ESTUARINE CIRCULATION

K. Dyer, University of Plymouth, Plymouth, UK

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Introduction

Estuaries are formed at the mouths of rivers where the fresh river water interacts and mixes with the salt water of the sea. Even though there is only about a 2% difference in density between the two water masses, the horizontal and vertical gradients in density causes the water circulation, and the mixing created by the tides, to be very variable in space and time, resulting in long residence times for pollutants and trapping of sedimentary particles. Both salinity and temperature affect density, but the salinity changes are normally of greatest influence.

Most estuaries are the result of a dramatic rise in sea level of about 100 m during the last 10 000 years, following the end of the Pleistocene glaciation. The river valleys were flooded by the sea, and the valleys infilled with sediment to varying extents. The degree of infilling provides a wide range of topographic forms for the estuaries. Those estuaries that have had large inputs of sediment have been filled, and may have been built out into deltas, where the sediment flux is extreme. These are typical of tropical and monsoon areas. Where the sediment discharge was less, the estuary may still have many of the morphological attributes of river valleys: a sinuous, meandering outline, a triangular cross-sectional form with a deep central channel, and wide shallow flood plains. These are termed drowned river valleys, and are typical of higher latitudes. Where the land mass was previously covered by the glaciers, the river valleys may have been drastically overdeepened, and the U-shaped valleys became fiords.

Because of the shallow water, the sheltered anchorages, and the ready access to the hinterland, estuaries have become the centers of habitation and of industrial development, and this has produced problems of pollution and environmental degradation. The solution to these problems requires an understanding of how the water flows and mixes, and how the sediment accumulates.

Definition

Estuaries can be defined and classified in many ways, depending on whether one is a geologist/geographer, a physicist, an engineer, or a biologist. The most comprehensive physical definition is that,

> An estuary is a semi-enclosed coastal body of water that has free connection to the open sea, extending into the river as far as the limit of tidal influence, and within which sea water is measurably diluted with fresh water derived from land drainage.

There are normally three zones in an estuary: an outer zone where the salinity is close to that of the open sea, and the horizontal gradients are low; a middle zone where there is rapid change in the horizontal gradients and where mixing occurs; and an upper or riverine zone, where the water may be fresh throughout the tide despite there being a tidal rise and fall in water level.

Tides in Estuaries

The tidal rise and fall of sea level is generated in the ocean and travels into the estuary, becoming modified by the shoreline and by shallow water. The tidal context is microtidal when the range is less than 2 m; mesotidal when the range is between 2 m and 4 m; macrotidal when it is between 4 m and 6 m; and hypertidal when it is greater than 6 m. A narrowing of the estuary will cause the range of the tide to increase landward. However, this is counteracted by the friction of the seabed on the water flow, and the fact that some of the tidal energy is reflected back toward the sea. The result is that the time of high and low water is later at the head of the estuary than at the mouth, and the currents turn some tens of minutes after the maximum and minimum water level. This phase difference means that the tidal wave is a standing wave with a progressive component. In high tidal range estuaries, the currents and the range of the tide generally increase toward the head, until in the riverine section the river flow becomes important. These estuaries are often funnel-shaped with rapidly converging sides. The volume of water between high and low tide, known as the tidal prism, is large compared with the volume of water in the estuary at low tide. Since the speed of progression of the tidal wave increases with water depth, the flooding tide rises more quickly than the ebbing tide, leading to an asymmetrical tidal curve and currents on the flood tide larger than those on the ebb tide. These are flood-dominant estuaries. The high tidal range leads to high current velocities, which can produce considerable sediment transport, also dominant in the flood direction.

When the estuary is relatively shallow compared with the tidal range, the wet cross-sectional area is greater at high water than at low water, and the discharge of water per unit of velocity is greater also. There is thus a greater discharge landward near high water than seaward around low water. This creates a Stokes Drift towards the head of the estuary that has to be compensated for by an extra increment of tidally averaged flow toward the mouth in the deeper areas. The Eulerian mean flow measured at a fixed point, the nontidal drift, is therefore greater than the flow due to the river discharge. Additionally, in the upper estuary where intertidal areas are extensive, the deeper channel changes from being flood-dominant to ebb dominance. This produces an obvious location for siltation and the need for dredging.

In microtidal estuaries, friction exceeds the effects of convergence and the tidal range diminishes toward the head. These estuaries are generally fan-shaped, with a narrow mouth and extensive shallow water areas. The currents at the mouth are larger than those inside, and the ebb current velocities are larger than the flood currents, i.e., the estuary would be ebb-dominant.

It has been observed that the ratio of certain estuarine dimensions frequently appears to be constant, leading to the concept of an equilibrium estuary. In particular, the variations of breadth and depth along the estuary are often exponential in form. The O'Brien relationship shows that the tidal prism volume is related to the cross-sectional area of the estuary. As the tidal prism increases, the increased currents through the cross-section cause erosion and the area increases until equilibrium is reached. This implies that there is ultimately a balance between the amount of sediment carried landward on the flood tide and that carried seaward on the ebb, leading to zero net accumulation. This is a widely used concept for the prediction of morphological change.

Circulation Types

From a morphological point of view, estuaries can be classified into many categories in terms of their shape and their geological development. These reflect the degree of infilling by sediment since the ice age. Present-day processes are also important in distinguishing those estuaries dominated by tidal currents and those whose mouths are drastically affected by the spits and bars created by wave-induced longshore drift of sediment. However, though important, these classifications do not tell us much about the water and how its movement affects the discharge of pollutants and of sediment. The classifications, originally proposed by Pritchard in 1952, describe the tidally averaged differences in vertical and longitudinal salinity structure, and the mean water velocity profiles. These have been extended to consider the processes during the tide that contribute to the averages.

Salt Wedge Estuaries

Where the river discharges into a microtidal estuary, the fresher river water tends to flow out on top of the slightly denser sea water that rests almost stationary on the seabed and forms a wedge of salt water penetrating toward the head of the estuary. The salt wedge has a very sharp salinity interface at the upper surface – a halocline. There is a certain amount of friction between the two layers and the velocity shear between the rapidly flowing surface layer and the almost stationary salt wedge produces small waves on the halocline; these can break when the velocity shear between the layers is large enough. The breaking waves inject some of the salty lower layer water into the upper layer, thus enhancing its salinity. This process, known as entrainment, is equivalent to an upward flow of salt water. It is not a very efficient process, but requires a small compensating inflow in the salt wedge. Salt wedge estuaries have almost fresh water on the surface throughout, and almost pure salt water near the bed. The slight amount of tidal movement of the water does not create much mixing, except in some of the shallower water areas, but does act to renew the salty water trapped in hollows on the bed. This process is shown in **Figure 1.** During the tide, the stratification remains high, but the halocline becomes eroded from its top surface during the ebb tide and rises during the flood tide because of new salt water intruding along the bottom. Fiords often have a shallow rock sill at their mouth that isolates the deeper interior basins. The renewal of bottom water is infrequent, often only every few years. Because fiords are so deep the lower layer is effectively stationary, and the mixing is dominated by entrainment.

Partially Mixed Estuaries

In mesotidal and macrotidal estuaries the tidal movement drives the whole water mass up and down the estuary each tide. The current velocities near to the seabed are large, producing turbulence, and creating mixing of the water column. This is a much more efficient process for mixing than

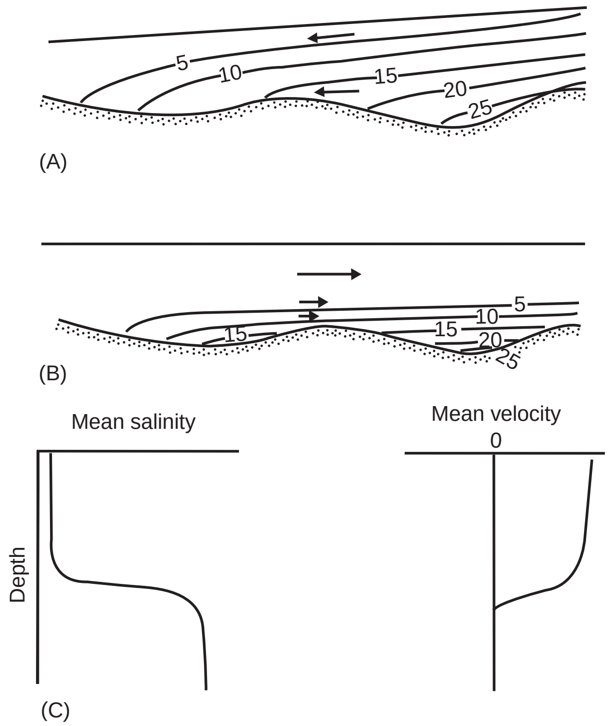

Figure 1 Diagrammatic longitudinal salinity and velocity distributions in a salt wedge estuary in PSU. (A) At mid flood tide. (B) At mid ebb tide. Contours show representative salinities; arrows show relative strength of currents. (C) Tidally averaged mean salinity and velocity profiles.

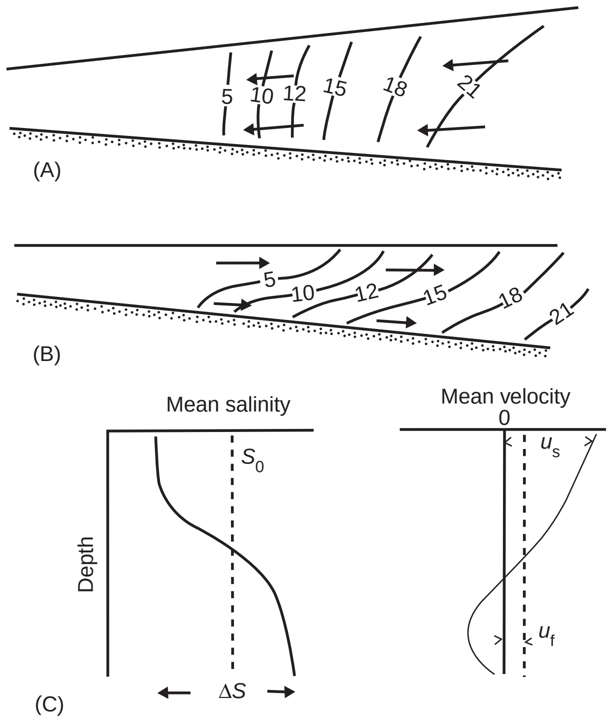

Figure 2 Diagrammatic longitudinal salinity and velocity distributions in a partially mixed estuary in PSU. (A) At mid flood tide. (B) At mid ebb tide. Contours show representative salinities; arrows show relative strength of currents. (C) Tidally averaged mean salinity and velocity profiles, including the definition of parameters for **Figure 4**: S, salinity; ΔS, salinity difference normalized by S_0 and circulation parameter u_s/u_f; u_s, surface mean flow; u_f, depth mean flow.

entrainment, but it is greatest near the bed, whereas entrainment is maximum in mid-water. However, both processes can be active together. Turbulent mixing is a two-way process, mixing fresher water downward and salty water upward. As a result, the mean vertical profile of salinity has a more gentle halocline (**Figure 2**). The salt intrusion is now a much more dynamic feature, changing its structure regularly with a tidal periodicity. During the flood tide, the surface water travels faster up the estuary than the water nearer the bed, and the salinity difference between surface and bed is minimized. Conversely, during the ebb, the fresher surface water is carried over the near-bottom salty water, and the stratification is enhanced. This process is known as tidal straining. It is to be expected that entrainment will be large during the ebb tide, and turbulent mixing will be dominant on the flood tide. Since each tide must discharge an amount of fresh water equivalent to an increment of the river inflow, and the water involved in this is now salty, there must be a significant mean advection of salt water up the estuary near to the bed to compensate for that discharged. There is thus a mean outflow of water and salt on the surface, and a mean inflow near the bed. The latter must diminish toward the head of the salt intrusion, and there is a level of no net motion near to the halocline where the sense of the mean flow velocity changes. At the landward tip of the salt intrusion there is a convergence, a null zone, where the tidally averaged near-bed flow diminishes to zero. The vertical turbulent mixing acting in combination with the mean horizontal advection is known as vertical gravitational circulation. Because of the meandering shape of the estuary, the flow is not straight but tends to spiral on the bends. This leads to the development of lateral differences in salinity and velocity, the shallower regions generally being better mixed and ebb-dominated.

Well-mixed Estuaries

When the tidal range is macrotidal or hypertidal, the turbulent mixing produced by the water flow across the bed is active throughout the water column, with the result that there is very little stratification. Nevertheless, there can be considerable lateral differences across the estuary in salinity and in mean flow velocity, as if the vertical circulation were turned on its side. This results in the currents on one side of the channel being flood-dominated while those on the other side are ebb-dominated, often separated by a mid-channel bank (**Figure 3**). As a consequence, during the tide the water tends to flow preferentially landward up one side of the bank, cross the channel at high water, and ebb down the other side. The bed sediment also is driven to circulate around the bank in the same way.

The above descriptive classification shows the general relationship between the structure of an estuary, the tidal range, and the river flow. Quantified classifications depend on producing numerical criteria that relate these variables. When the flow ratio – the ratio of river flow per tidal cycle to the tidal prism volume – is 1 or greater, the estuary is highly stratified. When it is about 0.25, the estuary is partially mixed; and for less than 0.1 it is well mixed. Alternatively, the ratio of the river discharge velocity (R/A, where R is the river volume discharge, and A is the cross-sectional area) divided by the root-mean-square tidal velocity gives values of less than 10^{-2} for well-mixed conditions and greater than 10^{-1} for stratified conditions. There are many alternative proposals that depend on describing the processes controlling the tidally averaged vertical profiles of salinity and of current velocity. One example uses a stratification parameter, which relates the surface to near-bed salinity difference (ΔS) normalized by the depth mean salinity (S_0), and a circulation parameter that expresses the ratio of the surface mean flow (u_s) to the depth mean flow (u_f) (**Figure 2**). Use of these classification schemes shows that estuaries plot as a series of points depending on position in the estuary, on river discharge, and on tidal range. They form part of a continuous sequence, rather than falling into distinct types, and an estuary can change in both space and time. Near the head of the estuary the river flow will be more important than nearer the mouth, and consequently the structure may be more stratified. Alternatively, if the tidal currents rise toward the head of the estuary, better-mixed conditions may prevail. **Figure 4** shows the classification scheme based on the stratification–circulation parameters, together with indication of the direction in which an estuary would plot for different circumstances.

Changes in river discharge of water force the estuarine circulation to respond. An increase will push the salt intrusion downstream and increase the stratification. Conversely, a decrease will allow the salt intrusion to creep further landward, and the stratification will decrease because the tidal motion will become relatively more important than the stabilizing effect of the fresh water input. Because of the drastic variation of tidal elevation and currents

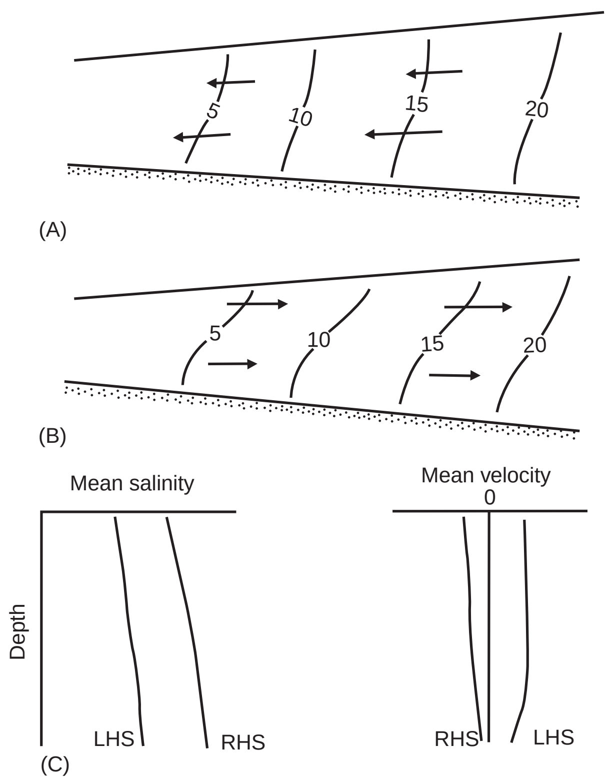

Figure 3 Diagrammatic plan views of the horizontal distribution of salinity in a well-mixed estuary (PSU). (A) At mid flood tide. (B) At mid ebb tide. Contours show representative salinities; arrows show relative strengths of currents. (C) Vertical mean profiles for left-hand side and right-hand side of the estuary looking down estuary.

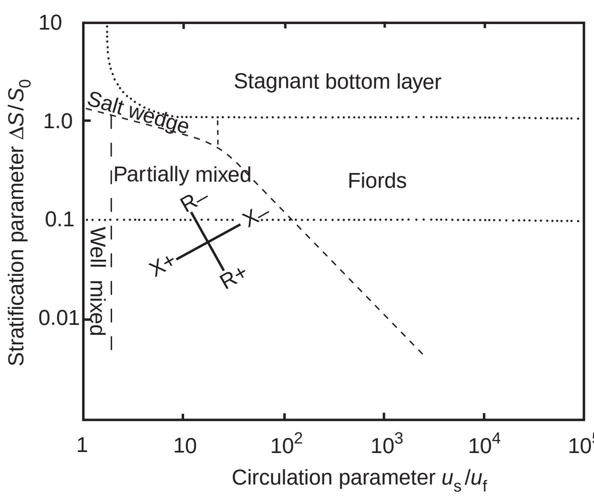

Figure 4 Quantified estuarine classification scheme based on stratification and circulation parameters. R – and R + show the direction of movement of the plot of an estuarine location with increase or decrease in river discharge; X – and X + with movement toward the estuarine head or mouth. Parameters are defined in **Figure 2**. From Dyer (1972) with permission. © John Wiley & Sons.

between spring and neap tides, well-mixed conditions may occur at spring tides and partially mixed at neaps. This must occur by a relatively stronger mixing on the flood tide during the increasing tidal range, and by increased stabilization on the ebb during decreasing tidal range. The change between the two conditions may occur very rapidly at a critical tidal range as the effects of mixing rapidly break down the stratification.

Additionally, a wind blowing landward along the estuary will tend to restrict the surface outflow, and may even reverse the sense of the vertical gravitational circulation. A down-estuary wind would enhance the stratification. Also, atmospheric pressure changes will cause a total outflow or inflow of water, as the mean water level responds. Thus large variations in the mixing and water circulation are likely on the timescale of a few days, the progression rate of atmospheric depressions.

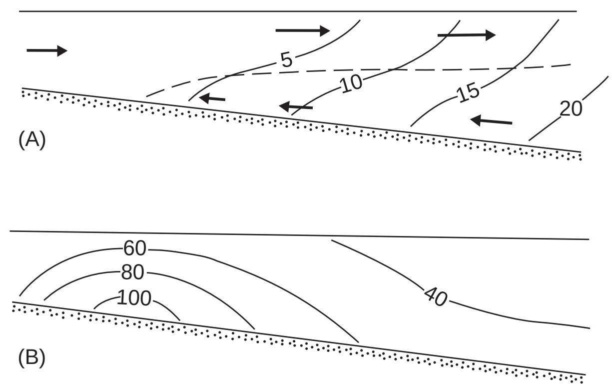

Figure 5 (A) Diagrammatic longitudinal distribution of tidally averaged salinity and current velocities in a partially mixed estuary. Contours show salinities; arrows show relative current velocities. Dashed line shows level of no net motion. (B) Diagrammatic distribution of mean suspended sediment concentration (in ppm), showing the turbidity maximum.

Flushing

Within the estuary there is a volume of fresh water that is continually being carried out to sea and replaced by new inputs of river water. At the mouth, not all of the brackish water discharged on the ebb tide returns on the flood, the proportion being very variable depending on the coastal circulation close to the mouth, and fresh water comprises a fraction of that lost. The flushing or residence time is the time taken to replace the existing fresh water in the estuary at a rate equal to the river discharge. From direct measurements of the salinity distribution it is possible to calculate the volume of accumulated fresh water and the flushing time for various river flows. The flushing time changes rapidly with discharge at low river discharge, but slowly at high river flow, being buffered to a certain extent by the consequent changes in stratification. Flushing times are generally of the order of days to tens of days, rising with the size of the estuary.

Turbidity Maximum

A distinctive feature of partially and well-mixed estuaries is the turbidity maximum. This is a zone of high concentrations of fine suspended sediment, higher than in the river or lower down the estuary, that depends upon the estuarine circulation for its existence. The maximum is located near the head of the salt intrusion (**Figure 5**), and the maximum concentrations tend to rise with the tidal range, from of the order of 100 ppm to 10 000 ppm, though there are variations depending on the availability of sediment. Often the total amount of suspended sediment exceeds several million tonnes. The location of the maximum coincides with a mud-reach of bed sediment, and with muddy intertidal areas. The continual movement of the turbidity maximum and the sorting of the sediment appears to create a gradient of sediment grain size along the estuary. Closer to the mouth, the bed is generally dominated by more sandy sediment. Because of the affinity of the fine particles for contaminants, prediction of the characteristics of the turbidity maximum is important. The position of the maximum changes with river discharge and with tidal range, but with a time lag behind the variation in the salt intrusion position. During the tide there are drastic changes in concentration. At high water the maximum is located well up the estuary and concentrations are relatively low because of settling. During the ebb the current reentrains the sediment from the bed, and advects it down the estuary. Settling again occurs at low water and there is further reentrainment and advection on the flood tide. Thus there is active cycling of sediment between the water column and the bed, and the whole mass becomes very well sorted in the process. The behavior of the sediment will depend on the settling velocity and the threshold for erosion. The settling velocity varies with concentration and with the intensity of the turbulence because flocculation of the particles occurs, forming large, loose but fast-settling flocs. Settling causes high-concentration layers to build up on the bed, and at neap tides these may persist throughout the tide, forming layers often seen on echo-sounders as fluid mud.

The turbidity maximum is maintained by a number of trapping mechanisms. Vertical gravitational circulation carries the fine particles and flocs downstream on the surface, and they settle toward the bed because the turbulent mixing is reduced by the stratification. Near the bed the landward mean flow carries the suspended particles toward the head of the salt intrusion, together with new material coming in from the sea. There they meet other particles carried downstream by the river flow and are suspended by the high currents. Additionally, the asymmetry of the currents during the tide leads to tidal pumping of sediment, the flood-dominant currents ensuring that the sediment transport on the flood exceeds that on the ebb. The sediment is thus pumped landward until the asymmetry of the currents is reversed by the river flow – somewhere landward of the tip of the salt intrusion. The pumping process is affected by the settling of sediment to the bed and its reerosion, which introduces phase lags between the concentration and current velocity variations and enhances the asymmetry in the sediment transport rate during the tide. Measurements have shown that all of these processes are important, but tidal pumping is dominant in well-mixed estuaries. Both vertical gravitational circulation and tidal pumping are important in partially mixed estuaries. As a result the sediment in the turbidity maximum is derived from the coastal sea as much as from the rivers.

In microtidal salt wedge estuaries the surface fresh water carries sediment from the river seaward throughout the estuary, discharging into the sea at high river flow. The clearer water in the underlying salt wedge is often revealed in the wakes of ships.

Estuarine Modeling

The water flows transport salt, thus affecting the density distribution, and the densities affect the longitudinal pressure gradients that drive the water flow. Turbulent eddies produced by the flows cause exchanges of momentum as well as of salt, and produce frictional forces that help to resist the flow. Estuarine models attempt to predict the salt distribution, the water circulation and the sediment transport through application of the fundamental equations for mass, momentum, and sediment continuity, which formalize the above interactions. In principle, it is possible to measure directly most of the terms in these equations, apart from those that involve the turbulent exchanges. In practice, approximations are required to solve the equations. Either tidally averaged or within-tide conditions can be modeled. For sediment, the definition of the settling velocity and the threshold are required.

One-dimensional (1D) models assume that the estuarine characteristics are constant across the cross-section, and that the estuary is of straight prismatic shape. For tidally average conditions the assumption is that the seaward advection of salt on the mean flow is balanced by a landward dispersion of salt at a rate determined by the horizontal salinity gradient and a longitudinal eddy dispersion coefficient. This coefficient obviously incorporates the effects of turbulent mixing, the tidal oscillation and any actual nonuniformity of conditions.

Two dimensional (2D) models can either assume that conditions are constant with depth but vary across the estuary (2DH), or are constant across the estuary but vary with depth (2DV). The eddy dispersion and eddy viscosity coefficients will be different for the two situations. Using the 2DH model one would not be able to explore the effects of vertical gravitational circulation, whereas with the 2DV model the effects of the shallow water sides of the channel would be missing. In many cases a further approximation may be made by assuming the water is of constant density.

Three-dimensional models are obviously the ideal as they represent fully the vertical and horizontal profiles of velocity, density, and suspended sediment concentration. The only unknown terms are those relating to the turbulent mixing, the diffusion terms. Although computationally 3D models are becoming less costly to run, it is still difficult to obtain sufficient data to calibrate and validate them.

Once realistic flow models have been constructed, they can be used to explore the transport of sediment and estuarine water quality. However, the limitations on the field data restricts their use for prediction. For instance, the majority of the sediment travels very near to the bed, and it is difficult to measure the concentrations of layers only a few centimeters thick.

An active topic for research and modeling at present is the prediction of morphological change in estuaries resulting from sea level rise. This involves integrating the sediment transport over the tide, for many months or years, in which case the accumulated errors can become overriding. These results can then be compared with the simple empirical relationships stemming from considerations of estuarine equilibrium.

See also

Breaking Waves and Near-surface Turbulence. Coastal Circulation Models. Elemental Distribution: Overview. Fiord Circulation. Fiordic Ecosystems. General Circulation Models. Intrusions.

Non-rotating Gravity Currents. Rotating Gravity Currents. Tides. Upper Ocean Mixing Processes.

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EUTROPHICATION

V. N. de Jonge, Department of Marine Biology, Groningen University, The Netherlands
M. Elliott, Institute of Estuarine and Coastal Studies, University of Hull, Hull, UK

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Introduction

Eutrophication is the enrichment of the environment with nutrients and the concomitant production of undesirable effects, while the presence of excess nutrients *per se* is merely regarded as hypernutrification. In more detail eutrophication is

> the process of nutrient enrichment (usually by nitrogen and phosphorus) in aquatic ecosystems such that the productivity of the system ceases to be limited by the availability of nutrients. It occurs naturally over geological time, but may be accelerated by human activities (e.g. sewage disposal or land drainage).
>
> (Oxford English Dictionary)

Anthropogenic nutrient enrichment is important when naturally productive estuarine and coastal systems receive nutrients from 'point sources', e.g. as outfall discharges of industrial plants and sewage treatment works, or human-influenced 'diffuse sources', such as runoff from an agricultural catchment. Whereas point source discharges are relatively easy to control, with an appropriate technology, diffuse and atmospheric sources are more difficult and require a change in agricultural and technical practice.

Coastal and estuarine areas with tide-associated accumulation mechanisms for seaborne suspended

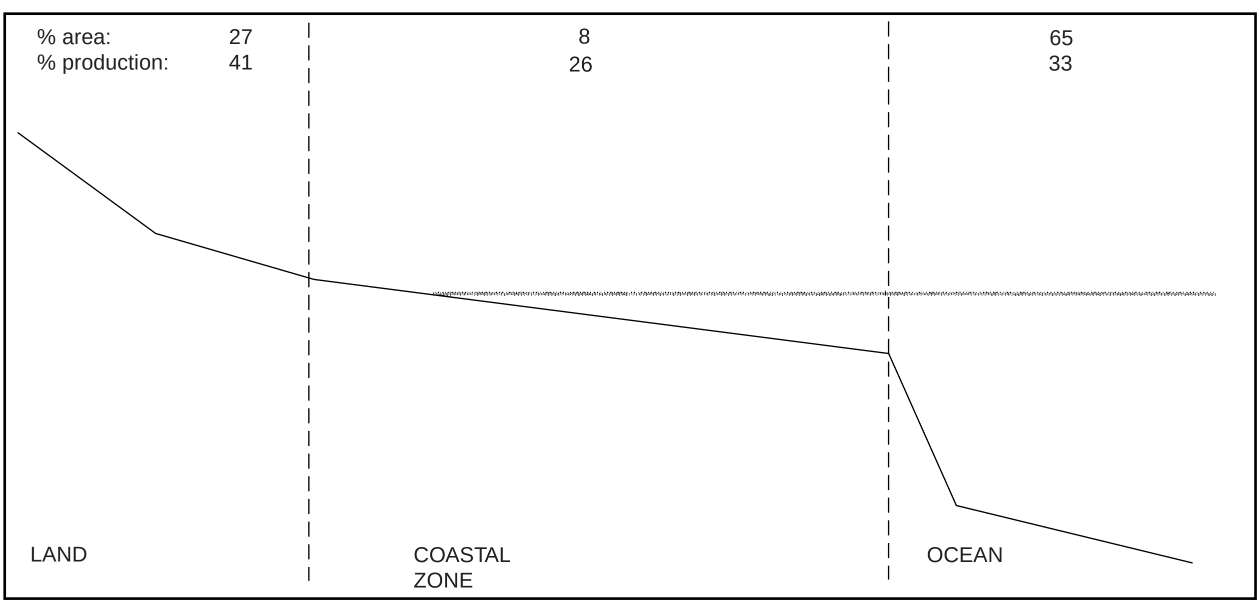

Figure 1 Indication of importance to primary production of different types of area (land, ocean, and shallow coastal seas and its fringes). (Redrawn after LOICZ, 1993. Report no. 25, Science Plan, Stockholm.)