10 Estuaries and Reefs

It was in the middle of a fascinating conversation on software engineering that Bob Martin asked me, "How much water flows out of the Mississippi River in a day?". Because I had found his comments up to that point deeply insightful, I politely stifled my true response and said, "Pardon me?". When he asked again I realized that I had no choice but to humor the poor fellow who had obviously cracked under the pressures of running a large software shop within Bell Labs.

My response went something like this. I figured that near its mouth the river was about a mile wide and maybe twenty feet deep (or about one two-hundred-and-fiftieth of a mile). I guessed that the rate of flow was five miles an hour, or a hundred and twenty miles per day. Multiplying

$$1 \text{ mile} \times 1/250 \text{ mile} \times 120 \text{ miles/day} \propto 1/2 \text{ mile}^3/\text{day}$$

showed that the river discharged about half a cubic mile of water per day, to within an order of magnitude. But so what?

At that point Martin picked up from his desk a proposal for the computer-based mail system that AT&T developed for the 1984 Summer Olympic games, and went through a similar sequence of calculation. Although his numbers were straight from the proposal and therefore more precise, the calculations were just as simple and much more revealing. They showed that, under generous assumptions, the proposed system could work only if there were at least a hundred and twenty seconds in each minute...

That was Bob Martin's wonderful (if eccentric) way of introducing the engineering technique of "back-of-the-envelope" calculations. The idea is standard fare in engineering schools and is bread and butter for most practicing engineers. Unfortunately, it is too often neglected in computing.

Jon Bentley, *Programming Pearls*

10.1 INTRODUCTION

Estuaries present one of the greatest challenges to environmental scientists, managers, and planners. They are important parts of the coastal ecosystem because their enclosed nature often protects them from extreme winds and extreme waves and because they provide a rich source of nourishment. Estuaries are often popular resorts for humans, whereas the high biological productivity of estuaries with marsh wetlands and mangrove swamps makes them popular breeding grounds for various fish and shellfish. Trade and industry find certain estuaries attractive locations in which to develop because they make fine sea ports. In many cases, this has generated large-scale alteration of the natural balance within the estuary through dredging, which alters the general shape, or through large-scale pollution. If humans are not to do undue damage to their environment, it is essential to understand and be able to predict these effects.

Tidal variations, irregular geometry, river flow, sediment transport, chemical pollution, and a specialized aquatic ecosystem interact to produce complicated mechanisms and behaviour patterns. Various classification schemes exist to try to make some sense of all these interactions. Many different schemes are possible depending on the particular estuarine behaviour under study. It is possible to classify estuaries in terms of their biology, their geomorphology, their sediment character, or their hydrology, and different schemes exist within each of these categories.

It is even hard to find an acceptable definition of an estuary. One simple view is to state that an estuary is where a river meets the sea. Unfortunately, a river can meet the sea without involving an estuary. Hydrologists prefer to think of it as "a semi-enclosed body of water having a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." The weakness in this definition is that there are many estuaries in Texas and Western Australia in which low river discharge and high evaporation combine to produce hypersaline water, the salinity of which exceeds that of sea water.

10.2 GEOMORPHOLOGICAL CLASSIFICATION OF ESTUARIES

Estuaries are often grouped on the basis of geological and geomorphological criteria. This method divides estuaries into three major types: coastal plain estuaries (which include rias), deep estuaries (fjords), and lagoon estuaries (bayous and limans).

10.2.1 Coastal Plain Estuaries

River deltas, drowned river valleys, and embayments on the sites of submerged coastal lowlands may all be considered coastal plain estuaries. The branched inlets formed by partial submergence of deep river valleys have been termed *rias* and are well exemplified by Sydney Harbour, San Francisco Bay, and any other similar branched inlet.

A typical ria consists of an estuary with several tributary rivers which may form estuaries in themselves. Alternatively, one can have an estuary with a single principal river at its head gradually opening into the sea at its mouth. The head of an estuary is defined as the upper limit of tidal penetration, and in certain estuaries there is an abrupt widening of the inflowing river where this occurs.

10.2.2 Fjords

Inlets formed by the submergence of the mouths of formerly glaciated valleys on steep coasts are known as *fjords* and may be found on the coasts of Canada, New

Zealand, Greenland, Norway, Scotland, Chile, and Siberia. Most of these consist of deep, almost rectangular, basins with a sill: that is, a region at the seaward end which is shallower than both the main basin and the sea outside. River discharge is small compared with the total fjord volume so that a typical fjord will have a thin layer of fresh water overlaying a large quantity of deep, salt water.

The whole of the Baltic sea, covering an area of 3.7×10^5 km^2, is a fjord-like estuary, and it suffers from the problem of stagnant bottom water. This is associated with the blocking effects of a sill and with strong water stability due to density variations. The stagnant water does not mix with the fluid above. During these stagnant periods, which last about 5 years, the supply of oxygen from the aerated surface water is cut off, so that the deeper layers may ultimately become completely exhausted of oxygen. The oxygen is used up in bacterial degradation of organic material present in the sediment and drifting down from the surface layer. This has been a progressive development in the Baltic over the past 75 years. One station, at a depth of 160 m in the central Baltic, shows an oxygen saturation decrease from 30% to near 0% during this period. The fears that the Baltic deep water may become devoid of life led to the installation of industrial and urban plants to treat their material prior to discharge to the Baltic.

10.2.3 Lagoons

Coastal lagoons are bar-built estuaries formed by the build up, through sedimentation or wave action, of a spit, barrier island, or bar. They occur all over the world in tropical and temperate climes, and the term *estuarine lagoon* covers both a river-fed coastal lagoon and the embayments that may exist behind it, as illustrated in Figure 10.1.

The configuration of lagoon entrances is the outcome of a contest between (1) the currents that flow through them, tending to keep them clear, and (2) the effects of onshore and longshore drifting of sand or shingle, which tend to seal them off. The position and dimensions of lagoon entrances change frequently in response to variations in these processes, and some have been stabilized by the construction of bordering breakwaters.

The dimensions of lagoon entrances influence the extent to which tides invade a lagoon and the salinity variations within it. Changes to the entrance may, in turn, affect aquatic vegetation within it. Near the entrance, banks of sediment are exposed at low tide, and the shores may be bordered by encroaching salt marshes and mangrove swamps. Away from the entrance, where the water is brackish and tidal fluctuations diminish, encroachment by salt marsh or mangrove swamp is much reduced. Mangroves, in particular, require regular tidal inundation.

Wind direction and lagoon shape interplay to control sedimentary processes within a lagoon. Winds blowing over the lagoon cause waves and currents which are related to wind direction and strength and the lengths of fetch across which these winds are effective. Long, narrow lagoons experience strongest wave action when the wind blows along the longest dimension, giving the maximum fetch. If the shores are not protected by vegetation, waves coming in at an angle move sediment to and fro along the beaches, eroding embayments and building up spits, cusps, and cuspate

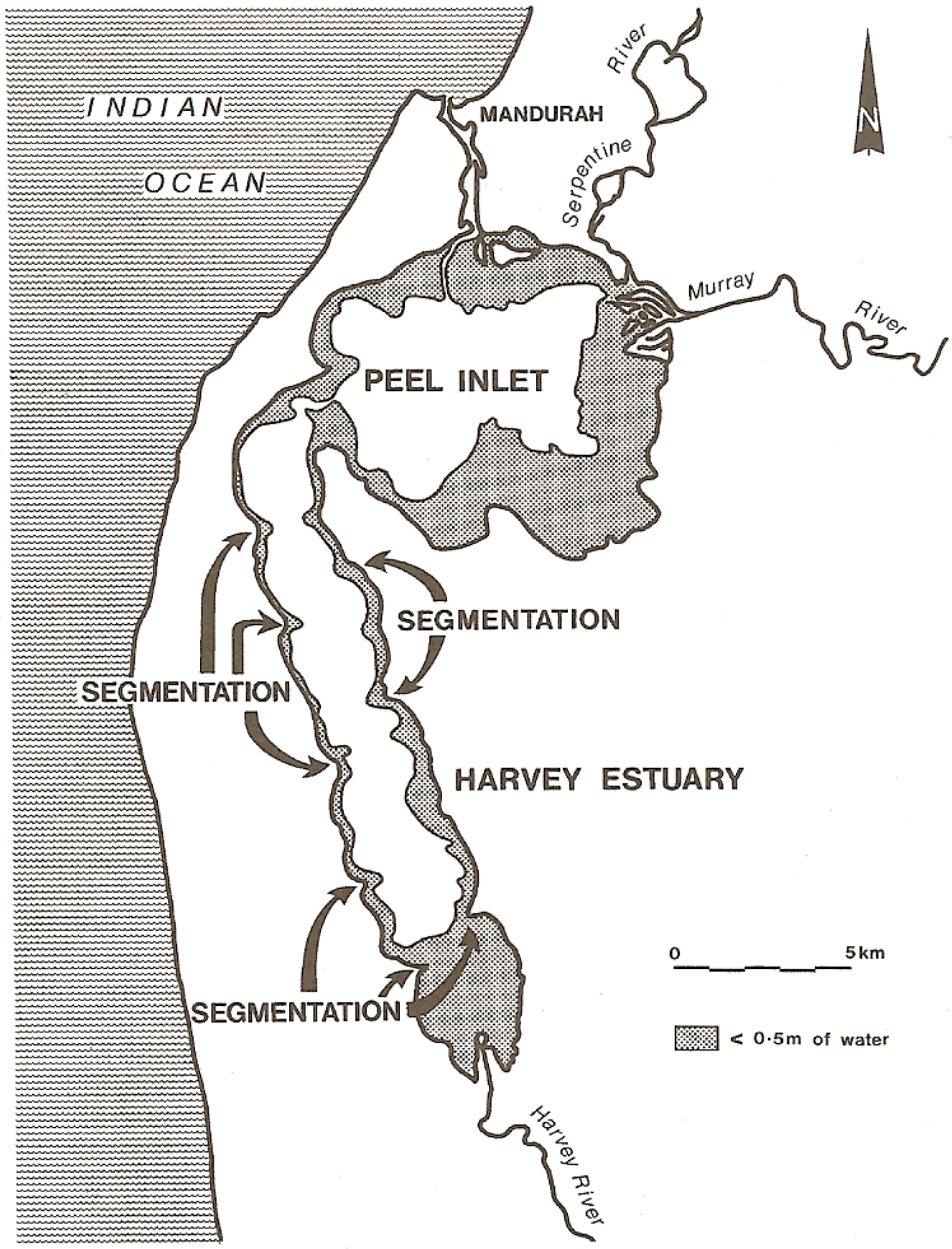

FIGURE 10.1 This map of the Peel Inlet and Harvey Estuary in Western Australia shows the process of segmentation which is dividing the Harvey Estuary lagoon into enclosed embayments. (From E.P. Hogkin, P.B. Birch, R.E. Black, and R.B. Humphries, *The Peel-Harvey Estuarine System Study (1976–1980),* Report No. 9, Department of Conservation and Environment, Western Australia, 1980. With permission.)

forelands which may grow to such an extent that the lagoon becomes divided into a series of small, round, or oval lagoons (Figure 10.1). This process is called *segmentation* and is essentially an adjustment of lagoon forms to patterns more closely related to waves and currents generated within the lagoon. Currents play a part in smoothing the curved outlines of the shore in the later stages of segmentation and may also maintain the connecting straits between segmented bays, but strong tidal currents deflect spit growth and inhibit the segmentation process.

10.3 ESTUARINE HYDROLOGY

From a physical viewpoint, the two most important variables controlling estuarine water are the amount of mixing between fresh water and salt water and the rate at which the mixing takes place. These are, in turn, controlled by six factors: river inflow, precipitation, evaporation, tidal variations, wind strength, and estuarine topography.

Figure 10.2 depicts the data obtained from weekly sampling of the Peel Inlet of Western Australia. This is a shallow estuary that is only 2.5 m at its deepest point. It is an estuarine lagoon, or actually an estuarine embayment, connected to the sea by a narrow channel. Because the tidal range on the Western Australian coast is slight, and because the narrow entrance channel chokes the tidal flows, the water in the estuary does not respond to the diurnal or semidiurnal tides but is only affected by longer period variations in water level, such as those due to shelf waves or meteorological perturbations. Let us now examine the abovementioned factors and see how they control the hydrology of the Peel Inlet.

10.3.1 Rainfall and Runoff

Figure 10.2 indicates the extreme variability of river flow into an estuary. In this particular case, long drought periods were interspersed with short, sudden flows. These flows are the river's response to the rainfall in the catchment area, but a river will only start to flow when the soil no longer absorbs the rain falling on it. Thus, a large, isolated rainstorm will produce far less runoff than a succession of more modest storms that saturate the ground and fall over a large part of the catchment.

Table 10.1 lists the mean flow from some of the major rivers of the world. These flows are much smaller than typical oceanic and coastal currents so that, with the possible exception of the Amazon, river flow affects only local estuarine and coastal circulations. Furthermore, Table 10.1 masks the huge year-to-year variations in the flow of major rivers. The Danube has a minimum annual mean flow of 200 $m^3\ s^{-1}$ and a maximum annual mean flow of 19,200 $m^3\ s^{-1}$. This range is typical enough for a large perennial river but, in general, the smaller the river the greater is its flow variability.

As a river flows down into the sea, it will continually displace the estuarine water and replace it with new river water. If the river flows fast, this will happen quickly, whereas the displacement will be slow if the flow is sluggish. A rough measure of the time taken to replace the estuarine fresh water is the flushing time, t_f, defined by:

$$t_f = V/Q \qquad (10.1)$$

where V is the estuarine fresh-water volume and Q is the river flow. It is a rough measure because it assumes that the river flows uniformly and displaces estuarine water over this entire cross-section. Genuine river flow is rarely like that, so that satisfactory ways of describing estuarine flushing rely on numerical models of the three-dimensional flow.

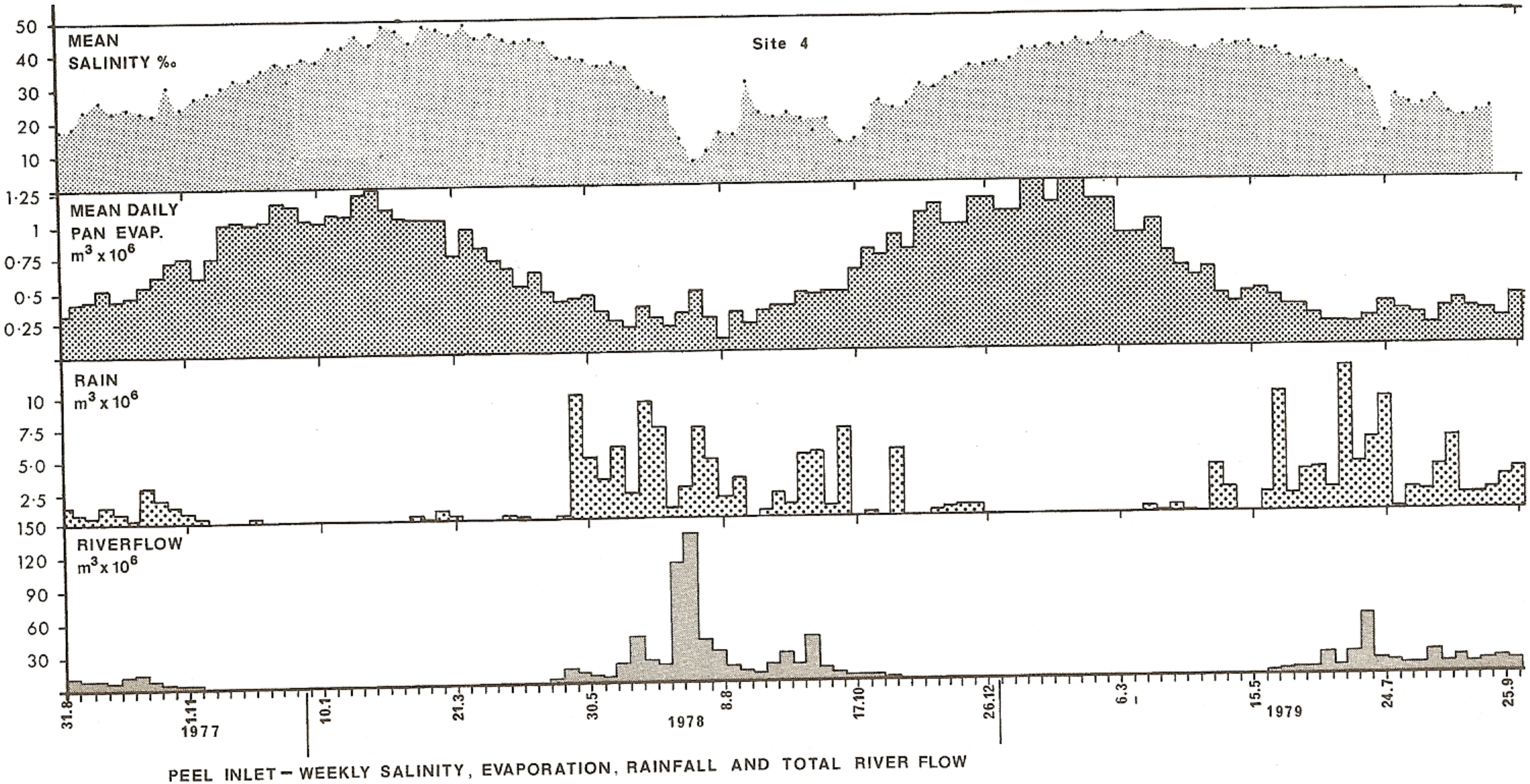

FIGURE 10.2 Weekly measurements of salinity, evaporation, rainfall, and river flow in the Peel Inlet show marked seasonal effects between summer (d

TABLE 10.1
Selected Rivers of the World Ranked by Annual Sediment Load

River	Location	Catchment Area (10^{12} m^2)	Mean Flow (10^3 m^3 s^{-1})	Sediment Load (Tg)[a]
Ganges/Bramaputra	Bangladesh	1.48	30.8	1670
Huangho (Yellow)	China	0.77	1.6	1080
Amazon	Brazil	6.15	199.6	900
Chang Jiang (Yangtze)	China	1.94	28.5	478
Irrawaddy	Burma	0.43	13.6	265
Magdalena	Columbia	0.24	7.5	220
Mississippi	USA	3.27	18.4	210
Orinoco	Venezuela	0.99	34.9	210
Mekong	Vietnam	0.79	14.9	160
Red	Vietnam	0.12	3.9	130
Fly	Papua New Guinea	0.05	6.0	118
Indus	Pakistan	0.97	7.5	100
MacKenzie	Canada	1.81	9.7	100
Godavari	India	0.31	2.7	96
La Plata	Argentina	2.83	14.9	92
Haiho	China	0.05	0.06	81
Purari	Papua New Guinea	0.031	2.4	80

Source: All data (except that for the Fly River) are from J.D. Milliman and R.H. Meade, *J. Geol.*, 91, 1–21, 1983. With permission. Fly River data are from Natural System Research Pty., Ltd., Burwood, Victoria.

[a] 1 Tg = 10^6 tonnes = 10^{12} g.

10.3.2 Rainfall, Evaporation, and Wind

In arid parts of the world and in the tropics where there are distinct wet and dry seasons, estuarine hydrology is influenced by daily evaporation and by the effects of rain falling directly on the estuary. Of course, when the rain is sufficiently widespread or prolonged to start rivers flowing, then riverine effects dominate, but at other times the balance between rainfall and evaporation will dominate the salinity of the estuary, as in Figure 10.2.

Wind will affect both the circulation and the salinity structure of an estuary. A sufficiently strong wind blowing long enough over all but the deepest estuaries will totally mix the water from top to bottom and will induce a windward flow at the surface and a return flow underneath. Short wind episodes can set up seiches within an estuary.

10.3.3 Tides

The volume of water in an estuary with an open connection to the sea will rise and fall with the rise and fall of the tides. At high tide, marshes will be covered; at low tides, mudflats exposed. The total volume of water exchanged between an estuary and the open sea over a complete tidal cycle is called the *tidal prism*. The tidal prism is approximately equal to the tidal range multiplied by the mean surface area of the estuary.

In estuaries subject to strong tides, estimates of the tidal prism can be used to estimate the extent of mixing and the resulting salinity distribution. One assumes that on the flood tide the volume of sea water entering the estuary is entirely of oceanic salinity and that it is completely mixed with a corresponding volume of estuarine water. On the ebb tide, this entire quantity of mixed water is completely removed from the estuary, and on the next flood tide the process is repeated with sea water of oceanic salinity. For a given freshwater inflow and tidal prism, one can then calculate the estuarine salinity.

In general, we do not expect complete mixing for the entire estuary during each tidal cycle, and we also anticipate that some of the mixed water will return on each succeeding flood tide. Box models allow for this by dividing the estuary into segments, over which the mixing takes place, rather than assuming that there is complete mixing over the length of the entire estuary during each tidal cycle.

Another important characteristic of tidal flows in shallow water, but one not at all obvious to the casual observer, is that superimposed on the back-and-forth flow is a net, steady circulation often called the *residual circulation*. Most estuaries have flood channels in which the flood current is stronger and ebb channels in which the ebb current is stronger. The process whereby a preferential direction is set up for the residual circulation is known as *tidal pumping*. In large estuaries (i.e., when the width exceeds the product of the inertial period and the tidal current speed) it is caused by the Coriolis deflection to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Therefore, in the Southern Hemisphere, flood tide currents are deflected toward the right bank (looking seaward) and ebb currents towards the left bank, resulting in a net clockwise circulation.

A second cause of residual circulation is the interaction of the tidal flow with the irregular bathymetry found in most estuaries. An example is an estuarine lagoon with a narrow entrance. The flood tide is forced to enter as a narrow jet, but the ebb flow comes from all around the mouth (and, of course, produces a jet of water into the sea). Averaging within the estuary over a tidal cycle yields an inward flow in the area of the jet and an outward flow elsewhere.

Another common example of a pumped circulation is the net flow around islands — or submerged banks — or in braided channels. An oscillatory tidal current flowing over an irregular bottom topography induces residual vortices, and various combinations of channel geometry can induce pumped gyres in most large bays.

10.3.4 Vertical Structure

Estuaries can be divided into four hydrographic types according to the degree of vertical mixing exhibited by their salt concentration: (1) vertically well-mixed, (2) partially stratified, (3) strongly stratified, and (4) salt wedge estuaries. Unlike open coastal waters, in which density differences arise predominantly from temperature changes, it is a characteristic of estuaries that the dominant density variations arise from salinity differences. The vertical stratification is one of haloclines, and the longitudinal variation of sea water at the mouth and fresh water at the head of the estuary produces a longitudinal density gradient as well. The salinity distributions in these four types are shown in Figure 10.3 in two ways. In the left-hand column of graphs, the property distributions are shown as vertical profiles of salinity at each of four stations between the head and the mouth of the estuary, as shown in the schematic plan view at the top. The right-hand column shows simplified longitudinal sections of salinity from head to mouth for the full depth of the estuary.

The vertically well-mixed estuary (Type A, Figure 10.3) is shallow and the water is mixed vertically by a combination of winds, tides, and riverflow, so that it is homogeneous from top to bottom at any particular place along the estuary. The salinity increases with distance along the estuary from head to mouth. The river water in such an estuary flows towards the mouth, while the salt progresses from the sea toward the head by means of a longitudinal dispersion. In the right-hand figure, the vertical isohalines indicate the homogeneity of the water at each location, while the arrows indicate that the direction of net water flow is seaward at all depths.

A partially stratified estuary (Type B) also is usually shallow. The salinity increases from head to mouth at all depths. The water is essentially in two layers, with the upper layer a little less saline than the deeper one, and a mixing layer between them. This type of estuary exhibits what has come to be thought of as the typical estuarine circulation in which there is a net seaward or outward flow of the upper layer and a net inward up-estuary flow in the bottom layer. In addition to this flow, at both levels there is vertical mixing of fresh and salt water giving rise to the longitudinal variation of salinity in both layers. The circular arrows in the salinity section indicate this mixing.

In the highly stratified estuary (Type C), of which fjords are typical, the upper layer increases in salinity from about zero, in the river at the head, to a value close to that of the outside sea at the mouth. The deep water, however, is of almost uniform salinity from head to mouth. This indicates that there is a unidirectional vertical mixing of salt water into the upper layer. This is a characteristic of turbulent entrainment (Section 8.3) and is a consequence of the stagnant deep water being entrained into the moving, wind-stirred upper layer. Again, there is a net outflow in the upper layer and inflow in the deeper water. In these estuaries there is a very strong halocline between the upper water and the deep water, particularly at the head where strong vertical salinity gradients may occur in summer during the period of greatest river runoff while the snows melt.

The longitudinal section for the salt wedge estuary (Type D) indicates the reason for its name. The saline water intrudes, from the sea, as a wedge below the river water. This situation usually occurs when the effects of river flow dominate tidal effects, when the wind is too weak to completely mix the estuary. It should be noted that, as usual, the section in Figure 10.3 is exaggerated in the vertical direction; the salt wedge is really a very thin one so that the isohalines are, in fact, almost horizontal except at the nose of the wedge. At the nose, the point of maximum penetration, the

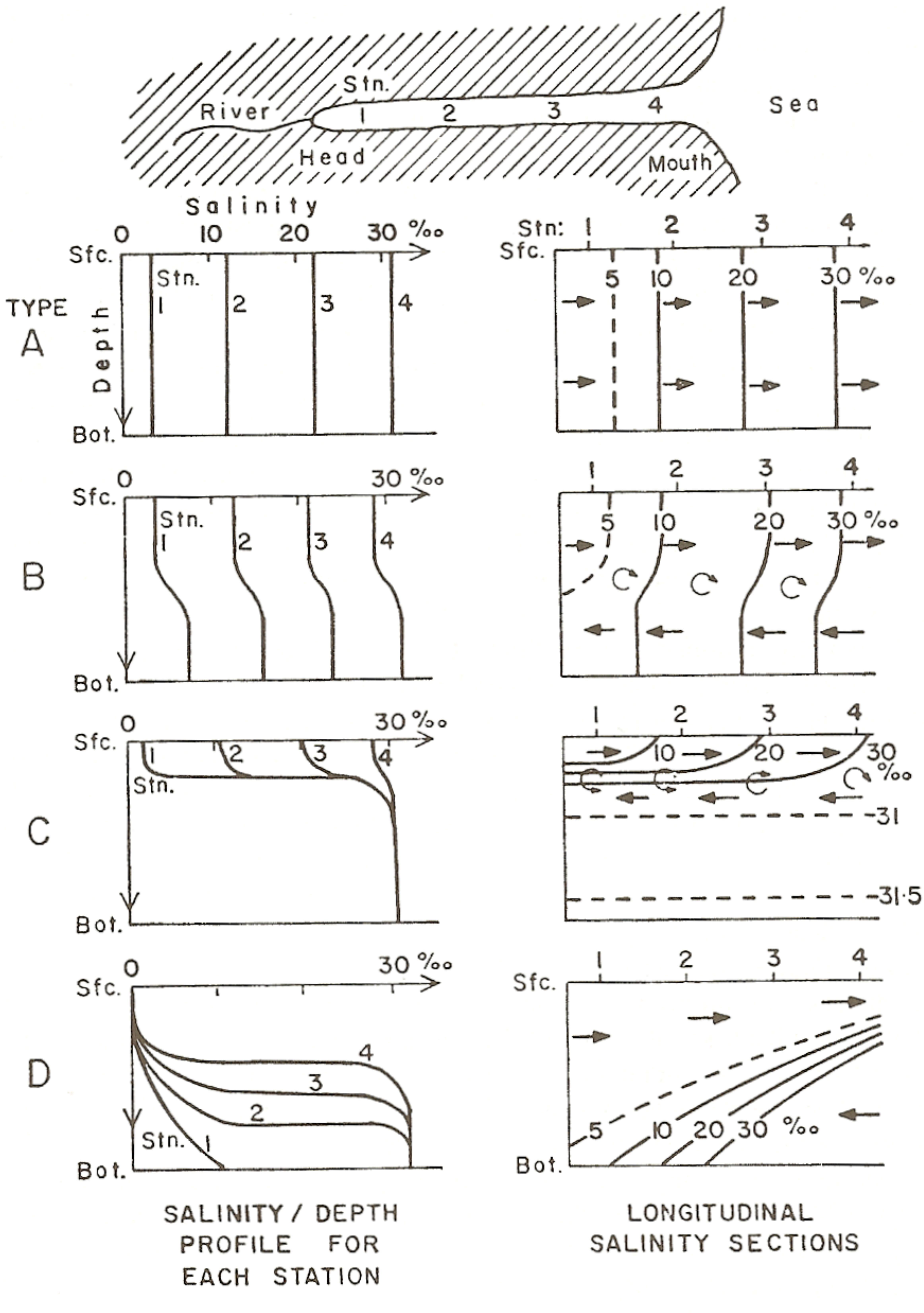

FIGURE 10.3 Typical salinity/depth profiles and longitudinal salinity sections in estuaries corresponding to (A) well-mixed, (B) partially stratifed, (C) strongly stratified, and (D) salt wedge conditions. (From G.L. Pickard, *Descriptive Physical Oceanography,* 2nd ed., Pergamon Press, Oxford, 1975. With permission.)

isohalines drop sharply to the bottom. The salt wedge estuary shares many features in common with stratified estuaries. The major difference is in the lack of a salinity gradient at the surface, the water there being fresh, or nearly so, until it debouches into the sea.