the spring from reservoirs located in the mouths of lower Bay tributaries (Tyler and Seliger, 1978)). Application of historical data in a trend analysis (U.S. EPA 1982a and 1983a) helped characterize the low dissolved oxygen problem. However, further research will be required to assess quantitatively the importance of each of the many processes involved and evaluate manageable contributing causes and possible corrective measures. In fact, the success of future water quality models designed to address the hypoxic condition will depend on our understanding of the processes involved, their tractability in terms of collecting appropriate data for verification of a water quality process model, and the development and use of appropriate trend models.

The inappropriate mis-matching of the characteristic scales of variation can interfere with the interpretation of trend data and correlations. No single sampling method or sampling program can give useful information about variability for more than a relatively narrow zone of time and space ranges (Platt et al., 1981). An effective monitoring program must be designed to minimize the effects of the variability associated with cross-over of measurements from different time and space scales (Harris, 1980). Guidance for a monitoring design results from the experience of the designer, often the product of research. An example will help clarify this topic. Figure 3, though it departs from specific Bay examples, shows

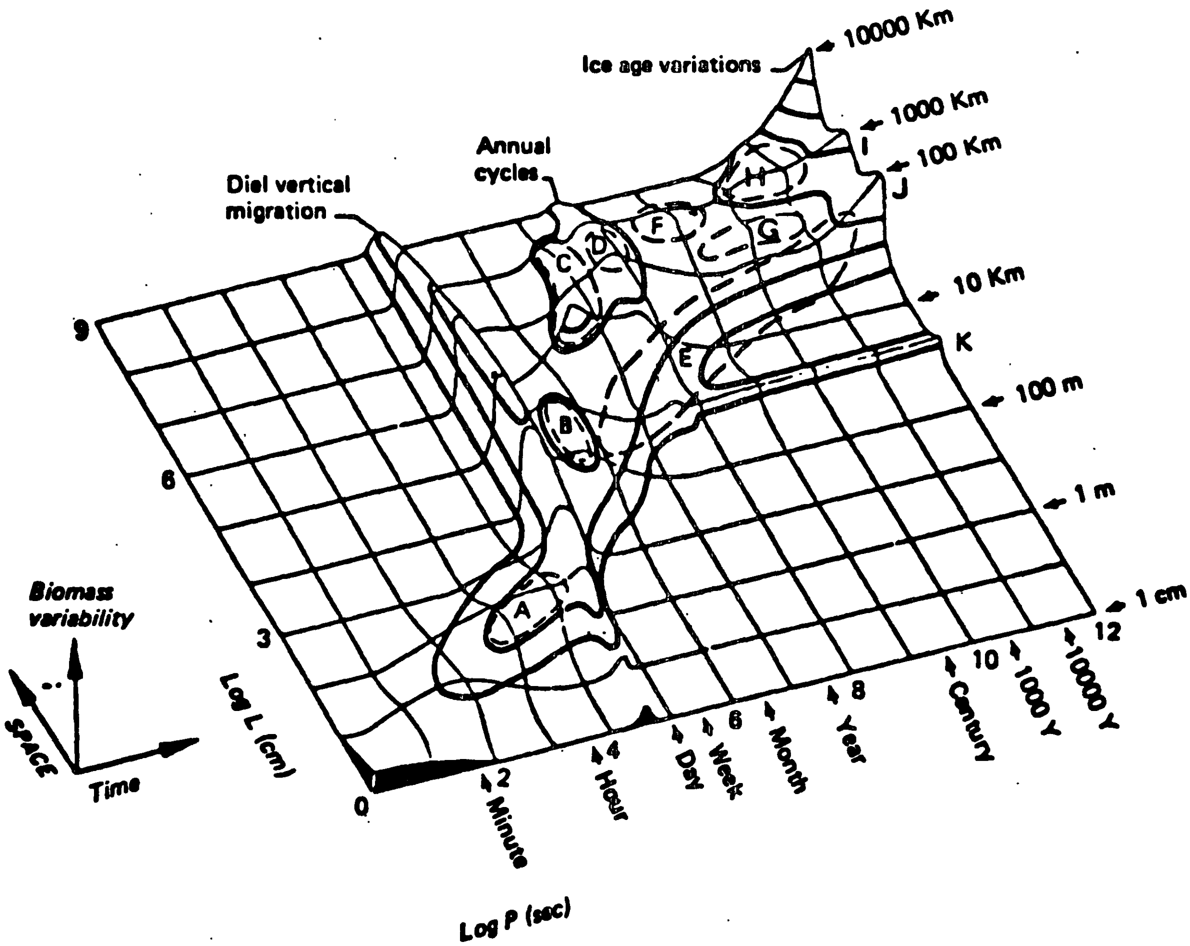


Figure 3. A three-dimensional representation of relative variability in zooplankton biomass over a range of time and space scales (from Haury et al. 1978). A, 'micro' patches; B, swarms; C, upwelling; D, eddies and rings; E, island effects; F, 'el Nino' - type events; G, small ocean basins; H, biogeographic provinces; I, currents and ocean fronts: length; J, currents: width; K, ocean fronts: width (from Platt et al. 1981).

the interaction of temporal (x-axis), spatial (y-axis) and zooplankton (z-axis) scales. Viewed from the surface as a topographic form (analogous to a topographic relief map in a physical sense), the graph displays the shape of observable phenomena. Note that time and space are plotted logarithmically, which distorts the scale but permits the scales to be conveniently graphed. Each of the "data peaks" has its characteristic variability. The actual statistical variability is not shown for simplicity. The difficulty in field sampling, especially at short time scales, is that the overlap of variability associated with one phenomena, e.g., "micropatches", may include the variability associated with another, e.g., diel vertical migration. The dynamics of processes contributing to these observations are described by both monitoring and research. Theoretically, the inability to discriminate patch size can affect our concepts of grazing efficiency which can affect our interpretation of nutrient cycling and the role of zooplankton as food for higher trophic levels.

The problem becomes more complex when we try to understand phenomena portrayed in a dynamic sense, e.g., the doubling time vs. size of organisms (Figure 4). The basic problem is to determine how phenomena with different scales are

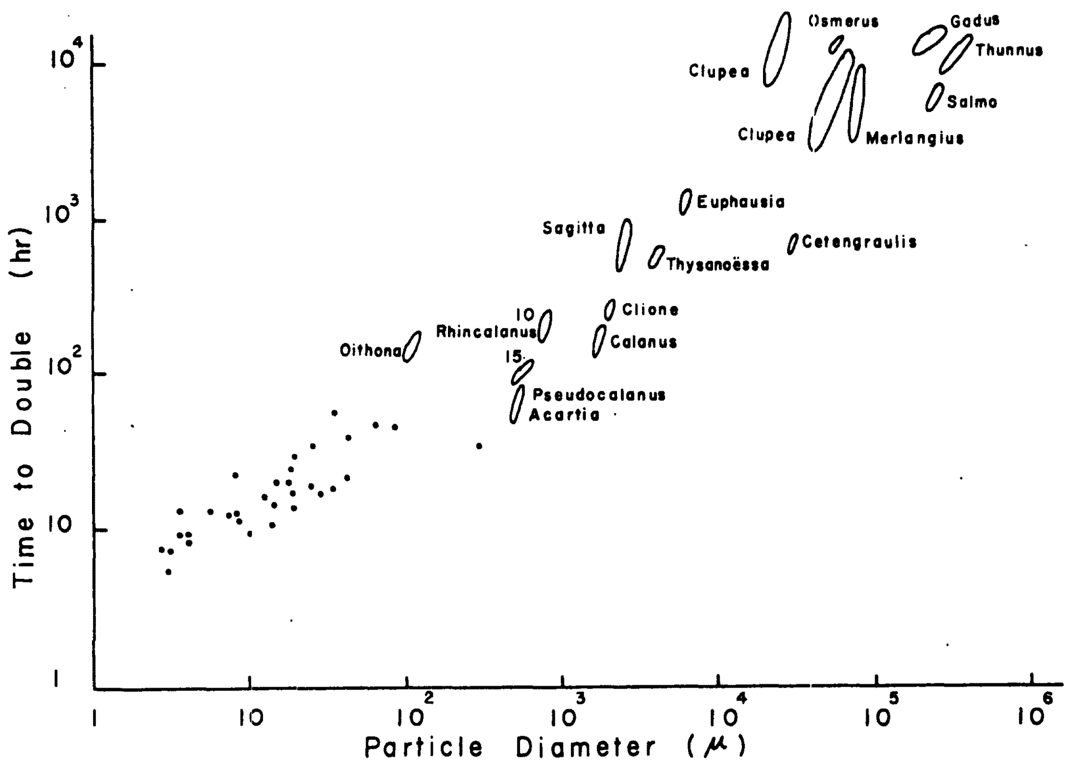


Figure 4. The relationship between rate of production and particle size. The numbers near to the Rhincalanus patches indicate the temperature at which the growth took place. The uppermost of the two Clupea areas represents C. sprattus. The lower area represents both the Atlantic (C. harengus) and Pacific (C. pallasi) herring (from Sheldon et al. 1972).

related, e.g., dominant time scales for food organisms are typically smaller than dominant time scales for predators. Small organisms such as bacteria can reproduce rapidly, e.g., minutes to hours, whereas larger organisms such as the copepod Acartia, small planktonic crustaceans which feed on phytoplankton and bacteria, require several days to reproduce. On the other hand, many fish require about one to two or more years before they can reproduce. This example clearly shows that to monitor changes in bacterial growth dynamics, it is necessary to sample on a very short schedule, minutes to hours, not the typical two week to monthly schedule often employed for higher organisms. Because bacteria and other micro-organisms play vital roles in the ecology of the Bay, principally as food for intermediate groups of animals which are eventually fed upon by higher animals and as chemical processors, i.e, in recycling nutrients. Our knowledge of their dynamics is essential to understanding the system, but still rudimentary in many respects.

Finally, we argue that an interdisciplinary approach to problems of scale will most likely couple monitoring and research as an effective management tool (Anon. 1983). Much in the spirit of the discussion by Yentsch (1980) who described the coalescence of disciplines to explain phytoplankton growth in the sea, we know for the Chesapeake Bay system that insights gained from an interdisciplinary approach provide valuable lessons. For example, understanding of the Bay ecosystem requires detailed knowledge of physical and geological processes in order to interpret the transport of biological forms including larvae, and explain plankton distribution and abundance and the concentration of nutrients and toxic materials. (Pritchard and Schubel, 1981; see other references in Neilson and Cronin, 1981).

To elaborate further, questions are being posed now and evidence given that sub-tidal variations have a significant effect on long-term water quality trends in estuaries (Najarian et al., 1983). We believe that the examples given above clearly demonstrate that to effectively monitor the Bay, a mixture of skills and approaches is required to explain the variability associated with the spatial and temporal scales of key processes. That variability must be known if monitoring or research is to be of high value.

Time Series

The foregoing discussion has pointed out the importance of understanding spatial and temporal scales associated with ecological processes. Many observable phenomena are periodic or cyclic and much useful information is lost if this feature is not included in the design of monitoring and research programs. A powerful technique used to discriminate meaningful signals from background noise (unexplained variability) is the application of time-series analyses. The measurements may be continuous or discrete in time. If discrete, they are most useful when they are taken on a regular or periodic basis and they must be made frequently enough to describe accurately cycling phenomena. There are also important mathematical reasons for these requirements.

Several examples of data taken in the Bay show the utility of a time series approach. Cory (1974) set up a monitoring station on the Benedict Bridge crossing the Patuxent estuary. Measurements were made frequently on dissolved oxygen (DO), conductivity (a measure of salinity), water temperature, turbidity, and several other variables. He was able to estimate daily rates of photosynthetic production by phytoplankton over a period of seven years. An important pattern in the data was the trend of the plankton community respiration in the estuary to increase in a regular way over the years 1963 to 1969. This change (Figure 5) was probably a response to the relatively rapid rate of nutrient enrichment that occurred in the river during the time of the study (Flemer et al, 1971). In fact, Cory warned of impending DO problems in the Patuxent estuary, a case of monitoring data being applied in a predictive sense.

Time series analysis was applied to monitoring data on the distribution and abundance of the croaker, an important Bay species. Norcross (1983) at the Virginia Institute of Marine Science (VIMS) developed a predictive model that showed that the time of summer wind cessation determines the time, place and success of fall croaker spawning ~~(Figure 6)~~. Further, winter temperatures, which influence their subsequent estuarine survival, are more responsible for both interannual fluctuations and longer term trends than the size of the parent stock. This analysis was conducted using 30-year data sets of juvenile croaker abundance, coastal winds, and winter river temperatures. She also showed that increases in Virginia croaker landings during the 30's and 40's were related to the general northern hemisphere warming trend. The juvenile fish data were taken from the VIMS 30-year monitoring program, winds were obtained from the Norfolk airport and temperature data were available from the VIMS pier. Here, a research program made use of previously collected monitoring data.

Time series data have also been useful for extraction of periodic components and random variations (Figure 6).

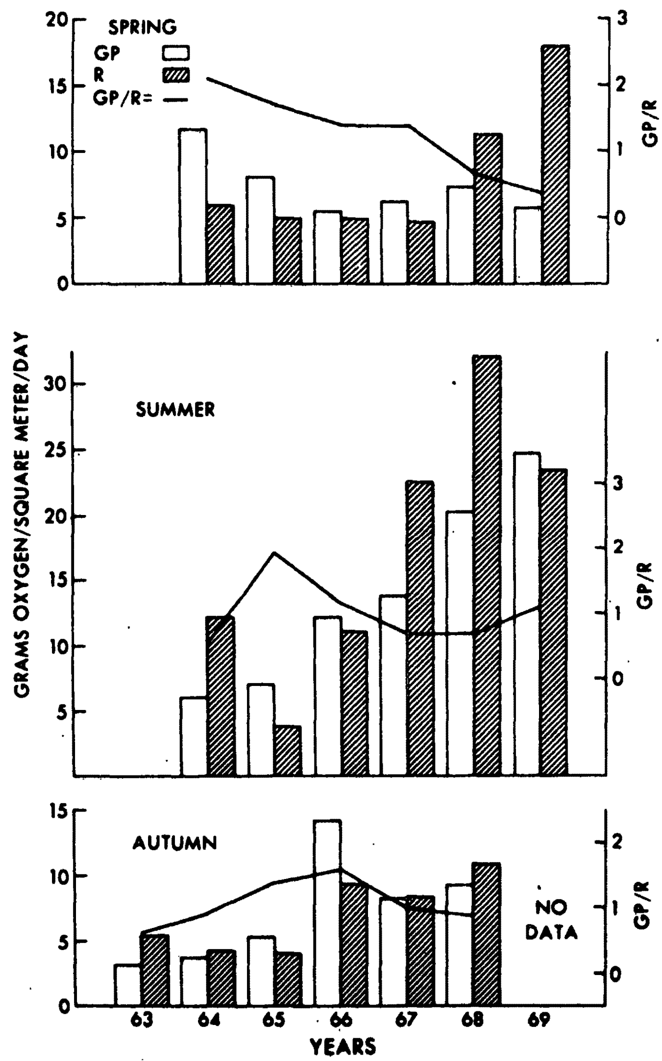
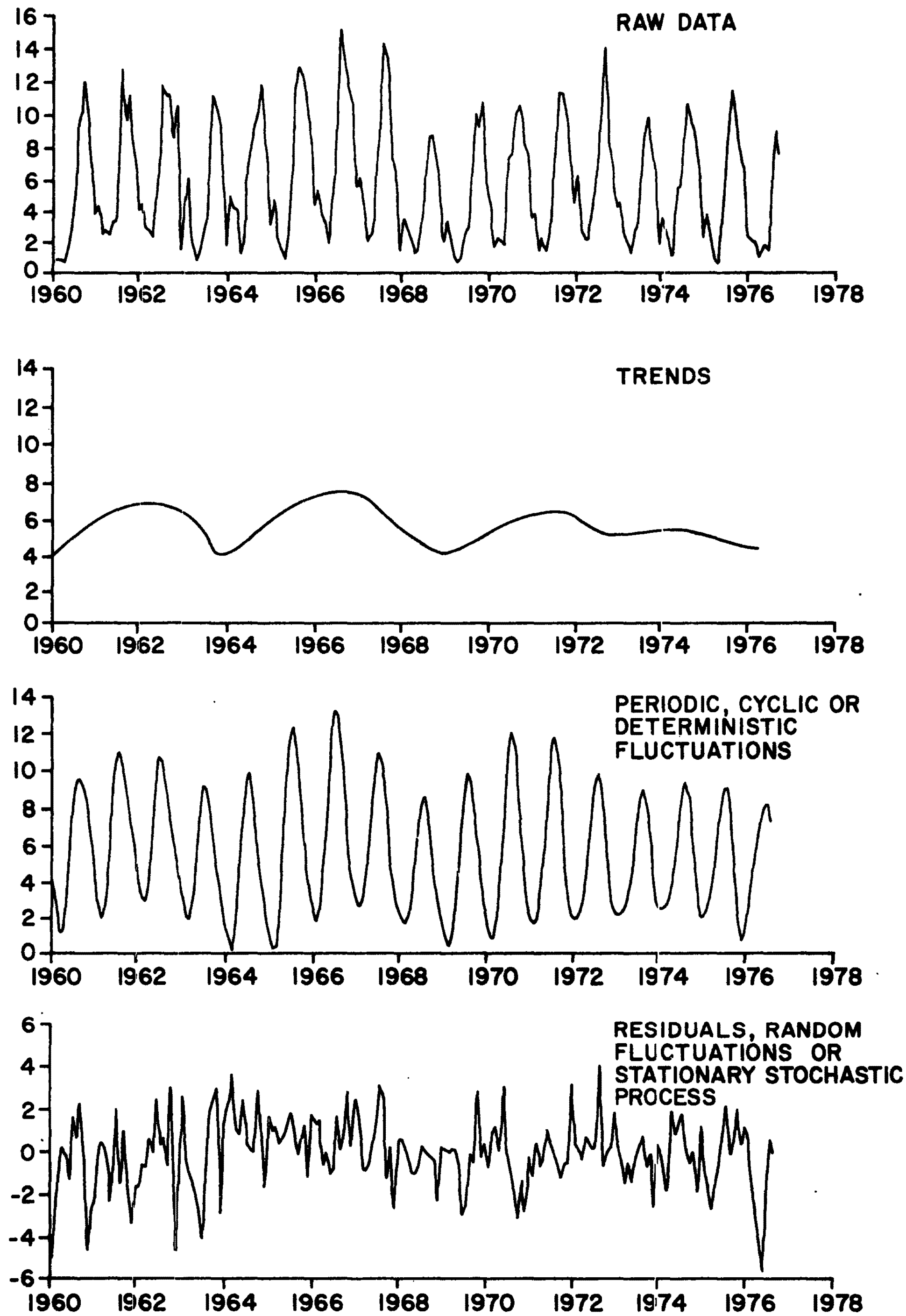


Figure 5. Gross photosynthesis (GP), respiration (R), and GP/R ratio of metabolism of Patuxent Estuary on days when large diurnal variations in oxygen content of water took place during three seasons of the year (from Cory 1974).

TIME SERIES SPECTRAL ANALYSIS



MONTHLY TOTAL CHESAPEAKE BAY CRAB CATCH TOTALS:
JAN. 1960 THROUGH AUG. 1976

Figure 6. Time series analysis of commercial crab landings for Chesapeake Bay in millions of pounds.

As another example, data on temperature and salinity have been taken regularly from the pier at the Chesapeake Biological Laboratory since 1939 and Virginia Institute of Marine Science since 1947. These unusually long records reflect climatic change over the 40-plus year period and studies have shown interesting correlations with salinity and the success of oyster spat set and blue crab spawning in the Bay with higher spat set and larval crab survival correlating with periods of higher salinity, an observation consistent with experimental field and laboratory work. The long record also demonstrates the variability of the Bay, with marked seasonal changes and occasional extremes. Research design must be appropriate to these natural patterns.

These examples are question-specific, but indicate the importance of linking monitoring and research. These uses of simple descriptive but fundamentally important data, taken with consistent methods over a long period, confirm the utility of monitoring by demonstrating the values of meaningful retrospective analysis. The most effective program will include both primary estuarine variables like salinity, temperature and transparency along with those selected to answer specific questions through well designed acquisition of data.

TOWARD ESTABLISHING CAUSE AND EFFECT RELATIONSHIPS

The Bay as Ecosystem

It has been said that all components in the natural world are interdependent. This truism, however, does not distinguish the relative strength of the various linkages. We know that there are many natural interdependencies in the Chesapeake Bay (see U.S. EPA 1982 b and 1983 a). The many ecological linkages (partially illustrated in Figure 7) are the basis for considering the Bay as an ecosystem. The ecosystem perspective provides an analytical framework to address cause and effect relationships. This is important because a pertubation at one point in the system may cascade through the network and show indirect effects at other locations.

The Bay and its sub-ecosystems are dynamic entities, seldom existing in unique steady-states for long. Variation exists at every level of organization and detail. Some variation is cyclic, (e.g., seasonal or longer cycles), some is progressive, (e.g., ecological succession) and some is random (noise) in our conceptual model (Figure 8). The importance of the previously emphasized knowledge regarding ecological processes, their spatial and temporal scales, and problems of "mis-match" should be more understandable in an ecosystem context.

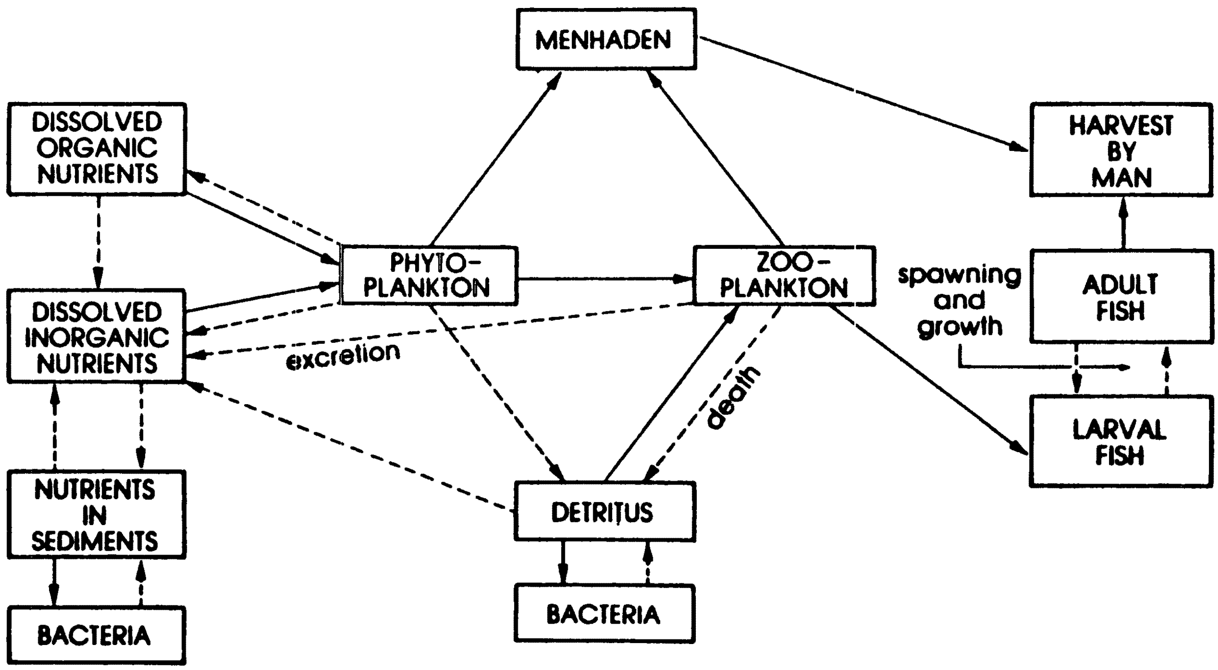


Figure 7. Simplified trophic diagram showing a pathway from phytoplankton to finfish (from U.S. EPA 1983a).

Though variation is a profound natural feature of the Bay ecosystem, we are aware that the various processes operate in a "fabric" that maintains certain distinguishable features. Otherwise, the system would appear chaotic on all scales of observation. One can gain a sense of the organic wholeness of the Bay system in the popular literature, e.g., Michener's Chesapeake, Warner's Beautiful Swimmers, and Schubel's The Living Chesapeake. The reason for strong integration between monitoring and research is that ecosystems are highly plastic in their structures and responses. As yet, there are no simple diagnostic factors that consistently explain ecosystem disruption of effects of stress (Levin 1982). Another reason is the need to be cost effective. The number of components which interact in natural and stressed ecosystems is so large that only a small percent can ever be monitored. Insights into which (or what, when, where, or how) to monitor are derived from a scientific understanding of the Bay as an ecosystem, the product of research. A small number of monitored systems become our indices of ecosystem stability and health.

Cause and effect relationships are difficult to establish because they are embedded in ecological reality. We show in the next section that the situation is not hopeless but that an operational philosophy is required that accepts reasonable certainty as a criterion. Open networks that have a high degree of flexibility such as the Bay ecosystem seldom permit completely deterministic predictions. This point is brought home to those who may be unfamilar with the Bay ecosystem but who can appreciate our point through the experience of traffic patterns in large metropolitan areas which are characterized as open networks. As open networks they exhibit considerable uncertainty in the flow of traffic.

Role of Research

This section focuses on the role of research in establishing cause and effect relationships but also shows how research must feed on monitoring data. Examples of important problems in the Bay system are used to explain the role of research.

Human intervention in the Bay often results in an undesirable change or impact on the system. Exploitation of a fishery, habitat disturbance (dams), or the introduction of a material (toxins, nutrients) can have undesirable effects especially on presently defined uses of the system. It is appropriate to stress that the public determines uses of the Bay - not scientists.

To provide structure and organization to a research program concerning pollutants, it is convenient to define the causal framework as follows:

Source (Emission) $\longrightarrow$ Transport $\longrightarrow$ Fate $\longrightarrow$ Environmental Exposure $\longrightarrow$ Effects.

This framework is directly applicable to studies of ecotoxicology (Levin, 1982) and was employed in a hierarchial research design to address the question of effects of the herbicide atrazine on the Bay's submerged aquatic vegetation (Kemp et al., 1983). The exposure component provides the causal link between sources, inputs and environmental concentrations, while the effects component provides the causal link between exposure concentrations (flux in a dynamic sense) and biological effects. This framework is being applied to problems of ocean disposal of wastes materials and the disposal of dredged material in central Long Island sound, New York (Bierman et al., 1982). The approach can be applied conceptually to problems such as the deep channel hypoxic condition in the upper Bay, though the spatial and temporal scales of ecological mechanisms require special attention to defining effects because the system naturally can produce hypoxic to anoxic conditions without the excessive nutrient enrichment characteristics of recent years. In this case, monitoring and research data have supported the observation that the volume of hypoxic waters has increased in recent years (U.S. EPA 1983 a) and appears to be related to nutrient enrichment. The mechanisms are poorly understood at this time.

Fisheries research, as distinguished from a water quality example, is complicated by ecological processes whose spatial and temporal scales and normal variability are of a magnitude that they seldom can be reduced to simple observation and measurement. Chemists and fish biologists are further frustrated when chemists measure significant environmental changes at ± 0.001 while biologist strive for values of ± 5,000.0. This disparity in accuracy is often the causes of poor statistical coherence between the biological and chemical systems. Monitoring environmental and fishery-specific end-points in a time series mode appears to be the most promising research approach. Here, monitoring and research merge into a common analytical structure.

Many Chesapeake Bay questions are directed towards fisheries. Fishery resource managers need two basic types of information from scientists - the rates of recruitment and the rates of mortality (both natural and fishing). For approximately the last 25 years recruitment rates have been estimated from such sources as the juvenile surveys conducted in the Bay and its tributaries and fishing mortality rates have been derived from catch statistics. Currently, only total fishing mortality can be estimated from catch statistics.

Recruitment and mortality rates are influenced by at least three mechanisms (see Mihursky, this volume). 1) Natural environment: For example, changes in climatically related variables are important (normal or extremes in seasonal temperature, hurricanes, droughts, and seasonal wind shifts) as well as natural ecological interactions (predator-prey relationships). There is no control. Effects are measureable in days to decades. 2) Pollution: For example, reduction in viable habitat occurs due to changes in water quality (addition of point and nonpoint source toxins and nutrients). Control is often exercised by several agencies, local, state, and Federal, and is directed towards "non-users", e.g., a polluting industry, not economically linked to the fishery. Effective mitigation may take years. 3) Fishing pressure: For example, the removal of biomass by recreational and commercial fishermen can have a major impact on the fishery. Control is directly effected on the users, the fishermen, and by a single state or regional agency. Mitigation may take 1 - 5 years depending upon the stock.

The three factors act synergistically in controlling stock distribution and abundance. Normally, stocks are capable of withstanding significant pressure from any one or even all three. However, low stocks can, under these pressures, exhibit failures of year classes which jeopardize the fishery. Repeated failures can lead to biological and economic collapse of the fishery.

There is a need to focus research away from (not eliminate) central tendency correlative models and toward time series (e.g., autoregressive) and spectral analyses (e.g., harmonic analysis) models to partition trends and identify mechanistic and stochastic components of the system. Natural environmental and fishing pressures need to be modelled first because natural environmental influences are widespread and overriding, and fishing is quickly controllable. Then the often cryptic, unpredictable and synergistic long-term effects of anthropogenic inputs to the system should be modelled. Further, the available data on recruitment, and particularly on catch, lend themselves best to stock/recruitment and climatological modelling, not to describing pollution effects.

In summary, an ecosystem perspective helps ensure that we have a balanced research and monitoring program. Management of living resources and ecosystem health requires that knowledge be developed and applied at the appropriate spatial and temporal scales of the ecological processes involved in the system outputs, e.g., fisheries, and services, e.g., waste assimilation. Water quality criteria and standards can sometimes serve as surrogate indices of the biological potential of an ecosystem. In this content, a strong inference regarding cause and effect must consider the "troika" of the mechanisms described above. This is a tall order that will continue to test our managerial and financial systems. However, we believe that the examples described in this essay are positive indicators that research and monitoring have and can continue to make a difference in how the human enterprise addresses future challenges in the Chesapeake Bay.

CONCLUSIONS

Effective management of the Bay's living resources requires that research, monitoring and management be integrated into a coherent structure. Collectively, they must achieve the separation of natural and man-made changes. It is suggested that this framework must be holistic in character, i.e., that it be based on the ecosystem concept. Knowledge of the spatial and temporal scales of environmental variability is of particular importance in the design of research and monitoring programs. Some questions require that research emphasize monitoring in an operational mode (i.e., fisheries); however, this approach must utilize the hypothesis approach of research to provide reasonable certainty in the explanation of variability associated with cause-effect relationships. The success of coupling research, monitoring and management will require attention to Bay-wide institutional mechanisms that permit data collection appropriate to the spatial and temporal scales of a problem. This consideration must transcend traditional managerial and political boundaries.

GUIDELINES

These general guidelines are intended to assist in effective integration of monitoring, research and management for the Chesapeake Bay system. We believe that they are consistent with, but not limited to, the discussions above.

* The goals and objectives of management must be clearly stated - and open to continuing improvement.
* The objectives of management should be employed to focus the specific purposes of related monitoring and research.
* Monitoring and research must continuously interact, with research results and judgement guiding the design of monitoring and with the results of monitoring providing guidance and data for research.

* Regional variables like climate, human activities like fishing, and special situations like disease, must be monitored and properly considered.
* The chemical content of water and sediment are useful indicators of existing conditions and potential effects.
* The spatial and temporal scales of the processes in the Bay must be adequately considered in the design of both monitoring programs and research projects.
* Effective use of time-series observations is exceptionally valuable in interpreting monitoring data.
* Advantage must be taken of the components of the Bay system which give unusually early and useful signals of change and threat. The sensitive stages of sensitive species, accumulator species and other sources of evidence of ecological stress can serve as "canaries" or "vital signs".
* In relation to pollution, monitoring and research must be designed to detect and track the sources, transport, fate and effects of undesired materials in the ecosystem.
* Marked chemical sets, such as employing the chemical "fingerprint" of an effluent, introduced chemical tags or other markers, permit efficient monitoring of the materials and should be fully utilized.
* The Chesapeake Bay and its tidal tributaries should be approached as a set of highly interactive compartments. Such units of area as the tidal freshwater region, the region of the turbidity maxima and the portion which is usually vertically structured can be observed usefully for many purposes.
* Monitoring and research should provide estimates of the fluxes of materials among ecological compartments.
* A primary set of perhaps 20 stations should be carefully established over the Bay system to provide a permanent <u>core set</u> of sites for frequent observations and use as reference points for all local studies.
* At appropriate intervals, perhaps every 2 years, an extensive <u>bench-mark set</u> of samples should be obtained from the water column, sediments and biota in all of the major habitats and analyzed thoroughly for potentially useful characteristics. These should yield statistically useful descriptions and permit early re-visiting of stations if problems exist.
* Samples from the long-term bench-mark series should be banked under excellent and appropriate storage conditions to permit, as far as is feasible,

future retrospective analyses related to new knowledge or problems.

* Emerging and innovative technologies should be promoted to obtain more powerful and cost-effective assays, including use of satellite surveillance, genetic signals, high-speed synoptic sampling by helicopter or hovercraft and improved long-term sampling buoys.
* Special studies, for the purpose of improving the efficiency of monitoring and its value in research and management, should include:
  - ° Detailed time series analysis of all significant variables at each core station throughout the annual cycles and over varying years.
  - ° The roles of episodic events in altering the components and processes in the Bay system.
  - ° Improved identification and understanding of early indicators - biological and chemical.
  - ° Statistical study of variability in time and space (preferably at core stations) to calibrate all sampling.
  - ° Development of screening assays for early detections of deleterious materials or conditions.
  - ° Improvement through bioassay studies of the ability to predict the effects of observed changes at various levels of ecological organization (see Cronin and Roberts, this volume).
  - ° Achieve better understanding of the routes, transport, sinks and releases of introduced contaminants (see Nichols on sediments, this volume, for examples).
  - ° Investigate biochemical, physiological and genetic markers of environmental stress for application in monitoring.
* A permanent Bay-wide group should be established to improve interactions among monitoring, research and management. All three of those communities must be well represented. They should overview all monitoring; assure Bay-wide quality control, data management and data availability; reach agreement on core stations and bench-mark sampling; strongly recommend improvements suggested by new knowledge; and generally protect the high quality and long-term robustness of monitoring programs.

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