1

Prelude to modeling coastal basins

1.1 Coastal basins

This book explains the basic dynamics of bays, estuaries, and lagoons through the use of simple models. There is a focus on physically simple systems for which easy-to-understand models give good insight into basic processes. These models may be either analytical or numerical (or ideally both). The book uses these simple models to present our basic ideas of processes in coastal basins with a deliberate emphasis on box models and simple one-dimensional and (occasionally) higher-dimensional models. The book avoids, as far as possible, the complexities of three-dimensional models in favor of the simplicity of lower-dimensional models.

I use the term *coastal basins* to represent the myriad of different water bodies which we find in the region between the land and the open continental shelf. They carry local names such as *estuary, bay, sound, inlet, gulf* although those names are also used for systems which lie on the continental shelf or form a part of deep ocean basins. Finding a generally accepted name is not easy and the obvious choice of *estuaries* is not really correct in so far as estuaries normally have a very dominant circulation due to density differences; whereas much of the basic dynamics of many coastal basins is due to tides, winds, and waves. The term *lagoon* is also a possibility but carries a connotation of certain types of morphology. I have therefore settled on the term *coastal basins* although I must stress that I am not including aquifer or drainage basins and I have not included models of surface water flow or groundwater systems. So, a *coastal basin*, in the context of this book, is a shallow system, i.e., typically less than 10 m (although possibly some tens of meters deep) forced mainly by wind, tide, and river flow. A key requirement of a coastal basin (in the present context) is that the coast has a dominant influence.

Much of our understanding of coastal basins is directly relevant to lakes and rivers but that is not a primary focus of this book. Although I have included a chapter on sediment dynamics, and wave models, I have avoided, any detailed discussion of *nearshore processes*. My reason is that these processes act on much smaller spatial and time scales and usually involve highly phenomenological laws of mechanical interaction between currents and solids. The processes are extremely important but do require more space than was available in the present book and are treated extremely well elsewhere.[1]

A coastal basin, in the context of this book is a shallow system, i.e., typically less than 10 m (although possibly some tens of meters deep) forced by wind, waves, tide, river flow, and other types of buoyancy flux such as surface heating, cooling, and evaporation. Topography and bathymetry play a major role in the dynamics of a coastal basin. Individual basins may carry names such as Bay, Estuary, Lagoon, Sound, Gulf, etc. We shall cover the material relevant to environment studies that can be represented by comparatively simple models, which illustrate basic concepts.

Coastal basins differ from the deep ocean and continental shelf in many respects. One of the most important differences comes through the effect of astronomical tides. It is usual to refer to the astronomical tides as simply *tides*, and we shall often use that abbreviation. We need to be aware, however, that a *tide* really refers to a change in water level which may come from a variety of causes, including winds and changes in atmospheric pressure. All of these tides are important in coastal basins, but astronomical tides are usually (but not exclusively) the most important because they are always present. Tidal ranges in most of the world's oceans are in the order of 1 or 2 m. Occasionally we find tidal resonances that produce *macroscopic* tides of ranges up to 10 m, or *microscopic* tides which range a few tens of centimeters.

1.2 Geomorphic classification of ocean basins

Coastal basins have historically attracted human populations and associated harbor construction, especially since they often provide very low energy wave environments. Construction of coastal outfalls from industrial and sewage plants have followed human development, and the *built environment* has markedly changed the physical and ecological dynamics of many of these basins.

There are many hundreds of thousands of coastal basins in the world, ranging in size from tiny inlets to huge estuaries and coastal seas. We try to develop ideas that are applicable to whole ranges of basins, because we cannot expect to develop new ideas for each particular basin. Science always tries to generalize the dynamic behavior of systems, so that ideas are portable between systems. So, an estuary in China may be very similar to another in south-west Australia, and we attempt to construct a conceptual model that applies to both of these basins and very many others involving only very minor changes in the value of some parameters. Clearly, we cannot expect one conceptual model to apply to all basins, but we can expect one model to apply to basins that are in some sense *very similar*. Hence, we try to develop a *classification system*, so that we can divide all basins into categories and develop conceptual models of each category.

[1] For example: Fredsøe and Diehards (1992).

Unfortunately, there is no single classification system because coastal basins have so many different facets. We might, for example, just classify basins in terms of area: small, medium, and large, but that would not be very helpful because there are so many factors other than area that control the behavior of basins. So, we try to devise classification systems that are based on what we consider to be the important controlling factors for some particular type of behavior. The two simple systems are *geomorphic* and *stratification*. The geomorphic classification system is based on topography, geology, and sediment dynamics, while stratification refers to the existence of strata, or layers, of water with different density (and often having dissimilar sources such as different rivers or the open ocean).

There are various types of geomorphology. All present-day estuaries date from the end of the last ice age (about 20 000 years BP) when sea level had its last significant change, and most have been severely modified by secondary changes since that date. All estuaries are in a constant state of geomorphic change, and so their classification may alter with time. There are basically seven types of geomorphically distinct basins, and these are discussed in the sections below. Most coastal basins have features that fall within several of the classes which we list here. So the geomorphic classification of a basin is not unique, and most basins have characteristics of several classes of basins. The names which have historically been given to basins do not usually help in the classification system. Just as botanists use strict Latin names for plants and ignore their common names, we need to ignore the historical names for basins. So, whether a basin appears on a map as a *lagoon, bay, sound, inlet, gulf, estuary, strait, sea, river, channel*, or *passage*, or any local variant, should not influence our attempt to classify the basin.

1.2.1 Coastal plain (or drowned river valley) basins

These basins are due to the invasion of an existing river valley by rising sea levels. A good example is Sydney Harbour shown as Figure 1.1.

The boundaries of this type of coastal basin are essentially one of the height contours of the terrain that was flooded. The terrain around Sydney is hilly, with complex and convoluted height contours. This produces a coastline with the same type of characteristics, making the area one with an abundant supply of *waterfront property* along its many small creeks and inlets. The name *coastal plain* is accepted but not very accurate, since the flooded terrain may be far from the coastline that existed prior to flooding, so we prefer the term *flooded valley*.

1.2.2 Fjords

Flooded valleys cut by a glacier are given the name *fjord*. These valleys have a distinct sill near the mouth of the basin, and are now filled with marine water with a river running into the basin at its head. Fjords are generally deeper than the coastal basins

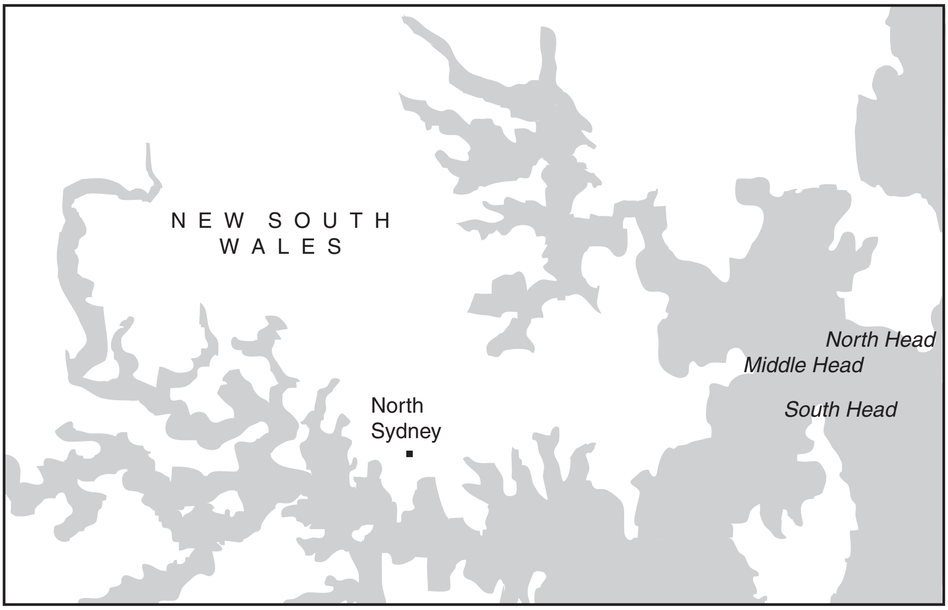

Figure 1.1 Sydney Harbour is a coastal plain estuary resulting from the rise of sea level at the end of the last ice age.

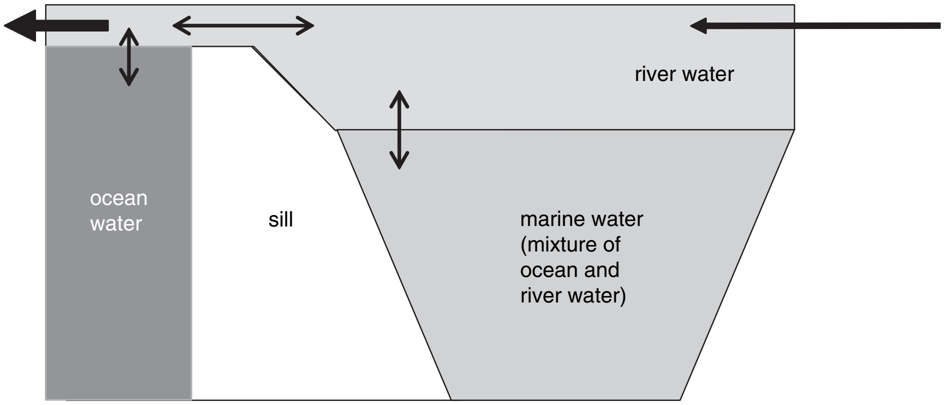

Figure 1.2 Schematic side view of a fjord.

which we consider in this book, and those depths have been created by the cutting action of the glacier (Figure 1.2).

The sill consists of debris carried by the glacier and dumped as the glacier melted into the ocean. Heavier marine water tends to be trapped at the bottom of the basin behind the sill. Similar sills are found acting as natural dams in mountain lakes. One occasionally finds sills in coastal basins that are not associated with glacial action, and these are termed *fjord-like* basins.

The sills again tend to trap ocean water at the bottom of the basin behind the sill. Usually the ocean water is brought into the basin by exceptionally high tides or by a storm event. The basin will then show a high degree of stratification, which inhibits vertical mixing. The usual sign of water that has been long trapped at the bottom of a basin is that it becomes hypoxic, i.e., the oxygen concentration is reduced well below the saturated concentration. This is a characteristic of stratified bottom water because the stratification greatly reduces the downward mixing of oxygen from the atmosphere, while the bottom water loses oxygen due to respiration by creatures and decaying bottom detritus. If the divide between the less dense surface water and denser deeper water (called the *pycnocline*) is close to the top of the sill, *internal waves* (waves along the pycnocline) can transport bottom water over the sill. Wind forcing can also be responsible for moving water over the sill. This is illustrated in Figure 1.2. It is basically an internal wind-driven tide that produces *upwelling* (upward movement of bottom water). If the basin is of uniform depth, the surface of the water is raised downwind by the action of the surface wind stress. This tends to produce a balance between wind stress and the pressure gradient produced by the surface elevation. Because the wind stress acts at the surface, it requires some mixing process to carry that stress down through the water column. In a rotating basin the penetration of the wind stress is limited by the Ekman layer. There is a water circulation downwind at the surface (wind driven) and a return upwind flow at the bottom driven by the pressure gradient.

1.2.3 Bar-built estuaries and inland lagoons

Shallow basins enclosed by a spit or bar are produced by littoral drift as in Figure 1.3. The basins are created by one or more rivers entering the coastal ocean and may have been wide open embayments at some time since the end of the last ice age.

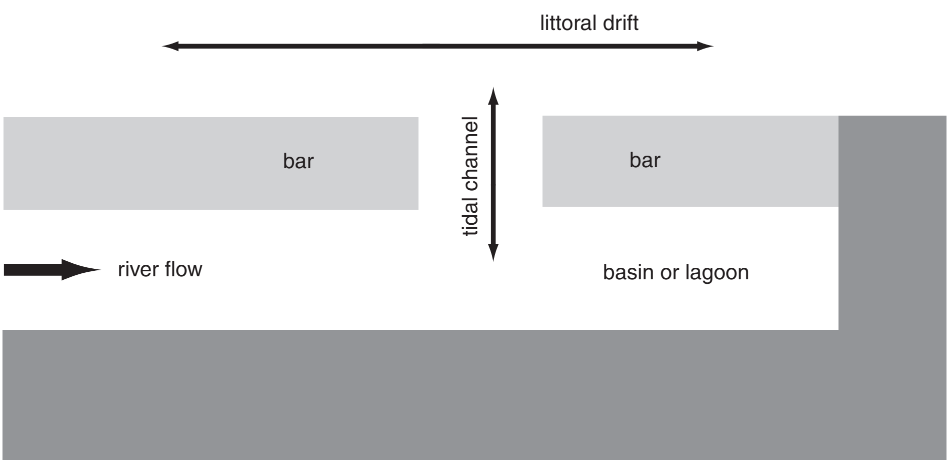

Figure 1.3 Schematic of a bar-built estuary or inland lagoon and tidal channel.

The size of the opening in the bar depends on flow of river (or other fresh water) or tidal flow, and in some cases the basin is closed except during floods. Bar-built basins are very common in regions having seasonal rainfall, so that there are months of limited precipitation in which the bar can form via *littoral* (alongshore) drift of sand along the coast. Most bar-built basins are very shallow (few meters) and have usually been formed by the retreat of sea level, as was common after its initial rise at the end of the last ice age. The opening in the bar usually carries strong tidal currents, with the size of this tidal channel contracting until tidal currents are strong enough to resuspend sand or larger-sized sediment ($0.15\,\mathrm{m\,s^{-1}}$ or higher). Other types of estuaries and lagoons may also have bars. The tidal channel usually restricts the magnitude of astronomical tides in the main part of the basin, because the channel itself requires a substantial pressure gradient to force the flow of water. This also creates a phase lag between the basin and the open ocean which can approach 90° in the limit of a very restrictive channel, so that the elevation of the water level in the basin is near zero at the times when the ocean elevation is maximal or minimal. Tidal channels can be very narrow and meandering, so that many *inland lagoons* are virtually hidden to an observer on the coastal ocean. Dutch explorers of the south-west coast of Australia in the late seventeenth century observed no river mouths.

1.2.4 Geological basins

Geological or tectonic basins are due to geological formations at the coast. The archetypal basin in this class is San Francisco Bay (Figure 1.4), which is associated with the San Andreas Fault. Such basins are often very elongated and also may have a bar and tidal channel, such as Tomales Bay (illustrated in Figure 2.3), and are the subject of many one-dimensional hydrodynamic models. Tomales Bay is just north of San Francisco Bay, but has very different dynamics. A common feature of such basins is the rapidly rising terrestrial topography either side, which can tend to direct wind stress along the basin. Similar structures exist inland (as we noted earlier in this section), for example, Loch Ness in Scotland. Loch Ness lies along the Great Glen Fault, and has additionally been carved to 200 m depth by glacial action.

1.2.5 Coral reefs and open-coast lagoons

Coral reefs are marine structures built by living coral that can create a limestone substrate that acts as a sub-tidal wave-break and barrier, behind which may form a lagoon. Such reefs may form around islands or along the continental margins. The hydrodynamics of water flow across reefs and through their lagoons has many unique features and properties that are familiar to other coastal basins. All coral reefs start as fringing reefs, because coral needs to be close to the water surface for sunlight. With changes in sea level these fringing reefs may move into deeper water and become

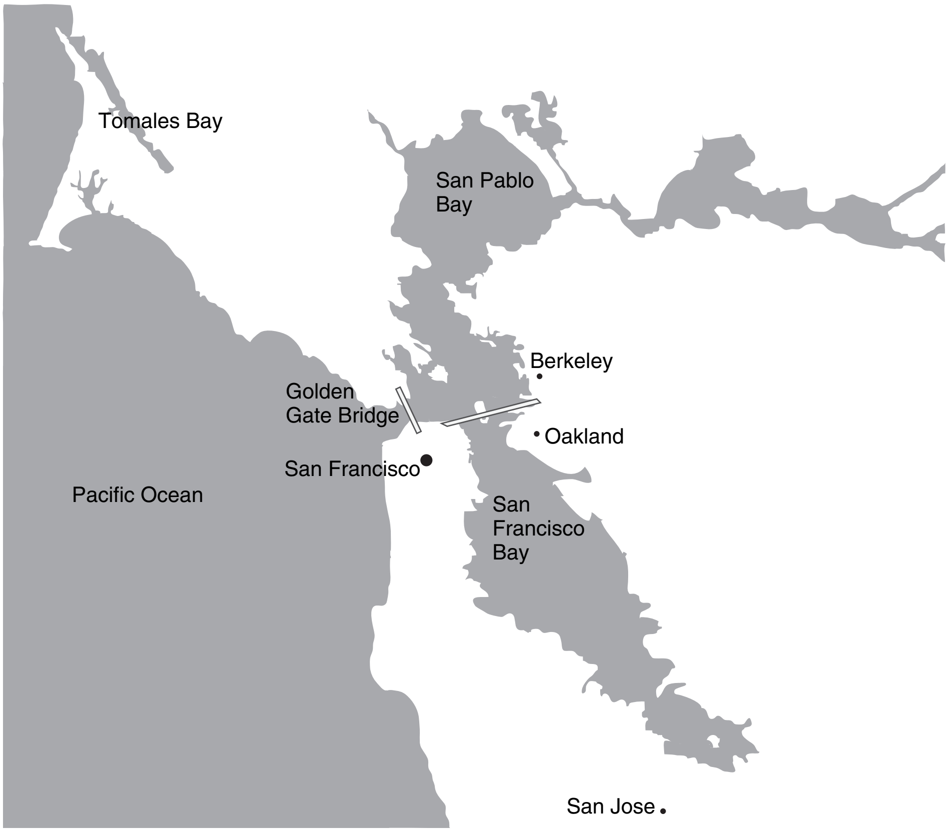

Figure 1.4 San Francisco Bay is a geological, or tectonic, basin with topography and bathymetry controlled by the San Andreas Fault. The city of San Francisco lies at the northern tip of the peninsula on the south-west side of the Bay. Notice Tomales Bay northward along the Californian coast.

barrier reefs, and possibly *atolls*. Most reefs have lagoons and most lagoons are very shallow, and either backed by land or other reefs. Water circulation in coral reef lagoons is often dominated by forcing due to breaking waves. We will consider some of these properties of coral reef lagoons and flow across coral reefs in Chapter 11. We have included the group *open-coastal lagoons* in the present class as distinct from lagoons in class 1.2.3. The intended distinction is that the lagoons in class 1.2.3 are separated from the open coast by a narrow channel. These are often called *inland lagoons*, despite the fact that they usually have a major marine component. Lagoons in the present class are on the open coast. The reef that forms the barrier around the lagoon is not necessarily a coral reef and may be, for example, a limestone reef formed by sea level rising over old sand dunes. Figures 1.5 and 1.6 show open-coast lagoons formed by a coral and limestone reef respectively.

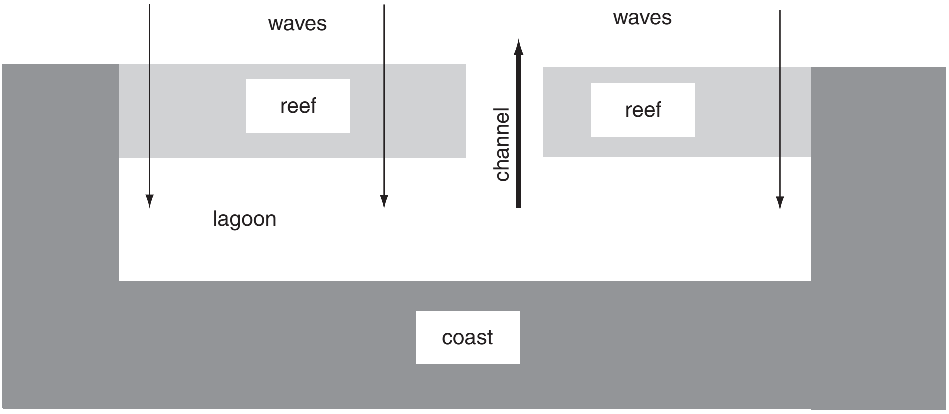

Figure 1.5 Schematic of a coastal basin formed by a fringing, or barrier, coral reef. The usual dynamic is that water is pumped across the reef by breaking waves and returns via a pressure gradient through a channel in the reef to the open ocean. Compare Kaneohe Bay discussed in Chapter 11.

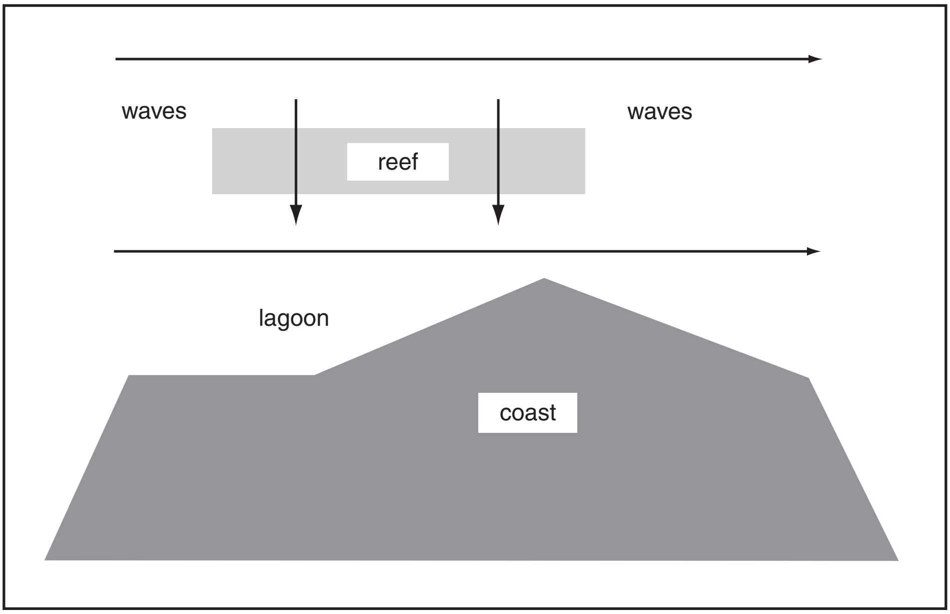

Figure 1.6 Schematic of the plan view of an open-coast lagoon. Such lagoons are often formed by limestone reefs. Dominant water flow is alongshore with some wave pumping across the reef. Compare Marmion Lagoon on the south-west coast of Australia. See Hatcher (1989).

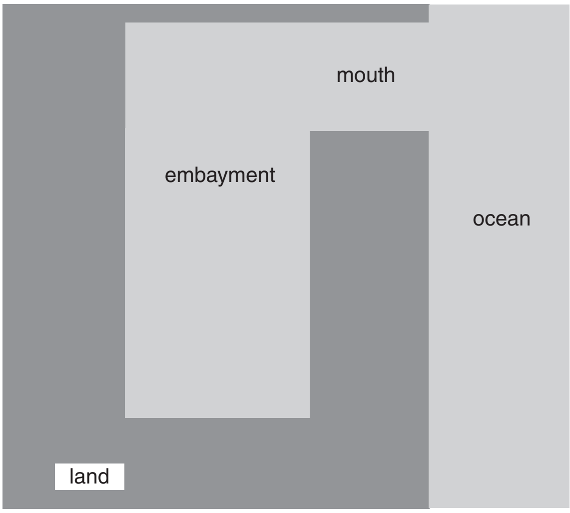

Figure 1.7 Schematic of a typical coastal embayment.

1.2.6 Coastal embayments

Open bays in the coastal ocean often form basins that are distinct from the coastal ocean. This is usually due to their topography (Figure 1.7). Water circulation inside embayments differs from that of the totally open coast, mainly through differences in tidal flow and regional coastal currents. As a result, coastal embayments usually show much more temperature and salinity variation than the open coast.

These embayments may be called Gulf, Sound, etc. Many embayments that have been produced by erosion since the rise in sea level at end of the last ice age can have many of the attributes of an estuary or lagoon, because fresh water flows into the bay and the exchange of water with the open shelf is slow.

1.2.7 Continental seas

These are essentially outside the scope of the present book but a part of our understanding of basin dynamics. They consist of enclosed, or partially enclosed, pieces of continental seas such as the Irish Sea, Baltic Sea, or Bass Strait. The distinction with most of the basins that we do consider in this book is mainly due to spatial scale, which is responsible for such processes as macrotides and high-energy wave conditions. In other ways they share many of the properties of coastal basins. For example, the Baltic Sea has lowered seasonal salinity due to freshwater runoff. The Baltic is on the outer limit of what we might reasonably call a coastal basin, but nevertheless shares some of their characteristics (albeit at much larger scale): it is strongly influenced by freshwater inflows, can freeze over, and also has comparatively limited entrances.

1.3 Distinctive features of coastal basins

1.3.1 Tidal currents

Tidal currents depend on the ratio of the astronomical tidal range to the water depth, which becomes large in coastal basins: typically 10% to 100%. This means that tidal currents are large. In some cases, parts of the continental shelf may well fall within our definition of a coastal basin, since tides may be macroscopic with ranges of up to 10 m. These currents have important effects on the movement of particles, and also on their horizontal dispersion and vertical mixing. Strong currents also erode the seabed and maintain sediments in suspension. The typical tidal range throughout the world's oceans is of order 1 m. In some oceans that may reach 2 to 3 m, but the range is rarely greater except on some continental shelves where we have *macrotides* due to resonance effect (which we discuss in Chapter 6). The tidal range may also drop to a fraction of a meter in regions close to what we call an *amphidrodal point*, but if we assume a range of 1 m that is correct to within a factor of perhaps five at the most. Only in very restricted coastal basins do we find tidal ranges (so called *microtides*) that are less than 20 cm. If there is a restriction in the width, currents are amplified accordingly. This is especially important in coastal basins where we find *tidal channels*, in which tidal currents can reach values only limited by the stability of the banks of the channel (typically 20 cm s^{-1} for sand, but reaching 1 to 2 m s^{-1} through rock or engineered surfaces such as armored walls). So, tides have a major influence on the dynamics of coastal basins, while in the deep ocean (and most continental shelves) they have minor effect. Most dynamical models of deep oceans are run quite independently of tides and indeed many are *rigid lid* models, i.e., the surface assumed fixed in time.

1.3.2 Wetting and drying

Wetting and drying of the shallow regions of coastal basins due to either tides or wind stress is a very important process for coastal models, and here lies a distinction from the deep ocean and most of the world's continental shelf; modelers talk of *fixed lid* models (for the deep ocean) and *variable surface* models for coastal basins. However, wetting and drying is not necessarily a major influence in all basins. This depends very much on the distribution of depth in the basin.

Figure 1.8 shows the depth distributions for some typical basins. The upper panel's depth (in meters) as a function of distance from the shore and the lower panels provide the corresponding histograms of basin area for each 1 m of depth. Basin (a) has steep sides and flat bottom over most of the basin. Basins of this type have often resulted from rivers cutting down through rock. Basin (b) has almost constant bottom slope and may have resulted from erosion through softer limestone whilst basin (c) has extensive shallows and a central deeper channel probably due to local sea level rise. The steep-sided basin has virtually no wetting and drying until water level drops below the bottom of the basin, while that with gently sloping sides may show a more gradual