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Definition and classification of estuaries

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This chapter discusses definitions and classification of estuaries. It presents both the classical and more flexible definitions of estuaries. Then it discusses separate classifications of estuaries based on water balance, geomorphology, water column stratification, and the stratification–circulation diagram – Hansen–Rattray approach and the Ekman–Kelvin numbers parameter space.

The most widely accepted definition of an estuary was proposed by Cameron and Pritchard (1963). According to their definition, an estuary is (a) a semienclosed and coastal body of water, (b) with free communication to the ocean, and (c) within which ocean water is diluted by freshwater derived from land. Freshwater entering a semienclosed basin establishes longitudinal density gradients that result in long-term surface outflow and net inflow underneath. In classical estuaries, freshwater input is the main driver of the long-term (order of months) circulation through the addition of buoyancy. The above definition of an estuary applies to temperate (classical) estuaries but is irrelevant for arid, tropical and subtropical basins. Arid basins and those forced intermittently by freshwater exhibit hydrodynamics that are consistent with those of classical estuaries and yet have little or no freshwater influence. The loss of freshwater through evaporation is the primary forcing agent in some arid systems, and causes the development of longitudinal density gradients, in analogy to temperate estuaries. Most of this book deals with temperate estuaries, but low-inflow estuaries are discussed in detail in Chapter 9.

1.1. Classification of estuaries on the basis of water balance

On the basis of the definitions above, and in terms of their water balance, estuaries can be classified as three types: positive, inverse and low-inflow estuaries (Fig. 1.1). Positive estuaries are those in which freshwater additions from river discharge, rain and ice melting exceed freshwater losses from evaporation or

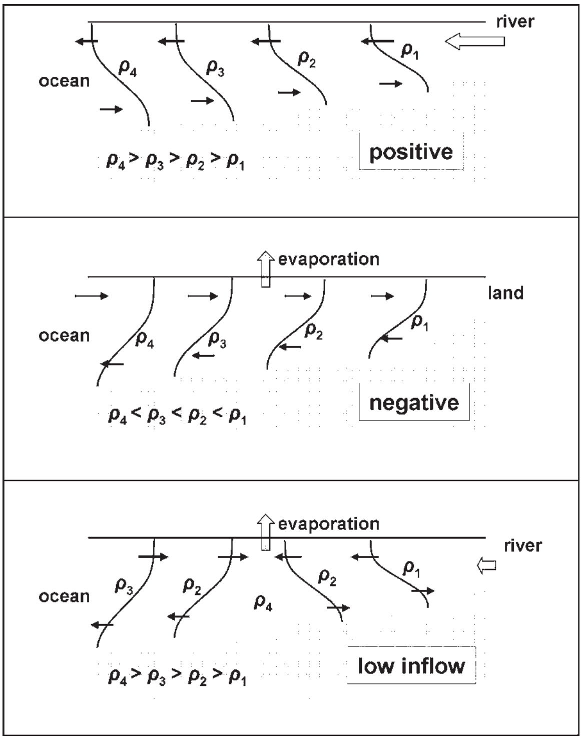

Figure 1.1. Types of estuaries on the basis of water balance. Low-inflow estuaries exhibit a “salt plug”.

freezing and establish a longitudinal density gradient. In positive estuaries, the longitudinal density gradient drives a net volume outflow to the ocean, as denoted by stronger surface outflow than near-bottom inflow, in response to the supplementary freshwater. The circulation induced by the volume of fresh water added to the basin is widely known as “estuarine” or “gravitational” circulation.

Inverse estuaries are typically found in arid regions where freshwater losses from evaporation exceed freshwater additions from precipitation. There is no or scant river discharge into these systems. They are called inverse, or negative, because the longitudinal density gradient has the opposite sign to that in positive estuaries, i.e., water density increases landward. Inverse estuaries exhibit net volume inflows associated with stronger surface inflows than near-bottom outflows. Water losses related to inverse estuaries make their flushing more sluggish than positive estuaries. Because of their relatively sluggish flushing, negative estuaries are likely more prone to water quality problems than positive estuaries.

Low-inflow estuaries also occur in regions of high evaporation rates but with a small (on the order of a few m^3/s) influence from river discharge. During the dry and hot season, evaporation processes may cause a salinity maximum zone (sometimes referred to as a salt plug, e.g., Wolanski, 1986) within these low-inflow estuaries. Seaward of this salinity maximum, the water density decreases, as in an inverse estuary. Landward of this salinity maximum, the water density decreases, as in a positive estuary. Therefore, the zone of maximum salinity acts as a barrier that precludes the seaward flushing of riverine waters and the landward intrusion of ocean waters. Because of their weak flushing in the region landward of the salinity maximum, low-inflow estuaries are also prone to water quality problems.

1.2. Classification of estuaries on the basis of geomorphology

Estuaries may be classified according to their geomorphology as coastal plain, fjord, bar-built and tectonic (Fig. 1.2; Pritchard, 1952). Coastal plain estuaries, also called drowned river valleys, are those that were formed as a result of the Pleistocene increase in sea level, starting ~15,000 years ago. Originally rivers, these estuaries formed during flooding over several millennia by rising sea levels. Their shape resembles that of present-day rivers, although much wider. They are typically wide (on the order of several kilometers) and shallow (on the order of 10 m), with large width/depth aspect ratios. Examples of these systems are Chesapeake Bay and Delaware Bay on the eastern coast of the United States.

Fjords are associated with high latitudes where glacial activity is intense. They are characterized by an elongated, deep channel with a sill. The sill is related to

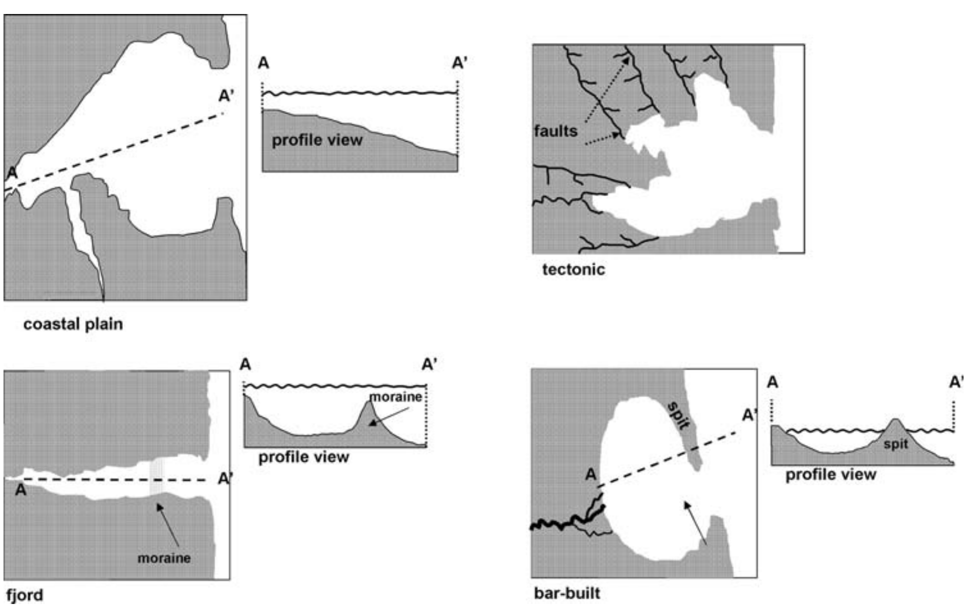

Figure 1.2. Classification of estuaries on the basis of geomorphology.

a moraine of either a currently active glacier or an extinct glacier. In the sense of the glacier activity, it could be said that there are riverine and glacial fjords. Riverine fjords are related to extinct glaciers and their main source of buoyancy comes from river inputs. They are usually found equatorward of glacial fjords. Glacial fjords are found in high latitudes, poleward of riverine fjords. They are related to active glaciers and their main source of buoyancy is derived from melting of the glacier and of snow and ice in mountains nearby. Fjords are deep (several hundreds of meters) and narrow (several hundreds of meters) and have low width/depth aspect ratios with steep side walls. Fjords are found in Greenland, Alaska, British Columbia, Scandinavia, New Zealand, Antarctica and Chile.

Bar-built estuaries, originally embayments, became semienclosed because of littoral drift causing the formation of a sand bar or spit between the coast and the ocean. Some of these bars are joined to one of the headlands of a former embayment and display one small inlet (on the order of a few hundred meters) where the estuary communicates with the ocean. Some other sand bars may be detached from the coast and represent islands that result in two or more inlets that allow communication between the estuary and the ocean. In some additional cases, sand bars were formed by rising sea level. Examples of bar-built estuaries abound in subtropical regions of the Americas (e.g., North Carolina, Florida, northern Mexico) and southern Portugal.

Tectonic estuaries were formed by earthquakes or by fractures of the Earth's crust, and creases that generated faults in regions adjacent to the ocean. Faults cause part of the crust to sink, forming a hollow basin. An estuary is formed when the basin is filled by the ocean. Examples of this type of estuary are San Francisco Bay in the United States, Manukau Harbour in New Zealand, Guaymas Bay in Mexico and some Rias in NwSpain.

1.3. Classification of estuaries on the basis of vertical structure of salinity

According to water column stratification or salinity vertical structure, estuaries can be classified as salt wedge, strongly stratified, weakly stratified or vertically mixed (Pritchard, 1955; Cameron and Pritchard, 1963). This classification considers the competition between buoyancy forcing from river discharge and mixing from tidal forcing (Fig. 1.3). Mixing from tidal forcing is proportional to the volume of oceanic water entering the estuary during every tidal cycle, which is also known as the tidal prism. Large river discharge and weak tidal forcing results in salt wedge estuaries such as the Mississippi (USA), Rio de la Plata (Argentina), Vellar (India), Ebro (Spain), Pánuco (Mexico), and Itajaí-Açu (Brazil). These systems are strongly stratified during flood tides, when the ocean water intrudes in a wedge shape. Some of these systems lose their salt wedge nature during dry periods. Typical

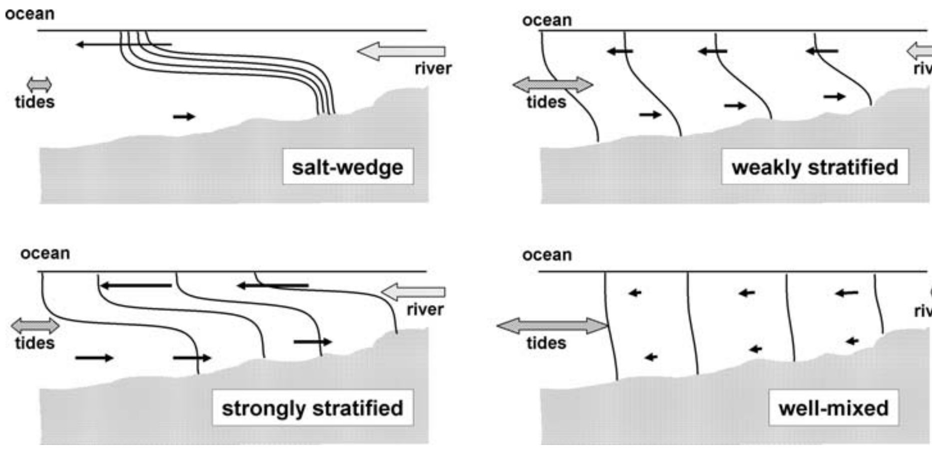

Figure 1.3. Classification of estuaries on the basis of vertical structure of salinity.

tidally averaged salinity profiles exhibit a sharp pycnocline (or halocline), with mean flows dominated by outflow throughout most of the water column and weak inflow in a near-bottom layer. The mean flow pattern results from relatively weak mixing between the inflowing ocean water and the river water.

Moderate to large river discharge and weak to moderate tidal forcing result in strongly stratified estuaries (Fig. 1.3). These estuaries have similar stratification to salt wedge estuaries, but the stratification remains strong throughout the tidal cycle as in fjords and other deep (typically >20 m deep) estuaries. The tidally averaged salinity profiles have a well-developed pycnocline with weak vertical variations above and below the pycnocline. The mean flow exhibits well-established outflows and inflows, but the inflows are weak because of weak mixing with freshwater and weak horizontal density gradients.

Weakly stratified or partially mixed estuaries result from moderate to strong tidal forcing and weak to moderate river discharge. Many temperate estuaries, such as Chesapeake Bay, Delware Bay and James River (all in the eastern United States) fit into this category. The mean salinity profile either has a weak pycnocline or continuous stratification from surface to bottom, except near the bottom mixed layer. The mean exchange flow is most vigorous (when compared to other types of estuaries) because of the mixing between riverine and oceanic waters.

Strong tidal forcing and weak river discharge result in vertically mixed estuaries. Mean salinity profiles in mixed estuaries are practically uniform and mean flows are unidirectional with depth. In wide (and shallow) estuaries, inflows may develop on one side across the estuary and outflow on the other side, especially during the dry season. Parts of the lower Chesapeake Bay may exhibit this behavior in early autumn. In narrow well-mixed estuaries, inflow of salinity may only occur during the flood tide because the mean flow will be seaward. Examples of this type of estuary are scarce because, under well-mixed conditions, the mean (as in the tidally averaged sense) flow will most likely be driven by wind or tidal forcing (e.g., Chapter 6).

It is essential to keep in mind that many systems may change from one type to another in consecutive tidal cycles, or from month to month, or from season to season, or from one location to another inside the same estuary. For instance, the Hudson River, in the eastern United States, changes from highly stratified during neap tides to weakly stratified during spring tides. The Columbia River, in the western United States, may be strongly stratified under weak discharge conditions and similar to a salt-wedge estuary during high discharge conditions.

1.4. Classification of estuaries on the basis of hydrodynamics

A widely accepted classification of estuaries was proposed by Hansen and Rattray (1966) on the basis of estuarine hydrodynamics. It is best to review this classification after acquiring a basic understanding of estuarine hydrodynamics, e.g., after Chapter 6 of this book. This classification is anchored in two hydrodynamic non-dimensional parameters: (a) the circulation parameter and (b) the stratification parameter. These parameters refer to tidally averaged and cross-sectionally averaged variables. The circulation parameter is the ratio of near-surface flow speed u_s to sectionally averaged flow U_f. The near-surface flow speed is typically related to the river discharge and, for the sake of argument, on the order of 0.1 m/s. The depth-averaged flow U_f is typically very small, tending to zero, in estuaries of vigorous water exchange because there will be as much net outflow as net inflow. In estuaries with weak net inflow, such as well-mixed and salt-wedge systems, the depth-averaged flow will be similar in magnitude to the surface outflow. Therefore, the circulation parameter is >10 in estuaries with vigorous gravitational circulation and close to 1 in estuaries with unidirectional net outflow. In general, the greater the circulation parameter, the stronger the gravitational circulation.

The other non-dimensional parameter, the stratification parameter, is the ratio of the top-to-bottom salinity difference ∂S to the mean salinity over an estuarine cross-section S_0. A ratio of 1 indicates that the salinity stratification (or top-to-bottom difference) is as large as the sectional mean salinity. For instance, if an estuary shows a sectional mean salinity of 20, for it to exhibit a stratification parameter of 1 it must have a very large stratification (on the order of 20). In general, estuaries will most often have stratification parameters <1. The weaker the water column stratification, the smaller the stratification parameter will be.

The two parameters described above can be used to characterize the nature of salt transport in estuaries. The contribution by the diffusive portion (vs the advective

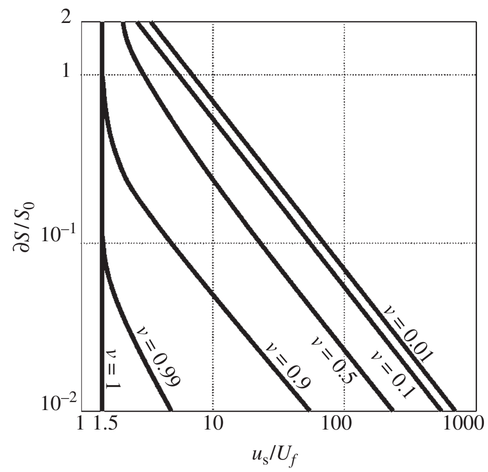

Figure 1.4. Diffusive salt flux fraction in the stratification/circulation parameter space (redrawn from Hansen and Rattray, 1966).

portion) of the total salt flux into the estuary can be called ν. The parameter ν may oscillate between 0 and 1. When ν is close to 0, up-estuary salt transport is dominated by advection, i.e., by the gravitational circulation. In this case, mixing processes are weak, as in a highly stratified estuary (fjord). When ν approaches 1, the total salt transport is dominated by diffusive processes (e.g., tidal mixing), as in unidirectional net flows. The parameter ν may be portrayed in terms of the stratification and circulation parameters (Fig. 1.4). This diagram shows that salt transport is dominated by advective processes under high gravitational circulation or strongly stratified conditions. It also shows that diffusive processes dominate the salt flux at low circulation parameter (unidirectional net flows) regardless of the stratification parameter. Between those two extremes, the salt transport has contributions from both advective and diffusive processes. The more robust the stratification and circulation parameters, the stronger the contribution from advective processes to the total salt flux will be.

These concepts can be used to place estuaries in the parameter space of the circulation and stratification parameters. The lower-left corner of the parameter space (Fig. 1.5A) describes well-mixed estuaries with unidirectional net outflows, i.e., seaward flows with no vertical structure or type 1 estuaries. These are well-mixed estuaries, type 1a, implying strong tidal forcing and weak river discharge (or large tidal prisms relative to freshwater volumes). There are also estuaries with depth-independent seaward flow but with highly stratified conditions. These type 1b estuaries have large river discharge compared to tidal forcing. In type 1 estuaries, in general, the upstream transport of salt is overwhelmingly dominated by diffusive processes (ν ≈ 1, Fig. 1.5B).

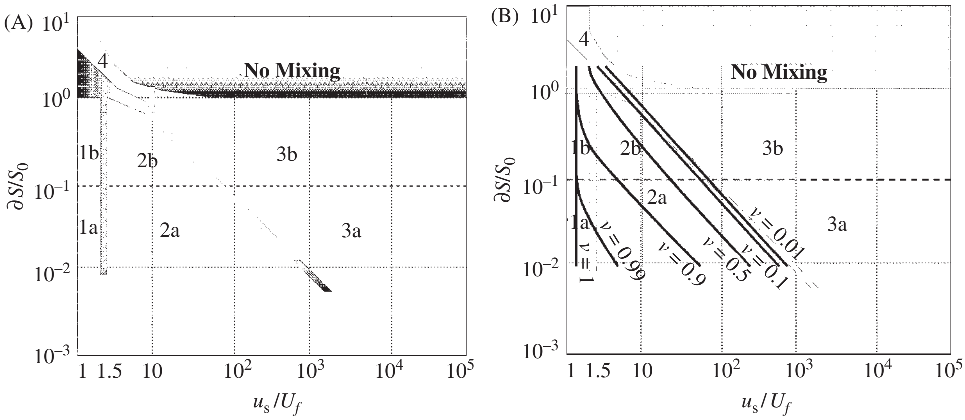

Figure 1.5. Classification of estuaries according to hydrodynamics, in terms of the circulation and stratification parameters (redrawn from Hansen and Rattray, 1966). (A) Type 1 estuaries show no vertical structure in net flows; in type 2 estuaries, the net flows reverse with depth; type 3 estuaries exhibit strong gravitational circulation; and type 4 estuaries are salt wedge. (B) Includes lines of diffusive salt flux showing the dominance of advective salt flux for type 3 estuaries and diffusive flux for type 1.

Type 2 (Fig. 1.5B) estuaries are those where flow reverses at depth, and include most temperate estuaries. These systems feature well-developed gravitational circulation and exhibit contributions from advective and diffusive processes to the upstream salt transport ($0.1 < \nu < 0.9$). Type 2a estuaries are well mixed or weakly stratified and type 2b estuaries are strongly stratified. Note that strongly stratified and weakly stratified estuaries of type 2 may exhibit similar features in terms of the relative contribution from diffusive processes to the upstream salt transport (Fig. 1.5B).

Type 3 estuaries are associated with fjords, where gravitational circulation is well established: strong surface outflow and very small depth-averaged flows, typical of deep basins. This flow pattern results in large values (>100–1000) of the circulation parameter (Fig. 1.5A). Type 3a estuaries are moderately stratified and type 3b are highly stratified. The peculiarity about these systems is that the upstream transport of salt is carried out exclusively by advective processes ($\nu < 0.01$, Fig. 1.5B).

Finally, type 4 estuaries exhibit seaward flows with weak vertical structure and highly stratified conditions as in a salt-wedge estuary. In type 4 estuaries, the diffusive fraction ν lines tend to converge, which indicates that in type 4 estuaries, salt transport is produced by both advective and diffusive processes. In the Hansen–Rattray diagram, it is noteworthy that some systems will occupy different positions in the parameter space as stratification and circulation parameters change from spring to neap tides, from dry to wet seasons, and from year to year.

Analogous to the classification of estuaries in terms of the two non-dimensional parameters discussed above, estuarine systems can also be classified in terms of the lateral structure of their net exchange flows. The lateral structure may be strongly influenced by bathymetric variations and may exhibit vertically sheared net exchange flows, i.e., net outflows at the surface and near-bottom inflows (e.g., Pritchard, 1956), or laterally sheared exchange flows with outflows over shallow parts of a cross-section and inflows in the channel (e.g., Wong, 1994). The lateral structure of exchange flows may ultimately depend on the competition between Earth's rotation (Coriolis) and frictional effects (Kasai *et al.*, 2000), as characterized by the vertical Ekman number (*Ek*). But the lateral structure of exchange flows may also depend on the Kelvin number (*Ke*), which is the ratio of the width of the estuary to the internal radius of deformation.

The Ekman number is a non-dimensional dynamical depth of the system. Low values of *Ek* imply that frictional effects are restricted to a thin bottom boundary layer (weak frictional, nearly geostrophic conditions), while high values of *Ek* indicate that friction affects the entire water column. The lateral structure of density-driven exchange flows may be described in terms of whether the flows are vertically sheared or unidirectional in the deepest part of the cross-section (Valle-Levinson, 2008). Under low *Ek* (< 0.001, i.e., < -3 in the abscissa of Fig. 1.6), the lateral structure of exchange flows depends on the dynamic width of the system (Fig. 1.6). In wide systems ($Ke > 2$, i.e., > 0.3 in the ordinate of Fig. 1.6), outflows and inflows are separated laterally according to Earth's rotation, i.e., the exchange flow is laterally sheared. In narrow systems ($Ke < 1$, i.e., < 0 in the ordinate of Fig. 1.6) and low *Ek* (still < 0.001, i.e., < -3 in the abscissa of Fig. 1.6), exchange flows are vertically sheared. In contrast, under high *Ek* (> 0.3, i.e., > -0.5 in the abscissa of Fig. 1.6) and for all *Ke*, the density-driven exchange is laterally sheared independently of the width of the system. Finally, under intermediate *Ek* ($0.01 < Ek < 0.1$, i.e., between -2 and -1 in the abscissa of Fig. 1.6), the exchange flow is preferentially vertically sheared but exhibiting lateral variations.

The main message is that under weak friction ($Ek < 0.01$), both depth and width are important to determine whether the density-driven exchange is vertically or horizontally sheared. This is illustrated by the fact that the contour values in the entire region of $Ek < 0.01$ (i.e., < -2 in the abscissa) in Fig. 1.6 vary with both *Ek* and *Ke*. In contrast, under $Ek > 0.01$ the depth is the main determinant as to whether the exchange is vertically or horizontally sheared. This is shown by the fact that the contour values in Fig. 1.6 vary mostly with *Ek* but very little with *Ke*. A future challenge of this approach is to determine the variability of a particular system in the *Ek* vs *Ke* parameter space. It is likely that an estuary will describe an ellipse of variability in this plane from spring to neaps and from wet to dry seasons, or from year to year.

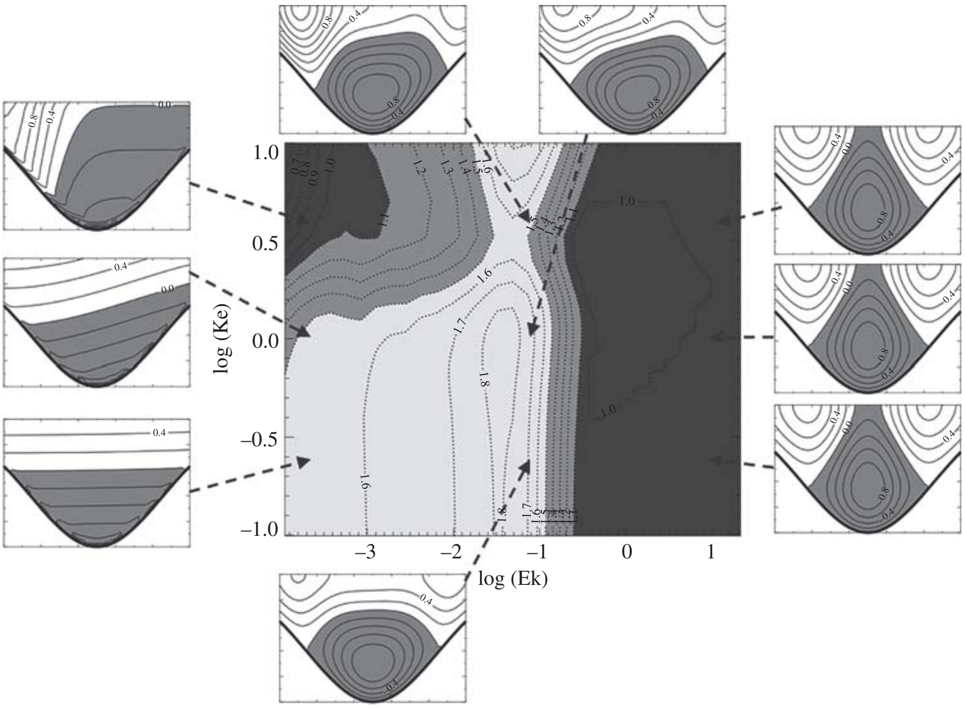

Figure 1.6. Classification of estuarine exchange on the basis of *Ek* and *Ke*. The subpanels appearing around the central figure denote cross-sections, looking into the estuary, of exchange flows normalized by the maximum inflow. Inflow contours are negative and shaded. The vertical axis is non-dimensional depth from 0 to 1 and the horizontal axis is non-dimensional width, also from 0 to 1. The central figure illustrates contours of the difference between maximum outflow and maximum inflow over the deepest part of the channel and for different values of *Ek* and *Ke*. Note that the abscissa and ordinate represent the logarithm of *Ek* and *Ke*. Dark-shaded contour regions denote net inflow throughout the channel, i.e., laterally sheared exchange flow as portrayed by the subpanels whose arrows point to the corresponding *Ek* and *Ke* in the dark-shaded regions. Light contour regions illustrate vertically sheared exchange in the channel as portrayed by the subpanels whose arrows point to the corresponding *Ek* and *Ke* in the light-shaded regions. Intermediate-shaded regions represent vertically and horizontally sheared exchange flow, similar to the second subpanel on the left, for log(*Ke*) = 0 and log(*Ek*) ~ −3.7.

All of the above classifications depend on diagnostic parameters that require substantial information about the estuary, i.e., on dependent variables. In addition, they do not take into account the effects of advective accelerations, related to lateral circulation, that may be of the same order of magnitude as frictional effects (e.g., Lerczak and Geyer, 2004). Some of these nuances are discussed further in Chapter 5 of this book. Future schemes will require taking those advective effects into account. In the following chapter, in addition to presenting the basic