2 Estuarine Geomorphology and Physical Oceanography

2.1 INTRODUCTION

To understand the processes affecting the distribution and cycles of particulates, pollutants, nutrients, and organisms in estuaries, it is insufficient to focus solely on the biological and chemical aspects of the processes. Equally important are the water movements and other hydrodynamic aspects of coastal systems, including circulation patterns, stratification, mixing and flushing, as well as a careful consideration of the time scales of these processes. When hydrodynamic changes occur quickly relative to biological, geological, and chemical transformations, they become the dominant controlling factors of many ecological processes in estuaries (Officer 1980), and it is now widely recognized that a thorough understanding of the marine ecology of estuaries requires a comprehensive knowledge and integration of the physical processes affecting the system. This chapter is aimed at organizing, classifying, and describing some of these important physical characteristics and processes. The terminology will be that of a shallow-water oceanographer and, hopefully, this chapter will encourage future marine ecologists to use physical terms more precisely and consistently than has sometimes been the case in the past.

2.2 GLACIATION CYCLES

Present-day estuaries are geologically ephemeral coastal features. They formed during the last interglacial stage as sea level rose 120 m from 15,000 years ago to

1By B. Kjerfve.
the present level, which was reached approximately 5000 years ago (Milliman and Emery 1968; Fig. 2.1.). Such glaciataion and deglaciation events have occurred regularly during the past few million years, causing shifts in the position of the coastlines worldwide. The locations of estuaries have shifted accordingly.

Presently, estuaries are common coastal features, constituting as much as 80-90% of the coasts along the east and Gulf coasts of North America, but as little as 10-20% along the United States’ Pacific coast (Emery 1967). Typically, estuaries are more abundant on coasts with broad flat continental margins than on coasts with narrow, steep continental margins (Schubel and Hirschberg 1978).

During glaciatic periods, a considerable fraction of the world’s oceans were frozen into continental glaciers, and sea level was much lower than now. Coastlines were then located on what is now the continental slope, and estuaries were both smaller and rarer. During interglacial periods, the glaciers melted, sea level rose worldwide, and estuaries became large and abundant (Schubel and Hirschberg 1978).

The present situation of high sea level and extensive estuaries has existed for only 10-20% of the time during the past million years, for once formed, estuaries quickly fill with sediments and essentially disappear. The sediment sources are river-borne terrestrial materials from the eroding continents and net up-estuary movement of sand-sized materials from the continental shelf (Meade 1969). From a geological viewpoint, the time scale of this infill is extremely short. Emery and Uchupi (1972) estimated that if sea level remained constant and all sediments were deposited into today’s U.S. estuaries, these would be filled within 9500 years, even if the load of the Mississippi River, which is half the nation’s total, was not counted. But all estuaries obviously do not infill at this
rapid rate, so that estuaries of various stages of geological development exist around the shorelines of the world (Schubel and Hirschberg 1978). One major reason is that the sea level has been rising for the past 10,000 years. Another is that coastal erosional forces remove sediments from estuaries.

2.3 FROM LAGOONS TO DELTAS

The type and rate of geologic development of estuaries depend not only on glacial cycles and local variabilities in sediment supply, but also on a combination of other factors including climatic variability, regional and local geology, and variability in marine energy inputs, particularly waves and tides impinging on the coast.

According to the scheme of Davies (1973), there is a continuum of estuarine types (Fig. 2.2). At one end of the spectrum exist lagoons produced by marine (wave) action, found typically behind a barrier, and characterized by sand-sized sediments. Good examples of this type of environment are the lagoons of the southern Texas and Mexican Gulf coasts (Lankford 1976). At the opposite end of the spectrum lie deltas. They are produced by river processes rather than by marine activities. They typically protrude into a receiving basin and are characterized by fine-grained silty sediments from terrestrial run off. In between lagoons and deltas lie estuarine lagoons, estuaries, and estuarine deltas, representing a mixture and gradation of the two extreme coastal environments. Presumably, a decrease in wave energy, coupled with an increase in river sediments, would shift a particular system from the lagoon extreme toward a delta.

![Figure 2.2](https://example.com/figure2.2) Schematic representation of the continuum of inlet types from lagoons to deltas (modified from Davies 1973).
extreme. Estuaries have probably shifted in such a fashion throughout geologic time as climates have changed.

2.4 DEFINITION

2.4.1 A New Definition

The existing definitions of estuaries are neither satisfying nor useful to the modern problems of estuarine ecologists or to the diversity of environments considered above. Thus I propose a new functional definition, one that I hope will be helpful to those who work with the spectrum of estuarine types, including lagoons, river mouths, and deltas. An estuarine system is a coastal indentation that has a restricted connection to the ocean and remains open at least intermittently. The estuarine system can be subdivided into three regions:

(a) A tidal river zone a fluvial zone characterized by lack of ocean salinity but subject to tidal rise and fall of sea level.

(b) A mixing zone (the estuary proper) characterized by water mass mixing and existence of strong gradients of physical, chemical, and biotic quantities reaching from the tidal river zone to the seaward location of a river-mouth bar or ebb-tidal delta.

(c) A nearshore turbid zone in the open ocean between the mixing zone and the seaward edge of the tidal plume at full ebb tide.

This definition differs considerably from those previously proposed in that it recognizes and includes a nearshore marine component, estuarine in character, which should be considered in the treatment of the physical or chemical dynamics, or ecology, of the estuarine system as a whole. Thus our definition of estuaries includes the adjacent coastal waters.

Dionne (1963) and Fairbridge (1980) chose to subdivide the mixing zone into an upper and lower region somewhat arbitrarily, and Hansen and Rattray (1965) subdivided the same zone into three dynamic regions. Such subdivisions can, of course, be made when the need arises, depending on the particular applications or local conditions.

2.4.2 Dynamic Boundaries

It should be recognized that the boundaries of the three zones listed above are dynamic. They will change positions continuously, on time scales from shorter than a tidal cycle, to annual cycles, to geologic time scales. The landward extent of the tidal river zone moves downriver with increasing fresh water discharge, and as the tidal amplitude changes from spring to neap tide. Similarly, the interface between the tidal river and mixing zones will oscillate over the tidal cycle and move seaward with increasing river runoff. The interface between the mix-
ing and nearshore zones changes much more slowly, since it is defined by the edge of the land, usually only on time scales longer than the seasonal cycle and most dramatically over thousands of years. A severe storm, however, could breach a barrier island or reef (see Hayes 1978) and thus dramatically relocate this interface overnight. The seaward boundary of the nearshore zone will change positions depending on the stage of the tide, river discharge, and prevailing oceanographic and meteorologic conditions.

In a given system, all zones may not be present. For example, lagoons in arid or semiarid coastal regions with a small tidal range may not exhibit a tidal river zone. An example of such a system is Cancun Bay, Mexico, on the Caribbean side of the Yucatan Peninsula. A given estuarine/lagoon system may not exhibit a mixing zone, as defined, if the river discharge is very large. In that case, the tidal river could border directly on the nearshore zone, so that fresh water leaves the river mouth with no mixing with salt water and the estuarine mixing processes would actually take place within the nearshore zone. Examples of such systems are the Amazon River (Gibbs 1970) and many large rivers at flood stage. Finally, the nearshore zone may be nonexistent in lagoons such as Cancun Bay, where the tidal range is small and there is lack of fresh water and sediment discharge. A particular estuary can in theory go through cycles so that the system alternately consists of one, two, or three of the defined zones on a seasonal basis.

2.4.3 Some Exceptions

Because an estuary is defined as "a coastal indentation," semi-enclosed inland seas such as the Baltic and the Mediterranean systems in their entirety are not included in the definition, nor are estuary-like systems that connect to large lakes rather than to an ocean (e.g., the Sea of Azov, which adjoins the Black Sea).

The large hypersaline (300 ppt) lagoons on the eastern shore of the Caspian Sea may be expected to exhibit processes similar to those operating in coastal lagoons (see Klenova 1968). Because these inland lagoons are emptied of water by severe wind action for half the year, the dynamics and ecology of the Caspian Sea systems are very different from the typical coastal lagoon. Some western Australia coastal salt flats/lagoons that flood probably behave similarly.

2.4.4 Water Balance

Pritchard (1952) proposed a classification of estuaries based on their water balance. He gives three classes: (a) positive estuaries, where the combined fresh water input from rivers, ground water, and rainfall exceeds evaporation; (b) neutral estuaries, with a balance between evaporation and freshwater input; and (c) negative or inverse estuaries, where the evaporation exceeds the combined freshwater input.

Most readers would think that "estuary" means what Pritchard calls a posi-
tive estuary, and that a coastal lagoon means a negative estuary. Depending on the hydrologic cycle, a system could change seasonally from being positive to negative or vice versa. The neutral estuary is not an important stage, but represents a temporal transition of a system between positive and negative stages.

Although it may at times be useful to think of coastal systems in terms of the water balance, this means of classifying an estuary is no longer in common use. With the exception of lagoons in arid or semiarid regions, most estuaries are positive. In fact, the traditional definition of an estuary (Cameron and Pritchard 1963; Pritchard 1967) as "a semi-enclosed coastal body of water with a free connection with the open sea within which sea water is measurably diluted by fresh water from land drainage" defines an estuary as a positive estuary. It certainly represents the estuarine system most commonly studied. It is, however, a much too restrictive definition in that it excludes negative estuaries, the tidal river, or nearshore zones. Using this definition, a system does not remain an estuary during high run-off conditions when the mixing zone disappears, as in the case of the Mississippi River flood or the Amazon River at all times.

2.5 GEOMORPHIC CLASSIFICATION

2.5.1 Estuarine Types

It is more useful to classify estuaries according to their geomorphology. Each geomorphic type exhibits at least a somewhat similar dynamic behavior in terms of water circulation and mixing. Estuaries can be divided into four main groups (Pritchard 1952b; Dyer 1973): (a) coastal plain estuaries, (b) lagoons (or bar-built estuaries), (c) fjords, and (d) tectonically caused estuaries.

2.5.2 Coastal Plain Estuaries: Classical

Coastal plain estuaries have been studied most extensively, because they are the most common type in regions where studies began. They formed during the last eustatic sea level rise, when river valleys became increasingly more flooded by the melting glaciers. Thus they exhibit the geomorphic characteristics of river channels and flood plains and are sometimes called "drowned river valley estuaries." The typical cross section of a classical coastal plain estuary consists of a V-shaped channel, seldom deeper than 20 m, bordered by broad shallow flats (Figs. 2.3 and 2.4). Coastal plain estuaries vary greatly in size up to that of the Chesapeake Bay, some 25 km long and on the average 25 km wide, the largest U. S. coastal plain estuary. Other good examples of large coastal plain estuaries are Delaware Bay and Charleston Harbor, South Carolina. Others have been described by Officer (1976) and Dyer (1973).
Figure 2.3 Examples of coastal plain estuaries: Winyah Bay and North Inlet, South Carolina. Winyah Bay is a classical coastal plain estuary, whereas the North Inlet system is a coastal plain salt-marsh estuary.

2.5.3 Coastal Plain Salt Marsh Estuaries

Another kind of coastal plain estuary, the salt marsh estuary or salt marsh creek, is found commonly along much of the U. S. East coast, particularly from Cape Fear, North Carolina to Cape Canaveral, Florida. It is characterized by the lack of a major river source but has a well-defined tidal drainage network, dendrit-
Figure 2.4 Cross-sectional profiles of an arbitrary coastal plain estuary, showing the same section in 50 times vertical exaggeration (top) and without any vertical exaggeration (bottom). Coastal plain estuaries have very wide and shallow cross sections. When these sections are presented with vertical exaggeration (which is most often the case), this gives a misleading impression.

...ically intersecting the extensive coastal salt marshes. These estuary-marsh systems are usually interconnected. Water and material exchange between the system and the coastal ocean occur through narrow, tidal inlets, which continuously change their configurations, sometimes dramatically, on time scales of less than 10 years (see Brunn 1978). Although these systems formed in a manner similar to lagoons, they have infilled to a much greater extent and now consist primarily of subaerial or intertidal salt marsh. The estuary proper consists of the drainage channels. These typically occupy less than 20% of the system area and resemble dynamically the classical coastal plain estuary. The size of the estuary is proportional to the size of the marsh drained. The typical cross section usually exhibits two deep channels separated by a shallow region. Channel depths seldom exceed 10 m, although it is known that localized, deep scour holes in excess of 25 m commonly occur at the junction of tidal creeks (Kjerfve et al. 1979).
2.5.4 Lagoons

Whether salt marsh estuaries are classified as "coastal plain estuaries" or "lagoons" is rather unimportant and certainly arbitrary. Lagoons, in my mind, exhibit a larger fractional area of open water compared with, for example, southeastern salt marsh estuaries. Whereas lagoons are oriented parallel to the coast, coastal plain estuaries are most often oriented normal to the coast (Fairbridge 1980) (Fig. 2.5). Lagoons have a less well-drained subaqueous drainage channel network and are uniformly shallow, often less than 2 m deep, over large expanses. The physical processes of lagoons are mostly wind-dominated, whereas diffuse fresh water inflow and tide tend to dominate salt marsh systems, at least in the southeast. Nevertheless, the origin of lagoons is similar to that of the southeastern salt marsh estuaries (Lankford 1976).

During the interglacial stage, 80,000 years ago, the Pleistocene shoreline stabilized some 6 m above the present mean sea level, leading to the formation of a narrow raised ridge system parallel to the coast. The ridge is most commonly a sand barrier, as in the case of Laguna de Terminos, Mexico, or a coral reef barrier, as in the case of the Belize barrier reef lagoon on the Caribbean side of the Yucatan Peninsula. Then, during the lowered level of the last glacial period, atmospheric and fluvial processes eroded much of that earlier coast. As sea level

![Diagram](image-url)  

**Figure 2.5** Example of a lagoon, Laguna de Terminos, Campeche, Mexico. Isobaths in meters are drawn and indicate that the lagoon for most parts is only 2 m deep (modified after Gierloeff-Emden 1977).
again rose to its present level, extensive areas behind the remnants of the raised ridge flooded, while marine and atmospheric processes maintained and re-shaped the barrier ridge (Lankford 1976). Sedimentation processes then caused the systems to infill differentially, and the estuary shapes were further modified by climate and vegetation.

True lagoons are common on all continents, and are far more prominent than the sparse literature implies. In North America, for example, they fringe the Gulf of Mexico and are abundant on the Pacific coast of Mexico. The physical characteristics and dynamics of a few have been described by Lankford (1976), Castanares and Phelger (1979), and Collier and Hedgepeth (1950). But, other studies of lagoons are rare; several have been studied in other countries: the Coorong in South Australia (Noye 1973, Noye and Walsh 1976); St. Lucia lagoon in South Africa (Orme 1974, Orme and Loehrer 1974); and those of southeastern Australia (Bird 1967).

2.5.5 Fjords: Classical

Fjords also owe their origin to the glaciation cycle. During the advance of continental glaciers, tongues of the leading ice edge scoured out many river valleys in latitudes above 45° (Fairbridge 1980; Dyer 1979). Where the ice edge reached its most seaward extent, on what was then a portion of the continents, a steep rock bar usually had formed seaward of the leading ice edge. It was there for two reasons. First, the ice had not yet been able to scour it away, in part because the ice began to float upon the salt water. Second, scoured material from the basin was pushed forward by the advancing glacier and deposited at the leading ice edge. When the glaciers retreated, the rock bar remained to provide spectacular relief at the seaward edge of the basin itself. Whereas the present water depth over the sill generally varies from 10 to 90 m, the depth of the interior fjord basin often exceeds 800 m. The overdeepened portion of the basin commonly extends several hundred kilometers inland. A further geomorphic characteristic of fjords and glacially carved inlets is their U-shaped cross-sectional form, due to the glacial scour.

Fjords and glacial inlets are common in both hemispheres where there has been glacial activity. They are particularly spectacular on coasts that serve as leading edges of tectonic plate margins, called subducted coasts. Good examples are the fjord inlets of southern Chile (Pickard 1971), Alaska, British Columbia (Fig. 2.6) (Pickard 1956), and New Zealand. Fjords also occur on the present or formerly glaciated coasts of Norway, Spitsbergen, Greenland, and Graham Land in Antarctica (Fairbridge 1980). A useful treatment of the oceanographic features of Norwegian fjords is that of Sælen (1967).

2.5.6 The Fjord-Like Fjärd

Closely related to fjords are fjärds (Swedish) or firths (Scottish). These occur commonly in southern Sweden, eastern Canada and New England, and Scot-
land, where the continental relief is less spectacular and the continental shelf more extensive compared with a subducted margin coast (Fairbridge 1980). Fjords or firths also formed as a result of glacier scour but do not exhibit the overdeepened basin or the U-shaped profile. Water depths are much shallower than for fjords, usually on the order of tens of meters. The shallow water depth, particularly in the case of Swedish fjärds, is due at least partially to the quick isostatic rebound of the continent, a response to the cessation of ice loading. This uplift rate has been measured as high as 15 m per 1000 years.

2.5.7 Tectonically Caused Estuaries

The fourth and final geomorphic classification category occurs on tectonically active coasts. These are the estuaries caused by faulting, graben formation, landslide, or volcanic eruption. The best and most extensively studied estuary in

Figure 2.6 Example of a fjord, the Gardner system in British Columbia, Canada (modified after Pickard 1956)
this group is San Francisco Bay (see Officer 1976; Conomos 1979). Tectonically caused estuaries exhibit much variability and different ones may behave oceanographically similarly to coastal plain estuaries, fjords, or lagoons, depending on the local constraints. In summary we see that estuaries are formed by specific physical processes. The extensive nature of estuaries today is due in large part to the extensive glaciation of 10,000 years ago.

2.6 CIRCULATION

2.6.1 Estuarine Circulation

Estuarine water circulation is a physical process that affects or controls many ecological processes. For example, the residence time of a given parcel of water in an estuary is a function of the circulation patterns, and the ratio of the residence time of the water to the biogeochemical turnover rate indicates the degree to which the hydrodynamics dominate or modify estuarine processes.

Thus computation of fluxes of dissolved constituents such as nutrients, pollutants, and salt, as well as of particulate materials such as sediments, detrital matter, and plankton, requires knowledge of the circulation. It is common to simulate estuarine physical processes with rather complex mathematical equations. But reasonable formulations for such equations usually can be achieved only after making several simplifying assumptions, and these assumptions depend very much on the assumptions we make about circulation. Very often the complexity of the real systems makes it difficult for us to produce realistic results from our simplified models. Also, the estuarine bathymetry is a function of the circulation, and in turn the circulation depends on the bathymetry (Kjerfve 1978). Thus care must be exercised in using estuarine hydrodynamic information. As will be shown, just because the circulation causes water to move in a certain direction does not necessarily mean that dissolved and particulate constituents will move in the same direction.

Estuarine circulation normally is defined as the residual water movement, meaning that short-term effects are averaged out. Because water motions occur on a continuum of time scales, it is critical to choose the appropriate time duration over which to estimate these residual currents. Thus our computations of circulation depend greatly on the averaging time scale used. As most of the current variability usually occurs with a tidal periodicity, the estuarine circulation is usually calculated as the residual water movement after the currents are averaged over one, two, or numerous complete tidal cycles. It is important to realize that the circulation can never be determined from a single set of instantaneous measurements, but represents a calculated quantity that requires systematic measurements over an extended time period for its determination (Kjerfve 1979).

The time-averaged currents that make up the circulation vary depending on location in the estuary and the particular depth at which an estimate is made. It
is common practice to refer to these time-averaged currents as net currents, tidal currents, tidal residuals, or nontidal flows.

2.6.2 Types of Estuarine Circulation

The energy that drives estuarine circulation is derived from either solar heating or gravitational attraction between the moon and sun, on the one hand, and the ocean waters on the other.

Solar heating differentials also cause wind, rainfall, and ocean water temperature differences. The rainfall, in particular, affects estuaries by the energy and mass associated with fresh water inflow from rivers, and these are major processes driving estuarine circulation. Estuarine circulation is also driven by wind stress on the estuarine water surface, a second major force driving estuarine processes.

Gravitational attraction on the sea by the moon and the sun is a third important process driving the estuarine circulation, which is responsible for the regular rise and fall of the tide and the more complex oscillatory water currents.

Although wind waves generated within the estuary or swells propagating into the estuary from the ocean could conceivably cause or alter circulation, such waves are normally not very important. But variability in the nearshore current structure has a modifying effect on the estuarine circulation and may drive the circulation in some cases, as will be discussed later.

Two other factors are important in determining the circulation—estuarine geometry and bathymetry (i.e., curvature and friction effects). Both effects are capable of modifying the circulation significantly, but they differ from the driving forces in that they are passive, that is, these factors alter the flow pattern only when currents already exist. Similarly both the existence of an ice cover on high-latitude estuaries and human activities in estuaries (e.g., dredging, channelization, damming, and diversion) can alter induced circulation patterns.

The three main driving forces are each responsible for a particular circulation type, respectively: (a) gravitational circulation (due to fresh water runoff), (b) tidal circulation, and (c) wind-driven circulation. Each type is discussed in more detail below. Although a given estuary usually is dominated by one circulation type, this may change temporarily. Also, two or all three circulation types could, in fact, be operating simultaneously in the same estuary. This makes for a situation difficult to interpret easily.

2.6.3 Gravitational Circulation

Circulation induced by density and elevation differences between fresh water runoff and salt water is called gravitational circulation. The less dense fresh water runoff has a tendency to remain primarily in the surface layer of an estuary (Fig. 2.7). The effect of tide and wind, however, is to mix the water column, causing a vertical exchange between fresher surface waters and saltier water from below. This mixing process explains the existence of longitudinal and verti-
Figure 2.7  Schematic representation of the net circulation in the mixing zone of a partially mixed estuary. Horizontal and vertical water volume exchanges are expressed in units of river flow R. Isopleths of salinity (isohalines) in parts per thousand are superimposed in the circulation, indicating the change of net salinity profiles (and thus stratification) from the tidal river zone to the nearshore zone (modified after Dyer 1979).

cal salinity and density gradients in the estuary. These may be reinterpreted in terms of time-averaged pressure gradients, which can be related directly to the gravitational circulation.

The pressure surfaces tilt seaward in the less dense surface layer, causing a net outflow. In the salty and dense bottom layer they tilt up-estuary, driving the flow landward. Somewhere in mid water column, the pressure surfaces become horizontal. A horizontal surface is called an equipotential surface and represents an arbitrary surface on which gravitational forces are constant. At the depth where the pressure surface becomes an equipotential surface, the net flow or circulation vanishes, that is, a level of no net motion, which for a given cross section may slope slightly across the section because of the earth's rotation (Pritchard 1952b and 1956) or a bend in the channel (Stewart 1957). The result is that the surface of such estuaries is characterized by net seaward flows and the bottom is characterized by landward flows.

The resulting circulation is called the "classical" estuarine gravitational circulation, and it has been described by Pritchard (1956), Pritchard and Kent (1956), and Dyer (1973), and has been represented in an elegant mathematical
solution by Rattray and Hansen (1962) and Hansen and Rattray (1965). Their "similarity solution" for the estuarine circulation still represents the state of the art of our theoretical understanding of the physical dynamics of estuaries.

Much more water takes part in the gravitational circulation than was introduced as fresh water runoff. For example, if the river discharge into the Chesapeake Bay estuary is R units (measured in m³/s), and the surface outflow at the mouth is 25 R units (Schubel and Pritchard 1972), there must be a net inflow and subsequent outflow of 24 R units (on the average) of water from the bottom layer of the adjacent ocean. This is a difficult concept to grasp, but has great ecological significance, relating to, for example, the computation of residence times and the reproductive patterns of fishes.

Although gravitational circulation in estuaries is related primarily to the salinity distribution, the temperature distribution can drive the circulation just as well under certain conditions. In shallow estuaries, salinity alone usually determines the water density (see Kjerfve 1979), because the fresh water inflow provides a source of less dense water that mixes with dense ocean water only slowly. Usually, there is no equally effective temperature source or sink which could create as large a density difference. An exception to this generality may be found in certain arctic or subarctic estuaries where chilly, and thus relatively dense, fresh water debouches into a less cold ocean. In this case, the temperature structure may be as important as the salinity in driving the gravitational circulation of the estuary. Pickard and Trites (1957) showed that a number of British Columbia inlets had this characteristic.

Similarly, temperature effects can be of importance in driving indirectional gravitational circulation in lagoons that receive little or no fresh water runoff. Heating by the sun of a shallow lagoon causes high evaporation and, therefore, superelevated salinities in interior lagoons with restricted passages to the ocean. Whereas the ocean salinity is 35ppt, lagoons commonly have salinities in excess of 90ppt (Noye 1973), and sometimes much higher. This is especially true during the summer in arid or semiarid regions. Collier and Hedgepeth (1950) suggested that this process sets up an inverse estuarine circulation, with oceanic inflows in a surface layer and outflow of denser salty lagoon waters in a bottom layer.

It is somewhat questionable whether this hypothesis actually reflects many estuaries. Lagoons are often very shallow, open, and exposed to the wind, and thus tend to be well mixed vertically by the wind. This mixing would inhibit the development of a two-layered vertical circulation, inverse or otherwise. Differences in time-averaged salinities would probably be manifested more often across the entrance to such systems rather than between incoming and outgoing waters. Thus winds, tides, and/or basin geometry are more important as driving or modifying factors in lagoon systems than is gravitational circulation.

It has been proposed that the Coriolis effect can modify the classical estuarine circulation (Pritchard 1952a). If this is true the surface net outflow would be stronger along the right side of an estuary in the Northern hemisphere, looking downstream. Similarly, the net bottom inflow would be strongest along the opposite side. It is rather questionable whether the Coriolis effect is generally sig-
significant in this respect. Channel curvature, bottom friction, or the flow of a major portion of the fresh water to one side of the estuary are probably of significantly greater importance.

2.6.4 Tidal Circulation

In the absence of density gradients and wind stress, the estuarine circulation is driven by tidal currents. This type of circulation often is referred to as tidal pumping. It may seem curious that tidal currents, which are largely oscillatory, produce a nontidal flow, but the tidal waves interact with the bathymetry in nonlinear, complex ways. Because the estuarine bathymetry varies, the interactions between tidal currents and bathymetry are seldom identical at two locations in an estuary. This is manifested by slight differences in the strength of maximum ebb and flood currents, and in the duration of ebbing and flooding tidal flows. The resultant spatial distribution of currents, both horizontally and with depth, is called the tidal circulation due to the tidal pumping.

Tidal circulation is particularly pronounced in estuaries with a shallow water depth and a large tidal range. Examples of such systems are North Inlet, South Carolina (Fig. 2.8) (Kjerfve and Proehl 1979) and the Bay of Fundy (Tee 1976). Tidal and gravitational circulations probably coexist in many systems, although this has received only scant attention. The salt-balance studies by Fischer (1972), Dyer (1974), and Murray et al. (1975) point to the likelihood of the simultaneous and equal importance of these two circulation mechanisms in many estuaries. In fact, in most shallow systems with a tidal range of approximately 2 m or greater and a moderate to high river inflow, neither tidal nor gravitational circulation can be ignored.

For tidal pumping to exist a nonlinear interaction between the tide and estuarine boundaries is required. This comes about because variable cross-sectional width, differences in water depth, existence of tidal flats, and channel curvature cause large spatial velocity gradients. The time-average tidal currents are often systematically ebb-directed on one side of an estuarine cross section and flood directed on the other (Kjerfve 1978; Kjerfve and Proehl 1979). The cause is the boundary interaction rather than the Coriolis effect. Oppositely directed net currents in a cross-section, that is, the existence of tidal pumping, does not imply a net loss or gain of water in the long term. Still, this circulation could on the average systematically export or import water-borne constituents.

The innermost basin of the Bay of Fundy on the Canadian Atlantic coast experiences the largest tidal range in the world, on the average approximately 12 m. Tee (1976) developed a numerical hydrodynamic model for the Minas Basin of the Bay of Fundy. The computer solutions showed that tidal pumping drives net currents and the circulation, explained by the importance of nonlinear inertial effects. Simulated net tidal currents were measured up to 0.76 m/s. The time-averaged tidal circulation manifested itself as large horizontal eddies with diameters on the order of 20 km—the width of the estuary. The sense of rotation
(i.e., cyclonic or anticyclonic) of these eddies was not attributed to the Coriolis effect but to particular coastal geometry (Tee 1976).

2.6.5 Wind-Driven Circulation

As implied previously, wind-driven circulation is thought to be particularly important in lagoons. Large expanses of open water, shallow water depths, a small tidal range, and low fresh water inflows are the conditions that favor dominance of wind-driven circulation. This type of circulation has not been studied well. First, it is often masked by gravitational and tidal circulations. Second, the wind is highly variable over a range of periods from minutes to weeks. A particularly
important wind variance component is associated with frontal passages, with periods typically from 3 to 9 days. The duration over which estuarine currents must be averaged to yield a picture of the wind-driven circulation is therefore very long, a multiple of the frontal passage cycle (see Weisberg 1976a, Weisberg and Sturges 1976) (Fig. 2.9). This usually makes it impractical and much too costly to measure.

There are several empirical studies, however, that point to a major response of the time-averaged estuarine flow to wind forcing. Weisberg (1976b) found that approximately 48% of the current variability in the Narragansett Bay was related to metereological variability on time scales longer than 2 days. Similarly, Cannon (1978) and Holbrook et al. (1980) showed that even deep currents in inlets and fjords are correlated well with meteorological events. Water surface slopes as large as $4 \times 10^{-5}$ radians (i.e., slopes of 0.4 m per 10 km distance) were attributed to 10 m/s wind forcing in a Louisiana bar-built estuary (Kjerfve 1973). and Smith (1977) found significant water exchange between Corpus Christi Bay, Texas and the Gulf of Mexico due to meteorological forcing. The wind tides of the Texas lagoons are well known (Collier and Hedgpeth 1950; Copeland et al. 1968). During winter northerns, water piles up in the south ends of the lagoons and a seiche (back and forth sloshing of the water) develops, having a period on the order of a few hours, or approximately equal to twice the length of the lagoon divided by the square root of the product of gravity and the average water depth. The ecological significance of these wind tides can be very large, as a minute change in water level could expose hundreds of square kilometers of mud flats or inundate an equally large area of coastal salt marshes and grass lands. These studies obviously do not provide the final answers to the dynamics of the wind-driven circulation, but at least indicate the likely importance of the wind as a mechanism driving the estuarine circulation. This becomes very

![Figure 2.9](image-url)  
**Figure 2.9** Schematic representation of the horizontal wind-driven circulation in a lagoon system (modified after Fischer et al. 1979).
obvious in shallow lagoons, but may be equally important in partially mixed estuaries such as Narragansett Bay or deep fjords.

Theoretical solutions of the hydrodynamic equations indicate that a steady, along-estuary wind stress will significantly augment the gravitational circulation (Rattray and Hansen 1962, Hansen and Rattray 1965) (Fig. 2.10). The effect of a down-estuary wind would be to increase the net surface ebb flow and at the same time increase the net inflow at depth. On the other hand, in the case of a steady wind blowing into the estuary, the resulting net surface current may be flood-directed, a midlayer would experience net ebb flow, and the net bottom-flow would be much reduced and flood-directed.

2.6.6 Circulation Modes

Traditionally most estuaries were thought to have a two-layered circulation with net outflow in the surface layer and net inflow in the bottom layer. There was, however, early evidence for the existence of significant deviations from this conceptual model. But the inconsistent data were initially not reported in the literature, for such periods of "nontraditional" circulation were thought of as being just "unusual events" (Pritchard 1978).

A recent study of the currents in the Potomac estuary, Virginia, put the classical two-layered estuarine circulation in a reasonable perspective. Elliott (1976) installed recording current meters at three depths on a vertical mooring for 1 year. After analysis of the data, Elliott defined six circulation modes (Fig. 2.11). These represent six separate states of the same partially mixed estuary:

2. Reverse circulation: surface inflow and bottom outflow.

![Figure 2.10 Schematic representation of the vertical gravitational circulation (heavy line) in a partially mixed estuary without wind stress. The dashed line represents the vertical circulation profile with the wind stress acting down-estuary with a magnitude of T. The other two lines represent the vertical net velocity profile with the wind stress acting up-estuary of magnitude T and 2T (modified after Rattray and Hansen 1962).](image-url)
Figure 2.11 Schematic representation of the six circulation modes found (Elliott 1976) to exist in a partially mixed estuary.

3. Three-layered circulation: surface and bottom inflow and outflow at middepth.

4. Reverse three-layered circulation: surface and bottom outflow and inflow at middepth.

5. Discharge circulation: outflow at all depths.


The most common of these circulation modes was the classical estuarine circulation. In the Potomac it occurred 43% of the time and lasted for an average of 2.5 days. The storage circulation occurred 22% of the time with an average duration of 1.6 days. Next followed reverse circulation for 21% of the time and with an average duration of 1.6 days; the reverse three-layered circulation for 7% of the time and an average of 1.5 days; discharge circulation for 6% of the time and an average duration of 1.3 days; and finally three-layered circulation for 1% of the time and an average duration of 1.0 day. Also, the classical estuarine circulation pattern is usually followed by either discharge or reverse circulation. Discharge circulation is most commonly followed by reverse circulation, which in turn is followed most often by the classical circulation mode.

Estuarine circulation is obviously not a simple matter. Estuaries are seldom in steady state, but rather exhibit complex temporal as well as spatial variabilities. Elliott's (1976) study focused on the vertical-longitudinal aspects of the circulation. Had lateral flow variabilities also been included in the analysis, still more complexity would undoubtedly have arisen. The detailed current measurements in an estuarine cross section by, for example, Kjerfve and Proehl (1979), indicate the great lateral variability that can exist in the flows.
2.6.7 Far-Field Effects

Several independent factors are believed to be responsible for altering the circulation from one mode to the next. Changing wind stress, variations in the river discharge, and the varying tidal range due to the fortnightly spring-neap cycle are all likely agents causing temporal changes in the circulation. Another less obvious factor is the influence that the behavior or "climate" of the coastal waters may have on the estuarine circulation, the slowly varying mean sea level at the location of the estuary, and the exchange of water and materials.

Coupling between the coastal ocean and the estuary occurs on many time scales. Estuarine tides, for example, are for the most part forced by ocean tides at the mouth. Similarly, the synoptic (large-scale) wind stress, acting on the coastal ocean surface, is often of far greater importance than the local wind stress on the estuarine water surface in imparting water accelerations. This is especially true in the case of narrow, branching, and winding estuaries.

The meteorological forcing of coastal and shelf waters by moving atmospheric pressure systems and wind-stress fields generates long waves that propagate along the coast. These can be either (1) Kelvin waves, (2) continental shelf waves, or (3) coastal trapped waves (Mysak and Hamon 1969, LeBlond and Mysak 1976, Gill 1982), each with their own characteristics (cf., Gill 1982). These long waves have periods from 2 to 15 days and wave lengths on the order of 1000 km. They travel parallel to the coast, on the continental shelf, at speeds from 0.1 to 1.0 m/s (Brooks and Mooers 1977). Their wave height decreases

![Water Level Graph](image)

Figure 2.12 Estuarine manifestation of nonlocal forcing is readily visible in a tidal record after appropriate smoothing. This year-long water-level time series from North Inlet, South Carolina was filtered to remove fluctuations with periods shorter than approximately 2 days (modified after Kjerfve et al. 1982).
exponentially away from the coast. The wave heights may be as great as 0.8 m at
the coastline and in estuaries (Kjerfve et al., 1982).

Long waves on the continental shelf are forced by either the synoptic meteorological conditions (i.e. wind and pressure) or what is known as "free-propagation," meaning that probably they were generated by a distant weather system. Long waves on the continental shelf are possibly the most dramatic, important, and commonly occurring form of far-field forced events in estuaries, although the estuarine sea level and possibly even the circulation may be influenced more by the wind-generated wave activity at the mouth of the estuary. For example, when high ocean waves of long period either break at or impinge on an estuarine entrance, wave momentum is radiated or transferred into the estuary. The result is a significantly raised estuarine water level compared with times of little or no oceanic wave action (Thomson and Hamon, 1979).

There are several ecological implications of these long-period estuarine events of nonlocal origin, for although they are most usually detected by analysis of tidal records, they produce significant low-frequency water flows and material transports. Tidal inundation of marshes and adjacent flats is considerably more extensive during the passage of a long wave crest compared with the passage of a trough for the same tidal conditions. Thus when one is making measurements of tidal transports or budgets, it is imperative to account for the nonlocal events with periods of a few days. Otherwise, the transport/budget estimates run the risk of being severely biased. Also, long waves produced on the shelf influence estuaries through long-periods of up-estuary-down-estuary oscillations of the turbidity maximum zone and the salinity fields.

2.7 ESTUARINE MIXING

2.7.1 Mixing Processes

Estuaries represent regions where salt water mixes with waters derived from land drainage. Mixing is the process whereby a water parcel or water mass is diluted by, or redistributed within, other water masses. The mixing process is either advective or dispersive. The distinction between the two is rather arbitrary, however, depending on the choice of an averaging time. Mixing on a longer time scale is called advection, and short-term mixing is called dispersion. The estuarine circulation movements are generally the most important mixing mechanism, but smaller-scale advective and dispersive processes may operate simultaneously and must be considered for the mixing to be characterized properly.

Water molecules from the ocean versus those from runoff sources cannot be differentiated easily. Thus it is usually impractical to determine mixing by use of isotopic ratios of stable and radioactive hydrogen or oxygen atoms within water molecules. Rather, the distribution in time and space of dissolved (and sometimes suspended) material in estuaries is used as a measure of the mixing. The dissolved substance can be naturally occurring (e.g., salt) or introduced for the
purpose of an investigation (e.g., dyes or radioisotopes). The estuarine salinity
distribution is the most commonly used indicator of mixing for three reasons: (1)
salinity is a conservative constituent, that is, the salt concentration essentially is
not altered by biogeochemical processes but only by mixing processes—dispersion
and advection—and, to a lesser degree, by local rainfall, evaporation, and
freezing; (2) most of the estuarine salt is derived from one source, the ocean
(though oceanic salinities are approximately 35 ppt, most land runoff has a
salinity less than 0.6 ppt); (3) salinity is easy and inexpensive to determine (see
Kjerfve 1979) and does not require great precision because of large temporal and
spatial salt gradients within most estuaries. However, in systems that receive
little fresh water runoff or that exhibit multiple ocean entrances, salinity is not a
good mixing indicator and it may be necessary to introduce a suitable tracer
substance to determine the mixing.

Dispersive mixing may be defined as the scattering of water parcels or parti-
cles dissolved in the estuary. It is due to the combined effect of several processes,
including (1) tidal sloshing, (2) shear effects, (3) eddy (or turbulent) diffusion,
(4) molecular diffusion, and (5) tidal trapping (or chopping). By the theoretical
decomposition of the flux of a dissolved constituent, Bowden (1963) showed how
the first four effects contribute to the dispersive mixing. The contribution of
trapping has been described by Pritchard (1969).

Diffusion within the water refers to the random scattering of water parcels or
particles by either random molecular or eddy (turbulent) motions. Molecular
diffusion is always several orders of magnitude less than eddy diffusion in estu-
aries and can be ignored. Bowden (1963) showed that eddy diffusion also is neg-
ligible in most estuarine situations, compared with the sloshing and shear ef-
fects, at least with respect to net dispersive mixing over one or more tidal cycles.
Sloshing, which refers to the time-averaged flux of particles by oscillatory tidal
currents, is usually the dominant longitudinal mixing process. When attempting
to determine the mass transport of a substance by time averaging the product of
estuarine velocity and particle concentration (meaning there is generally some
material left behind at one place or another), the integral seldom vanishes be-
cause of phase differences between current and concentration time representa-
tions (see Kjerfve 1975). Thus particles are systematically scattered or trans-
ported in one direction over a tidal cycle, causing longitudinal mixing by the
sloshing mechanism. The shear effect is mixing over a tidal cycle due to system-
atic covariations of velocity and particle concentration over the estuary. In other
words, shear results from different velocities of parallel currents. This can be in
three dimensions: (1) depth (vertical shear, Bowden 1963); (2) width (lateral
shear, Fischer et al. 1979); or (3) cross section (cross-sectional shear, Hansen
and Rattray 1965). It is an important mixing effect. Whereas vertical shear was
considered most important earlier, it is now clear that lateral shear is equally
important (Dyer 1974, Fischer 1976, Murray et al. 1975, Rattray and Dworski
1980). Finally, tidal trapping occurs when water is temporarily trapped within
shoreline indentations and branching channels. As the tidal current oscillates
past these shoreline features, the trapped water parcels and particles are re-
leased into the flow and replaced by new water and particles. The net effect is one of longitudinal dispersion (Okubo 1973, Fischer et al. 1979).

2.7.2 The Forces That Cause Mixing

The energy required to mix estuaries is derived from several sources: (1) tidal forcing; (2) wind stress; (3) wave motions other than tides; and (4) river runoff. All effects, of course, ultimately are driven by energy from solar heating or gravitational attractions, as was the case with respect to circulation.

Tidal forcing is usually the most important cause of mixing in estuaries. Interaction between tidal currents and estuarine boundaries generates turbulence and causes large-scale mixing such as tidal pumping (advective mixing) and dispersive effects (i.e., sloshing, shear, and trapping). Direct wind mixing is usually of lesser importance in estuaries unless the tidal range is small or the estuary consists of large open areas or is shallow, as in the case of many lagoons. The wind is usually responsible for the generation of surface waves, internal waves, basin seiches, and Langmuir wind rows/cells. Each of these wave types at times enhances mixing in estuaries significantly.

Finally, rivers represent a source of buoyancy and also cause mixing. The density difference between river and ocean drives the gravitational circulation, which is a form of advective mixing. Pressure gradients occur because of sloping isopycnals (usually isohalines) and control the direction of mean density-driven (baroclinic) flow, often resulting in the classical estuarine circulation pattern (i.e., gravitational circulation). The estuary is then mixed advectively by a net seaward surface-layer flow and a net landward flow in a bottom layer, and in some cases, by winds. In view of the previous discussion of circulation, this picture of estuarine behavior is obviously quite simplified. Sometimes lagoons and other shallow estuaries are mixed completely in the vertical direction by wind or bottom turbulence. Even in lagoons, though, the horizontal differences in density due to freshwater input can still drive an internal circulation and are thus instrumental in mixing.

The degree of mixing is by no means steady. The same estuary may at times mix quickly and completely because of a frontal passage or strong winds and at times slowly and incompletely because of lack of winds. Similarly, variations in tidal range have a profound effect on vertical mixing in the Chesapeake Bay (Haas 1977). During neap tides with a small tidal range, tidal energy is limited, and the water column becomes stratified vertically because of denser bottom waters and a less dense surface layer. This represents stable stratification and inhibits vertical mixing. During spring tides, the tidal range and maximum currents are increased, and a sufficient level of tidal energy is available to break down the vertical density stratification. The result is an enhancement of vertical mixing, allowing nutrients and food particles in the bottom layer to mix up into the photic surface zone and enhance production and, in addition, force oxygen-rich surface waters to the bottom, replenishing oxygen. Thus Chesapeake Bay and similar estuaries can be expected to alternate between being stratified (lim-
ITED vertical mixing) and well-mixed (effective vertical exchange) on the fortnightly spring-neap tide cycle (Haas 1977).

2.7.3 Mixing Diagrams

As a dissolved or suspended constituent is transported into an estuarine region, it is subjected to advective and dispersive mixing processes as well as changes in salinity. The end result is often that various constituents will settle out within the estuary, making the system act as a material sink. This is largely the case with fine-grained sediments from river sources as well as sand-sized sediments from the coastal ocean (Meade 1969). Thus an important question to ask is whether a dissolved or suspended constituent mixes conservatively within the estuary versus whether it is added to or subtracted from the water column. It would mix conservatively if the material concentration changes proportionately to the change in salinity. Salinity is a conservative constituent, and if a material concentration is plotted linearly against salinity, it too would be conservative. Such a plot of salinity against a material concentration is referred to as a mixing diagram. Systematic deviation of a measured estuarine concentration from a straight line in a mixing diagram is interpreted to imply nonconservative behavior of the constituent. This would then usually imply that the estuary is a sink or a source for a given constituent.

However, extreme care must be exercised in using a mixing diagram. The transformation from distance along the estuary to salinity assumes (1) one-dimensional (longitudinal) mixing; (2) quasi steady state; and (3) that all data are averaged over one or more complete tidal cycles (Officer 1979; Officer and Lynch 1981; Loder and Reichard 1981). These assumptions are seldom met in the strict sense and thus deviations from a straight line in a mixing diagram may not necessarily mean non-conservative behavior. In particular, it is well known (Loder and Reichard 1981; Officer and Lynch 1981) that temporal variations in either the riverine or oceanic material concentrations can cause non-linear mixing curves in spite of a constituent behaving conservatively. Corrections can be made, with difficulty, for this problem if sufficient data are available. The idea of mixing diagrams is developed further in Chapter 3, which also contains some examples in the figure.

2.7.4 Dynamic Classification

Rather than classifying estuaries according to geomorphic characteristics, Pritchard (1955) proposed a useful classification scheme based on circulation and stratification. The three basic estuarine types are A (highly stratified), B (partially mixed), and C (well mixed). The C type may be subdivided into C1 (vertically homogeneous with laterally reversing net flow) and C2 (vertically and laterally homogeneous).

The highly stratified type A estuary is exemplified by the lower Mississippi River. The density (or salinity) stratification is extremely sharp, so that pure
fresh and pure salt water are virtually adjacent, and vertical salt exchange occurs as a function of the breaking of internal waves along the mid-depth pycnocline. The type A estuary usually exhibits a low tidal range, which cannot break down the vertical stratification, and a moderate to great amount of fresh water input.

The partially mixed estuary, type B, is exemplified by the Chesapeake Bay estuarine system. The vertical salt gradient has the shape of the cotangent curve with time-averaged salinity differences from 2–10 ppt between surface and bottom waters. The classical estuarine circulation (i.e., a well-developed gravitational circulation), would be typical for the type B system, which for the most part would be a coastal plain estuary or a fjärd or shallow fjord system. These systems are characterized by a moderate to large tidal range and moderate fresh water inflow.

The well-mixed estuary, finally, is exemplified by North Inlet, South Carolina. Tidal mixing is intense because of a large tidal range and little fresh water influx. Accordingly, there are no vertical density (or salinity) gradients. The net circulation is either everywhere seaward (C2), or with one side flowing in and the other side flowing seaward in cross section. In the latter case, tidal pumping is the dominant circulation mode.

Pritchard (1955) suggested further that in managing estuaries, it would be possible to change the circulation and mixing characteristics of a particular estuary from A toward C or from C toward A. By dredging an estuary and thus making it deeper, the estuary can be expected to alter its characteristics from A to B or B to C. Similarly, by widening a channel, the characteristics of that section can be expected to change toward a B or a C type if all other parameters are held constant. The damming of rivers leading into an estuary can likewise change the estuarine dynamics because of the change in buoyant mixing. The greater the discharge, the more likely is the A-type estuary because of a well-developed vertical stratification. With decreasing river input the type A may become a type B, and the type B a type C.

### 2.7.5 Circulation—Stratification Diagram

Hansen and Rattray (1965) proposed an improvement on the dynamical classification of estuaries by a dimensionless circulation—stratification diagram (Fig. 2.13). By plotting a stratification parameter versus a circulation parameter, they managed to describe a continuum of estuaries and show how a given estuary may change over a season.

The stratification parameter is simply the ratio of the salinity difference between bottom and surface layers and the depth-averaged salinity. Each of these salinities are first averaged over one or more complete tidal cycles. The circulation parameter is likewise a ratio between the net surface flow and the fresh water flow. The net surface flow is taken as a representative value across an estuarine section to smooth out lateral effects and with the assumption of a steady state. Thus changes in water level from beginning to end of a tidal cycle
are averaged out. The fresh water flow is simply the steady fresh water discharge divided by the cross-sectional area.

Hansen and Rattray (1965) found that most estuaries could be grouped into four regions on their diagram. Class 1 estuaries are either lagoons or bar-built estuaries. Class 1a is vertically mixed and includes North Inlet, whereas 1b exhibits more of a vertical stratification. Both, however, have a total lack of gravitational circulation. Upstream salt mixing takes place by longitudinal dispersion mechanisms alone. Most estuaries studied fall into class 2, which overlaps with coastal plain and partially mixed estuaries. Again, this type was subdivided into a well-mixed (2a) and a weakly stratified (2b) subclass. This class is characterized by a reasonably well-developed gravitational circulation and longitudinal mixing by both dispersive and advective mechanisms.

Class 3 estuaries, on the other hand, are dominated by advective mixing processes, with dispersive effects playing a negligible role. Most systems in this class show moderate to strong stratification and are further characterized by a well-developed gravitational circulation. This class includes most fjord and some fjärd estuaries and a number of estuarine straits.
Class 4 estuaries, finally, coincide with Pritchard's (1955) type A, the strongly stratified system. Vertical mixing is limited and the gravitational circulation is weak or nonexistent.

Hansen's and Rattray's (1965) classification represents an improvement over previous classification schemes in that it allows a direct comparison of estuarine dynamics and mixing processes between systems. This, in turn, makes it possible to generalize to some degree about different estuaries. With this basic background in the physics of estuaries it is now possible to consider the chemistry and biology of estuaries, which are very much influenced by these basic physical properties.

REFERENCES


Dionne, J.C., 1963. Towards a more adequate definition of the St. Lawrence estuary. Z. Geomorphol., 7:36-44.


ESTUARINE ECOLOGY

JOHN W. DAY, JR.
Louisiana State University
Baton Rouge, Louisiana

CHARLES A. S. HALL
State University of New York
Syracuse, New York

W. MICHAEL KEMP
University of Maryland
Cambridge, Maryland

ALEJANDRO YÁÑEZ-ARANCIBIA
Universidad Nacional Autónoma de México
México D.F., México

1989

WILEY

A WILEY-INTERSCIENCE PUBLICATION
JOHN WILEY & SONS
New York • Chichester • Brisbane • Toronto • Singapore