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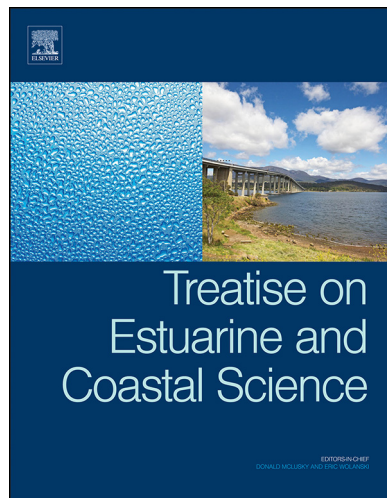
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1.07 Ecosystem and Biotic Classifications of Estuaries and Coasts

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Abstract

Numerous publications are available covering specific aspects around the classification of estuaries and coasts but very few have attempted a global review of the topic. In this treatise, we synthesize the available information on definitions and classifications of estuaries and coasts, as well as the occurrence and significance of major coastal habitats from around the world. We also examine the origins of estuaries and project into the future to indicate how climate change may affect the classification of individual estuaries and coastal systems.

1.07.1 Introduction

Numerous scientific papers and book chapters have dealt with definitions and classifications of estuaries and coasts in different parts of the world. However, most of these works have tended to focus on those systems in particular regions or hemispheres, with only a few having attempted to adopt a global perspective. There is widespread acceptance that diverse aquatic environments exist between the land and sea and that these transitional waters (TWs) are influenced by both end members of the continuum. This chapter aims to describe and discuss the types of habitats within that continuum and to present an overview of definitions and classifications for these ecosystems that will be useful to scientists and managers.

In broad terms, an estuary is where the flow of the river meets the flood of the tide. As will be described in more detail later on, the transition zone between inland freshwater and coastal marine ecosystems retains some characteristics of both freshwater and the sea ([Figure 1](#)), and it also has unique

properties all of its own and so should be regarded as an ecosystem in its own right, rather than merely an ecotone, the merging of two adjacent systems.

There are a number of processes that occur in estuaries but are absent from either river or marine ecosystems. [Reid and Wood \(1976\)](#) suggested that there are three main factors involved:

- Usually there are two opposing current systems that vary according to relative magnitudes of river flow and tidal regime. These water currents exert considerable effects upon sedimentation, water mixing, and other physical features within an estuary.
- The mixing of sea- and freshwater produces a chemical environment, represented mainly by salinity change, unlike that of either the marine or river ecosystem.
- The changing salinities in association with tidal and riverine movements necessitate physiological adjustment by all inhabitants of the estuary.

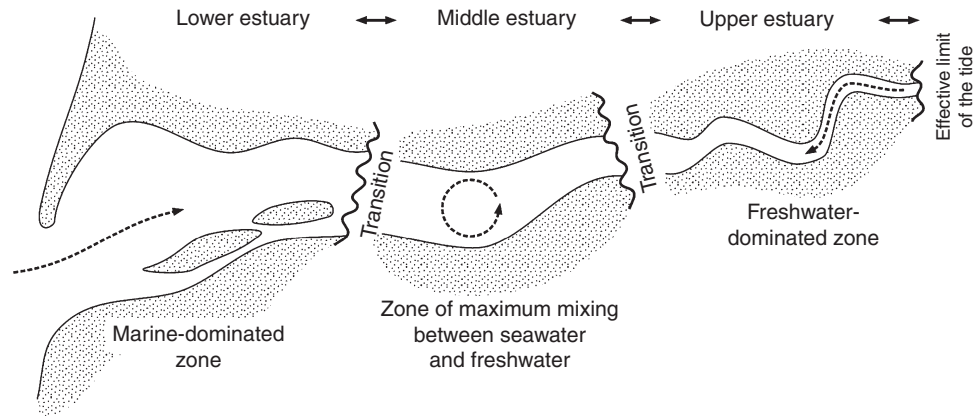


Figure 1 Diagrammatic representation of a 'standard' estuary. Modified from Perillo, G.M.E., Piccolo, M.C., Pino Quivira, M., 1999. What do we know about the geomorphology and physical oceanography of South American estuaries? In: Perillo, G.M.E., Piccolo, M.C., Pino Quivira, M. (Eds.), *Estuaries of South America: Their Geomorphology and Dynamics*. Springer Verlag, Berlin, Germany, 223 pp.

Thus, estuaries are characterized by a 'buffer zone' sharing some characteristics of both the river and sea, but identical to neither (Reid and Wood, 1976). In a similar vein, Carter (1988) identified an estuary as being a 'hybrid' environment incorporating terrestrial and marine as well as lake and ocean dynamics – although this downplays the importance of these transitional habitats as well-defined ecosystems. This concept has been taken further by Attrill and Rundle (2002), who suggest that estuaries are a combination of two ecotones, the river-brackish area and the sea – brackish area. Other authors (e.g., Greenwood, 2007) have suggested that the biota in an estuary represent an ecocline, where riverine or freshwater species are confined to either the head or extreme upper reaches of the estuary, with estuarine and marine species forming a cline between the head and mouth region of the system. However, there is broad consensus that the ends of an estuary represent ecotones (e.g., Winemiller and Leslie, 1992; Able, 2005), which are areas of rapid ecological change between the river and estuary and the estuary and sea.

Although the most important features of estuaries are (1) physicochemical variability (much greater than in any other aquatic system) and (2) the presence of gradients/ecotones/ecoclines, there are many estuaries where these features do not apply for much of the time. For example, temporarily closed estuaries may be cut off from the sea for long periods and stable conditions usually prevail during this phase. In contrast, some systems (e.g., river mouths) exhibit an abrupt change at the river–estuary and/or estuary–marine interfaces, thus not conforming to the gradient or ecotone concept.

Despite the above exceptions to the rule, conditions in estuaries are more variable than those in either the freshwater or the coastal marine environment. This variation is primarily associated with the salinity of the water that increases horizontally from virtually zero in the river to coastal water salinities that are usually in the range 30–35. The salinity of the water may vary vertically and horizontally, depending on estuarine morphometry, river flow, and tidal regime. In larger systems, the hydrographic conditions will even be influenced by Coriolis force in which waters get diverted to the right in the direction of flow in the Northern Hemisphere and to the left in the Southern Hemisphere (Dyer, 1997).

Seasonal and/or annual changes in river flow introduce another timescale of salinity variation that affects the estuarine fauna and flora. To survive in such a variable environment, organisms have developed various mechanisms to withstand the osmotic stress imposed by salinity changes. Aquatic biota that cannot adapt to these fluctuations simply cannot survive within the estuarine environment (Ketchum, 1983). In some parts of the world, evaporation from the surface of enclosed coastal water bodies (with or without a free connection to the sea) may exceed local surface precipitation and the runoff from land drainage. This often leads to the development of hyperhaline conditions, which place additional stress on even euryhaline organisms living within these systems (Whitfield et al., 2006).

Estuarine morphometry is highly variable but can often be very similar on a regional basis. For example, fjords are common along the Norwegian, Alaskan, and Chilean coasts, whereas in the Mediterranean region estuaries are typically triangular in shape, broadening from the river valley toward the mouth (Reid and Wood, 1976). Furthermore, wave action on the Mediterranean coast is limited and the estuaries are microtidal (Figure 2). Along many coasts of the British Isles, however, estuaries also broaden toward the mouth but are not constrained by spits or berms. This morphology is associated with moderate wave action and a considerable tidal range (Figure 2) that scours the estuary channels. In contrast, estuaries in some other parts of the world (e.g., South Africa) may experience heavy wave action (Figure 3) but have a limited tidal range (Figure 2). Sand bars develop in the mouths of these systems, causing the water to spread out behind the berm to form estuarine lakes and lagoons.

Estuaries along the coasts of temperate and subtropical North America also deviate to varying degrees from the 'classical' form. From New England southward many estuaries have been deprived of a direct entrance into the sea by the formation of barrier beaches. Similarly, estuaries in other parts of the world have offshore barrier island systems that result in estuarine embayments between the estuary mouth and the offshore islands (e.g., Dutch Wadden Sea in Europe and Morton Bay in Australia).

Apart from estuaries and coasts being subject to different marine wave action, there are also different tidal regimes that

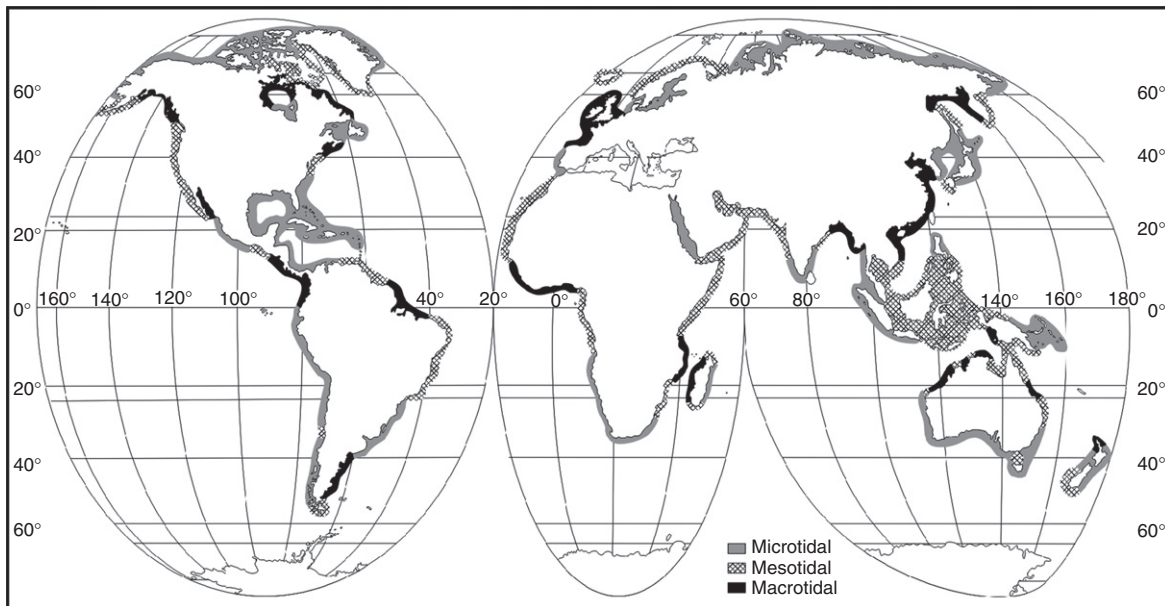


Figure 2 Microtidal, mesotidal, and macrotidal coastal regions of the world. Modified from Perillo, G.M.E., Piccolo, M.C., Pino Quivira, M., 1999. What do we know about the geomorphology and physical oceanography of South American estuaries? In: Perillo, G.M.E., Piccolo, M.C., Pino Quivira, M. (Eds.), *Estuaries of South America: Their Geomorphology and Dynamics*. Springer Verlag, Berlin, Germany, 223 pp.

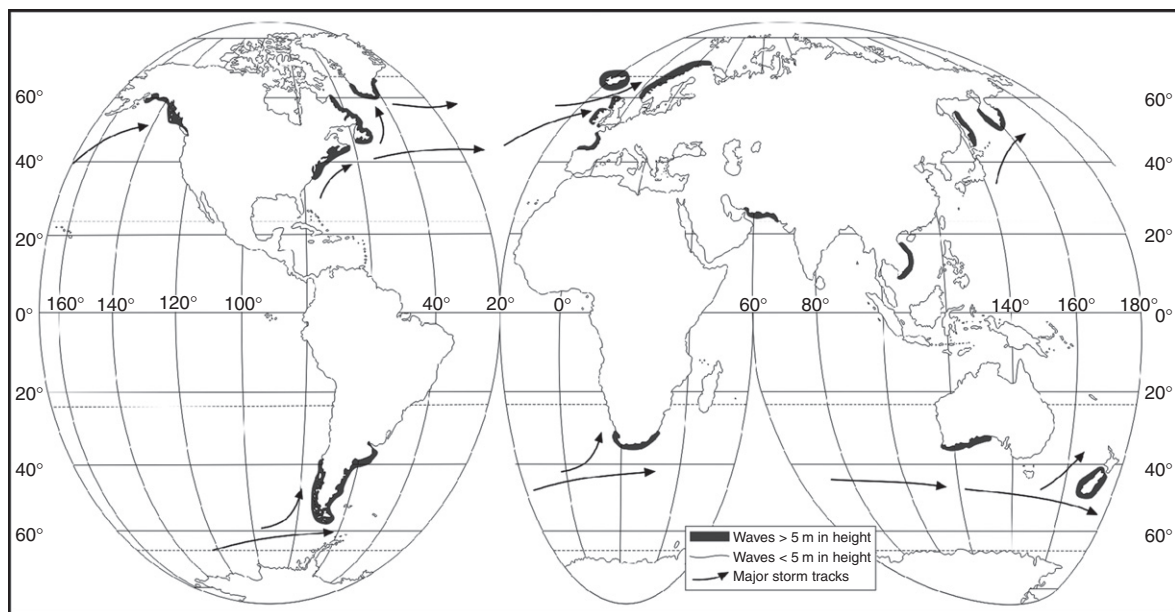


Figure 3 Map showing coasts experiencing >5 m high waves that are usually generated by stormy seas. Modified from Briggs, D., Smithson, P., Addison, K., Atkinson, K. 1997. *Fundamental of the Physical Environment*. Routledge, London, 557 pp.

influence the functioning of these ecosystems (Figure 4). This is a significant factor for certain estuarine and marine biotic components whose behavior is tightly linked to tidal conditions.

In parts of the world where glaciers or ice sheets had major impacts in the past (e.g., Norway, Alaska, and southern Chile), steep headlands and deep U-shaped valleys give rise to estuarine fjords that are strongly influenced by tidal action (Reid and Wood, 1976). However, fjords are also characterized by the

presence of a sill at their mouth, which constricts estuarine mixing in the deeper basin within these systems. From the above it becomes apparent that estuarine water exchange is influenced by both tidal regime and estuarine morphometry that will, in turn, impact on the processes that occur within the ecosystem.

In his classification of coastal environments, Clark (1978) separated the coastal zone into shorelands and coastal waters. The terrestrial coast was divided into the following ecosystem

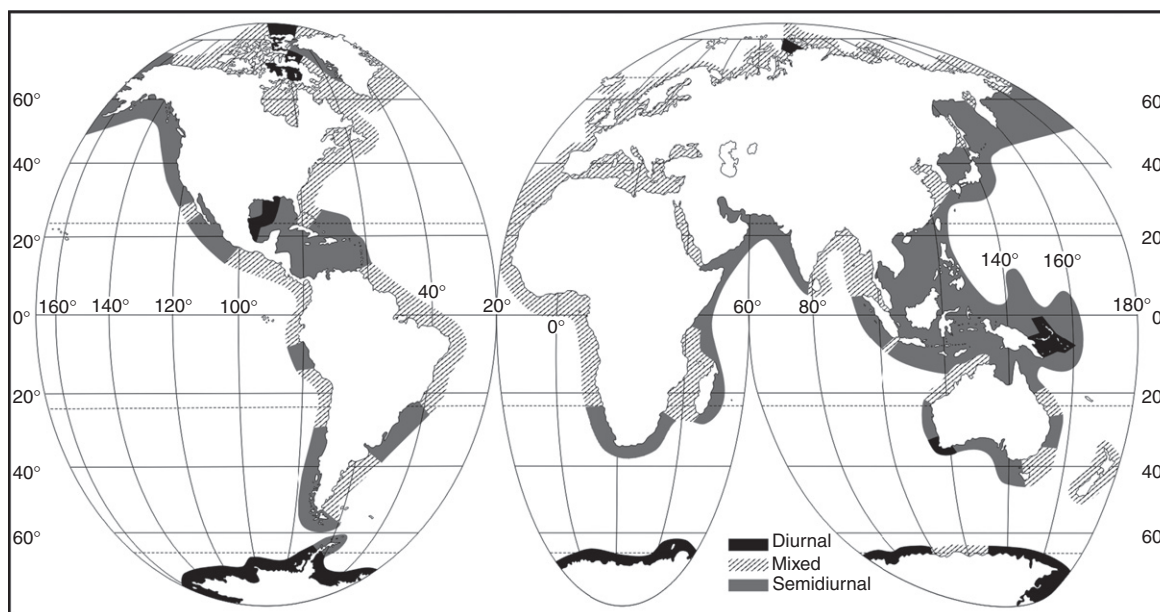


Figure 4 The distribution of tidal cycles in coastal areas around the world. Modified from Briggs, D., Smithson, P., Addison, K., Atkinson, K. 1997. *Fundamental of the Physical Environment*. Routledge, London, 557 pp.

types: watershed, floodplain, wetland, shoreland, dune, and beachfront. Coastal waters were subcategorized into estuarine bay, embayment, lagoon, nearshore, and oceanic regimes. In contrast to the above approach, this chapter will focus only on aquatic coastal ecosystems with a marine or estuarine influence, that is, the more terrestrial (e.g., dunes), freshwater (e.g., wetland), and oceanic (e.g., upwelling) categories are excluded from this analysis.

1.07.2 Origins of Present-Day Estuaries and Coasts

Estuaries are common coastal features today but were probably rarer during much of the Earth's geological life, for example, when the coastline of the Pangea was relatively smaller in relation to the landmass. Evidence exists, however, that the estuarine environment has been widespread around the world for at least 200 million years. The origins of estuaries are controlled mainly by the erosion of river valleys and the inundation of the coastal section of these valleys caused by eustatic sea-level changes that are driven primarily by global climatic variations. During the Pleistocene, climatic conditions fluctuated markedly and continental glaciations and deglaciations occurred repeatedly, with corresponding sea-level variations often exceeding 100 m. Estuaries were most abundant and extensive during warm, interglacial periods when continental ice masses receded and global sea level rose, leading to flooded river valleys and continental margins (Kennish, 1976). Conversely, estuaries were smaller and rarer during glacial episodes, which were characterized by receding sea levels and very active valley erosion within the coastal zone.

Individual estuaries are regarded as being generally ephemeral (geologically) and dependent on sea-level changes, isostatic adjustment of continents, and sedimentation rates. On a geological timescale, most estuaries persist for only a

few thousands to a few tens of thousands of years, although it can be argued that with changing sea levels they merely migrate inland (as long as they are not constrained by natural or anthropogenic structures) or seaward. A decline or rise in sea level will completely change the shape and nature of an estuary, especially if these water-level changes coincide with major alterations in coastal geomorphometry and river water supply. Under conditions of a relatively constant sea level and large sediment supply, estuaries will fill rapidly and be converted into swamps, marshes, and ultimately land. Bar-built estuaries, such as estuarine lakes and lagoons, are especially vulnerable to sediment infilling because of their extreme shallowness and shelter from hydraulic scouring (Kennish, 1976).

When a shoreline is submerged, coastal processes of erosion, transport, and deposition immediately begin to modify the topography of the adjacent regions, including newly created estuaries. The deposition of sediments by rivers as they meet the newly created estuary initiates the building of a delta in the upper reaches. Continued building by sedimentation gives rise to broad mud and silt deposits, which eventually become tidal flats. Meanwhile, water currents and tidal action of the sea continue their erosional processes in the channel and deposition of sedimentary material at the seaward end of the estuary. These deposits may develop as bars and spits in various positions relative to the estuary mouth (Reid and Wood, 1976).

The extent of a newly formed estuary also depends on local and regional tectonic movements that result in changes in sea level relative to the land. For example, in northwest Europe, isostatic adjustment following the end of the last ice age has resulted in Scandinavia and Scotland rising and southeast England and parts of Germany and the Netherlands sinking. With a relative sea-level rise, due to this isostatic adjustment and global climate change, this will result in 'coastal squeeze' in which the overall extent of intertidal areas will decrease. The widespread occurrence of tectonic movements makes it

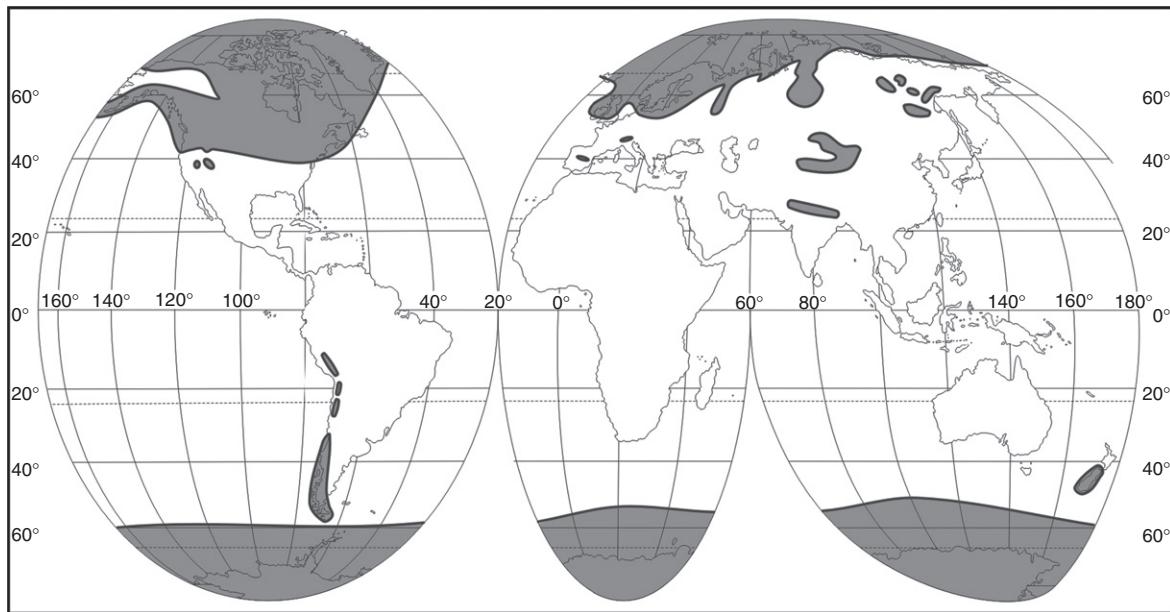


Figure 5 Area covered by glaciers and sea ice during maximum Pleistocene glaciation. Redrawn from Broecker, W.C., 1983. *The ocean*. Scientific American 249 (3), 100–112.

difficult to distinguish small worldwide changes in sea level from local or regional ones.

Climate influences the total volume of seawater chiefly through the formation of continental ice sheets during 'ice ages'. During the most recent global cold period (Pleistocene), approximately 8% of the Earth's surface was covered with ice (Figure 5), whereas during the interglacial periods, such as the present one, this figure is about 3%. Because of the storage of water in the form of continental ice sheets during the glacial periods, sea level was lowered worldwide by at least 100 m during the Pleistocene (Eisma, 1988).

At present, approximately 16% of the continents are covered with seawater, thus converting this part of the continents into shelf seas (Schopf, 1980). During the Devonian, about 50% or more of the continents were covered by the sea, in contrast to a coverage of only 5% during the Pleistocene. The corresponding changes in sea level between these two periods are between about +400 and –100 m relative to the present sea level. As has been mentioned, such changes can be caused by tectonic movements of the land or by changes in sea level or both. During most of the Earth's history, the area covered by the sea was much larger than it is now, meaning that global coastline length was shorter in the past and the number of estuaries was probably fewer than at present (Eisma, 1988).

In glaciated or formerly glaciated areas, subsidence and uplift are at least partly related to the formation of an ice cap or ice sheet. An ice cap on a land mass, which can be several kilometers thick, bends the Earth's crust downward. At present, this is the case around Antarctica where the shelf edge lies at 300–400 m depth; this is at least 200 m deeper than it would be in the absence of ice pressing the continent down. When the ice melts, the shelf lifts upward again, but this isostatic upward movement is slower than the rise in sea level, which is the result of ice melting. Thus, parts of the coastal areas formerly covered

by ice tend to be flooded by the sea before emerging again at a later stage (Eisma, 1988). Based on the above evidence, it becomes apparent that the original form of both coasts and estuaries in different periods is strongly linked to the size of global ice sheets and the prevailing sea level.

During periods when sea level is rising or falling, the coast undergoes rapid changes brought about by the redistribution of shoreline materials. One change is the overall sediment availability; the other is the intensity of wave action. The level of sediment supply is crucial, with undersupply resulting in coastal drowning and oversupply in progradation (Carter, 1988). Local examples of this process can be seen in salt marsh sedimentation, which may or may not be able to keep pace with the rising sea level. In some localities, thick stratigraphic sequences, far exceeding tidal range, have been detected (Redfield and Ruben, 1962) and these sequences show the ability of some marshes to keep pace with the sea-level rise.

The rate and extent of sedimentation and filling of an estuary are primarily dependent upon the original size of the estuary, its age, catchment sediment erosion and deposition by the river, and marine forces such as tides and longshore currents. Where river discharge and tidal currents are relatively slight, coastal currents tend to build depositional features such as spits across the mouth of the estuary, thus restricting the entrance. Under such circumstances, the process of estuary filling is likely to be accelerated. On the other hand, if the scouring action of the river and tidal currents is sufficiently strong, the deposition of entrance barriers is inhibited, fluvial sediments are carried farther from the estuary, and the filling process is slowed down (Reid and Wood, 1976). It is also important to note that sedimentary processes vary on a daily, weekly, seasonal, and annual basis and can change from erosion to deposition at any time.

The shape of an estuarine basin is of primary importance in determining the nature of the hydraulic forces operating within

an estuary (Kasai et al., 2000). These dynamics, in turn, have an influence upon the animal and plant communities that develop and their relationship with the environment. A triangular-shaped estuary with a wide, deep mouth permits the incursion of marine waters for a considerable distance upstream, depending upon tidal amplitude and stream gradient. This type of estuary will tend to have increased mixing of waters from the river and sea, greater overall circulation, and often the development of strong currents. Conversely, a narrow-mouthed estuary is characterized by decreased circulation, more pronounced longitudinal and vertical salinity gradients, and a more rapid development of sedimentary features such as spits and bars (Reid and Wood, 1976).

Clearly, the above two types of estuaries, with their differing physicochemical conditions being driven by contrasting geomorphic attributes, are likely to function very differently at the ecosystem level. Evidence to support this view is provided by classifications and models of geomorphic development in Australian estuaries over the past 125 000 years. Studies by Kench (1999) using lateral and vertical sedimentary sequences have shown that fluctuating sea level over this period, and the changing geomorphology of the estuaries, has resulted in a variety of different ecological communities being recorded over time.

The physiography of non-estuarine coastlines is also primarily due to submergence or emergence of the marine littoral zone. According to Reid and Wood (1976), the forms of coastlines may be classified under two headings: (1) features developed as a result of movements of the sea and land in relation to each other (called 'initial forms') and (2) shoreline patterns resulting from the action of marine forces (e.g., wave action) on the above land masses (called 'sequential forms'). However, the classification system proposed in this chapter does not distinguish between the origin of coastal features but deals with coastal ecosystem types that exist today.

1.07.3 Existing Classifications of Estuaries and Coasts

1.07.3.1 Definitions of Estuaries and Coasts

Fundamental to the definition of an estuary is the necessity to distinguish between an 'estuary' and 'estuarine waters', with the former requiring a physiographic form and the latter (e.g., an estuarine plume on an open coast) not constrained by this requirement. An example of where this distinction is not made is that by Ketchum (1983), who defines an estuary as a body of water in which river water mixes with and measurably dilutes seawater. A more conventional approach is the oft-quoted Pritchard (1967) definition that states that "an estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which the sea water is measurably diluted with fresh water derived from land drainage." However, according to Day et al. (1989), this definition is too restrictive in that it excludes negative estuaries, tidal rivers, and coastal zones that have certain estuarine attributes. Day (1980) also contested Pritchard's definition on the grounds that it excluded the temporarily closed or 'blind' estuaries and suggested a slightly modified definition to overcome this omission. Another critic of Pritchard's definition was Ketchum (1983), who stated that it leaves both the landward and the seaward boundaries of the estuary vague.

The seaward boundary of an estuary can be defined geographically by a line between the land masses on each side of the entrance to the estuary from the coastal waters and where there is a notable break in the line of the coast. However, according to Ketchum (1983), this can be ambiguous where deltaic structures are formed at the mouth. The above-mentioned problem can be overcome by including geomorphological discontinuities (e.g., an ebb tidal delta) along the coast as part of the estuary. It has also been suggested that the seaward limits of an estuary be defined by salinity distribution, but this view is widely contested. A recent definition of an estuary using the salinity theme is provided by Elliott and McLusky (2002), who suggested that the seaward limits are represented by "an area receiving freshwater inputs where the waters on a depth-averaged basis have a salinity of less than 95% of the adjacent local offshore seawater for 95% of the time." This chapter favors the geomorphological criterion for the seaward boundary of an estuary, with plumes of estuarine water entering the sea being regarded as part of the TWs within the coastal marine environment rather than the estuary *sensu stricto*.

Some very large rivers (e.g., Congo) produce such large volumes of freshwater that saline penetration of the 'drowned river valley' is seldom possible, even at high tide. In many of these cases, plumes of river water flow on top of the more dense offshore seawater and these plumes can be traced a considerable distance from the geographical estuary mouth (Ketchum, 1983; Figure 6). Riley (1937) traced the effect of the Mississippi River water as far as 90 km into the Gulf of Mexico, and Ryther et al. (1967) indicated that the river plume from the Amazon River formed a lens of appreciably freshened surface water up to 500 km in diameter, several hundred kilometers to the north and east of the estuary. McHugh (1967) has defined these offshore estuarine zones of the world as those waters bounded by a surface salinity of 33.5 (Figure 6) and Frankignoulle et al. (1998) defined this zone as being 'outer estuaries' (as opposed to 'inner estuaries' that are semi-enclosed by land).

The river boundary of an estuary has also been the subject of much debate. Ketchum (1951) defined the inner end of the estuary as the cross section above which the volume of water involved in raising the level of water from the low tide mark to the high tide mark is equal to the volume contributed by the river during one half of the tidal cycle. Unfortunately, this definition is impractical because it is almost impossible to define these parameters in quantitative terms and is therefore seldom used.

The upstream tidal area which seawater fails to penetrate is commonly known as the tidal river reach and can undergo large fluctuations in water level in macrotidal systems. The interface between the river and estuary is known as the river–estuary interface (REI) in southern Africa and the freshwater–brackish water interface (FBI) or freshwater–seawater interface (FSI) in Europe (McLusky, 1993; Bate et al., 2002). Above the FBI in tidally dominated European estuaries is the tidal freshwater area (TFA), where the tidal influence reaches further inland than the saline influence due to the tide holding back the river flow (McLusky and McIntyre, 1995). This saline boundary, which normally marks the upper limits of an estuary if estuarine biota are absent from the tidal freshwater portion of the system, must be of recent marine origin rather than geological origin (which could introduce brackish water from the catchment).

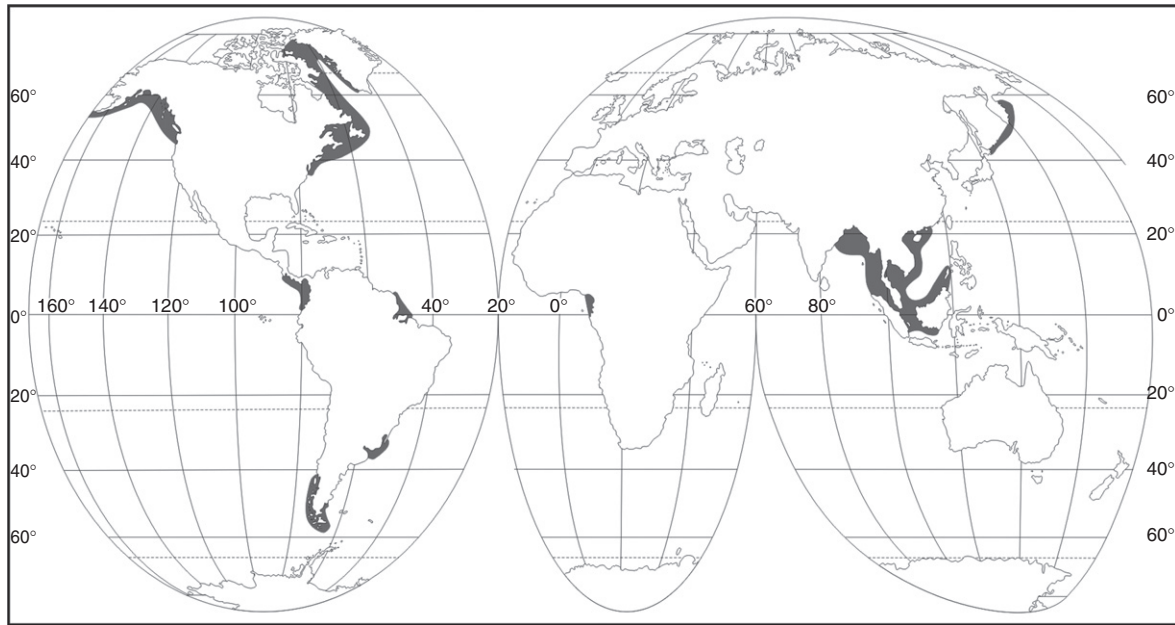


Figure 6 Offshore estuarine zones of the world (dark areas) as proposed by Ketchum, B.H. (Ed.), 1983. *Ecosystems of the World. Vol. 26. Estuaries and Enclosed Seas.* Elsevier, Amsterdam, 500 pp.

The above discussion shows that the upper boundary of an estuary can sometimes be vague, especially where riverine topographical gradients are low and freshwater flow is high. Within Europe, there is widespread acceptance of the addition of a TFA to the estuary but, in many other parts of the world, estuaries do not have a tidal freshwater zone. Based on an acceptance of the TFA as being part of the estuary, provided estuarine biota are present, the lower Amazon River which is tidal may be considered estuarine (Perillo, 1995), that is, an estuary that only has the upper or fluvial sector as per the definition from Fairbridge (1980). A variation on the three-sector approach by Dionne (1963) is provided by Perillo (1995), who identified hierarchical estuaries such as Chesapeake Bay where the Elizabeth and Lafayette rivers (tertiary estuaries) discharge into the James River (a secondary estuary) that in turn flows into Chesapeake Bay (the primary estuary).

Dionne (1963), using the St. Lawrence estuary as an example, described an estuary as "an inlet of the sea, reaching into the river valley as far as the upper limit of tidal rise, usually divisible into three sectors: a) a marine or lower estuary, in free connection with the open sea; b) a middle estuary, subject to strong salt and freshwater mixing; and c) an upper or fluvial estuary, characterised by freshwater but subject to daily tidal activity." This definition was strongly supported by Fairbridge (1980) but the limits of these sectors are variable and subject to constant changes in river discharge and tidal pumping of seawater into an estuary.

Wolanski (2007) combined the Dionne (1963) estuarine definition with elements from Pritchard (1967), Perillo (1995), Kjerfve (1989), and Dalrymple et al. (1992) and concluded that "An estuary is a semi-enclosed body of water connected to the sea as far as the tidal limit or the salt intrusion limit and receiving freshwater run-off, recognising that the freshwater inflow may not be perennial (i.e. it may only occur for part of the year) and that the connection to the sea may be closed for part of the year (e.g., by a sand bar) and that the tidal

influence may be negligible." The definition includes fjords, fjards, river mouths, deltas, rias, lagoons, tidal creeks, as well as the more classical estuaries. Wolanski (2007) also indicated that it is sometimes difficult to determine where an estuary ends because the change from estuarine to marine conditions often does not coincide with the physical break in the coastline.

Almost without exception, estuaries are basins or river valleys of non-marine origin that have been invaded by the sea. These basins were originally formed by fluvial erosion (e.g., rias), glacial action (e.g., fjords), or tectonic subsidence (e.g., grabens) (Carter, 1988). As discussed earlier, most estuaries are the result of river valley inundation due to the global rise in the postglacial sea level. Some are further constricted by the development of spits, shoals, or barriers across their mouths. The importance of morphology in defining an estuary, most notably the mouth, is illustrated by Dyer (1996), who used the coastline form and underwater topography, together with the associated sediment distribution, to indicate the outer limits of an estuary. It is also important to note that the upper limits of estuaries worldwide have been truncated by the construction of weirs and other concrete structures in the headwater regions of these systems (Elliott and McLusky, 2002).

Day et al. (1989) proposed a short and simple definition of an estuary as "a coastal indentation that has a restricted connection to the ocean and remains open at least intermittently." Although the above definition has considerable merit, it makes no reference to riverine input that is elaborated upon in their general description of an estuarine system that is divided into three regions: a tidal river zone where ocean salinity is lacking, a mixing zone where physicochemical gradients are strong, and a nearshore turbid zone in the open ocean where estuarine water forms a tidal plume. A definition that follows the above description is that of Kjerfve (1989), who defined an estuary as the zone that stretches from the tidal limit to the seaward edge of the tidal plume in the open ocean. Unfortunately, one of the weaknesses

of the above approaches is that estuarine lagoons and lakes are often not tidal, sometimes do not take on the form of a 'coastal indentation' (may be completely enclosed by land at times), seldom exhibit conventional estuarine salinity gradients, and rarely have turbid estuarine plumes entering the sea.

Conley et al. (2000) defined an estuary as "a partially enclosed body of water open to saline water from the sea and receiving freshwater from rivers, land run-off or seepage." Although this definition makes no mention of the presence or absence of tidal conditions, and does not cater to the 'blind' or temporarily closed estuaries that are common in the Southern Hemisphere, it does include bays or lagoons that have no riverine inputs but do receive land-based freshwater from aquifers or groundwater seepage (Whitfield, 2005). The definition of coastal lagoons that was accepted by Barnes (1980) was "an area of salt or brackish water separated from the adjacent sea by a low-lying sand or shingle barrier." Some of these lagoons are estuarine and some are permanently isolated from the sea; however, the above definition does not distinguish between these two very different types of ecosystems. Coastal lagoons that are permanently isolated from the sea are also referred to as albuferas in certain parts of the world and Perillo (1995) went so far as to place 'blind estuaries' in this category because he claimed that these systems do not exhibit estuarine characteristics during the closed phase. This supposition is incorrect as has been shown by numerous studies in intermittently open estuaries in both Australia and South Africa (Potter et al., 1990; Allanson and Baird, 1999).

A novel way of defining an estuarine area has been proposed by Elliott and McLusky (2002), which involves a checklist approach that is compiled and used based on expert judgment. The approach is designed to extract information from both the published and gray literature, as well as informed local sources, to indicate estuarine and marine features within a given geographical area. Despite the information

often not being precise, by using the tick-box approach to a series of questions it is possible to indicate an area as an estuary and to describe it spatially and temporarily. This method presents a more habitat and functionally based approach, rather than a detailed physical approach, and lends itself to assessments to determine whether a particular estuary differs from reference conditions with regard to its biological, physical, and chemical characteristics. The authors proposed this method as a result of not being able to define all estuarine types within a single sentence but needing to encapsulate the characteristic features shown by estuaries.

Elliott and McLusky (2002) have also highlighted the increasing amount of environmental legislation and protocols relating to estuaries. This trend dictates that scientists have to provide lawyers and planners with useful definitions that will assist in the wise management of these systems. As already discussed, there are a large number of mainly physical definitions pertaining to estuaries. It is also apparent that whereas physical definitions are probably more objective, biological-based definitions are likely to be more subjective, particularly given the spatial and temporal variability and mobility of many of the biotic components. However, with increasing environmental awareness and associated legislation, there is a need for ecological, conservation, socio-economic, legal, and administrative definitions that have practical use in a management context (Table 1).

Perhaps the value of a comprehensive system of estuarine definition and classification is epitomized by the European Union (EU) Water Framework Directive (WFD; European Union, 2000), which requires all surface waters to be classified, monitored, and compared against reference conditions as components of catchment management plans. The Directive includes estuaries in the term 'transitional waters' (TWs); hence, European estuarine scientists will have to use TWs as a means towards understanding and managing estuaries and

Table 1 A multidisciplinary approach to defining estuaries (after Elliott and McLusky, 2002)

<i>Discipline</i>	<i>Character</i>	<i>Mechanism of definition</i>
Physical	Physiography Marine-based hydrographic processes	Abrupt break between estuary and open coast Penetration of tides Penetration of marine waves Presence of density-driven currents Sea-derived sediment transport
Chemical	Salinity Sensitivity	Reduced from seawater but greater than freshwater To nutrient enrichment
Biological	Community type	Penetration of marine plankton Presence of recognized sea fishes Migration route for diadromous fishes Presence of 'estuarine' community
Environmental quality Management	Classification Sea fisheries Transition waters	Based on biology, aesthetics, chemistry, and with estuarine features Inland penetration of species 'widely recognized as marine' Based on differences (by default – neither marine nor freshwater)
Legal	With a recognized hinterland Area widely regarded as 'estuarine'	Based on a catchment with a recognized coastline and transition area An area regarded as such by both expert judgment and public perception
Conservation	Receiving a catchment Support of estuarine important biotopes	As the area where a river discharges As an area notable for its functioning (e.g., as for wading birds) or typical biotypes (e.g., saltmarshes, seagrass beds)

From Elliott and McLusky (2002).

Table 2 The estuarine definition adopted for nature conservation purposes under the European Union Habitats and Species Directive

<i>European Union definition</i>	<i>Relevance to the definition for an estuary</i>
“Downstream part of a river valley, subject to the tide and extending from the limit of brackish waters. River estuaries are coastal inlets where, unlike ‘large shallow inlets and bays’ there is generally a substantial freshwater influence. The mixing of freshwater and seawater and the reduced current flows in the shelter of the estuary lead to the deposition of fine sediments,... ... often forming extensive intertidal sand and mud flats. Where the tidal currents are faster than the flood tides, most sediments deposit to form a delta at the mouth of the estuary.”	Assess the topography and physiography, and determine where the true freshwater stops. Assess the salinity contours and determine where noticeable reductions occur. Assess where low energy areas occur and determine where there are large intertidal flats which have a typical functioning. Determine whether this occurs although this may not be applicable to many temperate estuaries.

From Elliott, M., McLusky, D.S., 2002. The need for definitions in understanding estuaries. *Estuarine, Coastal and Shelf Science* 55, 815–827.

their related habitats (Elliott and McLusky, 2002). The EU definition (Table 2) considers that an estuary includes reedbeds, saltmarsh, and other intertidal habitats, and forms an ecological unit with the surrounding terrestrial coastal habitat types. Although this started as a convenient administrative term to encompass all waters that are neither the open coast nor true freshwaters, TWs have now been accepted as a well-defined set of ecosystems, each with its own set of characteristics different from the end members; and where all estuaries are TWs but not all TWs are estuaries.

Clearly, it has become imperative for the definition of estuaries to withstand legal scrutiny and it is questionable whether it is really necessary for each country to have its own definition of systems that are present throughout the world. Elliott and McLusky (2002) noted that in the UK rivers, tidal waters, and coasts all had legal definitions, whereas estuaries did not. South Africa, however, through the National Water Act of 1998, had legally defined an estuary as follows: “Estuary means a partially or fully enclosed body of water – (a) which is open to the sea permanently or periodically; (b) within which seawater can be diluted to an extent that is measurable, with freshwater drained from land.” The final part of this definition (b) was later modified in Regulation No. 1399 of the National Environmental Management Act of 1998 to include “... and in which the water level rises and falls as a result of the action of the tides whenever it is open to the sea.” Unfortunately, this definition does not cater to hyperhalinity, which can occur in some South African estuaries.

A similar problem exists in Australia where hyperhaline estuaries exist but are not included under existing estuarine definitions. This has led Potter et al. (2010) to propose the following definition: “An estuary is a partially enclosed coastal body of water that is either permanently or periodically open to the sea and which at least receives periodic discharge from a river(s), and thus, while its salinity is typically less than that of natural seawater and varies temporally along its length, it can become hypersaline in regions when evaporative water loss is high and fresh water and tidal inputs are negligible.” Hyperhaline estuaries are sometimes referred to as negative estuaries because salinities are often higher in the upper reaches when compared to the lower reaches. In contrast, positive estuaries have a more normal increasing salinity gradient from head to mouth.

In our opinion, there are three important components that need to be incorporated into the definition of an estuary, namely, coastal containment, the mixing of freshwater with seawater, and the presence of an estuarine biota. We therefore propose the following global definition: “An estuary is a semi-enclosed coastal body of water which is connected to the sea either permanently or periodically, has a salinity that is different from that of the adjacent open ocean due to freshwater inputs, and includes a characteristic biota.” This definition encompasses those estuaries that close and are therefore not tidal, as well as those that are sometimes hyperhaline. It also includes coastal systems (e.g., certain estuarine lagoons and bays) that do not have inflowing rivers but where groundwater inputs provide estuarine conditions that support an estuarine biota.

Definitions of the coast are equally diverse to those proposed for estuaries and have also posed problems from a social, legal, and environmental perspective. For example, the 1991 UK Water Resources Act considers coastal waters as including all estuarine waters up to the freshwater limit of rivers and that those limits are to be specified by the Secretary of State on maps. The seaward boundary of coastal waters is deemed to extend to the 3-nm offshore contour and the landward boundary to the limit of the highest tide or, in the case of nontidal systems, the freshwater limit.

The EU has recently adopted a Marine Strategy Framework Directive in which national control extends to 200 nm (or the midline between countries) and landward to the areas of marine influence. This latter boundary is being taken by most countries to be the high water level which, by definition, will have to also include estuaries up to the extent of tidal penetration. In the case of England and Wales, the regional Sea Fisheries Committees have regarded their landward limits as the limit of penetration by ‘typically marine fish species’ – this includes herring, sprat, smelt, etc., which can extend to the headwaters of estuaries in this region.

According to R.S.K. Barnes (personal communication, cited in Elliott and McLusky (2002)), the coastal zone “extends seaward and landward of the coastline. Its limits are defined by the geographical extent of natural processes and human activities related to the coast.” This very broad definition is unlikely to find favor with coastal scientists or managers who require more specific terms to define this zone.

1.07.3.2 Estuarine Classifications

Pritchard (1952) proposed a classification of estuaries based entirely on their water balance: (1) positive estuaries, where the combined freshwater input from rivers, ground water, and rainfall exceeds evaporation; (2) neutral estuaries, with a balance between evaporation and freshwater input; and (3) negative or inverse estuaries, where evaporation exceeds the combined freshwater input. Although it may be useful to think of coastal systems in terms of the water balance alone, this means of classifying estuaries is no longer in common use (Day et al., 1989).

A symposium on the Classification of Brackish Waters in 1958 led to the suggestion to divide estuaries into zones on the basis of their salinity (Table 3). This classification scheme, known as the Venice system, recognizes six distinct zones that can be linked to the classification of different biotic guilds and their distribution patterns within estuaries. In addition, the Venice system can easily be used to characterize different types of estuaries. Although the salinity pattern in most Northern Hemisphere estuaries follow the Venice system in terms of salinity gradients from the head to the mouth, this is not the case in many Southern Hemisphere systems where inflowing river water is often erratic and may cease altogether for months at a time, sometimes giving rise to hyperhaline estuarine conditions. This broad fundamental difference between Northern and Southern Hemisphere estuaries was highlighted by McLusky and McIntyre (1995).

The above-mentioned hemisphere differences were also commented upon by Elliott and McLusky (2002) who questioned whether the intermittently open estuaries in southern Africa and Australia, which can be closed to the sea for prolonged periods, should be accorded estuarine status. This view is contested by southern hemisphere scientists who have shown that temporarily open/closed estuaries (TOCEs) in southern Africa and intermittently closed and open lakes and lagoons (ICOLLS) in the southern parts of Australia are fully

functional estuarine ecosystems (Allanson and Baird, 1999; Brearley, 2005).

Fairbridge (1980) also focused on the importance of tides as a distinguishing feature of estuaries. Certain non-tidal seas (e.g., Caspian and Baltic seas) have salinities lower than that of seawater but are not classified as estuaries. Elliott and McLusky (2002) emphasized that all estuaries have brackish regions but not all brackish (salty) waters are estuarine, for example, catchment river or borehole water that has a high conductivity is often termed 'brackish'. Our recommendation is that the term 'brackish waters' should be confined to inland or non-estuarine coastal systems with very low salinities, which would equate to the 'oligohaline waters' found in estuaries. This approach allows for the classification of isolated brackish lagoons, lakes, and seas as non-estuarine coastal systems, some of which may be moderately saline (e.g., Baltic Sea). However, those lagoons and lakes that have permanent or intermittent linkages with the open ocean, and have a characteristic estuarine biota, should be classified as estuarine (Whitfield, 1992).

Pritchard (1967) produced a classification for estuaries based on water circulation, namely (1) salt wedge estuaries that are highly stratified, (2) partially mixed estuaries that are moderately stratified, (3) vertically homogeneous estuaries with a lateral salinity gradient, and (4) sectionally homogeneous estuaries with a longitudinal salinity gradient. Although these terms are often used in describing the hydrographical characteristics of particular estuaries, the classification system has not been applied on a global basis. Dyer (1972) followed a similar salinity structure approach to classifying estuaries and identified three mixing regimes: stratified, partially mixed, and mixed. Mixing was calculated mathematically as the relationship between the relative strengths of the tidal and riverine flows in relation to depth.

A different approach was adopted by Hayes (1975), who based his classification system on tidal range. Microtidal estuaries were identified as having a small tidal range (0–2 m),

Table 3 Classification of approximate geographic divisions, salinity ranges (Practical Salinity Scale), and distribution of different types of aquatic fauna found in a 'generalized' estuary

	Venice system		Ecological classification			
Estuary divisions	Salinity ranges	Salinity zones	Aquatic fauna and approximate distribution range in an estuary			
River reaches	<0.5	Limnetic	Anadromous migrants	Freshwater migrants	Estuarine residents	
Estuary head	0.5–5	Oligohaline				
Upper reaches	5–8	Mesohaline				
Middle reaches	18–25	Polyhaline				
Lower reaches	25–30	Polyhaline				
Estuary mouth	30–40	Euhaline		Stenohaline marine	Euryhaline marine migrants	Catadromous migrants

Modified from Carriker, M.R., 1967. Ecology of estuarine benthic invertebrates: a perspective. In: Lauff, G.H. (Ed.), Estuaries. American Association for the Advancement of Science, Washington, DC, vol. 83, pp. 442–487.

mesotidal estuaries with intermediate tidal ranges (2–4 m), and macrotidal estuaries (>4 m). These different tidal ranges result in large changes in tidal currents, with a concomitant influence on the sedimentary characteristics of the three types of estuaries. However, as mentioned previously, there are estuarine lagoons, lakes, and temporarily closed estuaries that have little or no tidal prism but are still fully functional estuarine ecosystems.

Rusnak (1967) focused on sedimentological criteria as the basis for classifying different estuaries. According to this scheme, estuaries filled entirely by river-transported sediment are termed 'positive filled'. A river with a large sediment load tends to fill an estuarine basin rapidly in the manner of a prograding delta front. When sediment input from river systems is low and most sediment deposited in the basin enters from beaches or the nearshore ocean during flood tide, an 'inverse-filled' estuary results. Clearly, the balance between sediment deposition in the upper and lower estuary is a function of the balance between the availability of riverine- and marine-generated sediments, together with the strength and direction of their associated water currents, all of which can change on a spatial and temporal scale. Non-filling estuaries, which are in a state of extended periods of equilibrium with little or no change in basin volume due to sedimentation, are classified as 'neutral filled' (e.g., certain estuarine bays and fjords).

Day et al. (1989) indicated that it is more useful to classify estuaries according to geomorphology rather than hydrology. This approach was also adopted by Dyer (1972), who divided estuaries into four main groups: (1) coastal plain estuaries; (2) lagoons (or bar-built estuaries); (3) fjords, fjards, and firths; and (4) tectonically caused estuaries resulting from faulting, graben formation, landslide, or volcanic eruption. A similar type of approach was followed by Davidson et al. (1991), who classified British estuaries into nine geomorphologic types, namely fjord, fjard, ria, coastal plain, bar-built, complex, barrier beach, linear shore, and embayment.

Ketchum (1983) went one step further and classified estuaries on the basis of their geomorphology, salinity distribution, and the characteristic type of water circulation. The four initial categories created were drowned river valleys, bar-built estuaries, fjords, and deltaic estuaries. Within these categories, five types of salinity and density distributions were identified: well-mixed, weakly stratified, strongly stratified, fjords, and arrested salt wedge. The first three types are self-explanatory, whereas in fjords the salinity distribution commonly consists of three layers: a surface brackish-water layer, an intermediate layer of increasing salinity with depth, and a deep-water layer within which the salinity is constant to the bottom. In the arrested salt wedge type system, the river flow is large, and undiluted freshwater may flow out of the estuary above a deeper layer of undiluted seawater that forms the salt wedge.

Whitfield (1992) followed a similar multidisciplinary type of approach to the classification of estuaries in southern Africa, using morphometrics, salinity regimes, mouth dynamics, and hydrodynamic processes to characterize five primary types of estuaries, namely, permanently open estuaries, temporarily open/closed estuaries, estuarine bays, estuarine lakes, and river mouths. This estuarine classification system has been widely used by scientists and coastal managers within the region (e.g., Turpie et al., 2002).

Roy et al. (2001) also used a multidisciplinary approach to classifying estuaries in southeast Australia by using a combination of geological properties, water-quality attributes, and environmental factors. This approach is based on the fact that the geology (including geomorphology) and environmental factors (e.g., salinity and sediments) affect ecological distributions and species richness within these systems. The four types of estuaries identified in southeast Australia were drowned river valley, barrier estuary, saline coastal lagoon, and mature riverine estuary. These groupings are strongly linked to their entrance conditions and salinity profile, with drowned river valley estuaries having a large and permanently open mouth with strong marine influences, and saline coastal lagoons having narrow mouths that close for extended periods (Roy et al., 2001).

Instead of the physical environment driving subdivision definitions within an estuary, as is the case with the Venice system, Bulger et al. (1993) used a multivariate approach incorporating the actual species distributions to define the salinity bands within estuaries. The salinity preferences of these species indicated that there were five overlapping salinity zones: freshwater-4, 2-12, 11-18, 16-27, and 24-marine. This approach allows for biologically relevant definitions of estuaries that can then be linked to ecosystem functioning. Unfortunately, this classification does not take into account those estuaries, or portions of estuaries, that can become hyperhaline during certain periods.

Jay et al. (2000) also advocated a process-based approach rather than a simple structural approach. They used both hydrographical and ecological change features in classifying estuaries. Elliott and McLusky (2002) emphasized that the definition of estuarine types requires a classification scheme that connects physical processes, such as water circulation and sediment dynamics, to biogeochemistry and ecological features. Physical-forcing variables such as hydrodynamics and bathymetry drive not only sediment dynamics and structure, but also the size and nature of primary producers. These, in turn, influence larval recruitment, zooplankton dynamics, and thus ecological processes within the lower trophic levels. Similarly, Gray and Elliott (2009) summarized the physico-chemical regime, including water balance/dynamics and thus salinity, creating the fundamental sediment and water-column niches that are then colonized by the estuarine biota.

Edgar et al. (2000) followed a detailed but different ecosystem approach to classification that was based on the premise that different estuary types are subjected to particular types and levels of human impact. To protect assemblages associated with all estuary types in Tasmania (Australia), the conservation significance of the 111 large- and moderate-sized estuaries in the state were assessed by first categorizing estuaries into nine groups on the basis of similarities in physical attributes. These attributes were quantified using geographic information system (GIS) maps of estuaries and their catchments together with field-collected data, with separation of groups primarily reflecting the presence of a seaward barrier, tidal range, salinity, estuary size, and river runoff. The adequacy of the physical groups as surrogates for biological patterns was assessed by comparison with data on the distribution of 390 macrobenthic invertebrate taxa and 101 fish species in 48 and 75 Tasmanian estuaries, respectively. Within each of the estuarine groups, human population and land development data were used to

assess the level of anthropogenic disturbance to each estuary, and the estuary with the least disturbance in each group was then assigned the highest conservation significance.

More recently, [Hume et al. \(2007\)](#) proposed a similar 'conservation orientated' approach to the classification of New Zealand estuaries. Their estuary environment classification (EEC) is based on a hierarchical view of the abiotic components that comprise the environments of estuaries. The EEC postulates that climatic, oceanic, riverine, and catchment factors 'control' a hierarchy of processes and broadly determine the physical and biological characteristics of estuaries. The classification separates estuaries at different levels of detail. Level 1 differentiates the global-scale variation based on differences in climatic and oceanic processes, which are discriminated by factors such as latitude, oceanic basins, and large landmasses. Level 2 differentiates variation in estuary hydrodynamic processes, which are discriminated by estuary basin morphometry as well as by river and oceanic forcing. Level 3 differentiates variation among estuaries that are due to catchment processes, which are discriminated by catchment geology and land cover. Estuaries were assigned class membership at each level of the classification by applying criteria in the form of decision rules to the database of assigned characteristics. GIS was then used to map the estuaries, with classes being defined by color at any level of classification. The resulting map provided a multiscale spatial framework that is suitable for environmental and conservation management applications.

1.07.3.3 Coastal Classifications

A wide variety of factors affect coasts and it is therefore very difficult to create an integrated classification scheme ([Finkl, 2004](#)). As a result, there have been a number of attempts to classify coasts according to single parameters ([Haslett, 2009](#)). Perhaps the most simple primary classification is that based on tectonics that focuses on the interaction between continental and oceanic crustal plates. On a broad scale, there is often a consistent relationship between the characteristics of a coastline and the type of plate boundary that it is nearest to ([Haslett, 2009](#)). This type of classification has led to the recognition by [Davis \(1997\)](#) of three major types of coasts, namely leading edge, trailing edge, and marginal sea coasts ([Table 4](#)).

Tidal range of different coasts can also be used to create a simple classification system ([Figure 2](#)). Different tidal ranges have a major influence on the extent and type of the intertidal zone and therefore the biota of these ecosystems. In addition, tidal regimes will influence the inundation and exposure periodicity of the littoral coastal zone, thus adding another dimension to any classification system based on tides.

[Inman and Nordstrom \(1971\)](#) proposed a first-order classification based on first-order effects of plate tectonics, namely collision coasts (those on the collision edge of a continent), trailing-edge coasts (those on the noncollision edge of a continent), and marginal sea coasts (those protected by island arcs). Within this classification, there are several subcategories, namely mountain coast, narrow shelf, wide shelf, deltaic coast, reef coast, and glaciated coast. The two shelves were further subdivided into headlands and bays, and coastal plains.

Although the above classification is useful on a global scale, it does not address the more detailed coastal features that occur on the various continents and in specific countries. In this

regard, [Klemsdal \(1982\)](#) classified the Norwegian coast into primary and secondary coasts. The primary coasts were sand flat, fjord, fjard, cliff abrasion, flat abrasion, and moraine topography coasts. Moraine cliff and sandy beaches were classified as secondary coasts. Also recognized were gently sloping ice-smoothed rocky shores, abrasion shores, stony beaches, and sandy beaches as shore-zone types.

[Odum and Copeland \(1974\)](#) took a different approach to the classification of coastal systems, using ecosystem energetics as the basis for differentiating between systems. In this broadly functional classification, six major ecological systems and subsystems were identified based on energy source: (1) natural stressed systems of wide latitudinal range; (2) natural tropical ecosystems of high diversity; (3) natural temperate ecosystems with seasonal programming; (4) natural Arctic ecosystems with ice stress; (5) emerging new systems associated with humans; and (6) migrating subsystems (e.g., fish) that organize and influence ecosystems. This complex classification system has not gained wide support among coastal workers.

The EU WFD requires member states to classify their coastal areas according to a typology system whereby surface waters (fresh, transitional, and coastal water bodies) are separated into types (or typologies in the terms of the WFD) and each of these then requires a reference state against which can be judged changes to anthropogenically affected systems. The WFD indicates that types should be created according to the physical parameters of salinity, mixing, exposure, and tidal regime. [Rogers et al. \(2003\)](#) carried out a multivariate approach to define the number of coastal and transitional types and concluded that although the approximately 170 estuaries in the UK could be grouped in ordination and cluster analysis, this essentially was a continuum, thus reinforcing the above-mentioned comments regarding our ability to classify these systems.

The coastal areas in both the Arctic and Antarctic feature extensive ice sheet contact zones that vary in shape, extent, and periodicity. These contact zones are strongly influenced by the seasons and global climatic conditions. According to [Nikiforov et al. \(2005\)](#), Arctic coastal evolution differs from that in other areas of the world as a result of interactions between currents, wave action, and ice factors, as well as the influences of glaciations and large-scale sea-level changes in the past. Indeed, polar coasts are more likely to change than any other coastal features and this has major implications for the biota associated with these seasonally fluctuating ecosystems.

Lagoonal systems are an important feature on most continents ([Figure 7](#)) and occupy approximately 13% of the world's coastline ([Cromwell, 1971](#)). The extent of each continent's coastline occupied by lagoons varies from approximately 17% in North America and Africa to 5% in Europe ([Table 5](#)). Overall, North America accounts for approximately 33% of the world's lagoonal coastline. Once formed, lagoons do not persist for long periods of geological time, mainly because most of them are shallow and therefore relatively easily converted into swamps, marshes, and ultimately land ([Barnes, 1980](#)). The succession from estuarine lagoon to freshwater swamp or marsh is linked to an increasing shallowness and decreasing connectivity with the marine environment. Conversely, rising sea levels can inundate existing coastal lagoons and result in a new 'inland' coastline that may have more or less of these systems, depending on coastal topography.

Table 4 Descriptions of estuaries and other coastal features

<i>Type</i>	<i>Description</i>	<i>Comments</i>
Estuary	Numerous descriptions of an estuary are presented and discussed in this treatise.	Successful definitions need to encompass all global estuarine types.
Transitional water	Term used to describe the estuary, the tidal freshwater zone above the estuary, and the estuarine waters beyond the mouth.	A very useful term that includes all coastal transitional waters that are not strictly riverine and/or marine.
River mouth	Description of those estuaries where oligohaline or even freshwater conditions persist for long periods along the length of the system.	This term is particularly useful in describing those estuaries with seasonal or perennial high freshwater inputs.
Tidal river	Description of the tidal freshwater portion of transitional waters and those 'estuaries' where there is no saline penetration into the system.	A useful term for non-estuarine parts of a transitional water or river mouths that are devoid of a marine saline influence.
Ria	Spanish word for estuary. Also defined as a drowned river valley in a coastal area of high relief.	In Latin American countries, estuario is used rather than ria.
Fjord	Long, narrow, deep, U-shaped coastal inlet that usually represents the seaward end of a glaciated valley that has been partially submerged.	Although many Norwegian estuaries fall into this category, this type of system also occurs in other parts of the world.
Fjord	A rocky inlet of the sea, formed by submergence of a glacial valley but more irregularly shaped than fjords.	There are many examples of this type of estuary on the northern coast of Sweden.
Estuarine bay	A coastal embayment that has mainly estuarine characteristics.	Estuarine bays are usually characterized by strong marine and riverine inputs.
Estuarine lagoon	A narrow coastal body of shallow estuarine water characterized by a permanent or intermittent link with the sea.	Estuarine lagoons are usually orientated parallel to the coast and separated from the sea by a sand spit.
Estuarine lake	A large coastal body of estuarine water with a permanent or intermittent link with the sea.	The basin of estuarine lakes may be either deep or shallow, depending on sedimentary history.
Intermittently closed and open lakes and lagoons (ICOLLS)	Term used mainly in southeast Australia to describe estuarine lakes and lagoons in that region.	Collective nature of the term results in different types of systems being grouped together.
Temporarily open/closed estuary (TOCE)	Term used in South Africa to describe small estuaries that are not permanently open to the sea.	Certain large estuarine lakes also close but are not referred to as TOCEs.
Permanently open estuary (POE)	Term used in South Africa to describe estuaries that do not normally close.	These estuaries sometimes close during prolonged or extreme droughts.
Coastal lagoon	A coastal body of shallow brackish or even freshwater, characterized by an absence of any direct link with the sea.	In Spain, a coastal lagoon is referred to as an albufera and in Russia as a liman.
Coastal lake	A large coastal body of fresh or brackish water, characterized by an absence of any direct link with the sea.	Some coastal lakes were once estuarine lakes but have since lost their marine connection.
Marine bay	A coastal embayment that is partially open to the sea and has mainly marine characteristics.	A marine bay will not have a perennial river entering the embayment.
Marine lagoon	A coastal body of shallow marine water that lacks a riverine input.	Marine lagoons may have permanent or intermittent connections with the adjacent sea.
Bahiras	Land-locked coastal basin that became filled with seawater during the holocene transgression and is often isolated from the sea by a sandy spit.	Arabic word for small sea and is sometimes used to describe large euhaline and hyperhaline lagoons in the Mediterranean and Arabian coastal regions.
Paralic environment	Term used to indicate a wide variety of coastal sedimentary environments and has been applied to estuaries, bays, deltas, and lagoons.	This term is used mainly in a geological context but has also been applied by European marine ecologists to coastal domains.
River delta	A delta that forms as a result of large quantities of mud, silt, and sand supplied by the river to the coastal zone and retained within the mouth region.	This type of delta includes all the major river deltas of the world where large and low-gradient rivers enter the sea.
Fan delta	Fan deltas differ from river deltas in that they are coarse-grained coastal features but are also associated with a fluvial source known as the feeder system.	These deltas often occur in association with tectonically active coasts.
Sabka	These are tidal flats in arid environments that often support algal mat communities that are tolerant of arid and saline conditions.	Salts often precipitate to form hard salt crusts on the surface of sabkas.
Tidal inlet	Narrow coastal channel that connects the open sea with a lagoon or lake and is often characterized by strong tidal currents.	Tidal inlets vary considerably in size, which is related to the volume of water being exchanged during each tidal cycle.

(Continued)

Table 4 (Continued)

Type	Description	Comments
Firth	A word used to denote various coastal waters in Scotland, from marine bay, strait, inlet to estuary.	A firth is generally the result of glaciation and is very often associated with a large river.
Sea loch	Name applied to certain sea inlets in the west and north of Scotland.	Sea lochs could also be classified as firths, fjords, marine bays, or straits.
Strait	A strait is a narrow channel of water that connects two larger coastal water bodies.	A strait is normally a navigable channel and can also be referred to as a sound.
Tidal creek	Blind inlet that is situated either on the open coast or in an estuary and subject to tidal action.	Some tidal creeks may be completely exposed at low tide.
Coral lagoon	A lagoon that is linked to the marine environment but is sheltered from the open ocean by a coral reef.	Coral atolls and mainland coral reefs are responsible for the occurrence of different types of coral lagoons.
Coral reef	Wave-resistant structure built largely by coral and consisting largely of skeletal and chemically precipitated material.	Coral reefs are best represented along tropical coasts where clear marine waters are present.
Coral reef coast	Coasts that are created as a result of coral reef erosion and deposition that is facilitated by wave-induced currents.	Coral islands or cays can be created by coral rubble (skeletal sediments) being swept into a pile.
Barrier island	Depositional offshore linear feature orientated parallel to the coast and separated from the mainland by a lagoon.	These are usually composed of sand that is built above the high-tide level and stabilized by vegetation.
Leading edge coast	This type of coast occurs where a continental geological plate converges with an oceanic plate, with the oceanic plate subducting beneath the continental plate.	These types of coasts are also known as convergent margin coasts. A coastal chain of mountains is often present along this type of coast.
Trailing edge coast	These are coasts that form as geological plates rift apart due to divergence, thus allowing the ocean to inundate the rift to create a new sea.	After rifting the topography of these coasts may resemble the high relief of leading edge coasts, but over time the relief is usually lowered.
Marginal sea coast	An uncommon coastal type where plate convergence takes place offshore, with a relatively wide continental shelf separating the plate boundary from the coast.	The Gulf of Mexico is an example of this type of coast.
Erosional coast	Coasts where the resultant landform is driven by erosional coastal processes.	Cliffs are the most well known of all coastal erosional landforms.
Shore platform	This type of platform can take various forms and is a consequence of cliff retreat that creates a platform that extends seaward from the base of the cliff.	Rock or tide pools are commonly associated with shore platforms.
Beach	The most familiar of all coastal environments and composed of loose, unconsolidated sand, gravel, and pebbles.	Because sand is highly mobile, beaches are able to readily change shape according to wave action.
Mudflat	Mudflats are located in the intertidal zone and comprise a high proportion of silt mixed with coarser sediment.	Mudflats occur in both estuarine and coastal areas where the deposition and retention of fine sediments are possible.
Coastal sand dune	Coastal sand dune systems occur landward of the shoreline, usually above the high-tide level, and mark the landward limit of marine influence on the coast.	Although these systems are formed primarily by aeolian processes, they are 'genetically' related to adjacent sandy beaches.
Rocky marine shore	Coastal shore that has a littoral substratum dominated by rock material.	The rocks can be in the form of large sheets/slabs and/or pebbles or boulders.
Sandy marine shore	Coastal shore that has a littoral substratum dominated by sandy sediments.	Sand particle size composition will vary according to the sediment source and wave sorting.
Polar ice shelf shore	Polar shore that consists of shelf ice that advances and recedes according to the season.	This type of shore is highly variable, in terms of both shape and extent.

Lagoons can be divided into two major categories, estuarine and coastal, with the former having a permanent or intermittent connection to the sea and the latter lacking such a connection. When these lagoons are examined more closely, it becomes apparent that numerous subcategories can be created on barrier type alone, for example, the stratigraphy of coastal barrier-lagoon systems in Maine (USA) are found in five distinct geomorphic forms, namely, barrier spits, pocket barriers, double tombolos, cusped barriers, and looped barriers (Duffy et al., 1989). Other authors have used different terminology and refer to leaky lagoons where the barrier between the lagoon and the sea is not continuous and involves water exchange between the two adjacent aquatic environments.

Tidal sand flats and mudflats are a feature of estuaries and coasts around the world. These coastal features are classified

according to the proportion of clay and silt mixed with coarser sediments, with sand flats comprising mainly sand particles and mudflats having a high proportion of clay and silt particles. Both types of flats are exposed at low tide and inundated at high tide. The formation and evolution of these intertidal habitats depend on a variety of factors, including local geology, sediment availability and mineralogy, shape and size of fringing wetlands, wave activity, tidal variations in water level, and current speed (Wolanski, 2007).

'Fan deltas' is a collective term for a number of different types of delta formations and are characteristically composed of coarse-grained sediment, rather than the finer material of a river delta (Haslett, 2009). Fan deltas are very varied in their morphology and three broad types have been recognized on the basis of gradient and water depth of the coastal shelf, namely shelf-type (shallow water) fan deltas, slope-type fan

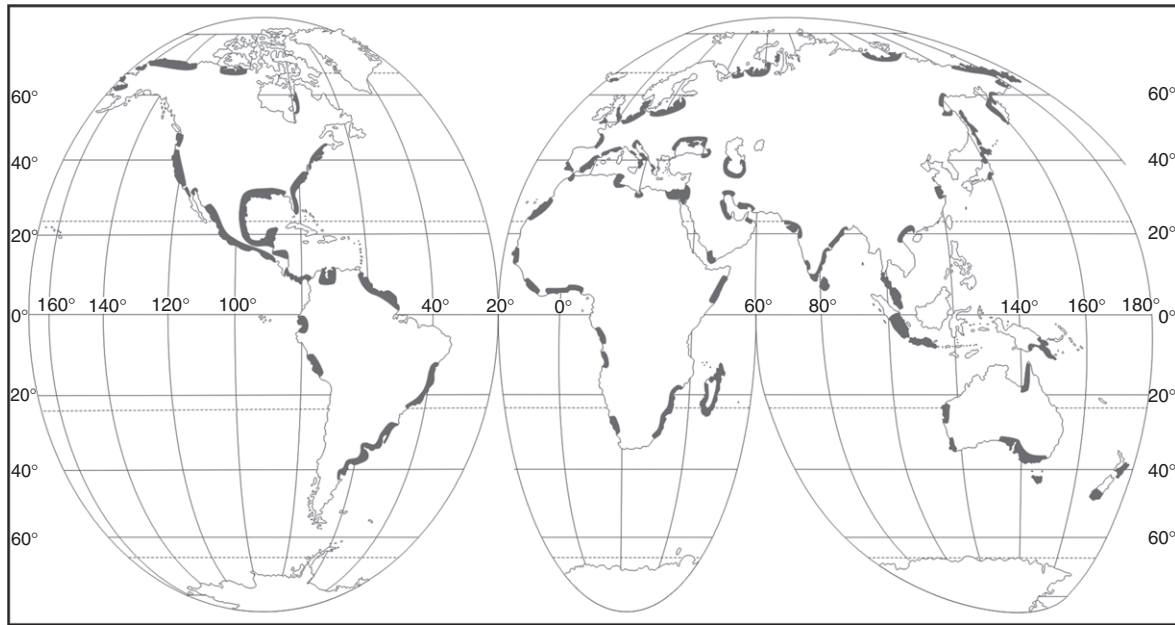


Figure 7 World distribution of major barrier/lagoonal coastlines. Redrawn from Barnes, R.S.K., 1980. *Coastal Lagoons*. Cambridge University Press, Cambridge, 106 pp.

Table 5 Extent of the world's barrier/lagoonal coastline

Continent	Length of barrier/lagoonal coastline (km)	Percentage of continent's coastline	Percentage of world's lagoonal coast
North America	10 765	17.6	33.6
Asia	7 126	13.8	22.2
Africa	5 984	17.9	18.7
South America	3 302	12.2	10.3
Europe	2 693	5.3	8.4
Australia	2 168	11.4	6.8
Total	32 038		

From Cromwell, J.E., 1971. Barrier coast distribution: a world-wide survey. 2nd National Coastal Shallow Water Research Conference, abstract, p. 50.

deltas, and Gilbert-type fan deltas (Reading and Collinson, 1996).

The level at which subsets of coastal classifications can be undertaken varies according to the discipline and resolution required. In some cases, even the pools on a rocky coast can be subdivided, based on their genesis and evolution. For example, De Pippo and Donadio (1999) identified 13 morphotypes of rockpools along Mediterranean coasts. Similarly, the paraglacial barrier systems on the New England (USA) coast also lend themselves to detailed classification, with Fitzgerald and Van Heteren (1999) recognizing six barrier-coastline types based on topography and geology, sediment abundance and size, exposure to wave and tidal energy, and sea-level history.

According to Fairbridge (2004), the simplest description of any given coast requires a minimum of three terms: (1) material (hard, soft; soluble), (2) agencies (erosive/constructive), and (3) historical factors (timescale). Agencies include the physico-

chemical, biological, and geographic setting (e.g., latitude, wave exposure) and historical factors cover the geological history of the coast (e.g., geotectonic, eustatic). The above approach appears to be sufficiently broad and flexible to be applied on a global scale.

Finkl (2004) criticized the above simple classifications of coasts on the basis that they lack specificity. The increasing availability of information, especially digital formats in GIS frameworks, opens up opportunities to address the complex management demands of the modern world. Finkl (2004) proposed a new classification system that covers a 5–10-km width of the coastal fringe and incorporates all the important parameters necessary to categorize geomorphic units at the appropriate scales. The approach employs differentiating criteria for hard rock (automorphic) and soft rock (allomorphic) coasts, which are then divided by parameters related to the antiquity of littoral landforms as well as other features such as relief types (morphoregions), relief features, and relief elements. Although only geomorphological properties are considered in the above approach, this type of classification could, in combination with biotic and other physical attributes, provide a very useful way forward when high coastal resolution is required, using a multivariate approach.

From the above it is obvious that most coastal classifications have tended to focus on the physical rather than biotic characteristics of these environments. However, within the coastal zone a number of ecosystem types have been recognized and most of these are based on substratum (rocky shore, sandy shore, etc.), spatial position (intertidal, neritic, etc.), or the predominant plants (kelp beds, mangals, etc.) found within this zone. Some biota may even create ecosystems within the coastal zone (e.g., coral reefs) but most biota that occur within this zone are present as a result of adaptations to the various geomorphological features and physicochemical conditions prevailing in the different coastal environments.

The biological categorization of coasts has a long history, albeit dominated by rocky area features. Ballantine (1961) produced a rocky-shore classification whereby the organisms present were identified according to the tolerance to exposure and Erwin (1983) produced a 'taxonomic' classification for hard-substratum areas. These approaches have been used to categorize communities according to their substratum and depth preferences by Petersen in the early 1900s and Thorsen in the 1950s (details in Gray and Elliott (2009)). More recently, the idea of defining biological communities according to their associations and physical preferences was taken further by the biotope concept (e.g., Connor et al., 2004; Olenin and Ducrotoy, 2005) and then embodied in the European Nature Information System (EUNIS) habitat classification for European areas (EEA, 2007). These classifications, in which the dominant organisms, the assemblage members and the prevailing physical conditions are recorded and coded, then provide a tool for conservation and environmental quality managers.

1.07.4 Major Macrophyte Habitats within Coastal Ecosystems

As indicated earlier, habitats can be defined according to their dominant biota and this is especially the case for the major plant groups. The algal and macrophyte habitats (i.e., seaweeds, seagrass beds, salt marshes, and mangals) sometimes classified as ecosystems within the coastal zone (Carter, 1988) are as follows.

1.07.4.1 Seaweeds

This type of habitat complements that of reefs and both occupy similar niches within often high-energy, turbulent marine environments. Seaweed habitats are best developed

in high latitudes on rock or gravel coasts where temperatures do not exceed 20 °C. Most seaweeds are permanently attached to the substratum and are well adapted to survive extreme physical stresses imposed by waves and currents. Seaweed communities flourish in the intertidal and subtidal zones down to depths of 20–40 m, depending on light penetration. The relatively sheltered seaweed environment provides food and shelter to large numbers of marine invertebrates and fishes. However, most seaweed communities are species poor when compared to coral reefs, and they usually comprise a limited variety of well-adapted individuals (Carter, 1988; Little and Kitching, 2009).

Subtidal seaweed species are dominated by the kelps, of which three genera are common, namely *Laminaria*, *Ecklonia*, and *Macrocystis*. Kelp communities are highly productive and the particulate organic matter (POM) and dissolved organic matter (DOM) sustain a food web that can include high densities of abalones, crustaceans, and sea urchins. The balance between predators and prey in seaweed ecosystems plays a major role in preventing switches in ecosystem state (Mann, 1982).

Intertidal rocky shores are dominated by rockweeds, for example, *Ascophyllum*, *Cystoseira*, and *Fucus*. Although productivity potential is high, it is seldom realized because these algae greatly suffer from environmental stresses due to alternating immersion and emersion, desiccation, and concomitant changes in temperature and salinity. Moreover, rockweeds only photosynthesize below water so that productivity is restricted to periods when high tide and daylight coincide. Gastropods, bivalves, and crustaceans are all common inhabitants of rockweeds and their distributions are determined primarily by wave and current forces (Carter, 1988).

1.07.4.2 Seagrass Beds

Seagrasses are found in shallow estuarine and coastal waters in most parts the world (Figure 8). These plants usually occur in

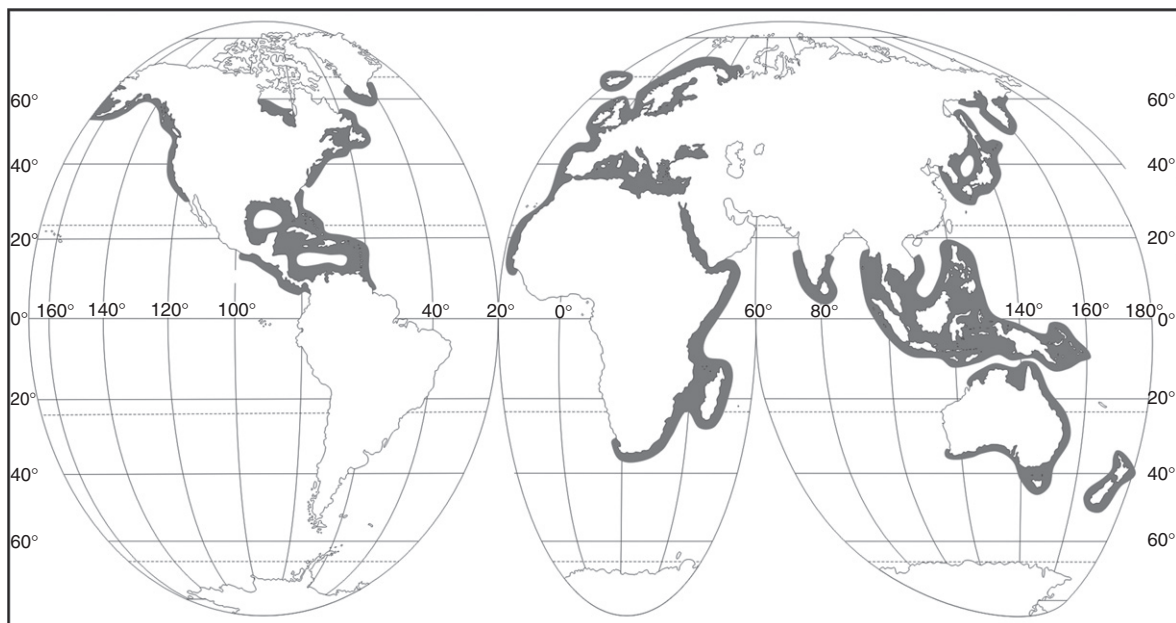


Figure 8 Worldwide distribution of major seagrass genera (e.g., *Zostera*, *Halophila*, and *Posidonia*) that occur in coastal systems. Modified from den Hartog, C., 1970. *The Seagrasses of the World*. North Holland, Amsterdam, Netherlands.

the shore zone stretching from the lower intertidal flats into water up to 4–5 m in depth, although the plants grow best in water 0.5–1.5 m deep where there is limited tidal and wave action (McRoy and Helfferich, 1977; Hogarth, 2007).

Seagrasses appear to be sensitive to temperature, turbidity, and saline stress, and are liable to sudden die-back or expansion as conditions change. Unlike kelps and rockweeds, seagrasses obtain most of their nutrient requirements from the sediment (Mann, 1982). Common seagrass genera include eelgrass (*Zostera*) in temperate regions and turtle grass (*Thalassia*) in the tropics. Some genera (e.g., *Ruppia*) occur in the appropriate biogeographical region in both the Northern and Southern Hemispheres.

The real importance of seagrasses is as a food supply and shelter for a wide range of invertebrates and fishes, with sea urchins, turtles, geese, and manatees all grazing directly on these plants. In addition there are numerous detritivores subsisting on the decomposing seagrass tissue and they are, in turn, preyed upon by various omnivores and carnivores (Carter, 1988).

1.07.4.3 Salt Marshes

Salt marshes are found in most extratropical regions of the world (Figure 9) wherever wave energy is low and there is a surplus of fine sediment. Salt marshes comprise salt-tolerant genera and, with few exceptions, tend to be habitats of low species diversity (Chapman, 1977). The maximum development of salt marshes occurs between the tidemarks with more species present in the higher than the lower marsh. At the lower limit, the inundation period limits growth and at the upper limit terrestrial species outcompete the marsh taxa (Carter, 1988).

Despite the global distribution of many genera, including *Spartina*, *Salicornia*, and *Juncus*, individual species are often very poorly distributed (Carter, 1988). Although some marshes are dominated by virtual monocultures, they appear to be reasonably immune to natural catastrophes, including temporary flooding by rivers and severe buffeting by wave action. Salt marshes also appear to be resistant to many diseases, pests, and consumers, with Pomeroy and Wiegert (1981) concluding that this was primarily because of the harsh physical and chemical regime within these habitats. However, large populations of a variety of resident crab species find food and shelter in salt marshes in many parts of the world.

Carbon budget studies have identified both carbon importing and exporting marsh systems. Export may be achieved by tidal flushing of dissolved organic carbon (DOC) and/or dissolved organic matter (DOM), or by animal migration involving fish, birds, insects, and crustaceans (Daiber, 1982). In this respect, marshes are sometimes important scavenging grounds for carnivores but vegetation grazing by herbivores rarely accounts for more than a small proportion of the total available biomass. The poor food value and/or low digestibility of salt marsh plants may play a role in this latter observation.

1.07.4.4 Mangals

Mangrove trees are most prevalent in coastal tropical and subtropical waters, extending between latitudes 30° N and 30° S (Figure 9), depending upon the presence or the absence of tropical or temperate ocean currents (Hogarth, 2007). They are able to colonize otherwise hostile shoreline environments by virtue of their halophytic and structural characteristics. Although anchored in intertidal and supratidal substrata, a high proportion of the mangal biomass is above the ground.

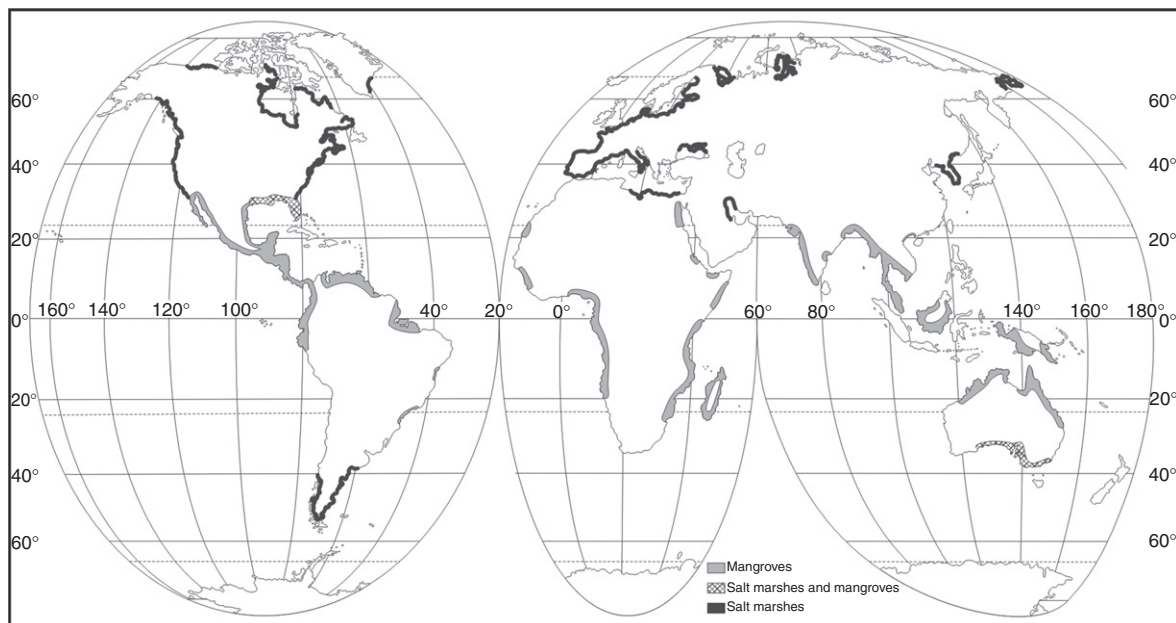


Figure 9 World distribution of salt marshes and mangrove swamps. Modified from Chapman, V.J. (Ed.), 1977. *Wet Coastal Ecosystems*. Elsevier, Amsterdam.

Both the tree trunks and root structures of mangroves provide a structural habitat that is utilized by fish and invertebrates for shelter, mostly at high tide.

Mangals form highly productive ecosystems capable of exporting energy and materials to adjacent areas and also support a diverse heterotrophic food chain, including fish, crustaceans, birds, small mammals, and numerous invertebrates (Odum and Heald, 1975; Hogarth, 2007). Some of these species are resident in the mangrove forests throughout their life cycle and others make use of this habitat only at particular stages.

As yet there have been few studies of nutrient cycling within these systems, although the pattern is likely to be very similar to that found in salt marshes. Odum and Heald (1975) have described a complex food web for mangals with indistinct trophic levels and many animals ingesting a wide variety of food. Very little of mangrove tree leaf production is grazed directly, with most leaves entering the food chain via the detritus cycle. Bacterial and fungal action elevates the nitrogen value of the detritus and this enriched food source is sought by resident and migratory detritivores (Carter, 1988).

1.07.5 A Global Approach to Classifying Coastal Ecosystems

Classifying estuaries and coastal ecosystems can be challenging and this is compounded by the diversity in terminology already in circulation (Table 4). Many of these systems reflect a continuum rather than discrete entities, and all types of coastal ecosystems (including estuaries) are occupied by mobile fauna that are often not confined to particular areas or habitats. This imparts another layer of variability to any coastal classification system (Elliott and McLusky, 2002).

Clearly, it is important for science to understand the basic processes that occur within estuaries and coastal ecosystems, and only by explaining the fundamental characteristics can we begin to understand the unique processes of a particular ecosystem. However, science cannot progress if every estuary or coastal ecosystem is seen as a unique coastal feature, especially as this would make it impossible to derive baselines or comparisons on a regional and global scale (Elliott and McLusky, 2002).

As mentioned previously, there are different levels of classification of estuaries and coasts depending mainly upon the number of criteria (e.g., geomorphology, hydrology, and biology) selected and the level of detail (e.g., local, regional, and global) required. The greater the number of criteria and the higher the geographical resolution, the more complex the classification becomes. Depending on the task or information required, a balance needs to be established between the number of criteria and the level of detail selected. For the purposes of this chapter, a global approach using broad criteria will be adopted.

1.07.5.1 A Primary Coastal Classification

1.07.5.1.1 Beach and intertidal flat ecosystems

Short and Wright (1983) defined six major sandy beach states that can be broadly categorized into three major types, namely, dissipative, reflective, and intermediate. Dissipative beaches

usually have relatively flat profiles and are often associated with spilling waves, whereas reflective beaches have steep profiles and are usually associated with plunging or surging breakers. Intermediate beach states lie between these two extremes. All the three beach types are characterized by highly mobile sands containing shifting populations of bacteria, protozoans, and metazoans. Periodic immersion serves to distribute nutrients and minerals throughout the communities (Brown and McLachlan, 1990).

There is very little primary production within the beach, although there are reports of diatom populations being present in intertidal sands (Easley et al., 2005). In sandy beaches, almost all organic matter is imported, either as dissolved (DOM) or in particulate (POM) form. Consumption of this material is largely by bacteria, rather than by herbivores or detritivores (Griffiths et al., 1983). Although the micro- and meiofaunal organisms dominate beach ecosystems numerically, there are often sizable populations of molluscs, polychaetes, isopods, and other invertebrates (McLachlan et al., 1981; McLachlan, 1983).

Most sandy beach ecosystems appear to act as major sinks (Koop and Griffiths, 1982) and those near marine macrophyte beds (e.g., kelps, rockweeds, and seagrasses) may receive large energy subsidies in the form of wrack lines, which in turn attract large faunal populations. These energy subsidies serve to emphasize the connectivity of coastal ecosystems.

Coastal mudflats are similar in structure to intertidal sand flats but differ primarily in that there is a much higher fine sediment component (e.g., silt) when compared to sandy shores. Mudflats have a higher organic content than sandy beaches and gradients tend to be low (with limited wave action) when compared to reflective or intermediate sandy beaches. The erosion of mudflats by water currents can be reduced by a surface layer of diatoms (biofilm) that produce extracellular polymeric substances that bind the sediments (Anderson, 2001). Conversely, bioturbation by burrowing animals has the effect of increasing the rate of erosion through destabilization of the sediments (Wolanski, 2007).

Mudflats are often associated with major river deltas and these ecosystems can be divided into three major categories according to whether they are river dominated, tide dominated, or wave dominated (Galloway, 1975). Criticisms of the river-tide-wave dominated model have been made because certain other parameters are not included in the categorization, for example, sediment grain size. Coastal mudflats are highly productive ecosystems that are utilized by a wide variety of consumers from microfauna, meiofauna, macrofauna, and fish to birds (Kuipers et al., 1981).

1.07.5.1.2 Rocky shore and reef ecosystems

Rocky shore and reef ecosystems can include cliffs, reefs, boulders, and pebbles together with the organisms that are attached to these substrata (e.g., Little and Kitching, 2009). There are a significant number of invertebrate taxa (e.g., oysters, serpulids, and bryozoans) that contain species capable of cementing their skeletons to the hard substrata provided by rocky shores and appear to benefit from the ecological advantages of dense packing (Fagerstrom, 1987). Although mature rocky reef ecosystems with an abundance of sessile fauna can take on the form of a marine organic reef similar to a coral reef,

they are classified here as being part of a primarily inorganic rocky shore ecosystem. This ecosystem can be divided into supralittoral, eulittoral, and sublittoral zones (Mathieson and Nienhuis, 1991; Gray and Elliott, 2009). The eulittoral is often further subdivided into the upper, middle, and lower eulittoral zones, which sometimes follow a biotic descriptor according to the dominant biota found in each band, for example, upper barnacle, mid-shore brown algal, and lower red algal zones (Foster et al., 1991).

Another type of rocky shore classification is based on two primary divisions, rocky intertidal and rocky subtidal ecosystems. The rocky intertidal ecosystem can be divided into four zones: the splash zone, high intertidal, middle intertidal, and low intertidal (Ricketts et al., 1985). The above classification has been used extensively on the northeast coast of America (Foster et al., 1991).

The geographical distribution of kelp forests (Figure 10) is very roughly complementary to that of coral reefs (Figure 11), kelps being limited in general to latitudes

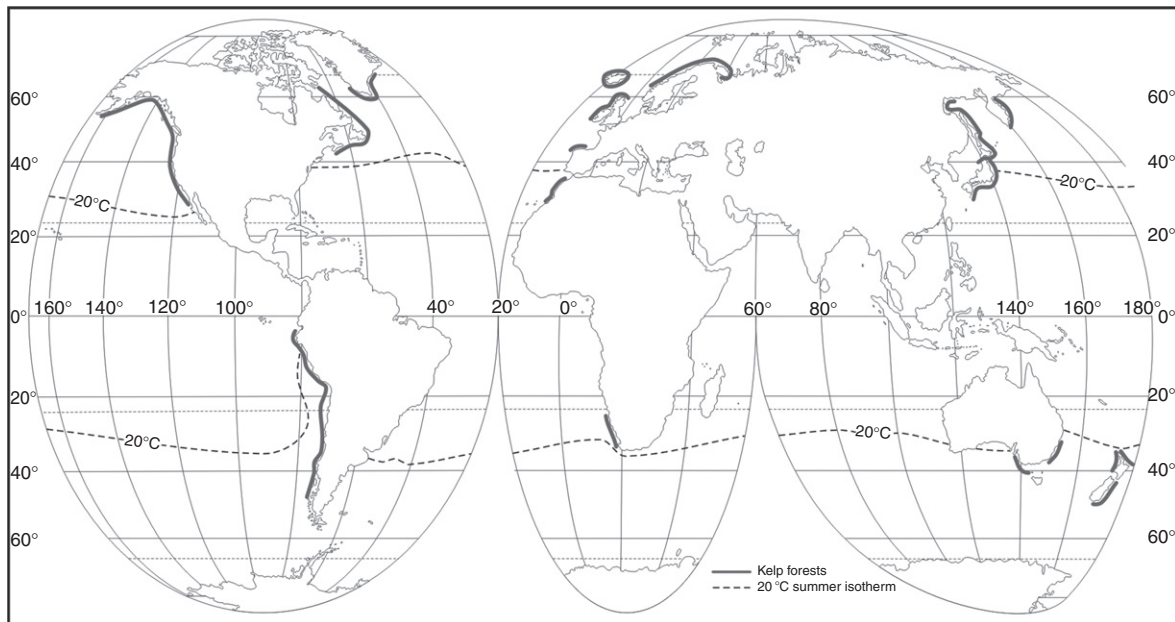


Figure 10 World distribution of major kelp forests. The 20 °C summer isotherms are shown. Redrawn from Mann, K.H., 1973. Seaweeds: their productivity and strategy for growth. *Science* (NY) 182, 975–981.

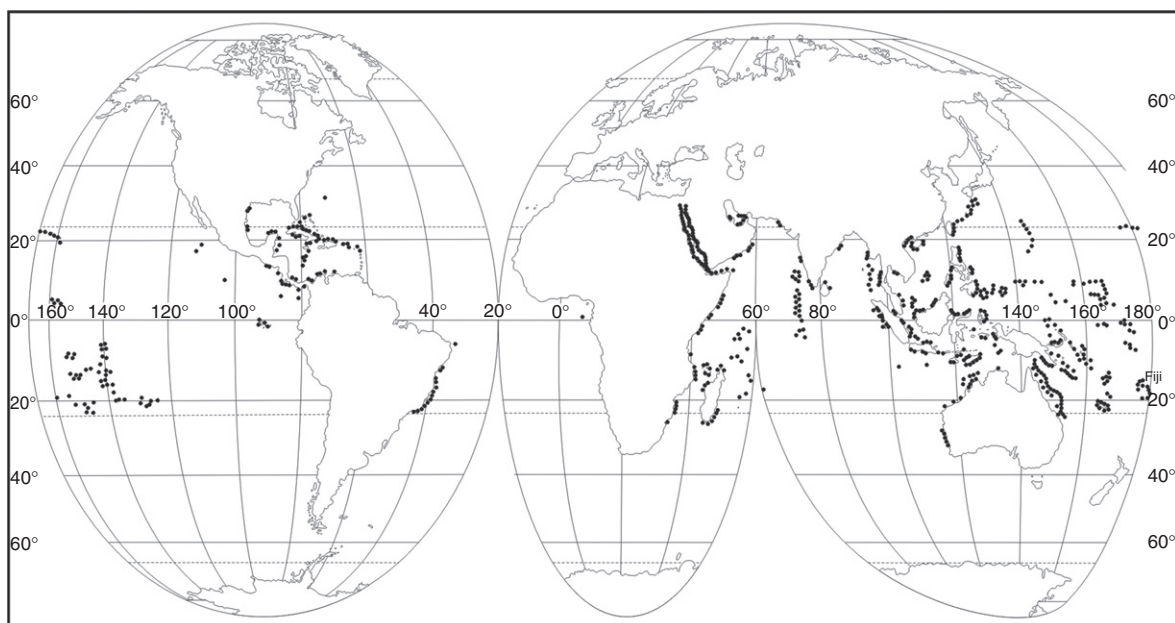


Figure 11 World distribution of coral reefs. Redrawn from Schumacher, H., 1976. *Korallenriffe*. BLV, Munich.

between the subpolar regions and the 20 °C summer isotherms, and corals to latitudes within the 20 °C winter isotherms. Extension of kelps into subtropical latitudes is facilitated by cold currents, usually associated with upwellings such as the California Current, Peru Current, and Benguela Current that flow along the coast toward the equator (Barnes and Hughes, 1999).

1.07.5.1.3 Coral reef ecosystems

Coral reefs occur in tropical waters (Figure 11) but may extend into subtropical latitudes depending on the presence of warm currents, for example, the Agulhas Current along the southeast coast of Africa. Coral reefs are usually of three main types: fringing reefs that follow shorelines and are inshore, barrier reefs that are also associated with land masses but develop at a much greater distance from the shore, and atolls that are horseshoe- or ring-shaped reefs surrounding a subcircular lagoon (Achituv and Dubinsky, 1990).

On a local scale, reef morphology is determined primarily by the interaction of water current direction and intensity (Done, 1983). As currents are also the main source of plankton upon which the corals feed, local flow patterns have great importance in shaping the mesoscale topography of reefs. In addition, there is some evidence to suggest that plankton-enriched currents and the associated fish schools feeding on them stimulate the growth of coral colonies on reefs (Hamner and Hauri, 1981).

Growth of hermatypic corals is limited by water temperature and the availability of sunlight to enable symbiotic zooanthallic algae to photosynthesize. The mean annual water temperature requirement is generally considered to be 18 °C (Carter, 1988). Coral growth is greatest in clear water less than 10 m in depth (Buddemeier and Kinzie, 1976), but may continue to 25–30 m with sufficient light penetration. Hermatypic corals of the class Scleractina are responsible for building massive tropical reef structures such as the Great Barrier Reef, the Red Sea reefs, and the numerous oceanic atolls (Carter, 1988).

1.07.5.1.4 Coastal lagoon and lake ecosystems

Although many authors (e.g., Barnes, 1980) have placed estuarine and coastal lagoons within the same category, the very different nature of their biota and ecosystem functioning necessitates their separation (Table 4). Coastal lakes and lagoons are ecosystems that have been cut off from the marine environment by sand or gravel spits. In some cases, these systems may have evolved from estuarine lagoons and lakes that have lost their linkage to the sea and become either brackish or fresh. Others may have evolved from offshore shoals or barrier islands (Carter, 1988) that subsequently formed a continuous link and then isolate the previously partially enclosed water body.

By virtue of the absence of a direct link with the sea, all nutrients and detritus entering coastal lagoons and lakes are 'trapped' within the system. This has the potential to make these ecosystems highly productive, depending upon nutrient supplies from freshwater streams, aquifers, or groundwater. Unfortunately, the severing of the sea connection results in an overall reduction in aquatic biodiversity due to the loss of marine species from the lagoon or lake. The coastal lakes and lagoons where the salinity declines such that they become

brackish or even fresh are then colonized by a mainly freshwater biota (Allanson et al., 1966).

1.07.5.1.5 Ice shelf ecosystems

These poorly studied coastal ecosystems are seasonally changing according to the freezing and thawing of polar waters. When polar ice sheets start to melt in spring the freshwater runoff, which may flow over a land or ice basement, mixes with the surrounding seawater to create TWs that sustain a variety of aquatic invertebrates, fishes, birds, and mammals. Refreezing of the Arctic and Antarctic ice shelf perimeter in autumn and winter results in a temporary loss of the 'estuarine' component of these coastal habitats.

Although polar ice shelf ecosystems have very few species, some of these (e.g., Antarctic krill) reach a high biomass and support large colonies of penguins, seals, and birds that feed on these resources (Benninghoff, 1987).

1.07.5.2 A Primary Estuarine Classification

Estuaries are very diverse, not so much in terms of their origins, but rather in form and extent. However, all estuaries still have a set of unifying characteristics, with the variation usually attributable to local modifications subsequent to original formation (Reid and Wood, 1976). Having identified certain key physicochemical features, which influence the biota of estuaries around the world, it is concluded here that the geomorphology (especially estuary morphometrics and mouth dimensions) and hydrography (especially river flow and salinity) of estuaries should be the initial drivers of a classification system for these systems. Based on the above, it is possible to divide global estuaries into three primary physiographic categories:

1. *Valley estuary ecosystems (includes drowned river valleys, fjords, fiords, firths, estuarine bays, and some tectonic estuaries).* This type of estuary is located in a drowned river valley and can consist of a single channel, in which case the estuary is said to be simple (e.g., Delaware estuary). Where the drowned valley has numerous tributaries in its lower reaches, flooding of these tributaries results in an irregular estuary (e.g., Chesapeake Bay) with many channels (Reid and Wood, 1976). The prevailing salinity regime of this type of ecosystem is typically estuarine and seldom hyperhaline.

2. *Estuarine lagoon and lake ecosystems (includes blind estuaries, some bar-built and intermittently open estuaries, many coastal plain estuaries, and some estuarine embayments).* This type of estuary is usually located on a coastal plain where there is a strong supply of marine sediment giving rise to barrier beaches, dunes, or bars. These systems are usually characteristic of, but not restricted to, shores of emergence (Reid and Wood, 1976). The prevailing salinity regime of this type of ecosystem is typically estuarine but can range from oligohaline to hyperhaline, with the latter state often being recorded in semiarid/arid areas.

3. *River mouth ecosystems (includes river mouths, delta front estuaries, and deltaic formations).* This type of estuary is completely dominated by riverine influences and may take the form of a single-mouth (e.g., Kunene) or multiple-mouth estuary (e.g.,

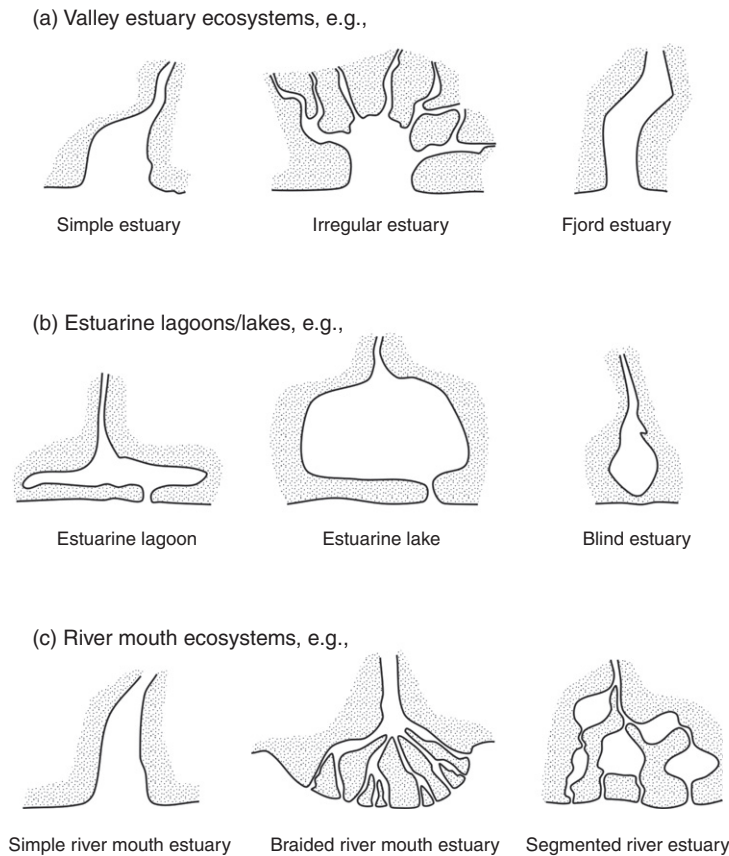


Figure 12 Examples of the three primary types of estuarine ecosystems: (a) valley estuaries, (b) estuarine lagoons/lakes, and (c) river mouths.

Mississippi). The prevailing salinity regime in this type of ecosystem is typically freshwater or oligohaline and conditions can range from riverine to estuarine.

Examples of the above three estuary types are shown in [Figure 12](#). Detailed subdivision of the above types into more specific subsets is encouraged, depending on the objectives of the particular study or conservation plan.

1.07.5.3 Secondary Classifications of Estuaries and Coasts

[Elliott and McLusky \(2002\)](#) make the very important point that estuarine management protocols and tools, such as classification systems, comparisons against reference conditions, modeling, and reporting and communication of results, all require an agreed and comprehensive system of definitions and classification. Environmental legislation increasingly requires scientists to provide concise information for lawyers and planners, and this will require high-level approaches to estuarine classification that are suitable to the aims and objectives of the legislation.

Detailed classifications of estuaries and coasts are possible and this is usually undertaken using particular features or processes within a biogeographic region or country. [Harrison and Whitfield \(2006b\)](#) examined three estuarine types in South Africa and were able to show, using multivariate analysis of fish catches in 190 estuaries, that each estuary type contained

somewhat distinct communities. These estuarine types are specific to South Africa and have also been used, together with the associated fish assemblages, to assess the 'health' of these systems ([Harrison and Whitfield, 2006a](#)).

A similar detailed approach to the classification of estuaries as a precursor to management and policy decisions was undertaken by [Ward et al. \(1998\)](#). They developed estuarine and coastal definitions applicable to Australia and then decided on indicators that included both physical and biological features. These features included important functional elements such as water flow, substratum types, habitats, species, and biodiversity. As discussed earlier, [Edgar et al. \(2000\)](#) adopted a similar high-level approach to estuarine classification in Tasmania by using physical, ecological, and demographic attributes of these systems.

Although most coastal classification models have tended to separate the hinterland from estuaries and the actual coast, [Clark \(1978\)](#) proposed that the coastal zone should be separated into shorelands (which extend far inland) and coastal waters, each of which has numerous subcategories and ecotones. Perhaps this type of classification is more useful for managers and planners than the more aquatic littoral ecosystem approach adopted by biologists and ecologists.

As suggested above in the description of biotopes, it is questioned whether the biota of different coastal ecosystems can and indeed should provide a basis for classifying and

separating these systems. For example, the estuarine biotope is not simply a result of an overlapping of factors extending from the sea and the land; there is also a unique set of intrinsic drivers provided by materials and forces contributed by its immediate environment (Carriker, 1967). This is especially the case in large estuaries or those systems that have a high degree of isolation from marine hydrodynamics and where riverine influences do not extend to the estuary mouth.

However, in those coastal water bodies where the isolation from the marine and riverine environment becomes complete, as is the case with coastal lagoons and lakes, the aquatic species composition changes completely (Allanson et al., 1966). As a generalization, marine taxa disappear when the water body becomes isolated and their vacated niches are then occupied by freshwater species if a stream or riverine connection to the system exists.

Rocky and sandy shore ecosystems often overlap and there are a number of fish species that will move between these habitats, depending on life stage or feeding opportunities (Afonso et al., 2008; Freire et al., 2009). Perhaps the ecosystems and habitats that will 'leak' the most are those that are used extensively as nursery areas by both fish and invertebrate species (e.g., estuaries and mangals). Similarly, there can be strong diel and seasonal movements of biota between coral reef ecosystems and adjacent seagrass beds (Nagelkerken et al., 2008; Luo et al., 2009).

Table 6 provides a very useful overview of the major coastal ecosystems and the primary physical drivers that influence the biota within these areas. The table also highlights selected plant habitats within the coastal zone that are sometimes also referred to as ecosystems (e.g., Carter, 1988). As a generalization, those ecosystems or habitats with the greatest physical variability (e.g., estuaries and sandy shores) have the lowest species diversity within a particular biogeographic zone. Although coral reefs and mangals have a relatively low physical variability (Table 6) and a high species diversity, both these ecosystem types are situated in the tropics or subtropics where rich biodiversity prevails. Conversely, coastal lagoons and lakes in the tropics also have low physical variability but biotic diversity within these ecosystems is reduced due to the

inability of marine species to colonize these habitats. In contrast, estuarine lagoons and lakes, although being subject to greater physical variability (Table 6), usually have a higher biodiversity than equivalent-sized habitats that have been isolated from the sea.

Apart from the biogeographic locality and prevailing physicochemical environment influencing biotic diversity within the coastal zone, the maturity of ecosystems over time is also important. In more mature communities (e.g., coral reefs), many species are congeneric, having evolved together for mutual benefit (Carter, 1988). This contrasts to estuaries, or more specific habitats such as seagrass or salt marsh beds, where there are few species that are congeneric. Perhaps this lack of congeneric associations in the latter environments is partially a function of the ephemeral nature of these particular habitats and ecosystems.

Estuarine ecosystems can be characterized by relatively few species, but these species may be very abundant. Several authors have attempted to explain this low biodiversity and Sanders (1968) developed a theory based on the stability or predictability of the environment as well as its geological history. The main elements of this theory, as applied to the zoobenthos of estuaries, are as follows:

1. In estuaries, the environmental drivers usually show an unstable and unpredictable behavior.
2. Speciation is less probable and extinction is more probable in estuaries than in more stable environments.
3. Estuaries are geologically ephemeral phenomena, thus increasing the likelihood of extinction.

Elliott and Quintino (2007) and Gray and Elliott (2009) suggested that this was the result of the prevailing stressful conditions and that while physicochemical stress (such as salinity) reduced the number of species, for those taxa that could tolerate these stressors they were often present in high abundances. For the above-mentioned reasons the number of species adapted to the estuarine environment is generally lower than in either the adjacent marine or the freshwater environment. This theory has been supported by studies on other estuarine taxa, for example, fishes (Whitfield, 1994).

Table 6 Some selected physicochemical characteristics of identifiable littoral coastal ecosystems and plant habitats

<i>Coastal ecosystem</i>	<i>Salinity regime</i>	<i>Temperature regime</i>	<i>Turbidity regime</i>	<i>Tidal regime</i>	<i>Wave regime</i>
Sandy shore	Marine	Tropical/temperate	Low/variable	Present (intertidal/subtidal)	Variable/high
Muddy shore	Estuarine/marine	Tropical/temperate	High/variable	Present (intertidal/subtidal)	Variable/low
Rocky shore/cliffs	Marine	Tropical/temperate	Low/variable	Present (intertidal/subtidal)	Variable/high
Coral reef	Marine	Tropical	Low	Present (intertidal/subtidal)	Variable
Estuary	Estuarine	Tropical/temperate	Variable	Usually present (supratidal/intertidal/subtidal)	Low/variable
River mouth	Riverine	Tropical/temperate	High/variable	Present (supratidal/intertidal/subtidal)	Low/variable
Estuarine lake/lagoon	Estuarine/hypersaline	Tropical/temperate	Low/variable	Sometimes present	Low/variable
Coastal lake/lagoon	Freshwater/brackish	Tropical/temperate	Low	Absent	Low/variable
<i>Plant habitat</i>	<i>Salinity regime</i>	<i>Temperature regime</i>	<i>Turbidity regime</i>	<i>Tidal regime</i>	<i>Wave regime</i>
Kelp forest ^a	Marine	Temperate	Low	Present(subtidal)	Variable
Seaweed ^a	Marine	Tropical/temperate	Low	Present (intertidal/subtidal)	Variable/High
Seagrass beds ^a	Marine/estuarine	Tropical/temperate	Low	Present (intertidal/subtidal)	Variable/Low
Salt marsh ^a	Marine/estuarine	Temperate	Low/variable	Present (supratidal/intertidal)	Low
Mangal ^a	Marine/estuarine	Tropical	Variable	Present (supratidal/intertidal)	Low

^aThese plant habitats are sometimes referred to as ecosystems and occur within physical coastal systems.

From the above discussion it becomes apparent that species diversity and associations cannot be used to distinguish all coastal ecosystem types. However, this approach will be a useful tool when comparing the structure and functioning of adjacent ecosystems (e.g., sandy shores and coral reefs) or classifying systems according to broad ecological characteristics (e.g., low species diversity but high productivity).

Can nutrient and productivity characteristics of coastal ecosystems be used as a classification tool? Ecosystem linkages involve the flow of nutrients and energy. In a coastal context, many of these are achieved with the direct assistance of physical processes – breaking waves and tidal currents being two examples (Carter, 1988). Nutrients are constantly reused, and in some coastal ecosystems recycling is highly efficient and sophisticated, for example, coral reefs. However, in estuaries, recycling appears to be less important and export of both nutrients and energy to the marine environment can be very high, especially following river flooding.

There is also considerable transfer of nutrients from one coastal system to another; indeed, ecosystems of relatively poor nutrient status often import from adjacent higher nutrient producers. For example, rivers and estuaries on the east coast of South Africa are important suppliers of nutrients to the adjacent oligotrophic marine pelagic waters (Heydorn et al., 1978).

Productivities ($\text{g-C m}^{-2} \text{yr}^{-1}$) of some coastal habitats and ecosystems are given in Table 7. Although the minimum recorded net production values show a high degree of variation, and would be dependent on the size and density of the plants in a particular habitat, maximum values are not that dissimilar. What these figures do highlight, however, is the relatively high productivity of both estuarine and coastal ecosystems.

The exchange of nutrients and productivity between estuaries and other coastal ecosystems depends upon a variety of

factors, not least the spatial separation between the systems. Turbid estuaries in the tropics or subtropics will seldom occur in the vicinity of coral reefs and therefore the connectivity between these two ecosystem types is likely to be very weak. In contrast, turbid tropical estuaries often have a close association with coastal mangrove systems and there may even be a complete overlap in habitat types. Similarly, the movement of invertebrates, fishes, and birds between these latter ecosystems is likely to be high and will result in elevated exchanges of both nutrients and energy. Therefore, any classification scheme based on nutrients and productivities is unlikely to be useful in distinguishing these estuarine and coastal ecosystems.

Wolanski et al. (2004) have proposed that from a management perspective the estuary should be viewed from the catchment headwaters to the coastal zone and not be confined to estuarine waters *sensu stricto*. This ecohydrology concept recognizes that estuarine ecosystem health is driven by links between the biology and physics, and that the best course of action to assist the estuary to cope with human stresses is to use a combination of physical and biological interventions that increase the system robustness (Wolanski, 2007).

1.07.6 Coastal Classifications and Climate Change

Both estuaries and coasts and their connectivity will be affected by climate change, particularly eustatic changes in sea level. Sea-level fluctuations have the potential to alter the classification of individual estuary types as the shape and nature of the coastline change under scenarios of inundation or exposure of coastal land forms. Some estuaries could increase and others decrease in size, depending upon the nature and shape of coastal forms surrounding the existing system. Similarly, a decline in sea level on a rocky coast has the potential to expose extensive sandy subtidal sediments, or expose subtidal rocky areas on a sand coast. Under both the above scenarios, there will be major changes in coastal classification for these regions and for ecosystem functioning. However, in most cases, increasing sea levels will merely make a coast or estuary migrate landward unless the inner/upper boundaries have been constricted by human actions and infrastructure. Hence, the estuaries may still look the same but will be further inland, and new river mouths and lagoons may be created.

Conversely, coastal coral reefs could be more greatly and adversely affected by a rapid rise in sea level, as they would be unable to grow fast enough to keep pace with the rising oceans (Potts, 1985). In addition, increasing water temperatures associated with global warming places further stress on corals in tropical regions because these biota live at temperatures only a few degrees below their upper lethal limit (Johannes, 1975). Coral bleaching has become a recurrent problem in some areas over the past few decades and could result in the loss of coral reefs in some areas (Oliver, 1985). Newell (1971) suggested that climatic changes affect coral reefs at the periphery of their distribution where the most recently evolved genera would not yet have developed physiological tolerance allowing them to resist suboptimal climatic conditions.

Changes in rainfall associated with climate change will not only have a direct impact on estuarine ecosystems, but also affect the transport of organic and inorganic material into coastal ecosystems and therefore influence their functioning.

Table 7 Net productivity comparisons for selected coastal plant habitats and ecosystems

Plant habitat	Productivity range ($\text{g-C m}^{-2} \text{yr}^{-1}$)
Kelp forests	1500–3000
Salt marshes	100–1650
Seaweeds	800–1500
Seagrass beds	60–1500
Mangals	350–1200
Coastal ecosystem	Mean productivity ($\text{g-C m}^{-2} \text{yr}^{-1}$)
Coral reefs	2100
Intertidal algal beds and subtidal reefs	2000
Estuaries	1800
Coastal upwelling zones	500
Continental shelf	360

Data from Barnes, R.S.K., Hughes, R.N., 1999. An Introduction to Marine Ecology. Blackwell, Oxford, 286 pp.; Carter, R.W.G., 1988. Coastal Environments. An Introduction to the Physical, Ecological and Cultural Systems of Coastlines. Academic Press, London, 617 pp.; Day, J.W., Hall, C.A.S., Kemp, W.M., Yáñez-Arancibia, A., 1989. Estuarine Ecology. Wiley, New York, NY, 558 pp.; Dawes, C.J., 1981. Marine Botany. Wiley, New York, NY.; Kennish, M.J., 1976. Ecology of Estuaries. Volume 1, Physical and Chemical Aspects. CRC Press, Boca Raton, FL. McLusky, D.S., 1981. The Estuarine Ecosystem. Blackie, Glasgow, 150 pp.; Wiegert, R.G., 1979. Ecological processes characteristic of coastal *Spartina* marshes of south-eastern USA. In: Jefferies, R.L., Davy, A.J. (Eds.), Ecological Processes in Coastal Environments. Blackwell, Oxford, pp. 469–490.

Similarly, changes in river flow and land erosion associated with climate change will have a direct effect on all coastal ecosystems, especially coral reefs.

Seagrasses are distributed over most of the globe (Figure 8), wherever there is suitable shallow water but salt marsh and mangrove swamp habitats replace each other geographically (Figure 9). Salt marshes typify cooler and/or drier coasts and mangrove swamps hot, wet areas (Barnes and Hughes, 1999). If climate change were to alter the balance between tropical and temperate waters, it can be expected that the distribution of salt marsh and mangal ecosystems would change accordingly. Perhaps the first sign of ecosystem shift would occur in those areas where both vegetation types are present along the same stretch of coastline, for example, southeastern Australia and eastern South Africa.

A major difference between salt marshes and mangrove swamps on the one hand, and seagrass meadows on the other, is that the first two are intertidal and rarely extend below mean tide level, whereas the seagrasses extend well below low water (Barnes and Hughes, 1999). If climate change results in major changes to sea level and hence coastal topography, then the vertical distribution and spatial extent of all these plant habitats will be affected. If sediment supply into a salt marsh system is sufficient to balance sea-level rise, the salt marsh will emerge and survive; however, if the rate of accretion is less than the rate of sea-level rise, the salt marsh will submerge and drown (Reed, 1995).

Climate change will also have a major impact on the classification and ecology of polar coastal regions, mostly associated with elevated precipitation and river discharge, as well as increased rates of glacial and sea-ice melting. The freshening and stratification of Arctic coastal shelf waters have already been linked to changes in the abundances and seasonal cycles of phytoplankton, zooplankton, and higher-level consumer populations (Greene et al., 2008). Similarly, Clarke et al. (2007) have documented how the Antarctic Peninsular is experiencing one of the fastest rates of regional climate change on the Earth, resulting in the collapse of ice shelves and thus having a direct impact on the coastal marine fauna, principally through shifts in the extent and timing of habitat for ice-associated biota. These climate-change impacts are not restricted to the polar coastal zone and are also likely to cause changes in the productivity of offshore marine ecosystems in both the Arctic and Southern Ocean waters (Weller, 1998).

From the above it is apparent that in the short to medium term (thousands of years), the classification of both estuaries and other coastal ecosystems is likely to be modified at a local level as a result of climate change, driven primarily by the effect of sea-level changes on these systems and habitats. Some estuaries and coastal features will simply change position in a slightly modified form, whereas others will be completely transformed due to geological and/or geomorphological characteristics of each locality.

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