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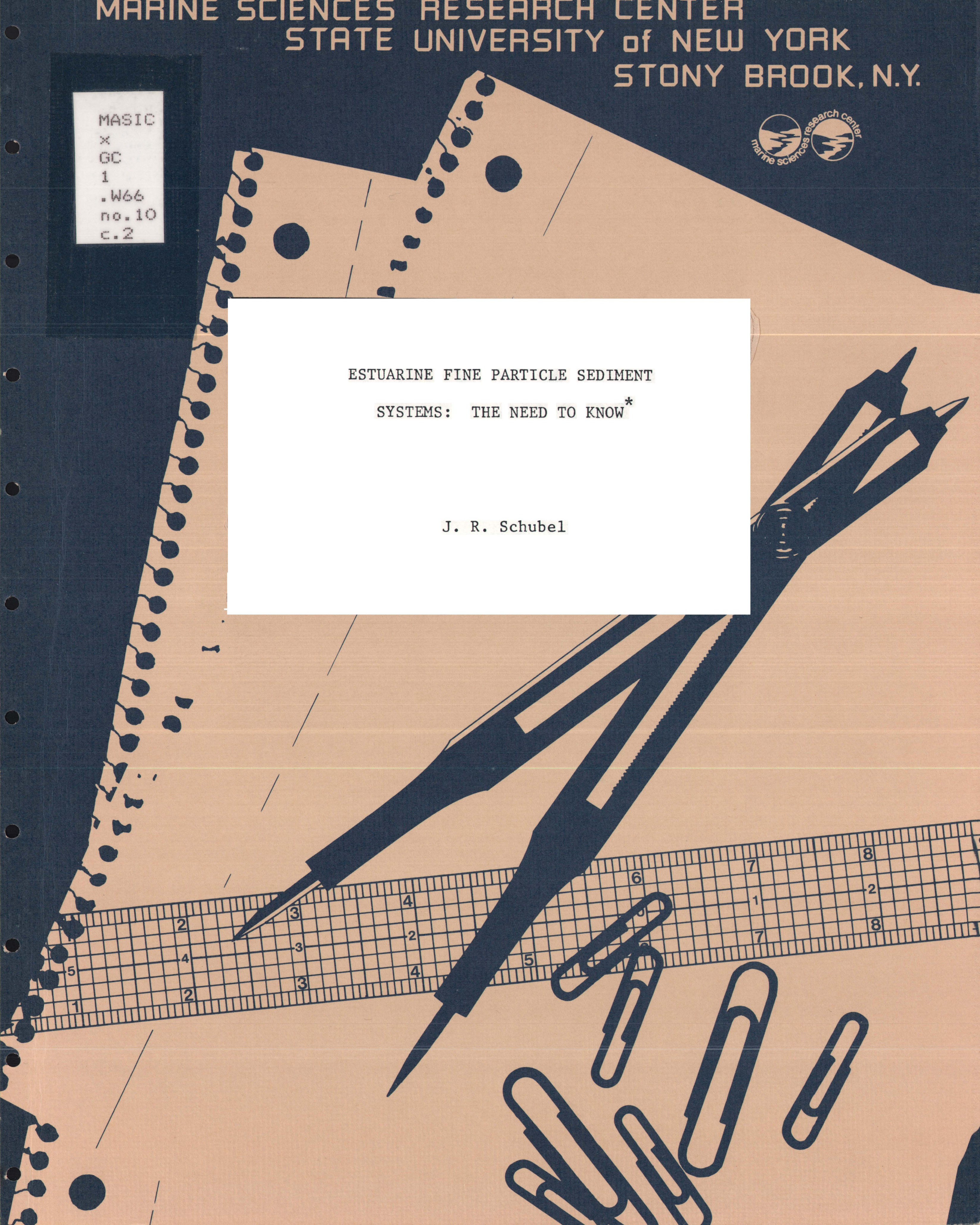

ESTUARINE FINE PARTICLE SEDIMENT SYSTEMS: THE NEED TO KNOW[*]

J. R. Schubel

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JRSchubel

J. R. Schubel, Director

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 also have introduced significant quantities of anthropogenic particulate matter and have stimulated the production of organic 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. The effects are direct and indirect. In most estuaries the sediment that fills navigation channels and must be removed by dredging at a cost of millions of dollars each year is mud--silt and clay. Fine particles also are important in determining water "quality" of the estuarine environment.

It is well known that many of the potentially most insidious contaminants are relatively insoluble in water and have a high affinity for adsorption to fine particles. Among these contaminants are petroleum hydrocarbons, heavy metals, polychlorinated biphenyls and other chlorinated hydrocarbons, polynuclear aromatics, pesticides, herbicides, and some radionuclides. Because of their insolubility, these substances are scavenged rapidly from solution in the water column near their points of introduction by fine suspended particles. Once adsorbed onto fine particles, their distribution, transportation, and accumulation--and their environmental and ecological effects--are determined primarily by the suspended sediment dispersal system of that particular water body. The processes that control dispersal are not all physical.

Filter-feeding organisms ingest fine suspended particles and associated contaminants and 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. 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 particles can also serve as sources and sinks for nutrients.

Fine-grained suspended sediment also can 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. The 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.

Increases 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 sand does not have the same effect on water color and transparency as does the same concentration of organic-rich silt and clay.

Regardless of the criterion one selects to measure environmental quality, influxes of fine-grained particulate matter into estuaries have a deleterious effect on many uses of these environments and a salutary effect of few. This is true whether the particles are suspended in the water column, or are deposited on the bottom. It probably is not an exaggeration to state that fine-grained particulate matter has a greater effect--direct and indirect--on environmental quality and on the uses society makes of the Nation's estuaries than any other single factor.

There are 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 by physical-chemical processes, the reworking of sediments by benthic organisms and the consequent changes they produce in the physical properties of the sediment, and the processes that control the uptake and release of substance by fine particles. 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--hardly have been considered. Where estuarine sedimentary systems have been characterized it usually has 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 (Inglis and Allen, 1957). It is to studies of the second kind--studies of estuarine fine particle sediment systems--that we direct out attention in this report.

The same processes--biological, chemical, geochemical, geological and physical--are at work in all estuaries, but the relative importance of these processes vary dramatically not only from one estuary to the next, but among different segments of an estuary at any given time. And there are large temporal variations within any segment of an estuary. One can learn a great deal about the mechanics of sediment transport and about the other processes important in estuarine sedimentation through laboratory flume experiments and isolated, short-term field studies; by experiments of the first kind. These studies, however, often provide little insight into the long-term manifestations of estuarine sedimentation and the identification of the specific processes that control 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. It requires studies of the second kind; studies of estuarine fine particle systems.

ESTUARINE FINE PARTICLE SEDIMENT SYSTEMS:
WHERE TO BEGIN.

Ideally, one would like to know for each estuary: (a) the sources of sediment--their locations and strengths, (b) the character of the sediment introduced--its size distribution, composition, and associated contaminants, (c) the routes and rates of sediment transport--including the transient repositories, (d) the sites of final accumulation within the estuary and, (e) the amount lost to the ocean. There are also many important biological and geochemical questions; these will be touched on only lightly in this report. The problem is already too large. Our primary 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 disturbed occasionally 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.

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 and processing, 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 also have 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 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 distinguishing between those present features of the surficial sediment distribution which will be permanent characteristics of the sedimentary system--characteristics that will be incorporated into the Record--and those which may be transient features.

Once the areas of estuarine mud are located, the thickness of the deposits may be measured 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 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 frequently are 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 also are disturbed episodically by major storms. Because of these perturbations, direct observations of the rate of sediment accumulation may require observational periods of tens or even 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.

Useful information also can be obtained on the average rates of accumulation of sediment over approximately the past century by a careful comparison of old and recent 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.[1]

One effective way to improve significantly our understanding of fine-grained estuarine sediment systems is through collaborative investigations by geochemists and oceanographers. Geochemists possess

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[1] National Ocean Survey, Rockville, Maryland 20852

powerful tools for improving our knowledge of estuarine sedimentation and for chronicling man's impact on these systems, but they sometimes have misused these tools.

Most estuaries are highly heterogeneous, patchy, in many of their characteristics and are not amenable to facile studies by itinerant geochemists and oceanographers. If one sets out to understand an estuary by spot sampling the waters that enter it, and the waters that temporarily reside within it, or by spot sampling the bottom at a few stations, one had better have some notion of the temporal and spatial scales that govern that estuary before writing its biography. There is a distressing tendency among some geochemists to model the fine-grained sediment systems of estuaries and to write their pollution histories on the basis of a few cores without assessing whether or not their samples are representative of substantial portions of those systems, or whether or not the cores have even retained their chronology.

Schubel and Hirschberg (1980) outlined the procedure shown schematically in Figure 1 as one that could improve the effectiveness of geochemical studies in adding to our understanding of fine-grained estuarine sediment systems, particularly of the rates at which fine-grained sediments are accumulating. The necessity for each of the steps should be obvious, but a number of them are frequently overlooked.

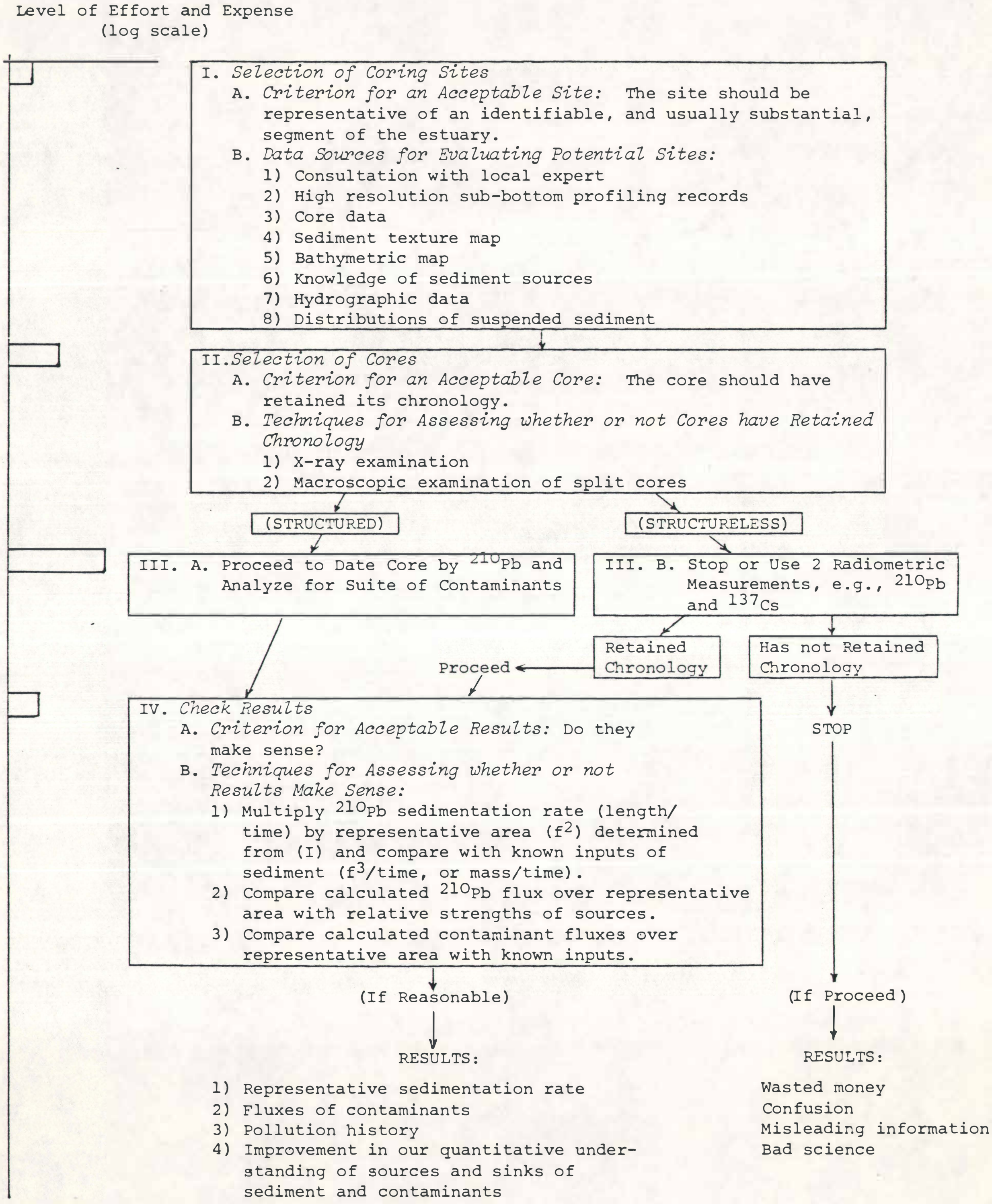
Two Case Studies

Schubel and Hirschberg (1980) examined most of the published papers on studies in which geochemical techniques had been used to study the recent sedimentary history of estuaries. Few adequately meet the most important criteria shown schematically in Figure 1. Failure to do so resulted in some studies being far less valuable than they could have been, and in other studies being inadequate and with incorrect conclusions.

Schubel and Hirschberg (1980) selected two case studies as examples: the first illustrated how a combination of geophysical and geological studies and radiometric dating significantly improved our understanding of an estuarine sediment system and man's impact on it; the second illustrated how an inappropriate and inadequate application of geochemical techniques led to erroneous results.

The studies of Bokuniewicz et al. (1976) and Benninger (1978) provide a good example of the success that can be obtained in understanding an estuarine sediment system by thoughtful integration of geochemical, geological, and geophysical data. Using high resolution seismic reflection profiling, Bokuniewicz et al. (1976) were able to delimit the areal extent and thickness of Recent fine-grained deposits on the floor of Long Island Sound. A distinctive late-Wisconsin reflector and the absence of gas bubbles entrapped in the fine-grained sediments made this approach possible. Even though these investigators had little data on the strengths of the sediment source terms, they were able to estimate the mean sedimentation rate from the volume of sediment, determined geophysically, by assigning an age to the Wisconsin reflector based on arguments from sea level curves. Using these data, they estimated a mean sedimentation rate for the lacustrine mud of 0.5 - 1.0 mm y^{-1}. From their data for Recent marine muds, one obtains a mean sedimentation rate of not more than 0.4 mm y^{-1} for approximately the past 8,000 years.

Using the lead-210 method, Benninger (1978) obtained a mean sedimentation rate of Recent fine-grained material in Long Island Sound of only 4.5 mm y^{-1}. At Steps II and III (Fig. 1) it was clear that the disagreement between the long-term sedimentation rate of Bokuniewicz et al.



I. *Selection of Coring Sites*
  A. *Criterion for an Acceptable Site:* The site should be representative of an identifiable, and usually substantial, segment of the estuary.
  B. *Data Sources for Evaluating Potential Sites:*
    1) Consultation with local expert
    2) High resolution sub-bottom profiling records
    3) Core data
    4) Sediment texture map
    5) Bathymetric map
    6) Knowledge of sediment sources
    7) Hydrographic data
    8) Distributions of suspended sediment

II. *Selection of Cores*
  A. *Criterion for an Acceptable Core:* The core should have retained its chronology.
  B. *Techniques for Assessing whether or not Cores have Retained Chronology*
    1) X-ray examination
    2) Macroscopic examination of split cores

III. A. Proceed to Date Core by ^{210}Pb and Analyze for Suite of Contaminants

III. B. Stop or Use 2 Radiometric Measurements, e.g., ^{210}Pb and ^{137}Cs

IV. *Check Results*
  A. *Criterion for Acceptable Results:* Do they make sense?
  B. *Techniques for Assessing whether or not Results Make Sense:*
    1) Multiply ^{210}Pb sedimentation rate (length/time) by representative area (f^2) determined from (I) and compare with known inputs of sediment (f^3/time, or mass/time).
    2) Compare calculated ^{210}Pb flux over representative area with relative strengths of sources.
    3) Compare calculated contaminant fluxes over representative area with known inputs.

RESULTS:
1) Representative sedimentation rate
2) Fluxes of contaminants
3) Pollution history
4) Improvement in our quantitative understanding of sources and sinks of sediment and contaminants

RESULTS:
Wasted money
Confusion
Misleading information
Bad science

Figure 1. A conceptual framework for improving the usefulness of radiometrically-determined sedimentation rates in understanding estuarine sediment systems.

(1976) of 0.4 mm y^{-1} and the lead-210 rate calculated by Benninger (1978) of 4.5 mm y^{-1} was caused by bioturbation of the core dated by lead-210. X-radiographs of the core gave equivocal results regarding the presence of sedimentary structures. Even though reworking had destroyed the chronology, analytical integration of the lead-210 profile provided an estimate of the lead-210 flux to the core site which, when multiplied by the "representative" area of accumulation of modern estuarine muds determined by sub-bottom profiling, yielded a value for the total lead-210 deposition in the Sound. This value was in close agreement with the rate of input estimated previously. The resulting conclusion that Long Island Sound is an efficient trap for fine-grained sediment and lead-210 is an important one; a conclusion that also has many important implications for substances discharged into the Sound by man.

This case is especially illustrative since many valuable conclusions about the study area (Long Island Sound) were obtained even though the core dated by Benninger (1978) was bioturbated. Useful and geologically reasonable conclusions about the rates and patterns of sedimentation were obtained through a comparison of results obtained by geophysical (Bokuniewicz et al. 1976) and geochemical (Benninger, 1978) means (Step IVB). Many of the important geochemical conclusions about the estuary were possible only by reference to the geological and geophysical data.

If La Rochefoucauld was correct that "history never embraces more than a small part of reality," then the paper entitled "A Pollution History of Chesapeake Bay" (Goldberg et al. 1978) has succeeded admirably. Goldberg et al. (1978) took a series of cores at five stations along the axis of the main body of Chesapeake Bay and analyzed them for lead-210, plutonium, and a variety of metals. From the slopes of the lead-210 depth profiles, these authors calculated sedimentation rates. Using these rates and the results of the metal analyses, they calculated fluxes of metals to the sediments at the various stations and constructed a pollution history for Chesapeake Bay. The basis for reconstructing that history was the lead-210 method.

These investigators began their study appropriately at Step I shown in Figure 1 (Goldberg, personal communication 1979) but they apparently proceeded to invest a great deal of time and effort in dating and analyzing the cores (Step III) without satisfactorily demonstrating that the cores had retained their chronologies (Step II). More importantly, they apparently did not ask whether their sedimentation rates made sense. They did not compare their lead-210 sedimentation rates with other estimates of sedimentation rates for the same areas, nor did they compare their sedimentation rates with measured inputs from known sources of sediment. Unlike Long Island Sound, the volume of Recent fine-grained sediments deposited in Chesapeake Bay is poorly known. There is no distinctive and ubiquitous late-Wisconsin reflector of known age, and large areas of the Chesapeake Bay's near-surface sediments are opaque to high-frequency seismic sound sources because of high concentrations of entrapped gas bubbles (Schubel and Schiemer, 1973). But, the sources of sediment to the main body of Chesapeake Bay are known far better than those of Long Island Sound.

The sedimentation rates reported by Goldberg et al. (1978) are 5-10 times greater than previous estimates and than rates that can be accounted for by all known sediment inputs to each of the several segments of Chesapeake Bay they studied (Schubel, 1968; Biggs, 1970; Schubel and Carter, 1977; Schubel and Hirschberg, 1977). Previous estimates of sedimentation rates have been based on simple sediment-budget models (Schubel, 1968;

Biggs, 1970; Schubel and Carter, 1977) and on lead-210 data (Schubel and Hirschberg, 1977; Hirschberg, 1977; Hirschberg and Schubel, 1979). The rates presented by Goldberg et al. (1978) clearly are not representative of substantial segments of the Bay. For example, sediment inputs required to support the sedimentation rates estimated by Goldberg et al. (1978) for the middle and upper Bay are 10 times greater than measured sediment inputs, assuming the sedimentation rates are representative of more than local conditions.

Schubel (1968, 1972) and Gross et al. (1972) have estimated that the long-term mean input of fluvial sediment to the upper Chesapeake Bay from the Susquehanna River--the source of more than 99% of the total fluvial sediment input to this segment of the Bay--is about 1×10^6 tons per year. If all of this sediment were deposited in the upper reaches of Chesapeake Bay north of 39° 12'N, it would account for a sedimentation rate of 7-8 mm per year--less than 10% of the sedimentation rate (8 cm per year) estimated by Goldberg et al. (1978) for a station in this segment of the Bay 39° 14'N). Shore erosion may contribute an additional 0.1×10^6 tons per year of fine-grained mataerial. Clearly, Goldberg et al.'s (1978) sedimentation rate is not representative of a substantial segment of the upper Chesapeake Bay. It may reflect the local sedimentation rate, but I doubt it. Their estimate of the sedimentation rate probably is anomalously high because the sediments have been bioturbated.

Schubel and Hirschberg (1980) reconstructed in Figure 2 Goldberg et al.'s (1978) lead-210 depth profile for station CHSP 1212 located in the upper reaches of Chesapeake Bay (39° 14' 12"N; 76° 14' 18"W). These data were interpreted by Goldberg et al. (1978) to represent a sedimentation rate of 8 cm per year. Although the data in Goldberg et al. (their

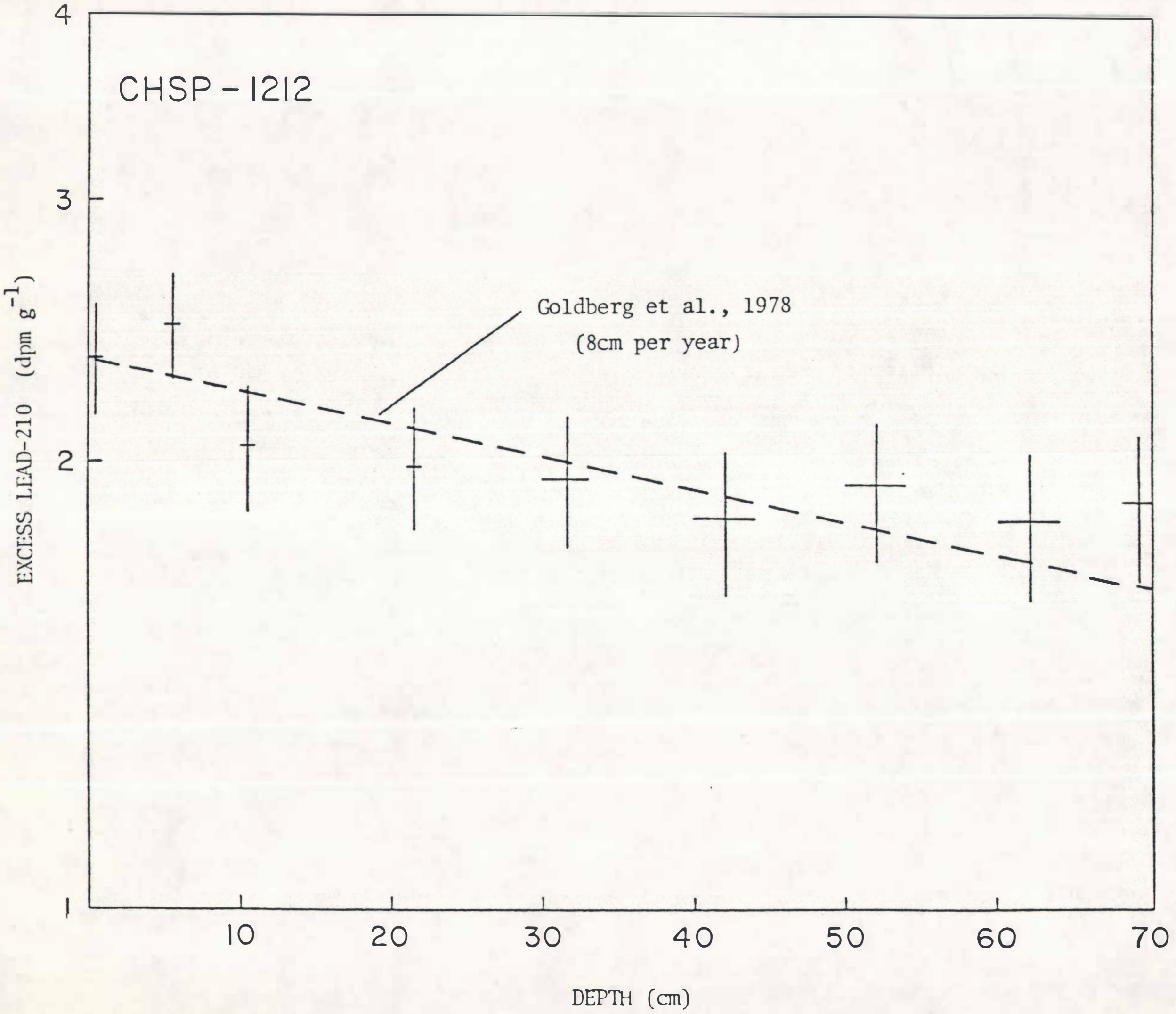


Figure 2 Lead-210 levels in Chesapeake Bay sediments at Station CHSP 1212 (39°14'12"N, 76°14'18"W) in upper Chesapeake Bay (based on Figure 2 in Goldberg *et al.*, (1978)). We have added uncertainty estimates based on comparisons with other published analyses using the same techniques as Goldberg *et al.* (1978).

Figure 2) were reported without uncertainty estimates, comparison with other published lead-210 analyses using the same techniques indicate an appropriate uncertainty of about ± 0.2 dpm g^{-1} which have been added in Figure 2. Considering these uncertainty bounds, a slope of approximately zero is consistent with their data. This corresponds to an infinitely high sedimentation rate. The reported occurrence of plutonium to a depth of 72 cm in the sediment confirms the lead-210 data, but not the chronology of this core. The interpretation offered here is consistent with the distribution of lead-210 and explains the anomalously high sedimentation rate.

Collaborative investigations by geochemists and oceanographers can, if done properly, add substantially to the understanding of estuarine sediment systems and to the impacts of man on those systems. Too frequently, however, potentially powerful geochemical tools have been misapplied leading to erroneous results and confusion.

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 resuspended easily. 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.

Sources of Sediment

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

Fluvial Inputs

River (fluvial) inputs are one of the most important sources of sediment to estuaries. 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 whch 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 move the positions of existing ones closer 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 load and bed load.

These stations should be maintained permanently so that the relative importance of occasional floods can be assessed. Only a few rivers have been monitored long enough for documentation of 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 (Schubel and Carter, 1976). Estimates of the inputs of sediment from shore erosion have been made for only 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 shoreline positions 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 determilning erosion rates.

Internal Sources: Primary and Secondary Productivity

In some estuaries internal sources can account for a large fraction of the total sediment input. In the Delaware Bay, 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, relaiable estimates of the flux of fine-grained suspended sediment through the mouths of estuaries. Even the direction rarely is 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 reliable measurements over extended periods of time, recording *in situ* optional devices are crudeby comparison. The difficulty and expense associated with making concomitant direct measurements of the concentrations of suspended sediment preclude extensive time series observations. 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 (JRS get Refs). Pollen is another tracer that rarely has been exploited in unraveling the sedimentary history of estuaries. Grace S.Brush (1982) has demonstrated clearly the utility of pollen in chronicling the recent sedimentary of Chesapeake Bay and the effects of man. 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 available for resuspension, sediment that is on the bottom part of the time and in the water column part of the time. The greater 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, transient fluid mud layers form on neap tides. These deposits are mobilized on the next spring tide. The bottom is so unstable that benthic communities are unable to 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 topics need to be addressed in characterizing 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 wind waves. 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. 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 described adequately.

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 individual mineral and organic 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 also will be altered by the burrowing activity of animals.

The individual processes described above can be studied in detail either in the field or in the laboratory. Some are being studied systematically now; others receive only 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 which animals can inhabit any given area of the bottom depends on its stability, which depends on its erosion resistance and on the physical environment. There is a web of interactions among these effects of animal populations and bottom properties, among bottom properties and sediment supply, and among the power dissipation spectrum and the nature of the sediments on the bottom and in the water column. These inter-relationships will be resolved only by field studies of 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 might 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 spends 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 (1972) were 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 understanding 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 or any other Federal Agency 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 agencies and by those Federal agencies charged with responsibility for our coastal waters.

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 estuarine 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 discharges 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 most important experiments that are occurring in our coastal waters--those associated with catastrophes.

Some Research Priorities

For each major estuary with substantial imputs of fine-grained sediments and/or contaminants, studies of the kinds described in this report should be conducted to characterize the fine-grained sediment systems sufficiently well for purposes of estuarine management. Some of the specific kinds of studies of fine-grained particulate matter that should, in this author's opinion, be given a high priority are listed below. They are unranked.

(1) Studies to determine the fluvial inputs of suspended solids, both naturally occurring and anthropogenic, to important estuarine systems.

(2) Studies to determine the routes and rates of movement of fine-grained materials to and within estuarine systems, and the sites of accumulation.

(3) Studies to determine the discharge of suspended and bed loads to the ocean from major rivers and estuaries.

(4) Studies to assess man's impact on prevailing fine sediment dispersal processes, and to devise ways of ameliorating undesirable effects.

(5) Studies to characterize the composition, the chemical nature, and the reactivity of fine-grained suspended matter in a variety of estuarine environments.

(6) Studies of fine suspended matter to determine the directions and rates of reactions involving nutrients, metals, halogenated hydrocarbons, and a variety of other contaminants as a function of environmental parameters.

(7) Studies of biologically-mediated reactions involving fine suspended particles.

(8) Studies to assess the role of climate on the inputs of dissolved and suspended loads of rivers to estuaries.

(9) Studies to assess the relative importance of various agglomeration processes in controlling the size distribution of suspended particles in estuaries, and the sedimentation (deposition) of fine particles in a variety of coastal environments.

(10) Studies to assess the importance of events (floods, hurricanes, tsunamis, etc.) in estuarine sedimentation. Successful conduct of such studies will require the establishment of funding mechanisms capable of rapid response.

(11) Studies of the geochemical processes that control the composition of dissolved and suspended loads in rivers and estuaries.

(12) Studies to characterize the processes that cause estuaries to function as filters for the signals they receive from rivers and from the sea, and to develop the capability to predict how an estuary's "filter factor" changes with environmental conditions.

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