SEDIMENT TRANSPORT IN ESTUARIES

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Summary

Estuarine sediment transport processes, significant to food supply, commerce, recreation, and the natural environment, are the result of complex flows and complex

physical and chemical processes. Cohesionless sediments, such as sand, hop or roll along the bed and are lifted into suspension, where they move at about the speed of the water. They settle to and are lifted from the bed by turbulent fluid forces. Fine sediments exhibit cohesion, in which particles bind together because of electro-chemical forces, forming aggregate particles of perhaps millions of individual grains when flow and water chemistry conditions are conducive to particle aggregation. Cohesive sediments travel in suspension as individual grains or as aggregates of many grains, and settle toward the bed only when they grow heavy enough to overcome flow turbulence. Prediction and analysis of estuarine sediment transport is often accomplished by use of numerical models, which use computational techniques to solve the equations of sediment behavior. Human behavior can affect the transport, deposition, and erosion of sediment through watershed alterations, river regulation, navigation projects, and pollution.

1. Introduction

Estuaries, loosely defined as those water bodies where the river meets the sea, serve human communities by providing food, recreation, and waste assimilation, and enabling commerce through navigable waterways and safe ports. As food producers they are important to fishing, providing a home for many species and nurseries for many more.

Any of these uses can be compromised either by too much sediment or by too little. Too much sediment prevents light penetration that aquatic vegetation needs, smothers benthic habitat, and clogs navigation channels. Too little sediment can increase predation of some species or cause land and marsh loss, as in the Louisiana coast of USA, that loses 65 km^2 of land each year as sediment-starved marshes crumble under wave attack and subside beneath the Gulf of Mexico.

Some contaminants, such as metals and chlorinated compounds, bind to fine sediment particles, sequestering them from the aquatic environment to some extent, but also altering the transport paths of the contaminants and causing problems with dredging and disposal. Sediments also incorporate nutrients in the form of nitrates and phosphates and can contribute to eutrophication by releasing them into the water column.

Despite the environmental and economic importance of estuarine sediment transport, its complexity makes it one of the least understood of the geophysical processes. First, estuarine flows are complex, with unsteady, daily- or twice-daily-reversing flows from tidal action, salinity ranging from that of sea water to fresh water, and vertical and horizontal circulation patterns induced by water density, geometry, and tidal asymmetry. Second, sediments exhibit a range of behaviors from independent settling of sand grains to flocculation of colloidal clays that cannot settle as individual grains. Finally, estuarine sediment moves in multiple modes: in free suspension moving with the water, as bedload bouncing along the bed or advancing in sand waves, and creeping in highly viscous near-bed layers.

2. Estuarine Hydrodynamics

The hydrodynamic regime of estuaries is characterized by marked variation of flows in time and all three spatial dimensions. Tides rise and fall, producing flow velocities that wax, wane, and usually reverse direction in diurnal or semi-diurnal cycles. Freshwater runoff meets slightly denser sea water and creates vertical circulation patterns that tend to trap and recirculate suspended material. Ocean waves propagate into the estuary mouth, joining locally generated wind waves to agitate bottom sediments and cause longshore currents. These hydrodynamic processes are often further complicated by wind-induced currents, storm surges, and seiching.

3. Estuarine Sediment Characteristics

Sediments carried by estuarine waters typically encompass a range of sizes from less than 2 m (0.002 mm) to more than 4 mm, but the finer sizes dominate most estuaries. In a few, such as the Columbia River estuary in USA and the Changjiang estuary in China, the beds are composed primarily of sand sizes greater than 62 m, at least in the main body of the estuary. A very few estuaries transport gravel and larger size sediment. The bed and banks of most estuaries, however, tend to be dominated by clays and silts, with sand and larger sizes depositing either at the head of the estuary (from upstream sources) or at the sea or ocean entrance (from downstream sources). Fine-grained sediments—clay sizes and some silts—include both inorganic and organic materials and are almost universally called mud. Examples of fine sediment dominance include San Francisco Bay in USA, the Loire Estuary in France, and the Amazon in Brazil.

For transport purposes sediments are principally characterized by their size, by constituent composition, and by cohesion. Sediments in waterborne transport are usually classified as fine if the grain size is less than 63 μm, based on the Wentworth Scale division between sands and silts. The Wentworth size scale divides fines into silts (size > 4 μm) and clays (size < 4 μm) and then further divides each category into coarse, medium, fine, and very fine. However, within the general class of fine sediments, those size distinctions are less important to transport processes than cohesion, although size and cohesion are related, as shown in Table 1.

Size μm	**Wentworth Scale Classification**	**Cohesion**
> 2000	Gravel and cobbles	Cohesionless
63 - 2000	Sand	Cohesionless
40 - 63	Medium silt to coarse silt	Practically cohesionless
20 - 40	Fine silt to medium silt	Cohesion increasingly important with decreasing size
2 - 20	Coarse clay to very fine silt	Cohesion important
< 2	Very fine clay to medium clay	Cohesion very important

Table 1. Size and cohesion in sediments.

Estuarine sand is typically composed of quartz, although other minerals such as feldspar or various heavy minerals such as magnetite may be present or even predominate, depending on the sediment source. Fine sediments in estuaries are mixtures of inorganic minerals, organic materials, and biochemicals. Mineral grains consist of clays (e.g.

montmorillonite, illite, and kaolinite) and non-clay minerals (e.g. quartz and carbonate). Use of the word "clay" to distinguish both a size class and mineral composition causes some confusion, and hereafter the word "clay" will be used to describe the mineral composition only. Organic materials include biogenic detritus and bacteria. The relative organic/non-organic composition of estuarine sediments varies over wide ranges between estuaries and within the same estuary spatially and seasonally. Organic fractions in suspended sediment ranging from 18% to 85% have been reported in Cape Lookout Bight, North Carolina, with higher organic concentrations in February than November.

Cohesion describes the tendency of fine sediment grains to bind together (aggregate or flocculate) under some circumstances, which significantly affects sediment behavior, as described below. In general, smaller grains are more cohesive, with diameters greater than 40 μm essentially cohesionless, and cohesion becoming progressively more important as grain size decreases, as shown in Table 1.

Clay minerals consist of silicates of aluminum and/or iron plus magnesium and water and typically contain sorbed anions (e.g. NO_3^-) and cations (e.g. Na^+) that can be exchanged with ions in the surrounding fluid. Clay crystals occur in plate-like and rod shapes, usually with the long faces exhibiting a negative electrical charge and the edges exhibiting a positive charge due to the exposed lattice edges and sorbed ions. The surface charges are measured in terms of the ease with which cations held within the lattice can be exchanged for more active cations in the surrounding fluid—the cation exchange capacity (CEC) being expressed in milliequivalents per 100 gm of clay. Table 2 lists the four most common clay minerals, their characteristic size, their CEC, and the salinity critical to aggregation (also called flocculation or coagulation), which is discussed below. Cohesion of estuarine fine sediment may be changed from that of its constituent clay minerals by metallic or organic coatings on the particles.

Immersed grains of micron-sized clay minerals cannot settle in a quiescent fluid, because Brownian motion is sufficient to overcome their small submerged weight. Only when many individual grains are bound together by inter-grain forces into an aggregate do they gain sufficient weight to settle, and therefore the aggregation process is critically important to fine sediment transport.

Clay Mineral	**Grain Size μm**	**Equivalent Circle Diameter μm**	**Cation Exchange Capacity meq $100g^{-1}$**	**Critical Salinity for Aggregation ppt**
Kaolinite	1 by 0.1	0.36	3 - 15	0.6
Illite	0.01 by 0.3	0.062	10 - 40	1.1
Smectite (montmorillonite)	0.001 by 0.1	0.011	80 - 150	2.4
Chlorite	0.01 by 0.3	0.062	24 - 45	--

Table 2. Common clay minerals and their typical characteristics.

4. Cohesionless Sediment Transport

4.1. Transport Modes

Cohesionless sediment—sand size and larger, plus coarser silts—are transported as single grains in several modes. At very low flow speeds, when the flow exerts tractive forces on the bed that are lower than a critical value (discussed below), no motion occurs. If the flow-induced forces slightly exceed the critical value for initiation of motion, individual grains begin to tumble or hop along the bed.

At higher flow speeds the hops become longer jumps and the bed surface sediment is generally in motion, but with individual grains remaining on the bed between jumps. Finally, jumps of some grains take them high into the water column, where they can be transported significant distances before touching the bed again. Thus cohesionless transport modes are classified by the amount of time the grains spend in contact with the bed of the waterway.

The simplest classification scheme divides the total sediment transport rate into bedload and suspended load, where bedload consists of grains rolling, sliding and jumping in frequent or continuous contact with the bed, and suspended load consists of grains in suspension above the bed for extended periods of time. That part of the suspended load that is not found in the bed is referred to as wash load.

While conceptually convenient, the division between bedload and suspended load is not easily quantified. Measurements of suspended load become increasingly difficult and inaccurate near the bed, and bedload can be satisfactorily measured only in special circumstances such as laboratory or small scale field experiments.

Thus transport is often expressed as total load, the sum of bedload and suspended load, and transport rate measurements are often expressed as measured load (sometimes inaccurately called suspended load) and unmeasured load.

4.2. Initiation of Motion

The above discussion mentions initiation of motion, the point at which cohesionless grains in the bed first begin to move. Also called incipient motion, it occurs when the vector sum of forces on a sediment grain forms an angle with the bed that exceeds the sediment's characteristic angle of repose.

Incipient motion is usually expressed by means of a Shields' diagram as shown in Figure 1, expressed as a relationship between a dimensionless critical shear stress, τ_*, and a particle Reynolds number (also called a boundary Reynolds number), R_*, given by, respectively:

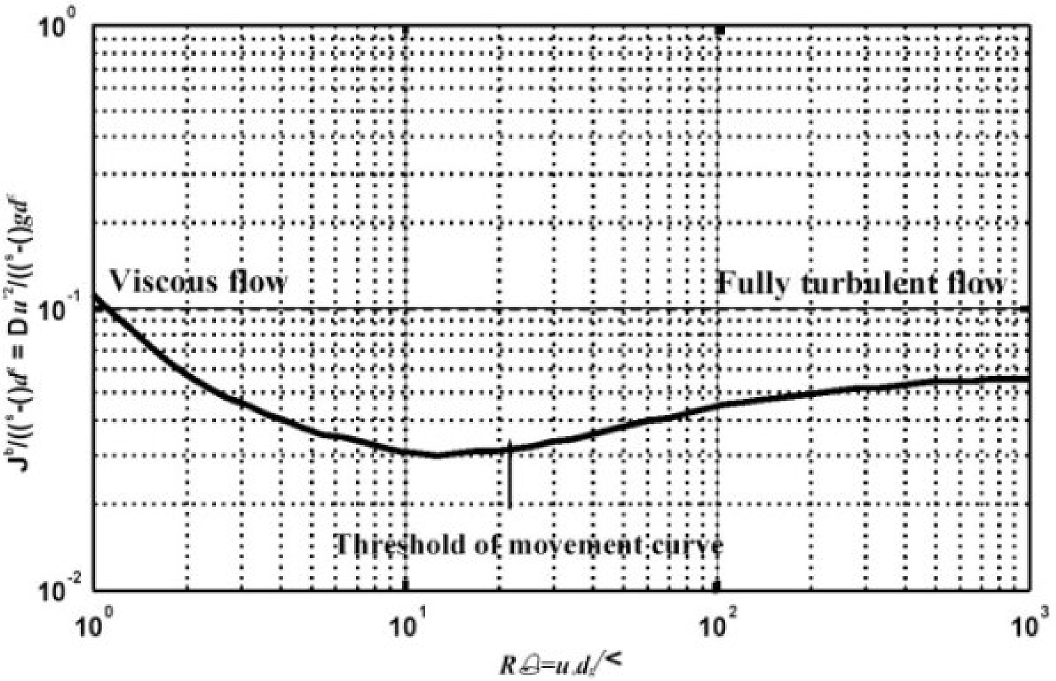

Figure 1. Shields Curve for incipient motion of cohesionless sediment

$$\tau_* = \frac{\tau_b}{(\gamma_s - \gamma)d_g} \quad (1)$$

$$R_* = \frac{u_* d_g}{\nu} \quad (2)$$

where τ_b = bed shear stress, γ_g = unit weight of the sediment grains, γ = unit weight of the fluid, d_g = grain diameter, u_* = shear velocity of the flow $\sqrt{\tau_b / \rho}$, ν = kinematic viscosity of the fluid, and ρ = density of the fluid.

4.3. Bed forms

The shape of the cohesionless bed surface varies with flow and the rate of transport. An initially smooth, planar bed will remain smooth for low transport rates, then become covered with moving ripples at a slightly higher transport rate. At still higher rates the ripples coalesce into large sand waves (or dunes) in which sediment particles eroded from the upstream dune face land on the steeper downstream face and the waves march slowly downstream.

Under the reversing flow of estuaries, sand waves reverse their migration direction every few hours, but often exhibit a locally dominant direction that can be interpreted to establish dominant flow and transport directions. For example, in the Columbia River mouth between the states of Oregon and Washington, 1 to 2 m high sand waves show a dominant seaward transport direction in the central deep channel and dominant landward direction on the shallower side slopes.

At somewhat higher flow and transport rates, the sand waves and ripples flatten out and a plane bed occurs once more. At very high transport rates antidunes form, which migrate upstream even as sediment moves downstream, eroded from the downstream face of one antidune and deposited on the upstream face of the next antidune. Antidunes are rare in estuarine environments.

4.4. Transport Rate Calculations

Transport rate equations for cohesionless sediment are usually derived for steady-state flow conditions atypical of estuaries; however, several formulations have been used successfully in estuarine calculations because the flow can be assumed to be quasi-steady on physical grounds. Commonly used formulations include the Ackers-White total load equations and van Rijn bedload and suspended load equations, given below. For grain sizes of 0.2 to 2 mm, bedload transport rate, q_b, is given by van Rijn:

$$q_b = 0.053\left[(s-1)g\right]^{0.5} d_{50}^{1.5}\left[\frac{T_*^{2.1}}{D_*^{0.3}}\right] \qquad (3)$$

where s = specific density of sediment, g = acceleration of gravity, d_{50} = median grain diameter, T_* = transport stage parameter, given by

$$T_* = \frac{\left(u_*'\right)^2 - \left(u_{*,cr}\right)^2}{\left(u_{*,cr}\right)^2} \qquad (4)$$

and D_* = dimensionless grain size, given by:

$$D_* = d_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \qquad (5)$$

where u_*' = bed-shear velocity related to grains, $u_{*,cr}$ = critical bed-shear velocity, and ν = kinematic viscosity of the fluid (water).

The suspended load cohesionless sediment transport rate is given by:

$$q_s = \bar{u} h c_a \left[\frac{\left(\frac{a}{h}\right)^{Z'} - \left(\frac{a}{h}\right)^{1.2}}{\left(1-\frac{a}{h}\right)^{Z'}\left(1.2 - Z'\right)}\right] \qquad (6)$$

where $\bar{u}$ = mean flow velocity, h = mean flow depth, c_a = reference concentration, given by:

$$c_a = 0.015 \frac{d_{50}}{a} \frac{T_*^{1.5}}{D_*^{0.3}} \tag{7}$$

where a = a reference height above the bed, related to grain size, and Z' = suspension number, given by:

$$Z' = \frac{w_s}{\beta \kappa u_*} + 2.5 \left(\frac{w_s}{u_*} \right)^{0.8} \left(\frac{c_a}{c_0} \right)^{0.4} \tag{8}$$

where w_s = particle fall velocity, β = factor (ranging from about 1 to 3) representing the ratio of sediment diffusion to fluid diffusion, κ = von Karman constant (about 0.4), u_* = overall bed-shear velocity, and c_0 = maximum concentration (0.65).

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