'When low tides drain the estuary gold
Small intersecting ripples far away
Ripple about a bar of shifting sands'

_North Coast Recollections_, John Betjeman.

Estuaries are regions where rivers meet inlets of the sea, and most estuaries still retain the main features of river valleys, often having meandering courses and numerous tributaries. Their upper limit is generally considered to be the furthest point where the tidal rise and fall can be detected. Estuaries can usually be divided into three sections: a lower (or marine) estuary, in free connection with the open sea; a middle estuary, where most of the mixing between seawater and river water takes place; and an upper (or fluvial) estuary, dominated by freshwater influences but nevertheless subjected to daily tidal rise and fall, like the rest of the estuary (Figure 6.1).

Estuaries are ephemeral features on geological time-scales, having an average life of at most a few tens of thousands of years and generally much less. Most estuaries are geologically very young, for they developed during the latest post-glacial rise of sea-level, which inundated coastlines and drowned the mouths of river valleys (Figure 6.1(b)). So the world may be unusually rich in estuaries at the present time.

![A schematic map of a typical estuary showing the divisions into lower, middle and upper estuary. The boundaries are transition zones that shift according to the seasons, the weather and the tides.](image)

(b) A river valley in South Devon drowned by sea-level rise after the last glacial period.
Estuaries occur at the mouths of rivers which transport relatively small amounts of sediment and discharge it into coastal waters where wave and tidal current action are sufficiently strong to disperse the sediment. An estuary is less likely to develop where sediment discharge is high, and a delta may grow seawards from the river mouth instead (see Chapter 7).

The physiographic setting of estuaries can vary enormously. In glaciated mountainous areas, for example, where river valleys have been deepened by glaciers, they end in fjords having a rock bar or 'sill' near their mouths, above which water depths can be as little as a few tens of metres. Inside the fjord, however, the water can be hundreds of metres deep and fjords may extend more than a hundred kilometres inland. Along low-lying coastlines, on the other hand, estuaries often develop as extensive shallow lagoons between rivers and the sea. Despite this wide range of possible settings, the processes controlling transport and deposition of sediments are much the same in all estuaries.

Estuaries have a global significance for continental shelf and oceanic processes because of the exchange of water and sediment with coastal seas. During transport through estuaries, the grain-size distribution of the sediment becomes altered by repeated deposition, re-erosion and transport, and some sediments become permanently trapped. Estuaries act as a sort of filter for sediment input to the oceans, and chemical reactions in estuarine waters can alter the character of some mineral particles, especially clays, which can thus influence pollutant transport. Suspended sediment concentrations are generally high, and the sediments are often richly organic, because of high biological production, both in the water column and in the sands and muds of the estuary bed.

Estuaries are also characterized by strong gradients of salinity (and hence of water density), of suspended sediment concentration, and of chemical and biological properties. There is considerable interaction between physical, chemical, biological and sedimentological processes.

6.1 SEDIMENT DISTRIBUTION IN ESTUARIES

Estuaries consist of one or more channels and intertidal flats, which are alternately covered and uncovered by the rise and fall of the tides. There is a progression in grain size from mud-dominated sediments at the high tide level to sand-dominated sediments at the low tide level. Intertidal flats typically have very low gradients, usually in the order of 1:1000. Figure 6.2 illustrates the zonation that commonly develops in estuaries in temperate regions.

1 The main tidal channel is the deepest part of the estuary, submerged for all or most of the tidal cycle and subjected to strong tidal currents and minor wave action. Sediments consist of well-worn sands (and sometimes gravels), which are partly exposed at low spring tides and may be locally colonized by mussels, especially where the underlying bed rock protrudes through the sediments.

**QUESTION 6.1** What sort of bed forms might you expect to see in the main tidal channel?
Figure 6.2 (a) Intertidal zonation in a typical estuary (see text for explanation of zones). Vertical scale greatly exaggerated. (You may see alternative terminology used for the various zones in other books.)

(b) Photomosaic of part of a typical estuary at low tide showing the main channel, with its banks rising to the intertidal and high tidal flats and narrow salt-marsh, and (c) the same estuary at high tide.
2 The intertidal flats commonly form the widest zone, being submerged and exposed for roughly similar periods. As they are usually submerged during mid-tide, when tidal currents tend to reach their maximum speeds, sediment movement is mainly controlled by these currents; but wave action may also be a factor, especially when the water is shallow during low tide, and small bed forms (ripples) are commonly developed.

The sediments of this main zone of intertidal flats often consist of alternations of sands or silty sands and fine muds, in which the layering is commonly disturbed (bioturbated) by dense populations of burrowing organisms such as lugworms (*Arenicola*) and - where sands predominate - cockles (*Cerastoderma*) and other bivalve molluscs. In some estuaries, muds deposited on the lower part of the intertidal flats form a lower mud-flat zone, where the gradient steepens down to the main channel.

3 The high tidal flats are mud flats submerged only at high tide when current speeds fall close to zero, and are generally reached by waves of only low amplitude. Little bedload transport occurs, but during periods of slack water at the turn of the tide, muds settle out of suspension onto the mud flats. The transport of fine-grained silts and clays (i.e. muds) over the high tidal flats, and their subsequent deposition there, is encouraged by settling lag (Section 4.3.2). As the flood tide inundates the tidal flats and the current begins to slacken, these smallest particles begin to settle from suspension. However, they do not settle vertically through the water, but are carried into shallower water by the slowly moving current as they sink, eventually to be deposited some distance shoreward of where they began to settle.

Muds are cohesive sediments which, once deposited, are difficult to erode (Section 4.1.2). On tidal flats, therefore, the flow of water required to erode (or re-erode) fine sediment on the outgoing (ebb) tide is greater than that at which it can be deposited on the incoming (flood) tide. So suspended sediment will not be moved back downstream (with the ebb tide) as far as it has been moved upstream (with the flood tide).

An additional factor that promotes sediment accretion on tidal mud flats is binding of sediment particles by mats of filamentous algae, and/or biological 'glues' (known as extracellular polymeric substances or EPS) from various types of algae, especially *diatoms*, and/or bacteria (Figure 6.3(a)). In summer, the topmost layer of mud can contain extremely high concentrations of stabilizing organisms. In winter, these decline and wave activity during storms may lead to periods of erosion. However, high tidal flats are generally zones of sediment accretion, whose level rises as the muds accumulate, with the result that the depth and duration of submergence during high water progressively decreases.

4 Ultimately, the high tidal flat is exposed for sufficiently long periods for colonization by salt-tolerant higher plants to begin, leading to the development of a salt-marsh, flooded normally only during the highest spring tides (Figure 6.3(b)). The most common pioneer salt-tolerant plants in western Europe are *Salicornia* (the fleshy marsh samphire) and *Spartina* (the tough marsh cord grass). The plant roots bind the sediment and help prevent further erosion, while the plant stems retard the water flow and trap the mud, encouraging still further deposition. This helps to consolidate the sediment and build up the level of the salt-marsh, so that the older, higher parts are flooded less frequently. Erosion by waves and undercutting of the compacted sediments along the edge of the salt-marsh can locally form small "cliffs" up to several tens of cm high.
The relative widths of zones 1–4 can vary widely, even within a single estuary, and the complete zonation is not always developed in all estuaries. For example, in relatively narrow estuaries and on shallow intertidal flats, where there is insufficient wave action to cause winnowing, there are mud-flats (Figure 6.3(c)) but the intertidal flats of Figure 6.2 are missing; this can also happen if little or no sand is being transported into the estuary. By contrast, in more exposed estuaries where wave action is greater, the high tidal mud flats may be poorly developed or even absent, and salt-marsh development may occur on a silty or sandy substrate. There will of course be no intertidal mud flats at all where the tidal range is zero.

In summary, there is a general progression in grain size, from the mud-dominated sediments of the high tidal flats to the sand-dominated sediments of the main channel. All intertidal flats are dissected by networks of tributary tidal channels flowing into the main one (Figure 6.2). The rising tide first fills the channels and then spills out over the intertidal flats. Conversely, as the tide falls, water from the flats drains into the channels, which are the last to empty. Over long periods of time, the salt-marsh gradually grows seawards as the estuary fills with sediment, but the network of drainage channels can persist long after the marsh has become dry land.

Figure 6.3 (b) A high tidal flat in a small estuary in southern Portugal. Clumps of Salicornia and Spartina pass into a fully vegetated salt-marsh on the right.
(c) Photograph of a typical estuarine tidal mud flat, in a tributary valley of the River Dart estuary, Devon.
6.1.1 AGGREGATION OF SEDIMENT IN ESTUARIES

QUESTION 6.2
(a) Approximately how long would it take sediment particles c. 2μm in diameter to settle through 1 m of water to the bed of the estuary? Settling velocities for particles of this size are of the order of $5 \times 10^{-3}$ mm s$^{-1}$, i.e. $5 \times 10^{-6}$ m s$^{-1}$ (cf. Figure 4.6(c)).

(b) Would you expect your answer to (a) to be greater or smaller if these were flaky clay particles?

Your answer to Question 6.2 indicates that if very fine-grained sediments are to be deposited, another process must be operating in the estuarine environment. This is the aggregation of the tiny grains to form larger ones which are deposited more rapidly. There are two principal ways in which aggregation can happen:

1 **Biological aggregation** is locally important in some estuaries. Clay particles are ingested by filter-feeding animals and excreted in faecal pellets up to 5 mm long, with settling velocities measured in centimetres per second, rather than millimetres per hour. There may also be ‘fluffy’ aggregates of dead and dying planktonic material, including bacteria. In estuaries without a great deal of biological activity, however, these processes are less important than:

2 **Flocculation**, which occurs as the result of the molecular attractive forces known as van der Waals forces. These forces are not particularly strong, but they vary inversely as the square of the distance between two clay particles and become important when particles are brought very close together. In fresh (river) water, flocculation does not take place because clay minerals normally carry a net negative charge and similarly charged clay particles repel one another. In seawater, however, the positively charged cations in solution neutralize these negative charges, so that when clay particles are brought sufficiently close together, the van der Waals forces dominate, and flocculation occurs.

Flocculation is thus an important process where freshwater and seawater mix, and it occurs in all estuaries. There are three main ways in which clay particles can be brought close together for van der Waals forces to take effect:

1 By wind- or current-generated turbulence in the water column.

2 By Brownian motion: very small suspended clay particles are continually buffeted by the random motion of water molecules.

3 By being scavenged by larger particles which sink rapidly through the water column, collide with smaller particles and ‘capture’ them.

Another process that occurs where freshwater and seawater mix is cation exchange between water and suspended clay mineral particles. The four main cations in seawater are sodium (Na$^+$), potassium (K$^+$), magnesium (Mg$^{2+}$) and calcium (Ca$^{2+}$), and they are the principal participants both in flocculation and in cation exchange. These same cations occur in clay minerals and the exchange reactions occur mainly with cations bound to particle surfaces by adsorption, and to a limited extent with cations inside the mineral structures themselves. The exchanges result in a net gain of Na$^+$, K$^+$ and Mg$^{2+}$ ions by clay minerals from seawater, and a net loss of Ca$^{2+}$ ions from clay minerals to seawater, although the balance of electrical change in both clay minerals and seawater remains unchanged.
Important though these reactions may be for the detailed chemistry of estuarine waters, their effect on the overall composition of both clay minerals and seawater is sufficiently small to be neglected for most practical purposes. However, in estuaries subject to contamination from industrial effluents, significant amounts of heavy metals can be removed from solution by adsorption on clay mineral particles, and then deposited in the sediments.

### 6.2 TIDAL CHANNELS OF ESTUARIES

The main channels of estuaries (Figure 6.2) are the principal conduits for both tidal and river flow and therefore control the transport and deposition of sediments. The magnitudes of tidal range and river discharge in the main channels enable all estuaries to be classified somewhere along a continuum between two extremes: highly stratified estuaries at one end, to well-mixed estuaries at the other, as illustrated in Figure 6.4 and described in the next Section.

#### 6.2.1 THE ESTUARINE CONTINUUM

Highly stratified estuaries (Figure 6.4(a), overleaf) develop where rivers discharge into seas with a low tidal range (<c. 2 m, e.g. the Mediterranean and Black Sea). The less dense (more buoyant) river water flows over the surface of the underlying denser seawater which forms a **salt wedge** that penetrates and thins up-river. The extent of the salt wedge varies with the river flow. When the discharge is low, the salt wedge penetrates further up the estuary than when the discharge is high.

There are very sharp salinity and density gradients between the overlying freshwater and underlying seawater: a stable **halocline** develops, and the resulting strong density gradient (**pycnocline**) inhibits mixing between the two water masses. However, shear stresses at the interface between the flowing river water and the salt wedge generate internal waves (Section 1.1.1). Where these break, small quantities of salt water are injected into the overlying freshwater – in other words, salt water from below is **entained** into the freshwater above, making it **brackish**. These are basic features of **salt wedge estuaries**, which develop only where the tidal range is small.

Where rivers discharge into a sea with a moderate tidal range (c. 2–4 m), the whole water mass moves up and down the estuary with the flood and ebb tides. Friction between the water and the estuary bed causes turbulence which mixes the water column more effectively than does simple entrainment at the freshwater/salt water interface. Salt water is mixed upwards, and freshwater is mixed downwards, so the **isohalines** are more steeply inclined, the halocline is less well defined, and the stratification is weaker (Figure 6.4(b)). There is a wide variety of such **partially mixed estuaries**, each with its own characteristics resulting from the combination of tidal range, river discharge, local topography and bathymetry, and climatic conditions; and as tidal ranges along coasts in most parts of the world are in the c. 2–4 m range, this is the commonest estuarine type.

Both tidal range and strength of tidal currents can fluctuate considerably between spring and neap tides. The stronger tidal currents of spring tides enhance turbulent mixing of salt water and freshwater, reducing the buoyancy of the surface layer and further weakening the stratification. By contrast, during neap tides and/or at times of high river flow, the stratification can be strengthened, i.e. the estuary may take on ‘salt wedge’ characteristics – though mixing at the interface is likely to be strengthened during times of high river flow.
Figure 6.4 (a–c) Diagrammatic representations of water circulation, salinity distribution and velocity gradients within the continuum of estuarine types from salt wedge (a), through partially mixed (b), to well-mixed (c). The broken vertical line shows the position of the salinity and velocity profiles. Note the progressive weakening of the halocline from (a) to (c), a consequence of increasing tidal influence. In well-mixed estuaries (c), the salinity of the water column at any particular point in the estuary depends upon the state of the tide. Curved arrows on the longitudinal sections represent mixing.

Residual (net) flows in (a) and (b) (horizontal blue arrows) are seawards at the surface because of the river flow, landwards at the bottom because of vertical mixing and entrainment across the river water/seawater interface. Net flow in (c) is landwards on the flood tide, seawards on the ebb. In (b), the dashed sub-horizontal line on the longitudinal section shows the depth at which there is no horizontal residual flow either seawards or landwards, and its intersection with the bed near the head of the salt water intrusion defines the null point (see the text). Note that although shown only in (b) for clarity, a null point can be identified in any tidal estuary (see text, p.158).
Residual flows and the null point: We have seen that in salt wedge estuaries, salt water is lost from the salt wedge by entrainment into the overlying freshwater with no corresponding gain of freshwater by the salt wedge. This has implications for continuity in the estuary.

What must happen in order to maintain the overall volume of water in the estuary?

The principle of continuity requires that the volumes of water flowing into and out of a given space in unit time must be equal (Section 2.4.1). Hence, water lost from the salt wedge must be replaced by a slow landward flow of seawater within the salt wedge itself. The principle of continuity also requires that, because of entrainment of salt water into the freshwater layer all the way from the apex of the salt wedge down to the estuary mouth, the total volume of water flowing out of the estuary in the upper layer in unit time (i.e., the net flow) must increase downstream. The slow landward flow within the salt wedge, and the ‘extra’ seawards flow in the freshwater layer, due to entrainment, are known as residual flows (cf. Section 2.4.1).

In partially mixed estuaries, the freshwater flowing seawards mixes with a large amount of salt water, so the total discharge of water via the surface layer can be an order of magnitude greater than the river discharge. Continuity requires that the salt water mixed into (and discharged by) the surface layer be replaced, and so the landward flow within the bottom salt water layer is significantly stronger than in salt wedge estuaries (cf. Figure 6.4(a, b)). Thus, in partially mixed estuaries, the vertical mixing between the upper (river water) and lower (seawater) layers produces larger landward and seaward residual flows. Although they vary from estuary to estuary, residual flows typically have less than 10% of the magnitude of the tidal and river currents superimposed on them, and they can occur even where mixing has reduced the salinity contrast between surface and bottom waters to little more than 1 (part per thousand).
The salt intrusion (Figure 6.4(b)) advances upstream as the tide rises, and retreats downstream as the tide falls, but the net (residual) flow within it is always landwards (upstream). Since net flow in the upper layer is always downstream because of the river flow, at any point in the tidal channel there must be a depth at which there is no net landward or seaward movement of water (where the velocity profile would cross the zero velocity line, cf. the profiles in Figure 6.4(a) and (b)). Where this depth coincides with the bed of the channel, there is a convergence (Section 1.2.1) where the landward and seaward flows along the bottom meet, and there is no net movement of water at the bed in either direction. This is known as the null point (Figure 6.4(b)) and it occurs near the head of the salt intrusion, where salinities are as low as 0.1 to 1 (part per thousand) in estuaries of low to moderate tidal range, up to about 5 (parts per thousand) or more where the tidal range is moderate to large.

Should we expect the null point to be fixed in position in any particular estuary?

No. The null point must move up and down the estuary with the tides, and over a greater distance during spring than during neap tides (though to a much smaller extent in salt-wedge estuaries, because the tidal range is small). In addition, there will always be some seasonal variation: the null point moves upstream when river discharge is low, and downstream when discharge is high.

A null point should thus be identifiable in any tidal estuary, even in well-mixed estuaries (Figure 6.4(c)), where the tidal range is large (> c. 4 m). Tidal currents are strong relative to river flow and the whole water column is mixed, so that salinity hardly varies with depth at all. The whole well-mixed water mass moves landwards and seawards with the tides, but (as in all estuaries) the average salinity decreases towards the upstream limit of tidal influence. Even where the estuary is otherwise well mixed, there will be some stratification in the upper estuary, with a residual (vertical) circulation and a null point (Figure 6.4(c)).

You need to bear in mind that nearly all estuaries are more or less funnel-shaped and widen seawards. In well-mixed estuaries, therefore, although the water column may be vertically homogeneous, there can be horizontal variations of both salinity and velocity across the width of the estuary, and a horizontal circulation can develop. This happens because the Coriolis force laterally deflects both the incoming tidal flow and the seaward-flowing river water. The result is that in the Northern Hemisphere seawater flows up-estuary on the left-hand side (facing downstream) and river water flows down-estuary on the right-hand side, while the reverse is true in the Southern Hemisphere. Mixing takes place laterally, and there is a horizontal residual circulation, as illustrated in Figure 6.4(d), rather than the vertical residual circulatory pattern that occurs in salt-wedge and partially mixed estuaries. This residual horizontal circulation is superimposed upon the main landward-and-seaward motion of the whole well-mixed water mass in the estuary, as it fills and empties with the tides.

**QUESTION 6.3** In a well-mixed estuary, how would you expect the salinity of the water column at a particular point to change with time?
It is important to stress here, however, that the horizontal circulation illustrated in Figure 6.4(d) is not confined to the well-mixed end of the estuarine continuum, and can occur in stratified estuaries as well, if they are wide enough. Also, you need to be aware that the classification scheme outlined above is a general one. The pattern of water flow can vary between the extremes illustrated in Figure 6.4 even within a single estuary, depending upon conditions. For example, as we have seen, stratification tends to be enhanced when river discharge is high, and to be broken down by vigorous mixing during spring tides. Moreover, because tidal influences tend to dominate in the lower estuary, riverine influences in the upper estuary, an estuary may approach well-mixed conditions near the mouth and yet be quite well stratified near the upper limit of tidal action. An individual estuary may be well-mixed during spring tides, and partially mixed or even well stratified during neap tides. Major storms can disrupt these general patterns. If the river discharge is high enough it can push the salt intrusion out of the estuary altogether, and/or weaken (even destroy) any stratification; and gale force winds can also cause sufficient mixing to break down the stratification.

The size and overall cross-sectional form of the main channel of an estuary can also influence the water movements within it. Thus, the deeper and narrower the estuary, the more likely it is to be stratified (e.g. as in fjords), whereas broad shallow estuaries are more likely to be well-mixed and to have horizontal variations of salinity across them. However, a broad and moderately deep estuary could well be both stratified and have horizontal variations of salinity across it (e.g. as noted above, Figure 6.4(d) should not be seen to apply exclusively to well-mixed estuaries). In short, the patterns of water flow are unlikely to be the same for two estuaries of different shape, even where river discharge and tidal range are similar. No two estuaries are the same, each will have its own characteristics – but they can all be placed somewhere along the continuum represented in Figure 6.4.

Some examples of estuarine types

Only rivers discharging small amounts of sediment into a virtually tideless sea can form salt-wedge estuaries, and examples include rivers draining Texas and flowing into the Gulf of Mexico (e.g. the rivers Brazos and Sabine).

**Partially mixed estuaries** are common along the coasts of eastern America (e.g. the James River in Virginia), and north-western Europe (e.g. the Mersey and the Thames).

**Well-mixed estuaries** include the Severn estuary, the Firth of Forth in Scotland, the Gironde estuary opening into the Bay of Biscay, the Rio de la Plata, which opens into the South Atlantic, and the Humber estuary on England’s North Sea coast. Large estuaries of this kind are commonly shallow and funnel-shaped: wide at the mouth and tapering inland (Figure 6.5, overleaf), and stratification is likely to develop at least some of the time.

**QUESTION 6.4** Look at the estuary in Figure 6.6 (overleaf). The tidal range in this region varies from about 4–5 m on neap tides to about 7–8 m on spring tides.

(a) Whereabouts in the classification scheme of Figure 6.4 would you place this estuary?

(b) Why are the waves breaking slightly further offshore opposite the mouth of the main channel than opposite the beach to the right?
6.2.2 REGIONS OF FRESHWATER INFLUENCE

The answer to Question 6.4(b) provides a useful reminder that the influence of estuaries can extend well offshore. As the river water flows from the confines of the estuary mouth into the open sea, it spreads out over the surface of the seawater as a plume of brackish water. These buoyant plumes give rise to **regions of freshwater influence** (ROFIs for short), which can extend offshore for distances that range from a kilometre or two to several hundred kilometres, depending upon the magnitude of the river discharge. The ROFI of the Amazon – the world’s largest river – can be detected more than 500 km from the mouth of its estuary (Figure 6.7).

Looking at Figure 6.7, would you expect the average salinity near the bed at the mouth of the Amazon to be greater or less than 0.1 (part per thousand)?
Even though this is a predominantly well-mixed estuary, we should expect some landward flow of seawater near the bed. The salinity near the bed should thus be greater than 0.1, because the water near the bed should be more saline than at the surface.

The degree of stratification and extent of mixing between river water and seawater in ROFIs depends upon both river discharge and tidal range, as well as upon weather conditions and the actual state of the tide (i.e. whether ebbing or flooding) – so it cannot remain constant with time, and Figure 6.7 is a time-averaged picture. As the plume of brackish water spreads out on leaving the river mouth, there is entrainment of seawater and mixing both at the base and along the margins, where there is convergence and mixing at river plume fronts. Because the fronts are surface convergences (cf. Figure 2.22), they are often delineated by froth or floating debris. River water is generally rich in nutrients washed off the land, so ROFIs are commonly regions of high primary productivity and hence of rich fisheries.

Where a ROFI does not extend very far offshore (i.e. the river flow is small), and where the tidal range is high and the mouth relatively narrow, the river plume can be forced back into the estuary by the strength of the flood tide, and a tidal intrusion front may form at the estuary mouth, sometimes in the form of a V pointing upstream. In some well-mixed estuaries, longitudinal fronts can also be observed at different stages of the tide, extending upstream for several kilometres from the estuary mouth. They show up either as areas of smooth or rippled water (‘tidal smooths’) or as irregular lines of froth or floating debris (Figure 6.8). These fronts are linear convergences resulting from transverse movement of surface water caused by lateral density gradients. Such gradients occur because tidal flows are strongest in mid-channel where the water is deepest, so that on the rising tide the water in mid-channel is slightly more saline (and therefore denser) than the water on either side – the situation being reversed when the tide falls. When such longitudinal fronts occur, the transverse surface currents can reach speeds of several cm s$^{-1}$. However, these are weak compared with tidal flows up and down the estuary, and they and their associated circulatory system have negligible effect on the transport and deposition of sediment.
6.2.3 SEDIMENTATION IN ESTUARIES

In most estuaries, the null point is associated with a **turbidity maximum**, the region where concentrations of suspended material in the channel are greatest. It develops because material moves towards the null point from both upstream and downstream, and because turbulent mixing of river water with brackish bottom water near the null point leads to flocculation (Section 6.1.1). Some of the suspended sediment supplied by the river flocculates near the head of the salt intrusion in the upper estuary and settles into the lower layer. The rest is transported by the river flow further downstream, where some settles into the lower layer and is carried back up the estuary by the residual flow, along with suspended particles brought in from the sea (Figure 6.9). The rest of the suspended sediment escapes to the sea (including much biological material, some of terrestrial and riverine origin, some from the salt-marsh or mangroves – see Figure 6.12). Concentrations of suspended sediment of around 100–200 mg l⁻¹ may occur in turbidity
maxima of estuaries with a small tidal range, where turbulent mixing is generally weak. In estuaries with a large tidal range, on the other hand, where turbulent mixing is likely to be strong, concentrations in turbidity maxima can reach $10^3$–$10^4$ mg l$^{-1}$ (1–10 g l$^{-1}$). High concentrations of suspended matter in the turbidity maxima cut down the light available for photosynthesizing organisms. The particles also adsorb pesticides as well as heavy metals (Section 6.1.1). In addition, particulate organic matter provides sites of microbial activity. Concentrations of suspended particulate matter can be further increased in estuaries where there is heavy shipping traffic, which stirs up the sediments.

Coarser sediment is moved upstream by the residual landward bottom flow and deposited near the null point, along with the bedload and larger suspended particles supplied by the river (including coarser aggregates produced by flocculation near the null point). The residual circulation therefore acts as a sediment trap which impedes the escape of sediment to the open sea. In salt-wedge estuaries, where the river meets the salt wedge, at the head of the estuary, the freshwater leaves the bedload behind as it flows over the salt water, and a coarse sediment bar may build up close to the tip of the salt wedge.

![Schematic diagram illustrating formation of the turbidity maximum in a partially mixed estuary](image)

As you might expect, the ebb and flow of the tide causes the turbidity maximum to shift up and down the estuary (Figure 6.10, overleaf). It is furthest upstream at high tide and starts to move seawards when the tide falls. Suspended sediment concentrations within it increase as sediment eroded from the bed joins sediment brought down by the river. At low tide, the turbidity maximum is near the mouth and, during slack water, near-surface concentrations decrease as some sediment settles from suspension. After the tide turns, the turbidity maximum moves back upstream and intensifies again, as sediment is eroded from the bed and turbulent mixing by the flood tidal currents increases. As the slack water of high tide approaches, there is re-deposition of suspended sediment, mainly in the middle estuary and especially on the high tidal flats (Figure 6.2); and suspended sediment concentrations in the turbidity maximum decrease again. In general, the turbidity maximum is better developed during spring than during neap tides. That is because tidal currents are weaker during neap tides, so less sediment is re-suspended and there is more opportunity for deposition during periods of slack water.
Figure 6.10 The turbidity maximum in the Seine estuary at intervals during a spring tidal cycle, when the river discharge was 780 m$^3$ s$^{-1}$. HIW = high water, LW = low water, HW ± 1 hr (etc.) = high water plus/minus one hour (etc.). Curved blue lines are isohalines with salinity values in parts per thousand. Note that salinities at the core of the turbidity maximum range from 1 (part per thousand) at low tide to 20 at mid-tide, decreasing to around 10 at high tide. (Vertical scale greatly exaggerated.)
The position and size of the turbidity maximum also vary with the river discharge. When discharge is high the turbidity maximum is pushed downstream and diminishes, because more sediment is transported directly out to sea. When discharge is low, on the other hand, suspended sediment is brought further into the estuary on the flood tide, and the turbidity maximum intensifies.

**QUESTION 6.5**  Figure 6.11 illustrates these two conditions.

(a) Which of the two cross-sections represents (i) high and (ii) low river discharge?

(b) Would you expect an estuary like the Seine to be better stratified during high or during low river discharge?

*Figure 6.11* The turbidity maximum in the Seine estuary with two different river discharge rates: 200 m$^3$ s$^{-1}$ and 800 m$^3$ s$^{-1}$, both at high spring tide. For (a) and (b), see Question 6.5. (Vertical scale greatly exaggerated.)

**Fluid mud:** In a number of estuaries, very high concentrations of suspended material occur near the bed, beneath the turbidity maximum. Concentrations may exceed 100 g l$^{-1}$, much higher than those normally found in the turbidity maximum itself – rarely more than 10 g l$^{-1}$, as we have seen. The suspensions are sufficiently coherent to flow, and they can form ‘pools’ in local depressions in the estuary channel bed. Accumulations of fluid mud can extend over distances of 1–10 km, and move backwards and forwards on the tides, with the turbidity maximum.

As the tidal amplitude and tidal currents decrease after spring tides, less and less material can be re-eroded and suspended, and more of the suspended load settles from the turbidity maximum to form the layer of fluid mud close to the bed. This effect is enhanced by the relatively long periods of slack water around high water during neap tides compared with high water during spring tides. During neap tides, the fluid mud tends to become a little compacted, so that when the tidal range and tidal currents increase again not all of the sediment is re-eroded and some is left permanently deposited.
6.2.4 ESTUARIES IN LOW LATITUDES

In tropical and equatorial regions, mud flats are commonly colonized by mangrove trees whose aerial root systems trap the muds (Figure 6.12). Mangrove swamps, rather than salt-marshes, dominate the zone around the high tide level in such regions.

The actual processes of estuarine circulation and sedimentation at low latitudes differ from those described in previous Sections only where there is high evaporation, leading to increased salinity in estuarine surface waters. In such situations, the dense hypersaline water sinks and flows seawards along the bed of the estuary. For continuity to be maintained, this seawards flow must be replaced by landwards flow of seawater at the surface. In other words, the ‘normal’ pattern of residual circulation (Figure 6.4(a–c)) is inverted, to produce a negative estuarine circulation (Figure 6.13), which can occur wherever surface salinities are increased by evaporation. Indeed, the outflow of Mediterranean Water at Gibraltar and its replacement by surface inflow of water from the Atlantic is a good example of this type of circulation (though on a much larger scale).

Estuaries of this kind occur mainly in countries with arid climates, and because the low rainfall means that rates of chemical weathering (which produces clays) are generally low, the sediment supply is usually also low, with a high proportion of sandy material. The sands are deposited from bedload where river flow slackens at the head of the estuary, and any fine-grained riverborne sediment that has not flocculated in the hypersaline water and settled from suspension, is carried seawards by the residual hypersaline flow just above the bed (Figure 6.13). Tropical storms in arid regions can cause rivers to flood catastrophically, and when that happens, the whole estuary is likely to be flushed out. Then, as the floods abate, it is possible that a ‘normal’ pattern of estuarine circulation may be set up, subsequently becoming replaced by negative circulation once more, when the river flow subsides and evaporation intensifies again.

Figure 6.12 The aerial roots of mangroves help to trap muds and bind sediments.
Figure 6.13  Diagrammatic representations of water circulation, salinity distribution and velocity gradients for negative estuarine circulation. Horizontal arrows on the longitudinal section show landwards flow of seawater at the surface and seawards flow of (strongly) hypersaline water near the bed. The broken vertical line shows the position of the salinity and velocity profiles. Note the reversed velocity profile compared with Figure 6.4(a–c), also the increase of salinity with depth.

**Question 6.6**  In an estuary with negative circulation, would you normally expect to find (a) a null point or a turbidity maximum, (b) mixing between the upper and lower layers?

**6.2.5 The Dynamic Balance of Estuaries**

Calculations based on measurements of sediment concentration and river discharge suggest that in many – perhaps most – estuaries, the turbidity maximum contains more sediment than is supplied by rivers, which means that large quantities of sediment are brought into the estuary from the sea. As we have seen, however, during periods of high river discharge much sediment is transported directly to the sea and the turbidity maximum is greatly diminished (Figure 6.11, Question 6.5). In fact, the erosive power of rivers rises very rapidly with increased flow rates, and during major storms, riverborne sediment concentrations can increase by more than an order of magnitude. At such times, the quantity of sediment discharged into the sea can exceed that discharged in a decade of normal flow. In other words, sediment discharge from estuaries mostly occurs over very short periods during extreme events. For most of the rest of the time, little or no sediment is being discharged from an estuary to the sea, and if erosion and deposition are in balance, the rate of sediment accumulation will be equal to the rate of supply of sediment from the river (the fluvial flux). Commonly, however, there is net accumulation of sediment in the estuary, and as we have seen, the sediment is supplied mostly from the sea. For example, calculations of sediment fluxes in the Humber estuary (Figure 6.5), based on measurements of current speeds, suspended sediment concentrations and rates of sediment deposition (accretion, Figure 6.14, overleaf), suggest that sediment deposition at the estuary mouth is about $9 \times 10^6$ tonnes per year. This is more than 40 times greater than the fluvial flux from the Humber catchment area (which is about $2 \times 10^4$ tonnes per year), and can only be achieved by net sediment transport into the estuary from the sea. Thus, since all estuaries are supplied with sediment not only by rivers but also from the sea, it is likely that all but the largest estuaries are being progressively infilled, as they adjust to the most recent post-glacial rise in sea-level.

This generally landward movement and accumulation of sediment in estuaries can be explained by reference to the tidal asymmetry discussed in Section 2.4.3. As a tidal wave propagates into an estuary, the wave crest (rising tide) travels faster than the wave trough (falling tide), because the speed of propagation depends upon water depth (Equation 1.4).
Because of the geometry of estuaries (Figure 6.2), as the tide rises, a large volume of water must flow through the relatively restricted cross-sectional area of the main tidal channel, so it must flow with high speed. At this stage, coarse sand (and even gravel) may be transported into the estuary as bedload.

**What will happen as the tide rises further and the water spills over the main channel and starts to flood the intertidal flats?**

The water speed will be rapidly reduced because the flow is no longer constrained to move through a small cross-sectional area. Conversely, on the ebb tide, the water initially flows slowly over the extensive areas of intertidal flats, then speeds up as the tide falls further and flow is constrained once more to flow in the channels. There is accordingly an asymmetry in the tidal current velocity between high and low tides. Figure 6.15 illustrates the general form of the resulting velocity curve, with maximum flood and ebb tidal currents either side of low water. Although Figure 6.15 shows the tidal current to be slower on the ebb than on the flood, it is generally augmented by the river flow, and in general it also lasts longer than the flood tidal current.

The settling lag of fine-grained sediments (Section 4.3.2) encourages deposition of muds on the intertidal flats as the current slows down near high tide. Since these are cohesive sediments, they are not easily resuspended, especially at the initially slow speeds of tidal currents when the tide starts to fall again. The result is accretion of the intertidal flats (cf. Figure 6.14).

In the case of large rivers such as the Amazon and the Congo, however, the net flux of sediment through the estuary is seawards. Large amounts of sediment are supplied to the continental shelf from such rivers, and eventually to the deep sea via the submarine canyons eroded by turbidity currents (cf. Section 3.1.1). They are deposited to form extensive ‘deep-sea deltas’ (submarine fans), building up the continental rise. Rates of sediment accumulation on the fans can be very high: as much as 25 m per thousand years on the Amazon fan, for example.
Estuaries generally make good natural ports and harbours, but as many are slowly silting up, attempts are commonly made to keep them open for shipping as long as possible, e.g. by building 'training walls' to semi-canalize the main channel, and/or by dredging.

**QUESTION 6.7** Silting up of the lower Savannah River Estuary (a partially mixed estuary in Florida) was threatening navigation as far upstream as the port of Savannah itself. To combat this, the navigation channel was deepened by dredging, which caused a concomitant increase in salt water penetration up the estuary. Can you suggest what happened as a result, and why?

Dams built across large rivers can have considerable effects on their estuaries, especially where there is high seasonal rainfall, which would normally lead to flooding of the river and flushing of the sediment.

What would happen at the mouth of such an estuary, if a dam were built across the river inland?

Sediment would continue to be transported into the estuary from the sea, and deposited, but seasonal flooding would be inhibited by the dam upstream, there would be no annual removal of sediment to the sea, and the estuary would silt up more rapidly. For example, barely a decade after a large dam was built across the River Porali in Pakistan, the estuary at its mouth (some 80 km north of Karachi) had shrunk to less than half its original width of about 8 km, because of sediment accumulation. The mangrove swamps of the tidal mud flats are also silting up, which impairs their efficacy as nursery areas for young fish. The local fisheries are in decline as a consequence, while waterlogging and saline waters are adversely affecting nearby agricultural land.

## 6.3 LAGOONS, TIDAL FLATS AND BARRIER ISLANDS

As noted at the beginning of this Chapter, on low-lying coastlines, estuaries can take the form of shallow lagoons, commonly behind sand or gravel spits formed by longshore transport (Section 5.2.3). To mention only a few examples, lagoons occur along the Malabar coast of south-west India, the eastern coast of the USA, the Texas Gulf coast, and parts of England's southern and eastern coasts. At low latitudes, of course, lagoons also occur in the shelter of coral reefs (though these have nothing to do with estuaries).

Being shallow, lagoons tend to be well-mixed (mainly by winds rather than by currents), and they vary from brackish to hypersaline, depending upon the balance between evaporation, precipitation and river flow. In tropical areas, lagoons can be hypersaline during dry seasons, but may become almost entirely fresh during rainy seasons. Lagoons generally have only narrow connections to the open sea, and although their water levels rise and fall with the tide, tidal currents within them are generally weak, increasing towards the narrow inlets. The lack of significant wave and tidal current action and the generally (but not invariably) low relief of the surrounding land, means that sediments entering lagoons tend mostly to be fine grained, and are deposited on tidal flats, as in the upper reaches of estuaries elsewhere (Figure 6.2). Sediments in lagoons associated with coral reefs consist mostly of calcium carbonate sands and muds.
Coastal lagoons vary considerably in shape and size, according to the balance between tidal range and freshwater supply (whether from rivers or rainfall) on the one hand, and between wave action and sediment supply on the other. Most are simply more or less elongate bodies of open water, but some larger lagoons have developed as extensive and complex areas of low-lying islands and meandering interconnected channels, which may be wide and deep enough to accommodate shipping and harbour works (Figure 6.16).

Where a sand or gravel spit is breached by wave or river erosion, a part may be isolated and a barrier island results, typically elongated parallel to the shore. Most barrier islands, however, probably originated during sea-level rise following the last glaciation. Longshore bars (cf. Figure 5.1) were formed by wave action on the sediments left behind by retreating glaciers. They migrated landwards as the sea advanced over the continental shelves, and many were built up above sea-level, especially where additional sediment was supplied by rivers and/or by longshore transport. Good examples are the Friesian Islands off northern Holland and Germany, which shelter the lagoons and extensive tidal flats of the Wadden Sea from the waves of the North Sea (Figure 6.17(a)). The tidal flats in the eastern half of the Wadden Sea merge with those of the estuaries of the major rivers.

![Two views of lagoons near Faro, Portugal.](image)

(a) Low-lying islands with channels, tidal flats and salt-marshes.
(b) Larger channels with harbour works.
Figure 6.17 (a) Part of the south-eastern North Sea, showing the West Friesian Islands sheltering the western Wadden Sea, in which large areas of tidal flats are formed. (b) Part of the extensive tidal flats in the Ems-Dollard estuary (far right in (a)).

**QUESTION 6.8** Does the configuration of the West Friesian Islands (Figure 6.17(a)) suggest that the longshore drift which probably contributed to their formation was to the east or the west?
Tidal flats can develop wherever wave action is weak, the tidal range is moderate to large, there are high concentrations of suspended sediment in the coastal waters, and the offshore slope is gentle. They are not necessarily confined to estuaries, lagoons and other sheltered embayments that are regularly filled and emptied by the tides. In some circumstances, they can even occur on coasts facing the open sea, e.g. in Surinam on the north-east coast of South America. They are relatively rare in such settings, however, as open coastlines tend to be subjected to significant wave action, and sandy beaches are more likely to develop there (Chapter 5).

You read in Section 6.1 that the sediments of high tidal flats can be colonized by algae which help to bind them. In the warm climates of low latitudes, extensive mats of blue-green algae can form in the intertidal zone, especially where evaporation leads to hypersaline conditions. Some species of these algae secrete calcium carbonate, and successive layers of algal mats can accumulate to form algal mounds known as stromatolites (Figure 6.18), which eventually harden into limestone and are well preserved in the fossil record.

Along arid coastlines, such as that of the United Arab Emirates bordering the Persian Gulf, the seaward accretion of sediments leaves the older areas of algal mat stranded above sea-level. They are subject to intense surface evaporation, particularly after they have been flooded by seawater during occasional storms and extra-high tides, so that salts are precipitated within the algal mats. This kind of environment is called a sabkha, the Arabic word for salt-flat. In other low latitude coastal regions, carbonate sediments can accumulate wherever terrigenous sediment supplies are low (which includes coral reefs, cf. Chapter 3), and sediments of the intertidal region may be dominated by carbonate muds.
### 6.4 SUMMARY OF CHAPTER 6

1. Estuaries are tidal inlets at the mouths of rivers where mixing of freshwater and seawater occurs. They are ephemeral features on geological time-scales, and most are now slowly being infilled with sediment. They are characterized by channels and intertidal flats. There is a progression of sediment grain size towards the estuary shore: from sands in the channels, through sands and silts (with some muds) on the main intertidal flats, to muds on the high tidal flats, which are only submerged when tidal currents are weak at slack water. Accretion of tidal mud flats is promoted by the cohesive nature of muddy sediments, by settling lag, and by colonization of the mud flats by algae and eventually by land plants, leading to the formation of salt-marshes at mid- to high latitudes and mangrove swamps at low latitudes.

2. Fine sediment is deposited through aggregation into larger particles with higher settling velocities. Aggregation occurs mainly by flocculation in saline water, aided by turbulence in the water column, and also by biological processes (formation of faecal pellets and ‘fluffy’ aggregates of organic material). Cation exchange reactions take place between seawater and clay minerals, which can also adsorb heavy metals from solution in contaminated waters.

3. Estuaries range from strongly stratified to well-mixed, depending upon the relative magnitudes of tidal currents and river flow in the main channels. Salt-wedge (well-stratified) estuaries develop in virtually tideless seas, and are dominated by seaward flow of freshwater at the surface, with only minor landward movement (residual flow) of salt water at the bed. Current shear at the halocline leads to entrainment of salt water up into the freshwater layer. Partially mixed (moderately stratified) estuaries develop where there is a moderate tidal range. Greater mixing of fresh and salt water occurs because of turbulence, both at the bed and at the freshwater/seawater interface, and there is significant movement of water both seawards at the surface and landwards at the bed. Well-mixed (unstratified) estuaries develop where the tidal range is high. There is very little variation in salinity with depth, though in wide estuaries (especially if they are well-mixed) there can be lateral salinity gradients because river and tidal flows are on opposite sides of the estuary (as a result of the Coriolis effect) and there is a horizontal residual circulation. Even so, the mean velocity is seawards at all depths.

4. An estuary can exhibit different degrees of stratification and mixing between spring and neap tides and/or as a consequence of changes in river flow: high river discharge promotes stratification, low discharge promotes mixing. The upstream limit of the landward movement of salt water near the bed is called the null point. It occurs at salinities of between about 0.1 and 5 (parts per thousand), depending upon circumstances, and moves up and down the main channel with the tides.
5 The plume of brackish water that flows from the estuary mouth can affect offshore waters over considerable areas, and regions of freshwater influence (ROFIs) can extend up to hundreds of kilometres from the estuary mouth, depending upon the magnitude of the river discharge. Seawater is mixed and entrained into the plume at the base and along the margins, where there are convergent fronts. Where tidal ranges are large, tidal intrusion fronts form on the rising tide at the mouths of some smaller estuaries; and in some well-mixed estuaries longitudinal fronts are observed, the result of transverse surface water movements caused by cross-estuary gradients of salinity (and hence density).

6 A turbidity maximum develops near the null point, because sediment is carried into it both by the river flow and by the landward flow of salt water near the bed, aided by flocculation near the null point. The turbidity maximum also moves up and down the river with the tides, and is the source of most of the muds deposited on the high tidal flats. It tends to be most intense at mid-tides, when erosion by tidal currents is greatest. It is also enhanced during spring tides and/or at times of low river discharge, but is reduced during neap tides and/or at times of high river discharge. In some estuaries, high concentrations of fluid mud may form near the bed during neap tides, to be subsequently dispersed by the spring tides. Most estuaries are net accumulators of sediment since they are supplied with material from both the river and the sea. The landward movement of sediment is aided by the asymmetry of tidal flows in estuaries.

7 Negative estuarine circulation can develop in arid regions, where very high evaporation rates at the head of the estuary lead to sinking of dense hypersaline water, and a landward flow of seawater of normal salinity at the surface to replace it. In such estuaries, sands may be deposited from the bedload at the head of the estuary, while the fine sediments are carried seawards in suspension by the hypersaline flow at the bed.

8 Lagoons commonly form in the shelter of sand or gravel spits formed by longshore transport. Most are shallow and well mixed, and have only narrow outlets to the sea, so that tidal influences and wave activity are relatively weak. Breaching of spits by wave action, or isolation of longshore bars by rising sea-level, can lead to the formation of barrier islands, behind which wave action is limited. If the tidal range is moderate to large, tidal flats (similar to those occurring in estuaries) can form behind barrier islands. In low latitudes, colonization of tidal flat sediments by carbonate-secreting algae leads to accumulations of layers of algal mats. Along arid coastlines, where evaporation is high, salt flats (sabkhas) develop, and where terrigenous sediment input is negligible, carbonate muds can accumulate.
Now try the following questions to consolidate your understanding of this Chapter.

**QUESTION 6.9**
(a) Whereabouts in the estuarine continuum of Figure 6.4 would you place the Seine, according to Figure 6.10?

(b) Does the core of the turbidity maximum in Figure 6.10 lie at the null point, or upstream or downstream of it?

(c) What are (i) the maximum, and (ii) the minimum concentrations of suspended sediment in the core of the turbidity maximum in Figure 6.10, and at what stage of the tide does each occur?

**QUESTION 6.10** Examine Figure 6.19.
(a) Suggest an explanation for the form of the surface isohalines in the main estuary.

(b) How confident would you be in concluding that the circulation pattern in this estuary is at the well-mixed end of the continuum in Figure 6.4?
QUESTION 6.11  Examine Figure 6.20.
(a) At approximately which station would you place the null point?
(b) Do the isohalines slope down landward or seawards?
(c) Approximately what is the salinity in the core of the turbidity maximum?
(d) How can you tell that the water column is well mixed to seawards of about station 17?

Figure 6.20  Distribution of salinity and suspended sediment concentrations in the Ems–Dollard estuary, on the German–Dutch border (cf. Figure 6.17).
(a) Map of area (main channel shown blue).
(b) Surface data. (Blue = salinity; brown = suspended material.)
(c) Data for 1 m above bed. Numbers are stations along the estuary; data are not given for all stations.
Question 6.4  (a) Given the large tidal range and the relatively broad aspect of the estuary, it would probably be classified as well mixed (and the water column is indeed likely to be well mixed at high tide over the wide expanse of intertidal flats to the right of the main channel (looking landwards)). Some stratification could well develop in the middle and upper estuary, however, especially during neap tides and periods of high river discharge.

(b) On the ebb, tidal currents in the channel run counter to the incoming waves, slowing them down, steepening them, and causing them to break further offshore (cf. Section 1.6.1).

(In answering Question 6.4, you may have concluded that the main channel in Figure 6.6 is on the right-hand side (looking seaward) because of the Coriolis effect leading to a horizontal residual circulation as illustrated in Figure 6.4(d). However, the tidal part of this estuary is not much more than about 6 km long, which is probably not sufficient to allow the Coriolis effect to influence the course of the tidal channel significantly. The estuary has its present form mainly because of late 18th century drainage and canalization works upstream of the present head of the estuary.)

Question 6.5  (a) Figure 6.11(b) represents (i) high river discharge (800 m$^3$s$^{-1}$), as the turbidity maximum is near the estuary mouth and relatively small, compared with Figure 6.11(a), which represents (ii) low river discharge (200 m$^3$s$^{-1}$), as the turbidity maximum is larger and extends further upstream.

(b) As outlined in Section 6.2.1, we would expect the Seine to be better stratified when river discharge is high (Figure 6.11(b)); this would increase the thickness of the low salinity (low density) upper layer, and would tend to ‘flatten’ the slope of the isohalines (cf. Figure 6.4(b)).

(These effects might be offset to some extent by greater suspended sediment concentrations in the turbidity maximum when river discharge is low. This would slightly increase the density of the lower layers and contribute to stratification at such times – but the density contrasts due to salinity differences are likely in general to be a more important determinant of stratification.)

Question 6.6  (a) Neither, under normal conditions. The pattern of flow (Figure 6.13(b)) is such that there is no convergence of flows at the bed, and therefore no null point; and since the sediments are mostly sands, there can be no turbidity maximum either.

(b) Yes, of course. The flows are in opposite directions from those in ‘normal’ estuaries, but there must be mixing and exchange of water between the upper and lower layers.

Question 6.7  The result was an increase in the rate of sedimentation in the estuary, because the increasing landward flow of seawater at the bed would have led to an increase in the sediment load brought into the estuary from the sea.

Question 6.8  The curving form of the island ‘chain’ in Figure 6.17(a), and the way it tapers off towards the east suggest that this was the prevailing direction of longshore drift – and it is consistent with the present-day residual current circulation in this part of the North Sea (see Chapter 8).
Question 6.9  (a) Sloping isohalines (as opposed to the near-vertical ones of well-mixed estuaries), a tidal range approaching 5 m, and high suspended sediment concentrations in the turbidity maximum show the Seine to be a partially mixed estuary.

(b) Assuming the null point to be at the intersection with the bed of the 1 (part per thousand) salinity isohaline, the core of the turbidity maximum lies well downstream of it for most of the time.

(c) (i) Maximum concentrations in the core are greater than 1 g l\(^{-1}\) (and extend throughout the water column) at low water, and (ii) minimum concentrations are 0.5–1 g l\(^{-1}\) (near the bed) during slack water around high tide.

Question 6.10  (a) The surface isohalines are not straight but are deflected further up-estuary on the eastern side, further down-estuary on the western side. There is a lateral salinity gradient, consistent with deflection by the Coriolis force being to the right in the Northern Hemisphere (cf. Figure 6.4(d)). However, the lateral salinity gradient could also result, in part at least, from greater supplies of freshwater from tributaries to the west of Chesapeake Bay.

(b) You should not be at all confident, in the absence of information about river discharge, main channel depth and so on (see last part of Section 6.2.1). You can infer that the tidal range is large, because a horizontal circulation appears to be developed, but no more. In fact, the estuary is commonly more or less stratified, because a comparatively shallow sill near the estuary mouth isolates the bottom waters, especially in summer, and anoxic conditions can develop in them. At such times, the estuary is certainly not well mixed.

Question 6.11  (a) According to Figure 6.20(b), the salt intrusion clearly penetrates upstream as far as about station 4, so the null point must be near there, where bottom salinity is in the order of 1 (part per thousand).

(b) Isohalines must slope down landwards, as in Figure 6.4(b). Comparison of Figures 6.20(b) and (c) shows that at any station between 1 and 17, near-bed salinity is greater than surface salinity. The difference is relatively small so this estuary is approaching the well-mixed end of the continuum (Section 6.2.1), i.e. the slope of the isohalines is quite steep.

(c) The core of the turbidity maximum (2.27 g l\(^{-1}\)) probably lies between stations 8 and 9, and the near-bed salinity approaches 20 (parts per thousand) there. At the surface, the turbidity maximum contains much less suspended sediment, and the maximum concentration is reached a little further upstream than it is near the bed.

(d) Seaward of station 17, salinities in both surface and bottom waters are the same, so the water column must be well-mixed. That is what you might expect at the mouth of the estuary, but the salinity data show no evidence of a ROFI, possibly because freshwater flow was low and/or tidal mixing was especially strong when the measurements were made.

CHAPTER 7

Question 7.1  (a) Salinities are very low at the surface (e.g. 4.5 at the station in the middle of the plume about 8 km from land), while at only 3 m depth they are all greater than 25. So by 5 m depth, salinities must be close to that of normal seawater (35). These plumes are thus very thin.