# Transportation and Accumulation of Fine-Grained Sediments in the Estuarine Environment:

## Recommendations for Research

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SPECIAL REPORT 14

REFERENCE 78-2

MARINE SCIENCES RESEARCH CENTER
STATE UNIVERSITY OF NEW YORK
STONY BROOK, NEW YORK 11794

# Transportation and Accumulation of Fine-Grained Sediments in The Estuarine Environment: Recommendations for Research

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and R. B. Gordon

July 1978

*Report of a workshop sponsored by: United States Environmental Protection Agency, United States Energy Research and Development Administration, Office of Naval Research: Geography Branch, National Oceanic and Atmospheric Administration: MESA, New York Bight Project, United States Fish and Wildlife Service, Office of Biological Services, the Stony Brook Foundation, and the Rockefeller Foundation.*

Special Report 14

Reference 78-2

Approved for Distribution

J.R. Schubel
J. R. Schubel, Director

# PREFACE

## *Origin and Purposes of the Workshop on Transport Processes in Estuaries*

In the spring of 1976 a symposium to review our knowledge of physical transport processes in estuaries was held at the Belle Baruch Institute. At the conclusion of the symposium the following statement, drafted by J. R. Schubel, was endorsed by the participants:

> "On 20-22 May 1976 a group of estuarine oceanographers from the United States, Canada, England, and South America met at the Belle Baruch Institute for Marine Biology and Coastal Research of the University of South Carolina to review and critically assess our knowledge of estuarine transport processes. It was the very strong consensus of the group that recent data show many of our previous ideas of estuarine transport processes to be overly simplistic and that a greater level of sophistication of our understanding of these processes is required not only for a significant scientific advancement, but also for effective environmental protection and management.
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> "A knowledge of the physical oceanography is fundamental to understanding the biological, chemical, and geological processes that characterize an estuary. This information is in turn necessary for the formulation of the predictive tools needed by governmental agencies for effective management and rehabilitation of the estuarine environment. Reliable predictions can not be made of the dispersion of pollutants, the resuspension and movement of dredged spoil, or the assimilative capacity of an estuarine system without a working knowledge of its characteristic physical processes.
>
> "While millions of dollars are being spent each year on monitoring of the estuarine environment, the resulting data are generally of little use to oceanographers interested in processes, or in formulating, constructing, and veryifying analytical, numerical, or physical models. The data are also, unfortunately, frequently of little value to regulatory agencies in attaining their long-term pervasive goal--effective management of the coastal environment. Through proper coordination and planning, experimental programs can be designed that not only satisfy the short-term needs of regulatory agencies, but also provide the oceanographers and managers with the data they require for development of predictive tools.
>
> "A proposal will be submitted to appropriate Federal agencies within a few weeks for support of a workshop to identify the important problems of physical transport processes in estuaries, and to explore the most effective ways of attacking these problems. Efficient utilization of existing manpower and facilities for an adequate field study of the dynamics of any single estuary will probably require collaborative efforts of scientists from several academic institutions and from governmental and management agencies."

Pursuant to the foregoing statement, a Workshop on Transport Processes in Estuaries was held at the Marine Sciences Research Center, State University of New York, Stony Brook, New York from 10 November to 14 November 1976. Thirty-one participants from some 18 institutions and agencies focused their discussions on transports of water, salt, and fine-grained suspended sediments.

The primary goal of the Workshop was to identify the important unresolved problems of physical transport processes in estuaries; problems that must be solved, not only for their scientific urgency, but also for effective management and rehabilitation of estuaries.

The secondary goals of the Workshop were:

(a) To assess the manpower and material necessary for the field experiments on which the solutions of important unresolved problems must depend.

(b) To explore the means for interinstitutional cooperation and collaboration which will be required if the necessary large-scale, extended field experiments anticipated are to be made feasible.

(c) To explore ways in which current monitoring programs which are relatively expensive, can be made more useful both to management and to science.

The present report was written with due consideration for the discussions which occurred during the Workshop and for the written suggestions submitted by the participants, but it should not be interpreted as a report which has been endorsed in full by all participants. In this report we have focused on the transportation and accumulation of fine-grained sediments. An earlier report[1] concentrated on the transports of water and salt.

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[1] Kinsman, B., J.R. Schubel, M.J. Bowman, H.H. Carter, A. Okubo, D.W. Pritchard, and R.E. Wilson, 1977. Transport Processes in Estuaries: Recommendations for Research. Marine Sciences Research Center, State University of New York, Special Report 6, 21 pp.

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## INTRODUCTION

Particles are added to the estuarine environment by rivers, by the atmosphere, by shore erosion, by biological activity within estuaries, by the sea, and by municipal and industrial discharges. The sources are thus external, internal, and marginal. The particles are both organic, living and dead; and inorganic, naturally-occurring and anthropogenic.

Man has clearly modified the natural flow of particles into the estuarine environment by deforestation, agriculture, and urbanization of drainage basins, by construction of dams and reservoirs on tributary rivers, by diversion of rivers, and by engineering projects to control shore erosion. His activities have also introduced significant quantities of anthropogenic particulate matter. Nutrient levels have increased as a result of sewage effluent and runoff from agricultural areas and, as a result, the local production of organic matter has been accelerated.

Because particulate matter can affect the estuarine environment in a variety of ways, the ability to predict its behavior is of the greatest scientific and practical importance. This is particularly true of the fine-grained fraction, silt and clay, which pose the greatest problems: economic, aesthetic, and environmental.

In most estuaries the sediment, that fills navigation channels must be removed by dredging at a cost of millions of dollars each year, is mud--silt and clay. Fine particles are important in determining water "quality" of the coastal environment; they serve as sites for adsorption of a variety of contaminants including: radioisotopes, petroleum products, halogenated hydrocarbons, pesticides, metals, and oils and greases. Since these constituents are rapidly scavenged from the water column, their transportation and deposition are controlled in large part by the fine-grained sediment dispersal systems. Filter-feeding organisms which ingest these particles and associated contaminants agglomerate the smaller particles into larger composite particles in their feces and pseudofeces thereby accelerating the accumulation of fine particles within the estuarine environment and providing the contaminants in a more concentrated form to deposit-feeding animals. Fine particles can also serve as sources and sinks for nutrients.

Fine particles suspended in the water column decrease the transparency of the water and therefore the depth of the euphotic zone which is important, not only in determining the distribution and primary productivity of phytoplankton, but also of rooted aquatic plants. The distribution and character of suspended and particularly bottom sediments are important factors in governing the distributions of benthic animals, including commercially important species of shellfish, such as oysters and clams.

Fine-grained suspended sediment can also decrease the amount of dissolved oxygen in estuarine waters both directly and indirectly. Resuspension of fine-grained, organic-rich sediments with a high oxygen demand may produce a sag in the oxygen distribution. This decrease in depth of the euphotic zone which accompanies increases in suspended sediment levels causes decreased production of oxygen by phytoplankton and by rooted aquatic plants. Areas of the bottom formerly within the euphotic zone can be removed from it as a result of man's activities.

Increase in the level of suspended particulate matter above some threshold level is aesthetically displeasing and inhibits recreational use. This level is a function not only of the total concentration, but also of the size distribution and the composition of the suspended material. A concentration of 100 mg/ℓ of fine quartz and sand does not have the same effect on water color and transparency as does the same concentration of organic-rich silt and clay.

In summary, fine particulate matter is one of the major factors in determining the "quality" of most coastal environments. Regardless of the meterstick (yardstick) one selects to measure environmental quality, influxes of fine-grained particulate matter into the estuarine environment have a deleterious effect on many uses of the coastal environment and a salutary effect of few, if any. This is true whether the particles are suspended in the water column, or are deposited on the bottom.

We recognize two quite different approaches to the study of estuarine sedimentation. One deals with specific processes such as: the physical mechanisms that control the deposition and erosion of mud, the formation of composite particles (agglomerates) by biological and physical-chemical processes, and the reworking of sediments by benthic organisms and the consequent changes in the physical properties of the sediment. The other approach deals with the characterization of the estuary as a sedimentary system.

Many studies of the first kind have been completed successfully; others such as the effects of organisms on the physical characteristics of sediments are only now being addressed. The prospects for resolving questions at this level are good, if scientists find them exciting and if reasonable support is provided through conventional funding mechanisms. But, studies of the second kind--studies of estuarine sedimentary systems--have hardly been considered. Where estuarine sedimentary systems have been characterized it has usually been in response to a crisis. One of the best examples of this is the work that led to the explanation of the formation of the mud deposits in the Thames and their relationship to maintenance dredging of the shipping channels to the London docks.[2]

One can learn a great deal about the mechanics of some sediment transport processes through laboratory flume experiments and isolated, short-term field studies; by experiments of the first kind. These studies, however, provide little insight into the long-term manifestations of estuarine sedimentation and the identification of the processes that control the sedimentation in different parts of an estuary. Attainment of this level of understanding--the level that is necessary for development of effective management strategies--requires a holistic approach, an approach that combines specific, short-term field and laboratory experiments with system-wide studies.

Ideally, one would like to know for each estuary: the sources of sediment--their locations and strengths--the character of the sediment introduced--its size distribution, composition, and associated contaminants--the routes and rates of sediment transport--including the transient repositories--the sites of final accumulation within the estuary and the amount lost to the ocean. There are also many important biological and geochemical questions, but these are not the subject of this report. The problem is already too large. Our task is to identify a strategy, or strategies, that have a reasonable chance of success in developing understanding of estuarine sedimentary systems.

Sedimentation processes in estuaries are extremely variable in time and space. They not only undergo tidal and seasonal cycles but are occasionally disturbed by major storms or floods which may dominate the sedimentation of the system, or at least segments of it. Because of these vagaries, it is frequently more effective to begin an investigation of estuarine sediment systems by examining the end products of these processes rather than the processes themselves. Indeed, where infrequent events dominate, there is no alternative.

[2] Inglis, C. C. and F. H. Allen, 1957. The regimen of the Thames estuary as affected by currents, salinities and river flow. Proc. Inst. Civil Eng. 7: 827-863.

## SEDIMENTARY DEPOSITS-- OR WHAT THE RECORD CAN TELL US

If one thinks of an estuary as a machine for handling sediment, then the products of this machine are the permanent, sedimentary deposits that line the estuary floor. The sedimentary deposits are the integrated results of many and variable processes--river flow, wave erosion and biological production, for example. To help design an efficient and effective study of the physical process of fine-grained sediment transport in the estuary, it is useful to know first where the estuarine mud deposits are found, the type and amount of material in these deposits, and the rates at which they are accumulating.

On nautical charts the designation of "soft" bottom is a fair indication of where muddy sediments can be found, but, for many estuaries textural maps of the surficial sediments have also been compiled. These maps not only show the location of fine-grained sediment deposits--the materials that are trapped within the system--but also help identify the types of materials that pass through the particular estuarine system. Development of surveying techniques that measure the acoustic reflectivity of the sea floor to identify sediment types would make rapid and more extensive investigations possible. Only in a few estuaries, however, has the thickness of these mud deposits been measured or have changes in composition of the sediment with depth been chronicled over the life of the estuary. As a result, there is usually no indication of how representative the present conditions are of the long-term behavior of the estuarine system; nor is there a basis for deciding which of the present features of the surficial sediment distribution are permanent characteristics of the sedimentary system--characteristics that will be incorporated into the Record--and which may be transient features.

Once the areas of estuarine mud are located, the thickness of the deposits may be meausred either with a network of cores or by high resolution seismic reflection. Ideally, contour maps of the thickness and composition of the estuarine mud would be produced using a combination of these methods. Acoustic surveys should be used to choose those locations where cores and bottom samples could be taken to most effectively map the sediment deposits and chronicle their depositional histories. Changes in the composition of the deposits with depth show the long-term trends in sedimentation and the relative importance of fluvial, littoral, and biological sources of material over the life of the estuary.

While the approach we have outlined to this point is conceptually straightforward, effecting it is anything but. To apply these methods, the estuarine muds must be readily distinguishable from relict deposits. Due to Pleistocene sea-level changes, the present estuarine environment was probably preceded by some combination of fluvial, sub-aerial, glacial, and lacustrine environments. Relict sediment deposits which are characteristic of earlier environments must be excluded from determination of the volume of estuarine sediments. Unfortunately, in many estuaries the contact between estuarine sediments and the underlying deposits is ill-defined and therefore not readily identifiable. To make matters worse, fine-grained estuarine deposits are frequently so highly charged with gas bubbles (primarily methane) that they are virtually opaque to the high frequency sound energy characteristic of high resolution seismic profiling systems.

Sedimentary processes in coastal waters not only undergo tidal and seasonal cycles but are also episodically disturbed by major storms. Because of these changes, direct observations of the rate of sediment accumulation may require observational periods of tens or hundreds of years to obtain a meaningful long-term average sedimentation rate. It is useful, therefore, to estimate the sedimentation rate by measuring the amount of material that has accumulated on a geological time scale and the time required for this accumulation. Such a procedure can only be applied if a starting time for the process is well-defined. If the thickness of estuarine sediment has been measured, one way to get the average sedimentation rate is to date the onset of estuarine conditions in the basin from the local rate of sea-level rise. A map of this long-term average sedimentation rate would identify areas of maximum and minimum accumulation and the regions where the sedimentation rate is likely to be uniform.

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Useful information can also be obtained on the average rates of accumulation of sediment over approximately the past century by a careful comparison of old and recent original bathymetric survey sheets. The surveys are usually at scales of 1:10,000 or 1:20,000 and have a high density of soundings along the original survey lines. Index maps summarize the surveys available for each region and bromide prints of original survey sheets are available from the National Ocean Survey.[3] In using this technique it is very important to make appropriate datum shifts for surveys conducted before 1927.

The chronology of the sediment deposit should also be examined by application of geochemical techniques to selected cores. The accumulation rate would be expected to vary not only from place-to-place, but also in time, and radiometric dating has the advantage of being able to detect accumulation rates on various time scales. For example, lead-210 has been used to investigate modern rates of accumulation over a period of the last 150 years while carbon-14 dating can span a range of about 40,000 years. Other indicators of the rate of accumulation include pollen and plankton assemblages and the depth of occurrences of culturally introduced tracers. When interpreting the distribution of any of these indicators in a core, care must be taken to distinguish among those features that are due to the sequential accumulation of material, those features produced by vertical mixing of sediment by burrowing animals, and those that may be the result of slumping or other local mass movement of sediment. Although this distinction cannot always be made, examination of sedimentary structures in cores visually or by x-radiography is sometimes useful in sorting out these disturbances. Geochemical indicators, such as Cesium-137, may also be useful in assessing the intensity of bioturbation of the sedimentary record.

Fine-grained sediment can be incorporated into the "permanent" sedimentary record by a variety of mechanisms. Particle-by-particle settling may proceed from the dilute suspension of sediment in the water column. These particles can be either individual mineral grains or mineral-organic agglomerates, and deposition can occur quasi-continuously or at periods of slack water. Deposition from dilute suspensions has probably received the most attention both in the field and in the laboratory, but it may be of minor importance in some systems. In some estuaries, the rate of sediment supply is so large that the flow cannot maintain it all in suspension. If the level of benthic biological activity is low, a fluid mud layer may be formed on the estuary floor. The rate of accumulation is then controlled by the rate of de-watering and consolidation at the base of the fluid mud layer. If the rate of biological processing is large, however, the estuary floor may become blanketed by a layer of fecal pellets that is easily resuspended. The transition of this material into the permanent mud deposit occurs at the bottom of the layer presumably by a combination of physical and chemical disagglomeration. For the two situations just mentioned, the mechanism of accumulation depends on a balance among the rates of sediment supply, resuspension, and biological processing. The transport and settling of sediment in the water column may have little direct bearing on the depositional processes.

In summary, the place to start studying an estuarine sediment system is with the record. Attention may then be more effectively focused on the most important areas and on those processes that are rate-limiting.

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[3] National Ocean Survey, Rockville, Maryland 20852

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## SOURCES OF SEDIMENT

The principal sources of sediment to most estuaries are: rivers, shore erosion, primary productivity, and the ocean.

### *Fluvial Inputs*

One of the most important sources of sediment to estuaries are the river (fluvial) inputs. The fluvial sources are the best understood of all sediment inputs, but even these are poorly known for most estuaries. The locations of these "sources"--the river mouths--are well known, but the strengths of most are poorly documented. The strength of the source is determined primarily by the riverflow and the sediment yields throughout the drainage basin which can vary by orders of magnitude depending on lithology, vegetative cover, and man's activities.

Few rivers are sampled at locations close enough to their mouths and at frequencies adequate to permit reliable estimates of sediment inputs to their estuaries. For less than half the estuaries of the United States do we have any kind of regular measurement of the input of river sediment. The U. S. Geological Survey should examine the locations of their gauging stations on the lower reaches of major rivers and streams and, where necessary, add new stations or adjust the positions of existing ones close to the landward limit of tidal action. Coverage should be adequate to ensure reliable estimates of the fluvial sediment discharges into estuaries, and of the character of the material--its size distribution; mineralogic and chemical composition; organic matter content; and associated contaminants of concern. Measurements should be made of both suspended and bedload.

These stations should be permanently maintained so that relative importance of occasional floods may be assessed. Only a few rivers have been monitored long enough to have documented the sedimentological importance of extreme events which may dominate the sedimentation in estuaries, or at least segments of them. During the hurricane flood of 1955 the Delaware River carried more sediment past Trenton in two days than it had in all five years combined in the mid-1960's drought. On three days in December 1964 the Eel River in northern California transported more sediment than in the preceding eight years; and during the week following Tropical Storm Agnes in June 1974 the Susquehanna discharged 20-25 times as much sediment into the upper Chesapeake Bay as it had during the entire previous year. Two events--Agnes in 1972 and the Great Flood of 1936--account for more than 50% of all sediment deposited in the upper Chesapeake Bay estuary since 1900.

*Shore Erosion*

In many estuaries, or at least segments of them, shore erosion is a major source of sediment. In the middle and lower reaches of the Chesapeake Bay, for example, it has been estimated that shore erosion is the primary source of sediment. Estimates of the inputs of sediment from shore erosion have been made for but a small number of estuaries, and the factors that control shore erosion are poorly evaluated. Nevertheless, these data are prerequisites to the understanding and modelling of estuarine sedimentary systems. The management value of this information is great.

The most reliable way of estimating the long-term average (over decades) input of sediment to an estuary from shore erosion is through a critical comparison of shorelines on old and recent topographic survey sheets. Areal losses (and gains) determined in this way can be combined with measurements of coastal relief and stratigraphy to estimate the added volumes and masses of sediment of different texture. Copies of original survey sheets, rather than published maps and charts, should be used to document changes in the shoreline because of their larger scale. Great care must be taken to ensure that appropriate datum shifts are made in charts prepared before 1927. This method of estimating shoreline recession rates and associated inputs of sediment to the estuary is relatively inexpensive and a more reliable indicator of long-term average conditions than short-term direct measurements of shoreline recession. Short-term direct observations can, however, provide useful information on relative importance of different weather and sea conditions in determining erosion rates.

*Internal Sources--Primary and Secondary Productivity*

In some estuaries internal sources may account for a large fraction of the total sediment input. In the Delaware, for example, diatom frustules have been estimated to account for up to 50% of the total amount of material dredged from the main shipping channels. In most estuaries living and dead plankton can account for a large fraction of the total suspended matter throughout the year.

More effective and diagnostic tools and techniques are required for estimating the abundances and kinds of organic matter present in the water column and accumulating on the bottoms of estuaries. Until such methods are developed, loss of total mass of particulate matter on combustion can be used to estimate organic content of suspended and deposited sediments. Estimates of suspended particulate organic matter should be available on a seasonal basis; for bottom sediments documentation of seasonal variability is not required except in areas dominated by rooted aquatics.

*Input from the Sea*

The sea may be an important source of sediment to the lower reaches of many estuaries. Coarse-grained material is transported into estuaries from the adjunct continental shelf as bedload; fine-grained material as suspended load. While information is available on the routes and rates of transport of marine sands into some estuaries, there are few, if any, reliable estimates of the flux of fine-grained suspended sediment through the mouths of estuaries. Even the direction is rarely known.

## ROUTES AND RATES OF TRANSPORT

*Sediment Flux*

There are few direct measurements of the fluxes of suspended sediment in streams and estuaries. Fluxes of suspended sediment in estuaries have been obtained by calculation from measured current velocities and concentrations of suspended sediment determined either gravimetrically or from optical measurements. Calculated fluxes from measurements made over short periods--a few tidal cycles to a few days--may be very poor indicators of long-term conditions. While current meters are capable of providing measurements over extended periods of time, recording *in situ* optical devices are crude. The difficulty and expense associated with making concomitant direct measurements of the concentrations of suspended sediment preclude extensive time series data. Until better suspended sediment sensors are developed, we must rely on other methods to determine average routes and rates of suspended sediment transport in estuaries.

*Routes of Sediment Transport and Rates of Accumulation*

There are a variety of natural and artificial tracers that can be used to infer routes of sediment transport and rates of sediment accumulation. These include distinctive naturally-occurring minerals with known source areas such as coal in upper Chesapeake Bay derived from the Susquehanna and glauconite in the lower bay of New York Harbor derived from New Jersey. Talc and other distinctive minerals can be intentionally introduced into aquatic environments to trace the routes and rates of fine-grained sediment dispersal. Radionuclides from natural and anthropogenic sources are also potentially powerful tools that have not been fully exploited by coastal marine scientists. Radionuclides from nuclear power plants can provide very useful tracers in many coastal environments. Pollen is another tracer that has rarely been exploited in unraveling the sedimentary history of estuaries. Natural and anthropogenic tracers have greater diagnostic value in assessing routes of fine sediment dispersal and rates of sediment accumulation than do calculated fluxes based on short-term measurement programs.

*Stability of the Bottom*

Sediment that enters an estuary will either be exported or deposited within the estuary eventually. Before it reaches either of these permanent repositories, it will pass into the water column many times as a result of repeated resuspension. In most, if not all estuaries, there is a supply of muddy sediment that is available for resuspension, sediment that is on the bottom part of the time and in the water column part of the time. The greater is the amount of this material, the less stable is the bottom. Bottom instability and resuspension are important in two ways to the overall properties of an estuary. First, resuspended sediment can react more freely with the ambient water and may have a controlling influence on some important geochemical processes. Second, an unstable bottom is a poor benthic habitat--bottom stability is one of the principal factors controlling the makeup of the animal communities that reside on and in the bottom.

There is reason to believe that there are marked differences in the bottom stability of different estuaries. In an estuary like the Severn (UK), which has powerful tides, deep, temporary, fluid mud layers form on neap tides. These deposits are mobilized on the next spring tide. The bottom is so unstable that no benthic communities can establish themselves: large quantities of silt-clay material periodically enter the water column and are available for chemical reaction. When the level of tidal energy in an estuary is lower than in the Severn, benthic animal communities may be able to establish themselves on the muddy bottom. Both deposit and filter feeding animals process new sediment entering the estuary, thereby altering its physical form and its susceptibility to erosion. The result is a completely different sedimentary regime, different estuarine geochemistry, and a different food supply for bottom-feeding fishes.

To characterize bottom stability, it is necessary to know the power that is available to resuspend sediment--its intensity and the way that it varies in time and space--and the susceptibility of the sediment to erosion, which depends on its mineral content, the degree and nature of benthic processing and the presence of cohesive materials in it. All of these questions need to be addressed in a characterization of the sedimentary system of an estuary.

The power required to move sediment through an estuary may be derived from the tide, from wind-driven circulation, or from waves on the water surface. The effect of waves is probably the best understood of these. In the shallower water around the margins of an estuary waves set water at the bottom in motion and disturb the sediment. This motion has been studied in detail by students of beach and continental shelf processes. Because the fetch in most estuaries is limited, waves of long wave length are not formed and the bottom in the deeper water remains undisturbed by wind waves on the surface. The depth of the wave-affected zone can be estimated fairly easily. In some shallow estuaries, wind-driven circulation is strong enough to move appreciable amounts of sediment but these are thought to be unusual. In most estuaries, the tide is the principal source of power causing movement of sediment. Tidal action is regular and predictable, and the resultant sediment movements should be too. The actual situation is not that simple. In Long Island Sound, for example, the amount of sediment resuspended by the tide is much greater under stormy conditions than in calm weather even though the water is much too deep to be affected by waves on the surface. Wind stress on the surface has been shown to increase the rate of dissipation of tidal power but the mechanism by which this happens is unknown. Similar effects are anticipated in other estuaries with deep water. This issue needs to be resolved before the stability of the muddy bottoms of estuaries can be adequately described.

The amount of resuspension that will occur on the muddy bottom of an estuary depends on the properties of the sediment as well as on the power dissipated. When dealing with sandy sediment, knowledge of the grain size usually suffices to characterize the erosion resistance of the bottom. This is not true for muddy sediment. Silt and clay particles are naturally cohesive because of electrostatic forces and organic matter secreted by bacteria may add significantly to the cohesion. Silt and clay particles are passed through deposit and filter feeding animals, emerging in altered form, usually as larger agglomerates. The resultant fecal pellets have a much greater settling speed than the mineral grains of which they are made. Processing of mineral material by benthic animals can alter the sedimentary characteristics of an estuary markedly. Chemical processes within the sediment will also be altered by the burrowing activity of animals.

The individual processes described above can be studied in detail in either the field or the laboratory. Some are being so studied now; others receive occasional attention. What has received almost no attention is the way in which these processes interact to produce a sedimentary regime within an estuary. For example, benthic animals have an important effect on the erosion resistance of the bottom, but what animals can inhabit any given area of the bottom depends on its stability, which depends on its erosion resistance and the physical environment. There is a web of interactions between these and between the effects of animal populations and bottom properties, between bottom properties and sediment supply, and between the power dissipation spectrum and the nature of the sediments on the bottom and in the water column. These inter-relationships will only be resolved by field studies on estuaries displaying a range of physical and biological characteristics. Very detailed studies may not be necessary or appropriate until those processes that are rate-limiting are identified in different types of estuaries. The types of measurements that are required include

(1) The physical form of the sediment subject to resuspension. This can be determined by examination of undisturbed samples of suspended material collected near the bottom by underwater photography.

(2) The amount of material available for resuspension and its relation to the sediment supply. This can be determined from the sediment inputs and the measured volume of the unconsolidated material.

(3) Time series of the total amounts of resuspended sediment in the water column under a wide range of seasonal and weather conditions. These can be estimated by regular programs of water sampling and data from continuously recording instruments.

## INSTRUMENTATION

The study of estuarine sedimentary systems described in this report contains elements of geology, geochemistry, biology and physical oceanography. Although a discussion of the relevant technical problems in each of these disciplines is beyond the scope of this report, three general classes of observations may be identified in which technical capabilities need to be developed further.

There is growing recognition of the importance of infrequent storms and floods in the sediment budget of the coastal zone. To document the effects of episodes, self-contained sensing systems are needed which are capable of measuring concentrations of suspended solids during these disturbances. Unmanned mechanical samplers, or self-recording acoustic or optical sensors could be designed to fill this need.

Many characteristic properties of sediments, whether suspended or deposited, are patchy. Point sampling in the water column or on the sea floor may miss important features of the distribution of particulate material. There is, thus, the need to design instruments or methods capable of taking "snapshots" of the distribution of sediment along extended transects or over large areas. For example, continuous measurements of acoustic reflectivity using signals in the 100 kHz range may be useful in distinguishing variations in texture, composition, and water content of bottom sediments and in selecting sampling stations for maximum information. Part of the lateral inhomogeneity is due to irregular, contagious distributions of benthic animals. Pulse-echo sounding with signals in the mega-hertz frequencies may be capable of resolving macrofauna and provide a method for assessing the distribution of organisms. Expanded use of remote sensors, aerial and submarine photography should also be considered.

There is a gap in our resolution of the temporal variability of sedimentary processes. Geological and geochemical methods are used to estimate mean sedimentation rates over periods of decades to thousands of years. The technology is also available to make direct measurements of sediment motions on time scales of from a few seconds to, perhaps, several weeks. The time variability of sediment distributions for intermediate periods, months to decades, is poorly documented. Instruments designed for this purpose would require some method of averaging measurements in order to record unattended for long periods.

## CONCLUSION

Schemes for classifying the hydraulic regimes of estuaries have been developed and widely used. There is, however, no comprehensive method for comparing different estuarine sedimentary regimes. Such a classification could be based on the hypothesis that there are a small number of parameters that characterize any estuarine sedimentary system. Although these parameters have not yet been identified, one possible quantitative classification would include:

1. The rate of sediment supply.
2. The amounts of sediment in the water column, in temporary storage on the sea floor, and in permanent deposits.
3. The rate at which transport proceeds; this rate is expected to be proportional to the power available to move sediment particles.
4. The total amount of time that a particle is in the water column.
5. The final partitioning of material between the ocean and the permanent estuarine deposits.

A classification based on these, or other similar parameters, would be useful not only for comparing different estuarine sedimentary systems, but also for recognizing the range of different conditions controlling a particular estuary's sedimentation. Emery and Uchupi[4] are correct in pointing out that far more effort has gone into making detailed studies of the sediments of individual estuaries than either into comparing results from a variety of estuaries with similar physical and geological characteristics, or into critical evaluations of processes.

The kinds of studies we are recommending are designed to produce, not only a better understanding of estuarine transport mechanisms, but more specifically to produce, a significant improvement of our knowledge of those sedimentary processes that characterize estuarine systems. This level of understanding is required for effective management of estuaries; many of the most serious and persistent environmental problems in estuaries are associated directly, or indirectly, with fine-grained particulate matter. Development of an estuarine sediment system will require sustained research programs over periods of years, perhaps decades. Scientists interested in understanding systems can not, and should not, rely entirely on agencies, such as the National Science Foundation for the uninterrupted support required for effective research programs. To a large extent, some of the more important research components of an estuarine sediment system may be of local, or regional importance and should be supported by appropriate State and Federal agencies.

Regional funding mechanisms should be established to ensure sustained support for research and monitoring of estuarine systems. This should include contributions from the state(s) bordering the estuary as well as support from appropriate Federal agencies. An appropriate administrative structure would have to be developed to ensure that dollars were spent effectively. Inter-institutional cooperation would be required, at least for large systems.

Events, natural and man-induced, can have dramatic and persistent impacts on the coastal environment and its biota. These include floods, hurricanes, extreme climatic deviations, and large accidental discharge of pollutants. Because of their episodic character, events are inherently unpredictable and at best are difficult to study. Rapid response is required for effective investigation, but present funding mechanisms are not geared to provide support or an appropriate time scale through the normal research proposal and review procedure. Contingency funds should be established to provide immediate, short-term support to initiate studies of events. These funds should be under the direction of top administrators who have authority to respond rapidly to research opportunities. They should be able to commit funds to initiate studies by phone and then send a representative to the scene to evaluate the scientific merit of the investigation and determine the resources that should be allocated to the study. Until this is done, we will continue to fail to take advantage of some of the more important experiments that are occurring in our coastal waters--those associated with catastrophes.

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[4] Emery, K. O. and E. Uchupi, 1972. Western Atlantic Ocean: Topography, Rocks, Structure, Water, Life, and Sediments. Amer. Assoc. of Petroleum Geologists, Memoir 17, 532 p., Tulsa, Oklahoma.

## APPENDIX A

*Organizations Supporting the Workshop on Transport Processes in Estuaries*

United States Environmental Protection Agency

United States Energy Research and Development Administration

Office of Naval Research: Geography Branch

National Oceanic and Atmospheric Administration: MESA, New York Bight Project

United States Fish and Wildlife Service: Office of Biological Services

Rockefeller Foundation

Stony Brook Foundation

## APPENDIX B

*Participants in the Workshop on Transport Processes in Estuaries*

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|---|---|
| K. Allen | U. S. Fish & Wildlife |
| R. Baltzer | U. S. Geological Survey |
| Malcolm Bowman | Marine Sciences Research Center |
| Burt Brunn | U. S. Fish & Wildlife |
| Harry H. Carter | Chesapeake Bay Institute |
| S. Chanesman | NOAA |
| Dennis M. Conlon | Office of Naval Research |
| T. John Conomos | U. S. Geological Survey |
| Bruno d'Anglejan | McGill University |
| Keith R. Dyer | Institute of Oceanographic Sciences |
| Alan Elliott | NATO SACLANT ASW Research |
| John Festa | NOAA |
| Robert Gordon | Yale University |
| R. G. Ingram | McGill University |
| Blair Kinsman | Marine Sciences Research Center |
| Bjorn Kjerfve | University of South Carolina |
| Ray B. Krone | University of California Davis |
| G. Mayer | NOAA |
| Tavit Najarian | Chesapeake Bay Institute |
| Maynard M. Nichols | Virginia Institute of Marine Science |
| Charles B. Officer | Marine Environmental Services |
| Akira Okubo | Marine Sciences Research Center |
| David H. Peterson | U. S. Geological Survey |
| Donald W. Pritchard | Centro de Investigacion Cientifica y de Educacion Superior |

APPENDIX B
(continued)

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| Maurice Rattray | University of Washington |
| William S. Reeburgh | University of Alaska |
| J. R. Schubel | Marine Sciences Research Center |
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DUE DATE