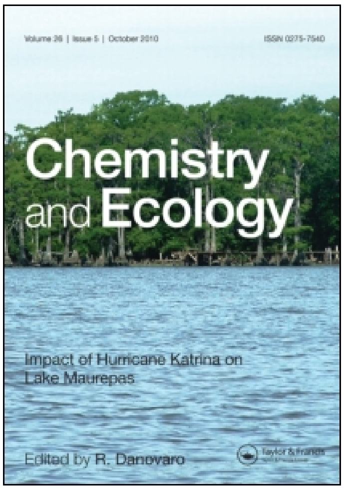

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

The Estuarine Component of the Us E.P.A.'S Environmental Monitoring and Assessment Program

John F. Paul[a]; K. John Scott[b]; A. Fred Holland[c]; Steven B. Weisberg[c]; J. Kevin Summers[d]; Andrew Robertson[e]
[a] US Environmental Protection Agency, Narragansett, RI [b] Science Applications International Corporation, Narragansett, RI [c] Versar, Inc, Columbia, MD [d] US Environmental Protection Agency, Gulf Breeze, FL [e] National Oceanic and Atmospheric Administration, Rockville, MD

To cite this Article Paul, John F. , Scott, K. John , Holland, A. Fred , Weisberg, Steven B. , Summers, J. Kevin and Robertson, Andrew(1992) 'The Estuarine Component of the Us E.P.A.'S Environmental Monitoring and Assessment Program', Chemistry and Ecology, 7: 1, 93 — 116

To link to this Article: DOI: 10.1080/02757549208055434

URL: http://dx.doi.org/10.1080/02757549208055434

Chemistry and Ecology, 1992, Vol. 7, pp 93–116
Reprints available directly from the publisher
Photocopying permitted by license only

THE ESTUARINE COMPONENT OF THE US E.P.A.'S ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM

JOHN F. PAUL,* K. JOHN SCOTT,** A. FRED HOLLAND,*** STEVEN B. WEISBERG,*** J. KEVIN SUMMERS† and ANDREW ROBERTSON‡

US Environmental Protection Agency, 27 Tarzwell Drive, Narragansett, RI 02882, Science Applications International Corporation, 165 Dean Knauss Drive, Narragansett, RI 02882,** Versar, Inc. 9200 Rumsey Road, Columbia, MD 21045,*** US Environmental Protection Agency, Sabine Island, Gulf Breeze, FL 32561,† National Oceanic and Atmospheric Administration, 6001 Executive Boulevard, Rockville, MD 20652‡*

(Received 26 September, 1991 in final form 3 January 1992)

The US Environmental Protection Agency's Office of Research and Development has initiated the Environmental Monitoring and Assessment Program (EMAP) to monitor status and trends in the condition of the nation's near coastal waters, forests, wetlands, agro-ecosystems, surface waters, deserts and rangelands. The programme is also intended to evaluate the effectiveness of Agency policies at protecting ecological resources occurring in these systems. Monitoring data collected for all ecosystems will be integrated for regional and national status and trends assessments. The near coastal component of EMAP consists of estuaries, coastal waters, and the Great Lakes. Near coastal ecosystems have been regionalized and classified, and an integrated sampling strategy has been developed. EPA and NOAA have agreed to coordinate and, to the extent possible, integrate the near coastal component of EMAP with the NOAA National Status and Trends Program. A demonstration project was conducted in estuaries of the mid-Atlantic region (Chesapeake Bay to Cape Cod) in the summer of 1990. In 1991, monitoring continued in mid-Atlantic estuaries and was initiated in estuaries of a portion of the Gulf of Mexico. Preliminary results indicate: there are no insurmountable logistical problems with sampling on a regional scale; several of the selected indicators are practical and sensitive on the regional scale; and an efficient effort in future years will provide valuable information on condition of estuarine resources at regional scales.

KEY WORDS: Estuaries, coastal waters, monitoring, pollution, indicators

BACKGROUND

The scientific community and the public are becoming increasingly concerned that the impact of pollutants now extends well beyond the local scale. Global climate change, acidic deposition, ozone depletion, non-point source pollution, and habitat alteration threaten our ecosystems at regional, national and global scales. Years of scientific study have heightened our environmental awareness of these problems, but unfortunately they have also convinced us that ecosystem responses to natural and anthropogenic disturbances are extremely complex. The status of the nation's ecological resources is not well documented and it is very difficult to establish quantitatively whether or not environmental policies and programs are effectively limiting anthropogenic impacts on natural ecosystems.

Despite the implementation of stricter environmental control programs in coastal regions, water and sediment quality and the abundance and quality of living marine resources are perceived by the scientific community and the informed public to have declined in the past 10 to 15 years. The perceived decline in estuarine and coastal environmental quality has been noted in the popular press (Smart *et al.*, 1987; Morganthau, 1988; Toufexis, 1988) and the scientific literature. These problems are exemplified by the following:

1. increases in the duration, frequency and size of water masses with low dissolved oxygen content (US Environmental Protection Agency (USEPA), 1984; Officer *et al.*, 1984; Parker *et al.*, 1991; Rabalais *et al.*, 1985; Whitledge, 1985);
2. accumulation of contaminants in the tissues of fish and shellfish at levels that pose a threat to human consumers and the quality of the resource populations (Office of Technology Assessment, 1987; National Research Council, 1989);
3. increased pathological problems in fish and shellfish in chemically contaminated areas (Sinderman, 1979; O'Connor *et al.*, 1987; Buhler and Williams, 1988; Capuzzo *et al.*, 1988);
4. increased frequency and persistence of algal blooms and associated impacts on water quality (USEPA, 1984; Pearl, 1988); and
5. increased incidence of closures of beaches and shellfishing grounds because of pathogenic or chemical contamination (Smart *et al.*, 1987; Food and Drug Administration, 1971, 1985; Hargis and Haven, 1988; Broutman and Leonard, 1988, Leonard *et al.*, 1989).

In 1988, the US Environmental Protection Agency's Science Advisory Board (Science Advisory Board, 1988) recommended the implementation of a program to monitor ecological status and trends that would identify emerging environmental problems before they reach crisis proportions. The Environmental Monitoring and Assessment Program (EMAP) is the Agency's response to the Science Advisory Board's recommendation. Coincidentally, the National Research Council's Marine Board, in a review of marine and estuarine monitoring systems (National Research Council, 1990), recommended the creation of a national network of regional monitoring programs for estuarine and coastal environments. This review recognized the need for new monitoring programs that build on the vast amount of existing information and expand the information base landward in order to identify the factors contributing to coastal pollution problems.

This paper describes the near coastal and estuarine components of EMAP: the design of the sampling program, indicators of ecological condition, the 1990 Demonstration Project in the mid-Atlantic estuaries, and the approach to data analysis and assessments of ecological condition. It borrows heavily from the EMAP-Near Coastal Program Plan (Holland, 1990), and the EMAP indicator strategy outlined in Hunsaker and Carpenter (1990) and Knapp *et al.* (1991).

THE ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM

The goal of the Environmental Monitoring and Assessment Program (EMAP) is to assess status and trends in the condition of the nation's ecological resources. It will provide information to evaluate the effectiveness of current policies and programs and identify emerging problems before they become either widespread or irreversible. The specifically stated objectives of EMAP are to:

1. estimate the current status, extent of changes, and long-term (decadal) trends in indicators of the condition of the nation's ecological resources on a regional basis with known confidence;
2. monitor indicators of pollutant exposure and habitat condition, and seek associations between anthropogenically induced stresses and ecological condition; and
3. provide periodic statistical summaries and interpretative reports on ecological status and trends to resource managers and the public.

A complement of long-term, coordinated monitoring efforts will be initiated over the next five to seven years. These programs, which will operate on regional (biogeographical) scales, will collect data from many resource categories: arid lands, agricultural systems, forests, lakes and streams, inland and coastal wetlands, the Great Lakes, coastal waters, and estuaries. Additional data on atmospheric deposition and exposure to air pollutants will be obtained. Maps, aerial photography, and satellite imagery will be used to describe broad regional patterns in the landscape.

Such an ambitious program cannot be accomplished solely by the EPA without integrating monitoring data networks and systems from other Federal and regional entities. Thus, to accomplish its objectives, EMAP is multiagency in nature and gives very high priority to building on existing efforts. For example, the near coastal portion of EMAP is coordinating its efforts with NOAA's National Status and Trends Program and EPA's National Estuary Program. The surface water resource group is working with the US Geological Survey and the forest group with the US Forest Service. Interagency coordination will avoid duplicative monitoring efforts, provide for a cost-effective means of gathering and exchanging information, and allow for the maximum use of existing and historical data.

Estuaries are the focus for the initial implementation of EMAP. This ecological resource was chosen as a high priority because:

1. the environmental quality and status of living resources in estuaries are strongly influenced by the environmental condition of adjacent wetlands and the draining watersheds (USEPA, 1983; Donovan and Tolson, 1987; Costanza *et al.*, 1990) (Figure 1);
2. estuaries are critical spawning and nursery habitats for many commercially and recreationally important species of fish and shellfish (Gunter, 1967; Tagatz, 1968; Lippson *et al.*, 1979);
3. estuaries are repositories for many pollutants released into the nation's waterbodies and atmosphere, and they are integrators of insults to the coastal environment (Biggs and Howell, 1984; Schubel and Carter, 1984; OTA, 1987; Nixon *et al.*, 1986); and
4. the threat to estuarine and coastal resources will continue to grow with demographic projections that more than 75% of the nation's population will reside within 50 miles of the coast by the year 2000 (OTA, 1987).

There are several functional components of the EMAP-Near Coastal resource (Figure 1). These include coastal and estuarine wetlands, estuaries, coastal waters, and the Great Lakes. Initially, attention is being focused in estuaries with full-scale regional projects in 1990 and 1991; a pilot study was conducted in tidal wetlands in 1991, and another will be conducted in the Great Lakes in 1992.

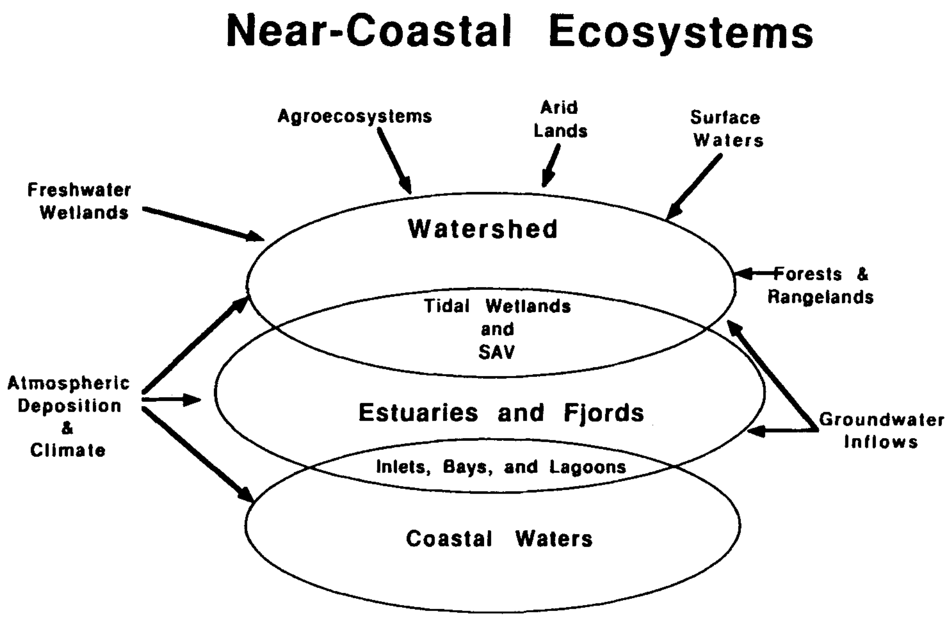

Figure 1 Components of near coastal ecosystems.

EMAP-ESTUARIES DESIGN

The goal of the EMAP sampling design is to provide unbiased estimates of the status and trends in indicators of ecological condition with known confidence. The various components of the estuarine resource are sampled in proportion to their abundance so that confidence limits can be placed on statements of estuarine condition as a whole. Probability-based sampling was employed within a systematic grid that is contiguous with other land-based resource groups (e.g., surface waters, forests).

There are four essential features of the design for EMAP-Estuaries (EMAP-E): regionalization, classification, index period and statistical sampling. A regionalization scheme partitions the estuarine and coastal resources of the United States into geographical areas with similar ecological properties and which provide reasonable reporting units. The classification scheme defines certain subpopulations of interest within regions that are functionally similar and can be sampled using a common approach. The statistical sampling allows for the determination of unbiased estimates of the status and trends of the estuarine ecological resources in a cost-effective manner.

Regionalization

The regionalization scheme used by EMAP-E is shown in Figure 2. Estuaries within these regions are defined by the landward boundary of the maximum inland extent of tide, and by the distal edge of the continental shelf. There are seven regions or "provinces" in the continental United States, five in Alaska and Hawaii and Pacific territories, and one for the Great Lakes.

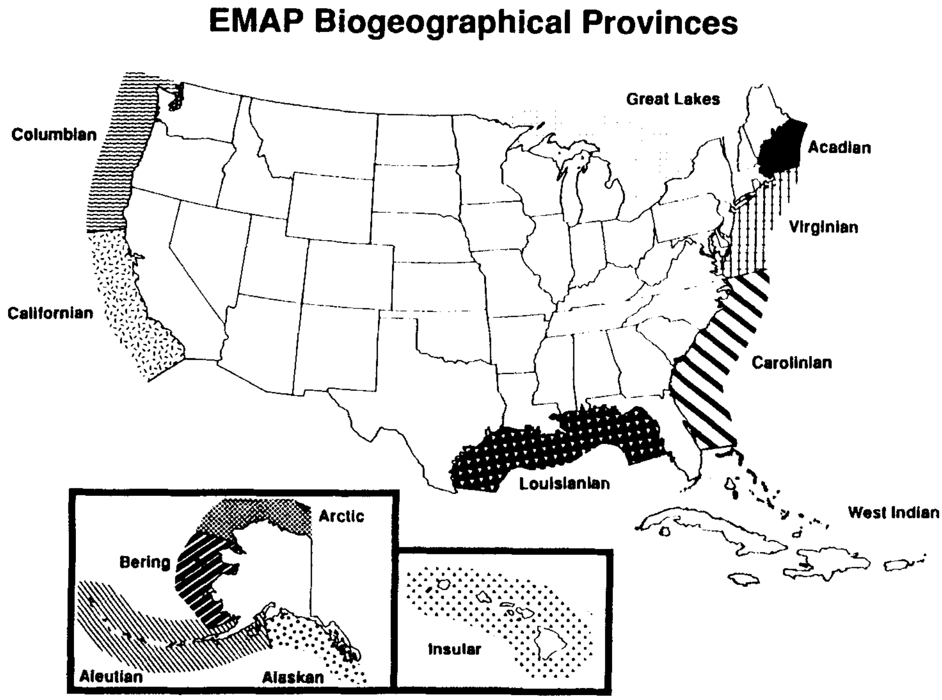

Figure 2 EMAP biogeographical provinces.

The boundaries of these provinces are those used by NOAA and the US Fish and Wildlife Service for their assessments (Beasley and Biggs, 1987; Terrell, 1979). They are based on two factors: climatic zones (Bailey 1983), and prevailing ocean currents (Terrell, 1979). The initial emphasis of EMAP-E will be on the seven maritime provinces in the contiguous United States:

1. Acadian Province – this province is characterized by a continental climate that is strongly influenced by the Labrador Current.
2. Virginian Province – this region includes many large estuarine systems and a substantial number of small estuaries and tidal rivers. It has a continental/ subtropical climate which is affected by both the Labrador Current and the Gulf Stream.
3. Carolinian Province – the Carolinian is entirely subtropical and is typified by wide, shallow estuaries, extensive barrier island and complex lagoon systems, and broad expanses of coastal marsh. The region is dominated by the Gulf Stream.
4. West Indian Province – the Florida current dominates in this province causing a tropical climate. Its ecological resources are very diverse, and include large coastal wetlands, extensive seagrass beds, coral reefs and heads, and mangrove islands.
5. Louisianian Province – this subtropical region has extensive sandy beaches, marsh and swamp areas, barrier island systems, hypersaline lagoons, and one of the largest deltaic systems in the world.

6. Californian Province – the California Current dominates this province resulting in a dry, Mediterranean climate. The shoreline is bordered by high cliffs, deep canyon estuaries, and extensive kelp beds. It contains only two large estuarine systems.
7. Columbian Province – this province is dominated by the Alaska and California Currents. It has a continental/temperate climate and is characterized by beaches bordered by high cliffs, high freshwater inflow, numerous rocky islands, extensive eelgrass beds, and only two large estuarine systems.

EMAP-E will be implemented in phases, which began with a demonstration project in the Virginian Province in 1990. Another demonstration project was initiated in the Lousianian Province in 1991. These will be followed by sampling programs in the Carolinian, West Indian and Acadian Provinces in 1993 and 1994, and the Californian and Columbian Provinces in 1995. A pilot project is scheduled for Lake Michigan in 1992. After a demonstration project is initiated in a province, sampling is continued regularly on an annual basis.

Classification

Estuarine resources vary widely in size, shape, and most importantly, ecological characteristics. Some estuaries are large, continuously distributed resources that consist of extensive regions with a wide variety of habitat types and salinity conditions. Others are small, and relatively discrete, resources composed of only a few habitat types. It is not cost-effective to sample all estuarine types on the same spatial scale because large systems would receive most of the samples, while less extensive, smaller systems would receive little attention. A classification scheme was established to organize estuaries into groups with similar physical and ecological characteristics in order to facilitate sampling and data interpretation.

There are several features that were evaluated as *a priori* classification variables. They included sediment type, salinity, and physical dimensions. An important characteristic of a classification variable is that it should not change significantly from year to year. As a result, successive yearly samples would be taken from the same population. The distribution of these variables also should be well described prior to sampling so that an adequate number of samples can be allocated to each class type.

Salinity does not meet the first of these criteria in that the spatial extent of the class would fluctuate depending in rainfall in any given year. Interannual salinity distribution is poorly known for most estuaries. While sediment type is relatively stable in time, its distribution in space is extremely variable, and not well described for most estuaries. The planar dimensions of the estuaries (surface area and aspect ratio) were chosen because of their stability, predictability, and ease of measurement and estimation.

Estuaries were classified into large estuarine systems, large tidal rivers, and small estuarine systems and tidal rivers (Table 1). Large estuaries have a surface area greater than 260 km^2 and an aspect ratio (length/average width) less than 20. Large tidal rivers, similarly, have surface areas greater than 260 km^2, but an aspect ratio greater than 20. Small systems have surface areas between 2.6 km^2 and 260 km^2.

This classification identifies 12 large estuarine systems in the Virginian Province that represent 74% of the total estuarine area. The five large tidal rivers represent 6% of the area and 137 small estuarine systems comprise 20% of the estuarine area. Specific size estimates and locations of each estuarine type are given in Holland (1990).

Table 1 Summary of the characteristics of estuarine classes.

Characteristics	*Large estuaries*	*Large tidal rivers*	*Small estuarine systems*
Surface Area	> 260 km^2	> 260 km^2	2.6–260 km^2
Shape	Aspect ratio < 20	Aspect ratio > 20	Any
Salinity	Strong salinity gradients	Partial salinity gradients	Generally does not have salinity gradients
Sediments	Heterogeneous	Heterogeneous	Relatively homogeneous
Watersheds	Large, complex	Large, complex	Small
Management Regions	Multi-state	Multi-state	Usually, a single state
Contaminant Sources	Multiple	Multiple	Relatively few

Index Period

The financial resources to fully characterize naturally occurring seasonal variability or to assess status in all seasons are not available. As a result, sampling is limited to that portion of the year (i.e., index period) when the measured parameters are expected to show the maximum response to pollutant stress, and when within-season variability is expected to be lower than at other times. The summer period (July–August) was selected as the index period for the Virginian Province. In most Northern Hemisphere estuaries, dissolved oxygen concentrations are lowest at this time (Holland *et al.*, 1977; US EPA 1984; Officer *et al.*, 1984). The cycling and adverse effects due to contaminants also are expected to be higher at this time (Connell and Miller, 1984; Sprague, 1985). In addition, the fauna and flora are more abundant in the summer, thereby increasing the likelihood of collecting the required organisms for biological assessments.

Statistical Sampling

Sampling sites in the large estuarine class were selected using a randomly placed systematic grid. The distance between the systematically-spaced sampling points on the grid was approximately 18 km. The grid is an extension of the systematic grid proposed for use by all EMAP resource groups (Overton, 1991). In the Virginian Province, the centrepoints of the grids are the sample sites. in the Louisianian Province, the sample points within each grid are randomly placed. In either case, the entire large estuarine resource will be sampled each year. For the Virginian Province Demonstration Project, 54 sample sites which could be sampled with the available boats (i.e., water depths greater than one metre) were identified in this class for 1990.

A linear analogue of the above design was used for site selection in the large tidal rivers. A systematic linear grid was used to define the spine of the five large tidal rivers in the Virginian Province, where the starting point of the spine was at the mouth of the river. The first transect was randomly located between river kilometre 0 and 25. Additional transects were then placed every 25 km up the river to the head of tide. A single sample site was placed across each transect resulting in 25 sample sites in the Virginian Province in 1990. Again, the entire large tidal river resource was sampled.

The 137 small estuarine systems were randomly sampled from the entire list of small systems in the province. They were ordered from north to south by combining adjacent estuaries into groups of four. One estuary was selected randomly from each group for the first year, yielding 32 sample sites for 1990. The location of the sample within each selected small system is also randomly placed. Subsequent random sampling from the unsampled estuaries remaining in each group of four will be conducted for each of the next three years. In this manner, the entire small estuarine resource will be sampled over the four year interval.

When fully implemented, EMAP-E will base its status assessments on data collected over a four year baseline. This multi-year cycle was chosen to dampen the year-to-year variability resulting from sporadic phenomena such as extremely dry or wet years and hurricanes.

EMAP-ESTUARIES INDICATORS

The EMAP Indicator Strategy

There are many parameters that could be measured in a monitoring program such as EMAP that are of interest to the informed public, Congress, decision makers, and scientists. Indicators that are selected should be directly linked to the ecological resource or the exposure of that resource to pollutant stress. In general, indicators should be quantifiable, easily interpreted, applicable across broad habitat and geographic ranges, relatively standardized, and of understandable value to society (Hunsaker and Carpenter, 1990).

EMAP indicators focus on the responses in biotic resources and the ability to associate those responses with well defined exposures. To accomplish this goal, EMAP has identified the following four types:

1. Response Indicators – measurements that quantify the integrated response of ecological components to individual or multiple stressors, e.g., population abundance, community composition.
2. Exposure Indicators – physical, chemical, or biological measurements that quantify pollutant exposure or other causes of degraded ecological condition, e.g., concentrations of dissolved oxygen versus sediment contaminants.
3. Habitat Indicators – physical, chemical, or biological parameters that yield basic information about the natural environmental setting, e.g., salinity, water depth, sediment characteristics. These indicators may be used to define sample subpopulations of interest and to normalize values for exposure and response indicators across environmental gradients.
4. Stressor Indicators – economic, social, or engineering measures that help to identify sources of pollution and causes of poor environmental conditions, e.g., land use patterns, demographics, and discharge records.

The relationships among these four indicator types are illustrated in Figure 3. The EMAP indicator approach seeks to identify linkages between biological and ecological responses, as measured by the response indicators, and specific exposures to environmental factors, as measured by the exposure and habitat indicators. In this case, emphasis is placed on estimating the effects of sediment contaminants and low dissolved oxygen on ecological condition. Ultimately, the stressor indicators will be used to define the source of the exposure conditions causing adverse biological or ecological effects.

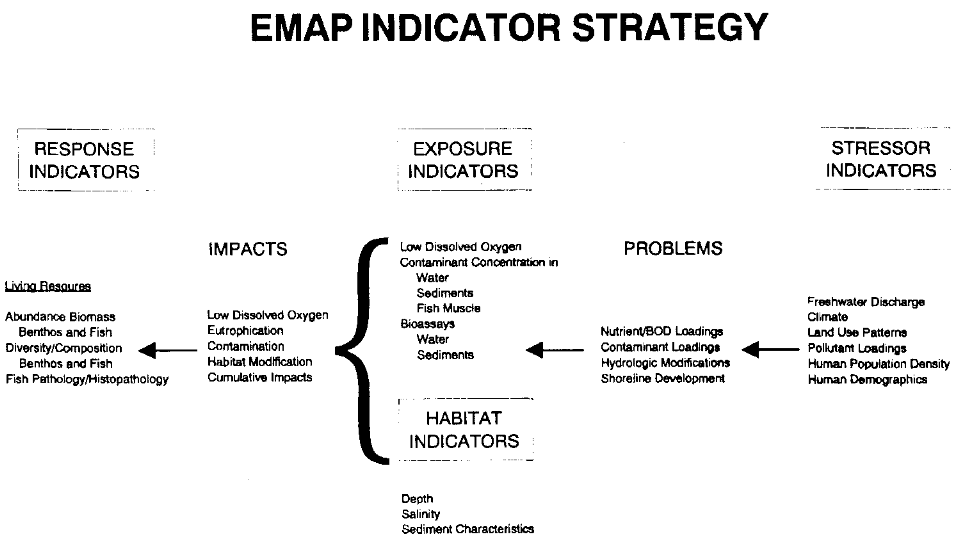

Figure 3 The EMAP indicator strategy and links among indicators.

The Framework for Indicator Selection

The selection of indicators in EMAP is an evolving process. It was recognized early on that a consistent rationale for indicator selection and development was necessary, and that the selection process needed to be flexible enough to incorporate new indicators as they became available and to modify existing measurement techniques as technologies improve. Since EMAP is envisaged as a long-term monitoring program that will span decadal time frames, a solid framework for indicator selection and continual evaluation is essential.

The selection process consists of six phases that lead from the identification of all possible candidate indicators to a well defined suite of core indicators for broad-scale implementation (Figure 4) (Knapp *et al.*, 1990). An indicator proceeds from one stage to the next based on a set of acceptance criteria that are generic to all EMAP resource groups. The stages in the selection process follow.

The first phase focuses on identifying assessment endpoints and anthropogenic stressors of concern, in essence, the two ends of a conceptual model linking sources (stressors) with receptors. Valued ecosystem attributes are defined as endpoints of concern or assessment endpoints. For EMAP-E, these endpoints were expressed as biotic integrity and human use. In the second phase, a conceptual model was used to identify all causal pathways by which stresses and ecosystem attributes were connected, thereby defining a list of candidate indicators. This process resulted in a list of over 150 potential indicators.

Whereas the first two phases of the selection process are designed to include all possible relevant indicators, the purpose of the next three phases is to systematically exclude indicators that do not meet specific criteria or cannot be fully evaluated. The

I. IDENTIFY ISSUES/ASSESSMENT ENDPOINTS

Approach: use conceptual models and management, technical and public opinion.

↓

II. IDENTIFY CANDIDATE INDICATORS

Goal: develop indicators linked to endpoints.
Approach: use conceptual models, existing literature and expert opinion.

↓

III. SELECT RESEARCH INDICATORS

Goal: prioritize candidate indicators.
Approach: use selection criteria, conceptual models, expert knowledge, and existing literature.

↓

IV. SELECT DEVELOPMENTAL INDICATORS

Goal: evaluate expected performance.
Approach: analyze existing data, conduct desktop simulations, pilot tests, and/or mock assessments.

↓

V. SELECT CORE INDICATORS

Goal: evaluate actual performance on regional scale.
Approach: conduct regional demonstration projects and/or regional statistical summarizes.

↓

VI. CONTINUAL EVALUATION OF INDICATOR SUITE

Goal: insertion of promising indicators into selection process.
Approach: conduct new vs. old indicator comparisons and calibrations, data analysis on responsiveness and precision.

Figure 4 A framework for indicator development and selection.

third stage of the selection process screens indicators according to the generic criteria given in Table 2, and by literature reviews and expert knowledge, in order to select a suite of research indicators for further evaluation. The key criterion for advancement to the research indicator category is responsiveness to specific stressors that have been demonstrated previously in the laboratory, or in the field along stress gradients. The ability to sample an indicator adequately during the index period must also be assessed at this point. A critical evaluation of the relationship to the assessment endpoints in a conceptual model, through literature review and expert opinion, continues in this stage.

Table 2 General indicator selection criteria.

Critical Criteria	
Regional Responsive	Must reflect changes in ecosystem condition and respond to stessors of concern across most resource classes and habitats within a region
Unambiguously Interpretable	Must be related unambiguously to an assessment endpoint or relevant exposure or habitat variable that forms part of the ecosystem group's overall conceptual model of ecological structure and function
Low Measurement Error	Exhibits low measurement error and stability of regional cumulative frequency distribution during index period (low temporal variation in regional statistics)
Simple Quantification	Can be quantified by synoptic monitoring or by cost effective automated monitoring
Low Year-to-Year Variation	Must have sufficiently low natural year-to-year variation to detect ecologically significant changes within a reasonable time frame
Desirable Criteria	
Sampling Unit Stable	Measurements of response indicator taken at a sampling unit (site) should be stable over the course of the index period (to conduct associations)
Available Method	Should have a generally accepted, standardized measurement method that can be applied on a regional scale
Historical Record	Has a historical data base, or a historical data base can be generated from accessible data sources
Retrospective	Can be related to past conditions via retrospective analyses
Anticipatory	Provides an early warning of widespread changes in ecosystem conditions or processes
Cost Effective	Has low incremental cost relative to its information
New Information	Provides new information; does not merely duplicate data already collected by cooperating agencies

On selection of the research indicators, the fourth phase involves a more stringent application of the selection criteria to assess spatial and temporal variability, data interpretability, and actual methods. Activities in this phase may include data analyses that would quantify responsiveness and variability using existing data, and actual pilot tests or applications of the indicators at a series of indicator testing and evaluation sites. This testing was accomplished in the Virginian Province in 1990, and in the Lousianian Province in 1990 and 1991. This process results in the identification of developmental indicators. These indicators are then evaluated in the fifth stage as to their appropriateness as core indicators.

The identification of core indicators requires a demonstration that the indicators are insensitive to natural environmental gradients at the EMAP regional scale, are responsive to stress, and are linked in the response – exposure – stressor hierarchy. Regional demonstration projects have been conducted in both the Virginian and

Louisianian Provinces. This step involves a series of considerations that include sampling and processing costs, logistic feasibility, and analysis of variability. Based on the results of these demonstration projects, a set of core indicators are then selected and implemented at the full spatial (regional) and temporal (four year cycle) scales.

In the sixth, and final, phase of the selection process, the core indicators are regularly evaluated for their utility in the process of status and trends assessment, while new indicators are continually considered for evaluation at any of the steps in the selection process. Further, most of the EMAP-E candidate indicators were not rejected outright, but were put into a state of "suspension" because there was either a technological limitation or a lack of data on responsiveness. As these conditions improve, these indicators will be brought into the research and developmental phases as potential replacements or improvements to core indicators. An example might be the application of remote sensing techniques for measuring certain properties of estuarine waters. These indicator technologies are currently suspended, but will be further investigated in the future.

The EMAP-E Indicator Suite

The response, exposure, habitat, and stressor indicators that were tested in the 1990 Virginian Province Demonstration Project are listed in Table 3. As noted previously, EMAP-E focuses on the response indicators which, in this case, primarily involve both the benthos and fish. These two indicator groups are directly linked to the endpoint of biotic integrity which was the primary focus of the initial EMAP-E sampling.

Table 3 EMAP-Estuaries indicators by major category.

Category	*Indicator*
Response	Benthic Species composition and biomass
	Fish community composition
	Gross pathology of fish
	Histopathology of fish
	Large indigenous bivalves
Exposure	Sediment contaminant concentration
	Sediment toxicity
	Contaminants in fish flesh
	Continuous/point measurements of dissolved oxygen
Habitat	Salinity
	Temperature
	Sediment characteristics
	Water depth
Stressor	Fresh water discharge
	Climatic fluctuations
	Pollutant loadings
	Land use patterns
	Human population density
	Fishery landing statistics

It is well established that benthic communities play an important role in estuarine ecosystems, and that they are responsive to the kinds of stressors EMAP-E is interested in (Rhoads *et al.*, 1978; Pearson and Rosenberg, 1978; Sanders *et al.*, 1980; Boesch and Rosenberg, 1981; Holland *et al.*, 1987). Benthic community studies have a history of use in regional monitoring programs and the resulting data have been shown to be effective indicators of the extent and magnitude of pollution impacts.

The response of fish communities to stress is less well understood, but most fish ecologists agree that the fish assemblage at a site is controlled by water and sediment quality parameters as well as habitat conditions (Weinstein *et al.*, 1980). However, the degree to which fish community parameters can be used to assess status and trends at regional scales is unknown. This issue will be evaluated during the first several years of the monitoring.

The incidence of gross pathologies in fish is a major means by which the public judges the quality of a water body. The interpretation of pathological disorders is scientifically based; severely polluted areas have a higher incidence of gross pathologies than similar, less polluted habitats (Sinderman, 1979; O'Connor *et al.*, 1987; Buhler and Williams, 1988; Malins *et al.*, 1984, 1988).

Exposure indicators are used to help explain changes observed in the response indicators. Metals and organic chemicals from freshwater inflows and non-point sources are known to concentrate in estuaries and to accumulate in bottom sediments (Turekian, 1977; Forstner and Wittman, 1981; Schubel and Carter, 1984; Nixon *et al.*, 1986). These bottom sediments are often contaminated to the point that they represent a threat to human and ecological health (Weaver, 1984; OTA, 1987; NRC, 1989). While the extent and magnitude of sediment contamination is only now becoming well described (NRC, 1989), it is recognized as an extremely important exposure indicator. Whereas contaminant concentrations indicate the potential for contaminant effects, sediment toxicity tests are a more direct measure of contaminant bioavailability. The commonly used amphipod sediment toxicity test is well established and has been employed in a variety of monitoring and testing programs (Swartz, 1987, 1989; Chapman, 1988; Scott and Redmond, 1989; Scott *et al.* 1990), and benthic assessments.

As an exposure indicator, dissolved oxygen concentration is of overwhelming importance to the biotic integrity assessment endpoint. Low dissolved oxygen is one of the more important factors contributing to fish and shellfish mortality in estuarine and coastal waters. Prolonged exposure to waters at less than 60% saturation can result in altered behaviour, reduced growth, adverse reproductive effects and mortality (Reish and Barnard, 1960; Vernberg, 1972). Low dissolved oxygen also has been shown to be caused by phytoplankton blooms resulting from excessive nutrient input. Important as this indicator is to EMAP-E, its measurement presents special problems because of the wide diurnal and tidal fluctuations in estuaries in concentrations that occur naturally. To address this problem, continuous and point sampling techniques currently are being evaluated.

The habitat indicators provide important information about the environmental setting that may modify exposure and effect relationships. Salinity and temperature are among the most dominant factors controlling the distribution of flora and fauna and the functioning of ecological processes in estuaries (Remane and Schlieper, 1971). Sediment grain size is an important factor regulating benthic community composition, and organic carbon affects the bioavailability of contaminants. Water depth itself can influence the temperature regime, salinity distribution, and dissolved oxygen concentration. These habitat variables are important for normalizing the responses of the exposure and response indicators, and to define subpopulations (e.g., fine versus coarse-grained sediment, low versus high salinity) for further analysis.

Representative stressor indicators are shown in Table 3. While these data are not collected concurrently with the response, exposure and habitat indicators, they are available from many other federal, state and regional agencies. Much of this information will be collated and provided to EMAP-E by NOAA during the assessment process.

While indicators related to the assessment endpoint of biotic integrity were emphasized in the initial EMAP-E sampling, some indicators of the human use endpoint also were considered. One of these is the concentration of chemical contaminants in fish flesh. This indicator is extremely relevant to public perception as to whether the fish are safe to eat. The actual measurement of contaminant concentrations is well established but, in order for it to be applied at the regional scale, demonstration projects were used to determine that certain kinds of fish could be collected at enough sites, and in sufficient abundance, for tissue analyses. Two other indicators related to human perception and usage are water clarity and the presence of anthropogenic debris. These indicators also were tested in regional demonstration projects in 1990 and 1991.

VIRGINIAN PROVINCE DEMONSTRATION PROJECT

Objectives

EMAP-E was initiated as a regional-scale demonstration project in the estuaries of the Virginian Province in 1990 because the available scientific information was not adequate to develop a cost-effective and scientifically defensible program for full-scale implementation. The goals of the 1990 program were to:

1. demonstrate the value of regional monitoring data by measuring a defined set of parameters, with a robust sampling design as a basis for status assessments;
2. identify, test, and evaluate indicators of environmental quality that can be applied over broad regions;
3. develop and apply standard sampling and sample processing methods;
4. evaluate alternative sampling designs and approaches for establishing a regional and national monitoring network;
5. develop analysis procedures for converting monitoring data into useful information for the public, decision makers, Congress, and the scientific community; and
6. identify and resolve logistical problems associated with large scale sampling during a restrictive index period.

The Virginian Province was chosen for the first demonstration project because of the large public concern for estuaries in this region and because of the fact that the major estuaries in this region already had established formal programs examining estuarine health. Additionally, many of the proposed indicators had already been tested and validated for broad regions of the province.

Design Enhancements

To accomplish the above objectives, the sampling design described previously for several large estuaries, large tidal rivers, and small estuaries was enhanced by several additions to the base sampling effort. These included: indicator testing and evaluation sites, supplemental sampling sites, index sites, and extended temporal sampling.

Some of the randomly selected base sites, and some additional judgemental sites, were designated as indicator testing and evaluation (ITE) sites. On the basis of existing information, these stations were characterized as polluted or unpolluted with respect to contaminants and dissolved oxygen, and they were intended to provide a means to determine the responsiveness of the proposed indicators. Equal numbers of ITE stations were selected from the northern and southern halves of the province, and across each of three salinity zones. After the sampling was completed, the exposure conditions of these stations were re-evaluated. Some stations were rejected because of misclassification and some additional sites were added to the indicator testing group, to arrive at a total of 34 ITE sites.

The supplemental sampling sites were established to ascertain if the spatial scale employed in this design is adequate to represent the ecological condition of estuarine systems in the Virginian Province. To this end, the Delaware Bay and River systems were sampled at a density equal to four times that of the base design. This spatially-intensive data set is being evaluated to determine the benefits of an enhanced grid for ecological assessments.

Index samples were collected at locations in small estuaries and large tidal rivers in conjunction with the random sampling at each base station. These index sites were determined by scientific judgement to represent depositional environments where sediments accumulate, and where the potential for exposure to contaminants and/or low dissolved oxygen was high. The purpose of these fixed location samples was to determine if the randomly placed base stations adequately characterize the ecological condition of these two classes.

Extensive temporal sampling was conducted to help define the temporal duration of the sampling (index) period. Three sampling intervals were employed between 19 June and 30 September 1990, each consisting of approximately 45 days. Based on the dissolved oxygen and benthic community data collected in each of these three intervals, the middle interval was selected as the index period for all subsequent assessments. Continuously recording dissolved oxygen meters were placed at 30 sites for the entire sampling period. These sites were expected to exhibit the greatest variability in dissolved oxygen concentration. Additionally, these sites were sampled in each period for benthic community composition and biomass, and fish abundance and species composition.

Lessons Learned

The results of the 1990 Virginian Province will be available early in 1992. While it is premature to present the information that will be contained in that report, some general conclusions related to the original project objectives can be drawn. They are as follows:

1. The use of small, trailerable boats and three, four-person field crews is feasible for the collection of the required samples within a typical index period of 45 to 60 days. It is thus logistically possible to execute the type of sampling required by EMAP-E.
2. The continuous records of dissolved oxygen indicated that the optimal period for measuring hypoxic stress in the Virginian Province is from mid-July to early September. Benthic community parameters did not vary significantly over the three sampling intervals.

3. There were no signficant differences between base and index samples for primary indicators in the large tidal rivers and small estuaries. These data indicate that the randomly placed stations could provide the same information as biased, judgemental sites, and thus are the preferred sampling option because of the greater statistical power associated with probabilistic sampling;
4. The approach to assessments appears to be reasonable in that changes in response indicators can be associated with changes in the exposure variables of sediment contamination, toxicity, and dissolved oxygen;
5. The indicator data from the original indicator testing and evaluation sites, and the *a posteriori* additions, showed that most of the proposed indicators were responsive to environmental stress, and that these indicators could be utilized over broad geographical ranges. Several indicators were rejected because they were inappropriate to the regional-scale sampling (water column toxicity testing) or logistical difficulties were encountered in sampling (presence of large indigenous bivalves).

Based on the Demonstration Project results, modifications to the indicators and design were incorporated into the 1991 sampling plan. For example, analysis of the continuous dissolved oxygen records indicated that the index period could start as late as mid-July and proceed until mid-September. This analysis also showed that a two- to three-day deployment of continuously recording meters would capture a significant amount of the variation in dissolved oxygen concentration. These deployments were conducted at each base station in 1991.

DATA ANALYSIS AND ASSESSMENT

The success of any monitoring program depends on the degree to which the data collected are used to answer the questions for which the program was designed (Wolfe *et al.*, 1987; NRC, 1990). EMAP is designed to assess the condition of ecological resources, to measure trends in that condition, and to identify the likely causes of changes in that condition at regional scales. However, the sampling design also allows questions to be answered for major classes of estuaries (i.e., large estuaries, large tidal rivers, and small estuarine systems) and selected subpopulations of interest (e.g., salinity and sediment strata, and certain large estuarine systems like the Chesapeake Bay). The design cannot address questions that are specific to a particular sampling site or identify quantitative cause and effect relationships.

Cumulative Distribution Functions

The principal means by which EMAP-E will present information graphically to technical audiences is through the use of cumulative distribution functions (CDFs). This format was chosen because CDFs present information on both central tendency, range, and extreme values in one easily interpreted graphical format (Overton, 1991). Figure 5 presents an example of the type of CDF EMAP-E will use to display the proportional area of estuarine waters exhibiting certain indicator or index values.

Cumulative distribution functions will be constructed initially for response indicators for each estuary class (i.e., large estuaries, large tidal rivers, small estuarine systems). Inclusion probabilities are used to weight the contribution of each station

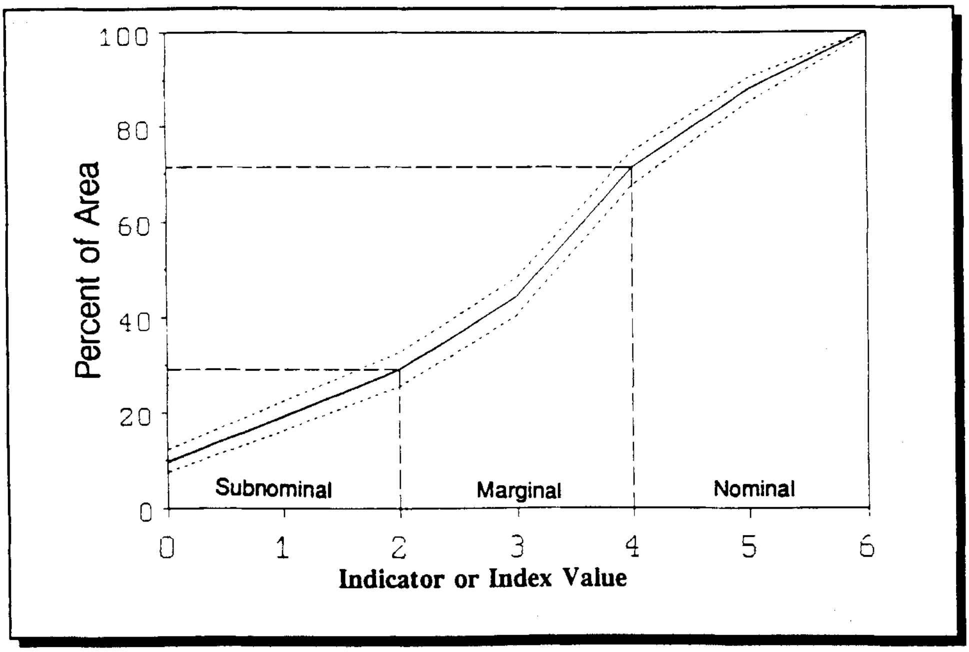

Figure 5 An example of cumulative distribution function. The dotted lines are the 90% confidence limits.

based on the spatial area represented by each station. For example, a "small" estuarine system has a lower inclusion probability than a "larger" small estuarine system, and a narrow tidal river segment (25 km long) has a smaller inclusion probability than a wide river segment. Thus, indicator values in larger systems are weighted more heavily than are those in smaller systems. All stations within the large estuaries are of equal weight since each station represents the area of one grid cell. The spatially weighted approach provides for a sensible, straightforward interpretation of the distribution of indicator values in estuarine systems in proportion to the abundance of the resource type.

Definition of Nominal and Subnominal Boundaries

The data analyses and assessments of estuarine condition have little value unless some scientific judgement can be used to establish which conditions are acceptable and which are unacceptable. EMAP uses the terms "nominal" to refer to response and exposure indicator values that are acceptable or desirable and "subnominal" for those that are unacceptable or undesirable. Values that cannot be categorized because of ambiguity or statistical uncertainty are referred to as "marginal".

There currently are few generally accepted limits delineating subnominal conditions for most indicators. Federal and state regulatory programmes provide some guidance relative to certain exposure indicators such as fish tissue contaminants, sediment contaminants, dissolved oxygen and sediment toxicity. The nominal and subnominal boundaries for the benthic and fish indicator values are being assessed as part of the indicator testing program. Association analyses for response and exposure indicators are also being used to establish these boundaries. However they are established, or however controversial the nominal and subnominal boundaries become, the basic data presentation, in the form of the CDF, allows for the visual estimation of the proportion of the resource above or below any indicator value.

Environmental Indices

While individual response indicators are important measures of specific aspects of environmental condition, the goal of EMAP-E is to provide answers to questions with a more holistic perspective of estuarine systems. Single, integrated statements, or indices, about the overall status of estuarine systems are more easily communicated and understood, and they are valuable for measuring progress towards goals. It is important, then, to integrate the data from multiple response indicators into an integrated assessment of the status of estuarine resources.

Some of the elements of a hypothetical "Estuarine Condition Index" are presented in Figure 6 (Holland, 1990). The essential features of any index selected are: it is based on multiple independent indices that reflect the two assessment endpoints of biotic integrity and human use; all indices are aggregates of information on indicators collected by the field program; and the relative contribution of each indicator to the overall index can be determined.

The mathematical procedures (i.e., weighting schemes) for combining indicators and indices are yet to be developed. The major source of information for the development of these indices will come from the first few years of data from the Virginian and Louisianian Provinces.

Associations

A decompositional approach will be used to determine which indices and indicators are associated with any particular status of condition as defined by an estuarine condition index. For example, a subnominal estimate of biotic integrity for an estuarine class can be examined, on a case by case basis, to determine the relative contribution of subnominal benthic conditions, fish conditions or a combination of both. Causal associations between each of these indices can be further decomposed into the relative contribution to degraded conditions due to contaminants or low dissolved oxygen, a combination of the two, or some other cause. This approach is illustrated in Figure 7. Ultimately, the final level of association will link exposure indicators to stressor indicators, e.g., contaminant concentrations to point versus non-point source discharges.

In addition to the associations generated at the province, class, and large system levels, index:response indicator:exposure indicator relationships can be developed for subpopulations of interest. For example, low salinity zones may experience certain types of problems and/or be controlled by different ecological processes than high salinity zones. The only limiting factor in the ability to conduct analyses of this type is sample size, which for most analyses should at a minimum consist of 25–30 members.

Status and Trends Assessments

Status assessments of ecological condition will be made using indices of biotic integrity and human use for the entire estuarine resource, each estuarine class, and

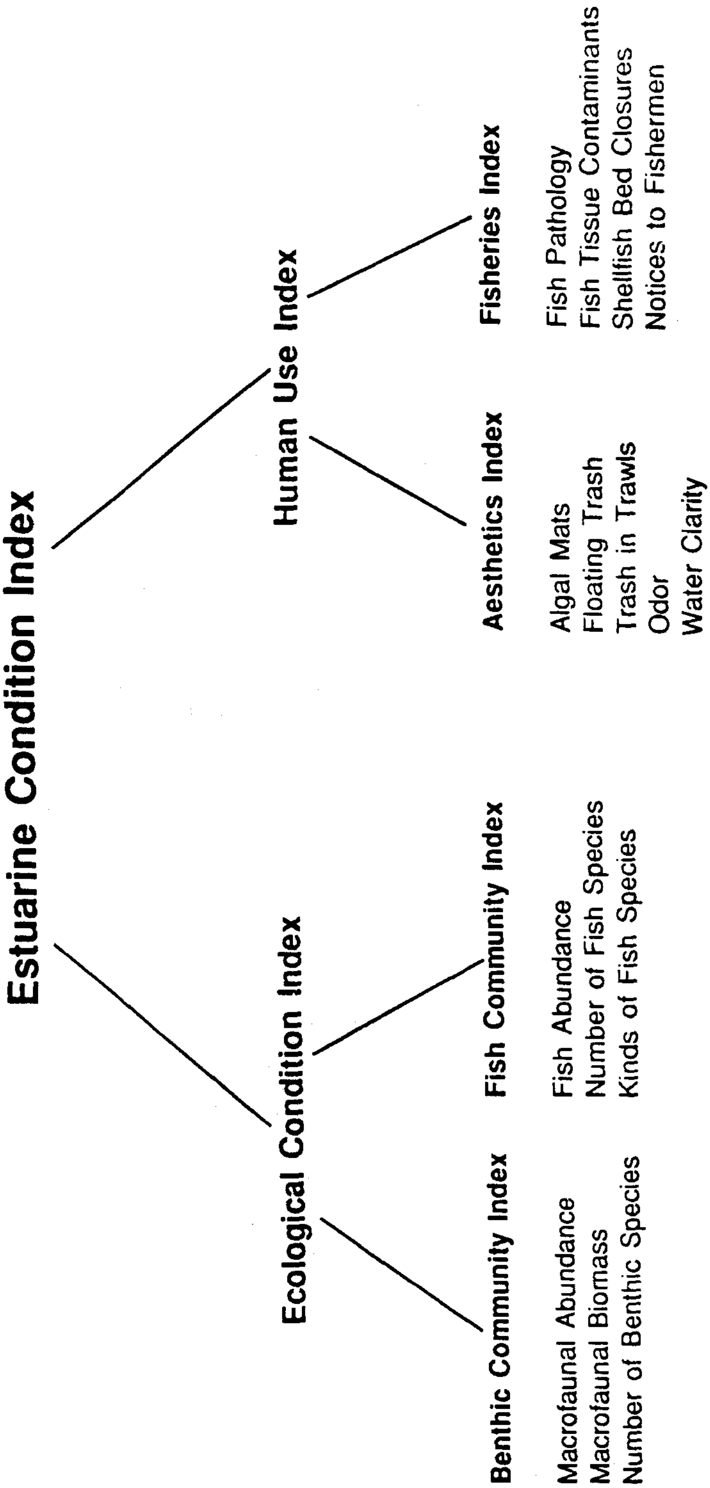

Figure 6 The components of a hypothetical Estuarine Condition Index.

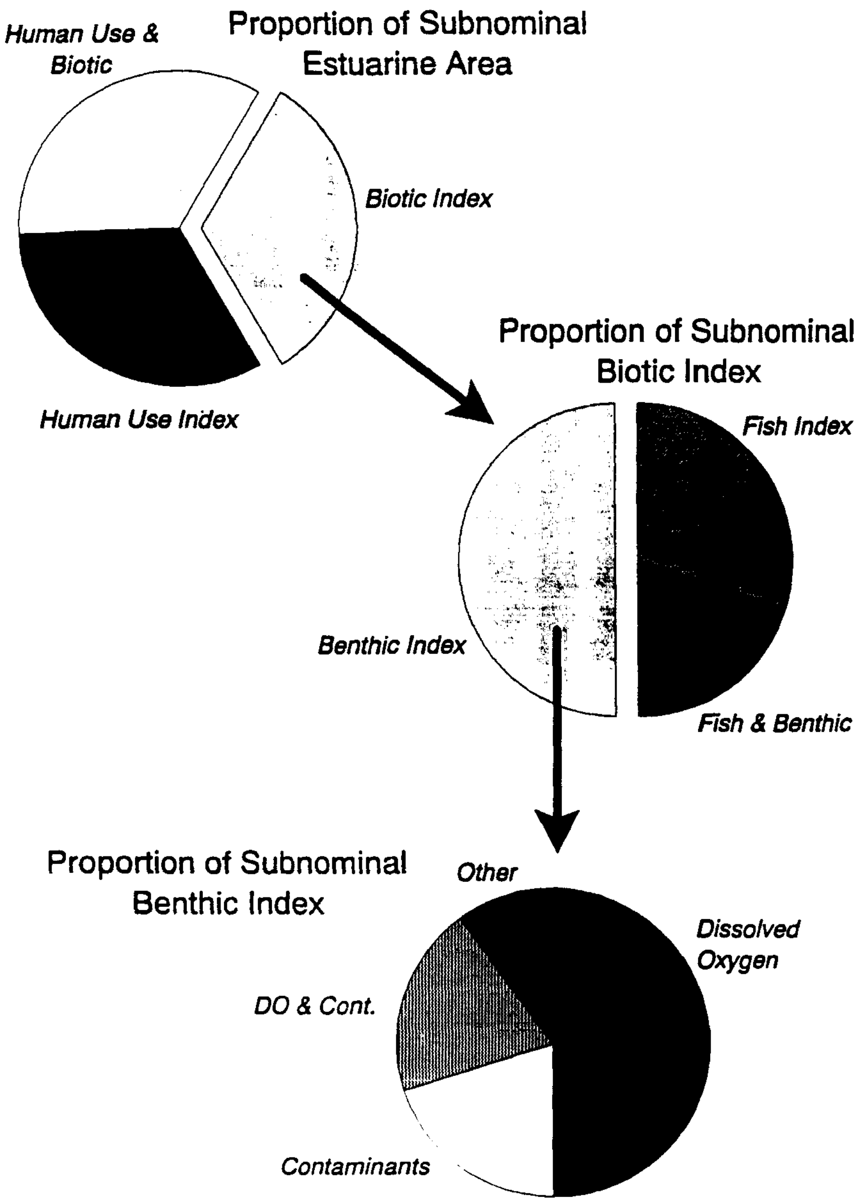

Figure 7 An example presentation of the decompositional approach to assigning causality.

certain large estuarine systems (e.g., Chesapeake Bay, Long Island Sound). A condition index for each assessment can be expressed as the proportion of the area within a province, class or system that is nominal, subnominal, or marginal. The subnominal component is further decomposed into the proportions of area that are subnominal because of unacceptable biotic integrity conditions, human use conditions, or a combination of both.

When EMAP is fully implemented, status assessments will be made using data collected over a four year period. The use of four years of data to describe status reduces the variance associated with climatological (e.g., hurricanes) or other unpredictable events (e.g., oil spills) that may strongly affect a particular estuary in any one year. Trends assessments will be made by comparing pooled data from successive four year intervals.

PROGRAM STATUS

The field sampling for demonstration projects was completed in the Virginian Province in summer 1990 and in the Louisianian Province in summer 1991. The assessment report for the former is in preparation and expected to be available in early 1992. Implementation of EMAP-E in the Carolinian Province is planned in 1993.

Joint activities with NOAA's National Ocean Service are continuing through an EPA/NOAA Joint Committee for Coastal and Marine Environmental Quality Monitoring. Some of the cooperating activities of this committee are: planning for the Carolinian Province sampling; development of a database on stressor indicators and sediment characteristics for the Virginian Province; and evaluation of the status of contaminated toxic sediments in the Virginian Province.

ACKNOWLEDGEMENTS

Some of the many individuals who contributed to the EMAP-Near Coastal effort include: Steven Schimmel, EPA, field manager; Richard Latimer, EPA, acting technical director; Rick Linthurst, EPA; Charles Strobel, SAIC, field coordinator; Raymond Valente, SAIC, quality assurance coordinator; Jeffery Rosen, CSC, information systems manager; and Jeffrey Frithsen, Versar, Inc. Although the research described in this article has been funded wholly by EPA, it has not been subject to EPA review, and therefore does not reflect the views of the Agency, and no official endorsement should be inferred. Support for the preparation of this manuscript was provided by EPA Contract #68-C1-0005 to SAIC, Patricia Gant, Project Officer. This is ERL-Narragansett Contr. # 1374.

References

Bailey, R. G. (1983). Delineation of ecosystem regions. *Environmental Management* **7**: 365–373.

Beasley, B. and R. Biggs (1987) Near coastal water segmentation. Report by the College of Marine Studies, University of Delaware. Lewes, DE.

Biggs, R. B. and Howell, B. A. (1984) The estuary as a sediment trap: Alternate approaches to estimating its filtering efficiency. pp. 107–129, *In:* V.S. Kennedy [ed.] *The Estuary as a Filter,* Academic Press, New York.

Boesch, D. F. and Rosenberg, R. (1981) Response to stress in marine benthic communities. pp. 179–200, *In* G.W. Barret and R. Rosenberg [eds.] *Stress Effects on Natural Ecosystems,* John Wiley and Sons, New York.

Broutman, M. A. and Leonard, D. L. (1988) National estuarine inventory: The quality of shellfish growing waters in the Gulf of Mexico. NOAA, Rockville, MD, 43 pp.

Buhler, D. R. and Williams, D. E. (1988) The role of biotransformation in toxicity. *Canadian Journal of Fisheries and Aquatic Sciences* **11:** 303–311.

Capuzzo, J. M., Moore, M. N. and Widdows, J. (1988) Effects of toxic chemicals in the marine environment: Predictions of impacts from laboratory studies. *Aquatic Toxicology* **11:** 19–28.

Chapman, P. M. (1988) Marine sediment toxicity tests. pp. 391–402 *in* J. J. Lichtenberg, F. A. Winter, C. I. Weber and L. Fredkin [eds.] *Chemical and Biological Characterization of Sludges, Sediments, Dredge Spoils, and Drilling Muds.* American Society of Testing and Materials STP 976, Philadelphia, PA.

Connell, D. W. and Miller, G. J. (1984) *Chemistry and Ecotoxicology of Pollution.* John Wiley and Sons, New York.

Costanza, R., Sklar, F. H. and White, M. L. (1990) Modeling coastal landscape dynamics. *Bioscience* **40:** 91–107.

Donovan, M. L. and Tolson, J. P. (1987) *Land Use and the Nation's Estuaries.* National Oceanic and Atmospheric Administration, Rockville, MD.

Food and Drug Administration (1971) *National shellfish register of classified estuarine waters.* Shellfish Sanitation Branch, Northeast Technical Services Unit, Davisville, RI, 19 pp.

Food and Drug Administration (1985) *National shellfish register of classified estuarine waters.* Shellfish Sanitation Branch with National Oceanic and Atmospheric Administration, Strategic Assessment Branch and the National Marine Fisheries Service, Rockville, MD, 19 pp.

Forstner, U. and Wittmann, G. T. W. (1981) *Metal Pollution in the Aquatic Environment,* 2nd revised edition. Springer-Verlag, New York. 486 pp.

Gunter, G. (1987) Some relationships of estuaries to the fisheries of the Gulf of Mexico. pp. 621–638 in G.H. Lauff [ed.] *Estuaries,* American Association for the Advancement of Science, Pub. No. 83, Washington, DC.

Hargis, W. D., Jr. and Haven, D. S. (1988) Rehabilitation of the troubled oyster industry of the lower Chesapeake Bay. *Journal of Shellfish Research* **7:** 271–279.

Holland, A. F. (1990) Near Coastal Program Plan for 1990: Estuaries. EPA 600/4-90-003. US Environmental Protection Agency, Environmental Research Laboratory, Office of Research and Development, Narragansett, RI.

Holland, A. F., Mountford, N. K. and Mihursky, J. A. (1977) Temporal variation in upper bay mesohaline benthic communities: I. The 9-m mud habitat. *Chesapeake Science* **18:** 370–378.

Holland, A. F., Shaughnessey, A. and Hiegel, M. H. (1987) Long-term variation in mesohaline Chesapeake Bay macrobenthos: Spatial and temporal patterns. *Estuaries* **10:** 277–245.

Hunsaker, C. T. and Carpenter, D. E. (1990) Environmental Monitoring and Assessment Program: Ecological Indicators. EPA 600/3-90-060, US Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC.

Knapp, C. M., Marmorek, D. R., Baker, J. P., Thornton, K. W., Klopatek, J. M. and Charles, D. F. (1991) The indicator development strategy for the Environmental Monitoring and Assessment Program. US E.P.A. Office of Research and Development, EPA 600/3-91/023, Washington, DC.

Leonard, D. L., Broutman, M. A. and Harkness, K. E. (1989) *National estuarine inventory: The quality of shellfish growing areas on the east coast of the United States.* National Oceanic and Atmospheric Administration, Rockville, MD, 54 pp.

Lippson, A. J., Haire, M. S., Holland, A. F., Jacobs, F., Jensen, J., Moran-Johnson, R. L., Polgar, T. T. and Richkus, W. R. (1979) *Environmental Atlas of the Potomac Estuary.* Prepared for Maryland Department of Natural Resources, Power Plant Siting Program by Martin Marietta Corporation, Baltimore, MD.

Malins, D. C., McCain, B. B., Brown, D. W., Chan, S. L., Myers, M. S., Landahl, J. T., Prohaska, P. G., Friedmand, A. J., Rhodes, L. D., Burrows, D. G., Gronlund, W. D. and Hodgins, H. O. (1984) Chemical pollutants in sediments and diseases in bottom-dwelling fish in Puget Sound, Washington. *Environmental Science and Technology* **18:** 705–713.

Malins, D. C., McCain, B. B., Landahl, J. T. Landahl, Myers, M. S., Krahn, M. M., Brown, D. W., Chan, S. L. and Roubal, W. T. (1988) Neoplastic and other diseases in fish in relation to toxic chemicals: An overview. pp. 43–47 in D. C. Malins and Jensen, A. [eds.] *Aquatic Toxicology, Toxic Chemicals, and Aquatic Life: Research and Management,* Elsevier Science, Amsterdam.

Morganthau, T. (1988) Don't go near the water: Is it too late to save our dying coasts? *Newsweek* August 1, 42–47.

National Research Council (1989) *Contaminated Marine Sediments – Assessment and Remediation.* National Academy Press, Washington DC. 508 pp.

National Research Council (1990) *Managing Troubled Waters: The Role of Marine Environmental Monitoring.* National Academy Press, Washington DC. 125 pp.

Nixon, S. W., Hunt, C. D., Nowicki, B. L. (1986) The retention of nutrients (C, N, P), heavy metals (Mn, Cd, Pb, Cu), and petroleum hydrocarbons in Narragansett Bay. pp. 99–122 in P. Lasserre and J. M. Martin [eds.] *Biogeochemical Processes at the Land-sea Boundary,* Elsevier, New York.

O'Connor, J. S., Ziskowski, J. J. and Murchelano, R. A., (1987) *Index of pollutant induced fish and shellfish disease.* National Oceanic and Atmospheric Administration, Special Report, NOS, Rockville, MD. 29 pp.

Office of Technology Assessment (OTA) (1987) *Wastes in Marine Environments.* Washington, DC. OTA-O-334, 312 pp.

Officer, C. B., Biggs, R. B., Taft, J. L., Cronin, L. E., Tyler, M. A. and Boynton, W. R. (1984) Chesapeake Bay anoxia: Origin, development, and significance. *Science* **223:** 22–27.

Overton, W. S., White, D. and Stevens, D. L. (1991) Design report of the Environmental Monitoring and Assessment Program. U.S. Environmental Protection Agency Environmental Research Laboratory, Corvallis, OR, EPA/600/3-91/053.

Parker, C. A. and O'Reilly, J. E. (1991) Oxygen depletion in Long Island Sound: a historical perspective. *Estuaries* **14:** 76–120.

Pearl, H. W. (1988) Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnology and Oceanography* **33:** 823–847.

Pearson, T. H. and Rosenberg, R. (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology Annual Review* **16:** 229–311.

Rabalais, N. N., Dagg, M. J. and Boesch, D. F. (1985) Nationwide review of oxygen depletion and eutrophication in estuarine and coastal waters: Gulf of Mexico. Louisiana Universities Marine Consortium, Data Report.

Reish, D. J. and Barnard, J. L. (1960) Field toxicity tests in marine water utilizing the polychaetous annelid *Capitella capitata* (Fabricius). *Pacific Naturalist* **1:** 1–8.

Remane, A. and Schlieper, C. (1971) *Biology of Brackish Water.* John Wiley and Sons, New York. 372 pp.

Rhoads, D. C., McCall, P. L. and Yingst, J. Y. (1978) Disturbance and production on the estuarine sea floor. *American Scientist* **66:** 577–586.

Sanders, H. L., Grassle, J. F. and Hampson, G. R. (1965) Salinity and faunal distribution in the Pocasset River, Massachusetts. *Limnology and Oceanography* **10:** 216–229.

Sanders, H. L., Grassle, J. F., Hampson, G. R., Morse, L. S., Garner-Price, S. and Jones, C. C. (1980) Anatomy of an oil spill: Long-term effects from the grounding of the barge *Florida* off West Falmouth, Massachusetts. *Journal of Marine Research* **38:** 265–380.

Schubel, J. R. and Carter, H. H. (1984) The estuary as a filter for fine-grained suspended sediment. pp. 81–104 in V. S. Kennedy [ed.] *The Estuary as a Filter,* Academic Press, Orlando, FL.

Scott, K. J. and Redmond, M. S. (1989) The effects of a contaminated dredged material on laboratory populations of the tubicolous amphipod, *Ampelisca abdita.* pp. 289–303. in U.M. Cowgill and L.R. Williams [eds.] *Aquatic Toxicology and Hazard Assessment: 12th Volume.* ASTM STP 1027. Philadelphia, Pennsylvania.

Scott, J., Berry, W., Cobb, D., Keith, D., Tracey, G. and Rubinstein, N. (1990) The application of the amphipod ten-day sediment toxicity test for dredged material evaluations. Tech. Rept. submitted to US EPA Region II, New York, NY, ERL-Narragansett Contr. No. 1181. 33 pp.

Science Advisory Board (1988) *Future risk: Research strategies for the 1990s.* The report of the Research Strategies Committee. Science Advisory Board. Washington, DC.

Sinderman, C. J. (1979) Pollution-associated diseases and abnormalities of fish and shellfish: A review. *Fishery Bulletin* **76:** 717–741.

Smart, T., Smith, E., Vogel, T., Brown, C., and Wolman, K. (1987) Troubled Water. *Business Week,* October 12, pp. 88–104.

Sprague, J. B. (1985) Factors that modify toxicity, pp. 124–163 in G.M. Rand and S.R. Petrocelli [eds.] *Fundamentals of Aquatic Toxicology,* Hemisphere Publication Co., New York.

Swartz, R. C. (1987) Toxicological methods for determining the effects of contaminated sediment on marine organisms. pp. 183–198 in K.L. Dickson, A.W. Maki and W.A. Brungs [eds.] *Fate and Effects of Sediment Bound Chemicals in Aquatic Systems,* Pergamon Press, New York.

Swartz, R. C. (1989) Marine and sediment toxicity tests. pp. 115–129 in *Contaminated Sediments – Assessment and Remediation.* National Academy Press, Washington, DC.

Tagatz, M. E. (1968) Biology of the blue crab, *Callinectes sapidus* (Rathbun) in the St. Johns River, Florida. *Fishery Bulletin* **67:** 17–33.

Terrell, T. T. (1979) Physical regionalization of coastal ecosystems of the United States and its territories. Office of Biological Service, U.S. Fish and Wildlife Service, FWS/OBS-79/80.

Toufexis, A. (1988) Our filthy seas: The world's oceans face a growing threat from manmade pollution. *Time,* August 1.

Turekian, K. K. (1977) The fate of metals in the oceans. *Geochimica et Cosmochimica Acta* **41:** 1139–1144.

US Environmental Protection Agency (1983) *Technical support manual: Waterbody surveys and assessments for conducting use attainability analyses. Vol. II: Estuarine systems.* Office of Water and Standards.

US Environmental Protection Agency (1984) *Chesapeake Bay: A framework for action.* Prepared for the U.S. Congress by the Environmental Protection Agency, Region 3, Philadelphia, PA.

Vernberg, F. S. (1972) Dissolved gases. pp. 1491–1526 in O. Kinne [ed.] *Marine Ecology, Vol. I, Part 3,* Wiley-Interscience, New York.

Weaver, G. (1984) PCB contamination in and around New Bedford, Mass. *Environmental Science and Technology* **18:** 22A-27A.

Weinstein, M. P., Weiss, S. E. and Walters, M. F. (1980) Multiple determinants of community structure in shallow marsh habitats, Cape Fear River estuary, North Carolina, USA. *Marine Biology* **48:** 227–243.

Whitledge, T. E. (1985) Nationwide review of oxygen depletion and eutrophication in estuarine and coastal waters: Northeastern Region. Brookhaven National Laboratory, Upton, NY. 730 pp.

Wolfe, D. A., Champ, M. A., Flemer, D. A. and Mearns, A. J. (1987) Long-term biological data sets: Their role in research, monitoring, and management of estuarine and coastal marine systems. *Estuaries* **10:** 181–193.