MARINE SCIENCES RESEARCH CENTER
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In September 1987, twenty-one scientists met to discuss an integrated framework for conducting basic research in estuarine sedimentation. With this topic, as with others, there is no dearth of outstanding research questions nor is there a shortage of leading scientists eager to address these questions. There is the need to better define common goals and to incorporate the diverse views of the community of estuarine scientists into a broadly based overarching strategy. While any of several objectives may serve as a target for the wide range of estuarine studies, one should be elected. We recommend an examination of the estuary as a biological, geochemical and geological filter in the broadest sense of the term.

ABSTRACT

Estuaries, of course, are enormously important to society and research in estuaries is often justified in terms of societal problems. Estuarine scientists, however, are attracted to estuaries as natural laboratories for pursuing exciting, fundamental research questions. The estuarine environment has three advantageous characteristics: (1) intense gradients in critical physical, chemical, and biological properties in alimited area, (2) strong interactions among the physical, chemical, and biological agents, and (3) a wide range of variability on both short and long time scales due to periodic changes, episodic events and progressive alterations. The strong gradients accentuate the processes which define and modify the estuarine filter by compressing the temporal and spatial scales to a degree unmatched in other marine realms. Estuarine studies should, therefore, reveal the fundamental nature and the degree of time dependent coupling among the physics, geochemistry, and biology. The estuaries themselves provide convenient natural laboratories for studies of the basic interrelationships among processes, the results of which will be generally applicable to other parts of the ocean.

The estuary accepts both inputs from its rivers and exchanges with the coastal ocean, and it alters those signals for transmission into the sedimentary record or to the ocean. We need to detect these signals and to understand the behavior of the estuarine filter in terms of different patterns of changes that are common to all estuaries. Many elements of the processes of aggregation, deposition and resuspension need to be better resolved. Efforts to determine the efficiency of the estuary as a filter are also limited by our understanding of regional dynamics, including the dependency on drainage basin

characteristics as well as sea level variations. To be able to average time and space scales adequately presents a major challenge, but one that can be faced with the new tools and techniques that have been developed recently. As a result, it would be fruitful to begin multidisciplinary experiments to determine the mechanisms governing the distribution of suspended sediment and its relation to accumulation of sediment in the estuary.

The theme of the estuary as a filter is a useful framework for the most pressing research questions in estuarine sedimentation. It is to be hoped that this approach will be equally fruitful for other topics. A steering committee might be established to encourage the development of a more coordinated research program in estuaries. Such a program would not only be interdisciplinary but also international in scope.

Why Study Estuaries?

The estuary is a filter for biological, geochemical, and geological fluxes. Acting in the broadest sense of the term "filter", any estuary accepts both inputs from its rivers and exchanges with the coastal sea, and alters those signals for transmission either into the sedimentary record or to the world ocean.

What Are the Advantages Enjoyed by Estuarine Studies?

The processes at work within the estuary are the same as those in all other parts of the ocean. In many marine environments, however, it is difficult to examine these processes because magnitudes are small and rates are low. This is not the case in estuaries.

The estuarine environment has three major characteristics:

1. intense gradients in critical physical, chemical, and biological properties in a limited area
2. strong interactions among the physical, chemical, and biological agents

3. a high degree of variability on both short and long time scales due to periodic changes, episodic events and progressive alterations.

The strong gradients inherent in estuaries accentuate the processes which define and modify the estuarine filter by compressing the temporal and spatial scales over which these processes occur; the gradients operate on periodic, episodic and progressive time scales amplifying the rates and magnitudes of marine processes to a degree unmatched in other marine realms.

Estuarine studies will reveal the fundamental nature and the degree of time dependent coupling among phenomena and the relative rates of physical, chemical and biological processes. The estuaries themselves provide convenient natural laboratories for studies of the basic interrelationships among processes, the results of which will be generally applicable to other parts of the ocean.

What Are the Critical Processes that Define and Modify the Estuarine Filter?

Our immediate goal is to understand the behavior of the estuarine filter in terms of different magnitudes in patterns of changes that are common to all estuaries. Although the overall strategy must be broadly based requiring the coordinated efforts of the diverse range of estuarine scholars, the tactics needed to achieve this goal will be different for studies of geochemical fluxes, of biological cycles or of estuarine sedimentation. Any tactic, however, must be interdisciplinary.

One variation of this approach to estuarine research can be illustrated with the general topic of estuarine sedimentation. Other research plans can similarly be developed for any other topic, but for the specific topic of sedimentation the objectives of estuarine research can be restated as follows:

> Sedimentation from all aquatic environments is the result of interaction of physical, chemical and biological processes. It is often difficult to identify the processes in the marine environment because rates are low and magnitudes are small.
>
> A major characteristic of estuarine environments, however, is the intensity of physical, chemical, and biological gradients. The gradients operate on periodic, episodic and progressive time scales, amplifying the rates and magnitudes of sedimentation processes to a degree unmatched in other marine realms. Our goals are:
>
> a) to identify the patterns of response of fine grained sediment to physical processes;
> b) to explore the extent to which biological and chemical cycles may modulate that response;
> c) to evaluate the ways in which the consequent behavior of particles may affect the delivery of river-bourne materials to the ocean;
> d) to assess the general applicability of estuarine sedimentation processes to other marine environments.

There is no dearth of outstanding research questions concerning sediment transport which are appropriate subjects of a research plan to achieve these specific goals. To focus on the most critical questions, it is necessary to subdivide topic, specify the range of processes needing further investigation and select one of these of high priority which offers the most promising prospect for significant advances. While there are many ways to perform the initial subdivision, for our example we chose to consider the processes acting on the three major interfaces in the estuary - the fluvial/estuarine interface, the sediment/water interface and the estuary/ocean interface. An overview of the existing fundamental research questions in each of these areas are as follows:

> The fluvial/estuarine interface. One of the most stimulating intellectual questions in the study of estuarine sedimentation is characterizing gross river flux of matter to the ocean, its dependency on drainage basin characteristics and the ultimate detection of that signal which is not filtered out by the estuaries. The strong physical, chemical and biological gradients inherent in estuaries accentuates processes which control particle dynamics by compressing temporal and spatial scales over which these processes occur. The fluvial/estuarine interface represents the initial and steepest portion of these gradients and exerts considerable impact on the subsequent dynamics of particles in estuaries and beyond.
>
> The most important processes or "forcing functions" are:
>
> a) freshwater flow rate or seasonal river discharge;
> b) salinity or changes in ionic strength;
> c) drainage basin characteristics, including:
>   1) upstream storage of sediments
>   2) change of particle character as a result of climate,
>   3) role of episodic events from both drainage basin (floods) and offshore (storms) sources;
> d) variations in sea level; and
> e) flocculation processes, both chemical and biological.
>
> Within this context the most pressing questions include:
>
> a) How important is the turbidity maximum in sedimentation processes? Can the turbidity maximum be related to short-term deposition or long-term accumulation of sediments?
> b) How does a change in length of the freshwater-saltwater mixing interface affect the ability of an estuary to trap sediment in its upper reaches?

c) How does a change in the length of the fresh/salt interface affect position of the turbidity maximum?
d) Does the turbidity maximum serve as a focal point for estuarine sedimentation and what escapes the turbidity maximum?
e) As the biological community changes, how does this effect sedimentation?
f) What are the time and space scales of exchange between dissolved and particulate materials?
g) How does the input of sediments affect primary production?
h) Can a small river or small estuary be used to predict the behavior of large rivers and estuaries? Is a small system an appropriate model?
i) Are there minimum or maximum temporal scales that can be reasonably addressed?
j) What are the effects of the sides or intertidal portions of estuaries with respect to sediment input?
k) How well are sedimentation patterns known in the riverine sections of estuaries?

Sediment water/interface. A conceptual model of particulate transport within estuaries is commonly accepted. Our understanding of the processes, however, are still largely dependent on empirical descriptions, and quantitative descriptions are limited by an inadequate understanding of the details of those processes that control the vertical flux of particles - settling velocity, turbulent mixing, deposition, consolidation and resuspension.

Outstanding questions have often been identified in other workshops, and, while any of these are interesting research topics in themselves, the need for attention to these details is critical for understanding how the estuarine sedimentary filters operates. One of the most pressing problems is the determination of the resuspension rate and the deposition rate under clearly specified forcing functions. For this task innovative, in situ instrumentation should be pursued.

Some of the other important questions are:
a) What is the relative importance of biotic and abiotic aggregation in

the context of overall biological processes (i.e. primary and secondary production cycles)?

b) What are the energy sources for fluid shear in various parts of the estuary and how is turbulent energy transferred to the size scale influencing particle collision rates?

c) What are the appropriate settling rates to use when modelling estuarine sediment transport?

d) To what extent does the production of biogenic particles enhance the vertical flux of suspended material?

e) Settling of flocs into the bed leads to the development of high concentration layers that may have a non-Newtonian response (fluid muds).
   1) How does the rate of consolidation depend on the rate of deposition?
   2) What is the character of the mean flow and turbulent damping in this layer and how does the offset of this layer affect the overlying boundary layer?
   3) What controls the stability of the upper interface of the fluid mud layer?

f) The production of biogenic particles substantially enhance the flux of suspended material.
   1) How does the settling of biogenic material or active scavenging by pelagic or benthic grazers influence the chemical nature and biological structure of sediments and, therefore, affect their stability?
   2) To what extent do sorption and aggregation processes affect the rate of transfer of both dissolved and particulate matter across the sediment-water interface?
   3) How do physiochemical micro-environments created by microbial activity affect fluxes across the sediment water interface?
   4) How do organic coatings modify absorption and aggregation processes; do they enhance or destablize the interface?

g) How do microlayer processes at the air/water interface promote aggregation and the lateral or vertical transport into the water column?

h) What factors govern the downward mixing of energy (including surface wave energy), momentum and mass and what is the effect on pycnocline development and/or deterioration?

i) In what form is surface wave energy transmitted to the sediment water interface in stratified systems?

j) What is the structure of the boundary layer and the turbulent shear over surfaces characterized by a wide range of roughness scales including biological micro-scale topography?

k) How do biota affect the consolidation process and erodability of sediments.

It is believed that a reasonable number of parameters can be identified for the construction of predictive models.

Estuary/Ocean interface. The quantification of sediment exchange between the ocean and estuary is needed as a boundary condition to model both the sediment transport into the estuary and out to the coastal ocean. There are two types of exchanges that might need to be specified:

a) the net flux into or out of the estuary
b) the total flux of fluvial sediment out of the estuary and the simultaneous influx of oceanic particles.

The approaches needed to understand these processes contain two specific requirements even though the details of any research program cannot be defined in general. First, any research plan must attempt to measure small differences between large gross fluxes. These fluxes are highly variable in time due to lunar tidal variations and fluctuations in river discharge, as well as episodic events. Second, the interface between the estuary and the ocean is not a fixed plane but rather is a water mass that spans a tidal excursion and that is alternately moved into and out of the estuary. As a result, Lagrangian measurements are needed to complement Eulerian ones.

To be able to average these time and space scales adequately presents a major challenge. There seem to be three basic approaches:

a) direct measurement of fluxes at a significant number of stations on a cross section at the mouth.

b) a sediment budget which defines the other inputs and exports from the estuary (river inflow and bed deposition/erosion.

c) an adequately calibrated numerical process model of the estuary.

The determination of a sediment budget to get a net trapping efficiency is probably adequate as a first approximation. However, such an approach is limited by the difficulties in obtaining long-time averages of the input and output, the spatially averaged depositional rates and the contributions of internal erosional sources. Further progress on the determination of estuary/ocean exchange can be made only be using an approach combining both observations and modeling. It would be better to define sediment exchanges in terms of particle exchange rather than fluxes, if specific numbers could be developed.

The observations must employ the most recent technology for high-frequency, long-term sampling (such as, perhaps, acoustic doppler techniques, laser measurements of particle characteristics, and concentration, etc.) to estimate fluxes under a wide range of condition (tidal strength, river flow, storm surges, etc.) The modeling must be done in three dimensions because important processes include resuspension and deposition of material on the margins of the estuary as well as flood-ebb asymmetry reflected in the geometry of the estuary mouth. For any particular estuary, the dominant processes will be a subset of the basic processes describing sediment transport. These include the processes that determine the:

a) settling velocity
b) eddy diffusion
c) frontal structures and mixing
d) sediment erosion and deposition
e) gravitational circulation

Such an approach favors beginning with estuaries having the following characteristics:

a) small dimensions but with a depth great enough to eliminate the variability due to winds
b) limited local marginal sediment sources (into tidal areas, tributaries, etc.)

c) limited man induced modifications
d) a strong seasonal river signal

These are likely to be the simplest cases we can find, and would be of a scale to allow adequate sampling for calibration and testing a model. The model would then be progressively applied to larger systems and refined to take account of further complexities.

Productive research could be carried out on any of the above topics (and many others) and the results applied to improving our understanding of estuarine filters. While many details of the processes of aggregation, deposition and resuspension need to be better resolved, efforts to determine the efficiency of the estuary as a filter are at present effectively constrained by our limited understanding of regional dynamics. As a next step, therefore, a multidisciplinary experiment would be fruitful.

A Multidisciplinary Experiment. It is proposed to undertake a multidisciplinary experiment in an estuary at the interface with the river in the region where the salinities are 0-10% and where the physical, chemical and suspended sediment gradients are highest. In this region the sediments transported down the river first encounter conditions under which flocculation can occur, where the flow becomes totally reversing, and alternating deposition and resuspension from the bed takes place. It is thought that the processes occuring in this region are critical in determing the eventual fate of particles brought in by the river, and transferred further down the estuary.

The objectives of the experiment would be to:

1. Determine the primary mechanics governing the formation, position and strength of the turbidity maximum; under what condition is the turbidity maximum dominated by the gravitational circulation, or by settling and erosion lag effects. Is flocculation an important process?
2. Determine how the turbidity maximum relates to the accumulation of sediment in the estuary.

The experiment will need to be carried out in one or more estuaries, with measurements of suspended particulate fluxes on several sections over tidal cycle periods. Particular emphasis needs to be put on lateral variations, as well as on fluxes in the bottom boundary layer, since fluid muds may be important. Repeated measurements over a seasonal timescale would allow measurement of the influence of biological processes, and episodic events. Attention needs to be made to adequate characterization of the properties of the suspended particulates in mineralogical, chemical and biological terms. The primary aim is to determine the relationship between the suspended sediment, the velocities and erosion/deposition at the bed, rather than determing cross-sectional mean fluxes in the estuary.

The deposition and erosion at the bed would need to be determined on a variety of timescales, ranging from minutes to years. Various tracers, especially radiochemical could be particularly useful. The fabric of the bed would need to be determined in geochemical, chemical and biological terms. This experiment would be the first in a series which would determine the variability of the processes between different types of estuary, would provide a comparative data set for calibration of numerical models, as well as providing the insights allowing development of specific proposals for geochemical and biochemical studies.

The experiment might then be extended to other estuarine types. In a simplistic sense, for example, we can consider estuaries as belong to two morphological end members - broad and shallow vs. deep and narrow.

Broad and shallow estuaries are often characterized by large mudflats, marshes at the upper end of the intertidal, and fairly distinct deep channels. The broad shallow areas are rich in biota including organisms such as filter feeders to remove sediments from suspension as well as benthic micro-algae which can act as sediment binders. Under moderate conditions then, these shallow areas accumulate sediments and act as an effective sediment storage facility. However, during storms, they are the first to release sediment by wind wave resuspension, direct rain impact on the intertidal zones, etc. Besides episodic events, seasonal climate changes can change biological populations, cause ice to form, etc., which modify the filtering behavior of these estuaries.

Deep narrow estuaries, on the other hand, may be less variable in terms of their filtering capabilities. Intertidal zones are small compared to tidal estuarine volume, and tidal currents are consistent and predictable estuarine events. These systems may act more like conduits than providing a filtering mechanism betwen the river and the ocean.

Where Do We Go From Here?

From a general experiment in estuarine sedimentation, like that just described, our research plans could follow several branches. It could be directed inward to the definition of particular limiting processes. It could be expanded geographically to identify and quantify processes at the estuary/ocean interface. It could be extended to other classes of estuaries such as those without well defined turbidity maxima.

The interdesciplinary nature of the questions is inescapable. Biological and geochemical studies will develop in tandem with geological and physical ones; the estuaries are also filters for geochemical fluxes and for biological cycles. Any program of estuarine research must examine the important biological filtering processes and the critical geochemical filtering behavior of estuaries. We recommend that this approach be explored for other specific topics and that an ad hoc steering committee be formed to encourage the development of a more coherent research program in estuaries.

A Framework for Research in Estuaries: the report of a workshop held at the Marine Sciences Research Center, State University of New York, Stony Brook, New York, 27 to 29 September, 1987.

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