Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology 53
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Chapter 2

DEFINITIONS AND GEOMORPHOLOGIC CLASSIFICATIONS OF ESTUARIES

GERARDO M.E. PERILLO

All sciences started with Philosophy asking the questions, and they spread out on the minds of humanity. When all answers are achieved, everything will collapse again in Philosophy.

INTRODUCTION

In the last 40 years many definitions and classifications of estuaries have been put forward. Before attempting to develop a new definition, I analyzed more than 40 different ones provided by common dictionaries and encyclopedias as well as by specialist in the different disciplines associated to estuaries. A structured account for disciplines of the most important definitions is given in the Annex 2-1.

From definitions found in dictionaries and encyclopedias it is sometimes difficult to obtain any valid interpretation of their actual meaning. This is specially true for dictionaries. However, in thematic encyclopedia the problem is not the lack of a clear definition but the contradiction among them, even though they may pertain to the same collection. The contradictory and interpretative problems are not language constrained since examples given in the Annex cover the three most common languages in the western hemisphere. The only difference is that in Spanish, the term *ría* is employed more often than *estuario* to represent the same thing, although this is only valid in Spain since in Latin American countries only the latter is used.

Most dictionary definitions and some others restrict an estuary to the mouth of a river or a tongue of the sea reaching inland. While others may carry the estuary out to the continental shelf (Ketchum, 1951) or even include all the Northern Pacific Ocean (McHugh, 1967) as long as there is dilution of sea water or the presence of euryhaline species. Between these extremes, there is a wide range of alternatives that may be grouped within specific disciplines. However, estuaries are no longer the domain of any individual discipline. Within the last 15–20 years, it has been evident that interdisciplinary research is needed to obtain an adequate understanding of a single estuary, or even of a particular reach within an estuary.

The lack of a definition that covers all the characteristics of estuaries, nevertheless, has not prevented researchers from studying them. On the contrary, despite the multiplicity of definitions our knowledge of world estuaries has been increasing steadily. Notable progress can be measured by the number of papers published every year in scientific journals, and the growing number of books that are concerned with the subject. Most major publishers have a book collection related to estuaries.

Then, if we have lived without a single, comprehensive definition that covers all

aspects of estuarine characteristics, why to bother in making one? The answer lies in urgently needed management and legislation (see, for instance, the definition used in the US Public Law 92-500, Annex) of estuaries and other coastal environments. From the viewpoint of coastal management, it is necessary to have a unambiguous, mutually exclusive definition that can provide a clear understanding of these coastal bodies, but also give an adequate framework to establish administrative priorities, pollution control, fishery regulations, recreation facilities among other things. In addition when multi and interdisciplinary research are planned, it is required that all components of the team should have the same understanding of the water body to be explored.

Looking back to the relatively short history of estuarine research, I am convinced that no definition will ever satisfy all members of the estuarine community. Nevertheless, for over 25 years, Cameron and Pritchard's (1963) definition (a modified version of the original Pritchard (1952) definition) has been used by many specialists. Although this has many interesting and useful features, as we will discuss in the following section, it has some shortcomings that impede a better generalization.

The aim of the first part of the present article is to provide a new and more comprehensive definition that essentially covers all disciplines involved in estuarine research. The second part of the chapter will deal with a new morphogenetic classification. The latter is based on a structured relationship between the form and the origin of the different morphological constituents of estuaries. The interaction between the marine and terrestrial forces in shaping the present morphology is also considered. As an introduction to the new classification, a discussion of previous classifications is also presented.

PREVIOUS DEFINITIONS

From a general viewpoint, one can say that each estuary is unique since every estuary has its own intrinsic characteristics that make it different from all the others. Consequently, as it happens with other objects, to establish a definition and classification is a very hard task. However, we need a base from which to proceed. Etymologically, estuary derives from the latin word *aestus* which means "of tide". That is to say that the term estuary has to be applied to any coastal feature in which the tide has special significance.

Although estuaries may be regarded only by their physiographic parameters: that is, their geomorphology and hydrology, their biological and chemical components should also be considered. Any comprehensive definition must necessarily include these aspects. Definitions presently available to the estuarine researcher do not fulfil all these criteria.

Each of the many disciplines that study estuaries has at least one definition, but normally one can find between three and ten different definitions. Some of them are strongly contradictory. The variety of definitions within one discipline may be due to several reasons, but the two most important may be: 1) different background of the researchers producing the definition, and 2) the location of the estuaries upon which their definition is based (Perillo, 1989b). An example

can be drawn from the existing geological and physical definitions. For instance, coastal plain estuaries are better known than other estuaries, and most definitions and classifications implicitly consider them as the classical estuaries. Perhaps most geomorphologists have considered only those estuaries associated to a typical river mouth (Lyell, 1834; Lee, 1840: both in Schubel and Pritchard, 1972). This bias is reflected in most dictionary definitions (Annex 2-1) as well as in many of the early definitions of estuarine oceanography. Fairbridge (1980) calls attention to this point when he discussed the definition by Pritchard (1967): "This [the definition] excellently describes certain estuaries familiar to him, but it has totally lost the original, and critical, tidal and river qualifications. ... Pritchard's model is thus completely unrealistic for a globally acceptable definition".

A general review of geomorphological and dynamical estuarine definitions was made by Schubel and Pritchard (1972). They analyzed more than ten classical definitions introduced by geologists, geomorphologists, geographers, physical oceanographers and biologists. Even though all of them address important characteristics of estuaries, the authors consider that all these definitions are "either too exclusive or too inclusive". Schubel and Pritchard (1972) make a case in favour of the definition given by Pritchard (1967). The later is also the most common used in physical oceanography (e.g., Dyer, 1973; Officer, 1976); but also in several biological textbooks (e.g., Perkins, 1974; McConnaughey and Zottoli, 1983). Nevertheless, it is necessary to comment that the first definition by Pritchard (1952) was different from the later one, since it indicated that

> "An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea water."

Obviously this definition expands upon the first physical and chemical definition of estuaries that I was able to detect: that given by Ketchum (1951) as

> "An estuary is a body of water in which the river water mixes and measurably dilutes sea water."

The first mention of the newer version definition was made in a review paper by Cameron and Pritchard (1963) (hereafter CP); although is common usage to attribute it to the second author. Their definition says:

> "An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and within which sea-water is measurably diluted with fresh water derived from land drainage."

This definition addresses four major characteristics of estuaries, from which others concepts have to be implied.

1) The estuary is a coastal feature corresponding to a morphologically controlled (semi-enclosed) water body but always open to the sea. This means that its lateral borders have to be clearly defined and have also a strong influence on the circulation within the feature.

2) There must be a continuous provision of salt water coming from the adjacent sea. The salt is introduced into the estuary either by advection or diffusion.

3) The dilution of sea water must be measurable.

4) Fresh water is generally provided by rivers and creeks discharging into the body of water. But non-channelized sources like groundwater cannot be forgotten, especially in sandy shores with large precipitation rates (e.g., Biscayne Bay; Bly Creek, Kjerfve and Wolaver, 1988).

Day (1980) introduces an important variation over CP's definition. Again the influence of the type of estuaries in which the author has worked becomes a substantial constraint in the elements contained in the definition:

> "An estuary is a partially enclosed coastal body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of sea water with fresh water derived from land drainage."

The above definitions do not take explicitly into account one of the most important features of estuaries, and from which derives its name: *the tide*. It is apparent from both definitions that the tide was averaged out and only the time-mean salinity structure and the gravitational circulation are considered. It is thus, that the mean salinity distribution is actually the basis for Pritchard's physical classification (Pritchard, 1967). Nevertheless, the tide is the major mechanism providing energy input for mixing in practically all estuaries. Sometimes wind influence may overpower tidal mixing (e.g., Oden estuary, Bokuniewicz, pers. commun., 1993) although this is normally related with local climatic conditions that enhance the diversity of estuarine characteristics.

An estuary is necessarily a coastal feature. According to Shepard (1973), the landward boundary of a coastal environment reaches as far as the marine influence into the continent. Therefore, the idea of tidal action even into the fluvial reach of the estuary, discarded by Cameron and Pritchard (1963) and Day (1980), cannot be eliminated from the definition.

Tidal action is not only relevant for salt related processes, but also is associated, for instance, to the erosion, circulation and deposition of sediments contributed by the rivers. The rise and fall of the tide in the fluvial reach produce major changes in river discharge, degree of exposure of the fluvial margins, etc., thus modifying the characteristics of the transport of sediment and other related organic or polluting substances, as well as the conditions for the biota living on the freshwater tidal flats. In addition, many tidal sedimentary structures are commonly found in the fresh-water tidal zone (Dalrymple et al., 1992). In summary, we can suggest that the geomorphologic evolution and the biological conditions of the upper reach of the estuary is heavily dependent on tidal dynamics, even though salt may not reach so far landward.

As an example, the estuary of the Rio de la Plata (Argentina–Uruguay; Fig. 2-1) has salinity intrusion up to the line Punta Piedras–Montevideo, and it may arrive further inland along the northern coast (e.g., Colonia) and rarely up to La Plata city on the southern coast (Boschi, 1988). However, many features (e.g., ebb and flood sinus, etc.) of the banks in the upper reaches are formed by tidal action.

Although it may be small, all large saline water bodies (e.g., Mediterranean, Baltic, Aral, Caspio seas) have tides, either by direct astronomical effect, by cooscillating

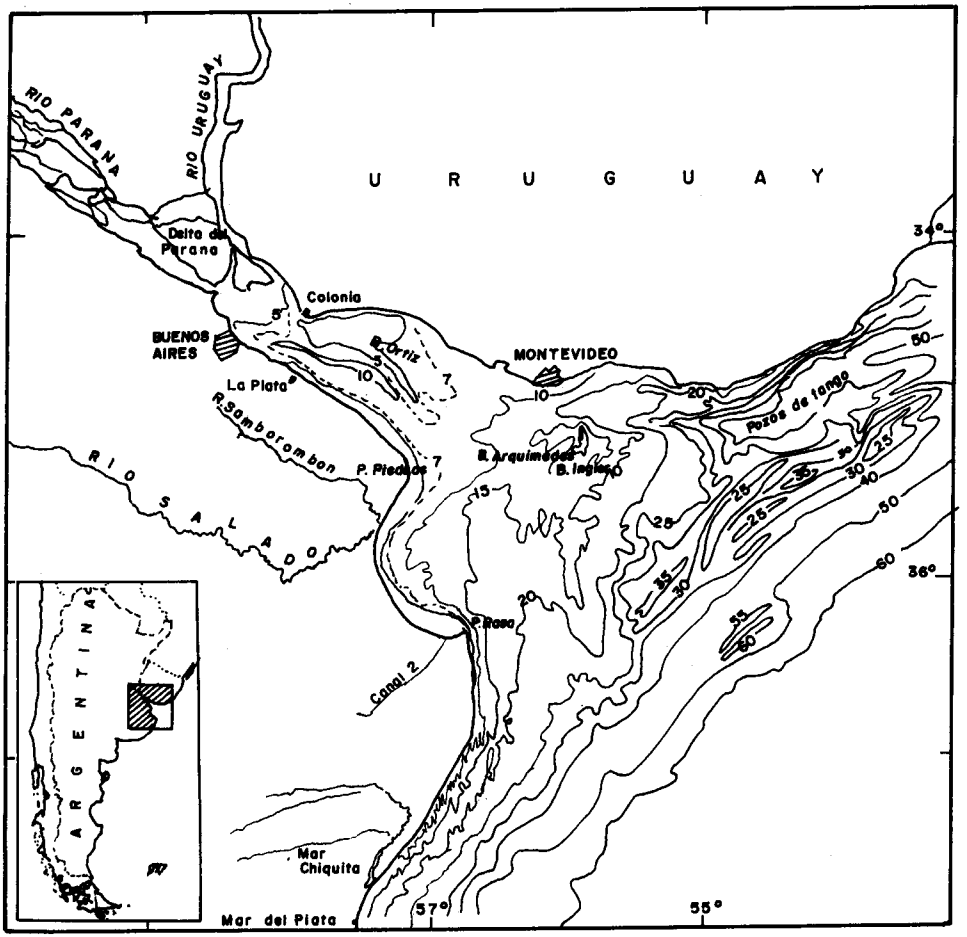

Fig. 2-1. Rio de la Plata estuary (Argentina–Uruguay), an example of a wide tidal river estuary. Salinity intrusions are found up to the line Punta Piedras–Montevideo. Some of the banks in the inner estuary show ebb and flood sinuses, products of tidal currents.

processes or through wind generated seiches that, to the effect, have similar properties than tides. Therefore, as long as the proposed estuary has any interaction with another saline water body having tidal movements, it can be considered an estuary (of course, if the other required elements also hold). Obviously, as it is discussed later, tidal effect has to be strong enough to provide significant modifications to the different components of the estuary.

CP and Day definitions contemplate only those estuaries discharging directly into the adjacent sea. Estuaries flowing into other estuaries are not included into their idea; although, the most important contributions by Pritchard were made from studies of the Chesapeake Bay (Fig. 2-2). The later constitutes an excellent example of a complex and hierarchical estuary were tertiary estuaries (e.g., Elizabeth and

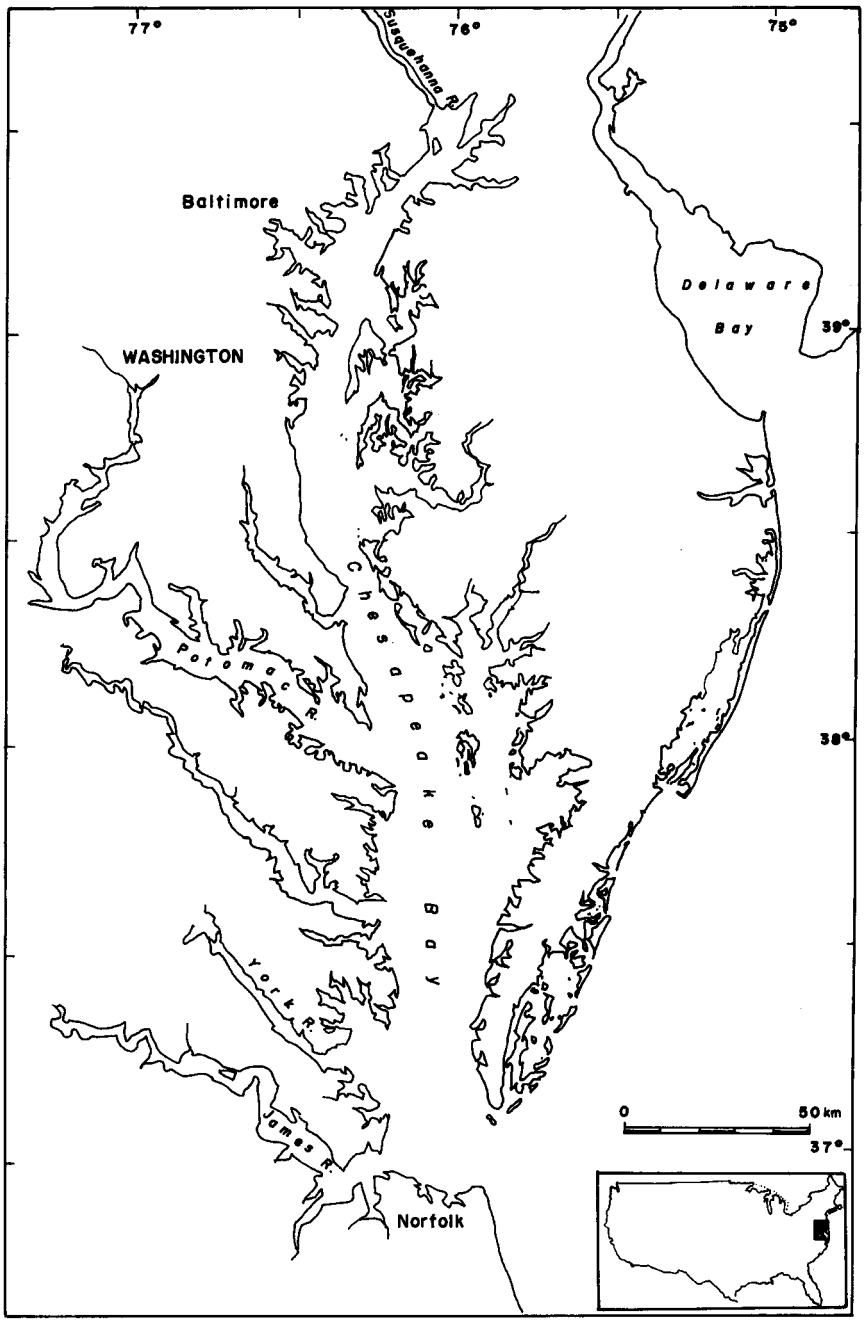

Fig. 2-2. Chesapeake Bay (USA), an example of hierarchical estuary. In the main estuary (actually the Susquekahama estuary) flow other estuaries such as James river, Potomac. The latter estuaries have other estuaries flowing into them.

Lafayette Rivers) discharge into a secondary estuary (James River) which itself flows into the primary estuary (Chesapeake Bay).

On the other hand, Day (1980) proposed the inclusion of intermittent estuaries within his definition. Although the idea is interesting, the circulation processes and type of biological occurrences (or survivals) differ whether the connection is open or closed. In these circumstances, this type of "blind estuaries" should be considered as estuaries only when they have an open connection, otherwise they become an albufera without any resemblance to an estuary.

Furthermore, the fact that estuaries must be connected either directly to the open sea or any other saline water body rules out the idea proposed by Herdendorf (1990), and partly supported by Odum (1990) and Dyer (1990), which rivers discharging into freshwater lakes subject to tidal action or other tide-like water-level movement (e.g., seiches) are also estuaries. It is not enough that changes in the chemical characteristics of the lakes' and rivers' waters are significant to induce an estuarine circulation pattern, even though all other elements proper of an estuary are present.

Even if either CP or Day's definitions are regarded as the most adequate for describing estuaries in general, the word "measurably" should be changed to "significantly". Measurable means that a researcher ought to have an instrument sensitive enough to detect the dilution; otherwise, if a certain degree of dilution (not specified in the definition) cannot be measured, he is not in an estuary. The word measurable puts a restriction in the definition based on the "most available present day technology". We can further ask, what is the degree of precision required to detect any dilution? Fig. 2-3 is a crude example showing the possible differences between researchers in developing (Fig. 2-3A) and advanced (Fig. 2-3B) countries may consider what measurable actually means.

Also, in very extreme conditions, we need to have continuous information on the salinity of sea water being introduced into the estuary during the measurement period. Average salinity values of the adjacent sea are not adequate for estimating the amount of dilution. Additionally, even if there is a certain dilution and it can be measured, it can be so small that it does not provide the necessary density gradient to drive any thermohaline circulation. Hence, it is essential that *the dilution must be large enough, not only to be detected, but to produce a gravitational movement of water masses.*

Furthermore, the use of "significantly" introduces a statistical criterion within the definition. That is to say that one single measurement (as it can be literally interpreted from "measurable") it is not enough to establish the particular condition of the water body.

Day (1980) proposed the inclusion of hypersaline estuaries, which called "negative estuaries" in Pritchard (1952) scheme. Normally, hypersaline conditions occur when freshwater input does not exist or is very small. These estuaries are normally associated with very dry, continental climates that only provide land drainage in specific occasions along the year, after long drought periods or when evaporation is much larger than runoff. As long as freshwater is introduced into the coastal embayment, a dilution of the marine water is occurring. Consequently, hypersaline embayments (that fulfil the other requirements necessary to be an estuary) that

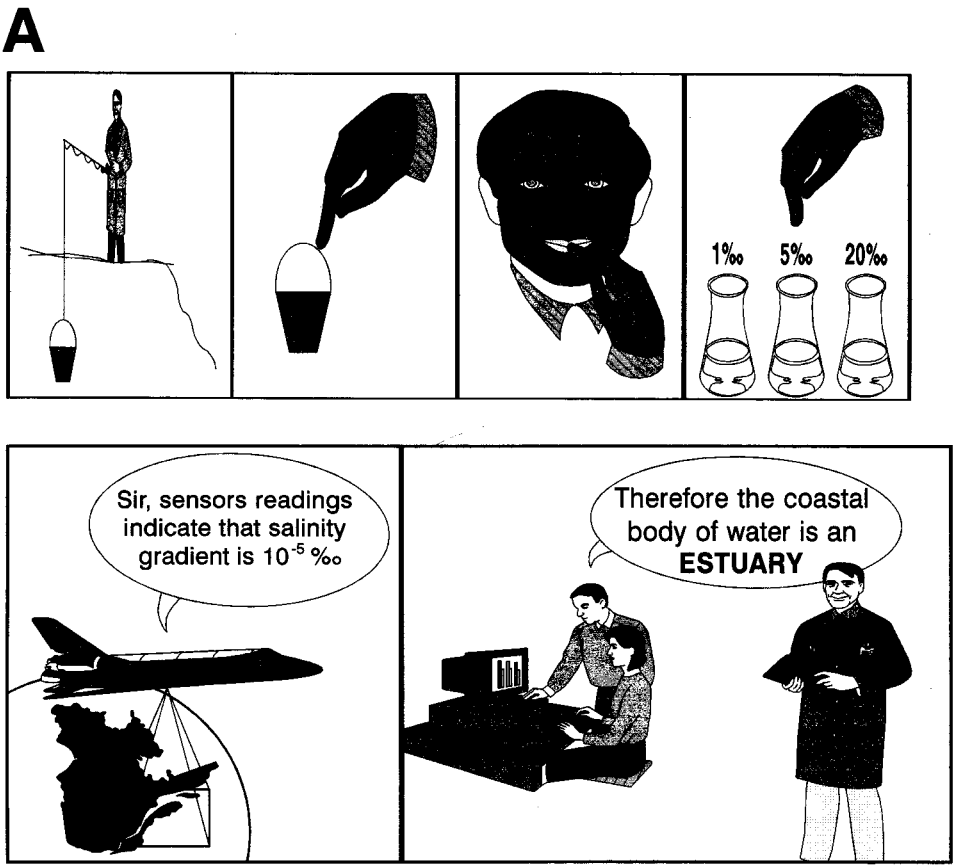

Fig. 2-3. Interpretation of the word "measurable" depending on the available technology. A) In a developing country salinity measurements may be made with quite primitive instruments providing only a rough estimation of salinity. B) However, the degree of sophistication found in instruments in advanced countries may provide information much deeper than the actually required.

receive freshwater are not excluded from the estuarine definitions (including the one proposed in the next section). Extreme evaporation is a local climatic factor that is superimposed over the relationship between the amount of fresh and seawater that enters the estuary, and should not be taken into account as it occurs with the wind or air pressure. For instance, Piccolo et al. (1990) found salinities up to 39‰ at the mouth of the Sauce Chico estuary (the main freshwater input for the Bahía Blanca estuary) with typical average river discharge (3.8 m^3/s). The hypersaline conditions are produced here by the tidal washing of a back-estuary salt flat (Piccolo and Perillo, 1990); a local attribute independent of basic estuarine processes.

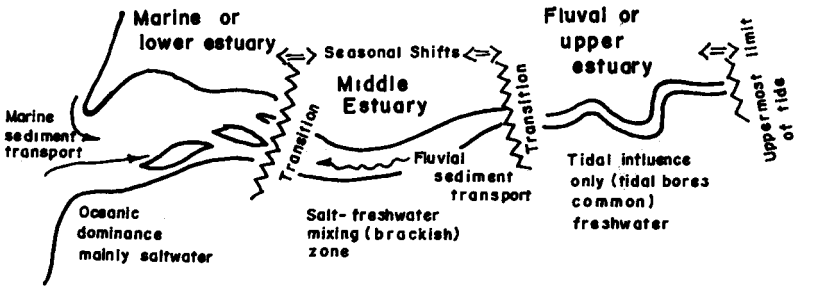

Fig. 2-4. Description of the parts of an estuary as proposed by Dionne (1963).

On the contrary, if there is not freshwater input, then the hypersaline body does not cover a basic premise required to be included into the category of estuaries. Moreover, we can accept the criteria for the existence of "intermittent estuaries". Meaning that coastal water bodies that fulfil the conditions to be an estuary only part of the time should be judged as estuaries only in those periods.

Another definition to be discussed here is that given by Dionne (1963, in Fairbridge, 1980) which says:

> "An estuary is an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being 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, characterized by fresh water but subject to daily tidal action." (Fig. 2-4)

In my understanding, Dionne's statement is properly speaking a definition only in the first sentence, where it does not differ too much from almost all other geological and geomorphological definitions, plus many of those encountered in dictionaries. The division into three major sectors is, at best, a description of what is expected in an estuary. The main importance of this definition is that it is the one that best summarizes the different criteria given for most other geological definitions (Annex 2-1).

More recently, Dalrymple et al. (1992) introduced a new, geologically-oriented definition developed as the base for constructing an estuarine facies model.

> "The seaward portion of a drowned valley system that receives sediment from both fluvial and marine sources, and contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the inner limit of tidal facies at its head to the outer limit of coastal facies at its mouth." (Fig. 2-5)

Only water bodies that are formed in valleys effected by relative sea level rise can be accepted as estuaries if this definition is followed. Therefore, those developed by the action of littoral transport with no definitive valley or those existing where the local (relative) sea level is descending (as described by Pino, this volume) cannot be estuaries. Likewise, the Bahía Blanca estuary should be eliminated as an estuary because in the long and short term averages does not receive sediment from outside its mouths. On the contrary, in the last 3,000 years associated to a lowering of

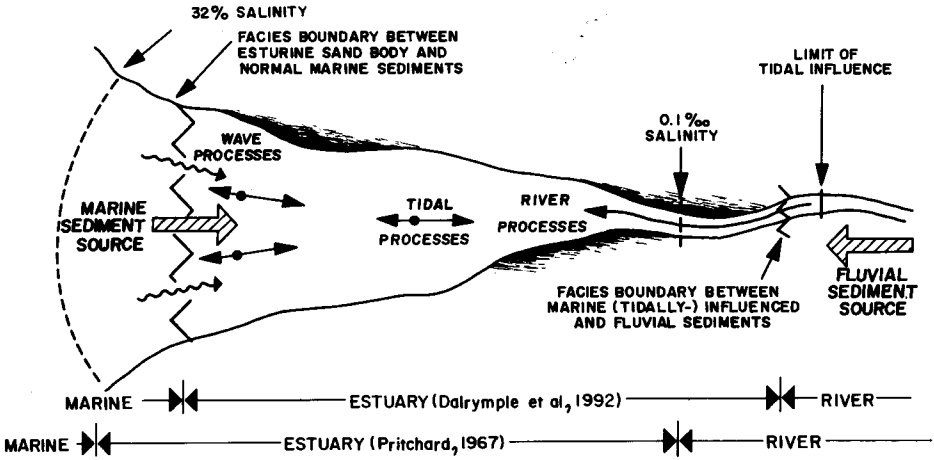

Fig. 2-5. Description of an estuary as proposed by Dalrymple et al. (1992). Note that it does not differ substantially from that of Dionne (1963) (Fig. 2-4).

the local sea level as described by Gómez and Perillo (1992b), the estuary is in a strong erosional stage and all its internal coasts (formed by tidal flats) are retreating. Sediment is continuously exported into the inner shelf and toward the coast of the Buenos Aires Province to the north of the estuary (Perillo, 1989a; Perillo and Cuadrado, 1990).

A PROPOSED NEW DEFINITION OF ESTUARIES

From the foregoing general analysis of the most used definition and others that subsume the arguments found in many other definitions, a new definition of estuaries is proposed here:

> "An estuary is a semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle."

The definition has derived from previous ones proposed by Perillo (1989b) (see Annex 2-1) where only the geomorphological and physical elements were considered and by Perillo (1992). Besides including parts of some previously cited definitions, this definition considers other aspects not incorporated before. First of all is the existence of hierarchical estuaries like Chesapeake Bay in which there are primary to tertiary estuaries. Second, there is the explicit indication of more than one free connection. In this form, coastal lagoons or the so called bar-built estuaries, both having significant dilution, are clearly included in the definition. Contrary to most geological definitions, the present one does not incorporate the character or origin of the

depression in which the estuary has formed. Normally those definitions explicitly say "a river valley," thus excluding coastal features not originated only by fluvial action as fjords and some bar-built estuaries. The later are sometimes not originated by fluvial action but related to alongshore transport of sediments closing an existing bay.

In addition, the coexistence of tidal action and intrusion of sea water is now formally established. In effect, the estuary extends inland up to the effective limit of tidal action, but it is within the segment that stretches from that inland point to the mouth in which seawater dilution can occur. This model permits the differentiation within the estuary of the three sectors proposed by Dionne (1963) and further described by Dalrymple et al. (1992), and also allows for estuaries that have only one or two of the sectors. For instance, the Amazon river then may be considered as an estuary (a tidal river estuary in the morphogenetic classification proposed later) that only has the upper or fluvial sector.

The suggested definition has a quality that makes it different from all others previously proposed: it spans all basic disciplines dealing with estuaries. Both geomorphological and physical criteria have been common in many definitions, and the chemical criterion is met by the part related to the dilution of salt water (meaning that there is a change in the elementary composition from the standard seawater solution). The biological aspect is uncommon in estuarine definitions. Most biological definitions as described in Annex 2-1 clearly represent the estuary as "...primarily a hydrographical phenomenon" (Barnes, 1974). But in the new definition the biological criterion is specifically included when the estuary can be the habitat of species that are adapted to resist important changes in salinity as has been first proposed by Ringuelet (1962) (see Annex 2-1). The euryhaline (from greek eury = wide, broad) term is used here just to describe biological species that can withstand those modifications in salinity and have no relation with any specific salinity range.

PREVIOUS GEOMORPHOLOGICAL CLASSIFICATIONS OF ESTUARIES

Estuaries may be classified as any other object: after defining the object, it is necessary to characterize and order its outstanding parameters. The next step is to define the viewpoint of the classification, that is, which are the criteria and objectives of the classification. Since this book is devoted mainly to the geomorphology and sedimentology of estuaries, I will only consider the parameters related to these disciplines.

Within the geological parameters the most important in this case are the genetic, geomorphologic and sedimentologic criteria. While the physical concepts may involve all those parameters that can be measured in an estuary (i.e., salinity, temperature, tides, wind, currents, etc.). Although all of them may be employed, usage of one or a combination of parameters requires that it/they must be common to all estuaries and also must have some kind of differentiation from one estuary to another. Sediments, for instance, are common enough to all of them; nevertheless, their variation within a single estuary may be so large and dynamical and geomorphologically dependent that

a classification based only on sediment distribution patterns seems impracticable. The same occurs with tidal current intensity or winds.

In the present section a review of several of the most common classifications is presented. The objective of the descriptions that follow is two fold: to introduce the classification *per se*, but further on is to introduce the readers with the basic terminology and the particular environment that will be tackled in the following chapters. As a result, the particular description given for each element of any classification is composed from what the author originally indicated plus general interpretations added from other authors and myself. Each subtitle will be accompanied by the name of the researcher(s) that developed the classification. Afterward, a new morphogenetic classification is introduced.

Physiographic classification (Pritchard, 1960)

The first known classification of estuaries from a geomorphologic point of view is due to Pritchard (1952) who divided the estuaries in three groups: drowned rivers, fjords and bar-built estuaries. Later, Pritchard (1960) completed the classification by including a fourth category that contemplated those formed by tectonic processes. Some features of the estuaries included in this classification will be discussed at length since they will be employed also in the following classifications.

Drowned river valleys

This term has been wrongly employed in many occasions as synonymous of coastal-plain estuaries. They are basically what everybody thinks an estuary should be. They were formed by sea flooding of Pleistocene–Holocene river valleys during the Flandrian transgression. In Fig. 2-6 a schematic view of a classical drowned river estuary is exhibited. Normally they have a funnel shape with an exponential increase of the cross-section toward the mouth (Fig. 2-6a). The longitudinal profile shows a seaward gradient which is, in general, not interrupted by a sill (Fig. 2-6b) formed by either the original material of the valley or a barrier deposited previously to the drowning of the valley. On the average, these estuaries are about 10 m deep reaching some 20–30 m at the mouth. The valley has an acute V-shape when formed on

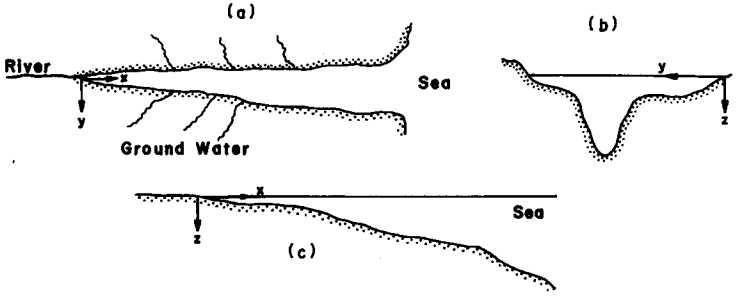

Fig. 2-6. Schematic diagram of a drowned river valley estuary: a) plan view; b) longitudinal profile; c) cross-section profile.

mountain and cliffy coasts, but the classical coastal plain estuary has a more open V-shape restricted only to the channel. Normally the valley presents "shoulders" or terraces either on one or on both sides. Modifications of this general description may be produced by the regional setting of the feature, the climate and the type of rock in which they were carved. Therefore, the width to depth ratio may vary over a large range being from the order of 10–100 in ria valleys (northern Spain coast) to 1000 (Chesapeake Bay) to 20000 (Rio de la Plata) in coastal plain estuaries.

In general, drowned river valleys exhibit important sediment deposits and the exponential dependence of the cross-section seems (although it has not been proved) to be related to a long-term adjustment between sedimentation and erosion toward an equilibrium shape. Most estuaries of the world correspond to this category. The classical examples are Chesapeake and Delaware Bays, and the Thames and Gironde rivers.

Fjords

As drowned river valleys estuaries have developed in low and middle latitudes, fjords are associated to high latitudes which were covered by the Pleistocene ice-sheets (northern Europe and Canada) or coasts affected by alpine glaciation (southern coast Chile). Usually the glacial tongue invaded a previous river valley and by its effective and characteristic method of erosion carved a totally different new valley. As the glacier retreated, the sea advanced drowning these glacial valleys.

The general physiographic characteristics of a fjord type estuary are presented in Fig. 2-7. Valley width is relatively uniform (Fig. 2-7a) and in cross-section it has an U-shape (Fig. 2-7c). However, a variety of drowned glacial valleys called fjards have developed in the low-relief rocky coast of northern Sweden, having cross-sections with less steep walls and presenting some lateral terraces which may be confused with strandflats. Another major difference between fjards and fjords, which is also due to the different coastal relief, is that the former has highly irregular inner shores and the tributaries are mostly lateral.

One outstanding feature of most fjords is the presence of a shallow sill near or at their mouth, that closes the very deep valley (Fig. 2-7b). While the sill can be as shallow as 4 m, as in the Norwegian coast or as deep as 150 m (British Columbia

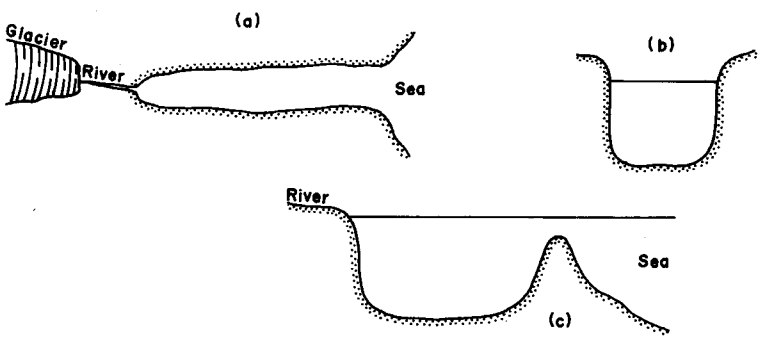

Fig. 2-7. Schematic diagram of a drowned glacial valley estuary: a) plan view; b) longitudinal profile; c) cross-section profile.

coast), the valley can be normally between 200 and 800 m deep, reaching maxima of 1200 m as in the Mercier Channel (Chile). In general, the sill corresponds to the most advanced frontal moraine formed within the valley. Minor sills can be found within the inlet produced by other frontal moraines either due to fluctuations during the main glacier retreat or by discharge of tributary glaciers. The latter will appear nearly parallel to the main valley sides though, and may be confused with relicts of the lateral moraine.

Because of their regional setting, fjords are located in rocky shores and sediment supply is relatively scarce and seasonally variable. Coarse sediments are found normally at the head of the estuary, near the main river entrance. Meanwhile bottom material appears as a veneer of mud deposited in a reducing environment. The muds are the product of the settling of suspended sediments through water column as water circulation is very low or null. The level of recirculation of the water column below the sill level is dependent on the depth of the sill and the depth of the valley.

Bar-built estuaries

These estuaries are also called Coastal Lagoons. Most bar-built estuaries are located on river valleys of very low relief coasts with small tidal ranges and river discharges. Although there are examples in meso- and macrotidal shores, littoral processes appear as dominant in the local environment. Consequently, dynamical dominance is produced by wind and littoral transport which can build up a barrier that encloses the lagoon (Fig. 2-8A). Although the most commonly described bar-built estuaries (Eastern and Gulf coast of USA) respond to the previous characteristics, there are many other examples worldwide in which the lagoon is located on previous (Mar Chiquita lagoon, Argentina; Dos Patos lagoon, Brazil) or present (Queule and Lenga estuaries, Chile) embayments restricted by the formation of a barrier. There are many differences between both types of barriers, being the most remarkable their length, width and number of inlets. South American lagoons occupy more restricted areas (although Dos Patos lagoon is the world largest) and are closed by a relatively short and wider barrier with only one inlet. Overwashing of the barrier seldom occurs even during the strongest storms.

The lagoons proper are normally shallow (about 2 m deep) bordered on the land side by either the original coast (microtidal environments) or tidal flats but most commonly by salt marshes or mangroves in tropical climates. Highly sinuous tidal channels are developed on the muddy bottom sediments. Only the inlets, where tidal currents are stronger due to the jet-like behaviour, are deeper and sometimes limited in both extremes by tidal deltas.

Tectonic estuaries

The last category in Pritchard's classification is, as defined by the same Pritchard (1960) "...a catch-all for estuaries not clearly included in the other three divisions". He actually described in this category San Francisco Bay and its tributaries, the San Joaquin and Sacramento rivers. All of them formed by movements of the San Andreas' fault system. Other examples of tectonic type of estuaries are the Valdivia river (Chile) (Pino et al., 1992) and Itamaracá (Brazil) (Medeiros and Kjerfve, 1993).

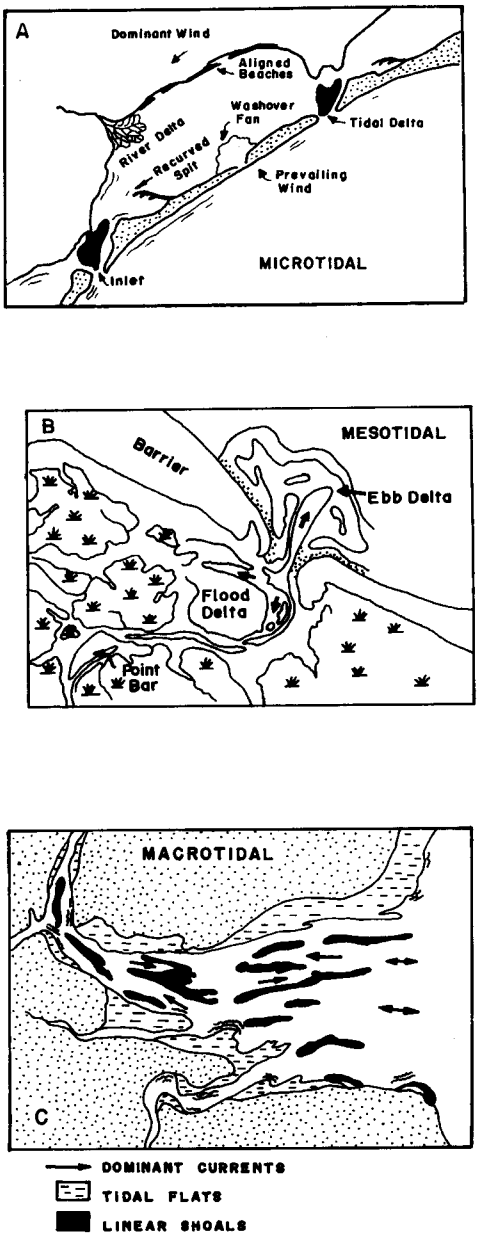

Fig. 2-8. Schematic diagrams representing the estuaries within the Hayes (1975) classification: A) microtidal, which are commonly associated to coastal lagoons; B) mesotidal; C) macrotidal.

Although Pritchard called his classification Topographic or Physiographic, it is a genetic classification since he based the nomenclature on genetic attributes. Nonetheless all categories are quite broad and obviously inclusive, providing similar

characteristics to estuaries that are produced by the same process but have a totally different setting (e.g., rias and coastal-plain estuaries). Evidently geological processes may be similar on a regional or worldwide basis, but their dynamical and actual physiographic effects were not considered. For instance, estuaries located on terminal deltas or those not fully drowned (e.g., Amazon and de la Plata rivers) are not considered at all in the classification.

Classification by tidal range (Hayes, 1975)

Although based on a physical parameter, namely the tidal range, it is included as a geomorphologic classification because the tide is only employed as the leitmotiv for correlating several physiographic characteristics. Hayes (1975) in analyzing the morphology of sand deposits affiliated with estuaries recognized their different characteristics depending on tidal range. Following the coastal classification scheme given by Davies (1964), Hayes defined thus three types of estuaries: microtidal–tidal range <2 m; mesotidal–tidal range 2–4 m, and macrotidal–tidal range >4 m (Fig. 2-8).

Microtidal estuaries

Dynamically, microtidal estuaries (Fig. 2-8A) are dominated by wind and wave action. If rivers are important, their influence can be decisive in the rapid evolution of the feature toward a deltaic environment. Tidal influence is felt mainly at inlets. This type of estuary may be associated to the bar-built estuaries of Pritchard or wave-dominated of Dalrymple et al. (1992). Nevertheless, some major rivers discharge on microtidal coasts (e.g., Mississippi, Nile). Chesapeake Bay is also a microtidal estuary which only in broad terms can be fitted into Hayes's classification. The principal forms of deposition are flood deltas, wave built features (spits, bars, beaches, etc.), storm deposits (overwash fans) and river deltas.

Mesotidal estuaries

These estuaries are probably the most common and widely studied estuaries in the world (Fig. 2-8B). Many estuaries on the southeastern and western coast of USA and some others elsewhere (e.g., Orinoco, Niger, several in Indonesia, Bahía Blanca, etc.) are located on mesotidal coasts. Tidal currents are dominant as a form-generating agent over other marine, fluvial or climatic agents. The major forms are tidal deltas (both flood and ebb), salt marshes and tidal flats.

Macrotidal estuaries

They are the least studied (Fig. 2-8C), although there is a strong tendency toward their analysis within the last two decades. Some examples are the Bay of Fundy (Canada), Tay (Scotland), Gironde (France), Rio Gallegos (Argentina). Hayes (1975) considered that these estuaries are broad-mouthed and funnel-shaped with linear sand bodies occupying the central portion and extensive tidal flats and salt marshes bordering the coast. Tidal currents are overall dominating and wave action may be important, as in all other cases, at the mouth.

If Pritchard's classification is considered as purely genetic, Hayes' one is totally geomorphologic although is based on only one physical parameter: the tide. It is important to point out that Hayes intention was not to produce a classification but to correlate depositional sand bodies in estuaries with different coastal environments represented by distinct tidal ranges. Another drawback of this classification, is that there are other factors that control the morphology of an estuary that were not taken into account. The examples and the morphological elements contained in each of them were all taken from the eastern coast of North America, where there is a general continuity of morphological patterns that no necessarily repeats itself in other coasts of the world.

Evolutionary classification (Dalrymple et al., 1992)

Closely related to the one developed by Hayes (1975), Dalrymple et al. (1992) estuarine classification is part of a more complex facies model that combines the relative importance of river outflow, waves and tides with time. The result is a triangular prism that represents the different coastal environments associated to the three essential parameters (Fig. 2-9A). A cut through the prism reveals a single time-independent triangle that correlates the percentages of each environment for a particular sea level condition. Deltas (river dominated environment) are located at the fluvial apex while strand plains and tidal flats are positioned along the wave-tide side. Differentiation between them and also in the two types of estuaries is based on terms of wave or tidal dominance (Fig. 2-9B).

Wave-dominated estuaries

The energy and facies distribution for wave-dominated estuaries is presented in Fig. 2-10. Waves are strongly dominant at the mouth producing littoral transport and normally developing some kind of barrier that partially closes the mouth. Tidal influence may be observed in its capability to maintain open the inlet(s), becoming practically null toward the head, where only the river input is dominant (Fig. 2-10A). The resulting facies distribution (Fig. 2-10B) clearly corresponds to a bar-built or microtidal or coastal lagoon estuary from other classifications. At the mouth of the barrier-inlet system and adjacent areas, it is possible to find flood deltas and washover fans. In the central portions sedimentation of fine sediments is dominant in a shallow basin crossed by tidal channels where the major process is the resuspension of the bottom material by local waves produced by the passage of storms. At the head, the river forms a delta as it enters a basin with very low capability of reworking and redistributing its input.

Tide-dominated estuaries

Tidal dominance does not require necessarily of strong tidal currents or large tidal ranges, although those conditions make the analysis more clear. Simply lack of any wave activity is enough even in microtidal coast to produce tidal-dominance. Tides and waves may have similar amount of energy at and near the mouth, but tides are much stronger than both waves and river discharge in the middle and upper

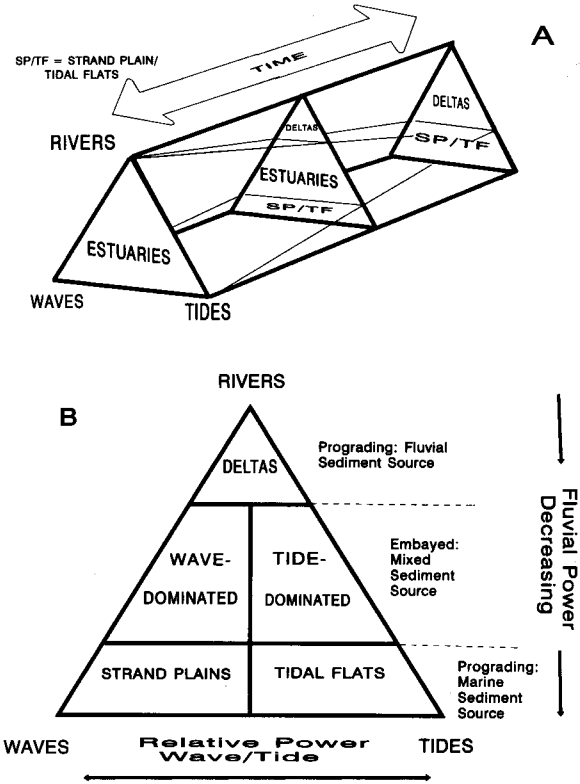

Fig. 2-9. Classification of coastal environments associated to estuaries according to Dalrymple et al. (1992). A) General classification structure considering river input, wave and tidal processes and their variation in time (sea level changes); B) a cross-section through the prism presented in (A) showing the classification of estuaries in wave- and tide-dominated.

estuary. River influence becomes progressively larger within the river valley proper as friction drains tidal energy (Fig. 2-11A). As the energy is about the same along the estuary, sand sediments and facies are found also respectively distributed (Fig. 2-11B). Obviously the larger concentrations are found at the mouth, being reduced to the tidal channels as we move landward. Finer sands are found at the zone of minimum energy. Fine sediments are distributed on tidal flats and salt marshes.

Dalrymple et al. (1992) classification is purely geological rather than geomorphologic. No consideration of fine sediments transported in suspension is given since their movement is independent of the zonation. Nevertheless, fine sediments deposited from this transport make more than 60% of the sediment facies in most estuaries and in some up to 90%.

Separation between wave and tide dominance may be useful if one considers only the estuarine mouth or a system quite small. Waves and wave-related sedimentary structures are only important at the mouth even if there is not tide at all. Local waves within the central basin are occasional and seldom produce major sedimentary

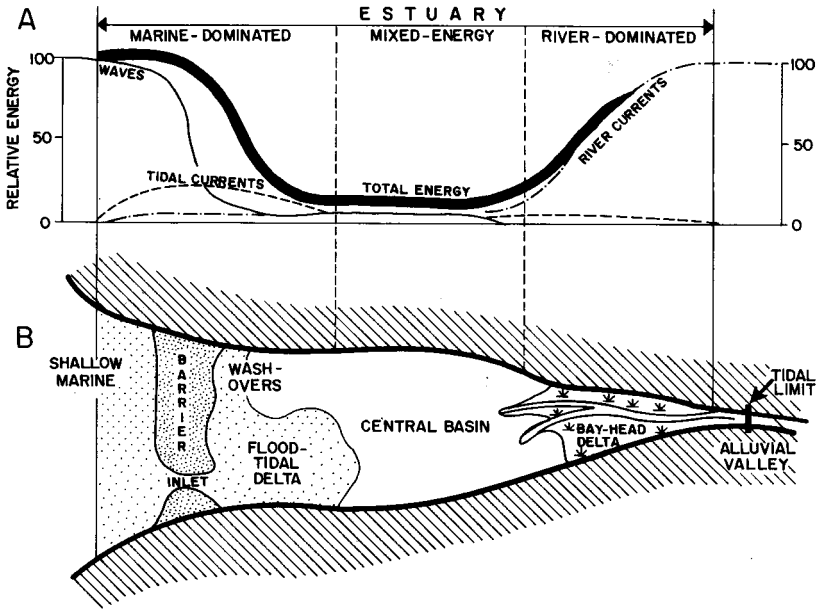

Fig. 2-10. Wave-dominated estuaries: A) distribution of dynamical processes along the estuary; B) distribution of major morphological components (modified after Dalrymple et al., 1992).

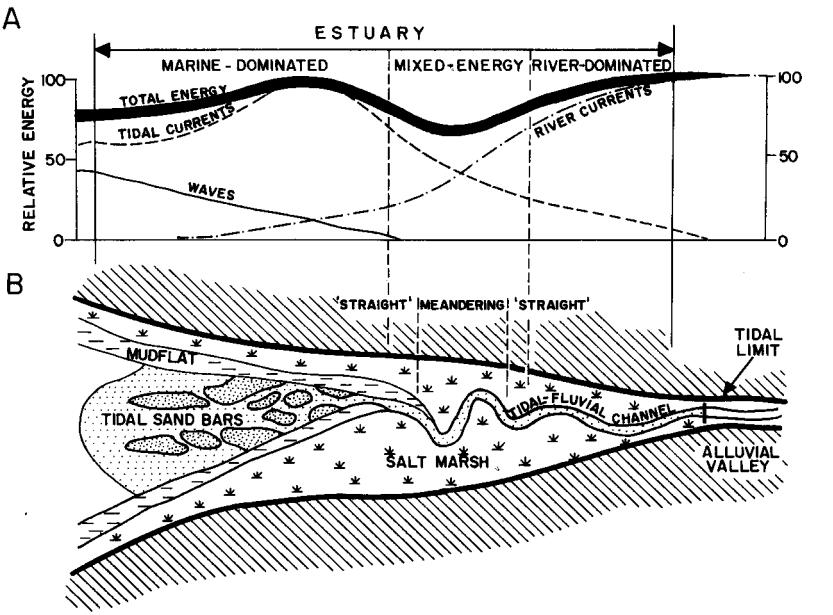

Fig. 2-11. Tide-dominated estuaries: A) distribution of dynamical processes along the estuary; B) distribution of major morphological components (modified after Dalrymple et al., 1992).

structures other than some stratification formed by fine sand layers, originated by the winnowing and resuspension of the fine material, intercalated in mud sediments. Even in wave dominated mouths, tidal influence is important since tides are necessary to develop tidal deltas and the tidal channels within the central basin. A question to ask is: how can waves dominate river action at the head, if they do not reach that part of the basin but for local, low energy waves?. Furthermore, there is not entrance for river dominated estuaries (e.g., delta-front or tidal rivers, see proposed classification) because they are directly assumed as deltas out of the estuarine part of the classification, or estuaries where sedimentation processes may be relatively poor in comparison with the basin (e.g., rias and fjords).

In summary, Dalrymple et al. (1992) classification is very useful to establish the spatial and temporal correlation among river, waves and tides and from then on to define the facies distribution within the estuary. However, it does not cover enough elements to be an effective geomorphologic classification. Furthermore, there is even no clear differentiation between this and Hayes' classification: if the names are taken out, both are considering the same structured classification. The only difference is that Dalrymple et al. (1992) make a good case in pointing out that there is a continuous evolution between the two extreme cases while in the case of Hayes (1975) one ought to assume such continuity.

Morphological classification (Fairbridge, 1980)

More recently Fairbridge (1980) provided the embryo of a new and more comprehensive physiographic classification of estuaries. It is based on both physiographic and hydrodynamic factors. The physiographic categories were organized according to their relative relief and degree to which the circulation is restricted at the mouth. The seven categories are presented in Fig. 2-12 and described by the author very summarily as follows:

(1a) High relief estuary with U-shaped valley profile = *fjord*.

(1b) Moderately high relief estuary = *fjard, firth, sea loch*.

(2) Moderate relief estuary with V-shaped valley profile and winding valley = *ria, aber*; and those formed on karst coasts = *calenque, cala*.

(3) Low relief estuary with branching valleys and funnel shaped plan view = *open coastal plain estuaries*; those flask-shaped and partly blocked by bars or barrier islands = *barrier (semi-enclosed) coastal plain estuaries*.

(4) Low relief estuary, L-shaped in plan with lower course parallel to the coast = *bar-built estuaries*.

(5) Low relief estuary, seasonally blocked by longshore drift and/or dunes, with/or without eolianite bars = *blind estuaries*.

(6) Delta front estuary in ephemeral distributaries = *deltaic estuaries*; in interlobate embayments = *interdeltaic estuaries*.

(7) Compound estuary, flask-shaped, ria backed by low plains = *tectonic estuaries*.

In this classification, the geodynamical conditions are related to the long term relationship between the sea level changes, estuarine-fluvial dynamics, and neotectonics. Fairbridge (1980) considered that "disequilibrium" estuaries "...are mainly

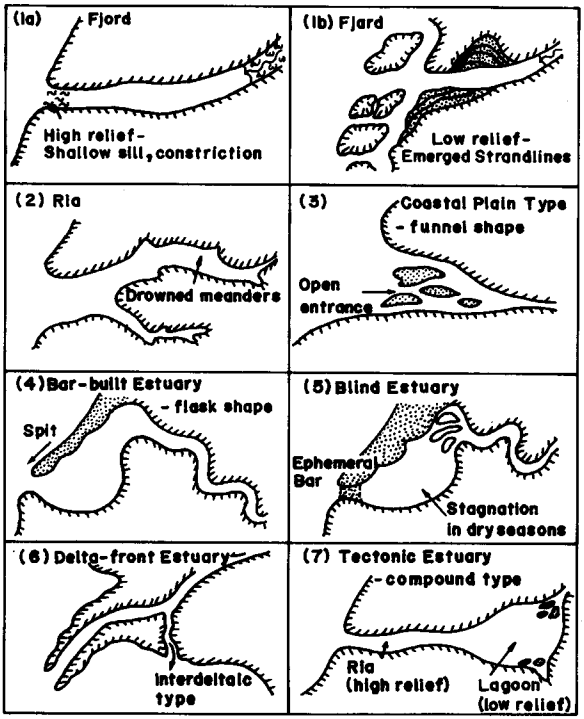

Fig. 2-12. Morphological classification of estuaries as introduced by Fairbridge (1980).

due to the early Holocene sea-level rise where it has been offset in some way by tectonics..." While "equilibrium estuaries" are constructional (e.g., delta channels). Following Jennings and Bird (1967), Fairbridge (1980) indicates that the dynamical environmental factors that produce regional variabilities are: 1) fluvial hydrology, 2) wave energy, 3) tidal range, 4) biological sedimentary factors, 5) sedimentology and mineralogy, and 6) geotectonics and neotectonics. Here, Fairbridge (1980) defines neotectonics as any youthful structural change in the height of the earth's crust.

A PROPOSED NEW MORPHOGENETIC CLASSIFICATION

Although the classification by Hayes seems quite coherent, clustering of estuaries only by tidal range does not reveal more specific differences (e.g., setting, relief, etc.) between them. The method is partial because it does not consider some dynamical factors such as river discharge, littoral processes, etc. They have been contemplated by Dalrymple et al. (1992) but, in both cases, there is no correlation with the previous structure and relief in which the estuary has formed. On the other hand, Fairbridge's classification is more thorough but less detailed than the others discussed.

All previous classifications can in general be considered as too inclusive since many

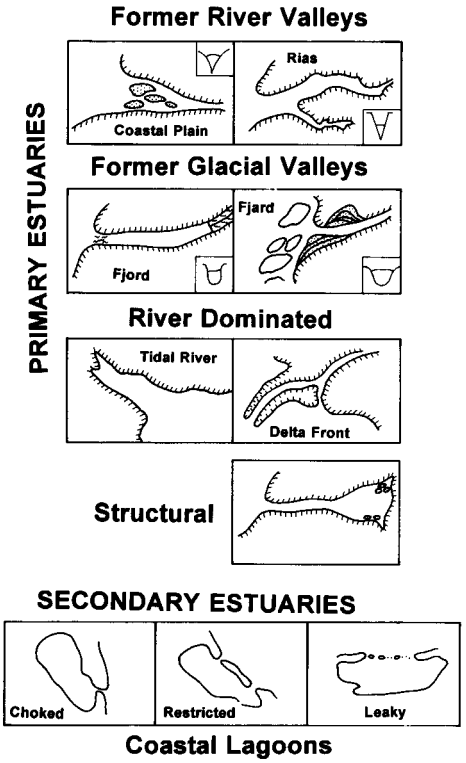

Fig. 2-13. Morphogenetic classification of estuaries introduced in the present paper.

different estuarine types can fit within one category. Then a new classification is introduced here, which opens much more the spectra by covering all possible categories of estuaries that are established by the definition given before. This classification is based on genetic and morphological considerations. The first division is the necessary genetic differentiation of estuaries as either primary and secondary estuaries (Fig. 2-13) following the criteria given by Shepard (1973) in his classification of shorelines.

Primary estuaries: the basic form has been the result of terrestrial and/or tectonic processes and the sea has not changed significantly the original form. Specifically, these are those estuaries that have essentially preserved their original characteristics up to the present.

Secondary estuaries: the observed form is the product of marine processes and their relative influence over river discharge acting since the sea level has reached nearly its present position.

Further discussion on the different categories will be limited only to new aspects not addressed for categories of the same or similar names in previous classifications. Nevertheless, detailed descriptions of them are give in Chapters 3 to 9, this volume.

Former fluvial valleys: formed by sea flooding of Pleistocene–Holocene river valleys during the last postglacial transgression. This category corresponds to the drowned river valleys of Pritchard. According to their coastal relief, they have been divided in two subcategories:

Coastal plain estuaries: normally occupy low relief coasts produced mainly by sedimentary infilling of the river(s). Typical examples are Thames (UK), Gironde (France), Yangh-Tse (China).

Rias: are former river valleys developed in high relief (mountainous or cliffy) coasts. Examples of these are the Pontevedra (Spain) and Deseado (Argentina) rias.

Former glacial valleys: formed by sea flooding of Pleistocene glacial valleys during the last postglacial transgression. Also, based on the coastal relief to which they are associated, they are divided in two subcategories:

Fjords: occupy glacially formed troughs located in high relief coasts. Examples are Oslo (Norway), Mercier (Chile).

Fjards: occupy glacially formed troughs in low relief coasts. Examples are those formed in the northern coast of Sweden.

River-influenced: in high discharge rivers like the Amazon, Mississippi and de la Plata the valley is not presently drowned by the sea. However, the circulation in the lower portions of the river is highly affected by tidal dynamics, including reversing currents, resulting in characteristic morphological patterns. They have been divided in two subcategories:

Tidal rivers: include those rivers that are affected by tidal action but salt intrusion may be limited to the mouth or it is totally absent within the valley. Normally these estuaries are associated to large discharge rivers that either by their coastal setting (e.g., de la Plata river) or the relatively strong coastal dynamical processes occurring at their mouth (e.g., Amazon) do not develop a delta. The degree of salt intrusion is seasonally and climatically dependent; however, tidal processes are very important in sediment transport dynamics and morphological evolution within the valley.

Delta-front estuaries: this category includes the estuaries found in the portions of deltas affected by tidal dynamics and/or salt intrusion. The classic example is the outer Mississippi channels.

Tidal rivers and delta-front estuaries' subcategories have seldom been taken as part of the estuarine environment which may have occurred due to the influence of Pritchard's definition. When they were included, the chosen category was coastal plain estuaries. In line with the viewpoint of the definition introduced in the present article, tidal influence is as important as salt intrusion in establishing the characteristics of an estuary.

As suggested, high discharge rivers may have their valleys undrowned by the sea. Some drowning may have occurred during high sea level stands but that is not today situation. However, river discharge is affected by tidal action large distances upstream. In general, the interrelation between river and tide generates characteristic sedimentary processes such as the large shoals with marked ebb and flood sinus observed at the mouth of Rio de la Plata (Fig. 2-1).

Structural: their valleys were formed by neotectonic processes such as faulting, vulcanism, postglacial rebound, isostasy, etc. occurred since the Pleistocene.

Pritchard and the other authors (e.g., Fairbridge, 1980) employing Tectonic or Structural terms have not included an important argument in their consideration of this type of estuaries: time. All the structural processes that give place to the formation of the valley must be active in the present time or being occurring from the Pleistocene. Otherwise, since almost all rivers are controlled by structural (e.g., faults) conditions their corresponding estuaries should all be tectonic. Examples are San Francisco Bay (USA) and Valdivia river (Chile).

Coastal lagoons (after Kjerfve and Magill, 1989): inland water bodies usually oriented parallel to the coast separated from the sea by a barrier and connected to the ocean by one or more restricted inlets. In the present classification I included the subdivision suggested by Kjerfve and Magill (1989) based on the nature of the entrance:

Choked: only one long and narrow entrance (Dos Patos, Brazil; Mar Chiquita, Argentina).

Restricted: few inlets or a wide mouth (Pamlico Sound, USA; San Sebastian Bay, Argentina, Terminos, Mexico)

Leaky: large number of entrances separated by small barrier islands (Belize Lagoon, Mississippi Sound).

The coastal lagoons as proposed by Kjerfve and Magill (1989) and sustained here correspond to the bar-built and blind estuaries mentioned earlier. However, in the classification given by Kjerfve and Magill (1989) and in the present one blind estuaries are not considered. As indicated during the discussion of Day's (1980) definition, water bodies whenever they are not connected to either the sea or any other saline coastal water body are not longer an estuary. It becomes an estuary as the inlet opens again. This is a common process occurring not only in South Africa but along the Atlantic coast of Uruguay where there is a series of Choked type lagoons that are closed during part of the year.

SUMMARY

There is a clear need for a definition that spans all disciplines related to the study of estuaries. Analysis of over 40 definitions show that none of those developed to the present fulfil this basic requirement. Neither they state the basic criteria necessary to establish the existence of an estuary, which are: coastal bodies, border control, tidal action, uni- or multiple connection with adjacent sea or a coastal saline water body, freshwater input that produces a statistically and circulation-wise significant dilution of the seawater, the existence of characteristics species that live in the estuary either through part or the whole of their life cycle. All these aspects are included within the definition proposed here as:

"An estuary is a semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water

derived from land drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle."

Following the criteria introduced by the definition, a morphogenetic classification of estuaries has also been presented (Fig. 2-13). The main concepts involved are: 1) preservation or not of the original features of the valley; 2) coastal relief; 3) process that originate the valley.

In any case both are necessarily a step to reach a final definition and classification of estuaries. They can evolve (as they actually have done in the last five years) or being strongly modified by changing the phrasing or adding some further elements. However, the criteria in which they have been built cannot be overlooked in future definitions and classifications. Furthermore, I consider this article as practically the beginning of an international discussion that can actually carry us, devotees of Estuarine Oceanography, to that ultimate consideration. Having a unique definition and a unique classification will show us that we finally reach the point to say: "we really know what an estuary is".

ACKNOWLEDGEMENTS

This article greatly benefited by a long, epistolary, discussion with Henry Bokuniewicz, even though some "significant" terms still require to be "measured". Many other colleagues have made comments at different stages of the evolution of both the definition and classification, they all provided a different perspective that resulted in the ideas presented here. Partial support for the present article has been provided for National Geographic Society Grant 4540/91 and CONICET PID 3886/92. Instituto Argentino de Oceanografía, Contribution No. 281.

ANNEX 2-1. DEFINITIONS OF ESTUARIES IN DICTIONARIES AND ENCYCLOPEDIAS

Concise Oxford Dictionary

Tidal mouth of a large river.

Webster's New 20th Century Dictionary

An arm of the sea; a frith or firth; a narrow passage, or the mouth of a river or lake, where the tide meets the current.

Webster's New International Dictionary

a) A passage, as the mouth of a river or lake where the tide meets the river current; more commonly, an arm of the sea at the lower end of a river, a firth. b) In physical geography: a drowned river mouth, caused by the sinking of land near the coast.

Ediciones Garriga, 1958. Enciclopedia General del Mar. Barcelona

Estuario: lugar donde entra y sale la marea al flujo y reflujo.

Ría: canal o embocadura de río o brazo de mar que se interna en la tierra donde suben las mareas y se mezclan las aguas dulces y saladas.

Estuary: a place where the tide enters and leaves by flow and ebb.

Ría: a channel or river mouth or arm of the sea that penetrates inland where the tides rise and fresh and seawater mix.

Editorial Larousse, 1967. Pequeño Larousse de Ciencias y Técnicas. Buenos Aires

Desembocadura de un río por el cual penetra el agua del mar al subir la marea. Se distingue de la ría por el mayor caudal del río correspondiente.

Mouth of a river through which seawater penetrates as tide rises. It is distinguished from the ría by the larger discharge of the corresponding river.

Grindley, J., 1969. Estuarine sedimentation. In: F.I. Firth (Editor), The Encyclopedia of Marine Resources. Van Nostrandt, Reinhold, Co. New York

The area in which sea water and freshwater have mutual influences.

Encyclopedia Americana, 1970. New York

Where a shoreline is sinking or has been recently depressed, the rivers, unless large and heavily charged with sediments, have their valleys invaded by the encroaching sea, forming roughly funnel-shaped bays. Such bays are called estuaries...

Real Academia Española, 1970. Diccionario de la Lengua Española. Madrid

Estuario: estero de la orilla de una ría.

Estero: (del lat. aesterium) terreno inmediato a la orilla de un río por el cual se extienden las aguas de las mareas.

Ría: Penetración que forma el mar en la costa debido a la sumersión de la parte litoral de una cuenca fluvial de laderas más o menos abruptas. Ensenada amplia en la que vierten al mar aguas profundas.

Estuario: estero at the bank of a ria.

Estero: (latin: aesterium) land at the bank of a river over which tidal waters extend.

Ría: Penetration that forms the sea on the coast due to the drowning of the littoral part of a fluvial basin which sides are more or less abrupt. Wide mouth in which deep waters flow into the sea.

Fairchild, J.E., 1972. In: Collier's Encyclopedia

A geographical and geological term for an unusually broad river mouth.

Stevenson, R.E., 1972. Estuarine hydrology. In: R.W. Fairbridge (Editor), The Encyclopedia of Geochemistry and Environmental Sciences. Van Nostrandt, Reinhold, Co. New York

An estuary is a wide mouth of a river, or arm of the sea, where the tide meets the river current, or flows and ebbs.

La Grande Encyclopedia Larousse, 1973. Paris

Bras de mer entrant dans les terres a l'embouchure d'un fleuve ou une riviere.

Arm of the sea that penetrates inland at the mouth of a river.

American Geological Institute, 1976. Dictionary of Geological Terms. Anchor Press, New York

Drainage channel adjacent to the sea in which the tide ebbs and floods. Some estuaries are the lower course of rivers or smaller streams, others are no more than drainage ways that lead seawater into and out of coastal swamps.

Berthois, L., 1978. Estuarine sedimentation. In: R.W. Fairbridge and J. Bourgeois (Editors), The Encyclopedia of Sedimentology. Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA

An estuary is that part of the river subject to oceanic influence.

Libraire Larousse, 1979. Larousse de la Langue Française, Paris

Sinuosité du littoral, qui n'est couverte d'eau qu'in maree haute. Golfe formé par l'embrochure d'un fleuve. Partie aval du lit d'une riviere où se font sentir les marées.

Littoral sinuosity, that it is covered by water only in high tide. Gulf formed by the mouth of a river. External part of a river bed where tides are felt.

Hachette, 1980. Dictionnaire Hachette de la Langue Française. Paris

Embouchre d'un fleuve, formant un golfe profond et étroit.

Mouth of a river, shaping a deep gulf and strait.

Grand Dictionnaire Encyclopédique Larousse, 1983. Paris

Embrochure fluviale, soumise à la marée formant une indentation profonde dans la tracé littoral.

Mouth of a river affected by the tide forming a deep indentation on the littoral.

Encyclopedia Britannica, 1984. Chicago

An estuary is a partly enclosed body of water that forms where river water is mixed with and diluted by sea water.

Allaby, M., 1984, A Dictionary of the Environment. Translation in Spanish. Ediciones Pirámide, Madrid

Valle fluvial cubierto por agua a causa de los cambios en el nivel del mar con respecto a la tierra después que el río ya ha excavado su canal.

Fluvial valley covered by water due to changes in sea level in relation with land after the river has excavated its channel.

Physical and geological definitions

Lyell, C., 1834. Principles of geology, Vol. 3. London

Inlets of the land, which are entered both by rivers and the tides of the sea.

Lee, C.S., 1840. Elements of geology

Inlets of the sea into the land. The tides and fresh-water streams mingle and flow into them. They include not only the portion of the sea adjacent to the mouths of the rivers, but extend to the limit of tide-water on the streams.

Ketchum, B.H., 1951. The flushing of tidal estuaries. Sewage Ind. Wastes, 23: 198–209

An estuary is a body of water in which the river water mixes and measurably dilutes sea water.

Pritchard, D.W., 1952. Salinity distribution and circulation in the Chesapeake Bay estuarine system. J. Mar. Res., 11: 106–123

An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea water.

Emery, K.O. and Stevenson, R.E., 1957. Estuaries and lagoons. I. Physical and chemical characteristics. In: J.W. Hedgpeth (Editor), Treatise of Marine Ecology and Paleocology. Geol Soc. Am. Mem., 67: 673–693

Bodies of water bordered and partly cut off from the ocean by land masses that were originally shaped by non-marine agencies.

Also: The wide mouth of a river or an arm of the sea where the sea water meets the river current or flows and ebbs.

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

An estuary is an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being 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, characterized by fresh water but subject to daily tidal action.

Cameron, W.M. and Pritchard, D.W., 1963. Estuaries. In: M.N. Hill (Editor), The Sea, Vol. 2. Wiley-Interscience, New York, pp. 306–324

An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage.

Pritchard, D.W.,1967. What is an estuary: physical viewpoint. In: G.H. Lauff (Editor), Estuaries. AAAS Pub. 83, Washington, DC, pp. 3–5

An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage.

Gorsline, D.S., 1967. Contrasts in coastal bay sediments on the Gulf and Pacific coasts. In: G.H. Lauff (Editor), Estuaries. AAAS Pub. 83, Washington, DC, pp. 219–225

An estuary is an indentation in a coast in which tidal circulation meets land runoff and generally prevails over the land contributions.

Morgan, J.P., 1967. Ephemeral estuaries of the deltaic environment. In: G.H. Lauff (Editor), Estuaries. AAAS Pub. 83, Washington, DC, pp. 115–120

An estuary is any coastal embayment periodically affected by brackish oceanic waters.

Visser, W.A. (Editor), 1980. Geological nomenclature. R. Geol. Min. Soc. The Netherlands. M. Nijhoff, The Hague, 540 pp.

A more or less funnel-shaped river mouth, affected by the tides.

Kjerfve, B. and Magill, K.E., 1989. Geographic and hydrodynamic characteristics of shallow coastal lagoons. Mar. Geol., 88: 187–199

An inland river valley or section of a coastal plain, drowned as the sea invaded the lower course of a river during the Holocene sea-level rise, containing sea water measurably diluted by land drainage, affected by tides, and usually shallower than 20 m.

Perillo, G.M.E., 1989. New geodynamic definition of estuaries. Rev. Geofís., 31: 281–287

An estuary is a semi-enclosed coastal body of water that extends to the upper limit of tidal influence, where sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with freshwater derived from land drainage.

Dalrymple, R.W., Zaitlin, B.A. and Boyd, R., 1992. A conceptual model of estuarine sedimentation. J. Sedim. Petrol., 62: 1130–1146

The seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the inner limit of tidal facies at its head to the outer limit of coastal facies at its mouth.

Biological and ecological definitions

Odum, E.P., 1959. Fundamentals of ecology, 2nd ed. W.E. Saunders Co., Philadelphia, Penn

An estuary is a river mouth where tidal action brings about a mixing of salt and fresh water.

Ringuelet, R.A., 1962. Ecología acuática continental. EUDEBA, Buenos Aires, 138 pp.

Un cuerpo de agua permanente o temporalmente abierto, con intercambio entre el curso fluvial y el mar, poiquilohalino y favorable para la vida de organismos eurihalinos y anfibióticos.

A water body permanent or temporarily open, with interchange between the river and the sea, poiquilohaline and favourable for the life of euryhaline and anfibiotic organisms.

Barnes, R.S.K, 1974. Estuarine biology. E. Arnold Ltd., London, 77 pp.

An estuary is a region containing a volume of water of mixed origin derived partly from a discharging river system and partly from the adjacent sea; the region usually being partially enclosed by land mass.

Perkins, E.J., 1974. The biology of estuaries and coastal waters. Academic Press, London, 678 pp.

Uses Cameron and Pritchard definition.

Day, J.H., 1980. What is an estuary? South Afr. J. Sci., 76: 198

An estuary is a partially enclosed coastal body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of sea water with fresh water derived from land drainage.

McConnaughey, B.H. and Zottoli, R., 1983. Introduction to Marine Biology. C.V. Mosby Co., St Louis, 638 pp.

Use Cameron and Pritchard definition.

Chemical definitions

Portmann, J.E. and Wood, P.C., 1985. The UK national estuarine classification system and its application. In: J.G. Wilson and W. Halcrow (Editors), Estuarine Management and Quality Assessment. Plenum Publ. Co., pp. 173–186

An estuary is the transition zone along the quality of water changes from that of freshwater, characteristic of inland river water, to that of saline water, characteristic of the open sea.

Freshwater estuaries

Bates, R.L. and Jackson, J.C., 1980. Glossary of Geology. Am. Geol. Inst., Falls Church, Va, 2nd ed., 749 pp.

A freshwater estuary is the lower reach of a tributary to the lake that has a drowned river mouth, shows a zone of transition from stream water to lake water, and is influenced by changes in lake level as a result of seiches or wind tides.

Offshore estuaries

McHugh, J.L., 1967. Estuarine nekton. In: G.H. Lauff (Editor), Estuaries. AAAS Pub. 83, Washington, DC, pp. 581–620

Offshore estuaries are limited by the salinity front rather than the boundaries.

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Cameron, W.M. and Pritchard, D.W., 1963. Estuaries. In: M.N. Hill (Editor), The Sea. Wiley-Interscience, New York. 2: 306–324.

Dalrymple, R.W., Zaitlin, B.A. and Boyd, R., 1992. A conceptual model of estuarine sedimentation. J. Sediment. Petrol., 62: 1130–1146.

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Day, J.H., 1980. What is an estuary? South Afr. J. Sci., 76: 198.

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Jennings, J.N. and Bird, E.C.F., 1967. Regional geomorphological characteristics of soe Australian estuaries. In: G.H. Lauff (Editor), Estuaries. AAAS Washington, DC. Pub. 83, pp. 121–128.
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Kjerfve, B. and Magill, K.E., 1989. Geographic and hydrodynamic characteristics of shallow coastal lagoons. Mar. Geol., 88: 187–199.
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