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Measuring the Health of the Chesapeake Bay: Toward Integration and Prediction

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The health of an ecosystem is a function of its vigor (useful productivity), organization (complexity of interspecific interactions), and resilience (ability to maintain itself in the face of disturbance). The health of the Chesapeake Bay ecosystem has deteriorated largely as a result of nutrient overenrichment, concomitant reduction in light availability, and loss of habitats that provide complexity. This has resulted in an ecosystem that is a less vigorous producer of valuable fish and shellfish, less diverse and well organized, and more susceptible to and slower to recover from disturbances. It is not clear that degraded ecosystem health directly threatens human health; in fact sanitation and reductions in loadings of potentially toxic substances have reduced human health risks in recent decades. On the other hand, recently observed outbreaks of the toxin-producing dinoflagellate *Pfiesteria piscicida* could be a result of deteriorated ecosystem health and pose a human health risk. Monitoring of the environmental conditions, ecosystem health, and human health risks is critically important to the adaptive management of the Chesapeake Bay. Although this monitoring has produced very useful information, monitoring can be more effective if it more directly addressed the multiple uses of the resulting information, applied new technologies, and were more effectively integrated across environmental media, among resources, over space and time scales, and with modeling and research. © 2000 Academic Press

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INTRODUCTION

The notion of the "health" of an ecosystem, such as the Chesapeake Bay, as an analog of the health of a human being has been used rhetorically for over a half century since Aldo Leopold (1941) wrote about "land sickness." Ecosystem health is seldom defined, however, and there are theoretical and practical limitations in the application of this concept in the same way we do for human health (Costanza, 1992). Ecosystems are less homeostatic and more changeable than the human body. It is more difficult to define the normal ranges of an ecosystem state than the physiologic or immunologic state of a human. And, it is less obvious whether observed changes in that state are good or bad. That is to say, implicit in the concept of health is how we value the performance of a system, be it a human or an ecosystem. Nonetheless, there have been significant recent advances in the conceptualization and measurement of ecosystem health (Costanza, 1992; Rapport, 1995; Rapport *et al.*, 1998) that allow us to describe and measure the health of a large and complex ecosystem such as the Chesapeake Bay.

At the same time, there is increasing attention to the connections between the health of ecosystems and human health and, in another dimension, between ecosystem and economic "health." In particular, arguments are being made that public health risks are increasing as a result of contamination of coastal environments with toxic chemicals and human pathogens or the compromised health of these ecosystems, which allows toxic algal blooms to develop and human pathogens to survive in the environment (Epstein, 1995, 1996; Burke *et al.*, 1999).

Whether conducted to protect human or ecosystem health, environmental monitoring is an important and informative means to determine status, detect trends, and protect against threats. However, monitoring is retrospective rather than predictive. Parameters that can be easily monitored are seldom those of direct concern. Environmental heterogeneity and temporal variability make it difficult to

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determine differences and detect changes. The lack of an equilibrium state means the concept of a benchmark against which to measure change has limited value. It often takes many years of monitoring to provide a suitable framework for confidently detecting trends. As a result of these limitations, environmental monitoring is sometimes viewed as a diversion of resources better spent on new research or actions to protect or restore the environment.

On the other hand, the emerging paradigm of adaptive environmental management (Walters, 1986; Lee, 1993) places an important premium on monitoring. Adaptive management is based on the premise that the outcome of environmental management is always somewhat unpredictable. Therefore, we should approach environmental and resource management as an experiment and emphasize learning while doing. This means that we must rely on effective and responsive monitoring of outcomes to inform the management process and the models on which that process is based. Adaptive management provides a new framework for environmental monitoring, one that demands close and regular integration of environmental modeling and monitoring.

The Chesapeake Bay has one of the most extensive and stable monitoring programs of any coastal area in the world (Boesch, 1996). The Chesapeake Bay Program has conducted strategic and coordinated monitoring of water quality and selected living resources since 1985. At this juncture it is appropriate to assess the potential for improvements in Chesapeake Bay monitoring in terms of its usefulness in assessing ecosystem health and risks to human health; effectiveness and efficiency of methods; integration of results across environmental media and agencies; application in conjunction with environmental monitoring to forecasting future conditions; and communication of results to decision makers and the public.

In this paper I briefly consider the health of the Chesapeake Bay ecosystem and the relationship between ecosystem health and human health. Then, I provide an overview of the variety of environmental monitoring activities relevant to the Chesapeake Bay, the uses of the results of this monitoring, and the new technologies and integration that will lead to more useful monitoring systems in the future.

ECOSYSTEM HEALTH

There is not a widely held, common definition of ecosystem health, even though many ecologists, environmental managers, and conservationists use the term. The concept of ecosystem health is, however, a very active area of thought and discussion (see Costanza, 1992; Mageau *et al.*, 1995; Rapport, 1995; Rapport *et al.*, 1998). Costanza (1992) reviewed various concepts and their limitations and concluded that ecosystem health should include three components: vigor, organization, and resilience. Vigor embodies the throughput or productivity of the ecosystem. Organization represents not only its species diversity but also the degree of connectedness of the constituent species. Resilience refers to an ecosystem's ability to maintain structure and patterns of behavior in the face of disturbance. Ulanowicz (1997) carried these concepts further, focusing on ascendency (the product of vigor and organization) as a central organizing concept for ecology.

A healthy ecosystem, then, is one that is active, maintains its biological organization over time, and is resilient to stress. Costanza also points out that ecosystem health is a normative concept, involving interpretation based on human values of overall ecosystem performance. For example, the gross productivity of the Chesapeake Bay has increased as a result of two centuries of cultural eutrophication (Boesch *et al.*, in press), but this increase results from rapidly growing, small organisms at the expense of larger, more long-lived organisms more valuable to humans. From this perspective, then, the health of the Chesapeake Bay has deteriorated as a result of nutrient overenrichment, concomitant reduction of light availability, and loss of habitats that produce complexity. This has resulted in an ecosystem that is a less vigorous producer of valuable fish and shellfish, less diverse and well organized, and more susceptible to and slower to recover from disturbance (Ulanowicz, 1997).

Vigor, organization, and resilience are easier to describe in theory than measure in practice. Consequently the way we try to monitor the health of the Bay is to measure indicators, or small pieces of the ecosystem. Some of these indicators reflect processes or rate measurements (primary production, flux of nutrients from bottom sediments, or yield as reflected by harvests), but most are measurements of state variables (temperature, light transmission, concentrations of salinity, nutrients, dissolved oxygen, and chlorophyll) or biological structure (biomass, community composition and diversity, incidence of diseases, etc.). Some efforts have been directed to the application of measures of biotic integrity (Karr, 1991) that relate the organization of parts of the ecosystem to a norm, reflecting what is considered the "healthy" condition. For example, an index of biotic integrity has been developed and applied for the macrobenthic communities of the Chesapeake Bay that reflects diversity, trophic structure, and life-history characteristics of species in the community to those presumed to characterize the unaltered benthos (Dauer *et al.*, 1993; Weisberg *et al.*, 1997).

Such composite indicators or other representations of vigor, organization, and resilience are, however, viewed as esoteric and uninformative by the public and decision makers. In order to represent the health of the Chesapeake Bay to a more general audience and in terms of human values, the Chesapeake Bay Foundation (1998) produced a composite index of the "State of the Bay" that can be periodically assessed to track progress in the restoration of this ecosystem. The index is based on component indices for 12 factors, each judged on a scale of 100, with 100 representing the conditions at the time of arrival of European colonists (Table 1). While some of these factors are periodically quantified and can be compared to reliable estimates of the precolonial conditions (e.g., wetlands), others are based on less certain knowledge of previous or current conditions. Furthermore, scaling the indices for factors that have increased (toxics and nutrients) is more arbitrary than for those that have decreased. Some factors, such as fish populations, are naturally highly variable in time, while others will be slow to change, even if gains in ecosystem restoration are made. Averaging over all factors to produce a composite index implies that all of the factors are of equal importance or value even though some of these factors are fundamentally more important to the vigor, organization, or resilience of the ecosystem than others.

Despite these technical criticisms, the Chesapeake Bay Foundation's State of the Bay index is a useful contribution from at least three perspectives: (1) it addresses the need to periodically take stock with regard to benchmarks in order to guide restoration activities; (2) it demonstrates the value of broad assessments rather than reliance on a single indicator, such as nutrient inputs, dissolved oxygen or underwater grasses; and (3) it illustrates the need to express the health of the ecosystem in terms that citizens can understand, status and progress.

TABLE 1

The Chesapeake Bay Foundation's State of the Bay Report Card for 1998

Factor	1998 index	How estimated
Wetlands	43	Agency inventories and remote sensing
Forested buffers	53	Estimated, difficult to measure remotely
Underwater grassses	12	Aircraft photos in annual surveys
Dissolved oxygen	15	Water quality monitoring
Toxics	30	Subjective estimate
Water clarity	15	Water quality monitoring
Phosphorus	15	Budgets, model estimates
Nitrogen	15	Budgets, model estimates
Crabs	50	Catch statistics, surveys
Rockfish	70	Catch statistics, surveys
Oysters	1	Catch statistics, surveys
Shad	2	Sampling migratory runs
Average	26.8	

Note. Each factor is scored on an index ranging to 100, which represents the precolonial condition. For each factor, the means by which the status of the factor is determined is indicated.

RELATION TO HUMAN HEALTH

Beyond the metaphorical relationship between ecosystem and human health, it has been suggested that deterioration in ecosystem health of coastal waters such as the Chesapeake Bay increases risks to human health. This relationship could be mediated by greater: (1) exposure to toxic chemicals; (2) risks of infection by pathogens, including those of human origin, under eutrophic conditions; and (3) frequency and intensity of production of biotoxins by harmful algae.

In the Chesapeake Bay, concentrations of toxic metals and organic compounds in waters, sediments, fish, or shellfish high enough to conceivably pose a human health risk are, with few exceptions, limited to areas of concentrated industrial and maritime activities (Velinsky *et al.*, 1994; Wade *et al.*, 1994; Eskin *et al.*, 1996). These include Baltimore Harbor, the Anacostia River (a tributary of the Potomac River that runs through the District of Columbia), and the Elizabeth River (a tributary of the James River that runs between Norfolk and Portsmouth, Virginia). The most significant risks to estuarine biota and ecosystem health are also in these regions of concern (e.g., Schlekat *et al.*, 1994; Hall and Alden, 1997; Greer and Terlizzi, 1997), but there are indications that biological effects of toxic contaminants may be in evidence in other areas as well (Chesapeake Bay Program, 1999).

Across broad classes of compounds, loadings of toxic substances have declined over the past 20 years as a result of source controls and treatment required by the Clean Water Act, reductions of atmospheric emissions of some substances (e.g., lead), and phasing out of persistent pesticides, PCBs, etc. (Chesapeake Bay Program, 1999). Reductions in loadings are reflected in declining concentrations of a number of contaminants in sediments (Owens and Cornwell, 1995) and biota. While this does not mean that risks to human health or estuarine organisms have been eliminated, it does suggest that such risks have, as a rule, been declining rather than increasing.

Similarly, human health risks from pathogens have been managed by sanitary waste treatment, monitoring of shellfish-growing waters for indicators of human fecal contamination, and safety requirements placed on seafood processing. Compared to earlier times when the discharge of untreated or poorly treated human wastes was the norm, the risks to human health from environmental pathogens have been substantially reduced during a period in which ecosystem health has deteriorated. For example, areas in the Chesapeake Bay closed to shellfish harvesting due to the risk of pathogen contamination have decreased in extent (Leonard *et al.*, 1991). However, this does not warrant complacency; responsible officials indicate that further reductions in risks are achievable through more intensive and more sophisticated monitoring for pathogens and toxic substances. One particular concern is the limitation of using fecal coliforms as an indicator of risks of exposure to enteric pathogens. Other human pathogens, including both bacteria such as *Cryprosporidium parvum* (Gaczyk *et al.*, 1999) and viruses (Rose and Sobsey, 1993), pose greater risks under these circumstances, but are not directly measured. In addition, naturally occurring microorganisms, such as *Vibrio* spp. (bacteria), also pose some risks of human infection. It has been suggested that eutrophication and climatic warming of coastal waters would increase survival or growth of some of these microbial pathogens (Epstein, 1996). But the uncertainties regarding this prediction, coupled with the mitigating efforts to protect public health, make it unclear that degraded coastal ecosystems in the developed world necessarily present greater human health risks.

A number of algae known to produce toxins are found in the Chesapeake Bay, some even in high densities. However, until recently, associated fish kills and conditions posing a risk of biotoxicity to humans were unknown. In 1992, the toxic-producing dinoflagellate *Pfiesteria piscicida* was identified from tidal creeks bordering the Bay (Lewitus *et al.*, 1995). This organism, which has numerous life-history states, some of which release potent toxins that attack fish "prey," has been shown to be responsible for extensive fish kills (Burkholder and Glasgow, 1997) and to pose human health risks (Glasgow *et al.*, 1995) in North Carolina estuaries.

Beginning in the fall of 1996 and continuing intermittently during the summer and early fall of 1997, there were reports of large numbers of fish with gross lesions and of fish kills in the Pocomoke River and several nearby tidal rivers along the middle reaches of the Eastern Shore of the Chesapeake. Field observations and laboratory cultures indicated that these incidents resulted, at least in part, from outbreaks of toxic *Pfiesteria* similar to, but on a smaller scale than, those observed in North Carolina. Medical evaluations demonstrated that several fishers, state workers engaged in sampling these rivers, and other individuals suffered impaired capacity for short-term memory (Grattan *et al.*, 1998). Based on the experience of North Carolina investigators and assessments of water quality conditions during the *Pfiesteria* episodes, a scientific consensus developed that nutrient overenrichment of these tidal rivers has likely made these waters more susceptible to toxic *Pfiesteria* outbreaks (Boesch *et al.*, in press). As a consequence of the public concerns and scientific assessments, the state of Maryland enacted legislation to mandate nutrient management for agriculture activities and to reduce the overapplication of poultry manure on fields along the Eastern Shore.

The putative nutrient enrichment-*Pfiesteria* relationship and the apparent increase in the worldwide incidence of harmful algal blooms have been cited as examples of the linkage between ecosystem health and human health. But, much yet needs to be learned about these relationships before drawing that conclusion. Although the incidence of harmful algal blooms has increased in recent decades in many parts of the world, some of these blooms are clearly unrelated to nutrient enrichment or other obvious human impacts (Boesch *et al.*, 1997). While the potential effects of environmental pollution and ecosystem alteration on human health should be taken seriously in a risk management framework (Burke *et al.*, 1999), scientists should be careful to refrain from vague notions, broad inferences, and overstatement of the evidence concerning the relationship between ecosystem health and human health.

CURRENT STATUS OF MONITORING PROGRAMS

There are many monitoring activities in the Chesapeake Bay region producing information relevant to the quality of the environment, the status of the living resources, and the risks to human health. They extend far beyond the water quality and living resource monitoring generally regarded as the

Chesapeake Bay Monitoring Program, which constitutes the largest and most centrally managed effort. For example, pollutant inputs into the ecosystem are monitored from numerous point sources, often as a condition of discharge or emission permits. Weather is monitored by the National Weather Service for reasons unrelated to the Bay, yet such data are critical for understanding this ecosystem. Gauging of stream flows and associated measurement of suspended and dissolved constituents provide important information on driving forces (such as freshwater inflows) and the delivery of sediments, nutrients, and chemical contaminants to the Bay. Inventories of land uses help us understand how our activities on the land affect the delivery of pollutants to the Bay. Air quality measurements are made for reasons related to human respiratory health, but yield information regarding pollutant inputs from the atmosphere to the Bay and its watershed. Fisheries are assessed by monitoring catch, as well as through independent measurement, for the purpose of their fisheries management and regulation. Waters and seafood products taken from them are monitored for human pathogens and toxic substances in order to protect human health. All of these provide rich, but seldom connected, information streams that serve to inform us regarding the health of the Bay ecosystem.

The Chesapeake Bay Monitoring Program, *sensu stricto*, was begun in 1984 and is a region-wide, cooperative effort involving state and federal agencies and research institutions in the region. It makes routine measurements at over 165 stations in the tidal waters of the Bay and its tributaries. In addition it incorporates a citizen's monitoring program begun in 1995. The Bay Monitoring Program measures, to varying degrees, nutrients, suspended sediments, toxicants in water and sediments, water temperature and salinity, water circulation, freshwater inflows, dissolved oxygen, submersed aquatic vegetation, plankton, benthos, and fish and shellfish.

The results of the Chesapeake Bay Monitoring Program are increasingly available to analysts and the public shortly after they are collected. The results are summarized and interpreted for periodic assessments of the state of the Bay (Magnien *et al.*, 1995) and progress toward its recovery (Chesapeake Bay Program, 1997). Monitoring data have also been extensively used by the research community to provide a larger spatial or longer temporal context for intensive scientific studies. They are also being used to validate improved water quality models of the Bay. However, there is a widespread feeling that we are not doing enough to extract useful information from the rich database that has been building (Scientific and Technical Advisory Committee, 1997).

The Bay Monitoring Program was designed to assess the state of the health of the Bay ecosystem and its recovery, not risks to human health. However, there are a variety of other programs managed by cognizant state agencies and the Food and Drug Administration that deal more specifically with human health concerns. These include monitoring of fecal pathogens in shellfish-growing waters under requirements of the Interstate Shellfish Sanitation Commission; similar monitoring of recreational waters where direct human contact is likely; monitoring of processed seafoods to meet FDA requirements; and monitoring of toxic substances in waters, sediments, and fish and shellfish tissues in certain impaired waters or areas of subsistence fishing. As discussed earlier, these programs although in many ways technically unsophisticated have been largely effective in protecting human health. Epidemics are unknown or extremely limited in scope. There is no strong evidence of widespread risks due to toxic contaminants in seafood. However, many state and federal regulatory agencies maintain that risks can be further reduced though more effective monitoring, including the application of modern technologies.

IMPROVEMENTS AND NEW DIRECTIONS

As we think about the design, effectiveness and value of environmental monitoring it is important to understand that monitoring results are applied to many purposes (Table 2). These multiple uses place different demands on monitoring programs in terms of the parameters measured, required accuracy and precision, sampling design, time frames for analysis, and mode of communication of information. Monitoring programs could improve by more explicit consideration of their primary objectives and collateral uses (National Research Council, 1990; Bernstein *et al.*, 1993).

Chesapeake Bay monitoring could also greatly improve by the application of new technologies that measure more interpretable parameters, sense more accurately and at more appropriate space and time scales, provide more timely access to information, and allow more effective integration of databases and observations and models. Technologies that offer significant opportunities for application in Chesapeake Bay monitoring include the following:

- Biotechnology, for example, in more accurately and unambiguously detecting pathogenic or toxic

TABLE 2
Results from Environmental Monitoring Are Applied to a Number of Different Objectives

Objective	Application
Trends	Determining of the present status and past trends in an environment or resource.
Goals	Gauging the degree to which specific goals have been met, for example, a certain level of nutrient reduction, dissolved oxygen concentration, or recovery of submersed aquatic vegetation.
Resources	Assessing stocks of living resources for management of harvests.
Precaution	Assuring precautionary protection by determining whether some action level (e.g., abundance of human pathogens or concentration of toxic chemicals in seafood) is exceeded.
Models	Applying to the calibration and verification of ecosystem, water quality, resource management, or exposure models.
Research	Providing the context for hypotheses tested by scientific research and the extrapolation of research results.
Public information	Informing the public about the world in which we live in order both to account for government programs and to promote citizen stewardship.
Emergencies	Supplying background information for response to unforseen effects and emergencies, for example, monitoring data were exceptionally useful in assessing the environmental factors involved in the toxic outbreaks of *Pfiesteria* in tidal tributaries along the Eastern Shore.

organisms and more efficiently measuring important ecological processes.

- Remote sensing from satellites and aircraft, which allows large-scale synoptic depiction of the Bay and its watershed. For example, quasi-synoptic aircraft sensing of color has improved understanding of the heterogeneity and large-scale dynamics of phytoplankton biomass in the Bay. When integrated with sparser measurements from vessels at fixed stations, whole-Bay biomass can be estimated (Harding and Perry, 1997).
- Continuous in situ sensors tell us what happens during the 2 to 4 weeks between monitoring cruises. The Chesapeake Bay Observing System is a growing network of buoys capable of measuring numerous variables and telemetering them to a central data processing base. Virtually real-time data on environmental conditions are then made available to the world via the Internet.
- Underway profiling from vehicles towed from vessels is now providing basic researchers with richly textured portraits of multiple, simultaneously sampled parameters. Vast volumes of measurements are provided though automated electrical, optical, and acoustic sensors. Together, these relational parameters open windows of understanding on both the important large-scale and the small-scale processes operating in the ecosystem. This technology could be transitioned from research to operational monitoring, producing the equivalent of high-definition "CAT scans" of the entire Bay from a 3- to 4-day survey.
- Information systems are now available to store, manage, and analyze the huge data streams coming from remote, continuous, and underway sensing. These allow the rapid acquisition, processing, and posting of data and information and the opportunity for incorporation of near real-time data into nowcast and forecast models, much as is done in weather forecasting.

As mentioned earlier, achieving greater integration of data is a major challenge for Chesapeake Bay monitoring as we move into the 21st century. This integration must have multiple dimensions (Table 3). In particular, the Bay scientific community has identified four key challenges for more integrated analysis of Chesapeake Bay monitoring data and has made recommendations on how to address them: (1) linking monitoring with predictions of the Bay water quality model, (2) linking living resources and water quality monitoring, (3) improving the sensitivity of monitoring small watersheds, and (4) bridging spatial and temporal scales in monitoring and research (Scientific and Technical Advisory Committee, 1997). The scientific community has also recently considered in greater depth the needed improvements in integration of monitoring and modeling in predicting watershed responses to changes in nutrient loadings (Scientific and Technical Advisory Committee, 1998b).

Monitoring systems of the future, then, should be more fully integrated across media, resources, space, and time; produce not only data but information rapidly; match these results to the scale of the management questions; and routinely assimilate monitoring data into forecast models much better grounded in reality than those that we now rely on. Only then can we fully harness the tremendous material and intellectual resources in regular assessments of our progress that guide course corrections in this incredible voyage in restoring the Chesapeake. Only then will we truly be practicing adaptive management (Gunderson *et al.*, 1995; Boesch, 1996).

TABLE 3

To be Effective, Monitoring Programs Require Integration in a Number of Different Dimensions

Dimension of integration	Examples
Across environmental media (air-land-fresh waters-estuary-ocean)	Develop a better hand off between measurements of atmospheric deposition, in-stream concentrations, and estuary loadings (for example Jaworski *et al.*, 1997)
Among resources (water quality-habitats-living resources-human health)	Practically managing fisheries in a multispecies and ecosystem framework (Scientific and Technical Advisory Committee, 1998b)
Over space and time scales	Relate intense local observations to spatially extensive surveys and transient variations to secular changes
With modeling and research	Add mechanistic understanding to statistical correlation and improve the realism of management models

The advance of innovative environmental monitoring is difficult to sustain. First, there is the inherent conservatism of monitoring programs, based on often well-founded concerns about the loss of continuity in the design or methodologies that could compromise the ability to describe long-term trends. Furthermore, there are few incentives for the practitioners who self-manage the monitoring program to take a different approach. Managers and sponsors may see monitoring programs as static, not producing new or exciting information, and too costly. Because of the decision-making time scales on which they must operate, they may lack the long-range perspective into a time frame in which the value of long-term monitoring is fully realized. The classic example is repeated decisions to end support for carbon dioxide measurements on Mauna Loa: after all this year's results were very much like last year's. Indeed it is the failure to develop or sustain a commitment for the high monitoring costs that has doomed many efforts to apply adaptive management (Walters, 1997).

This dream about the Chesapeake Bay monitoring system of the future must also be tempered by the difficulty in conveying the behavior of this complex ecosystem to the citizens who must financially support and personally contribute to its restoration. From that perspective the Chesapeake Bay Foundation's report card of the Bay's health is instructive. Few of the 12 component indices can be directly determined from the Chesapeake Bay Monitoring Program (Table 1). Perhaps we should evaluate ways in which features or products of the environment of interest to society can be more directly measured. Furthermore, if monitoring is to assess ecosystem health, we should do much more to synthesize diverse information in order to better determine the vigor, organization, and resilience of this ecosystem and convey this in terms relevant to humans and their well being.

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