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Coastal lagoons

Sanctuary ecosystems, cradles of culture, targets for economic growth

Pierre Lasserre

Unesco's recent international endeavours in the field of coastal lagoons are aimed at giving support to their scientific management. Its Man and the Biosphere (MAB) and marine science programmes are jointly collaborating with various committees of ICSU, the activities of which include the creation of committees of scientific experts capable of producing a synthesis from the already considerable stock of basic knowledge assembled in recent years on coastal areas, including not only lagoon ecosystems but also mangroves, estuaries and deltas, coral reefs and continental shelves. Considerable encouragement is being given to the organization of regional workshops. These committees and workshops started out by defining the conceptual framework for integrated research and teaching programmes, and have now gone on to highlight the strong points and shortcomings of the current state of knowledge in a series of specialized reports and manuals. Ways and means of transferring knowledge and setting up priority pilot programmes for the developing countries are also being contemplated.

The work accomplished by the SCOR/Unesco Advisory Panel on Coastal Lagoons and the Unesco/IABO Seminar on Coastal Lagoon Research: Present and Future points to the timeliness of conducting scientific research on lagoons. Unesco will shortly publish a world-wide survey and an updating of guidelines for the organization of lagoon research.[1]

Man's association with coastal lagoons goes back to very remote times. It has been instrumental in producing highly original life styles, especially in Asia and Europe, often flourishing economies, and architectural creations that are at times in admirable harmony with their setting, as in the case of Venice. Today, the sheer scale of the spontaneous occupation of the shoreline, as can be seen from the tourist boom or the growth of industrial or port facilities on lagoon complexes, was bound to arouse the interest of land developers, for whom factors of economic growth have priority; but all too often their schemes do not blend well with the local economic fabric, and give rise to conflicts between new and traditional uses of the coast, or resentment of its excessive appropriation.

Coastal lagoons are born of the intermingling of the sea and the water from the land mass. Natural ecological systems sheltered by lagoons, such as marshes, brackish and hypersaline pools and tropical mangroves, are among the most productive ecosystems of the world; their vulnerability, however, is on a par with their potential. Owing to their partial isolation behind offshore bars, lagoons tend to be closed systems, and can evolve very quickly. They are particularly vulnerable to over-exploitation of their resources, which alters the balance of the ecosystem, and exposed to the aggressive pollution of urban, industrial and agricultural wastes.

Only urgent action to safeguard these sensitive coastal areas can restore their original salubrity and result in controlled exploitation and development. Oyster- or mussel-breeding or fish-farming in lagoons, for instance, cannot be successfully developed unless the environment is protected from chemical and bacterial contamination.

Lagoon systems are subject to constant natural changes. Where human action adds to and combines with the phenomena inherent in the natural variability of the habitat, the outcome may be beneficial in some instances, catastrophic in others; but it is almost always unpredictable, since the factors involved are not understood in sufficient depth.

Scientific knowledge of lagoons has hitherto been chiefly descriptive. It is essential that it be geared rather to a holistic analysis. A functional, multidisciplinary approach, placing emphasis on analysis of the workings and evolution of lagoon systems and their interfaces—the ocean, the landmass and the water courses—must take account of geomorphological and physical processes, chemical exchanges, and their impact on living systems. Only such an approach can lead to the concrete proposals and forecasts which will enable developers to assess the economic requirements and the risks entailed.

WHAT IS A COASTAL LAGOON?

The terms 'estuary', 'delta' and 'lagoon' are generally used to designate littoral infilling formations which owe their originality to very specific hydrodynamic and sedimentation conditions. These areas provide shelter for plants, for animals, and for men. Coastal lagoons are shallow coastal stretches situated between the main-

Pierre Lasserre, *Professor at the Institute of Marine Biology of the University of Bordeaux I (France), is consultant to the Division of Marine Sciences at Unesco.*

1. *Coastal Lagoon Survey*—Results of a world-wide inquiry made by the SCOR/Unesco *ad hoc* Advisory Panel on Coastal Lagoons (1976-78) (in English and French); *Coastal Lagoon Research: Present and Future. I: Guidelines*—Unesco/IABO Seminar, Duke University, September 1978; *Coastal Lagoon Research: Present and Future. II: Proceedings*—Unesco/IABO Seminar, Duke University, September 1978 (all to be published shortly in the Unesco collection, 'Technical Papers on Marine Science', Nos. 31, 32 and 33 respectively).

land and an offshore bar, usually cut through by narrow passages or inlets. The feature distinguishing lagoons from estuaries is the presence of the offshore bar. Being more or less isolated from the sea, lagoons take on a character of their own. Their water, for example, may be appreciably desalinated or, conversely, it may become excessively saline through evaporation. Internal wave action on lagoons shapes the back slope of the coastal spit, and the areas furthest from the sea become choked with silt. Local names for lagoons are often used as geographical terms. People speak of the *Haffen* of the southern Baltic, *limans* on the Ukrainian coast of the Black Sea, 'pools', 'lakes' and *lidos* in southern Europe, *rias* in Spain, *wadden* and *vader* in the Netherlands and Denmark, *pols* in Norway, and so on, but all of these are the same lagoons, and all undergo active sediment deposition. Coastal lagoons are usually in permanent communication with the sea and also receive limited freshwater inputs, resulting in fluctuating salinity regimes. They may be temporarily, sometimes permanently, isolated from the sea. In countries with hot, desertic climates, they may become hypersaline; in temperate or cold latitudes, they may turn into freshwater lagoons or 'lakes'.

In addition to an often luxuriant halophile plant cover due to high primary productivity, many 'amphihaline' animal species pass through coastal lagoons in the course of their biological cycle. These include crustaceans, molluscs, anadromous[1] and catadromous[2] fish.

Lagoon ecosystems are frequented by adult fish, crustaceans and molluscs, and by very large numbers of the larvae and immature forms of the same species, which may either settle in the lagoon or migrate to the rivers or the sea. Human exploitation of the live output of lagoons through fishing and breeding is often spontaneous, and integrates very readily into traditional socio-economic contexts.

ORIGIN AND MORPHOLOGY

Coastal lagoons are very widespread along low-lying seaboards the world over. They develop on formerly submerged continental zones which have been banked up over the past 22,000 years. Two main patterns of formation can be distinguished:

Lagoons formed in submerged coastal depressions at the mouths of rivers, of which the offshore bars (coastal spits) have been formed through the migration of sediments produced by coastal erosion (Fig. 1). Lagoons may also be formed in marginal depressions in the course of delta sedimentation processes.

A second very widespread type of lagoon evolves from a beach sheltered behind beach-dune ridges (Fig. 2), with very characteristic formations running parallel to the coast. Following the slow rise in sea-level which has taken place over the past 5,000 years, the beach ridges have evolved into what are known as 'barrier ridges'. If the sediment load is greater than the transport capacity of the tidal currents, the lagoon becomes completely sealed. Closed lagoons such as these may continue to receive ocean inflows as a result of seawater infiltration of the offshore bar, especially if it is composed of coarse sand or pebbles. The bar may be breached from time to time by heavy swell, but the currents subsequently re-plug the breach.

Present-day physical, chemical and biological factors, such as tidal currents, river inflows, wave and wind action, the biological activity of plants and micro-organisms and colonization by animals and man, together with long-term changes in sea-level, all combine to produce a wide variety of coastal lagoons.

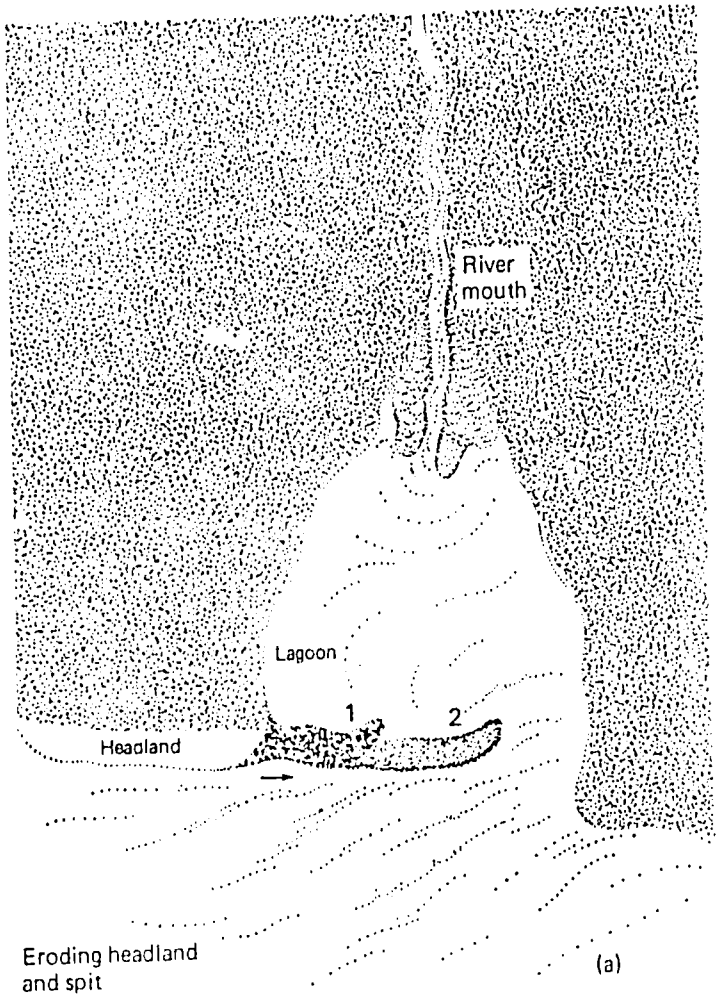
WORLD DISTRIBUTION

Coastal lagoons exist all over the world. In terms of area, they represent 1 per cent of the present seaboard. They are found in northern Alaska and Iceland, but they are comparatively rare in regions where coasts have emerged through the isostatic formation of glaciers, as in the Baltic and the Hudson Bay. The emergence process in such cases tends to produce steep coastlines where sediment loads capable of forming offshore bars are rare. On tropical coasts, by contrast, sediment loads carried down by rivers often produce lagoon formations.

The most developed lagoons are found along the coasts situated in the middle latitudes. This is true of the Gulf of Mexico, which is subjected to an ocean swell of moderate intensity and to low-amplitude tides.

Lagoons are common along the coasts of closed seas like the Black Sea or the Caspian. In regions where tidal amplitudes are low (less than 2 metres), mechanical wave action on the sediment builds up elongated offshore bars, pierced by small inlets or 'narrows'. In regions with average tides ranging from 2 to 4 metres in amplitude, combined wave and swell action is responsible for the formation of shorter spits of offshore bars containing a larger number of inlets. Regions subjected to tidal amplitudes of more than 4 metres tend to produce open

1. Reproducing in freshwater.
2. Reproducing in saltwater.



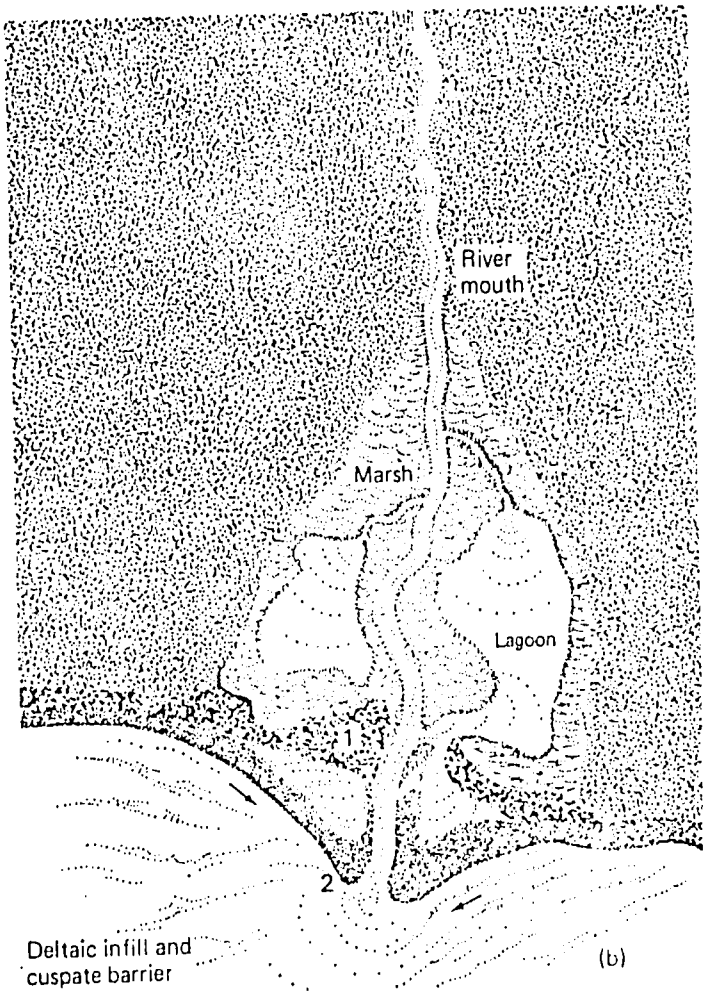


FIG. 1. A type of lagoon formation occurring at the mouth of a stream: (a) where the coast is eroded; (b) where the delta is filled in with marsh. Lagoons appear in the marginal depressions.

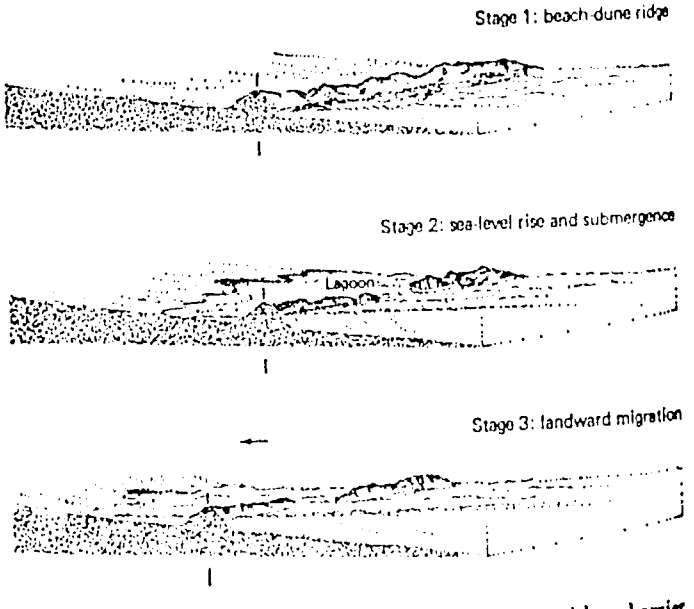


FIG. 2. Stages in the formation of a coastal lagoon with a barrier ridge. Stage 1: 5,000 to 6,000 years ago, when the sea-level was lower than it is at present. Stage 2: rise in sea-level and submergence of the ridge, with resulting lagoon formation. Stage 3: the barrier ridge, together with the lagoon, is driven landwards.

lagoon formations, as on the Black Sea and the Waddenzee.

CLIMATES AND COASTAL LAGOONS

The light energy received and dissipated by coastal lagoons depends on their geographical location. To a large extent, the amount of solar energy received controls physical processes such as temperature, evaporation and precipitation, and the processes of biological reproduction.

Boreal lagoons

Lagoons can be found in the Arctic, along the north coast of Alaska (e.g. the Simpson and Sasegaluk lagoons). These lagoons, which average 1 to 3 metres in depth, are not combined with marshes. Owing to the low amplitude of the tides and prolonged periods of frost, dynamic sedimentary, chemical and biological processes are virtually stilled, and the lagoons are covered by more than 2 metres of ice for eight months of the year. When the lagoons freeze, the salt in the surface water increases the salinity of the free water under the layer of ice, which may rise to more than 60 grams of salt per litre of water (60 parts per thousand). Photosynthesis stops and the environment rapidly loses oxygen. When the ice-break occurs the following spring it has a decisive impact. Substantial inflows of fresh runoff from pools in the tundra carry down sediments and lower the salinity of the lagoon water, which becomes brackish (23 to 29 parts per thousand) and well oxygenated for two to three months. There is some primary production but it is relatively slight, owing to the reduced light and nutrient salt inputs. The animal population is sparse as well. However, in spite of the long periods of frost and the low light intensity, the formation of water-plant communities of marine phanerogamia (zosteraceae or eelgrass) has been observed.

Lagoons in temperate, Mediterranean and sub-tropical regions

Typical examples of these lagoons are found on the coastlines of the Gulf of California and the Gulf of Mexico. The lagoons are formed behind virtually continuous beach-dune bars forming broad spits, with parallel beach ridges broken by narrow channels. The sediment load is mainly carried by the water courses, which have a regular horizontal salinity gradient ranging from less than 1 to 30 parts per thousand. In spite of the low amplitude of the tides, the currents are strong enough, at the channel entrances, to drive sediment into the lagoons. The banks are consolidated by salt-meadow or salt-marsh formations.

The light energy and nutrient salt inputs are sufficient to support the production of benthic algae and flowering-plant and phytoplankton communities in considerable numbers. The organisms living on the lagoon bed engage in intense burrowing, and this has the effect of continually turning over the sediment's structure, in a process known as 'bioturbation'. It is interesting to note that, in lagoons of this type, oyster beds can contribute significantly to sediment deposition, owing to the oysters' filtration of particles in suspension.

Periodically, rivers carry down very heavy sediment loads, transforming the bays at river mouths into partly closed lagoons (Fig. 3 (c)). This is true of the *Haffen* coast in the southern Baltic and the *limans* of the Black Sea. The sounds south of Norfolk on the Atlantic coast of the United States are very similar, on a wide-open seaboard. The most striking offshore bars are those stretching along the south-eastern coast of the United States and forming the celebrated 'V' of Cape Hatteras.

The *lido* lagoons on the Mediterranean littoral of the Golfe du Lion or the Adriatic coast differ from the *liman*-type coasts only in that they are less deep. The lagoons or *étangs* of the Languedoc and Roussillon, in France, occupy a vast 185-kilometre arc bisected by the Cap d'Agde. These *étangs* are generally shallow, measuring from 1 to 2 metres in depth, and gradually become silt-choked. The depth of the Etang du Buc, near Montpellier, was 1.5 metres deep in the eighteenth century, but is now, on the average, only 30 centimetres deep.

Along the Atlantic coast of Europe, the action of tides and currents generates vast movements in the offshore bars. The sand or pebble headlands stretching across a bay form a spit extension or 'bay-mouth', and the expanse of water isolated behind it eventually becomes a lagoon. The inlet becomes increasingly narrow until it reaches stabilization in relation to the discharge of the water-course, if there is one. Where the dominant swell strikes at an oblique angle to the coast and causes littoral drift, the bay-mouth increases in size in the direction of the drift; the opposite headland is eroded, so that the inlet is pushed back in the direction of the drift, and the river-mouth lengthens out along the coast. A good example of this phenomenon can be seen in the bay-mouth of the Arcachon Basin, which is encroaching southwards. The German *Nehrungen* can also be included in this type of formation. In some cases, the river-mouth is closed completely. *Etangs* formed in this

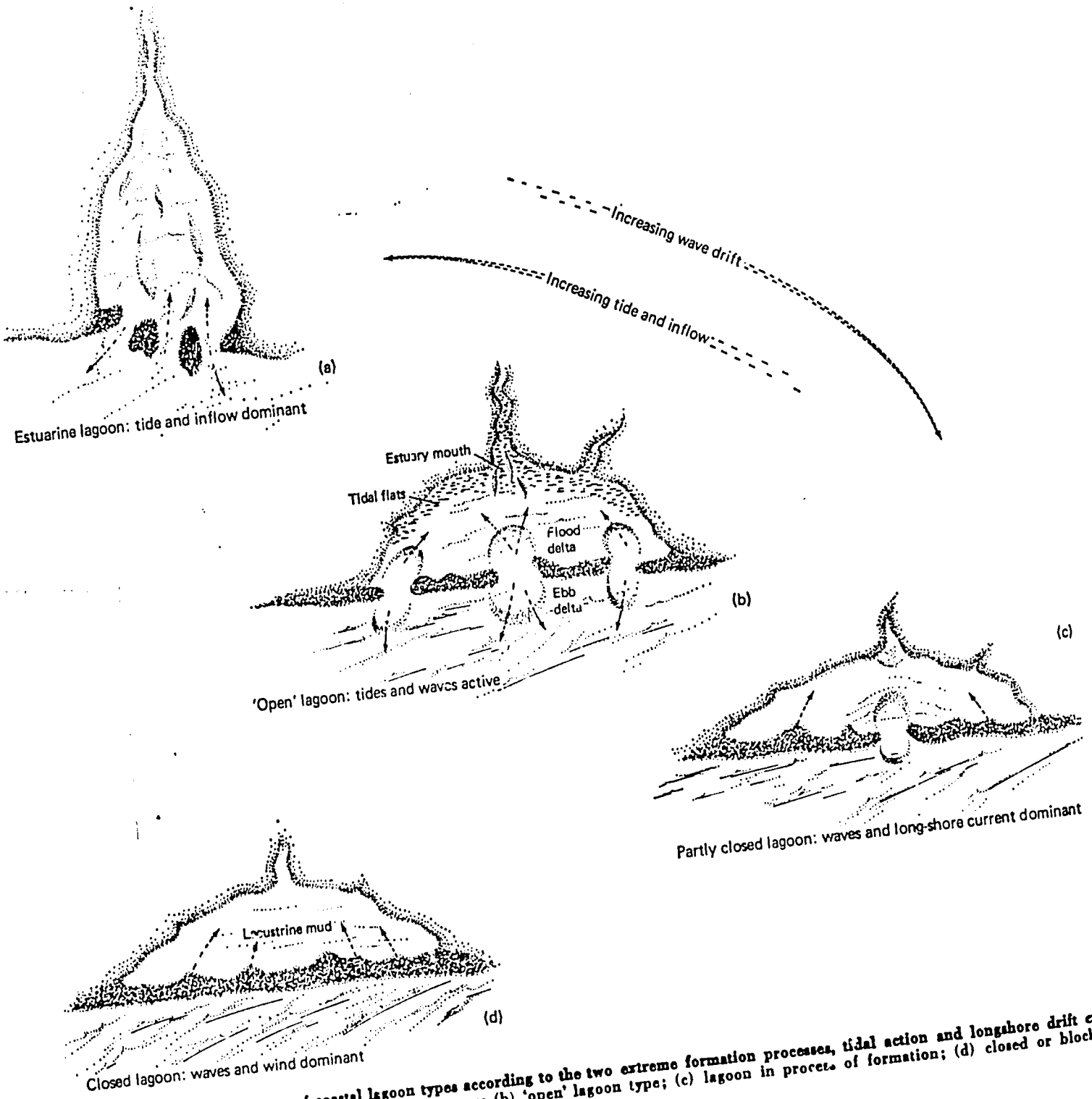


Fig. 3. Schematic classification of coastal lagoon types according to the two extreme formation processes, tidal action and longshore drift currents: (a) lagoon type very similar to an actual estuary; (b) 'open' lagoon type; (c) lagoon in process of formation; (d) closed or blocked lagoon type.

way are emptied only by infiltration through the offshore bar, as at Pwll Du in Wales and south of Concarneau in France. When rivers are in flood, the lagoon overflows and the resulting scouring current hollows out a deep bed which the sea usually fills in again. This can give rise to alternating closing and opening patterns which may sometimes be man-assisted. Other closed *étangs* flow one into the other in a strung-out pattern. These have only one, generally narrow, outlet to the sea. This is true of the *étangs* in the Landes on the Aquitaine coast of France which are of this type. These closed lagoons flowing one into the other are found in combination with coastal dunes formed by wind action, and these dunes occur very high on the Aquitaine seaboard. Similar formations can be seen in Morocco, on the North Sea, along the Baltic coasts, in Australia—some of the dunes in Queensland are more than 200 metres high—and along the Pacific coast of the United States.

Hypersaline lagoons of the arid regions

The lagoons of the Arabian Gulf and the Red Sea are good examples of arid lagoons. The coastal spits have been formed by submerged dunes which have been increased in size and consolidated by coral formations, beaches and new dunes. Dune bars have been extended laterally through the action of the coastal currents, but also transversally to the coast as a result of intense winds. These lagoons average between 2 and 5 metres in depth, and the tidal amplitude is 1 metre or less in the lagoons compared with 3.5 metres in the Gulf. Salinity varies between 39 and 45 parts per thousand in the coastal waters of the Gulf, and between 54 and 70 parts per thousand in the lagoons. The salinity of some closed lagoons in Saudi Arabia and on other coasts of the Red Sea can range from 80 to 300 parts per thousand (Solar Lake). The wind is responsible for the formation of most of these lagoons. The barchanes and parabolic dunes may migrate over distances amounting to more than 4 kilometres, leaving trails parallel to the wind separating the lagoon basins. A substantial amount of organic matter is produced in these regions, in spite of the limited nutrient salts input. Thick blankets of algae can be seen between tidal areas and above the littoral. The chemical precipitation of calcium carbonate and calcium sulphate produces formations characteristic of evaporites and dolomites.

Tropical lagoons

Lagoons are highly developed along tropical coasts, and characterized by broad spits and parallel beach ridges. Worthy of mention are the lagoons of the Atlantic seaboard of Brazil, which are sheltered behind offshore bars stretching over tens of kilometres (the Lagôa dos Patos), the very extensive lagoons of West Africa with the elongated spits of Walfish Bay, Lobito, Pointe Noire and Cape Lopez, or of the Guinea coast, and the sheltered lagoons of the Ivory Coast, Benin and Nigeria. These lagoons are strung out over several hundred kilometres and range from 2 to 8 kilometres in width. The rivers are diverted naturally and flow along the coast behind sand 'barriers' in the Ivory Coast, Gabon and Senegal.

Lakes Childa and Pulicat along the eastern coast of India and the string of lagoons along the seaboard of Kerala on the west coast occupy considerable areas. The coastal lagoons of Sri Lanka cover an area of 142,000 hectares. In Madagascar, the east coast has fine lagoon complexes running along 250 kilometres of littoral. Lagoons occur frequently all over South-East Asia, along the Mexican part of the Gulf of California, and on the Gulf of Mexico.

Tropical lagoons usually run parallel to the coast and have arms extending between the offshore bars. There are few inlets. The easterly drift currents are instrumental in creating parallel beach ridges between which lagoons are formed, while the coast advances seawards. There are considerable upland freshwater inflows during the rainy season. When the rivers are in flood, the lagoons overflow and discharge considerable quantities of sediment into the sea. During the dry season, on the other hand, seawater may flow up into the lagoons for distances of as much as 32 kilometres. Thus, depending on the season, the salinity of the lagoons varies from 0 to some 25 parts per thousand; sporadically very high salinity rates can be found. Tidal currents play an important role in carrying sediment and organic matter into the lagoons. Little is known in quantitative terms about the sedimentation rates and organic matter inputs, but they are probably much higher than those of lagoons in other climates.

The occurrence of mangroves behind the line of offshore and littoral bars is another original feature, which is common to most infilling littorals here. The often impenetrable forest on the fringes of the mangrove forms a barrier at low tide and prevents fine particles from escaping. Mangroves are usually located behind the lagoons proper, but can be found in front of them.

CLASSIFICATION OF COASTAL LAGOONS

Broadly speaking, four main types of coastal lagoon can be distinguished (see Fig. 3):

Type (a) is characterized by marked water-level differentials, which are largely due to the considerable tidal action. This type of formation is widespread, particularly in northern Europe (Germany and Belgium).

Type (b), the 'open' lagoon, is formed by the combined action of moderate currents and river inflows. Strings of islands or bars built up along coastal flats can often be observed. Mud sediments tend to accumulate in the internal part of the lagoon and accordingly form vast marsh areas, while sand tends to accumulate at the entrance of these lagoons. Examples of formations such as these are the fens of Norfolk and Lincolnshire (United Kingdom), the polders of the Netherlands, the *wadden* of Friesland and the Danish *vader*. The lagoons of the Gulf of Mexico, such as the Terminos Lagoon, and of the eastern coast of Venezuela, are also rather similar.

Type (c) represents partially closed lagoons. In this case, the action of coastal currents is considerable, and is responsible for the formation of substantial offshore bars. Rivers alter the coastal alignment to only a slight extent and build atrophied deltas which are 'plugged' or enclosed, as on the River Casamance in Senegal, in Spain, in the Arcachon Basin in France, and in the Adriatic. Owing to the limited tidal action inside the lagoons, a substantial volume of mud accumulates, while on the littoral side, wave action fosters the deposition of sand. In shallow lagoons subject to strong winds, sand tends to accumulate in the channels and inlet, while mud builds up in the protected internal parts. Exchanges between the open sea and the lagoon are not very significant.

Type (d) consists of closed or 'barred' lagoons. These are formed under the influence of the wind and of strong longshore drift currents. The absence of tides and adequate river inflows eventually closes them completely. In some instances, during heavy storms or flooding in the uplands a lagoon may overflow and drive a breach through the offshore bar; but this will subsequently be plugged again. Examples of lagoons of this type can be seen in the barred lakes of the Aquitaine coast in France, Solar Lake in Israel and Lake Togo on the coast of Guinea.

LIFE IN COASTAL LAGOONS

Lagoon ecosystems

Coastal lagoons are among the world's most productive natural systems, not excepting the best-fertilized inland environments. In the lagoons of Asia and West Africa, fishing yields have exceeded 1 tonne of fish per hectare per year, which is significantly more than the output of very good grazing land.

In temperate zones, lagoons are sometimes permanently in communication with the sea through inlets, more often temporarily, and the channels are often man-made. But the growth of algae and phanerogam grass may quickly seal them off. The inner lagoon areas are colonized by reeds, phragmites, bulrushes and typha. Freshwater areas are populated by paludous euphorbia and are the habitat of batrachians and a large number of wading and web-footed birds such as rails, herons, flamingos, wild duck and teal.

Areas closest to the sea are formed, as in the case of estuaries, of salt marshes (also called 'schorres'), consisting of an almost flat surface of dried mud which is partly desalted and covered with a luxuriant plant cover of spartina, pucinella, sueda and atriplex; in the tropics, it is overgrown with mangrove.[1] This plant cover is flooded only during high spring tides or storms. The higher elevation of salt marshes is due more to an accumulation of plant debris than to the continuing deposition of fine sediment particles. As the water from tides or lateral water courses flows outwards, it forms small, steep-sided channels, or crecks, which spread over areas where the mud is still uncovered. Salt marshes are often cut through by micro-cliffs situated above areas where the mud is soft and has no plant cover. This is followed a gradual change to a transition zone consisting of a mud flat, an area in the process of being taken over by halophilous plants. The fixation process initiated by the first vegetation to take root is partly instrumental in channelling tidal flows and maintaining a network of small channels or creeks which carve up the still rising mud into blocks. Closer to the main channel, there is an area of soft mud flats, or *slikkes*, which are flooded at every high tide.

The salt marshes and mud flats bear succulent flowering plants and algae (fibrous algae and sea lettuce or ulva) which are capable of withstanding long periods

1. See the article on mangroves in *Nature and Resources*, Vol. XIV, No. 3, April-June 1978.

out of water. At sea-level and under the water, zostera grass communities—or posidonia communities in the Mediterranean—colonize the marine parts of the lagoon, while *Ruppia* communities spread profusely in the more sheltered brackish areas, as is the case of lagoons in Europe and of the Lagôa dos Patos in Brazil.

In lagoons that have been temporarily plugged following a storm, areas that are still saline are populated by a dense network of salicornia sea-grass which holds back the sand and mud and allows the process of emergence to continue. A scrub growth formed of salicornia and therophytes, statices (sea-lavender) and sea-wort takes root on the still moist and salt-saturated silt which has risen above sea-level.

A mixture of mangrove and barren sand is found in the tropics. The inner areas located in fresh and brackish water are populated by a tangled growth of palm trees (raffia and calanus) or else, in well-drained parts, of prickly palms and shrubs (pandanus). The more saline parts, which are the equivalent of salt marshes, are occupied by white or grey mangroves forming veritable forests of medium-sized trees or bushes. The latter give the mangrove a very typical dense appearance. The plants most commonly encountered belong to the *Avicenia* genus, and the area they occupy takes on the appearance of a hard-bristled carpet, since the ground surface is punctured by a vast number of digitate roots or 'pneumatophores', which are the organs through which the plant breathes. *Avicenia* grow in north-west Africa and western and southern Australia, and on the silty desert-like coasts of Mauritania and the Red Sea. Owing to their ability to withstand drought conditions, they also occupy lagoons in regions with long dry seasons. The exposed roots of the mangrove rhizophora spread in gnarled and arch-shaped patterns above the level of the mud and intertwine to produce an inextricable tangle.

Coastal lagoons are populated by a rich and varied fauna. Many fish and crustacean species migrate through them, and they are the homes of molluscs such as oysters and mussels which are often harvested by man.

The most common fish are catadromous migratory species, which are capable of withstanding significant variations in temperature, salinity and dissolved oxygen content. The most widespread species in Asia and the entire Indo-Pacific region are grey mullet, tilapia and milkfish, and these are also encountered in Africa and South America. Grey mullet, sea bass, sea bream, eels and flatfish are abundant in temperate and subtropical lagoons. Shrimps of the peneid group offer significant economic potential in lagoons of the subtropics and tropics. Most of the lagoons provide sanctuary for immature forms of fish and crustaceans, and it is not without reason that they are spoken of as 'nurseries'. The exceptionally abundant bird life warrants the establishment of reserves.

The natural productivity of coastal lagoons

The generally unlimited mineral-salt input and the high renewal rate of *in situ* organic matter, combined with the shallow depth of water and the highly penetrative solar radiation, engender very high photosynthesis production values. In terms of primary productivity, lagoons, along with other estuarine systems, are estimated to produce some ten to fifteen times more than the waters of the continental shelf. Gross annual primary production is estimated to amount to approximately 10,000 to 35,000 Kcal per square metre per year.

As in other estuarine systems, the productivity of coastal lagoons reflects the interaction of influences emanating from the land, freshwater sources and the sea. Specialists are tempted to represent these interactions in terms of a simple conceptual model in which lagoons receive terrigenous and freshwater inputs, convert them and partially evacuate them through the volume of water discharged into the sea. This idea has been the key to thinking about sea-marsh systems over the past twenty years and has had an influence on many concepts in coastal oceanography. It is now beginning to be realized that the situation is much more complex, however, and that seasonal inputs of mineral salts, organic matter and trace elements originating from the open sea have an important role to play in the fertilization of coastal lagoons.

The interaction between lagoon-water and sea-water masses is particularly important, since freshwater inflows are relatively slight compared with the size of an estuary area. Recent research on lagoons in the Rhode Island area of the United States shows that the lagoon ecosystem receives inorganic oxidized forms of nitrogen and phosphorus from the open sea and then returns them in reduced forms. Over an annual cycle, the outflow of organic matter exceeds the inflow of inorganic nutriments, as a result of which there is a net loss of carbon, phosphorus and nitrogen from the lagoon into the open sea. A process of adsorption by the lagoon sediment is instrumental in maintaining generally low phosphate concentrations in lagoons. The inflow of oxidized inorganic phosphorus from the sea is of prime importance in sustaining a high primary productivity in lagoons. Organic inputs from the sea into lagoons are more important in terms of quality than of quantity. Fish-eggs,

larvae and lagoon plankton have a greater impact on the water in the open sea, and vice versa, than their contribution to the total mass of carbon exchanged would suggest.

In many lagoons, blankets of fibrous green algae and diatoms float on the surface or just beneath it. The superficial film of sediment on the lagoon bed may be covered by a blanket of unicellular algae (blue or cyanophyceae algae, peridinians, dinoflagellates and diatoms). Through the intense browsing action of herbivorous fauna such as small gastropods and crustaceans, this plant matter is converted into increasingly fine debris, which is quickly colonized by a large number of microorganisms and small-sized invertebrates (microalgae, bacteria, meiofauna, crustaceans, annelida, etc.). The colonized blanket of plant debris—known by specialists as 'detritus' —forms a trophic element with high food value. It is actively consumed by large numbers of immature and adult fish and by shrimps. Grey mullet are omnivorous and can absorb considerable quantities of this detritus, which moves through an intestine more than a metre long in a fish measuring only 20 centimetres!

Considerably more organic matter is produced than is used. It is stored in the sediment, carried out of the lagoons by the currents, and thus goes on to fertilize the open sea.

'Dystrophic crises'

When natural fluctuations in photosynthetic production become sufficiently large, as a result, say, of excessive mineral or organic inputs originating from natural sources or urban wastes, the ecosystem enters a period of crisis which is described as 'dystrophic' and is accompanied by such spectacular occurrences as the reddening or whitening of the water and the release of hydrogen sulphide and even acetylene, due to the intense activity of anaerobic bacteria. In the fish ponds or *tambaks* of Indonesia (see page 13 below), the acetylene given off undergoes spontaneous combustion as a result of the very high air temperature, and the will-o'-the-wisp effect on the water surface produces an impression that is both enchanting and eerie.

These occurrences are always accompanied by very marked nightly reductions in the dissolved oxygen content, followed by the wholesale deaths of aerobic fauna, especially of fish, crustaceans and molluscs. Such instances of dystrophy are common in temperate and tropical lagoons, particularly if they receive excessive organic matter inputs due to their being too isolated or to their receiving untreated domestic, industrial or agricultural wastes.

The structural order and disorder of the food chain

The chemical and physical instability of lagoon environments exerts selective pressure on the flora and fauna. Indigenous species are capable of withstanding wide-ranging variations in temperature, salinity and dissolved oxygen. Some hypersaline lagoons are inhabited by a fauna composed of bacteria, invertebrates and even fish that are capable of withstanding salinity rates two to three times higher than those of normal seawater.

The main structural features of the food chains in coastal lagoons are not fundamentally different from those in other longshore marine systems such as estuaries and deltas, but the confined space, shallow depth of water and intense sunlight foster the growth of a dense vegetation of algae and flowering halophilous plants. This substratum is used by all kinds of epiphytic organisms, such as diatoms, fibrous algae and micro-organisms, and offers a place of refuge for young fish from predators such as adult fish and birds. Two extreme types of food chain can be distinguished in lagoons:

The first type is characterized by wide variety, in other words a large number of species, and a balanced population structure. The ecosystem is virtually stable. Examples can be found in Lake Menzalah in Egypt and the Terminos lagoon in Mexico.

The second type is characterized by periods during which the physical and chemical conditions are relatively stable, and well-balanced and interdependent biological communities are established, but these periods are interrupted by natural or man-induced disturbances or 'dystrophic crises' which upset the ecosystem. As a general rule, a more or less regularly alternating pattern is set up between a dystrophic phase, when the ecosystem is disorganized, and the subsequent balanced phase, when order is restored. The study of the mechanisms responsible for these alternating patterns of order and disorder in lagoon ecosystems is a complex matter; it involves research into the dynamics of natural production (the demographic approach), types of adaptation to the environment of indigenous and immigrant populations (the ecophysiological approach), and the biological and biochemical transformations of energy (food consumed, production, energy loss through heat, and energy excreted and recycled in the ecosystem). It is through this type of holistic approach that man can control live production in lagoon and estuarine ecosystems.

MAN IN THE COASTAL LAGOONS

Marine littorals, and coastal lagoons in particular, are used for an extraordinary variety of human activities, ranging from subsistence and fall-back economies, as is the case on the Asian seaboard and the Casamance in Senegal, to major drainage works, large-scale concentrations of port activities and tourist schemes which 'urbanize' whole stretches of coastline.

From gathering to fish-farming

Coastal regions in which lagoons are common have formed the habitat of human groups since neolithic times. In lagoons, their accompanying deltas, and on coastal plains, fish-farming and agriculture has advanced as the endemic civilizations stabilized. Taking advantage of the onset of a milder climate in Europe, man hit on the idea of gathering shellfish for food from a very early stage. The longshore dunes on the southern shores of the North Sea were occupied by about 2000 B.C. Around the year A.D. 500, the Friesians who had settled on artificial mounds, or *terpen*, were already engaging in lagoon fishing.

Enormous piles of mollusc shells are found along lagoon and marsh coasts from Scandinavia to Brittany and from the Gulf of Gascony to the Tagus, including Asturias. There are logical archaeological arguments to support the theory that these piles of shells represent kitchen middens. The oyster-shell deposit discovered at Chauds, in the Poitou marshes of France, dates back to A.D. 1000. These oysters were certainly cultivated by the monks of the abbey of Saint Michel en l'Hern between the tenth and twelfth centuries. It has been estimated that some 2,000 to 6,000 million shells were dumped on the pile over the centuries! The island of Fadiouth, in the marshy plain at the mouth of the River Saloum in Senegal, was likewise inhabited from prehistoric times, as evidenced by the mounds of shells from molluscs consumed by man. Similar ancient life-styles are found on the seaboards of India, the Maghreb, Siberia, Palestine, America and Australia.

In Asia, man very probably succeeded in moving beyond the elementary gathering stage several thousand years B.C. The agricultural and fish-farming techniques of the Middle East may have been transmitted via the eastern Mediterranean seaboard. In Pharaonic Egypt, dykes were built to develop fish-farming in the lagoons of the Nile delta as early as the fourth millennium B.C.

Venice and the vallicoltura

In the last centuries of the Roman Empire, the leading centres of civilization were located on the mainland. The few inhabitants of the lagoons, such as fishermen and salt-gatherers, led a simple, hard life. However, with the decline of the Roman Empire, the populations fleeing before the Lombard invasion took refuge in the shifting areas of the lagoons round the Rialto islands or further east on the Grado. Venice was established in the amphibian zone of the lagoons, in a shifting landscape where the threat of subsidence was ever-present. The first consolidation works were dictated by natural conditions; the area of the most stable islands had to be increased, and the lagoon level stabilized, by keeping the main inlets (the *porti*) open. By the end of the eleventh century, when Venice had acquired considerable economic power, significant progress had been made in introducing controlled fish-farming in the lagoon through the development of the *valli*. Risen from the mud of the lagoons, the city of Venice is the incomparable affirmation of a prestigious past, and its survival and protection are of concern to the whole of mankind.

From the twelfth century onwards, the lagoons of the Adriatic coast were developed by the Venetians. Their conversion into giant fish nurseries began in the fifteenth and sixteenth centuries, and the first *valli* were built in the Comacchio lagoons on the Adriatic shoreline.

The *valli* of the Adriatic are situated in areas where the tides rise more than 1 metre. Communication with the adjoining marine environment is designed in such a way that young fish can get into the pools but cannot get out. A *fossa circondaria* surrounds the shallow parts, and it is in this 2 metre deep channel that the fish can find shelter from the summer heat or the severity of winter. Since the natural migration of the fish into the *valli* is insufficient for restocking purposes, they are regularly replenished with young fish taken from the sea and from adjacent lagoons which have not been set up as *valli*. The fish, which include grey mullet, sea bream, sea bass, eels and flatfish, are caught in a *lavoriero*, which is a kind of fish-crawl or labyrinthine dam located in the communicating channels between the lagoon and the sea and in which the only openings are catch chambers.

Up to the end of the nineteenth century, more than 4,000 hectares of *valli* had been set up in the lagoons on the Adriatic seaboard and near the mouth of the Po and Adige. Present-day installations for an area of 300 to 500 hectares consist of a complex network of dykes, gates and pumps which adjust the salinity rate and oxygen content of the water and control the inflow of young fish.

Fixed fishing grounds in the Mediterranean lagoons

At more or less the same time that *vallicoltura* was being developed in the Italian lagoons, the first *cherfia* (fixed fishing grounds enclosed by palm-frond hedges) were being built in the lagoons of the Maghreb. It has been estimated that the Kerbenah islands alone had about 1,000 such *cherfias*. Fish-crawl systems are of more recent date. These are dammed enclosures with openings equipped with concave basketwork trellises which admit young and adult fish but prevent large fish from escaping. These systems, which are similar to the Italian *lavoriero*, are installed in large numbers at the mouths of the Mediterranean lagoons, particularly in Tunisia and in the lagoons on the seaboard of the Languedoc and Roussillon in France. Along the *lidos* of the Mediterranean and the Adriatic, the orientation of the villages is an indication of the dominant sphere of traditional activity; some of them focus on the lagoon, others face out to sea. The marketing of fish products is still not very highly organized and is primarily concerned with supplying the regional and local market through a small number of wholesale fish-merchants. Over the past few years, the systems have been renovated and attempts made to introduce industrial-type marketing.

In the lagoons of South-East Asia, fishing on the receding tide is widespread in the vicinity of the generally densely populated villages. Bag nets towards which the fish are drawn by means of decoys are used to catch the much sought-after *Câ-nuc*, from which *nuoc-mam* sauce is made. Families often make their homes on small junks.

The acadjas *of West Africa*

In West Africa, lagoon fishing is still very traditional, and the family structure of the small groups living on the coast, the pressing demands of eking out a living, and the difficulties entailed in conserving fish or agricultural products are all factors contributing to the survival of rather rudimentary practices. The Baga of Guinea and the Malimba and Batanga in the south of the United Republic of Cameroon fish with harpoons from dug-out canoes. The Betsimisaraka living on the lagoons on the east coast of Madagascar merely use spoon-nets to fish on the unfailingly calm edges of the lagoons, and dams made of bamboo, rushes and raffia, where the fish are driven towards a rudimentary hoop-net which the fishermen raise periodically from dug-out canoes.

The Tofinnu or 'men of the water' are descendants of the Aja refugees living on the lagoons of the lower So river. In the eighteenth century, they founded Ganvié, a settlement built on piles in the Nokoué lagoon north of the present-day port of Cotonou, in Benin. The Tofinnu are primarily fishermen and breeders who have devised highly ingenious fish-farming methods.

The technique employed in the *acadjas* is a combination of fishing and fish-farming, and consists of immersing heaps of branches in the lagoon and attaching them to the bottom. Two qualities of wood are needed for the purpose: a hard rot-proof wood for the outer enclosure and a soft wood which decays easily for filling the space inside. When they are first set in place, the *acadjas* act both as a refuge and a trap. The fish get into the habit of withdrawing into them for shelter from predators. They soon start reproducing in them, and obtain a substantial secondary source of food from the algae and invertebrates which attach themselves in large numbers to the decomposing branches inside the enclosures. The biomass of the fish increases very quickly in the first twelve months, and natural mortality, especially of young fish, is much lower in these sanctuary environments than in open water. Fishing starts in the *acadjas* after a period of from four to eight months, and takes place twice a year in the medium-sized enclosures, which measure some 3,000 square metres, and once a year in the larger *acadjas*. The fishing method is simple: the *acadja* is surrounded by nets or basket-work frames which allow only the small and very young fish to escape. The branches are then removed from the inside, and the fish held back by the outer enclosure are caught with nets of various kinds, harpoons, and so on. Most of the catch is composed of *Tilapia* and *Chrysichtys*. In 1959, there were more than 35,000 *acadjas* covering a total area of 433 hectares, or 3 to 4 per cent of the total lagoon surface. Average yields amounted to more than 1 tonne per hectare per year. In the experts' view, Dahoman fishermen, using a well-tested ancestral method, managed to secure yields that were close to the optimum without any evidence of over-fishing. The same would be true today if recent development schemes in the port of Cotonou and the entrances to the Nokoué and Porto Novo lagoons had not caused a swift decline in the overall productivity of the lagoons. All in all, the number of *acadjas* has fallen by half, and production has plummeted by 80 per cent. From 1959 to 1969, i.e. over a ten-year period, output from the lagoon complex fell from 15,000 tonnes to 5,000 tonnes, and this has compelled some of the fishermen to emigrate to Nigeria.

The Indonesian tambaks

In Asia and the East Indies, the delta systems and their numerous coastal lagoons are the home of civilizations where the practice of fish-farming is highly sophisticated and based on ancient empirical knowledge. The creation of fish ponds in brackish water probably dates back as far as the fifteenth century. These fish ponds, known as *tambaks*, were first devised and created by a group of outcasts who were prohibited from farming the land or plying the seas. Originally confined to eastern Java and Madura, they gradually extended to central and western Java. The first *tambaks* in the Jakarta region came into being in about 1870.

Tambaks are fish-breeding systems installed in brackish water. They form a particularly propitious medium for raising Peneidae shrimps, *Chanos* (milkfish) and grey mullet. The functioning and production of these fish ponds depend on sufficient supplies of sea-water, alevins and shrimp larvae. Subsidiary inflows are provided by precipitation and freshwater river discharges. A perimeter trench measuring from 5 to 10 metres in width and averaging from 60 centimetres to 1 metre in depth surrounds a central platform immersed in water to a depth of 30 to 40 centimetres. The earth removed when the ditch is dug is used to build up an embankment around the pond. A sluice gate left in the embankment links the *tambak* directly with the sea, or else with a river or connecting channel. The working unit needed to raise a stock of Chanos from the alevin stage to that of fully-grown fish ready for consumption is usually 5 hectares. But there are much larger *tambaks*, covering as much as 20 to 30 hectares. The basic 5-hectare unit corresponds to a set of lagoon ponds which are separated by embankments but can be made to intercommunicate. This compartmentalized arrangement makes it possible to stagger the fish-harvest over a period of several months by fishing in alternate compartments which have previously been replenished with alevins and young shrimps. At the present time, the Chanos yield may be as high as 2,000 kilograms per hectare per year, but it is usually in the 500 to 1,000 kilogram range. It has proved possible to control the breeding of the species reared in the *tambaks*, and this factor further enhances the advantages of this type of fish-farming in developed lagoons (Fig. 4).

The estimated fish production of the whole of Indonesia, i.e. conventional fishing plus fish-farming, amounts to 400,000 tonnes, out of which fish-farming in the *tambaks* alone accounts for 120,000 tonnes. This highly profitable practice could be applied in other lagoon environments in South-East Asia. There are virtually unlimited outlets for the fish produced in the *tambaks*, since offshore fishing and cattle-raising can by no means provide all the animal protein needed by the increasingly large populations of the coasts.

From salt pans to fish-farming in brackish water

In Europe, salt pans have been installed on the marshy banks of deltas and lagoons since the Roman occupation —both on the coasts of the Mediterranean and in the countries of the Atlantic seaboard. Salt pans require a flat and impermeable soil, the presence of salt-water, and a climate which fosters evaporation and in which no rain falls for a certain period of the year. The topography of temperate and tropical lagoons is suited to the creation of salt pans, and the lagoons of Asia (especially China) and of tropical America have long been equipped for that purpose. In West Africa, in the Sine Saloum area of Senegal, the population has created salt pans forming a distinctive pattern on the long-shore landscape (as at Foundiougne).

In the Middle Ages in Europe, the monks of the great abbeys and some of the feudal lords set about creating salt pans in coastal marshes, particularly in western France, but their efforts were partly frustrated by war and by lack of interest and upkeep. Even so, the salt pan ditches were used from very early times for storing wild oysters, and it is probably at a very remote period —it is difficult to say exactly when—that ways were discovered of maturing and greening oysters in the manner still practised in the oyster beds of the Marennes-Oleron basin.

Early in the eighteenth century, Netherlands engineers, with the support of the local authorities but at times in the face of the hostility of the population, embarked on the systematic reclamation of salt marshes throughout Europe. The piecemeal dykes and erratically positioned intakes of the Middle Ages were superseded by geometrical layouts, large embankments and orderly networks of canals. With the assistance of these engineers, the aristocrats who owned the salt pans on the Atlantic coast of France, and were fervent adepts of Jean-Jacques Rousseau's ideas on nature, conceived the idea of converting their salt pans into fish ponds. These 'fish reservoir' schemes flourished all through the nineteenth century right up to the end of the Second World War, and they still occupy large areas of marshland on the French Atlantic coast (Fig. 5). The old salt-evaporation areas and the salt-pan runoff ditches are separated by embankments from the sea or the channel running

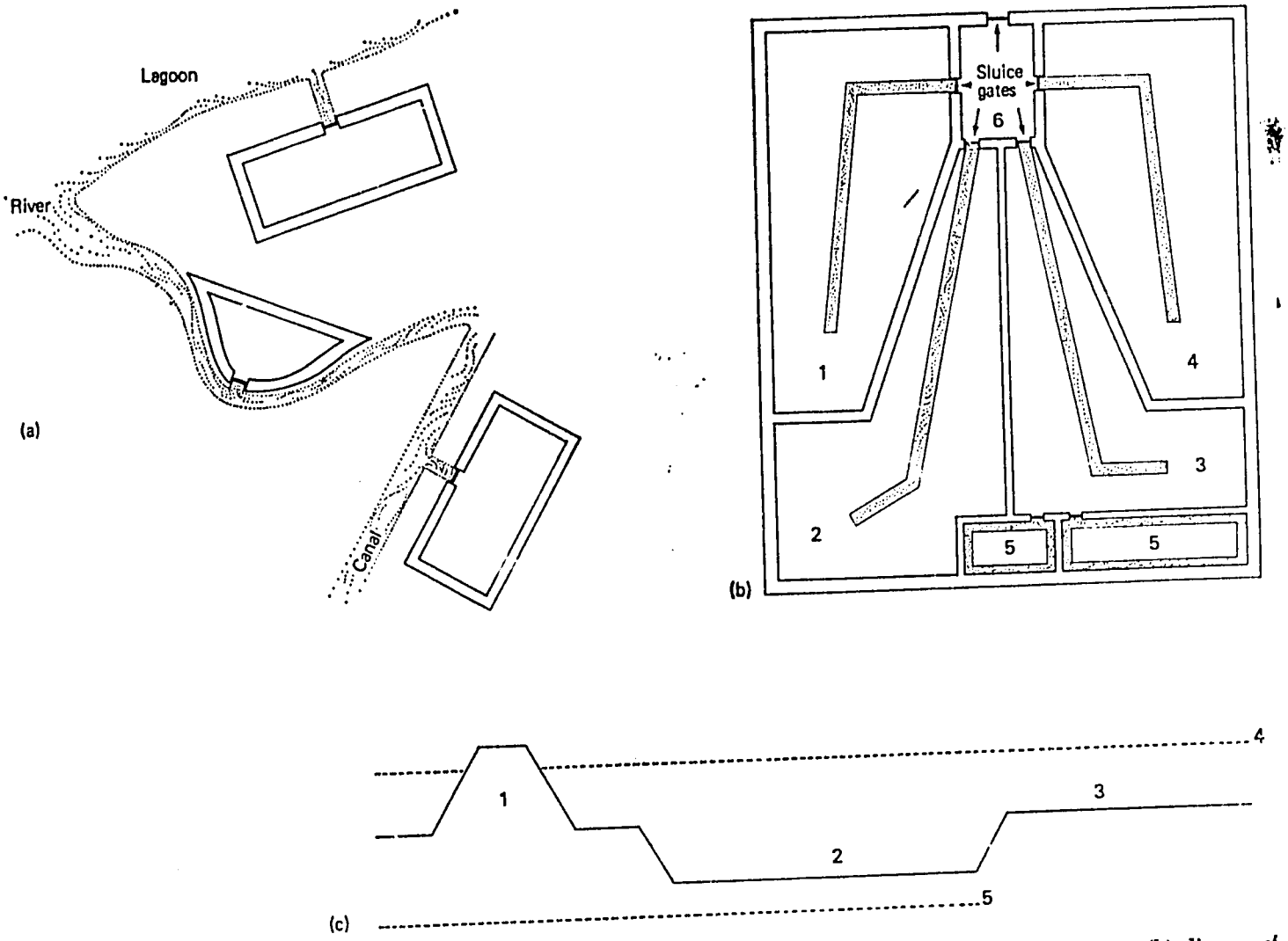


FIG. 4. *Tambak* systems, in use in Indonesia since the fourteenth century. The Porong-type *tambak:* (a) water supply system; (b) diagram of Porong-type *tambak* (1, 2, 3 and 4—fish-breeding compartments; 5—tanks for alevins and initial fattening; 6—fishing pool; the outlet ditches are represented by dotted lines and the embankments by full lines); (c) cross-section of a *tambak* (1—embankment; 2—ditch; 3—platform; 4—high-water filling level; 5—average low-water level).

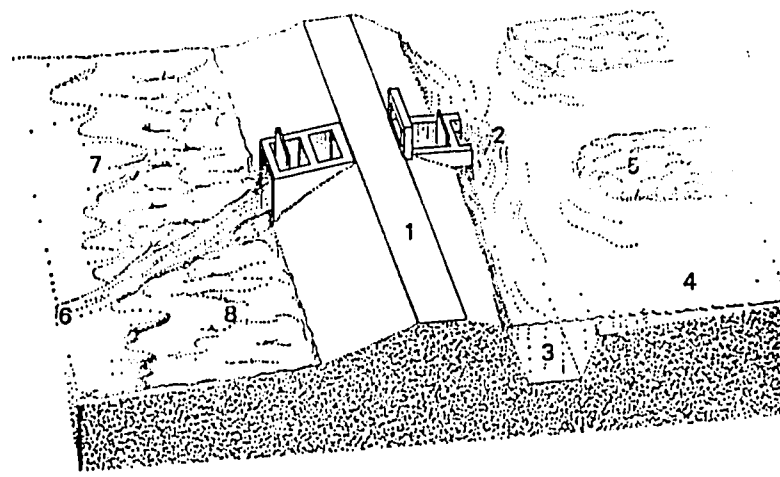


FIG. 5. Block diagram of a fish reservoir used in France since the eighteenth century (note similarity to Figure 4); 1—embankment; 2—sluice gate; 3—ditch; 4—platform; 5—earth dyke; 6—small channel connecting the sluice and the basin; 7—mud flats (*slikke*); 8—salt marshes (*schorre*).

alongside them, while tidal inflows and outflows are regulated by sluice gates. The breeding-ponds or fish reservoirs have a characteristic shape: channels or ditches measuring 1.5 to 2 metres in depth feed large expanses known as 'flats', each of which covers an area ranging from 1,000 to 10,000 square metres. These flats, 50 centimetres deep, are separated from each other by ridges formed of the mud or sand removed when the ditches were being dug. All inflows and outflows can be regulated by sluices located at intervals along these embankments.

At high tide, the sluices are manoeuvred in such a way that a current is created and the fish, both immature and adult, are drawn into the reservoirs. The fish are prevented from returning to the open sea by a system of meshwork frames. The main handling operations are those involving inflows and outflows. These do not take place in winter, since the fish are in a torpid state owing to the cold and are therefore not very active. They are usually carried out in the milder seasons from March to November. Every two weeks, when high tides occur at the time of the full or new moon, water from the sea is allowed to flow into the reservoir through the sluice gates. This operation lets in the young fish and natural mineral salts, and the reactive operation replenishes the reservoir by discharging the water held in storage for a long time back into the sea. This operation is carried out at low tide. The fish population, consisting of grey mullet, sea bass, eels, sea bream and flatfish, is free to move about inside the complicated network of lagoons, in which the salinity may vary from very diluted brackish water to actual seawater.

Some of these breeding-ponds consist of artificially fabricated tanks. More frequently, especially when they consist of former salt pans, their broad and irregular surrounding embankments are used to grow agricultural produce, and hence a double source of income can be secured from combining agriculture and fish farming on one and the same property. Fish reservoirs such as these still cover an area of 1,000 hectares in the Arcachon Basin, and are found in other lagoon marshlands in the Vendée and Charente on the French Atlantic coast. These fish nurseries thrived in the nineteenth and early twentieth centuries, but they have since gone into decline because of the scarcity of labour and the unwarranted loss of interest in this type of farming. Current yields from these systems, which are still worked by traditional methods, range between 100 and 200 kilograms of fish per hectare per year. Recent scientific research points to the possibility of obtaining yields between 500 and 800 kilograms per hectare per year of fish suited to aquaculture, such as sole. There is a revival of interest in fish reservoirs, which are very similar in conception and operation to the Italian *vallicoltura* and the Indonesian *tambaks*.

The shellfish industry

Although the Roman aristocracy was familiar with oysters and acquired a taste for them, systematic oyster-rearing is a relatively recent phenomenon. Oysters have been raised in the Far East since the eighteenth century, but the trials carried out in Europe at about the same period proved inconclusive, and it was not until the mid-nineteenth century that an actual oyster-breeding industry came into being, when the techniques of oyster-spat collection were popularized. The lagoon environments of the coasts of France, Great Britain, Zeeland and Friesland very soon took the lead, and the resulting pattern imprinted on the landscape prefigures urbanization of the sea coasts. There are some 45,000 oyster-farmers in France and, with its oyster beds in the Gulf of Morbihan, the Seudre Bay and the Arcachon Basin, the country is still Europe's leading producer. The holdings are chiefly run by families, and in some cases co-operatives are set up. There are similar oyster farms in Mediterranean lagoons, as in Tunisia. The intensive Japanese method is practised throughout the Far East—in Malaysia, India and China. In the United States, there is extensive oyster-farming on Chesapeake Bay, and especially on the Pacific coast and the Gulf of Mexico, the distinctive feature being the industrial diversification—the bulk of the oyster production is shelled and deep-frozen or used in the preparation of cooked dishes; the shells are crushed to make soil ameliorators and poultry feed.

Mussel-farming is rather specifically European. It is carried on from Spain to Denmark, but on a less industrial scale than oyster-breeding. There is some controversy as to when the practice first started, but it existed in the Gulf of Taranto, and also probably in the lagoons of the Atlantic seaboard, in the twelfth century. Mussel-farming has also spread on the Mediterranean coast in recent times, and in Zeeland and Denmark, mussels are used to produce flour for cattle feed.

There have recently been successful attempts at raising baby clams and cockles *(Cardium)* in beds set out in lagoons that are relatively open to the sea. These are produced for canning. In Galicia, Spain, three-quarters of the 6,000 tonnes of *berberechos* harvested in the *rias bajas* (low lagoons) are sent to local canneries. In the United States, clams are raised after removal from the muddy sands of New England inlets.

The reclamation of lagoon marshes

Under the pressures of population growth, man set about creating reclaimed polders on stretches of lagoon. The first large dykes were built in Flanders and the Netherlands in about the ninth century. The pumping of the inside areas of 'wet marshes' is a practice that has been going on all over Europe from the Middle Ages right up to the present day, the idea being to drain the land and at the same time to pump out the water stagnating below sea-level. The work done by Netherlanders all over Europe in the eighteenth century was considerable; and they designed plans and devised arrangements for pumping and disposing of the water as well.

In Italy, drainage of the marshes of the Po delta and on the Adriatic coast from Trieste to Ravenna began at the end of the nineteenth century, the first marsh development scheme of the Roman Empire having been interrupted by the barbarian invasions. The Pontine marshes south-east of Rome were formed of lagoon areas isolated from the hinterland by a line of quaternary dunes. The marshes, flooded in winter by fast-flowing streams, were an endemic source of malaria, but the land was fertile, and attempts were made to drain them in the Middle Ages at the instigation of the Papacy. These projects did not fully materialize, however, until 1939. It was to Venice's advantage to leave marsh areas in their inaccessible state, and it only invested very cautiously in agricultural activities involving land reclamation.

Delta and lagoon development hinges on the extent to which man exercises control over nature, the technical standards involved, and the degree of social and political organization. Lagoons and the marshes associated with them are, *a priori*, unfavourable environments owing to the prevalence of malaria and to the isolation caused by river flooding and cyclones. But they are attractive in that their constantly enriched alluvial soils, unlike inland tropical soils, are immune to rapid ageing. Furthermore, it is possible to navigate on them, and substantial extra food inputs are provided by fishing and fish-farming.

Right from the time large modern polders were created, use was made of a combination of dykes and de-watering pumps. Powerful pumping stations make it possible to reclaim thousands of hectares in the space of a few years. Work on closing the Zuyder Zee went on until 1932; it involved the construction of a dyke 32 kilometres long and the 'regulation' of sluice gates to control the level of the Ijsselmeer freshwater lake, which covers an area of some 120,000 hectares. The Netherlands has now been completly polderized, but the success of the Zuyder Zee venture prompted similar schemes in other countries, and these have been highly controversial in some instances, where estuaries or bays have been turned into polders in parts of Europe in which there were no population pressures, particularly in natural areas of considerable ecological importance.

The use of polders for agriculture is becoming more expensive and less profitable in the Netherlands, and this factor is working to the advantage of Randstad-Holland, which needs space for urban development, leisure areas and industrial zones. In Italy, at the beginning of this century, private capital was used to set up companies which launched into large-scale agriculture on the de-watered marshes of the Po delta, the Adriatic and the area around Rome. Owing to the population influx caused by these improvements, new towns were created on the thousands of hectares of 'developed' land and, as a result, the de-watered areas from Trieste to Ravenna and the suburbs of Venice have become over-populated (about 120 inhabitants per square kilometre).

On the African deltas of such rivers as the lower Benin and the Volta, flood and falling-flood crops are grown in combination, but techniques are pragmatic and empirical, and the degree of control exercised is irregular. In part of the Mekong delta, redistribution of flood water is organized for the development of rice fields. In this type of project, the water usually has to be drained off seawards and the inlets closed to prevent seawater from flowing upstream at high tide. Sluice gates are essential on lagoons and deltas if they are to be protected against occasional rises in water level. The construction of embankments and the subsequent development schemes are likely to have at least some effect on river-mouth sedimentation.

Engineering design of these controls entails making a prior study of the dynamic longshore conditions. It has been demonstrated that changes in the sediment transport pattern following the construction of port works, dams, and so on, may step up the pace of coastal erosion. Furthermore, it is often impossible to halt human activities which have an adverse impact on coastal equilibrium because of economic factors.

Some of the lagoons running along the West African seaboard have undergone significant ecological changes as a result of the construction of port facilities which close or open inlet channels. These works have had far-reaching effects on the natural productivity of the lagoons, and have been responsible for a sharp decline in their fishery resources. Rationally planned develo

ment, in which all countries dependent on the same lagoons or the same coast are involved, is an urgent necessity and programmes of this type have been going on for some years under the auspices of UNDP, Unesco and FAO.

Lagoons in jeopardy

Ever-growing human needs have provided the incentive for defending and taking over new areas for which land and sea compete. People are still 'discovering' that coasts, and especially lagoons, can be prospected for non-renewable resources such as minerals, gravel or oil, or for renewable live resources. These practices are all too often of a speculative nature and run the risk of irreversibly over-exploiting the production potential of coastal lagoons.

Increased production is liable to destroy more than it creates. Lagoons provide sheltered stretches of water and accordingly make it possible to set up tidal reservoirs or create natural flushing systems, but schemes such as these entail developing the lagoon inlets and their deep-water areas. The creation of artificial inlets and the closure of the natural communicating channels with the sea are unfortunately accompanied by serious disturbances which affect sedimentation, salinity and productivity conditions, and these may reduce fishing yields and prevent species that are important for the equilibrium of the ecosystems from entering the lagoons.

The growth of towns along lagoon shores produces an increase in domestic, industrial and agricultural wastes. The impact of domestic refuse is well-known: it tends to enrich the environment to an abnormal degree, and this exacerbates the natural tendency of lagoon ecosystems to become dystrophic. Degradation sets in very quickly and becomes even more pronounced as a result of the rapid multiplication of micro-organisms and the corresponding decline in the oxygen content of the water. Fish, crustaceans and molluscs die on a massive scale in such cases. The waste water from domestic refuse and faecal substances are full of bacteria, and since these are not fully purified by the lagoon water, they are liable to spread highly contagious diseases such as viral hepatitis, cholera and typhoid. The self-purifying capacity of lagoons seems to be less effective than that of the open sea, since lagoon water is generally warmer and has a lower salt content than seawater.

Industrial and modern agricultural wastes tend to enrich lagoons in hydrocarbons, synthetic detergents, heavy metals and agricultural pesticides, and little is known about the biological and chemical form these substances eventually take. Hydrocarbons and detergents are partially broken down by the bacteria, but heavy metals and pesticides are concentrated along the food chains, or at best, trapped in the sediment, and their long-term effects are not fully understood.

If pollutant substances in lagoons are to be eliminated altogether, complete control must be excercised over the dumping of wastes. It is on this control that the future of the ecosystems and of human health in lagoon environments depends.

LAGOONS AS TARGETS FOR ECONOMIC GROWTH

An original and promising economy

There can be no doubt that coastal resources will be required to feed increasing numbers of human beings. Traditional gathering and cultivation are giving way to more 'aquacultural' techniques involving the takeover of marine areas and the organized reproduction and raising of its plants and animals. Lagoon aquaculture can be expected to play a very important role in years to come. Traditional aquaculture, ranging in style from extensive to semi-intensive, will be obliged to evolve along increasingly industrialized lines, and these already call for thorough scientific knowledge of the ecosystems over which man wishes to exercise control.

It is impossible not to be struck by the extraordinary similarity of the methods of lagoon exploitation that have been spontaneously devised by peoples of very different origins and cultures. They have been focused on controlling animal migrations and improving fish-stocking, and the yields obtained from the *tambaks* and *acadjas* are often close to the optimum, without any evidence of over-fishing. Although most of the old pond fish-breeding systems—such as the *acadjas* in Africa, *tambaks* in Indonesia, fish-crawls in the Mediterranean, *vallicoltura* in the Adriatic and fish reservoirs on the Atlantic coast—are capable of further improvement, they can also serve as models for new low-investment schemes in tropical and temperate lagoons. Depending on the suitability of the natural site, such installations may be very simple—perhaps nothing more than fish nurseries. Actual fish-farming involving human intervention requires a modicum of infrastructure, even if only the closing off of a coastal inlet with nets or the building of rudimentary dykes equipped with gates or sluices, but a great deal can still be learnt from traditional models.

The future of lagoon aquaculture is highly promising.

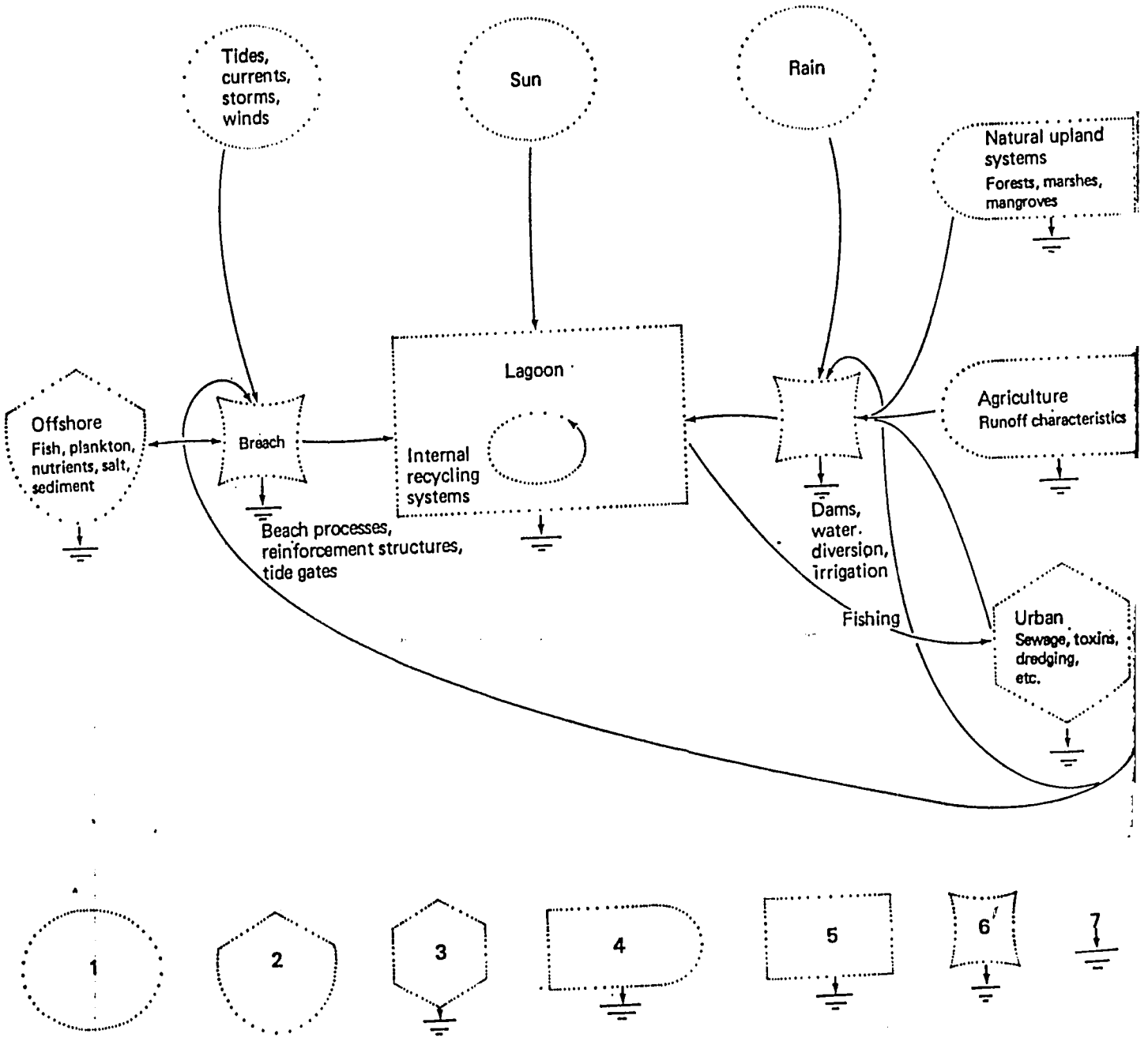


FIG. 6. Lagoons and their open sea/landmass interface. Legend of modules: 1—external energy sources; 2—energy reserve; 3—consumers, secondary production (animals); 4—primary production (plants, agriculture); 5—lagoon ecosystem (see detailed model, Fig. 7); 6—inlet/outlet regulating channel; 7—calorie loss (work, respiration).

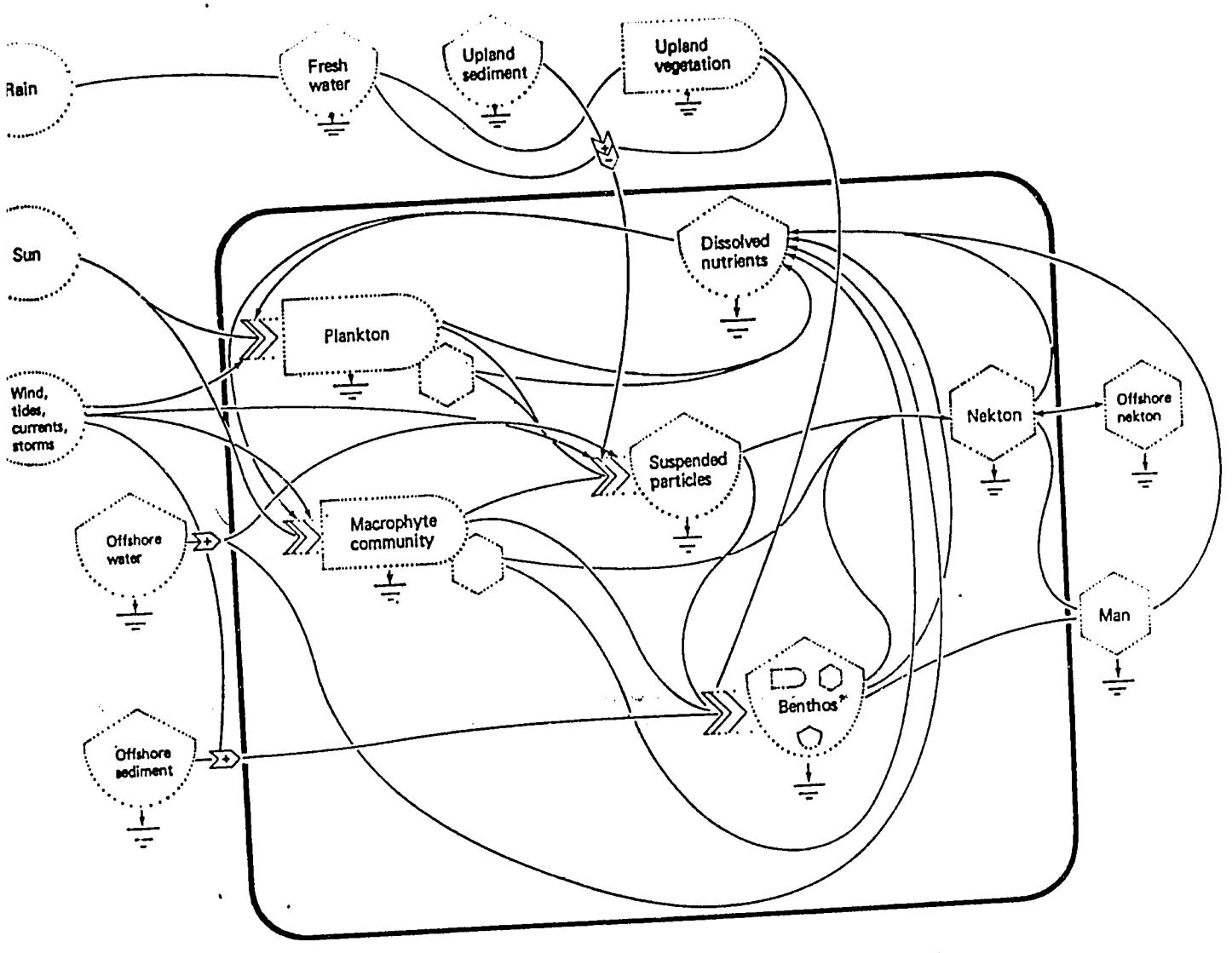


FIG. 7. General model of the lagoon ecosystem. (Energy circuit symbols in Figures 6 and 7, after H. Odum.)

There are signs that fishing may soon go into decline all over the world, owing to the impoverishment of stocks. Aquaculture is a judicious and profitable way of making use of considerable lagoon areas, with no damage to the natural environment. The environmental changes wrought by aquaculture are minor and neutral—they do not attack the ecosystems.

More developed than the elementary gathering and extensive production stages, with their relatively uncontrolled yields, an industrial stage can be set up for the selective production of the most attractive species. But ecosystem and intensive fish-breeding schemes must be properly prepared and monitored, and every endeavour made to incorporate the latest research findings into the technology. The most sophisticated forms of lagoon farming are still confined to a few countries and species.

The fact is that difficulties do exist: in many instances, there is no control over the reproduction of economically profitable species. At least there are a great many unknown factors. Production must be geared to markets; and there are inherent risks, even in the present surplus production which is due to overly intensive monoculture, as is the case of oyster-farming in Europe. But activities are being diversified, and the organization of production creates employment, makes high population densities possible and guarantees an original life-style that blends well with traditional socio-economic contexts.

Safeguarding and developing coastal lagoons

Projects for safeguarding and developing the littoral, and especially lagoons, marshes and 'wet areas', are prompted by awareness of the urgency of the problem. They must take account of threats to the biological equilibrium and, more specifically, of the following three fundamental facts:

First, the fragility of the environment, which is very vulnerable to attacks originating in the activities of societies that are already industrialized or in the process of industrialization.

Second, the utility of the lagoon environment for the harmonious development and continuance of human groups.

Third, the uninterrupted and rapid growth of the elements forming the 'aggressive mass'.

The active protection of coastal lagoons and of the seaboard generally should not be confined to conservation practices alone, however discerning these may be. Technical changes and advances in research must be taken into account, as well as the new needs of societies seeking variety in the elements of their life-styles. It is not eas to lay down a body of law for seaboard development since legal obligations are created that are liable t conflict with third-party interests. The tendencies in th recent directives put out by countries concerned abou environment are:

To slow down the pace of longshore urban developmen

To protect natural environments, especially marshe and wet areas, and control the removal of materials an the construction of embankments.

To adapt collective amenities to the coastal featur particularly with respect to ports, tourist areas an road systems.

To monitor architectural standards.

Research priorities

A holistic scientific approach is necessary to solve th many specific problems raised by the development an exploitation of lagoons.

In most instances, a purely descriptive approac usually consisting of the compilation of a long and cost series of inventories of the physical, chemical and biol gical parameters, does not permit objective evaluation the production potential of an ecosystem, or control ov production.

The main task is to collect and analyse comprehe sive data on the functioning and evolution of the ecos tems. This requires the collaboration of scientists fro the widest of backgrounds—biologists, chemists, phy cists, mathematicians—and the close co-operati between specialists and developers necessary to devel a comprehensive model, and reflect the real image of t workings of lagoon ecosystems and their interfaces. A the dynamic features are brought together under t common denominator of energy—the concentration chemical substances, synthesis of matter (productio biomass), vector flows linked to hydraulic regimes (ti and currents), trophic patterns, impact of human ac vities, human exploitation, etc. (see Figs. 6 and 7).

Towards the scientific management of coastal lagoons

Under the weight of present-day socio-economic demm traditional land-use technology in the lagoons is longer adequate. But there are few instances of 'envir mental plans' applying innovative, let alone futuris strategies based on far-reaching, objective scientific re tion involving a wide range of skills and appropriate search facilities. Such plans are essential to determine what extent coastal lagoon ecosystems and their interfa

can withstand the myriad changes imposed by man, without running the risk of irretrievably losing the capacity for renewal on which their continued existence depends. This is the essential issue governing the management and development of natural lagoon resources, if they are not to disappear altogether in the relatively near future.