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STUDIES IN GEOPHYSICS *SE*

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on Estuaries:
The Importance of an
Interdisciplinary Approach

5 Panel on Estuarine Research Perspectives

**4* Geophysics Study Committee

3 Geophysics Research Board

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and Resources

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FUNDAMENTAL RESEARCH ON ESTUARIES: THE IMPORTANCE OF AN INTERDISCIPLINARY APPROACH

Charles B. Officer and L. Eugene Cronin, *panel cochairmen*, 1983, 79 pp.

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PREFACE

In 1974 the Geophysics Research Board completed a plan, subsequently approved by the Committee on Science and Public Policy of the National Academy of Sciences, for a series of studies to be carried out on various subjects related to geophysics. The Geophysics Study Committee was established to provide guidance in the conduct of the studies.

One purpose of the studies is to provide assessments from the scientific community to aid policymakers in decisions on societal problems that involve geophysics. An important part of such an assessment is an evaluation of the adequacy of present geophysical knowledge and the appropriateness of present research programs to provide information required for those decisions.

This study was motivated by the recommendation in a previous report (*Estuaries, Geophysics, and the Environment*, 1977) in the Studies in Geophysics series that "an overall review of the national efforts in estuarine research should be conducted." This study examines the need for basic research to understand estuarine processes. The major unanswered questions relate to the interrelationships of estuarine circulation, biota, geology, and chemistry, where an interdisciplinary coordinated effort will be necessary.

The Panel met and agreed that the basic research problems to be assessed are those estuarine processes that require an interdisciplinary solution and that the questions should be tractable within the next ten years. The Panel selected four broad areas of research and established subpanels, which included active participation of additional experts from the scientific community, to address each of the areas. The areas were organized around a traditional disciplinary facet of estuaries but focused on the interdisciplinary needs.

**FUNDAMENTAL RESEARCH ON ESTUARIES:
THE IMPORTANCE OF AN
INTERDISCIPLINARY APPROACH**

1

OVERVIEW AND RECOMMENDATIONS

The 850 estuaries of the nation represent, in proportion to their size, one of the most valuable portions of our environment. Knowledge of the complex interactions of the physical, chemical, geologic, and biological processes in estuaries is fundamental to our understanding of behavior in estuarine systems. However, these interactions have not been studied comprehensively. Most estuarine research has been conducted along specific disciplinary lines. This report addresses the need for interdisciplinary research on the entire estuarine system of which three major components that need to be integrated are the following:

1. Environmental effects on estuarine biota,
2. Circulation and mixing in estuarine and coastal waters, and
3. Suspended and dissolved matter in estuaries.

The interplay of these major components is significant in almost all estuarine processes, however, details within the confines of the interactive processes can differ among specific estuaries or in specific portions of a single estuary. The understanding of these processes can be applied to improve management decisions and efforts related to the entire estuarine environment--helping in determining their best use and survival as a productive and valuable resource. Most important in the management of estuarine systems is the development of predictive models,¹ which are both process-oriented (causal) and empirically based. Much of the past estuarine research has been based on "after the fact" or present condition analysis of the system that provides an empirical data base. However, to develop and verify useful predictive

models, more attention needs to be focused on understanding the processes involved.

In the following chapters, teams of appropriate experts comment on recent significant research within the major estuarine components, explain the need for further progress, note the necessity for integrating the other components, and identify important tractable research topics.

USES OF ESTUARIES

Estuaries are semienclosed bodies of water--bays, sounds, inlets, fjords, and lagoons--that have free connection with the open sea and contain water from land drainage and seawater. Each estuary is unique in its totality, but there are primary characteristics that permit judicious transfer of at least some of what is learned in one estuary to some or all of the others. All estuaries contain chemical gradients between their saline and fresh sources of water input. Frequently, there are other gradients found in estuaries--temperature, sediment burden, and dissolved materials. Most estuaries are subjected to relatively violent environmental changes with fluctuations in riverine inflow, seasonal temperatures, and influences of meteorological events. All estuaries are recipients of the composite chemical burden of the waters from land--waters from urban centers and from all other parts of the contributing watersheds. Most estuaries are or have been extraordinarily productive of biological crops, many of which are useful to man. Each estuary is subject to effects of changes in water quality in those adjacent ocean waters that provide about half of the water in the average estuary.

The value to humans of the estuaries in the United States is high. A major fraction of commercial shipping begins or ends in them. The shoreline is attractive to millions of people for residential sites, for many water-related industries, and for use in recreation (typically on the order of hundreds of millions of visitor-days per year). Boating, swimming, surfing, sunning, hunting, fishing, and nonspecific personal enjoyment are intensive at many sites. Sand, gravel, oil, gas, shell, and commercially useful quantities of many chemicals are mined from the floors of estuaries. The generation of electricity often involves use of estuaries for the release of waste heat and other materials and for transportation. The

military agencies of the nation use bays for transportation, firing ranges, research on vessels and equipment, storage of vessels, vessel construction and maintenance, and education in naval and air operations. Estuaries are excellent sites for the training of scientists and the conduct of research; laboratories exist in every coastal state for this kind of activity.

The biological harvest of species dependent on estuaries includes more than 70 percent of the total national landings by all commercial fisheries and 65 percent of the national recreational catch in marine waters. In more specific terms, estuaries were essential for the production in 1980 of 5186 million pounds of commercial species with a dockside value of \$1790 million and a capitalized annual value of over \$35 billion.² The recreational fishing dependent on estuaries involves annual expenditures of over \$1 billion and a catch of about 190 million fish.

The other major use of estuaries is for the placement--misleadingly referred to as disposal--of wastes. These bodies of water receive partially treated human wastes, sediment and chemicals from agricultural activity and urban runoff, and an enormous array of industrial products and by-products.

Every one of these uses is predicted to increase, and each of them can substantially affect the primary components and processes of estuaries so as to reduce the resource capacity of the system.³ The legislated but unaccomplished water-quality goal that all pollutants be eliminated has an uncertain future, and it must be assumed, for the near term at least, that wastes will continue to be introduced.

COMPLEXITIES OF ESTUARINE PROCESSES

Each of the principal components--physical, geologic, chemical, and biological processes--of an estuarine system is complex in itself and intimately interactive with the others. For example, the interactions of population densities in the biological community have been the subject of a significant amount of research, but when the topic is considered in light of changes in circulation patterns, water chemistry,⁴ or meteorological effects, the subject becomes increasingly more complex and dependent on understanding the other components. Figure 1.1 illustrates some of the complexities of external factors that affect

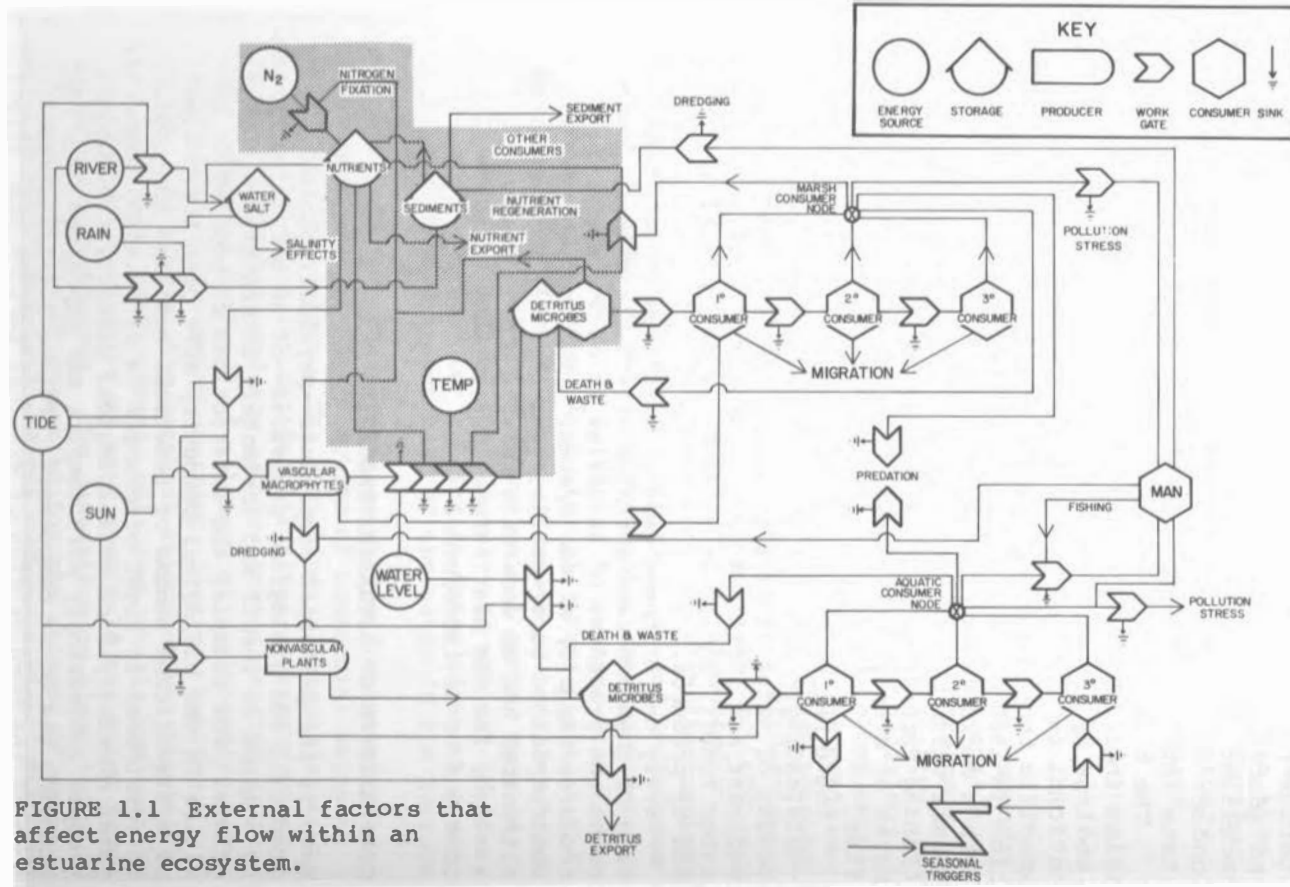


FIGURE 1.1 External factors that affect energy flow within an estuarine ecosystem.

the energy flow within an estuarine ecosystem, such as the sun, tide, weather, runoff, pollution, fishing, and man himself.⁵

The above illustration of energy flow, however, represents only an essentially instantaneous image of interactions. Large-scale and long-term dynamic changes also occur. River flow commonly varies several orders of magnitude within the average year and far more with exceptional events, such as floods. Large ranges in temperature can occur from summer to winter. Tides may be semidiurnal, diurnal, or mixed. Tidal currents move vast quantities of water through the system, changing the depth and flooding and draining the edges of the estuary. These tides vary both cyclically and irregularly; fortnightly, spring to neap, over lunar periods and longer cycles; and in close response to meteorological events, especially storms. Even the mean sea level can vary on both short- and long-time scales because of eustatic or local geologic changes or changes induced by humans.

The hydrographic pattern in estuaries changes continually. Circulation is principally dependent on the morphology of the estuary, riverine input, winds, and differences in water density between estuary and ocean and between parts of the estuary. All of these vary with time. The classic pattern exists in many estuaries in which the density structure causes net downstream transport of surface water, net upstream movement of saline deep waters, and substantial mixing between. In each estuary, this pattern is modified by many factors, including tidal, seasonal, and meteorological effects.

Similar illustrations of complexity could also be drawn from the transport and behavior of the dissolved and particulate materials that perpetually enter these systems, from the chemical processes that involve such materials as nutrients or toxic substances, and from the effects of both small-scale and large-scale engineering activities.

Estuaries are remarkably resilient to natural events, such as storms, seasonal temperature extremes, and changing freshwater flow; however, they are highly vulnerable to the following kinds of anthropogenic changes:

1. Excessive burdens of natural materials (sediments, nutrients, other normal chemicals) can overwhelm the capacities of estuaries for accommodation. An estuary may recover if the excess of nutrients, for instance, is removed, but high sediment loading as a result of increased

human activity speeds the natural filling process and creates irreversible loss.⁶ Through other processes, large-scale engineering changes for special purposes can modify the morphology of an estuarine system, redirect important volumes of freshwater to other systems, seriously modify the seasonal patterns of freshwater input, or alter the shoreline and important exchanges between land and bay.

2. Estuaries are fragile under effects of powerful biocides that have only recently been invented. These biocides are alien to the genetic history of the estuarine organisms involved, which may have no mechanisms for defense. The principal food web in estuaries comprises a relatively small number of species; and an unseen wipe-out of a species could cause fundamental changes and diminish the utility of the system.

INTERDISCIPLINARY PROBLEMS--EXAMPLES

Many of the most critical needs for knowledge about estuaries can be met only through interdisciplinary fundamental studies. The following are important examples:

- In the San Francisco Bay system,⁶ the proposed diversion of increasing quantities of water to southern California would affect (1) hydrographic behavior of the lower San Joaquin and Sacramento Rivers and of major portions of San Francisco Bay; (2) input of nutrients and other chemicals; (3) salinity distributions; (4) standing stocks of many biological species and communities; (5) distribution of predator and prey species; (6) input, movements, and behavior of sediments; and (7) water quality for many uses.

- In a study area of 11,500 square miles of coastal Louisiana, the highly productive marsh and wetlands are declining at the rate of approximately 40 sq. mi. per year.⁷ In comparison, there was accretion in the nineteenth century and annual loss at rates of 6.7 sq. mi. in 1913, 15.8 sq. mi. in 1948, and 28.1 sq. mi. in 1967. The causes and effects involve the changes that have been made in the distributary outlets from the Mississippi River by engineering of levees, allocation of flow between the Mississippi and Atchafayla systems, decay of old deltas, hydrographic patterns, waves, storms, deposition rates, erosion rates, subsidence, modification of wetlands for

petroleum exploration, flood-control practices, dredging, the production and nourishment of a variety of fish and shellfish important for human use, and other components and processes.⁸

- The development of large volumes of anoxic or nearly anoxic water off New Jersey in recent years, with its extensive threat to fish and shellfish and to the waste-assimilation capacity of the region, is apparently linked to meteorological sequences as well as to nutrient inputs from the adjoining New York metropolitan area.⁹

- In the Chesapeake Bay, the deep waters of the mid and lower Bay are progressively depleted of oxygen during mid and late summer in some years.¹⁰ Depletion is not fully understood, but the causes involve (1) high inflow of freshwater during spring and warm weather, which increases stratification and reduces vertical mixing; (2) respiration in the deep water, which may be enhanced by organic debris from the previous year and which in turn may be increasing because of greater nutrient loading from the tributaries; and (3) perhaps benthic respiration. The effects of the development and extension of the depleted mass may be of biological importance, because such deep waters are potentially useful for fish, crabs, and other species and because the up-estuary transport of juvenile blue crabs, some juvenile fish, and other species occurs only in these deeper waters--although not necessarily at this season. Seiche-like rocking of the low-oxygen mass is suspected as the direct cause of substantial mortalities among fish, benthic species, and trapped blue crabs. Other biological relationships are modified. Chemically, anoxic conditions substantially alter the processes in the sediments and in the water column. Only well-designed interdisciplinary investigations can adequately link the physical, chemical, and biological components and provide predictive capability.

- Most efforts to understand the populations of estuarine species--efforts that are important not only for scientific objectives but also for the management of fisheries--are frustrated by our inability to deal simultaneously with the processes of physical transport (nutrients; planktonic food; eggs, larvae, and juveniles); biological relationships with prey, predators, and diseases; and the potentials for chemical injury or enhancement from toxic wastes or nutrients, as well as the effects of the migratory movements guided by estuarine conditions.

THE PATTERN OF PREVIOUS RESEARCH AND PUBLICATION

Much research has been devoted to estuaries. A review of the journals and volumes makes clear the abundance of disciplinary publications and the paucity of comprehensive approaches that simultaneously investigate the interactive, physical, geologic, chemical, and biological components and processes in an effort to develop predictive capability in the estuarine system.

Officer et al.¹¹ located 1699 refereed published papers from a five-year period as gleaned from a wide variety of scientific, engineering, and technical journals and edited volumes. For the Chesapeake Bay, more than 9000 published reports exist, of which many, but not all, were refereed prior to publication. Officer et al. also found papers in 34 diverse journals and 19 edited volumes. One American journal, *Estuaries*, and the international journal, *Estuarine Coastal and Shelf Science*, are exclusively devoted to estuarine and coastal papers. In addition, there is a large but unmeasured production of other kinds of publications, especially in-house papers and reports. Many of these are known to be of high quality and value, but they may not have been subjected to the rigors of independent peer review.

Officer et al. also analyzed the institutional affiliation of senior authors of refereed papers and the identifiable federal funding of estuarine research. They report that the academic community produced 77 percent of the refereed publications, followed by federal laboratories (15 percent) and state, municipal, industrial, and other sources (8 percent). An analysis of federal funding related to ocean pollution research, development, and monitoring reports that the projects in fiscal year 1978 were funded at a total of \$164 million, of which \$131 million was ascribed to research, including \$40.6 million related to estuaries.¹² Of that, the academic community was granted \$14.0 million or 37 percent of the estuarine research funds.

Most of the estuarine research has been along disciplinary lines, devoted to relatively specific aspects of biological, geologic, chemical, or physical processes. A recent analysis by W. J. Hargis and T. M. Armitage (Virginia Institute of Marine Science, personal communication) of published papers directly relating to the Chesapeake Bay from 1971 to 1982 cataloged 2056 research products. Specific disciplinary studies (1688) made up 82 percent (946 in biology; 559 in physics or chemistry; 98 in eco-

nomics; and 85 in social, behavioral, or institutional studies). Many of these involved more than one narrow discipline, but only 18 percent were identified as interdisciplinary in design or interpretation. Chesapeake research was heavily influenced by the program of Research Applied to National Needs (RANN) in the National Science Foundation, which emphasized an interdisciplinary approach, but the program has been terminated.

There has been notable progress in the understanding of estuaries during recent decades. The emergence of the two journals devoted to coastal and estuarine papers, both of which have backlogs of good manuscripts, is one evidence of production of knowledge. A new *Journal of Shellfish Research* was initiated in 1981 and will be dominated by coastal studies. The Estuarine Research Federation, a confederation of societies representing New England, the Mid-Atlantic, South Atlantic, Gulf of Mexico region, and Pacific Coast, was established in 1971; it has conducted biennial international conferences that have produced a series of volumes.¹³ Other edited volumes entirely or substantially directed to research on estuaries and the inshore coastal region are listed by Officer *et al.*¹¹ and in note 14 at the end of this chapter.

RECOMMENDATIONS

The limits to success in balancing the uses of an estuarine system for any set of desired objectives are set by the available fundamental understanding of the components and processes of the system. Empirical trial-and-error management and decision-making techniques have been employed in matters pertaining to estuaries, but these techniques involve high risks because of the value and potential fragility of estuaries. The store of reliable knowledge and predictive capability is the primary source of useful guidance when decisions must be made.

Because of the complexity of the components and processes in estuarine systems and the need for this knowledge in managing these systems, the Panel recommends the following:

1. *The primary focus of future research in estuaries should be on interdisciplinary relationships.* However, there needs to be an explicit recognition that disciplinary investigations provide the building blocks necessary to an interdisciplinary framework. Although the disci-

plinary knowledge bases are currently incomplete, they are adequate to start establishing the interdisciplinary understanding.

Productive research on such complex problems is now feasible. Much is known of the various components and processes, and even of the interactions. Research facilities, including well-equipped vessels, can be simultaneously brought to focus on appropriate facets of the problem. Computer and analytic capabilities have advanced to a point that will permit a combination of theoretical and mathematical efforts that were previously impossible. Scientific experience and expertise now available in systems modeling and analysis can also be attracted to this kind of challenging problem.

However, it is exceptionally difficult to design and conduct such complex studies--and even more difficult to obtain adequate funding for an appropriate period. The Panel is satisfied that the scientific community will respond with competence and exceptional achievement if funding becomes available. Team study, the use of consortia, *ad hoc* linkages, and other cohesive procedures have frequently been effective in other areas of earth science (particularly if coordination is an integral element in the design of such studies), and they can be developed and used for estuarine studies.

Examples of possible research focuses developed within the remainder of this report are the following:

(a) Unless the estuary in question is studied carefully and thoroughly, some of the most important processes that affect it may go unnoticed; however, it is unreasonable to consider, in detail, each and every relationship between all the species of an estuary. This points to the necessity of conducting detailed spatial and temporal surveys of estuaries for qualitative and quantitative stock assessment of plant and animal populations and combining this assessment with the nature of the variations in circulation and chemistry.

(b) Once the more important and quantitatively significant trophic and other interactions between species of an estuary are understood, research should consider how environmental stress of various kinds, natural and anthropogenic, affect those interactions and the general structure and function of the ecosystem. This may be done empirically, by observing changes in community organization in time or space following the onset of a given stress (e.g., a new waste-water discharge, a freeze, or a drought). The cause and effect of such changes may be

obscure even when the interactions of the community components are reasonably well known.

(c) The determination of Lagrangian (moving coordinate system) particle trajectories within estuaries exhibiting complex Eulerian (fixed coordinates) flow patterns is fundamental to a description of the movement and dispersion of materials within an estuary and their ultimate exchange to the adjacent water. A fundamental problem that exists is how best to develop our ability to provide a Lagrangian description of flow within estuaries and whether this is, of necessity, dependent on numerical simulations.

(d) Mechanisms for the generation of nontidal circulation patterns through residual vorticity produced both by the interaction of the tidal stream and surface wind stress with the bathymetry should be investigated. This problem is amenable to analytical, numerical, and experimental investigation. Useful experiments designed to investigate residual vorticity generation could be accomplished using moored current-meter arrays in areas of complex bathymetry.

(e) Mechanisms responsible for the often rather abrupt transition from stratified to vertically well-mixed conditions should be investigated, as well as the changes in internal circulation that accompanies this transition. The nature of these transitions needs to be investigated in relation to the suspended-sediment load and chemical distribution, particularly as these transitions affect the distribution of nutrients and the quality and quantity of light vital to the biological activity.

(f) Research is needed on how sediments are re-distributed as the results of tidal currents and episodic storms. What is the net effect in the coastal zone of estuarine flow and wind-driven upwelling or downwelling on the accumulation or exportation of sediments and their subsequent effects on chemical and biological distributions?

(g) The role of bioturbation in releasing chemical species to the water, in increasing the trapping efficiency of the sediment for other chemical species, and in the redistribution of nutrients needs to be investigated.

(h) The effects of episodic storms and floods on the biota, sediment load, and chemistry of estuaries need further investigation. A necessary component of assessing these effects is the existence of baseline survey data before such an episodic event in order to

assess the change and in determining the time needed and processes necessary to restore the estuary to the pre-episodic event.

2. *Such interdisciplinary research in both university and governmental laboratories should receive increased support to provide the basic framework for informed management of estuarine systems.* Research useful to the management of estuarine systems can take two closely related approaches. Baseline studies that determine the state of the system are necessary to assess the effects of both natural and anthropogenic change. The other approach involves understanding estuarine processes in order to develop and verify predictive modeling (what will be the result if part of an estuarine system is changed). The predictive modeling utilizes the baseline studies as a primary data base. The country's economic interests in estuarine resources are too great to allow us to continue with a trial-and-error management approach.

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2

ENVIRONMENTAL EFFECTS ON ESTUARINE BIOTA*

The biota is important to the fundamental processes in estuarine systems and to almost all human uses of these systems, especially food production, aesthetic enjoyment, and the assimilation of wastes. The most valuable and useful question to pose when physical, chemical, or biological alterations are considered is usually: What effect will this have on the biota? Predictive estimation of such effects have been explored, but the following discussion of efforts and needs demonstrates that the requisite research will be complex. It must involve several levels of biota and ecosystem components and processes and cannot be fully successful without interdisciplinary linkage to the physical and chemical components and changes in an estuarine system. Attention in this chapter is given to the responses of individuals, species, and communities. The roles and challenges of system modeling are discussed, and the importance and problems of usefully documenting alterations in the estuarine ecosystem and of estimating the integrated condition of such systems are presented as research challenges.

*This chapter was largely developed by a subpanel on estuarine biota, which consisted of the following: John H. Ryther, Harbor Branch Institution, *Subpanel Leader*; L. Eugene Cronin, Chesapeake Research Consortium; Robert Feller, University of South Carolina; Donald Heinle, CH₂M-Hill; A. Fred Holland, Martin-Marietta Laboratories; and Theodore Smayda, University of Rhode Island.

EFFECTS ON INDIVIDUAL ORGANISMS

Studies that investigate the effects of various environmental stresses on the survival, growth, or other vital functions of individual aquatic species are among the oldest forms of ecological research. Such studies were intended to provide information on where and when organisms could occur in nature and what factors of the environment limit and control their abundance and distribution; this approach is now recognized as being too simplistic in itself for general application. These studies, however, may provide useful information for range prediction, control, or management purposes in situations where certain species suddenly become a dominant or key component of an estuarine ecosystem.

A similar type of autoecological laboratory study has recently been pursued, particularly by the U.S. Environmental Protection Agency and its contractors, in which the effects of anthropogenic stress (i.e., toxic pollutants) on aquatic organisms are determined. These studies are, for the most part, designed to determine lethal concentration thresholds of toxic contaminants for the purpose of establishing discharge guidelines or standards (NRC Environmental Studies Board, 1981; Cairns, 1982). Bioassay studies of this nature are not, as such, particularly useful research tools for understanding estuarine processes.

Assuming that an ultimate objective is to understand and to be able to predict the complex dynamics of the estuarine ecosystem as a unit, reliable data need to be acquired on the rates of such fundamental processes as feeding, food conversion efficiency, metabolism, growth, maturation, fecundity, and reproductive success of as many as possible of the key organisms of a given estuary. Rate data on these processes must be determined as functions of the environmental variables that have significant effects, of which temperature is an obvious example. This type of information is, unfortunately, still rare except for a few species of plankton and some commercially important finfishes and invertebrates (the latter frequently as a spin-off from aquaculture research).

Detailed physiological rate studies of all the organisms that live in estuaries or even one representative estuary is not reasonable. Attention should be focused on numerically or functionally dominant (or key) species, with emphasis on species that have usually been neglected in the past and about which too little is now known to

attempt even rough approximations of the physiological rates. These include, for example, some of the small estuarine organisms: the meiobenthos, the microzooplankton and protozoa, and the bacteria including the autotrophic cyanobacteria of newly discovered ecological significance. Another group of organisms that periodically dominate many estuarine ecosystems and on which there is little information are the soft-bodied macrozooplankton, the jellyfishes, tunicates, and ctenophores. Another important but often neglected group of organisms is that of the smaller, commercially unimportant finfishes that often outnumber and may outrank in functional significance the more familiar food species.

Simple feeding, growth, and metabolic rate measurements, perhaps as a function of temperature, of a small, selected group of the above kinds of organisms would provide a key element for the long-range objective of predictive numerical estuarine-ecosystem modeling.

The autoecological laboratory studies described above must, however, be preceded or accompanied by appropriate field studies, without which neither the most important organisms nor the appropriate physiological process to study can be determined. Before feeding rates are measured, for example, it is necessary to know what food or foods the animal in question utilizes in the estuary, a characteristic that is often poorly known even for some of the most thoroughly studied species. It is here that autoecology and synecology merge and that laboratory and field studies become mutually interdependent and complementary.

EFFECTS ON COMMUNITIES

To assume that one can study the effects of environmental stress on estuarine communities and ecosystems is to imply that the normal structure and function of estuarine ecosystems is already well understood. Such, unfortunately, is far from the truth. Ecosystem components may, in some cases, be described in qualitative and even in numerical terms by means of exhaustive field surveys, but even the most painstaking of surveys fail to reveal the intricacies of the relationships, trophic and other, between its members.

Estuaries are, in fact, more complex in this respect than other aquatic ecosystems, with both freshwater and marine inputs and usually at a shallow depth where the

pelagic and benthic communities functionally merge into one. Jellyfish in Chesapeake Bay have been observed to settle and feed on the bottom during parts of the day. The adult hard clam, *Mercenaria*, living on the bottom of Narragansett Bay has been estimated to equal or even exceed zooplankton as a grazing influence on phytoplankton abundance and species composition. Meroplankton, the temporary larval forms of larger benthic or pelagic invertebrates, may far exceed copepods and other holoplankton organisms in biomass and in feeding intensity during the brief periods when they are present, and each group (fish, crustacea, echinoderms, molluscs) may have a different annual periodicity as well as different feeding habits, food preferences, and other behavior. Phytoplankton production is much more closely coupled with the benthos in estuaries than is the case in the ocean. Algal blooms, which are not immediately consumed by zooplankton because of the lack of synchrony between the plant and animal populations, can quickly sink to the bottom before the cells have time to decompose and recycle their nutrient contents. As much as 90 percent of a spring diatom bloom may end up on the bottom of an estuary, in contrast to 10 percent or less in the ocean, resulting in benthic communities orders of magnitude more dense in estuaries. The bottoms of shallow estuaries may also support their own producer communities in the form of both unicellular and macroscopic algae, as well as higher rooted vegetation, and the productivity and ecological role of this benthic flora are not well understood.

Another factor that adds to the complexity of estuarine communities is that of migratory populations that may enter and leave the estuary or its tributaries, seasonally or aperiodically, to spawn or feed, actively or passively, and predictably or unpredictably. Large populations of small bottom-feeding finfishes, such as spot and croaker, move into the tributaries of Chesapeake Bay where they may devastate the benthos before they leave—a significant factor affecting the flux of organic matter and nutrients into and out of these areas that may be missed completely if their movement is not observed during the few days of the year in which it occurs. Similarly the soft-bodied jellies (coelenterates, ctenophores, tunicates) may move into estuaries virtually overnight and decimate zooplankton communities with disastrous consequences to larval and juvenile resident planktivorous finfish populations, yet their impact has often been ignored completely in simplistic trophic-dynamic models.

A major direction of modern fisheries biology is that of multispecies management, a concept that recognizes the trophic interactions of the several commercial species with themselves and/or a common food supply. Heavy exploitation or poor annual recruitment of a planktivorous species such as herring in a coastal fishery may result in an increased yield of benthic fishes as the uneaten food sinks to the bottom. No such simple relationship occurs in estuaries, where, as noted above, the planktonic and benthic biota are one community and where year-class success of a food species is as apt to result from competition for space as for food. Fishing pressure may exert an influence on the abundance or species composition of the food supply of an estuary, even by the offshore capture of migrant fishes hundreds of miles away.

The foregoing examples are intended to illustrate the extreme complexity of the estuarine community. Many more could be given. It is the first job of the ecologist to understand these interactions qualitatively and to try to assess their relative importance and magnitude in the normal flow of matter and energy through the ecosystem. To consider in detail each and every relationship between all the species of an estuary is unreasonable, but as is evident from the previous discussion, unless the estuary in question is studied carefully and thoroughly, some of the most important processes that affect it may go unnoticed. This fact points to the necessity of conducting detailed spatial and temporal surveys of estuaries for qualitative and quantitative stock assessment of plant and animal populations.

However, the abundance and distribution of species still does not reveal many of the subtleties of their interactions, for which there is often no substitute for direct observation. There is still a need in estuarine research for the old-fashioned natural historian whose efficiency may be immeasurably increased today by means of modern life support, television, photography, electronic data recording, and other submarine equipment and technology.

Once the more important and quantitatively significant trophic and other interactions between species of an estuary are understood, one may begin to consider how environmental stress of various kinds, natural and anthropogenic, affect those interactions and the general structure and function of the ecosystem. This may be done empirically, by observing changes in community organization in time or space following the onset of a given stress (e.g., a new

waste-water discharge, a freeze, a drought). The cause and effect of such changes may be obscure even when the interactions of the community components are reasonably well known. For example, various trace contaminants (hydrocarbons, heavy metals) through selective toxicity tend to cause a shift in phytoplankton community structure from large diatoms to small flagellates. Such a change is often considered undesirable. Diatoms are the first step in a food web that normally leads to copepods and finfishes, whereas a flagellate-dominated phytoplankton community often supports a grazing community of soft-bodied invertebrates that represent a trophic dead end. However, this type of shift is not consistent. In the Marine Ecosystem Research Laboratory (MERL) experiments at the University of Rhode Island's Narragansett Marine Laboratory, ecosystems experimentally stressed with oil resulted in a bloom of diatoms. In that case, the phytoplankton shift resulted from the toxicity of the added hydrocarbon to benthic animals that had exerted grazing pressure on and suppressed the diatoms. The latter kind of interactions is difficult to detect and virtually impossible to prove through simple observation of community change in a natural environment. One sees the end result and, if appropriate baseline studies have been conducted, may determine that a community alteration has occurred, but the mechanisms that caused it remain obscure.

Probably the only way in which the actual interacting community processes resulting from environmental stress can be identified and documented is by means of experimental ecosystems. These may be simple or complex, large or small, and of a wide variety of shapes and configurations. The large and rather complicated systems such as MERL (12 cylindrical tanks, about 2 m in diameter and 5.5 m high, of 13 m³ volume) and the National Science Foundation-International Decade of Ocean Exploration-sponsored Controlled Ecosystem Pollution Experiment (CEPEX) (three units, 9.5 m in diameter and 29 m deep, of 1700 m³ volume, that were submerged in Sannich Inlet, Vancouver, B.C.) have both been rather troublesome to operate over the long periods of time necessary for community equilibria to become established. The high cost of the CEPEX units also made it difficult to achieve adequate replication and experimental controls. Smaller experimental tanks, 1 m³ or less in volume, even including plastic trash barrels, often suffice for certain kinds of experiments and may be replicated many times at modest price.

It is usually preferable to conduct several experiments including different levels of an environmental stress or even several stresses, suitably replicated and with adequate experimental controls, all simultaneously rather than in sequence. A typical ecosystem experiment can last for periods of one to several months, and sequential experiments will therefore necessarily occur over two or more seasons during which environmental conditions other than those being tested are certain to vary significantly. The alternative of conducting such studies in controlled environmental chambers is so costly as to be usually prohibitive, and the chances of mechanical failure of some part of the system over prolonged periods of time are so high as to be almost certain.

Not only do small, simple experimental ecosystems lend themselves to the possibility of conducting several replicated experiments simultaneously, but the simpler the experimental design, the less likely that experiments will be aborted because of mechanical failure. There are, of course, limitations to the kinds of experiments that can be conducted and, in particular, the complexity of the ecosystem that can be studied in small, simple systems. Accordingly, there is a need for a range of such experimental systems, both in size and complexity.

Even large experimental ecosystems carefully inoculated with all the significant constituents of a natural estuarine environment cannot and will not duplicate events in the natural system. Rather, it must be considered as a microcosm unto itself that will respond to the interactions of its organisms and to the environmental stresses to which it is exposed. These reactions will be understandable and interpretable only by comparing them with similar experimental systems that differ to some slight degree--usually one species or unit of environmental stress--not by comparing them with the natural environment.

It follows that the simpler the experimental system and the more accurately it can be replicated and controlled, the greater will be the chance of observing reproducible results. At the same time, the more simple the experiment and the more removed it is from nature, the interpretation of results in terms of natural events becomes more difficult and tenuous.

Another approach to experimental estuarine ecosystems might involve the creation of artificial estuaries by digging canals or channels off a natural estuary or restricting a small, manageable arm of an estuary by netting

or some other barrier that would permit the natural flow of water but prevent the movement of most organisms. It is even possible to replicate such experimental estuaries so that the effects of stress added to one may be compared with an unstressed control. To our knowledge, few if any attempts have been made to do this, but the concept would appear to have some advantages over purely artificial systems (e.g., tanks, plastic bags) in that a more natural and more complete community would be available for experimental manipulation, and it is quite possible that unanticipated community interactions could result in alterations quite different from those obtained from artificial systems.

Finally, experiments may be conducted within estuaries on completely natural communities, for example, excluding benthic or intertidal organisms from predators by constructing wire-mesh cages over them, enclosing parcels of the bottom or water and stressing them with toxic pollutants, and introducing predators or competitors to an estuarine area in which they do not naturally occur.

All the above experimental methods are useful in providing insight to the mechanisms by which environmental stresses alter estuarine ecosystems. They do not, for the most part, provide the kind of quantitative data that may be used for predictive or regulatory purposes. But through the combination of identifying the significant trophic interactions of estuarine ecosystems through field observations and experimental ecosystem studies of various kinds and the experimental measurement of the rates of these identified processes, it may ultimately be possible to express the effects of stress on the estuary as an ecological unit in quantitative terms through appropriate numerical modeling techniques.

ECOSYSTEM MODELING

While predictive numerical modeling of complete ecosystems should be considered as the long-range goal of ecological research, it should be emphasized that it is not realistic for the immediate or near future, particularly in the complex estuarine environment. As pointed out earlier, it is first necessary to obtain basic information on the nature and rates of at least the more important trophic and other interactions of the key organisms as well as stock sizes and distributions. This does not mean, however, that there is not a place for the simpler heuristic type of models in contemporary estuarine research.

Simple, empirical predictive procedures, often referred to as models, have been and are being used for estimating or forecasting various aspects or functions of the plankton, fish, and shellfish populations of estuaries. As an example, the timing of the onset of spawning or the setting of spat of oysters (important for the placing of culch or other devices for collecting the oyster spat and avoiding other epibiota) can often be correlated with temperature and/or salinity. The species composition, density, and distribution of phytoplankton blooms in Great South Bay and Moriches Bay, Long Island, have been related to the source and nature of their nutrient source (duck farms located on tributaries to the bays), temperature, salinity, wind speed and direction, and the flushing rate of the bays. The year-class success of striped bass in Chesapeake Bay, currently in serious decline and believed by many to have suffered the impact of anthropogenic stresses, is now believed to be dependent on a combination of climatic factors (temperature, rainfall) in the upper regions of the estuary during the critical postspawning period. Elaborate models have been developed to predict the loss of striped bass larvae through entrainment in power-plant cooling water systems in the Hudson River, and many similar predictions have been made involving other species and other utilities, existing or planned. A reasonable short-term goal of estuarine ecosystem studies is to try to understand why simple predictive procedures do or do not work, to refine and improve on them, and to arrive at other gross predictive procedures for those fortuitous cases where only a few environmental factors control important biological events.

Somewhat more sophisticated numerical modeling can and should be employed as an ancillary tool to help guide and direct basic studies of estuarine ecosystem structure and function. Such modeling may be used to predict what *might* happen if certain processes were the controlling factors. Modeling can point out what components, rate constants, processes, and interactions are both poorly known and of sufficient potential significance to merit special attention. Modeling may also point out what relative effects specific processes may have on other parts of the ecosystem.

For example, for a model of a relatively simple aquatic ecosystem consisting of nutrients, phytoplankton, and zooplankton, the numerical relations are intricate. They involve a set of temporally and spatially dependent, coupled differential equations involving one or more nutrient conservation equations, one or more phytoplankton

community equations, and one or more zooplankton community equations. Each equation includes both the hydrodynamic advective and nonadvective terms and the constituent source and sink, growth and decay, and transformation and coupling terms.

In some cases, particularly those for lakes and the deep ocean where the hydrodynamics affecting the ecosystem can be defined in somewhat simpler terms than that for estuaries, analytical solutions may be given. In other cases, scientific modeling solutions, though limited in their applicability, can be derived that do point out the potential importance of various factors such as nutrient limitation, zooplankton grazing, self-shading, hydrodynamic residence time, and mixing effects on phytoplankton populations.

DOCUMENTATION OF ECOSYSTEM ALTERATION

Estuarine ecosystems are often assumed to have changed in historical times and are, in fact, now in the process of alteration. The implicit changes are not often well defined but generally have to do with such human-use values such as aesthetic or recreational enjoyment or commercial food production. Most often, the change is also believed to have occurred in the direction of a deterioration of such values. Unfortunately, there are not often many scientific data to substantiate or document such changes in specific estuaries, not to mention the associated problem of trying to relate such changes, if they have occurred, to some one or more causes, anthropogenic or other. If for no other reason, current thorough descriptive accounts of representative estuarine ecosystems are needed to ensure that future alteration may be well documented.

Examples of the kind of study that can provide useful baseline data against which future change may be assessed is the recently completed *Environmental Atlas of the Potomac Estuary* prepared for the state of Maryland (Power Plant Siting Program) by Martin Marietta Corporation, the eight-volume *Comprehensive Study of San Francisco Bay* produced by the staff of the College of Engineering and School of Public Health, University of California at Berkeley, in the 1960's, and the ten-volume *Delaware Bay Report Series* published under a grant from the National Geographic Society. There are many other examples of estuarine baseline studies, particularly during the past

decade, when state and federal regulatory agencies first began to require electric power utilities and other industries to make studies prior to the construction of facilities impinging on the estuarine environment. Designed as part of a "before and after" type of study, to demonstrate any measurable effect of the industrial operation in question after it went into operation, such studies have more recently lost favor to predictive modeling efforts as a more useful tool for decision making before the fact (the severe limitations of the modeling approach notwithstanding).

Baseline studies are useful only in direct proportion to their quality. Poorly conceived or executed surveys are not only wasteful of time and effort but may lead to erroneous conclusions. The San Francisco Bay study referred to above and others were closely scrutinized by Nichols (1973) with the following commentary:

Efforts to describe the structure and function of benthic communities of the bay and to quantify the effects of waste discharge on them have been hampered by inconsistent and often faulty sampling methodology and species identification. Studies made show a lack of information on the normal life processes of the organisms concerned. The diversity index (a mathematical expression of the number of kinds of organisms present at a location), commonly used to describe the "health" of the benthic community, has been employed without regard for the need for standardizing methodology and species identifications or for understanding natural biological processes that affect such mathematical indices. There are few reliable quantitative data on the distribution of benthic organisms in the San Francisco Bay with which future assessments of the "health" of the benthic community might be compared. Methods for study of the benthos must be standardized, identifications of species verified by trained taxonomists, and new field and laboratory studies undertaken before we can expect to obtain an accurate description of the benthic fauna and its relations with the environment.

Commercial fish landings from larger estuaries represent some of the oldest and most complete relevant data that are available to document changes in the ecosystem. How well they relate to stock size of the species in question is problematical. In some cases, the correlation is

thought to be high, as in the case of striped bass in the Chesapeake Bay. More often, social and economic factors affecting fisheries so confuse the issue that landings can be expected to bear little relationship to population size.

There are certainly a few cases, particularly with respect to the larger estuaries where there are one or more well-established marine laboratories located in the close vicinity, where old environmental data are available. Care must be taken in the interpretation and use of such information, as techniques and equipment for measurement and sample collection have changed significantly in the past decade or two. Those parameters that are simple and easiest to measure such as temperature, salinity, phosphate and silicate concentrations, and secchi-disc transparency are the most reliable. The ability to determine seawater nitrogen chemistry has greatly improved in recent years and now includes routine measurement of the concentration of ammonia, often urea, and sometimes total dissolved organic nitrogen, all of which are equally or more important than nitrate and nitrite--the fractions originally and not very accurately measured. Fluorometric determination of chlorophyll, as an index of phytoplankton biomass, is also a relatively recent measurement not comparable with older data obtained by other methods.

Similarly, comparison of old and new data on the species and numbers of the biota of different major groupings--for example, the phytoplankton, zooplankton, benthic invertebrates, fishes--may be difficult because of differences in the collection, sample processing, or preservation techniques used. Phytoplankton was routinely sampled with fine-mesh nets until it was discovered, some 20 or more years ago, that only the larger fraction of the unicellular algae--the 5-10 percent of the community greater than about 75 μm in diameter--were taken by even the finest nets. Subsequently, whole-water samples have been collected and preserved, the cells sedimented in settling chambers and counted by inverted microscopy. Today still another fraction of the autotrophic plankton community, the tiny cyanobacteria 1-2 μm in size that have usually gone completely unobserved by conventional microscopic examination, are found to be functionally a highly significant part of the photosynthetic or "producer" community. There has been a similar history in the earlier neglect and more recent inclusion of the smaller benthic inverte-

brates (meiofauna), the microzooplankton, and the smaller, noncommercial species of finfishes.

Despite these difficulties, there are certainly historical data sets, published and unpublished, that can provide useful information when interpreted with care on changes, permanent and reversible, cycles, and trends. The location, screening, processing, and synthesis of such data is a research undertaking in its own right, particularly where raw, unprocessed, and unpublished data collections are involved, the value, interpretation, and significance of which require value judgment by trained scientists. A notable example of environmental change in an estuary that has been carefully documented from the scientific literature and the historical record is the report *Historical Review of Water Quality and Climatic Data from Chesapeake Bay with Emphasis on Effects of Enrichment*, submitted to the Environmental Protection Agency by members of the Chesapeake Research Consortium, Inc. (Heinle et al., 1980). Following is the draft summary from that manuscript:

Review of the available data on water quality in Chesapeake Bay has revealed changes caused by enrichment with nutrients. In the upper and middle Bay, and several tributaries, concentrations of algae present during the summer months have increased. There have been decreases in the clarity of the water associated with the increased algal stocks. Nutrient concentrations have also increased, phosphorus more notably so than nitrogen. In some of the tributaries, such as the Patuxent for which we have the best data, increased algal production has led to reduced concentrations of oxygen in the lower two-layered part of the estuary. The variations in concentration of oxygen are more extreme in surface waters than in the early 1960's in the Patuxent. Oxygen concentrations in the open Bay have not changed greatly, with the possible exception of extreme conditions during periods of extensive ice cover.

There have been historical variations in the abundance of commercial fishery stocks that are closely related to climatic variations. Beginning in 1969 or 1970, however, stocks of all anadromous spawning species and marine spawners representing higher trophic levels have declined to new long-time lows. The only exceptions are menhaden (marine-spawning

planktivorous fish) and bluefish (marine-spawning top predators). That same time interval has, however, been a period of above average rainfall and reduced salinities in the Bay, making any conclusions concerning effects of enrichment difficult to achieve.

There is evidence for progression of the effects of enrichment down the Bay with time. Increased inputs of nutrients may well lead to major changes in the lower Bay, similar to those already observed in the tributaries and middle Bay.

It is usually difficult or impossible to separate the effects of natural environmental stresses from those caused by man, an unanswered problem recognized by fishery biologists. Weekly quantitative plankton samples and related environmental data collected in Narragansett Bay since 1959, first by D. M. Pratt and subsequently by T. J. Smayda, both of the University of Rhode Island, have revealed trends somewhat similar to those described above for Chesapeake Bay. Over a 20-year period the maximum populations characterizing the winter-spring phytoplankton bloom have varied tenfold in density, as have summer maxima. But in 6 of the 9 years between 1970 and 1978, the annual peak abundance of algae occurred in summer, in contrast to the winter-spring annual maximum that occurred every year prior to 1970. During that time, there was also a doubling of both phytoplankton and zooplankton biomass, an increase in primary production by 50 percent, and a decline in stocks of winter flounder. All three changes closely correlated. It is tempting to ascribe them to human enrichment (eutrophication) of the Bay, though this was not obvious from just nutrient loadings. However, since 1978, there appears to have been the beginning of a return to the earlier conditions, with a winter-spring annual phytoplankton maximum, a decline in plankton biomass, and an increase in winter flounder stocks.

In both the Chesapeake Bay and Narragansett Bay data there are suggestions of a 10-20-year cycle in the abundance of various populations, particularly of some of the commercial finfishes and invertebrates, similar to and closely following recognized climatic cycles. Robert Dow of the Maine Department of Natural Resources pointed out some time ago the same correlation between climatic cycles and those of several commercial species in the estuaries of that State (Dow, 1964). Presumably, if the apparent relationship of stock size to climate is real, it should be evident over a widespread region and testable by study-

ing the records from several estuaries over the same time periods, thereby perhaps separating anthropogenic from natural effects.

As far as we are aware, a science of "comparative estuarine ecology" has not yet become developed, but it would appear to be a promising field of research. Comparative studies of estuaries in urbanized areas with those in less-developed regions of comparable climatic and topographic characteristics could provide an insight to the long-term effects of anthropogenic stresses in the absence of (or as a supplement to) historical records. It would perhaps be necessary to travel far afield to find estuaries not heavily impacted by man, and it is likely that otherwise comparable estuaries would be normally populated with quite different species assemblages in different parts of the world, but major community characteristics and relationships should be essentially the same except as influenced by environmental stress. If the latter are predominated by anthropogenic factors, these should be apparent with the proper choice of environments.

The geologic record may also provide information useful in detecting and interpreting long-term changes in estuaries, though the technique has been used sparingly to date. Varved sediment cores in certain parts of Chesapeake Bay, dated by pollen and isotope techniques, have revealed changes in phytoplankton community structure, from centric to pennate diatoms, that may be related to historical cultural changes in the region (e.g., colonization, industrialization, intensive farming with the use of inorganic fertilizers). More work of this kind in estuaries should be encouraged, though it is recognized that geologic chronology in soft estuarine sediments, often heavily worked by the benthic biota, is not easy to determine. Equally difficult to interpret, however, is the significance of the ecological changes revealed by these techniques. The change from centric to pennate diatoms, referred to in the example cited above, may be an indication of progressive enrichment of the estuary, but clear evidence for such a relationship is lacking.

Fish scales in varved sediments off the California coast revealed that the disappearance of the sardine in recent times and its replacement by the anchovy, an event sometimes blamed on overfishing or other human activity, has occurred many times in the past, well before anthropogenic influences. These and perhaps other preserved indicators of ecosystem change should be looked for in suitable estuarine deposits.

ESTUARINE HEALTH AND HEALTH INDICATORS

Contrary to one of the more commonly held attitudes of the day, change in itself may be neither good nor bad. Changes in productivity, species diversity, or other parameters of ecosystem structure or function can be used in reference to the nominative state (which incorporates natural variations) as described by Odum et al. (1979). One can use the state variables of a natural system as a means of comparison. It should be possible to define the state variables and the nominative state in assessing estuarine health and its natural variations. However, change is often referred to some human value concept, and what change is beneficial to one person may be bad for another. For example, the best conditions for certain kinds of commercial fishing may require plankton blooms dense enough to discolor the water and render it unpleasant for various aesthetic or recreational purposes.

The problem that the environmental manager faces is to detect early indications of deteriorating health of an estuary before serious damage occurs. However, early warning indicators of conditions leading to such catastrophic events are not always so obvious.

The monitoring of water, sediments, and organisms for toxic trace contaminants is the most common approach in use today. If the concentrations of heavy metals or toxic organics approach those that have been found (by bioassay) to be harmful to the biota or to man if he eats the organisms, it may be possible to locate and eliminate the source of the contaminant before serious damage occurs.

Chemical and physical processes of both the substance and the environmental medium, the estuarine system, are important in identifying pathways of potential transport. Such relationships as distribution of a material between soil and water, between air and water, within biological components, and the potential of transformation products should be determined. To understand how a substance is distributed within an ecosystem, we must determine its affinity to the various components of the system. With such understanding, transformation and degradation rates for a substance can be integrated with fugacity and partitioning equations (MacKay, 1979; McCall et al., 1981) to provide information regarding the expected concentrations in various components of the estuarine system.

Because of their notorious ability to concentrate a host of toxic material--metals, organics, pathogens--mussels have been used as monitors and whole-water bio-

assay organisms for coastal waters around the world. The "mussel watch" program is not, however, widely in use in estuaries and is, indeed, not a satisfactory approach for many estuaries or parts of estuaries whose waters are not suitable for the bivalve to live.

It is not sufficient, however, to look only for identified toxic materials in the environment, for those that are recognized hazards and that can be and actually are being monitored are but a few of the anthropogenic additions to estuaries. Further, toxic levels are known and standards set for only a few of those. A more useful and safer approach would be the routine monitoring of the health of the organisms themselves. Physiological parameters such as growth, feeding, oxygen consumption, fecundity/reproduction, osmotic/ionic regulation, hematology, nitrogen balance/excretion, and heartbeat/ventilation are all important indicators of organismal health, but baseline levels and normal steady-state conditions are not yet well known for most estuarine species. Carrying out the experimental measurements *in situ* in the environment to be monitored poses difficult logistic problems.

Another approach, perhaps more practical, is to monitor one or more biochemical variables that also provide evidence of environmental stress. Some of those that are being studied for this purpose are adenylate energy charge ratio, lysosomal changes, heavy-metal binding protein production, mixed-function oxygenase induction, and steroid metabolism change. Techniques for measuring these indices and the quantitative relationship of their change to various environmental stresses are still in the early stages of investigation, and adequate baseline data have not been established. Further work in this area should be encouraged.

Disease is a well-recognized, often critical problem in the artificial cultivation of marine finfish and invertebrates. It has, however, received much less attention and recognition in the natural environment with the exception of a few commercial species, such as oysters, utilization of which are usually also considered as a form of mariculture. Are such mariculture sites centers for the spread of infectious disease to native populations? What is the role of introduced exotic species in this regard? Are any of the infectious diseases of fish and shellfish in fact transferrable to man, as has been suggested? What factors affect the ecology of vibrios (e.g., *Lymphocystis*), and what is the role of pollution in their distribution in estuaries? Why are Pacific Coast estu-

aries epicenters of skin papillomas in flatfish? Is this an infectious disease? Why does it occur only in young? Is there a carrier or secondary host for the disease?

Fin rot/fin erosion disease is now known to occur in European, Southeast Asian, and Japanese estuaries as well as the larger urbanized estuaries of North America. Although it appears to be correlated with wastewater discharges, its basic cause and etiology are still unknown. Does this disease ever occur naturally? What is its relationship to water and sediment chemistry?

These are but a few of the unanswered questions in the challenging new field of marine pathology. Particularly important in this area is the relationship between disease and environmental stress, both natural and that caused by pollution, and there is no environment more appropriate for such study than that of the urbanized estuary.

There are other, much more subtle influences in estuaries that may significantly affect the health and survival of organisms. It has been recognized for at least three decades that coastal and estuarine water at certain times of the year are unsuitable for culturing phytoplankton and a variety of invertebrate larvae. This problem has been experienced by culturists working in such scattered areas as Woods Hole, Narragansett Bay, California coastal waters, and the English Channel. The phenomenon has never been satisfactorily explained nor the causative agent identified. Virtually unobservable in environmental studies, it may nevertheless be a major factor affecting the year-class success of a given species whose larvae may be in a critical developmental stage during such episodes. This is an area in which practitioners of mariculture and estuarine ecology could profitably join forces for the solution of a perplexing problem of interest and concern to both.

Not all environmental stress in estuaries is caused by toxic or inhibitory conditions or additions. The nutrients in domestic and certain industrial wastewaters and in agricultural runoff actually stimulate the growth of plants, as does the enrichment of waters by natural processes such as upwelling. Beneficial in moderate amounts and under some circumstances, since phytoplankton are the primary producers of organic matter responsible ultimately for virtually all other aquatic life, excessive enrichment or "eutrophication" may lead to conditions that are ecologically catastrophic as well as aesthetically displeasing.

Criteria for early warning of the deteriorating health of estuaries from excessive nutrient enrichment are usually considered to be the availability and concentrations of the nutrients themselves and their increase in the water, but such data may be misleading. Nutrients that are growth limiting are usually assimilated as quickly as they become available and reside in the tissues of the biota. Those that are not growth limiting may remain in the dissolved state in the water but are not, then, directly relatable to "eutrophication." A more reliable index of "eutrophication" may be the direct increase of phytoplankton or other plant life (e.g., seaweeds or higher plants, in some cases). However, the relationship between nutrient input, uptake kinetics by the phytoplankton and other autotrophs, and primary production and standing stocks of the plant communities and the herbivores that feed on them are an extremely complex series of interactions for which there are no simple indices.

One of the complicating factors is the identification of the rate-limiting nutrient(s) in estuaries. This is generally agreed most often to be phosphorus in the freshwater environment and nitrogen in the ocean, but it may be either in estuaries and may vary temporally and spatially in a given estuary. If runoff from fertilized farmland is the principal source, the phosphorus often becomes bound to the soil and becomes limiting in the estuary. If wastewater is the source, it is usually deficient in nitrogen relative to phosphorus and nitrogen becomes the growth limiting factor. Thus sources, routes, and rates of nutrient input are important basic data for the study of each individual estuary.

There are growing indications, however, that gross nutrient input is not the key to the onset and development of the unhealthy characteristics of estuaries usually associated with the term "eutrophication." As noted above, stimulation of the right kind of phytoplankton (e.g., centric diatoms, certain flagellates) leads on to increased production of pelagic and benthic finfish and invertebrates, including those of direct value to man. Upwelling areas that support the most productive fisheries on Earth are no less "eutrophic" by any definition of the term, and estuaries that are enriched by incursions of subsurface offshore water via a two-layered circulation are usually highly productive, healthy ecosystems. Enrichment from other sources such as wastewater or other anthropogenic activities, however, often results in blooms

of nonmotile green and blue-green algae, and sometimes toxic flagellates, that are not readily utilized as food by higher trophic levels and that accumulate in the water or on the bottom where they create undesirable aesthetic and damaging ecological effects. The same major nutrients may be added in both cases, but their chemical speciation (ammonia, urea, or dissolved organic nitrogen in sewage versus nitrate in deep ocean water), the presence or absence of other nutrients such as silicate that is required by diatoms, the presence of accompanying toxic contaminants such as copper in sewage that inhibits diatoms and favors that of other algae, and the concurrence of enrichment with low salinity and high temperature at the heads of estuaries, where discharges are often located, all may favor the growth of undesirable versus desirable species of algae.

Thus "eutrophication" is a qualitative as well as a quantitative characteristic of estuaries, resulting from a number of interacting factors of which the input of major nutrients is but one. The study of these factors and their interactions is therefore an important area of research needed for understanding and diagnosing the early stages of one of the major causes of the deterioration of estuarine health.

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3

VARIABILITY OF CIRCULATION AND MIXING IN ESTUARIES*

INTRODUCTION

This chapter provides a brief review of *some* of the important recent developments in our understanding and changes in our perceptions of physical circulation and mixing processes within estuaries. It also presents suggestions concerning future research needs in estuarine dynamics. Because much of the current interest in estuaries has focused on their biological, chemical, and geologic features, more interdisciplinary study of estuaries is called for, and the following discussions tend to emphasize those advances in kinematics and dynamics that are more directly relevant to the description of distributions of biomass, chemical constituents, particulate matter, and pollutants. One objective here is to show through examples that developments in our understanding of the physical forcing and response characteristics of estuaries provide us with at least some of the tools needed to deal with complexities associated with the biological, chemical, and suspended matter distributions in estuaries.

*This chapter was largely developed by a subpanel on circulation and mixing, which consisted of the following: Robert E. Wilson, State University of New York, Stony Brook, *Subpanel Leader*; William Boicourt, The Johns Hopkins University; Malcomb Bowman, State University of New York, Stony Brook; Leonard Haas, Virginia Institute of Marine Science; Takashi Ichiye, Texas A&M University; Donald W. Pritchard, State University of New York, Stony Brook; Maurice Rattray, University of Washington; Jay L. Taft, The Johns Hopkins University; and Mary G. Tyler, University of Delaware.

Another objective is to suggest that interdisciplinary research can serve not only as a platform for evaluation and refinement of existing ideas concerning estuarine circulation and mixing processes but also as a stimulus for significant advances into dynamics and kinematics.

RECENT DEVELOPMENTS AND RELATED RESEARCH NEEDS IN ESTUARINE DYNAMICS

Estuaries are typified by freshwater river and groundwater inputs and saline source waters that require a net outflow through an estuary and provide a longitudinal density gradient to drive a vertical circulation given sufficient estuary depth. Many, if not most, estuaries have appreciable tides and tidal currents that in addition to creating oscillatory variations in properties represent the dominant energy source for turbulence and mixing and contribute to the nontidal circulation through nonlinear effects. Important modifying effects can be provided by surface wind stress over the estuary and by sea-level variations at the mouth produced by meteorological forcing of the adjacent coastal waters.

All the above forcing mechanisms may exhibit temporal and/or spatial variability. Time scales range from geologic periods to seconds, but the range of most interest in terms of estuary-wide response usually lies between the annual and the tidal period. The event time scale of several days associated with meteorological disturbances is likely to result in the most complicated estuarine responses, for it is both broad banded and in the range of the natural time scales for many estuaries.

The spatial scales of variation of forcing mechanisms other than wind are fixed by the boundaries of the estuary, although even here the density variations at the mouth of deep estuaries may exhibit important spatial structure. The important spatial scales may range from the order of a kilometer to hundreds of kilometers.

The estuarine circulation processes of largest spatial scale and longest time scale is the "mean" or nontidal circulation, which is composed of components derived from the net river runoff, the longitudinal density gradient, laterally varying depth-dependent friction, the surface wind stress, and the characteristics of the tide itself; other processes governing the distribution of variables can be categorized as either stirring or mixing, the former resulting from resolved or deterministic motions

and the latter from unresolved or statistically described motions. The former would include nontidal longitudinal, lateral, and vertical circulations, and the latter would include bottom-generated turbulence produced by tidal currents, mean-flow shear-generated turbulence, boundary mixing from density currents or internal wave breaking, and shear and breaking of surface waves generated by the wind.

The foregoing circulation and mixing processes respond to the temporal and spatial variability of the forcing, and, in addition, the mixing and momentum flux processes produce motions of shorter time and spatial scales. While these smaller scales may not be of interest in themselves as part of the overall estuarine description, they must be investigated before their effects on the larger-scale processes can be predicted in terms of some suitable parameterization.

In a selective review of research in the United States on the dynamics of motions in estuaries, Carter et al. (1979) point to three of the most important research advances as an appreciation of

1. The variability in time and space of the nontidal motion in estuaries.
2. Nonlocal forcing of nontidal variations in water level and motion in estuaries and other coastal water bodies.
3. The effects of the nonlinear field acceleration terms on the tidal averaged dynamics of estuarine circulation.

This abbreviated list, which emphasizes the importance of temporal and spatial variability in both physical forcing and response characteristics, can certainly be expanded. In addition to temporal variability in nontidal circulation associated with both local and nonlocal meteorological forcing, Elliott et al. (1978) demonstrated the importance of forcing at the head of an estuary due to time-variable river discharge in producing temporal variations in nontidal circulation and in the distribution of water properties.

As far as spatial variability in circulation patterns is concerned, there is increased awareness of the importance of dimensional and topographic controls. There is substantial evidence that our usual two-dimensional (vertical and longitudinal) simplification of estuarine circulation is inadequate and that a nonnegligible portion

of the longitudinal transport is associated with effects in the cross-estuary (lateral) direction. While the lower layer in a two-dimensional regime is topographically limited by channels, the upper layer can be complex, exhibiting jet flows, stationary eddies, and sizable lateral shears. The rotation of the Earth can cause significant lateral gradients in the larger estuaries. Topographically driven secondary flows have been well documented in rivers, but little is known about these circulations in stratified tidal estuaries.

In addition to this relatively persistent spatial structure, which is associated with irregular topography, there is increasing evidence for the existence of small-scale and often short-lived fronts and related spatial features and for their possible biological consequences (Figure 3.1).

Temporal and spatial variability have so far been discussed primarily in connection with nontidal circulation--an advective process. The importance of both temporal and spatial variability can, however, also be considered in relation to mixing processes. Here we will consider specifically tidal mixing and its effect on water-column stability. In this case temporal variability is associated primarily with spring-neap variations in mixing intensity and spatial variability in mixing intensity within the estuary.

Tidal mixing intensity can be represented rather simply in terms of bulk parameters, tidal current amplitude, and mean depth. The more general problem of representing turbulent transport of mass and momentum remains a fundamental problem in estuarine dynamics and kinematics of considerable practical importance. Fluid dynamicists refer to this as the closure problem in turbulence; meteorologists or oceanographers may call this "parameterization"; and numerical modelers call it "subgrid simulation."

The vertical turbulent flux of momentum and mass results from correlation of the vertical fluctuation velocity with the horizontal fluctuation velocity or concentration fluctuation. In contrast to the horizontal fluctuation velocity and the concentration fluctuation, generation of the vertical fluctuation velocity, itself, seems to be caused by different mechanisms near the surface, in the mid-depth and near the bottom of estuaries. Near the surface, the vertical fluctuation velocity may be mainly generated by the wind-generated surface waves and by the shear in the near-surface flow. In the mid-

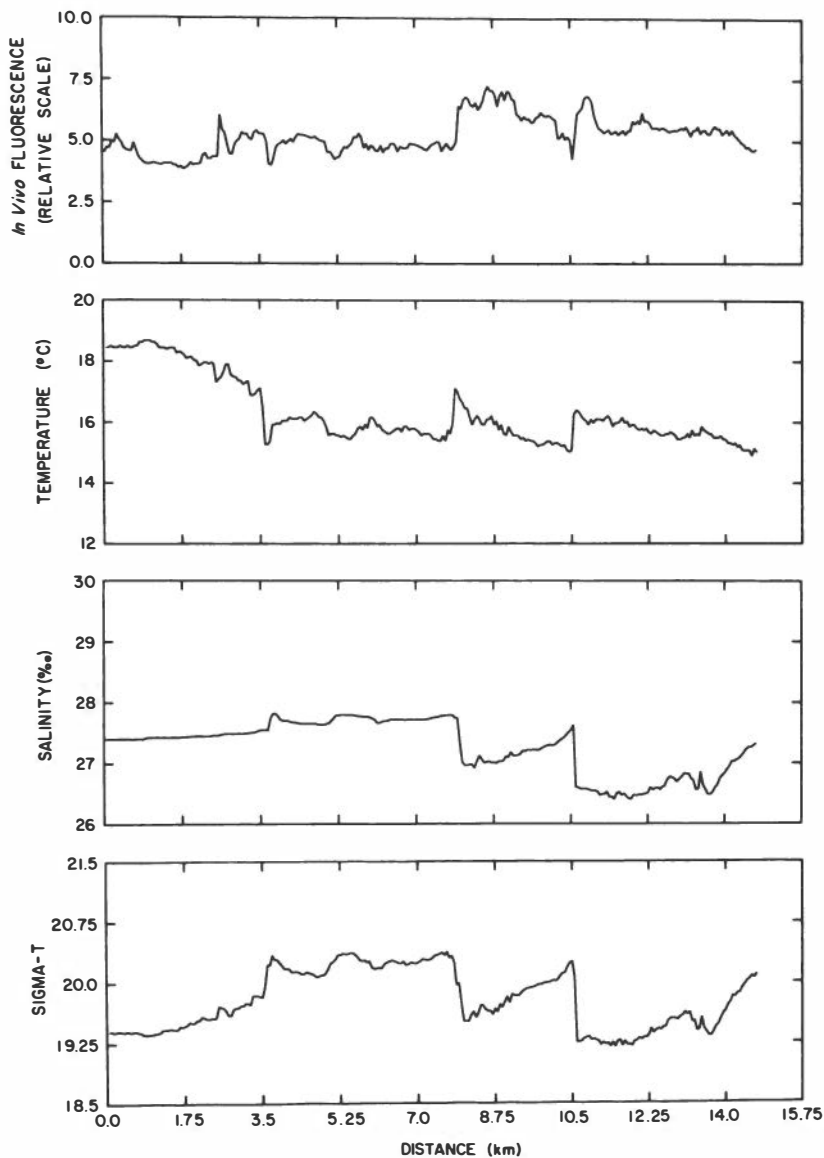


FIGURE 3.1 Small-scale structure in water properties at 1 m along a horizontal transect in Long Island Sound from 40° 59' N, 73° 04' W to 41° 07' N, 73° 05' W on 22 June 1977. Fronts at approximately 7.5 km and 10.5 km are from remnant river plumes; at 3.5 km is a stationary tidal front off Long Island.

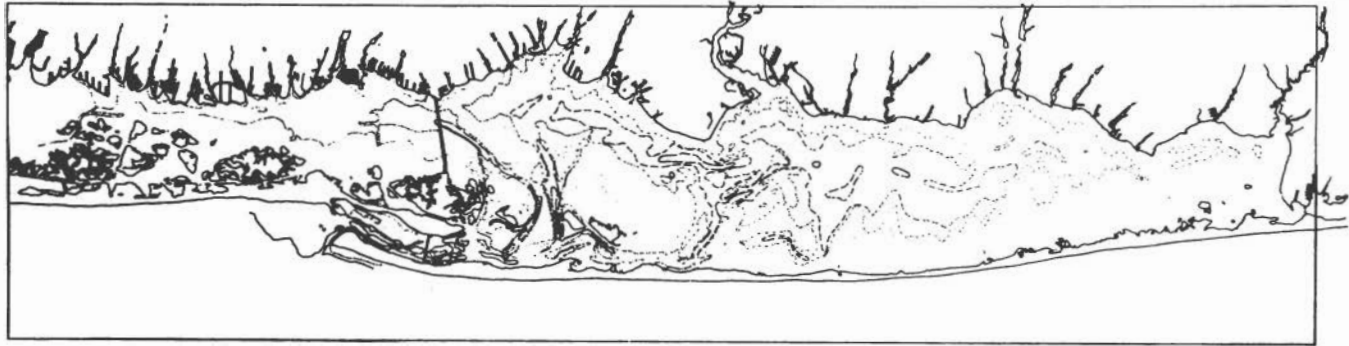


FIGURE 3.2 Bottom topography in a 60-km-long reach of Great South Bay, a bar-built estuary the south shore of Long Island, New York. MLW depth is 1.3 m; dotted isobath is 1 m.

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FIGURE 3.3 Numerical simulation of Lagrangian drift for a total of ten water parcels for a period of 30 days in the reach of Great South Bay shown in Figure 3.2.

depth the energy source of the vertical fluctuation velocity may be the current shear and the internal waves. Near the bottom, the topographic features combined with the current shear may be the main cause of the vertical fluctuation velocity.

Horizontal turbulent transports of mass and momentum tend to be associated with variations in velocity and concentration with time and space scales larger by orders of magnitude than their vertical counterparts.

We have so far emphasized appreciation of temporal and spatial variability in circulation and mixing processes in connection with important recent developments. Of possibly even more fundamental importance is the increased appreciation for the utility of a Lagrangian (with a moving coordinate system) description of the motion within tidal areas such as bays and estuaries rather than a Eulerian (with a fixed coordinate system) description, especially when considering the net displacement over a tidal cycle of dissolved and suspended materials. The movement of dissolved and suspended materials within an estuary is inherently a Lagrangian process, and for many purposes the Lagrangian trajectory is the representation most useful for understanding biological, chemical, and sedimentary processes and more relevant to the distributions of biomass and chemical constituents.

A problem of special importance is the residual non-tidal Lagrangian drift of a particle within an estuary in which tidal currents are spatially nonuniform and which is forced both locally and nonlocally at subtidal frequencies. In this case the residual Lagrangian drift will be strongly affected by an interaction between the spatially nonuniform tidal stream and the spatially and temporally variable (at subtidal frequencies) residual Eulerian velocity field.

Numerical modeling can provide a focus for many of the physical processes described above. To illustrate this point, we consider some numerical simulations of the depth-mean horizontal circulation patterns within Great South Bay (Figure 3.2), a bar-built estuary on the south shore of Long Island. The bathymetry is shoal (average depth 1.3 m, relative to mean low water) and spatially complex. Its surface area-to-volume ratio makes it highly susceptible to local wind forcing, and because it communicates directly with the adjacent continental shelf through four inlets, it is forced by both tidal and subtidal sea-level fluctuations on the shelf. Figure 3.3 shows a limited number of Lagrangian trajectories for a 30-day

numerical simulation with a finite-element model. These simulations were performed with the objective of tracing the time history of clam larvae within the bay during that time they are suspended within the water column. They are presented to emphasize the following basic points:

1. Realistic simulations must be of sufficient length to cover the primary flow variability due to local meteorological forcing, fluctuations in freshwater inflow, and forcing by subtidal sea-level changes on the adjacent shelf.

2. Simulations must be of sufficient resolution to represent adequately effects due to variations in bathymetry and to be of value to users concerned with transport processes. In the simulations shown, for example, the Lagrangian trajectories are spatially very complex and simulations on the coarse grid would have provided a poor representation of the structure of the "true" residual drift field.

The residual nontidal Lagrangian drift as represented by these trajectories is dramatically different from that which might be inferred from the residual Eulerian velocity field and even from the sum of the residual Eulerian field and the Stokes velocity field.

PROCESS-ORIENTED INTERDISCIPLINARY RESEARCH IN ESTUARIES

The nature of the developments in our basic understanding of physical circulation and mixing processes, more specifically, in our appreciation of the space and time scales involved, has enhanced our ability to identify and describe specific physical processes responsible for maintaining biological and chemical distributions and for producing temporal and spatial variability in these distributions. The following discussions are presented to show, by example, that interdisciplinary research involving the study of physical processes controlling the distributions of biomass and chemical constituents can provide insight into the nature of the physical processes that would otherwise be unobtainable, or nearly so.

A first example relates to effects associated with spatial variations in the intensity of tidal mixing and stationary tidal fronts in estuaries. Within shallow estuaries spatial variations in mixing intensity can give rise to changes in water-column structure from mixed to

well stratified in a few hundreds of meters or less. These variations are important to marine productivity since the same physical driving mechanisms that control the stratification also determine the availability of light and nutrients to the phytoplankton.

One approach to the problem of predicting vertical stratification in tidally dominated shallow seas is through the concepts of mixing energetics. During the heating season, there is a buoyancy flux through the sea surface due to the insolation radiation. This leads to warming of the subsurface layers and a tendency of the water column to stratify, lowering the potential energy of the column relative to the mixed state. Opposing this is the generation of bottom turbulence from tidal streaming. Simpson and Hunter (1974) showed that this dynamic imbalance can be expressed through a stratification index, h/u^3 (h is water depth and u is mean spring tidal current amplitude). The value of this index determines whether a coastal ocean region will remain mixed throughout the summer or whether at some stage of the heating season, onset of stratification commences and a thermocline develops.

A study was initiated in 1978 in Long Island Sound to see if a similar approach might prove fruitful in a partially mixed estuary when the observed stratification was almost entirely due to the two-layered gravitational circulation patterns, i.e., where the buoyancy flux into a given area was due to horizontal advection rather than a vertical input of buoyancy due to insolation. The Simpson-Hunter (1974) theory was extended to an estuarine environment (Bowman and Esaias, 1981) and was shown that as long as the ratio of upstream to downstream mean salinity was close to unity (equivalent to stating that the horizontal buoyancy flux is constant along the axis) then the h/u^3 index should be applicable.

Results of an extensive mapping cruise made in September 1978 in Long Island Sound are shown in Figure 3.4, where bulk stratification (σ_T difference bottom to top divided by depth) is used as a measure of water-column stability.

Contours of h/u^3 , derived from current measurements made by the National Ocean Survey, are illustrated in Figure 3.5. There is a remarkable similarity in the two maps. The $\log_{10} h/u^3 = s = 1.25$ to 1.5 contours appear to define accurately the limits of mixed waters in the eastern and central regions. The main eastern tidal channel is flanked by high s (>2) regions of stratified

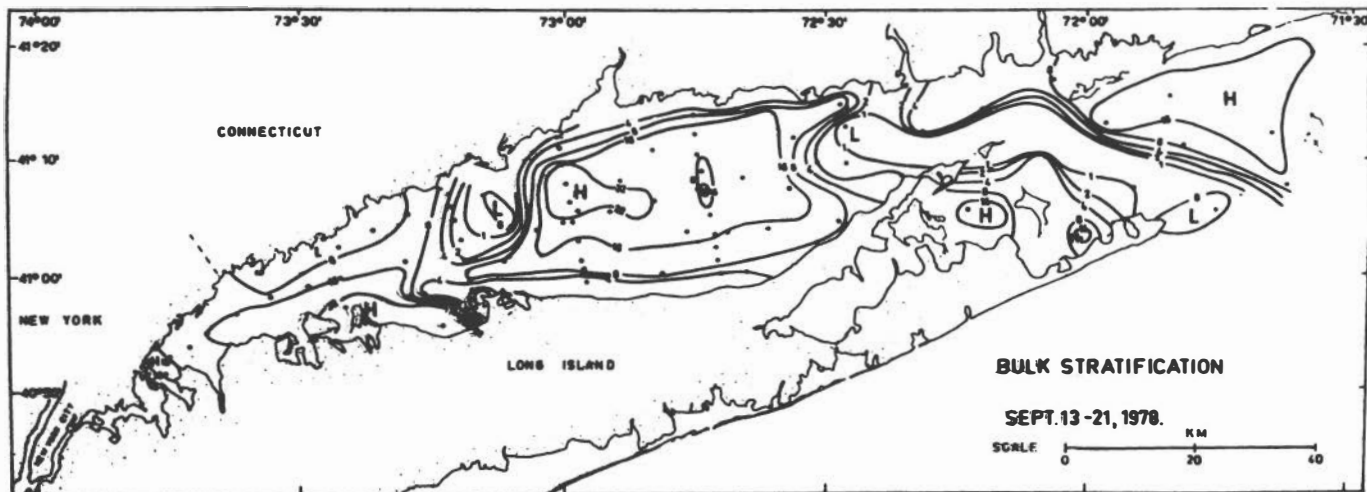


FIGURE 3.4 Bulk stratification (σ_T/h) map of Long Island and Block Island Sounds, September 13-21, 1978 (from Bowman and Esaias, 1981).

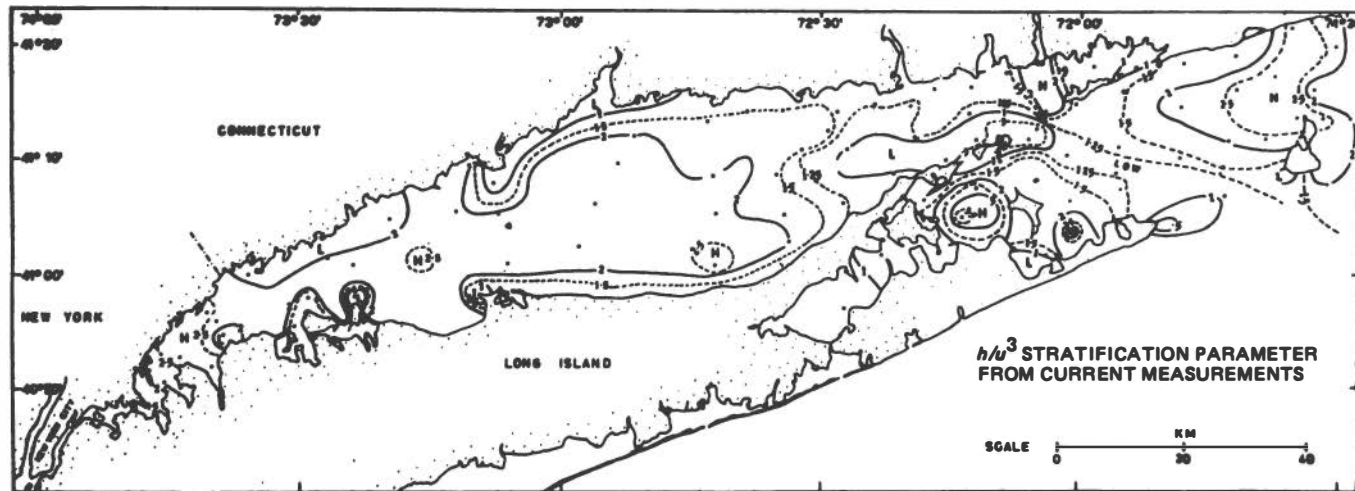


FIGURE 3.5 The h/u^3 stratification index derived from NOS current measurements and bathymetric charts (from Bowman and Esaias, 1981).

water. The central, stratified basins of Long Island Sound appear as a region of high s , with coastal mixing zones paralleling the shoreline and a major transverse front located at its eastern limits.

The distributions of phytoplankton observed on several sampling cruises are clearly related to these patterns of tidal mixing and stratification. Further research is needed to understand the temporal response of phytoplankton to these spatial patterns of mixing and stabilization and to test the usefulness of the method in other partially mixed estuaries.

A second example relates to effects associated with temporal variations (spring-neap) in the intensity of tidal mixing within partially mixed estuaries. Recently it has been recognized that some estuaries oscillate between stratified and destratified conditions on a fortnightly cycle that correlates with neap and spring tides, respectively. For example, the cycle has been observed in a variety of estuaries including the James, York, and Rappahannock Rivers (Haas, 1977), the St. Lawrence (Sinclair, 1978), Aulne and Gironde estuaries (Allen et al., 1980), Charleston Harbor (Wastler and Walter, 1968), and possibly Puget Sound (Winter et al., 1975) and Saanich Inlet (Takahashi et al., 1977). The stratification-destratification process encompasses the entire estuary, not just a small segment, and affects the fundamental hydrographic-circulation condition of the estuary. The time scale of the cycle is long enough for significant chemical and biological responses to occur. In the York River estuary the stratification-destratification cycle is strongly expressed and is predictable (Haas et al., 1980; Figure 3.6).

Other than its association with the neap-spring tidal cycle, little is known about the hydrographic processes causing the observed oscillation between stratified and homogeneous conditions. However, the fact that the stratification state of an estuary can be altered so dramatically on such a short time scale suggests that further research on this process will significantly advance our basic understanding of the hydrodynamics of estuarine systems in general.

Other aspects of the estuarine ecosystem are also affected by the stratification-destratification process. In the York River dissolved oxygen and inorganic nutrients, both important water-quality parameters, have been shown to vary systematically with the stratification state (D'Elia et al., 1980; Webb and D'Elia, 1980). During

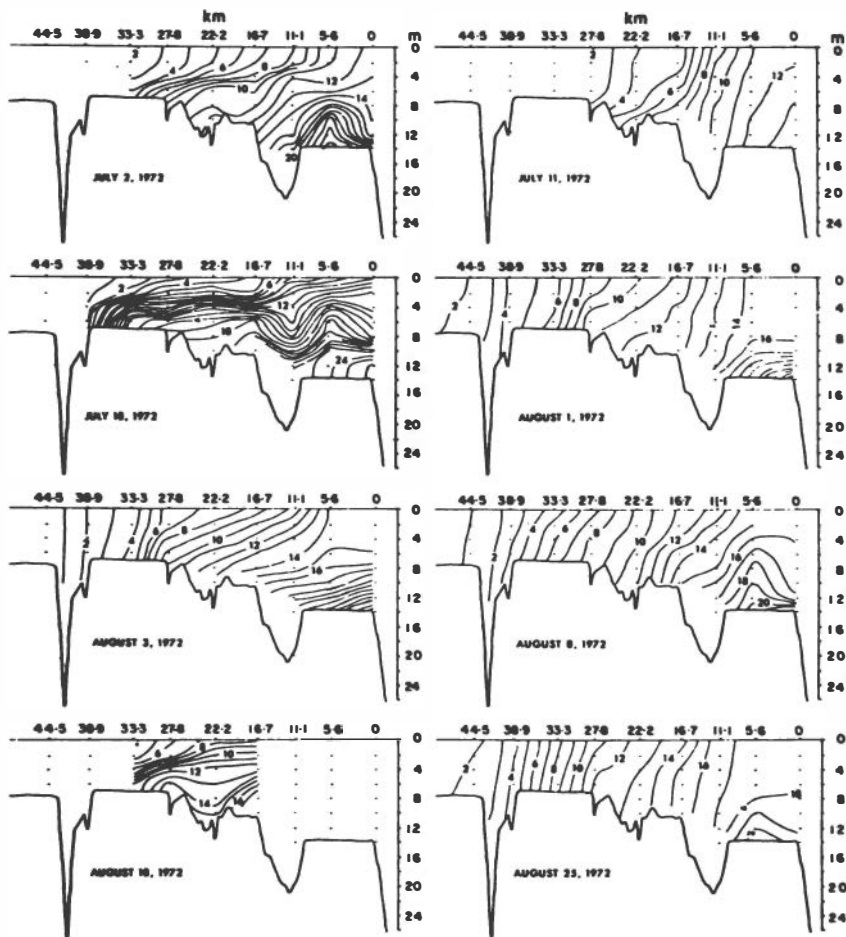


FIGURE 3.6 Vertical sections of salinity along the longitudinal axis of the York River Estuary showing the variation in water-column stratification associated with spring-neap variations in tidal current (from Haas et al., 1980).

stratified conditions in the summer months, water below the halocline becomes simultaneously anoxic and enriched in both ammonium and phosphate, both conditions apparently the result of benthic remineralization. This condition is altered fortnightly by the mixing of oxygen-rich, nutrient-poor surface waters with oxygen-poor, nutrient-rich deep waters. Thus, spring-tide associated destratification events serve to replenish periodically oxygen to the

deep water and nutrients to the surface waters. It is apparent, therefore, that the spatial and temporal variation in both oxygen and nutrient concentration is directly related to the stratification-destratification cycle and that this process may have a significant impact on biological processes of the system.

The last several years have witnessed a growing awareness of the episodic nature of phytoplankton processes and their relationship with physical processes in the oceans (McGowan and Hayward, 1978). Analogous events may be occurring in estuaries as well. For example, several investigations noted sequential phytoplankton blooms in estuaries associated with alternating periods of stratification-destratification (Sinclair, 1978; Takahashi et al., 1977; Winter et al., 1975). These observations suggest a direct association between phytoplankton and hydrographic processes in estuaries that heretofore has not been widely recognized. Other biological processes that may be keyed either directly or indirectly to stratification-destratification cycles include the timing of finfish-shellfish spawns, the survival of larval forms, phytoplankton species succession, fish migrations into or out of an estuary, the conservation or "trapping" of larval forms in an estuary, and zooplankton life cycles.

The spatial and temporal distribution of abiotic constituents as well may be regulated by the hydrographic process in question. Allen et al. (1977, 1980) proposed that the longitudinal distribution of sediments (i.e., the turbidity maximum) in the Gironde and Aulne estuaries is regulated by the observed cycle of neap- and spring-tide-associated stratification and mixing in these estuaries. This is an alternative hypothesis to the prevailing concept that estuarine turbidity maxima occur in the zone of net, zero nontidal flow in an estuary.

A third example, presented from the more general perspective of nutrient dynamics in estuaries, points to the importance of a number of longitudinal and vertical mixing processes. These include the longitudinal dispersion of nutrients contained in runoff, the maximization of vertical concentration gradients between water and sediments by horizontal advection, and vertical mixing across a pycnocline.

Nutrients entering estuaries from rivers may behave conservatively during periods of high flow when dilution with seawater is more rapid than phytoplankton uptake. This often occurs when nutrient concentrations are high. Nitrate input to the Chesapeake Bay during spring behaves

conservatively through most of the region north of the Potomac River. Linear regressions of nitrate versus salinity for several years in Chesapeake Bay show that slopes and intercepts change from month to month expressing source concentration changes. While this approach is approximate, with judicious choice of coefficients and intercepts estimated from historical data, it is possible to model some major nutrient inputs nearly as well as salinity.

Phytoplankton nitrogen demand appears to be satisfied by ammonium nitrogen (McCarthy et al., 1977; Taft et al., 1978) so that turbulent mixing with low-nitrate ocean water is the principal cause of decreasing nitrogen concentration. Analogous situations exist in the Hudson River estuary, Columbia River, Mississippi River, and others.

As sediment accumulates, so do nutrients that are remineralized from organic particles in the sediment. The nutrients dissolved in interstitial waters can diffuse back into the overlying waters, as long as the concentration of a given nutrient in the overlying waters is less than that in the interstitial waters. In this way nutrients entering the estuary from the land are augmented by remineralized nutrients from sediments so that the instantaneous mass of nutrients per unit volume steadily increases.

The input rate from sediments varies for different nutrient species. Ammonium probably diffuses at a constant rate according to concentration gradient. Nitrate may diffuse upward when the near-surface sediment is aerobic (Taft et al., 1978), but benthic chamber measurements have shown nitrate loss to the sediments (Boynton et al., 1980). Phosphate diffuses out at oxygen concentrations of less than about 1 ml/liter. At higher O₂ levels, phosphate may be bound to iron hydroxides (formation of ferric phosphate) and remain at the sediment surface.

Temperature-dependent remineralization of nutrients in the sediments can be approximated from the Arrhenius rate law expression

$$\ln \frac{r_2}{r_1} = \frac{E_a}{RT},$$

where r_1 is the rate at a given temperature, E_a is the apparent activation energy, R is the gas constant, and T is temperature. Sulfate reduction and ammonium remineralization have been treated this way (Goldhaber et al.,

1977; Jorgensen, 1977; Aller and Yingst, 1979). Once released from organic material, nutrients in interstitial waters may diffuse upward. Under conditions of deep-water anoxia both ammonium and phosphate diffuse into the overlying water according to

$$J = \phi D_s \left(\frac{\partial C}{\partial z} \right)_{z=0},$$

where J is the flux, ϕ is sediment porosity, D_s is diffusivity for nonbioturbated sediment or eddy diffusivity for biologically disturbed sediments, and $(\partial C/\partial z)_{z=0}$ is the interstitial water-concentration gradient (Berner, 1971). Krom and Berner (1980) determined diffusion coefficients for ammonium and phosphate in sediments as $D_s(\text{NH}_4) = 9.8 + 2.0 \times 10^{-6} \text{ cm}^2/\text{sec}$ and $D_s(\text{PO}_4) = 3.6 \times 10^{-6} \text{ cm}^2/\text{sec}$. Thus, estimates for remineralization rates and release rates from sediments can be made. Advection in the overlying water transports nutrients horizontally away from the sediments, and turbulence mixes them vertically. In this way gradients are maximized and diffusive fluxes maintained from interstitial to overlying water.

At present, estimates for release rates from sediments are better than estimates of mixing through the water column. This is because sediment release may be adequately modeled as a steady-state process, whereas circulation of the overlying water is not in steady state. However, water circulation is primarily responsible for bringing phytoplankton and nutrients together.

Under conditions of strong stratification, nutrients (predominantly ammonium and phosphate) accumulate in the lower layer. The pycnocline may or may not coincide with the bottom of the euphotic zone. Phytoplankton with limited mobility are thus virtually isolated from direct contact with the deep nutrient pool and depend entirely on physical mixing across the density discontinuity for new nutrients to support biomass increases. Dinoflagellates are an exception because they may migrate vertically to the boundary and take up the nutrients available there. Phytoplankton with limited mobility can be exposed to nutrients in two ways. First, new nutrients from below the pycnocline can be mixed or diffused up or the organisms can be mixed downward. In actuality, both probably occur, but rates are poorly defined. Thus the biomass or standing crop of phytoplankton is closely linked to the intensity of mixing within the upper layer and to the intensity

and characteristics (e.g., temporal variability) of mixing across the pycnocline. There is a need to further examine mixing rates in estuaries with tracers other than salinity and density. Errors in estimating diffusivities and transient mixing events may have significant impact on biological and chemical parameters but remain undetected by steady-state mixing or diffusion calculations.

A final example is presented to show that study of physical processes controlling biological distributions can serve to demonstrate the integrated effects of the interaction of transport processes operating over a broad range of space and time scales. It suggests also that biological species can be effectively used as a tracer to distinguish specific advective and nonadvective transport processes responsible for producing observed distributions.

Tyler and Seliger (1978, 1980) described the spatial distribution of plankton, primarily the dinoflagellate *Prorocentrum*, within the Chesapeake Bay in relation to the regulating physical processes. They described the seasonal distribution and transport of organisms by the "mean" nontidal density driven flow. Seaward flowing populations within the surface layers are transported into the bottom waters at frontal regions near the mouth of the Bay where the pycnocline intersects the surface. Algae are accumulated within the frontal region, giving rise to a surface patch as well as to concentrations entrained along the frontal interface (Figure 3.7A). A fresher from the northern Bay then causes this vertical discontinuity to become a horizontal pycnocline along with the associated algae (Figure 3.7B). These populations are then transported up estuary at depth by the nontidal flow and returned to the surface layers in the northern Bay. This process is inferred from a series of vertical sections along the longitudinal axis of the Bay (Figure 3.8): Figure 3.8B shows the low stratification and surface concentrations in the lower Bay in mid-winter; in early spring there is an onset of stratification and a transfer of algae to the bottom waters (Figure 3.8C); during the late spring organisms are transported to the northern Bay under high stratification (Figure 3.8D); by summer the delivery of algae to the northern Bay is complete (Figure 3.8E).

In addition to relating concentration distributions to "mean" nontidal circulation patterns, Tyler and Seliger (1978, 1980) considered low-frequency variability in algae distributions and the response to variability in physical forcing. They described the temporal variability in the

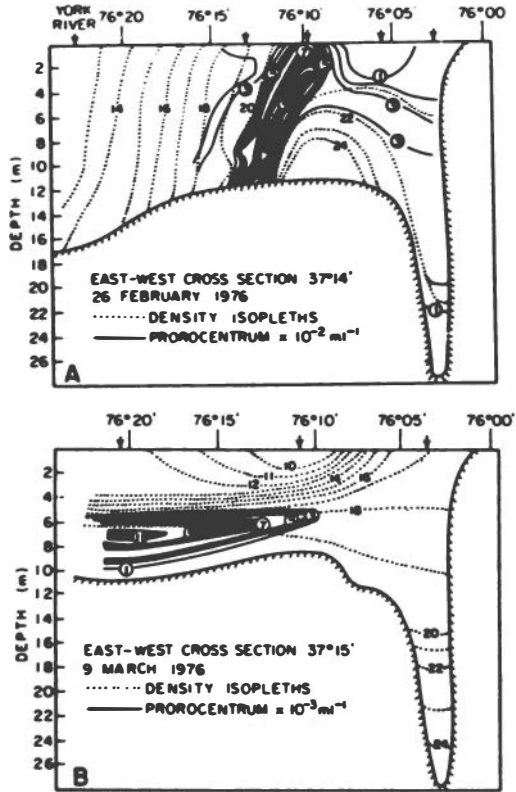


FIGURE 3.7 East-west cross section across the Chesapeake Bay looking northward (at York River entrance) showing displacement of *Prorocentrum* originally accumulated at frontal interface A downward beneath pycnocline B to produce a subsurface maximum (from Tyler and Seliger, 1980).

first appearance of algae accumulations along the frontal region in the lower Bay (February through March) and subsequent appearance of subsurface concentration maxima (February through June). They related variability in the first appearance of algae blooms in the upper Bay to the apparent variability in the intensity of subsurface density-driven transport that was produced, in turn, by variations in freshwater inflow.

Tyler and Seliger also showed that certain aspects of the spatial variability in the distributions of planktonic organisms are strongly related to the spatial structure of circulation and mixing patterns. In addition to algae

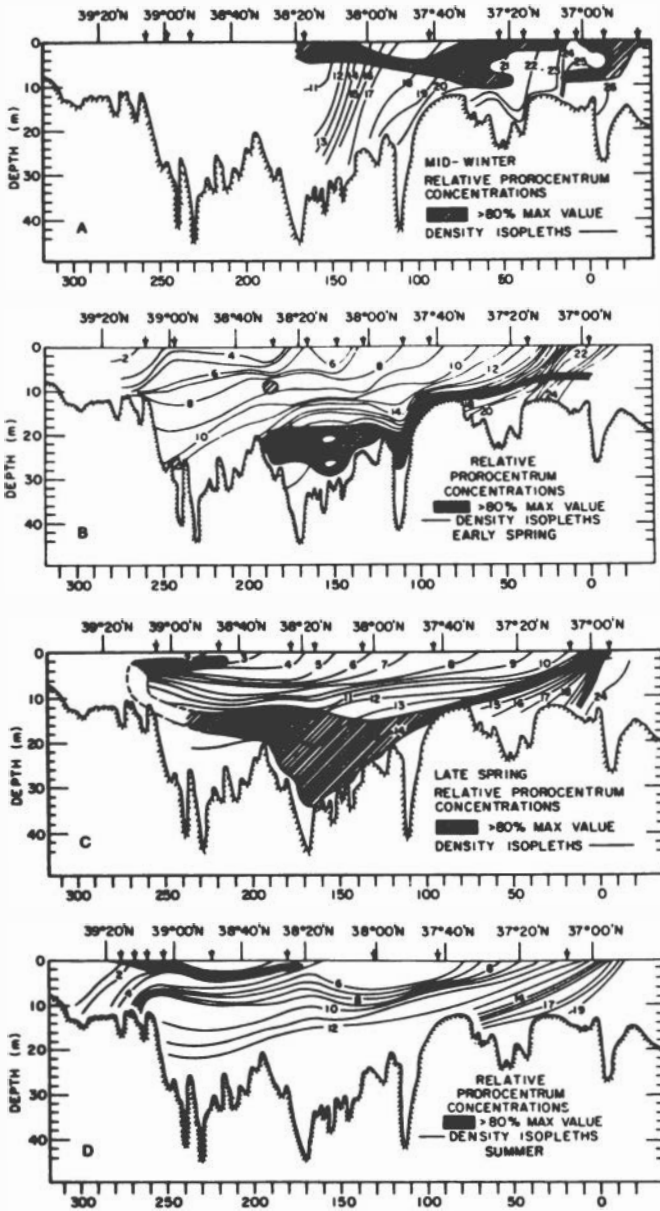


FIGURE 3.8 Series of vertical sections along the longitudinal axis of Chesapeake Bay showing the northward transport of depth of *Procoentrum* by the large-scale density driven flow (from Tyler and Seliger, 1978).

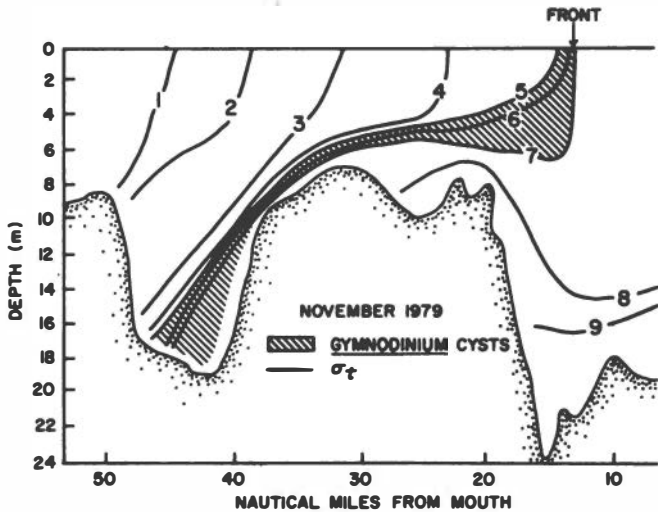


FIGURE 3.9 Longitudinal section of Potomac River showing the relation of longitudinal distribution of benthic *Gymnodinium* cysts and intercept of halocline with bottom.

accumulations within the frontal regions in the lower Bay, they demonstrated, for example, that the patchy distribution of benthic beds of resting cysts of the red tide organism *Gymnodinium neboni* in the Potomac Estuary can be delineated in the longitudinal direction by the extent of salt wedge penetration (Figure 3.9); in the lateral direction highest cyst concentrations were found where the pycnocline intersects the bottom on the south side of the estuary (Figure 3.10). They also discussed evidence for the importance of the smaller-scale frontal processes

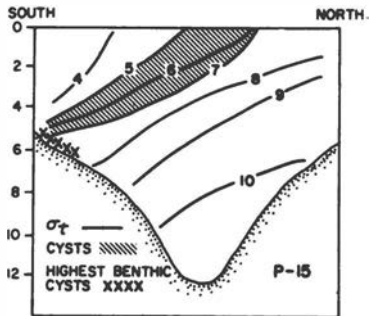


FIGURE 3.10 Lateral section across the Potomac River showing the relation of lateral distribution of benthic *Gymnodinium* cysts and intercept of halocline with bottom.

superposed on the larger-scale circulation patterns to the spatial distribution of plankton.

More general questions that appear answerable by this type of interdisciplinary research revolve around topics of patchiness of phytoplankton, bacteria and zooplankton, seasonal succession, productivity and bloom formation, and community structure.

Such research involving examination of biological and chemical constituent distributions should provide considerable insight into mechanisms of transport by both advective and nonadvective processes and into the effects of temporal and spatial variability in these transport processes on the distributions.

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4

SUSPENDED AND DISSOLVED MATTER IN ESTUARIES

INTRODUCTION

The sources of materials to the estuarine and coastal zone are both natural and anthropogenic. The fates of these dissolved and particulate substances, however, are controlled by the general properties of the system: geometry, currents, and organisms. Thus the study of the "physiology" of the system is fundamental to the identification, understanding, and remedying of any "pathology" of the system resulting from human actions.

Dissolved and particulate substances in estuaries, including both inorganic and organic materials, can be supplied by upland drainage, from the continental shelf, from atmospheric fallout, by shore and bottom erosion within the estuary, and by organisms within the system.

*This chapter was largely developed by subpanels on (1) suspended particulate matter and (2) fate of materials, which consisted of the following: (1) Robert B. Biggs, University of Delaware, *Subpanel Leader*; James M. Coleman, Louisiana State University; L. Eugene Cronin, Chesapeake Research Consortium; John Fischer, Clemson University; David H. Peterson, U.S. Geological Survey; and Jack Pierce, Smithsonian Institution and (2) Karl K. Turekian, Yale University, *Subpanel Leader*; Roy Carpenter, University of Washington; Christopher S. Martens, University of North Carolina; Willard S. Moore, University of South Carolina; Scott W. Nixon, University of Rhode Island; James Simpson, Lamont-Doherty Geological Observatory; and Herbert L. Windom, Skidaway Institute of Oceanography.

Suspended materials, as physical particles, can act as pollutants to organisms, by clogging gills or interfering with feeding, though most estuarine organisms are adapted to relatively high concentrations of suspended materials. Suspended materials can affect the aesthetics of estuarine waters, as high turbidity is regarded frequently as indicating pollution, at least for water-contact activities. The character and quantity of suspended solids has a direct effect on the quality and quantity of light reaching primary producers. Suspended solids serve as both a reaction substrate and as a carrier for a host of inorganic and organic pollutants, affecting both their form and fate.

The questions involved in understanding the fate of materials in the estuarine and coastal zone can be phrased as follows:

1. What is the riverine flux of dissolved and particulate substances? How does it vary with time in any one river, and what differences are there among rivers?
2. What reactions occur at the freshwater-seawater boundary to sequester or release chemical species to the ocean? What is the role, for example, of salinity changes and intertidal marshes in regulating the flow of dissolved species to the ocean?
3. What is the scavenging role of biological activity in the water column, in the resuspended sediments, and in the chemical precipitates of manganese and iron released from sediments?
4. How are sediments redistributed as the result of tidal currents and episodic storms? What is the net effect in the coastal zone of estuarine flow and wind-driven upwelling or downwelling on the accumulation or exportation of sediments?
5. What is the role of bioturbation in either releasing chemical species to the water or increasing the trapping efficiency of the sediment for the deposited elements?

Although there are many other questions that can be phrased to detail the answers more precisely, the above cover the main ones that have been the incentive for much innovative work done in estuaries in recent years. The answers to these questions are not entirely obvious.

TRANSPORTATION AND FATE OF REACTIVE CONSTITUENTS ASSOCIATED WITH PARTICULATE SUSPENDED MATTER

Natural weathering and erosion processes lead to river turbidity in the form of suspended-sediment load. The quantity of suspended sediment varies over several orders of magnitude, depending on the stage of fluvial development. Several small, natural, pristine rivers in the northeastern United States have concentrations of suspended solids ranging from 1 to 25 mg/liter as compared with pristine watersheds in the southwestern United States wherein suspended solids range from 10 to 50,000 mg/liter (U.S. Geological Survey, 1975).

Land uses such as agriculture, industry, and high-density housing may increase the susceptibility of land to erosion. The suspended-sediment contributions to streams can be highly variable. Contributions to the suspended-sediment load are known from industrial effluents, sewage-treatment effluents, parking-lot runoff, atmospheric fallout of particulate materials, and resuspension of materials already deposited. Soil-conservation practices and both large- and small-scale impoundments, may serve to reduce these high levels of suspended materials.

Concentrations of suspended matter in the open ocean are quite low, and gradients in estuaries typically show decreasing suspended matter concentrations in a seaward direction. Residual bottom currents are frequently directed up the estuary, contribute to the movement of sands into the mouth of estuaries and tidal inlets, and may transport near-bottom suspended materials upstream. Of the two potential source areas for suspended matter to an estuary, continental areas are much more important than the sea. Within the land-source area, a complex inter-relationship between environmental factors determines and controls the rate and volume of fine materials supplied to the estuaries.

Estimation of the net flux of material carried by fluvial processes to the ocean is difficult for a number of reasons, including the large degree of variation of properties of interest on a range of time and space scales within the estuarine zone of transition between freshwater and seawater. This is especially true for the fine particles (silt and clay), which accomplish much of the transport and accumulation of a number of substances of interest in marine chemistry. Tidal currents can carry large quantities of fine particles during maximum flow

velocities but may be slow enough during slackwater periods, in restricted embayments, or near the upstream end of two-layer estuarine circulation to effect deposition of a major portion of the suspended load. Resuspension may or may not occur, depending on many factors, and thus net fine-particle estuarine transport often consists of a long series of episodes of resuspension and deposition. Current velocity and suspended particle-mass or particle-size measurements, even over extended periods of time at a number of sampling stations are usually not sufficient to define the net flux averaged over periods of weeks to years.

The most successful approaches to defining net particle fluxes require measurements of water velocities and particle masses for guidance in choosing the most critical sampling locations, but they have depended primarily on budgets deduced from the distribution of "tracers" already in the system. Some of the most effective tracers for defining net fine-particle fluxes in estuaries are radio-nuclides, both natural and anthropogenic (Turekian et al., 1980). For example, plutonium derived from global fallout is strongly associated with soil particles and moves with fine particles carried in rivers and estuaries or deposited in the sediments. Radioactive cesium and other gamma-ray emitting radionuclides, derived from either global fallout or from low-level releases from nuclear facilities, such as commercial power plants, have also been used successfully to deduce net fine-particles transport and accumulation patterns of fine particles. Other tracers that have been valuable for these purposes include natural radionuclides such as ^{210}Pb , trace metals, and chlorinated hydrocarbons such as polychlorinated biphenyls.

In general, the fine particles carried downstream into an estuary have quite different relative concentrations of various potential tracer substances than of coastal marine particles, a portion of which may move into an estuary with the net upstream motion of the deeper water. Thus sediments accumulating in an estuary may include fine particles derived from both the freshwater and seawater end members. Resolution of the relative and absolute contributions of those two sources to the net fine-particle fluxes and sediment accumulation rates requires considerable effort to explore the differences in end-member tracer properties but is essential to provide a framework for deducing the behavior of other nonconservative substances in an estuary. This is especially true when

attempting to deduce the time history of net fine-particle and reactive substance fluxes over periods of years to decades.

An example of the use of chemical tracers in understanding the role of estuaries in modifying the riverine flux of materials to the ocean has been the study of radium and barium in these systems. Five years ago we had little understanding of the way reactions within estuaries modify the fluxes of these elements to the ocean. Now we can make rather precise statements about the reactions to be considered and the expected interactions with other variables within the systems. Studies in the Hudson River-New York Bight, Narragansett Bay, Long Island Sound, Winyah Bay, Chesapeake Bay, and Mississippi River reveal that there is an initial desorption of Ra and Ba from riverine sediments entering the low-salinity reaches of the estuary as well as a continued flux of radium from sediments throughout the estuary. These reactions significantly augment the fluxes of Ba and ^{226}Ra and possibly ^{228}Ra to the ocean.

The transport, reaction, and fate of manganese in estuaries are more complex. Manganese enters the estuary as (1) dissolved Mn^{2+} , (2) coating of MnO_2 on particles, (3) Mn^{2+} adsorbed to particles, and (4) complexes with other dissolved materials, particularly humic acids. Within the estuary, processes occur that affect the concentration and distribution of Mn (Sholkovitz, 1978; Aller, 1980; Elderfield et al., 1981). The most important of these are thought to be (1) flocculation of organic acids, (2) desorption of Mn^{2+} from particulates, (3) burial and reduction of MnO_2 in sediments, and (4) oxidation of Mn^{2+} in the water column. It has been observed that the total dissolved and particulate Mn concentration in the water column in the estuary often exceeds the total concentrations of Mn in the river and ocean end members. The following Mn cycle has been postulated to explain this surplus Mn.

Particulate Mn enters the estuary and settles into anoxic sediments. Here MnO_2 is reduced to soluble Mn^{2+} , which diffuses into the overlying water and moves up the estuary with the incoming saltwater. As it mixes into surface waters, the Mn^{2+} moves toward the ocean in accordance with estuarine circulation. During transport, Mn^{2+} may be oxidized to Mn^{4+} or adsorbed onto particles that settle back to the bottom, where the cycle begins again. This cycle produces a net retention of Mn in the estuary, leading to concentrations.

Although the concept of Mn cycling and the estuary trap is fairly well established, numerous areas of active investigation remain. One major problem is to distinguish chemical speciation (especially Mn^{2+} from Mn^{4+}) in the various phases. A second problem involves determining the role of bacteria in geochemical cycles. Mn oxidation and reduction seem to be mediated by bacteria, although conclusive proof of the relative contributions of biological and inorganic processes remain to be demonstrated. Furthermore, we know little about how floods or storms affect the system. How rapidly will the cycle be re-established after major perturbations? What materials are responsible for complexing Mn? How strong are these complexes? What other metals or materials are carried through the cycle because they bind with MnO_2 and are not sequestered in reducing sediments?

A further example of the use of chemical tracers is the combination of analyses of trace organic compounds (aliphatic and polynuclear aromatic hydrocarbons--PAH) with analyses of radioisotopes in the same sediment and particulate samples from Pacific Northwest estuaries (Prahl and Carpenter, 1979; Prahl et al., 1980). ^{210}Pb fluxes have been used to validate *in situ* essentially 100 percent trapping efficiency of the type of sediment traps used to collect sinking particulates for aliphatic and PAH analyses. If the traps were quantitatively sampling the vertical fluxes the yearly vertical fluxes of aliphatic and aromatic hydrocarbons collected in the traps could be compared with the total annual depositional fluxes in the bottom sediments 50 m below. This comparison showed the following: (1) 2-8 times faster recycling of marine than terrestrially derived aliphatic hydrocarbons and (2) fluxes of all the PAH except possibly perylene in the sediments could be accounted for by sinking preformed into the sediments, with no measurable diagenetic formation or degradation after burial in the sediments. From the ^{210}Pb -derived sedimentation rates it has been shown that the large increases in PAH and aliphatic hydrocarbon concentrations in Puget Sound region sediments began around 1900, long before major sewage treatment plant and oil refineries began discharging their wastes into the Sound in the 1960s.

A final example is the use of the radioisotopes ^{65}Zn and ^{210}Pb to trace Columbia River effluent and sediments in the northeastern Pacific Ocean. The ^{65}Zn was artificially produced at the Hanford reactors. Its distribution in the adjacent Pacific Ocean showed how the Columbia

River plume responds to seasonal changes in winds (Cutshall et al., 1971). In summer predominately northerly winds drive the effluent to the south and offshore, while in winter predominately southerly winds drive the effluent northward and along the Washington coast. The highest ^{65}Zn activities in sediments showed that the sediment discharge was primarily transported to the north along the middle of the Washington continental shelf, with 30-40 percent being transported off the shelf. Profiles of activity of the natural radionuclide ^{210}Pb with depth in sediment cores on the Washington shelf (Carpenter et al., 1981) showed that two thirds of the estimated Columbia River discharge of suspended solids accumulates in the north-northwesterly trending midshelf silt deposit heading toward the Quinault submarine canyon (Figure 4.1). This picture of the shelf sedimentation patterns is in agreement with bottom current meter measurements and seabed drifter dispersal patterns.

Scavenging of Chemical Species from Estuarine and Coastal Waters

The scavenging time scales of "reactive" chemical species by suspended particles in the estuarine and coastal zone has been determined by following the distribution of two short-lived thorium isotopes produced in the ocean, ^{228}Th (1.9 yr) produced from ^{228}Ra (5.7 yr) and ^{234}Th (24 days) produced from ^{238}U (4.5×10^9 yr). The mean residence time relative to removal to the sediment has been shown to be dependent on the particle concentration in the water column. In Long Island Sound the residence time of ^{234}Th is about a day. In the New York Bight it increases almost monatomically with distance from shore from a few days at the inner Bight apex to tens of days as the continental shelf break is approached. Thereafter the open-ocean value of hundreds of days becomes operative.

Any chemical species behaving like thorium can be expected to follow suit and thus be found in the sediment pile soon after injection into the estuarine zone. The standing crops of ^{210}Pb and several pollutant-associated metals in sediments of Long Island Sound confirm this expectation.

The introduction of ^{234}Th , ^7Be , ^{210}Pb , and plutonium into coastal sediments permits the determination of bioturbation rates at different levels in the sediment pile and through this an estimate of the final repositories of materials introduced into the estuarine zone. Because of

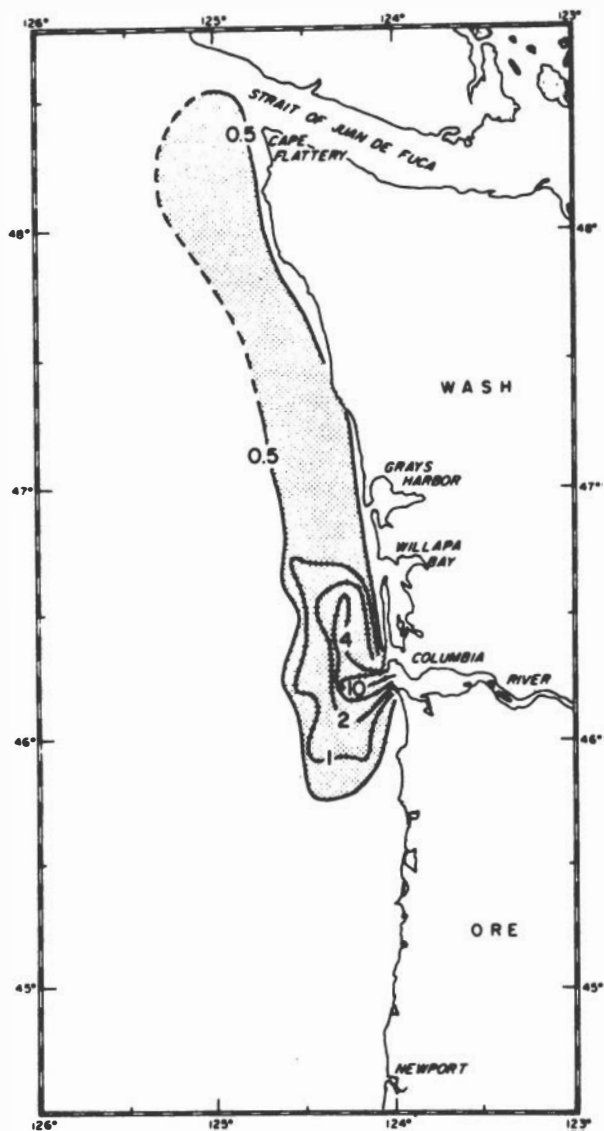


FIGURE 4.1 Isopleths of ^{65}Zn in the uppermost 1 cm of shelf sediments off the Columbia River mouth (after Cutshall et al., 1971). Activity per unit area is expressed in nanocuries/meters².

the role of biological and physical reworking the sediment accumulation rates in certain estuaries may be difficult to measure unless long cores (5 to 15 m) are raised, sufficient to sample below the depths of large animal burrows (e.g., *Squilla*).

At the same time that an estuary is sampled for trace elements, particle density, salinity, nutrients, and the distribution of ^{234}Th should also be made in the water column and the sediment column as a guide to the efficiency of scavenging and the time scale of homogenization of surface sediments, especially the clay-size fraction. This measurement will serve as a valuable guide to the short-term distribution of other reactive chemical species whether introduced isotopically (via the air) or point pollution sources (sewer outfalls or contaminated rivers).

Fate of Particulates--Research Questions

The fate of the particulate matter in estuaries includes change to dissolved or gaseous forms, burial, or transport to the sea. Except in short estuaries or in the case of extreme events, most suspended matter probably takes considerable time to transit the estuarine system or to befall one of its other possible "ultimate" fates. During the transit time, the material may be deposited, resuspended, ingested, filtered, and partially dissolved, and its composition and reactivity may vary along the estuarine gradient and with the various estuarine environments.

What is the importance of suspended particulate matter as a substrate for chemical reactions and reactants? What are the important interactions of suspended matter with phosphorus and nitrogen, major and trace metals, and natural and anthropogenic organic materials? It is fair to say that, with few exceptions, our understanding of estuarine particulate matter is rudimentary. We have not applied advanced, automated techniques to measure particle size, composition, or concentration. We have chemically analyzed suspended matter for elemental composition but have not investigated speciation. We know little about transformation of chemical species or reaction rates and can assemble only the simplest predictive models.

How can we measure physical parameters and chemical processes in the microenvironment ($<100\ \mu\text{m}$)? We should investigate the advanced "micro" techniques used by microbiologists and biochemists for applicability to suspended matter.

Major research questions concerning the behavior and interactions of suspended materials and their chemical environment include the following:

1. What is the role of the living (bacteria and phytoplankton) portion of the suspended matter in the overall accumulation and concentration of reactive materials? We do not know the relative importance of the biota and the nonliving organic portion of the particulate matter with respect to accumulation and speciation of reactive constituents.

2. Which species of important chemicals react with particulates, and how are they transformed after association? Both the reactivity and toxicity of important chemicals may change after association with particulates. Additionally, inorganic particulate-dissolved interactions may be affected by the mode of attachment of important chemical species to particles.

3. To what extent do clays serve as catalysts for important estuarine chemical reactions, retaining their own character while increasing reaction rates and reaction pathways?

4. What is the relative importance of suspended sediment reactions in the estuarine system as contrasted with those of the dissolved phase or those occurring in association with the benthic environment?

5. What environmental factors (pH, salinity, dissolved oxygen, density gradients) contribute to the partitioning of chemicals between dissolved and particulate phases or between water masses?

ESTIMATES OF THE EFFECTS OF APERIODIC EVENTS ON PARTICULATE MATERIALS

Unusual events can have enormous and important effects on estuarine systems, and one of the areas of greatest impact is on the quantity, composition, distribution, and effects of the particulate material in the system. It is not now possible to predict this impact with sufficient accuracy to protect public interests. That difficulty is evidence that understanding of the effects is seriously weak.

Events that are discussed here under the term "aperiodic" are those that occur rarely and without regularity and that have substantial effects on the individual system involved. Some are natural events, and some are anthropogenic in origin. Variety is great and includes the following:

1. *Floods*--ranging in scale from heavy rainfall in a marsh or small estuary to regional storms with rainfall of frequency of one event in several hundred years.

2. *Human modification of flow*--opening of the Bonnet Carré spillway from the Mississippi River to Lake Pontchartrain or collapse of a major dam are examples.

3. *Faunal or floral shifts*--widespread and rather sudden invasion of oyster beds by serious parasites or predators can remove a large sediment-affecting population. Conversely, extensive invasion of a new area by a filter feeder like *Rangia cuneata* can add a mechanism. Extensive reduction or increase in beds of submerged aquatic vegetation or in marsh stands has large effects on the particulate materials of the estuary.

4. *Spills and releases*--large-scale spills of oil or other chemicals and introduction over time of particle related chemicals like kepone can affect the chemical composition and other attributes of huge quantities of suspended material.

The general nature and magnitude of effects of some of these are known. Floods in the Susquehanna River raise the flow from an average of 40,000 cubic feet per second (cfs) to 650,000 cfs (in 1936) or even 1,000,000 cfs (in 1972). Such flows carry enough sediments into the upper Chesapeake to create new islands and raise the floor of the upper Bay, introduce enough pollutants to threaten useful stocks of animals and plants, carry enough pathogens to threaten public health and some of the estuary's biota, and modify the total hydrographic regime of the Bay (Chesapeake Research Consortium, 1976). Obviously, effects on particulate materials were enormous. Operations of the Bonnet Carré spillway has been observed to kill some species in Lake Pontchartrain, modify the floor of the lake, and, eventually, stimulate vigorous recovery of the biota. Spills of many kinds have been described, although the impacts on particulate materials is rarely well documented. In the James River, several tons of kepone have become associated with particulate matter and deposited throughout the estuary.

The effects of such events on the quantity, composition, distribution, and role of particulate materials is known to be great. This impact cannot be estimated in advance with useful precision, only partially measured after the event. Our ability to predict effects of extreme events is weak because we lack knowledge of the following three essential elements:

1. Sufficient baseline or reference information on the normal patterns of circulation, transport, and chemical processes and biotic response to permit quantification of the induced changes.

2. Sufficient description of the changes in chemical and physical content, transport, deposition, and biotic response associated with such aperiodic events.

3. Tested theory explaining observed effects of such events.

There are inherent and serious difficulties in this learning process. The events are usually unexpected, so that research often cannot be planned with assurance and efficiency. Many such events obviously occur during hurricanes, heavy winds, or other conditions involving high hazard for observers and observation equipment. Most interpretations will depend on the availability of good background or baseline conditions, and these are scarce indeed among American estuaries. Finally, knowledge will be dependent on adequate techniques and instrumentation to measure the concentration, composition, and distribution of particulate materials; present methods are far from adequate for these purposes.

CHEMICAL AND PHYSICAL PROCESSES IN THE BENTHIC BOUNDARY LAYER

Modeling the Benthic Boundary Layer

A reasonable end product to the understanding of any estuarine ecological system is the development of a conceptual model, written in quantitative form, in which one has confidence. This has been done for some relatively simple estuarine phenomena. Often the hydrodynamic variables and their associated vertical and longitudinal fluxes can be stated with some certainty. The processes and transformations within the water column related to such items as phytoplankton production respiration and decay, zooplankton grazing, and nutrient uptake and regeneration are understood to a lesser degree. The exchange between particulate and dissolved phases within the water column and on the bottom are poorly understood. *A priori*, it is difficult to develop a convincing ecosystem model in which these latter two processes may be important if we cannot quantify their relationship in the defining model.

This difficulty may arise in the modeling procedures in the following manner. As the benthic fluxes are often not measured directly, they are used as the adjustments to verify the model with observation of distribution in the water column. This adjustment could be taken as a means of indirectly determining the benthic effects, but it should be recognized as such and not as a proof of the model itself. Further, this adjustment factor can, and does, vary considerably from one modeling procedure and comparison with field data to another, which may or may not represent actual variations. In one model we may find a given constituent to be a bottom source, while in another it will be a bottom sink.

Why has this dilemma arisen? Within the water column we can measure fluxes, transformations, and the physical, chemical, and biological variations; we can understand these processes with varying degrees of certainty. On the other hand, bottom and near-bottom processes, of both a chemical and physical nature, are more difficult to observe because gradients are sharp over short vertical distances and because the physical and chemical structure may be modified rapidly and drastically with tidal oscillations and other changes in water movement. Because of this difficulty we simply do not understand them as well as those processes that occur within the water column, and we sometimes omit them from modeling considerations out of ignorance.

We consider it correct to state that processes and transformations relative to the bottom are one of the serious unknowns in our understanding of estuaries.

The zone in the immediate vicinity of the bottom is characterized by high suspended-particulate concentrations and high shear stresses. The processes of sedimentation and resuspension in this zone are highly variable and are influenced by a wide range of physical and biological parameters. An adequate description of these processes requires an understanding of the fluid velocity field, including the turbulent-boundary layer, the chemical and biological characteristics of the particulate (e.g., cohesive properties, organic slimes), and the particle settling characteristics.

The bottom morphology and the texture of the bed material have considerable influence on the processes of settling and resuspension. The range of bottom types found in different estuaries, and even within the same estuary, is broad, ranging from hard sands to thick fluid muds and dense grass beds. We can assume that the same

fundamental hydrodynamic principles hold for the entire range of bottom types; however, each will have a unique set of conditions and problems, and thus the entire range of bottom types should be considered. In many estuaries the bottom composition is ephemeral, changing with the seasons, extreme events, or variations in biologic activity. Additional complexity results from the mixture of organic and inorganic beds, including shell particles overladen with organic detritus and silts and clays within seagrass beds. These are but two examples of the diverse bed mixtures commonly found in estuaries. Although there have been a few basic studies of these types of problems, considerable research is needed in order to define the mechanism of suspended transport in these complex environments.

One of the more interesting, and better studied, bottom types is the cohesive mud deposit, or fluidized bed. Many estuaries have zones of thick accumulations of these mud deposits. The lack of a distinct interface makes it difficult to document the particulate fluxes in these deposits. The basic mechanism of erosion (including resuspension), bed migration, and accumulation rates need additional study.

The range and complexity of bottom morphologies and compositions are paralleled by the number of hydrodynamic variables that effect these beds. The transport processes of suspended particulate in estuaries are controlled by tidal currents, wind waves, and density currents. That is, the entire range of forcing functions that determine the flow field affect the suspended particulates. Particular emphasis should be placed on the role of extreme events on this system. A sudden change in freshwater inflow can have a dramatic effect on the suspension of otherwise stable particulates, Pickral and Odom (1977). Storm surges, extreme waves, and tides can also result in a significant increase in the suspended concentrations. While these responses are generally well recognized, we have insufficient data and understanding to develop even crude empirical predictive models of these events. Extreme temperatures and salinity changes can also have a significant impact on the rates and zones of suspended particulate transports. Little data are available to date to document these effects.

Our understanding of benthic fluxes of a chemical and biological nature, i.e., the bottom as a source or sink, is weak. There is a lack of reliable and readily available technology and instrumentation for measuring estua-

rine benthic flux rates that is generally acceptable by the scientific community. It would seem that an item of first importance is to develop a technology, or technologies, which can be tested and proved. Albeit a crude first attempt at this might be to take the existing procedures and test them together at a number of different benthic environments.

Such techniques would be useful in studying a variety of possible benthic flux effects including organic deposition, nutrient regeneration, absorbed metal constituents, bioturbation, benthic algae and aquatic vegetation effects, and benthic bacterial processes.

On a longer time scale examination and analysis of bottom cores in estuaries in conjunction with known sedimentation rates is important. Those examples of such analysis whenever there have been known tracers for dating have provided some of our most useful information on the bottom as a sink for certain constituent materials.

The use of numerical modeling and analytic solutions to hypothesized benthic effects and their comparison with field data can be a useful procedure for estimating the importance of certain benthic effects. In this sense the numerical modeling is used to predict what might happen under certain conditions rather than as a management prediction tool for what will happen. It is unreasonable to expect that predictive procedures, either in the form of a conceptual, analytic, or numerical model, can be carried out with any certainty for ecosystems analysis in which the benthic effects are considered to be important and are not known.

Benthic Remineralization and Recycling Processes

The importance of remineralization processes mediated by bacteria in organic-rich estuarine and coastal sediments has been documented through both direct measurements of the rates of these processes and mass balance budgets of overlying waters, which include significant benthic flux terms. For example, a large fraction of phytoplankton demand for nutrient elements such as nitrogen in coastal waters is supplied from the sediments. *In situ* flux measurements have confirmed the importance of benthic fluxes and have examined the sediment-water transport mechanisms involved.

We have learned a great deal about the rates and sites of the sedimentary respiration and fermentation reactions controlling these fluxes during the 1970s. A well-defined

TABLE 4.1 Microbially Mediated Reactions

Reaction	Hydrogen Acceptor	Reduced Product
1. Aerobic respiration	O_2	H_2O
2. Nitrate reduction	NO_3^-	NO_2^- , N_2O , N_2
3. MnO_2 reduction	MnO_2	Mn^{2+}
4. Fe_2O_3 reduction	Fe_2O_3	Fe^{2+}
5. Sulfate reduction	SO_4^{2-}	H_2S
6. Methanogenesis (Fermentation)	CH_3COOH	CH_4

vertical sequence of microbially mediated reactions has been established for sedimentary environments (Table 4.1) in which specific bacteria obtain energy for all growth and maintenance. This sequence appears to arise from competition in which the organisms capable of greatest energy yield utilizing available substrates and H acceptors dominate. Organic matter accumulating in estuarine sediments moves downward with time through these biogeochemical zones; however, the most rapid remineralization occurs near the sediment-water interface.

Because of the relatively high concentrations of dissolved oxygen and sulfate in marine waters and the importance of methanogenesis in freshwater sediments, reactions 1, 5, and 6 (Table 4.1) are observed to dominate in organic-rich estuarine sediments. Vertical dimensions of these zones change in response to the amount and kind of organic substrates available and to seasonal variations in temperature. Salt wedge control of dissolved sulfate distribution leads to upstream dominance of aerobic respiration and methanogenesis. Stable carbon isotope distributions in estuarine sediments indicate the mixing of apparently less degradable terrestrially derived organic matter from upstream and surrounding sources with more degradable planktonic debris downstream.

Recent studies of sediment accumulation and redistribution processes in estuarine and coastal environments utilizing geochronologic techniques such as excess ^{234}Th , excess ^{210}Pb , $^{239,240}Pu$, and ^{137}Cs provide quantitative means for determining the fate of particle-associated sedimentary organic debris and, thus, may provide the necessary framework for understanding the time scales of degradation processes.

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