



UNITED NATIONS ENVIRONMENT PROGRAMME

REGIONAL SEAS

A. C. Ibé and R. E. Quélenne:
Methodology for assessment and control
of coastal erosion in West and Central Africa

UNEP Regional Seas Reports and Studies (No. 10)

Prepared in co-operation with



UNEP 1989

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PREFACE

The United Nations Conference on the Human Environment, which took place in Stockholm, 5-16 June, 1972, adopted the Action Plan for the Human Environment, including the General Principles for Assessment and Control of Marine Pollution. In the light of the results of the Stockholm Conference, the United Nations General Assembly decided to establish the United Nations Environment Programme (UNEP) to "serve as a focal point for environmental action and co-ordination within the United Nations system" (General Assembly resolution (XXVII) of 15 December 1972). The organizations of the United Nations system were invited "to adopt the measures that may be required to undertake concerted and co-ordinated programmes with regard to international environmental problems", and the "intergovernmental and non-governmental organizations that have an interest in the field of the environment" were also invited "to lend their full support and collaboration to the United Nations with a view to achieving the largest possible degree of co-operation and co-ordination". Subsequently, the Governing Council of UNEP chose "Oceans" as one of the priority areas in which it would focus efforts to fulfil its catalytic and co-ordinating role.

The Regional Seas Programme was initiated by UNEP in 1974. Since then, the Governing Council of UNEP has repeatedly endorsed a regional approach to the control of marine pollution and management of marine and coastal resources and has requested the development of regional action plans.

The Regional Seas Programme at present includes eleven regions ^{1/} and has over 120 coastal States participating in it. It has been conceived as an action-oriented programme having concern not only for the consequences but also for the causes of environmental degradation and encompassing a comprehensive approach to combating environmental problems through better management of marine and coastal areas. Each regional action plan has been formulated according to the needs of the region as perceived by the Governments concerned. It is designed to link assessment of the environmental quality and the causes of its deterioration with activities for the management and development of the marine and coastal environment. The action plans promote parallel development of regional legal agreements and of action-oriented programme activities ^{2/}.

At the third session of UNEP's Governing Council (1975), a number of West and Central African States requested UNEP to study the problems of marine and coastal pollution of their region. Following that request, UNEP's exploratory mission visited fourteen States of the region during 1976. The mission's report identified major environmental problems of the region and recommended the development of a regional action plan for the protection and development of the marine environment and coastal areas.

^{1/} Mediterranean, Kuwait Action Plan Region, West and Central Africa, Wider Caribbean, East Asian Seas, South-East Pacific, South Pacific, Red Sea and Gulf of Aden, East Africa, South-West Atlantic and South Asian Seas.

^{2/} UNEP: Achievements and planned development of UNEP's Regional Seas Programme and comparable programmes sponsored by other bodies, UNEP Regional Seas Reports and Studies No. 1. UNEP, 1982.

After considering the report of the mission, the fifth session of the Governing Council (1977) decided that "steps should be undertaken for the development of an action plan and a regional agreement to prevent and abate pollution" in the West and Central African region.

Preparatory work on the development of the action plan and regional agreement included several expert group meetings, missions and surveys leading to the Conference of Plenipotentiaries on Co-operation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region (UNEP/IG.22/7) convened by UNEP in Abidjan, 16-23 March 1981.

The Abidjan Conference adopted the Action Plan for the protection and development of the marine environment and coastal areas of the West and Central African Region 3/, Convention for the Co-operation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region 4/, Protocol concerning co-operation in combating pollution in cases of emergency 4/, and a set of conference resolutions.

Subsequent intergovernmental meetings 5/, 6/, identified coastal erosion control as a priority area for action. Consequently, it was decided to initiate a project (WACAF/3) which would study the causes, evolution and assessment of measures for the control of coastal erosion. One report 7/ and a bibliography 8/ relevant to the coastal erosion problems of West and Central Africa resulted from that project.

The present project (WACAF/6) was conceived as an extension of WACAF/3 to produce a manual containing appropriate methodologies to monitor coastal erosion in the West and Central African region, including standardised procedures for coastal studies applicable to the region.

This manual, which is the outcome of the project, is intended principally to be used by local specialists responsible for coastal erosion assessment and control activities in the West and Central African region. It was prepared by Dr. A.C. Ibé (Nigerian Institute for Oceanography and Marine Research, NIOMR, Lagos, Nigeria) and Dr. R.E. Quélenec (Bureau de Recherche Géologique et Minière, B.R.G.M., Marseille - France), under the direction of Dr. Quélenec and the supervision of Mr. J.C. Sainlos, UNEP Programme Officer and Mr. A. Suzyumov, Unesco Programme Specialist.

3/ UNEP: Action Plan for the protection and development of the marine environment and coastal areas of the West and Central African region. UNEP Regional Seas Reports and Studies No. 27. UNEP, 1983.

4/ UNEP's Convention for Co-operation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region. Protocol concerning Co-operation in Combating Pollution in Cases of Emergency. UNEP, 1981.

5/ Meeting of the Steering Committee for the Marine Environment of West and Central Africa, Abidjan, 20-22 July 1981 (UNEP/WG.61/5).

6/ Meeting of the Steering Committee for the Marine Environment of West and Central Africa, Geneva, 22-23 April 1982 (UNEP/WG.72/3).

7/ UNEP/UNESCO/UN-DIESA: Coastal erosion in West and Central Africa. UNEP Regional Seas Reports and Studies No. 67. UNEP 1985.

8/ UNEP/UNESCO/UN-DIESA: Bibliography on Coastal Erosion in West and Central Africa. UNEP Regional Seas Directories and Bibliographies, 1985.

It is the first time that such a manual has been prepared for the scientists, technicians, decision-makers and managers of the coastal zone of the region. It aims to provide instructions based on the main results of the important studies prepared during the WACAF/3 project "Control of Coastal Erosion in the West and Central African region" executed by Unesco and UN/DIESA for UNEP.

The objectives of the manual are:

- to present scientific information necessary to understand the formation and dynamic behaviour of coastal sedimentary features; and
- to allow the national experts in each country of the region to identify, assess and combat undesirable coastal changes (erosion).

The manual is subdivided into five chapters:

- Chapter 1: Geological evolution, present geomorphology, sedimentology and erosion situation of the coast in the region;
- Chapter 2: Basic principles of geomorphology and coastal processes;
- Chapter 3: Factors influencing coastal erosion in West and Central Africa;
- Chapter 4: Coastal assessment, monitoring and control of coastal changes; and
- Chapter 5: A practical approach to coastal protection in the region.

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1. GEOLOGICAL EVOLUTION, PRESENT GEOMORPHOLOGY, SEDIMENTOLOGY AND EROSION SITUATION OF THE WEST AND CENTRAL AFRICAN REGION

It is important at the onset to discuss in broad terms the geological evolution, present geomorphology and sedimentology as well as the erosion situation of the West and Central African region so as to bring into proper perspective the presentations that follow in Chapters 2 to 5. (Fig. 1.1).

1.1 GEOLOGICAL EVOLUTION

The evolution of the continental margin of West and Central Africa is linked with the separation of America from Africa. The dating of this separation is not precise as it consisted of a series of overlapping events.

According to an account by Emery et al. (1974), the earliest of the events in the region was the development of basins and troughs (the Senegal, Liberia and Sierra Leone basins), when North America separated from Africa, about 180 million years ago. Then followed the separation of South America from Africa which probably began in the south and proceeded northward occupying a time span of about 135 million years to about 165 million years. The approximate date of separation is indicated by the general continuity of Precambrian and Paleozoic strata and structures in Africa and South America and the disruption of Jurassic and younger structures. This separation led to the formation of the basins further south (Mossamedes, Cuanza, Congo-Cabinda, Gabon, Cameroon, Nigeria, Dahomey (Benin) and Côte d'Ivoire basins (Fig. 1.2).

Continued separation of South America from Africa produced easily recognizable ocean-floor provinces. Very prominent is the continental margin and deep-ocean province of transform or translation faulting that is directed by many fracture zones stretching from the Mid-Atlantic Ridge to the continental slope and even inland. Based on these oceanic fracture zones and related tectonic trends onshore, Lehnert and Ruitert (1977) subdivided the Atlantic margin of Africa into four segments, three (A, B, C) of which occur in the WACAF region, each having its own basin history. In brief, these segments are (Fig. 1.3):

- the North West Africa segment (A),
- the Equatorial segment (B),
- and the Cameroon-Gabon-Angola segment (C).

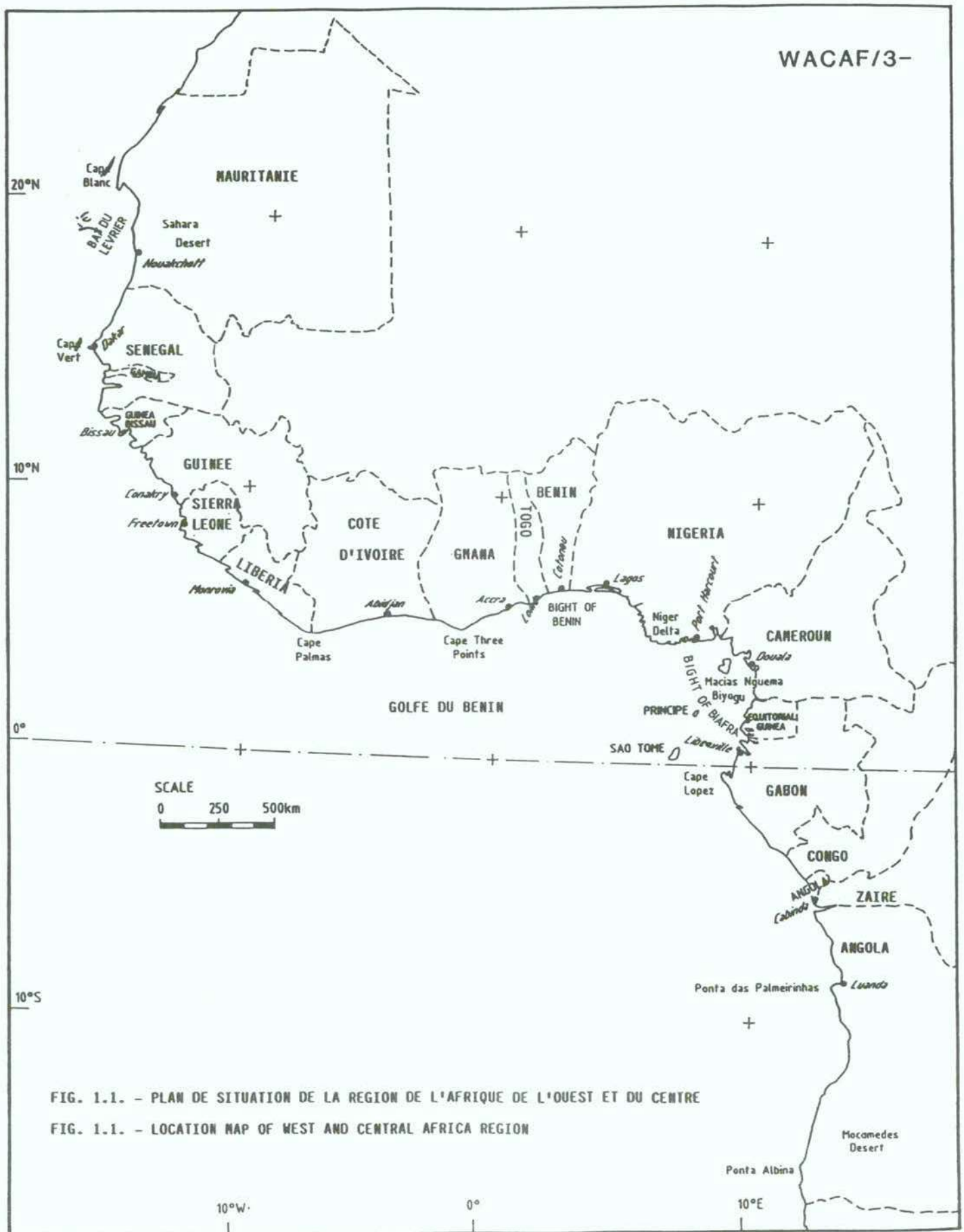
1.2 GEOMORPHOLOGY

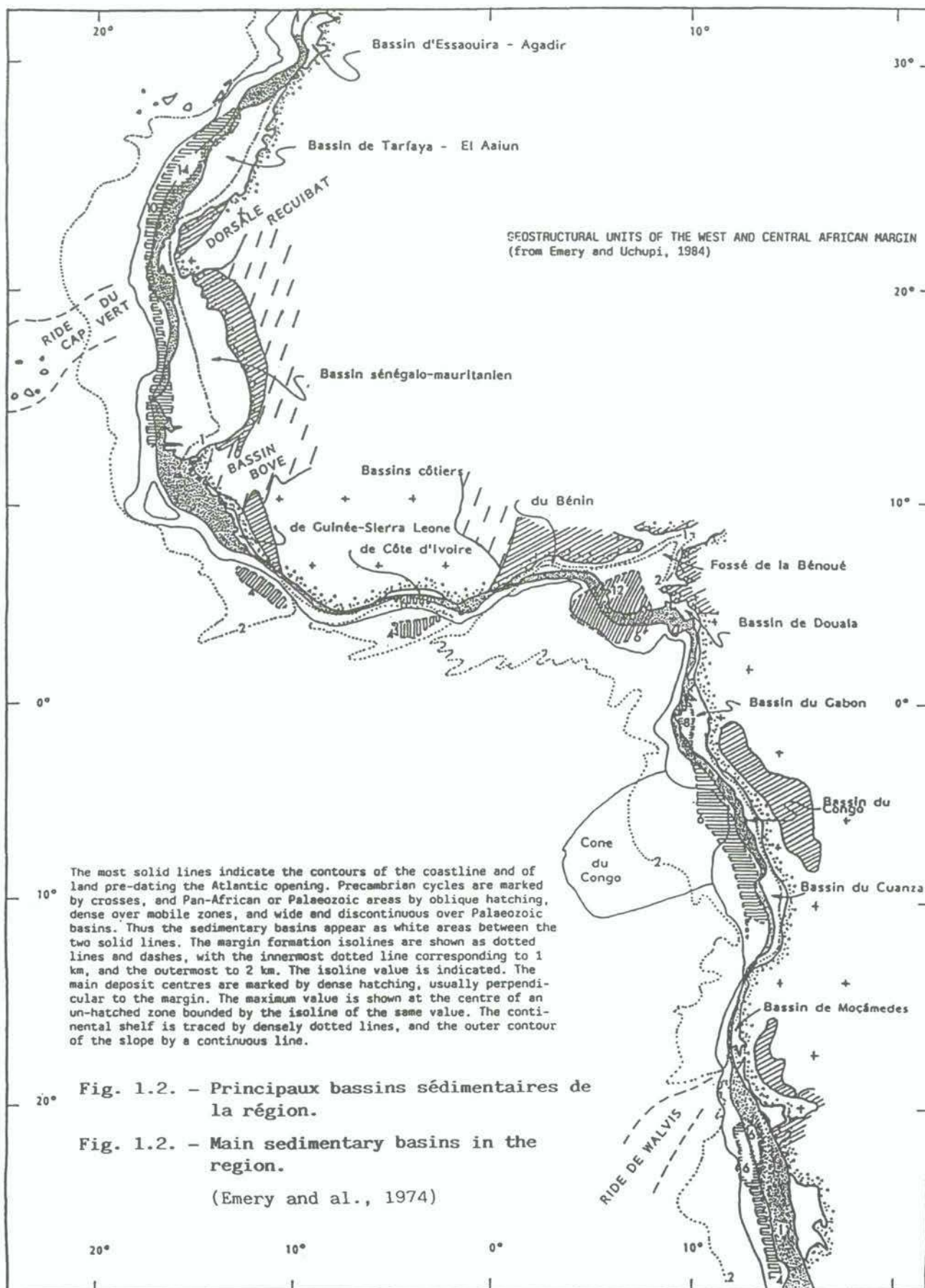
The coasts in the West and Central Africa region are mostly low plain, sandy and surf beaten. Four broad types are recognized:

- drowned coasts in the northern areas;
- sand bar or lagoon coasts along the North of the Gulf of Guinea;
- deltas associated with most of the major rivers (e.g. Niger Delta) usually with mangrove swamps and marshes;
- coasts with sand spits (and tombolos) formed by accumulation of longshore transported sand in bays found in the southern parts of Angola.

A further subdivision (UNEP, 1985) recognizes ten geomorphological provinces for the region as follows:

1. from Cape Blanc peninsula to the Cayar canyon (Mauritania to Northern Senegal): sandy coast, desert plain with a generally rather narrow shelf, interrupted by and bounded to the south by the Cayar canyon;





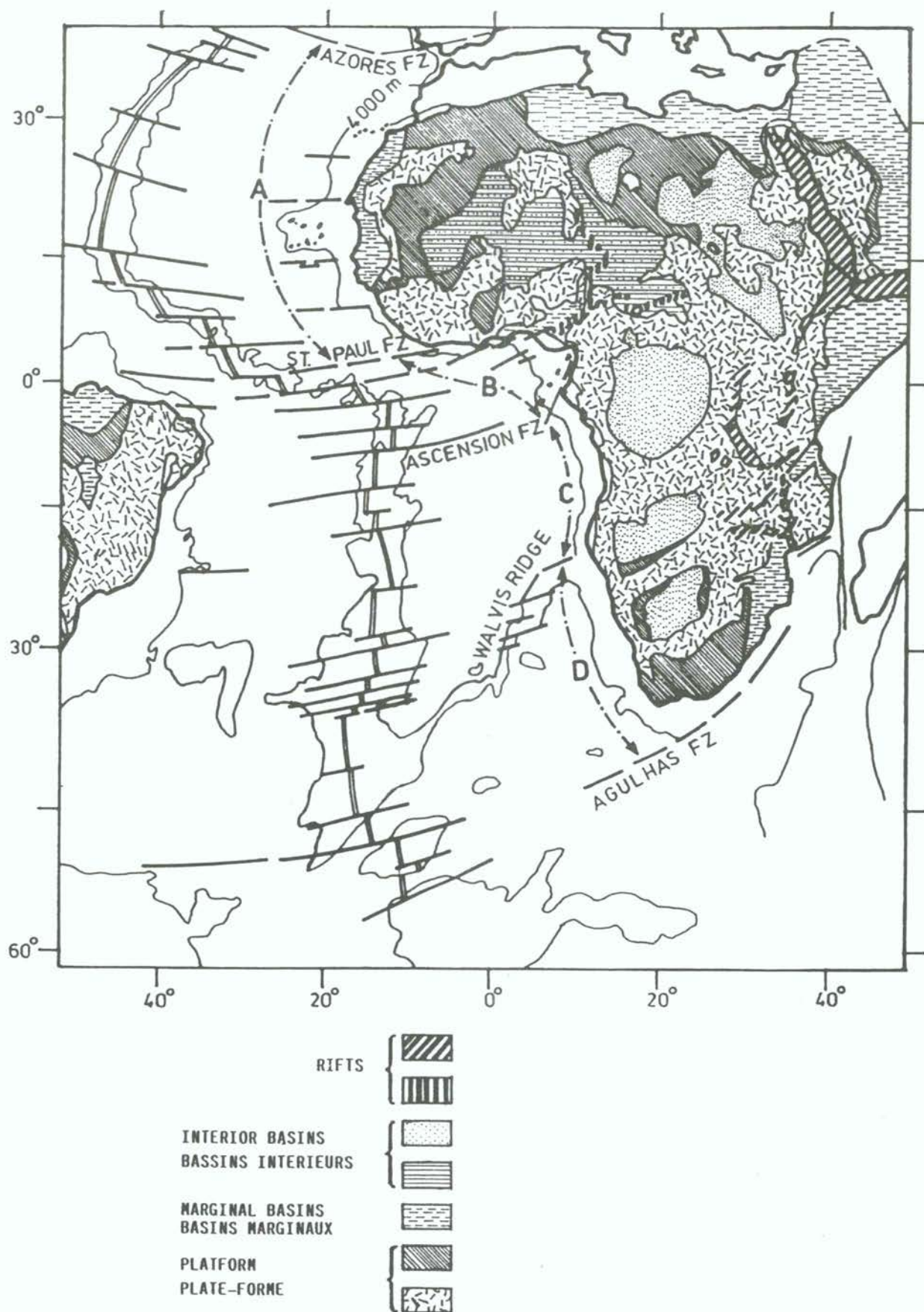


FIG. 1.3. - PRINCIPAUX SEGMENTS DE LA MARGE ATLANTIQUE DE LA REGION.

MAIN SEGMENTS OF THE ATLANTIC MARGIN OF THE REGION.

(LEHNER and DE RUITER, 1977)

2. from the Cayar canyon to Casamance (southern Senegal to Gambia): coastal plain with a rather large shelf, progressively more humid and swampy to the south owing to the presence of Saloum, Gambia and Casamance estuaries;
3. from Casamance to the Sherbro islands (Guinea-Bissau, Guinea and northern half of Sierra Leone): humid, narrow tropical plain and large shelf;
4. from the Sherbro islands to Cape Palmas (southern half of Sierra Leone to Liberia): humid tropical coast, narrow coastal plain, very narrow shelf;
5. from Cape Palmas to Cape Three Points (Cote d'Ivoire and the western end of Ghana): humid equatorial coast, first rocky, then with a coastal plain, and again rocky, with a narrow shelf;
6. from Cape Three Points to the Lagos lagoon (Ghana, Togo, Benin, western Nigeria): humid equatorial coast with a coastal plain, somewhat rocky to the west, and the shelf of a variable width. This segment is characterized by the presence of the vast Volta delta;
7. Niger delta (Nigeria): quite well individualized, owing to the large sedimentary supply, shelf of an intermediate width;
8. from the Ria del Rey to Cape Lopez (Cameroon, Equatorial Guinea, North Gabon): humid equatorial coast, with both rocky and coastal plain coasts, a relatively narrow shelf;
9. from Cape Lopez to the Congo-Zaire canyon (South Gabon, Congo, Cabinda, Zaire): equatorial plain coast with a narrow shelf, abruptly bounded by the head of the Congo-Zaire canyon;
10. from the Congo-Zaire canyon to the Cunene river (Angola): tropical coast, progressively arid toward the south, morphologically heterogeneous with a narrow shelf.

Landwards the coastal lowlands rise through series of steps which are essentially erosion surfaces, to the highlands inland. The highlands are for the most part outcrops of the basement complex, although resistant sedimentary formations, mostly sandstone, are also common.

1.3 CONTINENTAL SHELF

Oceanwards, the coasts descend to a generally narrow (100 km) continental shelf except near the northwestern limits of the region about 220 km northwest of Monrovia, where the shelf reaches its greatest width. The shelf break occurs in an average water depth of 100 m except to the southeast, inshore of Walvis Ridge, where it reaches around 400 m in width. The shelf appears to be flat except off seacliffs of basement rocks and in areas where beachrock and coral-algal reefs are present. At least seven large submarine canyons etch the seaward edge of the shelf and one, the Congo submarine canyon, crosses the entire shelf from at least 25 km within an estuary (Veatch and Smith, 1939; Heezen et al., 1964; Shepard and Emery, 1973).

The continental shelf descends through the continental slope which is dominated by salt (or shale) diapirs and is dissected by at least a score of submarine canyons into the continental rises and abyssal plains. Beyond the abyssal plains are the abyssal hills, Mid Atlantic Ridge and other ridges.

1.4 SEDIMENTOLOGY

The land margin of West and Central Africa is bordered by lowlands that mark the areas of basins underlying major river valleys (such as the Niger-Benue) and the coastal zone. The basins date from the Mesozoic and therefore have been filled with continental, lacustrine, evaporitic and normal marine sediments.

Seismic research and deepsea coring have revealed that the sedimentary basins in the region contain huge piles of sediment, that range from 1.0-1.5 km or less off Sierra Leone through 5-6 km in much of the gulf of Guinea to more than 8 km in the Niger delta.

The Gabon basin contains 16 to 18 km of sediment (Brink, 1984) but in the southernmost part of the region, the sedimentary layers again thin to about 3-4 km (Litvin, 1980). Calculated rates of sedimentation vary between 30-100 mm per 1,000 years north of The Congo decreasing to 10-30 mm per 1,000 years further south.

The fringing territory is mostly sandy beaches, although other types occur. Sediments of the shelf consist largely of sand being buried under recent silt and clay with an admixture of faecal pellets. The continental slope is covered by silt (e.g. Gabon basin and Cuanza basin) and shale (e.g. Niger delta).

Cores taken from the continental rises and abyssal plains show that they contain graded sand layers, while sediment in the complex topography of the abyssal hills, Mid Atlantic Ridge and the ridges that separate units from the continental rise are highly irregular (Ewing et al., 1964, 1966; Emery et al., 1974). Some volcanic sediment surrounds both St Helena and Ascension islands as well as the volcanic islands of Fernando Pô, Principe and Sao Tome.

1.5 EROSION SITUATION IN THE REGION

Erosion is a prevalent phenomenon along the Atlantic coast of West and Central Africa (Fig. 1.4). In many places, the rate of coastline retreat and the resulting environmental degradation and economic loss is on such a scale as to be alarming.

The following is a succinct review of the extent of the erosion problem (both natural and man-made) in the region based on several regional and country reports as well as on the material collected by fact finding missions. For clarity, a country by country approach is adopted. No attempt at completeness is intended either in the country or regional accounts.

1.5.1 Mauritania

Local marine erosion of the Pleistocene sea cliffs occurs in the Nouadhibou area, probably because of the mixture of dune sands and Aeolian dust with silty mud. In front of Cape Timiris, the Tiouillit canyon may be serving as a sediment trap and could well be one of the causes of coastal erosion above 30 km north of Nouakchott. The southern zone of the coast is characterized by some erosion which clearly affects the dune formations of the Agucitir and the Akchar.

1.5.2 Senegal

North of Senegal, the town of St Louis, built on a sand spit and on an island in the Senegal estuary (Photo Fig. 1.5) is exposed to submersion by the sea during heavy storms with sea level set-up.

In the Cape Vert peninsula, erosion of some beaches and cliffs occur between the head of the Fann spit and Cape Manuel.

Further south, between "cap des Biches" and Rufisque, the coast is subjected to erosion with an annual retreat of 0.33 m at the cliff of "cap des Biches" between 1969 and 1978. At Rufisque, the coastline retreat has averaged 1.30m/yr during 1933-1980.

Some areas on the "Petite cote" such as Bargny, Cape de Naze, M'Bour and Joal are currently being eroded. In front of Sarene, the coast is thought to have retreated an average of 2m/yr in the last 5 years. From Joal to Sangomar, the mean annual retreat of the coast is 1.2 m.

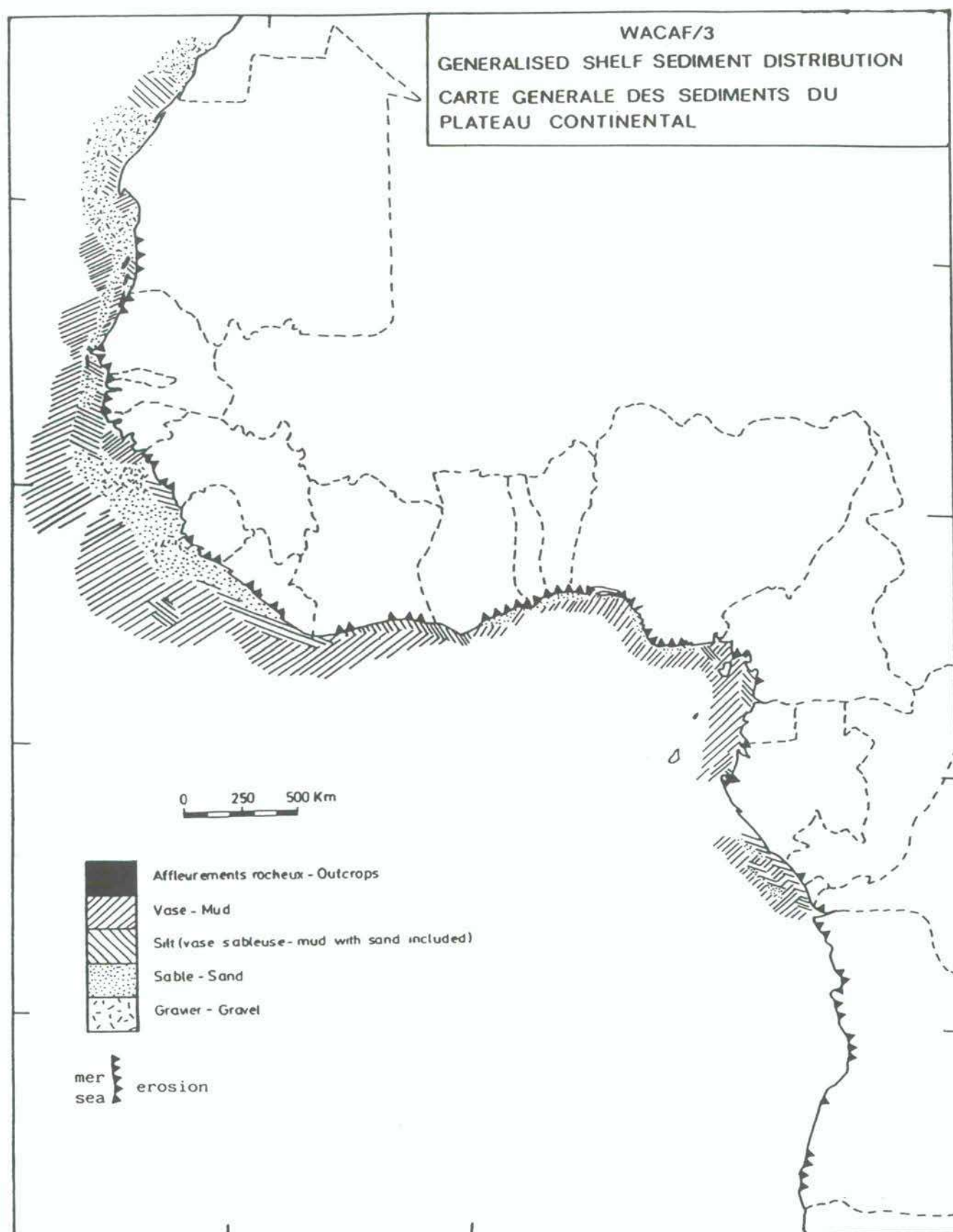


Fig. 1.4. - Carte récapitulative des problèmes d'érosion côtière dans la région (complétée par R.E. Quélenec)
Fig. 1.4. - Synthetic map of coastal erosion problems in the region (completed by R.E. Quélenec)

1.5.3 Gambia

According to the findings of a recent UNEP mission (Quélennec, 1988), erosion processes are intense in the following areas:

- Barra Point near Fort Bullen north of the Gambia estuary;
- Around the Cemeteries west of Banjul (Photo Fig. 1.6);
- Cape St Mary and Fajara cliffs (Photo Fig. 1.7);
- Cliffs at Solifor Point, and beaches between Bijilo and Fajara because of important beach sand mining at Bijilo (Photo Fig. 1.8).

1.5.4 Guinea Bissau

Erosion is experienced at various sites along the national coastline but definitive records are lacking.

1.5.5 Republic of Guinea

There are areas of erosion in the region of Conakry-Loos Islands, Sangreah Bay, the Port of Benty and generally in the area where mangrove have been destroyed. The shoreline retreat is approximately 290 m on the western part of the Camayenne peninsula between 1947 and 1974. In some areas, the retreat would be as much as 380 m.

1.5.6 Sierra Leone

Erosion is rapidly stripping Lumley Beach which is situated on the windward side of the tombolo which joins Aberdeen Island to the mainland at Lumley, to the northwest of the Freetown peninsula.

Erosion estimated at about 6 m/yr threatens to break through the narrow neck of the tombolo to join Aberdeen creek, thus effectively cutting off Aberdeen Island.

1.5.7 Liberia

Most of the erosional areas occur around Monrovia, Buchanan and Greenville which are located to the North of the harbours, the jetties of which create obstacles to the littoral drift. At Monrovia, the retreat is 2 m/yr. The prestigious OAU village is threatened with destruction by forces of erosion.

1.5.8 Cote d'Ivoire

Coastal erosion affects a limited site to the West of Abidjan, in the areas of San Pedro, Fresco-Grand Lahou. The most vulnerable area is the coastline around Port Bouet-Abidjan (Photo Fig. 1.9) where the situation is aggravated by the Vridi canal and the "Trou sans Fond" canyon (Quélennec, 1984c). To the east of Abidjan, the coastline experiences erosion problems, particularly in the built-up areas of Grand Bassam and the tourist zone of Assouinde-Assinie.

1.5.9 Ghana

Many places along the coastline of Ghana are affected by erosion. At Ada, near the Volta estuary, the annual beach retreat has averaged 2.3 m between 1939 and 1976. At Labadi east of Accra, erosion resulted in a 3 m/yr retreat of the coastline. Other towns between Cape St Paul and the Ghana/Togo border are also affected to varying extent. The enormity of the problem is depicted in front of Keta at Abutiakofe, east of the Roman Catholic church where the coast receded over 60 m within a 3-4 month period in the beginning of 1975 (Photo Fig. 1.10).



Fig. 1.5. - Vue aérienne de St. Louis (Sénégal) - (Iris).

Fig. 1.5. - Aerial photograph of St. Louis (Senegal) - (Iris).

Fig. 1.6. - Recul du rivage devant le cimetière musulman de Banjul (Gambie) - (Quélenec, 1988).

Fig. 1.6. - Coastline retreat in front of Muslim Cemetery at Banjul (Gambia) - (Quélenec, 1988).





Fig. 1.7. - Erosion des falaises côtières à Fajara (Gambie)
(Quélenec, 1988).

Fig. 1.7. - Erosion of coastal cliffs at Fajara (Gambia)
(Quélenec, 1988).

Fig. 1.8. - Extraction industrielle de sable sur la plage à
Bijilo (Gambie) - (Quélenec, 1988).

Fig. 1.8. - Industrial sand mining on Bijilo beach (Gambia)
(Quélenec, 1988).





Fig. 1. 9. - Recul brutal du rivage a Port-Bouet (Cote d'Ivoire)
(Quelennec, 1984).

Fig. 1. 9. - Brutal shoreline retreat at Port-Bouet (Ivory Coast)
(Quelennec, 1984).

Fig. 1.10. - Fragilite du mince cordon littoral dans la region de
Keta - Delta de la Volta (Ghana) - (Quelennec, 1986).

Fig. 1.10. - Fragility of the tiny littoral sand strip in the region
of Keta - Volta delta (Ghana) - (Quelennec, 1986).



1.5.10 Togo

The Togo coastline which is about 50 km long has been subjected to minimal erosion for over a century but since the sixties, the situation has been exacerbated by human intervention particularly through port development at Lome resulting in phenomenal rates of coastline retreat downdrift of these structures. A retreat of 160 m has occurred in 8 years east of the port Lome. Erosion poses hazards to the phosphate producing zone of Kpeme and to the city of Aneho (Oliveros, Quélennec, 1985). (Photo Figs. 1.11, 1.14 - Important coastal defence works are being built).

1.5.11 Benin

On the coast of Benin, erosion has wreaked some devastation. For example, the town of Gran Popo was once a prosperous commercial centre, but over the last 30 years, the coast has retreated approximately 200 m, claiming a lot of facilities in the town. As a result, the population has diminished considerably and it is presently an almost abandoned village. At Cotonou, the construction of a harbour jetty in 1960 has resulted in phenomenal erosion east of the jetty. In 1976 alone, a retreat of about 20 m was recorded downdrift of the jetty although harsh meteorological conditions contributed to this large retreat.

1.5.12 Nigeria

Erosion is a widespread nuisance along the 800 km national coastline. In the petroliferous Niger delta, the rate of erosion at many locations reaches a few tens of meters per year and risks of flooding of humid coastal zones are important (Photo Fig. 1.12). Man made erosion through port development is prevalent at Lagos and Escravos where recent erosion rates average 20-30 m/yr (Photo Fig. 1.13).

1.5.13 Cameroon

The Victoria region is being actively eroded. In the south part of the Cameroon estuary, the north-west end of the Sanaga delta is subjected to marine erosion. This erosion could be partly due to the construction in 1965 of the Edea dam, 70 km upstream of the Sanaga river mouth.

1.5.14 Sao Tome and Principe

Marine erosion of the ragged coastline of these volcanic islands is seasonal and concentrated in the season of heavy storms.

1.5.15 Gabon

The low lying barrier beaches enclosing large sized lagoons (Banio, Ndogu, Fernard-Vazet) between the Congo border and the Port Gentil peninsula coast are affected by erosion which is more pronounced at Port Gentil. The canyon Cape Lopez acts as a sediment trap thereby causing a sediment deficit and natural erosion.

1.5.16 Congo

Erosion is observed particularly to the north of Pointe Noire in Loango Bay where a retreat of the coastline to the east of Pointe Indienne measured 20 m in 1983 alone.

1.5.17 Angola

In the northern area, the coastal escarpments of Barra do Dande to Sea Tiago, extending to Cabo Ledo and of Porto Ambouim are undergoing very active erosion. On the spits of the Ilha de Luanda and of Lobito, some groins had to be built to stop the erosion of the spits.

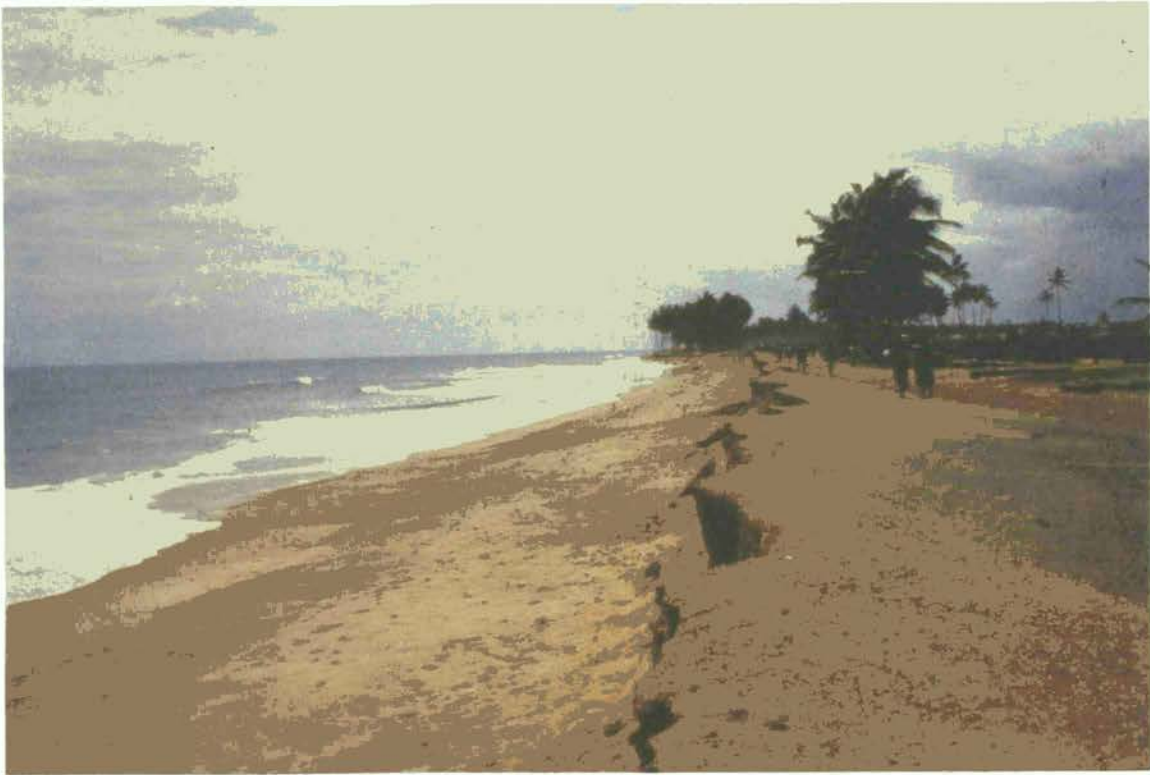


Fig. 1.11. - Recul du rivage avec destruction de la route côtière à l'ouest de Kpémé (Togo) - (Quélennec, 1984).

Fig. 1.11. - Shoreline retreat with destruction of the coastal road west of Kpémé (Togo) - (Quélennec, 1984).

Fig. 1.12. - Recul et submersion du littoral à Molume, partie occidentale du delta du Niger (Nigéria) - (Ibé).

Fig. 1.12. - Retreat and flooding of the littoral zone at Molume, western part of the Niger delta (Nigeria) - (Ibé).



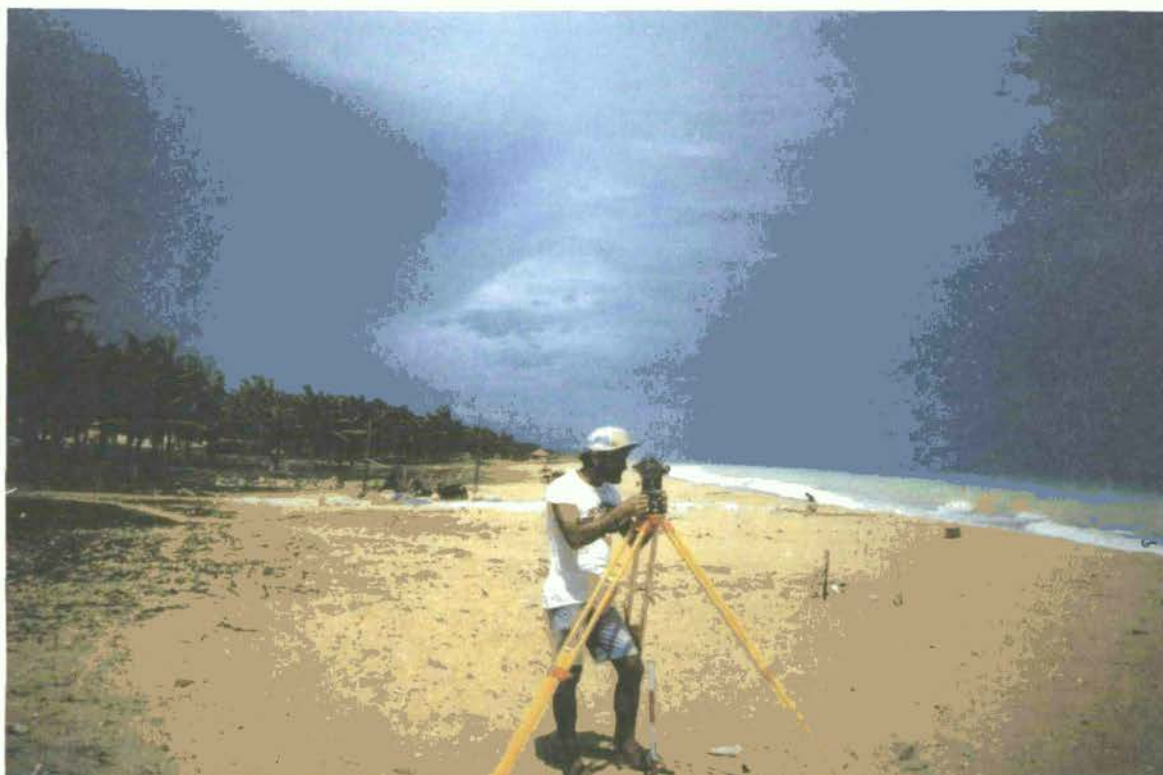


Fig. 1.13. - Erosion côtière catastrophique à Victoria Beach, Lagos (Nigéria) - (Ibé).

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Fig. 1.14. - Mesures topographiques de contrôle des profils de plage au Togo au moyen d'un théodolite/tachéomètre (Quélenneq, 1984).

Fig. 1.14. - Topographic survey for control of beach profiles in Togo, by using a theodolite/tacheometer (Quélenneq, 1984).



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2. COASTAL GEOMORPHOLOGY AND PROCESSES

In order to facilitate the understanding of subsequent chapters, we first recall several basic definitions of coastline formations (Para. 2.1) and sediments (Para. 2.2.), drawn from a recent manual (Quélennec, 1984b) written for the WACAF/3 project.

2.1 TYPES OF COASTLINE FORMATIONS

On the basis of geomorphological and sedimentological considerations, it is possible to draw up a simplified classification of coastlines, which distinguishes among various types of formations, according to the main forms of erosion and deposition. These different coastline formations are evidence of erosion-transport-deposition processes, occurring or having occurred anytime between the present and the distant past. Thus one can observe, over time, the erosion of old forms of accumulation and vice-versa.

2.1.1 Forms of erosion: Cliffs and rocky shorelines

The erosion of coastal cliffs is mainly the result of the mechanical action of waves (wave impact and abrasion of the cliff's base by rocky debris carried by waves), as well as of that of meteorological (rainwater infiltration, exertion of pressure, dissolving) and biological (burrowing animals) factors. The retreat of cliffs by erosion frees stone blocks and pebbles, which are gradually eroded by the swell, and transported in the form of shingle, gravel and sand onto the flat rocky strip that generally lies at the base of a cliff.

As in the case of cliffs, the erosion of rocky coasts depends on the hardness, the tectonics and the structure of the geological coastal formations, and on the force of the hydrodynamic factors causing the erosion. As a rule the erosion of rocky coasts is not easily detectable on the human scale. The most resistant geological formations constitute capes, between which one generally finds bays where beaches consisting of erosion-generated sediment can become established.

2.1.2 Forms of accumulation: dunes and littoral strands, spits, tombolos, deltas, mud flats

The generic term beach refers to a littoral zone of the "interface" type, subject to accumulation and shifting of non-consolidated sediments (sand, gravel, shingle), which will be characterized more precisely in Para. 2.3. Beaches are often subject to alternating processes of erosion and deposition.

Coastal dunes are the result of eolian transport of sand originating from beaches, in areas with strong regular winds. They can be formations of several dozen metres in height, which, when located close to the shoreline, form a buffer stock of sediment, that can be reshaped by the swell, and can influence the equilibrium of adjacent beaches.

Coastal strands or barriers are developed mainly in littoral areas where the tides and the swell energy are relatively weak. Their mode of formation, while probably varied, is often the subject of controversial discussion, the hypotheses including emergence of underwater bars, exposure of continental dunes after subsidence, extension of coastal sandspits, etc. These barriers often cut off lagoon type formations or coastal ponds from the sea.

Littoral spits, which are often associated with distinctive coastal features such as rocky points, capes, or mouths of bays and rivers, tend to smooth over such features. The extension of spits occurs in the direction of longshore transport. The end is closed off by a hook oriented towards the interior of the area, sheltered from the swell.

Tombolos are the result of swell diffraction against the shallow beds surrounding a rocky islet or an island located near a shoreline. The rotation of wave crests at the extremities of the islet, and the gradual decrease in the amplitude of the swell in the sheltered area allow for transport and accumulation of sediments between the rocky barrier and the coast.

Deltas are complex forms of sedimentary accumulation, occurring when it is impossible for hydrodynamic agents (swell, currents) to disperse the sedimentary inputs brought to the coast by rivers.

Mud flats are to be found most often in low-energy zones of the estuary type, and in zones sheltered from off-shore swell by islands or bays, where sedimentation of fine particles occurs; their degree of consolidation gradually increases and they come to be likely zones for the development of mangroves in tropical regions.

2.2 SOME CHARACTERISTICS OF LITTORAL SEDIMENTS

With a view to highlighting the hydrodynamic behaviour of sediments, under the influence of winds, swells and currents, we shall distinguish between mobile sediments, cohesive sediments and consolidated sediments.

2.2.1 Mobile sediments

These include rudites (diameter $D > 2$ mm) and arenites ($0.06 \text{ mm} < D < 2 \text{ mm}$). From the petrographic point of view, most littoral mobile sediments consist, particularly in temperate regions, of grains of quartz and feldspar, produced by the erosion of formations made up of granite, gneiss or slate, and also of calcareous particles, originating from sedimentary rock and from shell decomposition in zones with high biological productivity (Tropics).

The basic parameters influencing dynamics are cohesion, density, dimension, and, to a lesser extent, the shape of the grains; as a first approximation, it can be asserted that cohesion decreases with increasing grain diameter.

From the point of view of granulometric classification of sediments, it is of some interest to refer to the classification below, proposed by the AIPCN (Association Internationale pour les Congrès de Navigation - International Association for Navigation Congresses) for sea-bed dredging (see Table 2.1).

The porosity and the density of littoral sediments depend on factors such as the nature, the granulometry, the compaction and the state of saturation of the material. For instance, in the case of well sorted sands (uniform granulometry), the porosity (volume of empty space/total volume) runs from 0.46 to 0.34 according to whether the sand is loose or highly compacted, while at the same time, the dry and humid (saturation) densities respectively vary between 1.4 and 1.8 and between 1.9 and 2.1.

Along any given coastal segment, the three main factors determining the granulometry of mobile sediments are:

- the origin of the sediments (source zones);
- the energy of the swell (sheltered or exposed beach);
- the slope of the underwater beach (Fig. 2.1) and of the continental shelf.

The action of the swell and of currents on littoral mobile sediments results in granulometric sorting (CNEXO, 1976) - see Figure 2.2.

Various studies (Bascom, 1951) have shown that, for sandy beaches:

- with the larger grained sediments to be found at the level of the beach-comber bar (breaker zone);
- the sediment granulometry decreases away from this bar with rising depth, and also towards the coast, before increasing once again towards the swash zone.

TABLE 2.1
Grain size classification of sediments

Main types of soil	Identification of grain dimension (D)		Identification
	Scale of dimensions (mm)	BS sieve	
Stones Pebbles	200 mm 200 to 60 mm		Visual examination and sizing
Gravel	Large 60 to 20 mm Medium 20 to 6 mm Fine 6 to 2 mm	3" - 3/4" 3/4" - 1/4" 1/4" - No. 7	Easily identifiable by visual examination
Sand	Large 2,0 to 0,6 mm Medium 0,6 to 0,2 mm Fine 0,2 to 0,06mm	7 - 25 25 - 72 72 - 200	All the grains are visible to the naked eye. Very weak cohesion when the ground is dry.
Silt	Large 0,06 to 0,02 mm Medium 0,02 to 0,006mm Fine 0,006 to 0,002mm	Undersize particles from No. 200 sieve	The grains are usually invisible. Only the larger grains of silt can still be seen by the naked eye. The volume expansion test provides the best possible determination. Silt may be kneadable, but, once dry, it falls from the fingers when the hands are shaken; simple pressure of the fingers pulverises dried clots.
Clay	Below 0.002 mm, the distinction between silt and clay should not be drawn solely on the basis of grain dimension, since the most important physical properties of silts and clays are only indirectly related to grain dimension.		Clay has substantial cohesion and plasticity, but does not react to the shaking test. A moist sample sticks to the fingers and feels smooth and unctuous. Dry fragments do not break up into a powder, but in the course of drying they contract and crack, acquiring high shearing strength.
Peat and organic earth			Can generally be identified by their black or brown colour, and often by their strong odour and by the presence of fibrous or ligneous material.

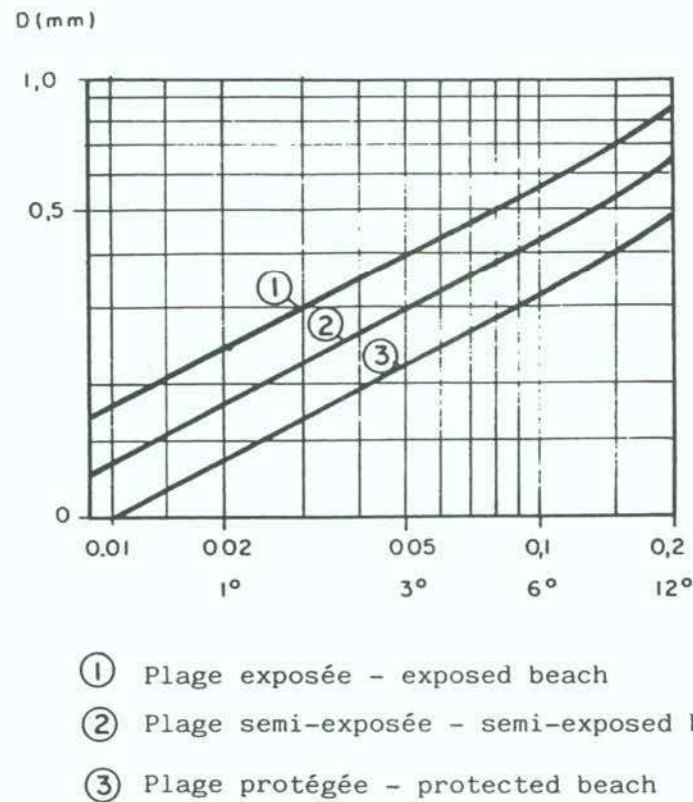


Fig. 2.1. - Pente de la plage $P = f(D, \text{exposition aux houles})$

Fig. 2.1. - Beach slope, $P = f(D, \text{exposure to waves})$
 (Wiegel, 1964)

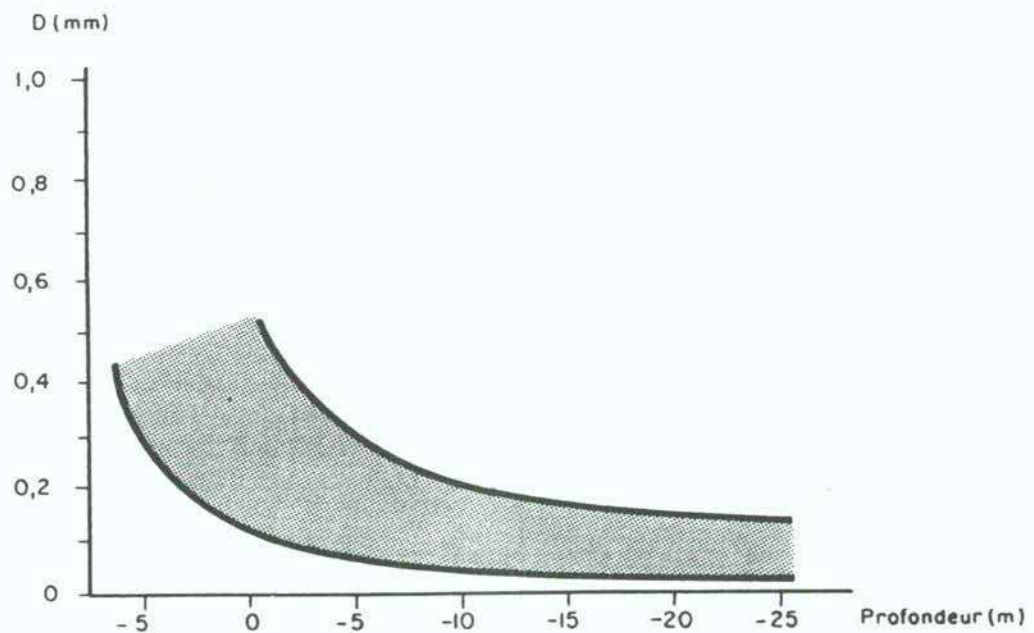


Fig. 2.2. - Diamètre (D) des sédiments de plage en fonction de la profondeur.

Fig. 2.2. - Beach sediment diameter (D) as a function of water depth.

(CNEXO, 1976)

The action of the swell and of littoral currents also gives rise to longitudinal granulometric sorting along the shoreline, with accumulation of finer sediments in low swell energy zones and vice versa.

In the case of littoral spits consisting of sand, gravel and shingle, one observes granulometric sorting with sediment grain diameter reduction in the direction of littoral transport.

The abrasion of coastal sediments under the action of the swell is not very significant for small diameter sands ($D < 0.2$ mm), because of their low inertia. The rate of abrasion increases with the dimension of sediment particles, becoming significant in the case of shingle transported by longshore currents along high energy shorelines: experiments have shown that one week of such action is sufficient for fragments with a 10 cm side, of the calcareous or marly type, to be transformed into well-rounded beach pebbles by swell with a 0.5 m amplitude. For quartzite type fragments, the same result is obtained in a month.

2.2.2 Cohesive sediments

These silty or pelitic sediments consist of particles with a granulometric diameter less than 64 microns (lutites). One generally distinguishes among:

Table 2.2

	<u>Diameter (D)</u>	<u>Mineralogical composition</u>
* finest sand	0.02 to 0.064 mm	. quartz
* powders	0.001 to 0.02 mm	. quartz, mica, clay
* pre-colloids	0.0001 to 0.001 mm	. clay
* colloids	$D < 0.0001$ mm	. silica, hydroxides, organic complexes

Because of their particular physical and chemical properties (flocculation, viscosity, consolidation, etc.), cohesive sediments have a rather complex specific behaviour in the presence of hydrodynamic action (swells, currents).

Flocculation of pelitic sediments is the result of aggregation into (0.1 to 2 mm) flakes of single particles of several microns each. This property, which has an influence on the rate of fall, is related to the occurrence of a weak zeta potential: in a colloidal suspension, the clayey particles, which bear a negative charge, will have a greater tendency to come close together and to agglomerate under the effect of Van der Waals forces, the weaker the zeta potential of the aqueous environment (presence of H^+ ions or Ca^{++} or Na^+ cations, etc.).

The flocculation and the rate of fall (W) of pelitic sediments vary mainly as a function:

- of the mineralogical nature and the characteristics of the elementary particles;
- of the characteristics of the aqueous host environment: concentration (MES), physical chemistry (salinity, temperature), degree of agitation.

It should be noted that, for an elementary particle of diameter 1 micron, the rate of fall $W_d = 0.001$ mm/s is multiplied by a factor of 500 after flocculation: $W_f = 0.5$ mm/s, which corresponds to the average rate of fall of silt flakes in the waters of a calm sea (2% to 3% salinity).

The water salinity of temperate seas, at the surface, varies from 3.2% to 3.8%, or an average of 35 g of dissolved salt per 1,000 g of water, corresponding to a density of 1.026.

The consolidation of deposits of pelitic sediments (silts) varies with time mainly as a function:

- of the characteristics of the sediment and the surrounding liquid environment;
- of the height of the deposits, which promotes settling by elimination of interstitial water (rise in the concentration of solid elements or reduction of porosity).

The slope of sedimentary deposits, as well as the ease with which they can be set in motion by swells and currents, is a function, in particular, of parameters such as rigidity and viscosity, which increase with rising deposit concentration and water salinity.

2.2.3 Consolidated sediments

2.2.3.1 Beachrock

Consolidated littoral sediments with a greater or lesser degree of brittleness, of the beach sandstone or beachrock type, consist of beach sands cemented together, generally by calcites or aragonites (calcium carbonates).

They are mainly to be found in hot regions, in terms of today's climate, of the arid to tropical type (Persian Gulf, Gulf of Togo-Benin, Pacific, Florida, South America, Mediterranean), where there is a high concentration of calcareous littoral sediments of the coralliferous, shelly or quartz type.

The two main hypotheses most often used to explain the formation of beachrock are:

- dissolving by precipitation of calcium carbonates contained in the sediments and terrestrial sands, their transport in underground waters, their migration and their fixation in the form of calcite in beach sands at low tide;

precipitation of the calcium carbonate contained in sea water (oversaturation), under the combined influence of an increase in temperature and evaporation of the sea water on shores with gentle slopes (humid and overheated), allows for the deposition of an intergranular cement that is aragonite in type.

The present positions of beachrock type formations (some of which are in the process of consolidation), with respect to shorelines, depend on the era of their formation, on phenomena such as sea level variation, tectonics, coastal retreat, and also on their ability to withstand erosion or destruction by swells and marine organisms.

One often finds several lines and levels of beachrock close to present shorelines (Gulf of Benin, Arabia, Brazil, etc.), which makes it possible to date the positions of old shorelines.

The presence of lines of beachrock rising up from coastal beds at several metres depth, on the underwater beach or the continental shelf, sometimes causes changes, as in the case of shallows or reefs, in the propagation of the swell towards the shoreline (refraction), which can result in the establishment of preferential zones of accumulation or erosion on the shoreline.

2.2.3.2 Corals

The coral reefs, that often emerge at the mean level of tides, are structures that dissipate the energy of the swell, having been formed in warm seas by algae and marine organisms through concretion of calcium carbonate (CaCO_3). Lagoons have been formed in the shelter of coral reef

barriers surrounding the islands of the Pacific and other warm seas. Both living and dead coral formations can be found near present shorelines in West and Central Africa.

2.3 COASTAL EROSION: PROBLEMS OF TERMINOLOGY AND EVALUATION

The contents of this section are partly based on a presentation made to the Biarritz seminar "Mer et Littoral: couple à risques" (Quélenec, 1987b).

2.3.1 Nomenclature of the theoretical beach

This nomenclature is shown in Figure 2.3.

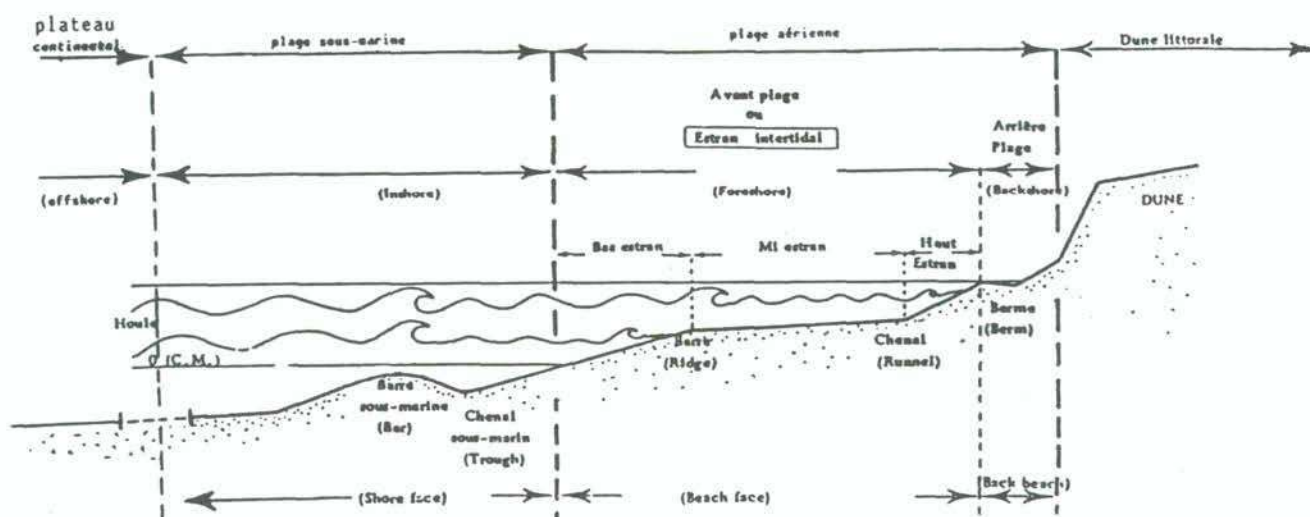


Fig. 2.3. - Nomenclature du profil de plage.

Fig. 2.3. - Terminology used for the beach profile.

The theoretical limit between the "underwater" beach and the continental shelf can only be defined arbitrarily. It can be chosen as the point corresponding to the depth from which bottom sediments cannot be "raised up" to the beach by the action of swells and currents, and therefore cannot provide input to the beach.

This being done, it is possible to isolate the "beach" system from the "continental shelf" system by considering that sedimentary exchanges between these two systems can only be unidirectional, consisting of flows of fine sediments transported mainly in suspension (except for the special case of mass movement) from the beach towards the continental shelf.

On the basis of field and laboratory experiments, many of them conducted in France, it would seem that off high-energy sandy coasts (such as in the Gulf of Gascogne), this limit occurs at depths of -20 to -25 m. The limiting depth (P1) can be estimated with the help of various empirical models, including that of Hallermeier (1981), from the relation:

$$P1 \approx 2 H_s + 11\sigma$$

where

H_s = significant height (amplitude) of the swell ($H/3$),
 σ = standard deviation.

2.3.2 Defining coastal erosion: a problem of choosing dimensions and concepts

2.3.2.1 Dimension 1 : the line of the coast

This is the simplest choice, whereby erosion is represented by the retreat (ΔX) of the shoreline, or the line of the coast, during a given interval of time (Δt).

Thus coastal erosion is expressed in m/year ($\Delta X / \Delta t$), and this parameter is the one most often used in studies and most often cited in international literature.

But this unidimensional parameter, while having the advantage of simplicity, presents the major drawback of not providing information on changes of exposed and underwater beaches, which can be either positive (accumulation) or negative (erosion) when the beach is shifted, quite independently of the position of the line of the coast.

2.3.2.2 Dimension 2 : the profile of the beach

In this case, coastal changes are represented by the variation ($\Delta p / \Delta t$) in the surface of the sedimentary prism (p) situated above a reference depth in the profile of the beach.

In most cases the profile of the beach is only measured by topographic (land-based) means, so that only changes in the profile of the "exposed" beach are observed. As a result, even though the method is an improvement over just measuring variation in the line of the coast, the information needed to understand littoral sedimentary processes is truncated, because attention is paid only to a small part of the "volumetric" changes in the morphology of the "active" beach.

And yet it is on the basis of such (very incomplete) measurements that the great majority of coastal protection studies, diagnoses and projects are carried out.

It is preferable that beach changes be measured and followed over the entire profile of the beach, including the exposed and the underwater part, right down to the limiting depth (P1), where variations in bed elevations are less than the precision of measurement by bathymetric procedures.

This remark is all the more pertinent in that sedimentary exchanges within the profile are substantial, and that, as in Togo, coastal erosion reveals structures, on the lower foreshore, of the beachrock type (beach sandstone), which tend to reduce sedimentary exchange from the underwater beach towards the exposed beach (Oliveros, Qu  lennec, 1985).

In other situations observed along coasts in danger, such as that of the Nile delta, it has been noted that erosion phenomena usually appear on the profile of the underwater beach before becoming significant on the exposed beach (Manohar, Qu  lennec, 1976): measurements taken on more than 300 beach profiles (from 0 to -6 m) in the Nile delta made it possible to distinguish between profiles in the process of erosion and of accumulation, thanks to the following equation (see Fig. 2.4):

$$Y = aX_b \text{ (Qu  lennec, 1984a)}$$

where

$$Y = \text{depth and } X = \text{distance to the coast.}$$

However, this study also made it possible to show that the shape of profiles of exposed and underwater beaches varies and adapts to conditions of erosion (insufficient input) and accumulation (excessive input).

Thus it may be desirable to replace the "static" concept of the equilibrium profile by that of the "dynamic profile" of beaches.

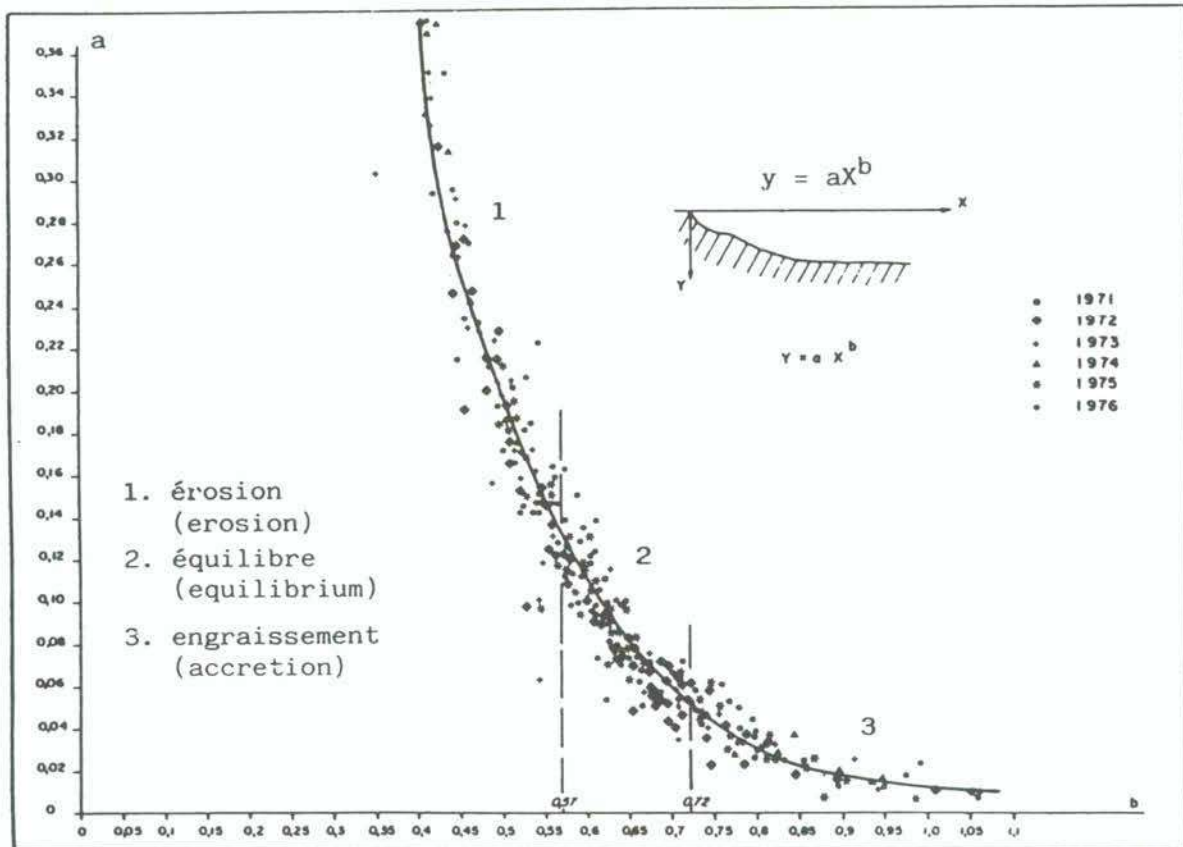


Fig. 2.4.-Discrimination des plages sujettes à l'érosion ou à l'engraissement sur le delta du Nil.

Fig. 2.4.-Discrimination between eroding and accreting beaches on the Nile delta.

(Quélenec, 1984 a)

2.3.2.3 Dimension 3 : coastal sedimentary system and budget

Morphological variations in the line of the coast and the profile of the exposed and underwater beaches are no more than "indicative" parameters, which represent only a part, and often not a highly "significant" one, of the information needed to understand the littoral processes and the morphological evolutionary trends of a given coastal zone.

Let us consider the case of a coastal zone (coastal segment, beach, bay, etc.), whose condition and evolution one wants to study with a view to protection or development. In order to do this, it is useful (if not necessary) to isolate the zone in question, in order to treat it as a sedimentary system (interface) having its own sedimentological and morphological characteristics. These characteristics are variable, over both time and space, as a function of exchanges of energy (swells, winds, currents) and of matter (sediments, bioconstruction) occurring through the ambient environments (water, air).

Figure 2.5 is a "classical" schematic representation of the "sedimentary exchange" possibilities of a littoral system "open" to the outside.

The sedimentary budget of such a "natural" system is a function of the sediment exchanges or transfers:

- laterally from the action of swells (longshore transport) and currents;
- with the inland beach: eolian transport, cliff erosion, fluvial deposit inputs, storage in dunes, lagoons and outlets, etc.;
- with the continental shelf: from the beach towards the open sea, with the limit of the system fixed at depth P1;
- with the biological environment: building up of reefs, shell production, biological perturbation, etc.

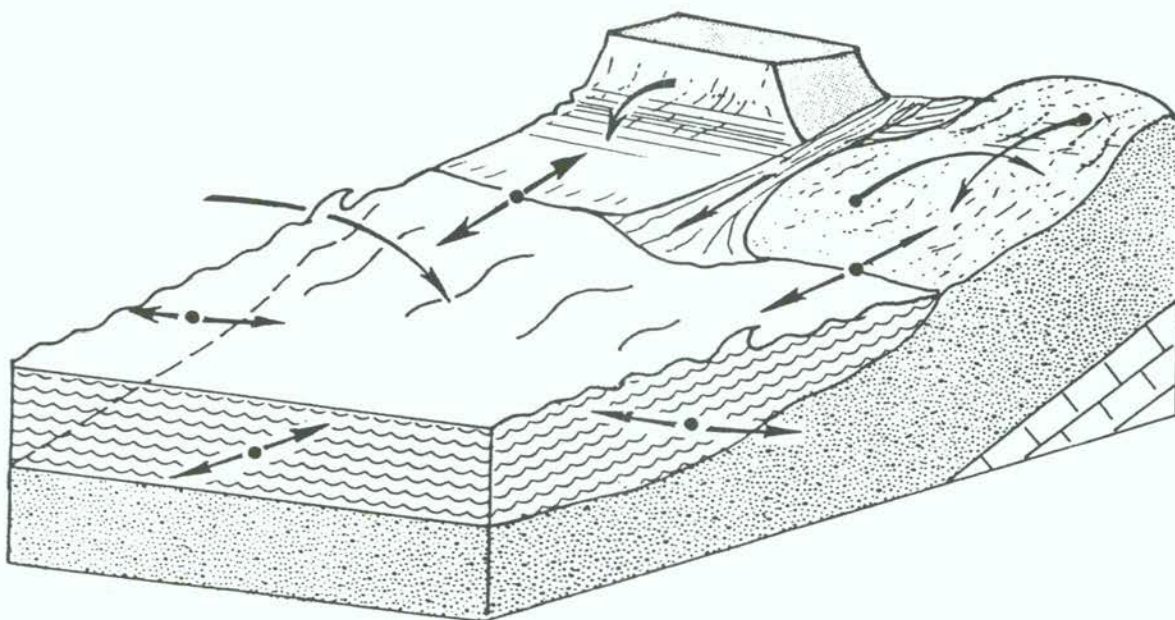


Fig. 2.5. - Budget sédimentaire - Principaux échanges.

Fig. 2.5. - Sedimentary budget - Main sediment transfers.

(Quélennec, 1987b)

The variations in these sedimentary flows, with respect to time (storms, floods, etc.) and space (within the system), determine the state of the mobile sedimentary stock (MSS) and the morphological evolution of the system.

Therefore, in thermodynamic terms this is an "open" system which maintains constant exchanges of energy and matter with the surrounding environment.

2.3.2.4 Dimension 4 : Time

It would seem preferable to replace the concept of beach equilibrium by that of dynamic stability of the "littoral system", which then involves introducing the fourth dimension of time.

The unit or interval of time (dt) to be used for evaluation of the stability of a "natural" littoral system (human actions excluded) can be chosen (there are two possibilities) as the interval during which:

- the energy exchanges with the surrounding environment can be viewed as stationary;
- or, variations in the "mobile sedimentary stock" (MSS) are negligible.

The first hypothesis would imply an "annual" unit of time. In the case of the second hypothesis, the choice of unit of time has to be variable (one to several years), as a function of the littoral system under consideration: there are cases of littoral zones subject to "massive" episodic inputs of sediments by river deposit, cliff erosion, bank migration, etc.

2.4 SEDIMENTARY TRANSPORT

In this section we recall several basic principles governing the transport of littoral sediments under the direct influence of wind, currents and swell.

2.4.1 Eolian transport

Accumulation of sedimentary stocks in the form of coastal dunes is the most obvious manifestation of the ability of winds to transport littoral sediments.

As a general rule, coastal dunes consist of sand transported from the nearshore towards the backshore. The amounts of transported sediment are all the greater if:

- the speed of the wind is high;
- the sands are fine-grained and non-cohesive;
- the width of the exposed surf zone is substantial;
- the sands are dry and not held in place by vegetation.

In some dry coastal regions, bordered by desert areas where a significant component of the wind's directional spectrum is oriented towards the sea (Mauritania, Angola), the coast is supplied with dune sands of terrestrial origin.

The mass flow rate of wind-borne sand crossing a vertical plane of unit width, perpendicular to the direction of the wind, can be evaluated, according to the work of Bagnold, from the following simplified formula proposed by the L.C.H.F. (Laboratoire central d'hydraulique de France - Central Hydraulics Laboratory of France):

$$q = 854 (D/0.25)^{1/2} u_*^3$$

with

- D = diameter of sediment particles in mm,
- u_* = velocity of wind to sediment grains friction in m/s,
- q = expressed in kg/m/H.

From Figure 2.6 it is possible to estimate an order of magnitude of this eolian rate of flow, provided one knows the velocity of the wind, as measured at ground level.

2.4.2 Transport by currents

Currents capable of causing sedimentary transport in the coastal and marine environments can be classified schematically into four categories, as follows:

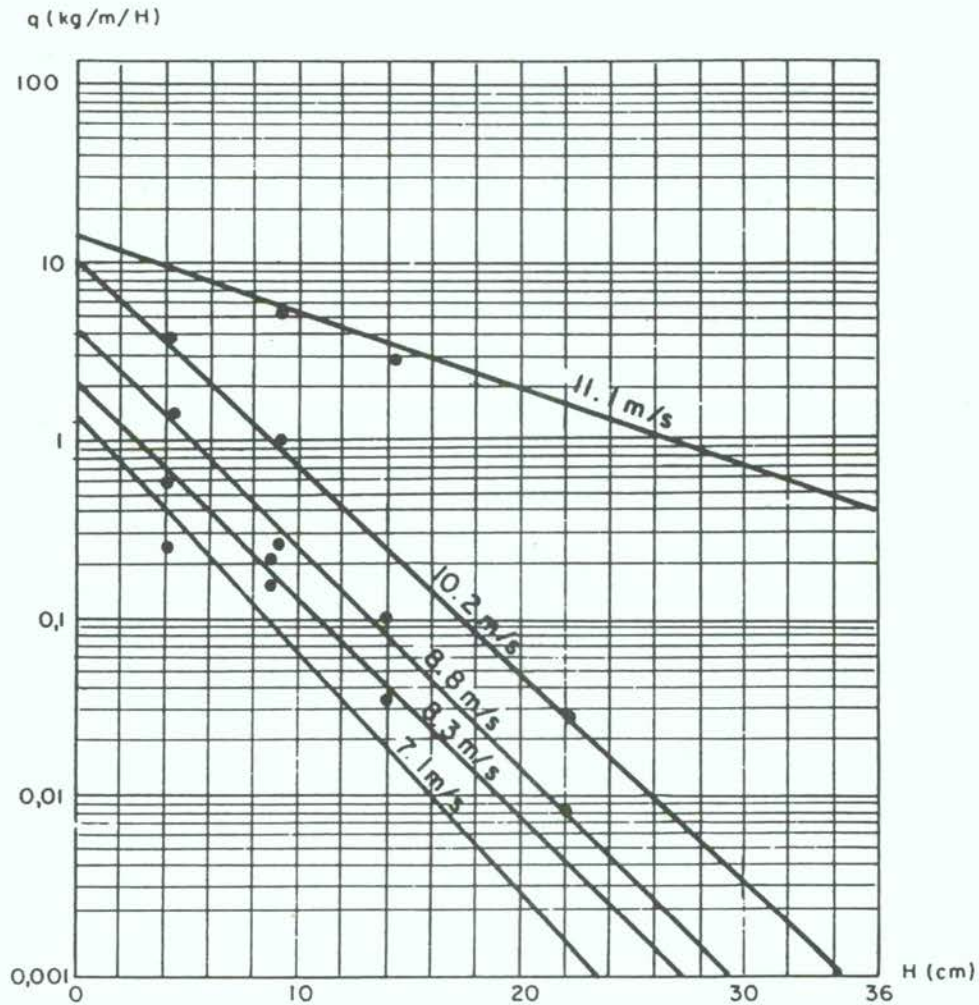


Fig. 2.6. - Débit sédimentaire éolien (q) en fonction de la vitesse du vent et de la hauteur H au-dessus du sol.

Fig. 2.6. - Aeolian sediment discharge (q) as a function of wind speed and elevation H above the ground.

(L.C.H.F.)

- general (or geostrophic) currents engendered by the circulation of ocean water masses, whose residual velocities near shorelines are generally low;
- tidal currents, which can develop substantial velocities in areas where the tidal range is large (4 to 5 m in Guinée Bissau), and also in estuaries, straits, closed bays and lagoon graus;
- currents generated by the wind, which are particularly important along the coasts of Mauritania and Northern Senegal, because of the coastal upwelling effect they are responsible for;
- longshore currents induced by the swell, whose influence will be discussed in Para. 2.4.3.

The processes of sedimentary transport by currents are governed by different laws depending on whether the sediments are transported as a load near the bed or in suspension.

For a grain of sediment to be carried along by a current, it must be subjected to a tensible force greater than the forces that maintain the grain in place. The critical tensible force (T_c) characterizing the start of sedimentary motion can be expressed by:

$$T_c = K (G_s - G) D$$

with

K = a coefficient ranging between 0.04 and 0.06,
 G_s and G = specific gravities of the sediment and the water,
 D = average diameter of sediment particles.

For sands with a density of 2.6 and T_c expressed in Newtons/m^2 , one finds that:

$$0.8 D < T_c < 1.0 D.$$

Once the shear force T_c is known, one can deduce from it the friction velocity u_* , as well as the average or instantaneous current velocity required to ensure that the grains will start to move.

For non-cohesive sediments such as quartz sands, the following values represent good estimates for the average current velocity required for sediments of particle diameter D to be put into motion by a current flowing under a given column of water:

Table 2.3

Diameter D (mm)	Average velocity (m/s)	Water column (m)
0.01	0.28	1
0.01	0.4	10
0.1	0.32	1
0.1	0.5	10
1.0	0.4	1
1.0	0.6	10
5.0	0.8	1
5.0	1.3	10

The above estimates are no more than orders of magnitude, obtained by making a number of simplifying assumptions: uniform and steady-state hydrodynamic balance, logarithmic distribution of velocities over the water column, uniform sediment granulometry.

In the case of cohesive sediments (silts, muds, clays), the preceding models are no longer valid, because the critical friction velocities, which determine the onset of erosion, depend on the sediments' rheological properties and on their state of consolidation.

After having been set in motion, sediment particles can be transported by the current, either as a load or in suspension form, depending on their diameter, and on the current's velocity and turbulence. Resulting solid flow rates are generally estimated by applying sediment hydrodynamics models developed for fluvial hydrodynamics, but first adapting them to the marine and littoral environment. The main difficulties involved in applying such models to littoral zones are due to the fact that the current balance there is rarely uniform and steady-state, and that current characteristics vary locally and over time, as a function, in particular, of bathymetric, morphological, meteorological and astronomic (tidal) conditions.

2.4.3 Transport under the influence of swell

The processes of sedimentary transport by swell are extremely complex. The following presentation is intended to recall the most important mechanisms involved.

Away from the shore, the swell acts on bottom sediments mainly through the intermediary of the orbital movements that it engenders in the body of water.

Depending on the characteristics of the swell (amplitude H , period T , wavelength L), and on the depth of the water (d), bottom sediments may be subjected to oscillations, and then placed in suspension and transported by the currents.

With the above notation, the maximal orbital speed ($U_{\max}$) on the seabed is given by:

$$U_{\max} = \pi H / T \operatorname{sh}(2\pi d / L),$$

so that, for a swell of period $T = 10$ s and amplitude $H = 4$ m, $U_{\max}$ rises to approximately 1.8 m/s at a depth $d = 10$ m.

In its propagation towards the shoreline, the swell generates a mass current with a component directed towards the shoreline at the surface and along the bottom, and an opposite component, directed towards the open water, at mid-depth (see Fig. 2.7).

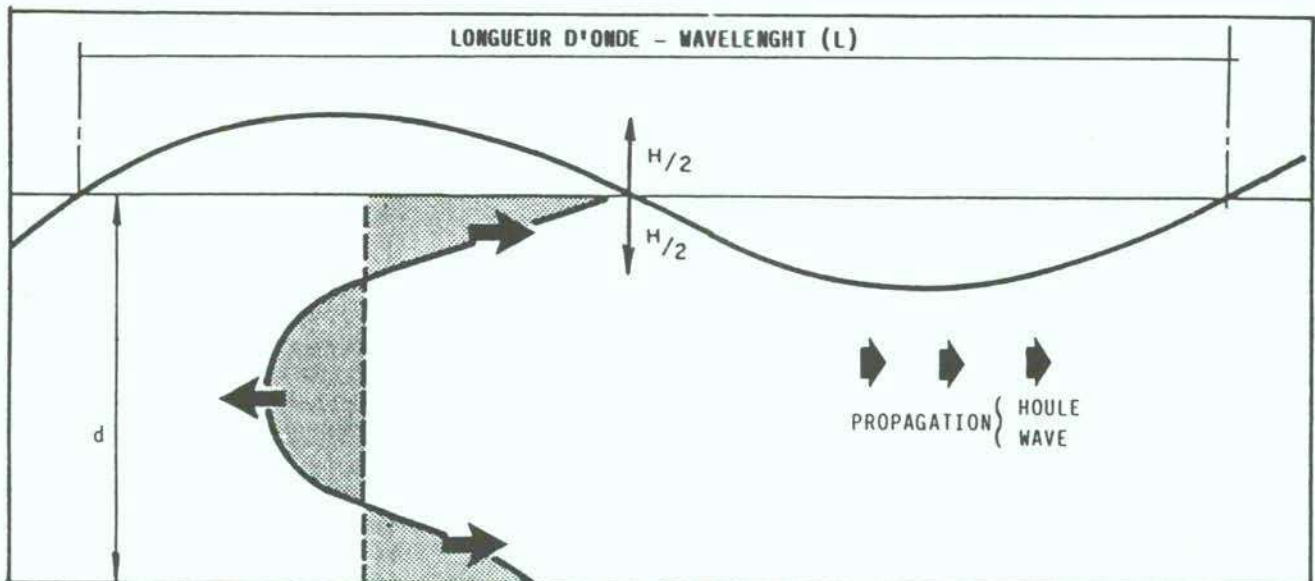


Fig. 2.7. - Courants induits par la houle.

Fig. 2.7. - Wave induced currents.

It is mainly because of this latter component that the finest littoral sediments are transferred in suspension towards the open water; this is reflected in the transversal granulometric sorting that one observes on most sandy coasts, with a decline in the average sediment diameter as one moves seaward from the shoreline.

The propagation of off-shore swells towards the shoreline gives rise to a refraction phenomenon: because of the fact that the speed of propagation (c) of the swell is a function of the depth ($c = gT/2\pi \text{ th } (2\pi d/L)$), swell crests tend to draw closer to the direction of bathymetric curves.

Closer to the shoreline, the swell breaks by liberating a substantial proportion of its energy at a depth (db) ranging from 1 to 1.3 times its amplitude (H_b) at the time of breaking, depending on the slope of the beach.

The sudden dissipation of energy by the swell when it breaks gives rise to a substantial reshaping of the sedimentary layer, with sediments being placed in suspension in the impact zone, and formation of bars, which can be almost permanently present along coasts with high swell energy and weak tides. After having broken, the trains of swell overflow onto the swash zone and finish releasing their energy through a series of alternating forward and backward surges, which give rise to "saw-tooth" sedimentary transport (Fig. 2.8).

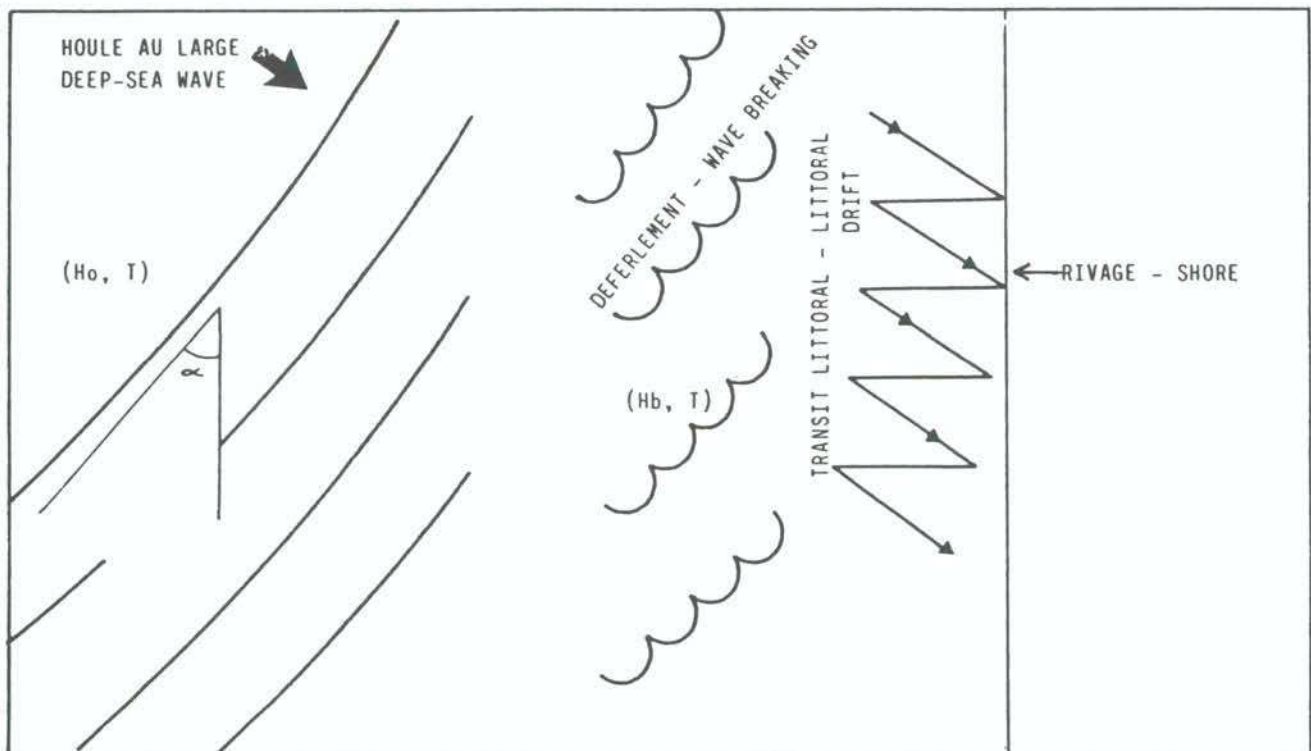


Fig. 2.8. - Transport sédimentaire littoral.

Fig. 2.8. - Littoral sediment drift.

When, after refraction, the swell propagation is parallel to the shoreline, most of the sedimentary movements and exchanges between exposed and underwater beaches take place transversally, that is, within the profile. On the other hand, when the swell approaches the shoreline obliquely, most of the sedimentary transport takes place longitudinally, because of the generation, between the zone of displacement and the shoreline, of a current that runs parallel to the coast, and that has a high capacity for transportation of solids, as loads or in suspension, at times of storms.

The level fluctuations and mass transfers connected with the propagation of swell and with its breaking give rise to phenomena of drainage of water masses accumulated at the shoreline. The transversal draining currents (rip currents), which are thereby generated, allow for evacuation towards the open sea of water bearing substantial loads of sediment in suspension. The longitudinal transport of sediments after breaking is called "longshore transport". There are a number of empirical formulae, based on laboratory experiments and on field measurements, available in scientific literature for evaluation of longshore transport. The following formulae, expressed in metric units, are among those most commonly used:

$$Q = (H^3/T) \cdot K_1(H/L, D) \cdot f(\alpha): \quad \text{Laboratoire national d'hydraulique, France (L.N.H.)}$$

$$Q = K_2 g(H/L) \cdot H^2 \cdot T \cdot f(\alpha) : \quad \text{Laboratoire central d'hydraulique de France (L.C.H.F.)}$$

$$Q = K_3 H^2 C_o \sin \alpha b \cdot \cos \alpha b: \quad \text{Coastal Engineering Research Center (C.E.R.C.) - U.S.A.}$$

with

Q = sediment transport (longshore transport) in m^3/s ;
 K_1, K_2, K_3 = empirical coefficients;
 $f(\alpha)$ = function of the angle of incidence of the swell with the shoreline;
 C_o = speed of propagation of the swell in open water;
 αb = angle of incidence of the swell at time of breaking.

In order to apply these empirical formulae to a given stretch of coast, it is necessary to know precisely the balance and the characteristics (H, T, α) of the swell in open water or near the point of breaking, the durations of swell action for different combinations of the parameters (H, T, α), the granulometry of the beach sediments, the morphology of the coast and the bathymetry of the sea bed.

These formulae cannot give more than an order of magnitude or a first approximation for the longshore transport of non-cohesive sediments, which it is preferable to verify by means of field measurements and/or laboratory simulations (reduced scale models), before building any port infrastructures or substantial coastal defence works.

It should be noted that the estimates given by these formulae do not make it possible to take into account either transversal sedimentary changes, in the profile of the beach, or sedimentary transport resulting from the combined action of the swell and of currents induced by wind and tide.

2.5 HAZARDS AND LITTORAL RISK

The ideas presented below are taken and adapted from a presentation made to the Biarritz seminar: "Mer et Littoral: couple à risques" (Quélennec, 1987b).

2.5.1 Hazards, vulnerability and risks: reminder of a few definitions

On the basis of the concepts favoured by UNDRO and UNESCO for "natural risks", the following definitions can be proposed:

- hazard (A): it is defined, at a given coastal site, by the probability of occurrence ($p(E(i)) = A$), over a given reference time period, of an event $E(i)$, with given intensity (i), which gives rise to a process of littoral erosion;

- vulnerability (V(i)): ratio of the cost of damages to the total cost (C) of replacement (works, dwellings), and of loss of use or restoration. The vulnerability of a work depends simultaneously on the intensity (i) of the event causing erosion, on the work's location with respect to the coast, and on its own characteristics: types of construction, protective systems, etc.;

- risk of littoral erosion (R): it can be defined, by analogy with seismic risk, as the expected value of damages associated with coastal erosion, on a given site and during a reference time period. For a given event (E), with intensity lying between i and i + di, R can be written as

$$dR = C.V(i).A$$

or

$$R = \int_0^{\infty} V(i).A$$

When several independent events (E1, E2, E3) combine to generate erosion processes (for example, a storm at spring tide during a period of earthquakes), the hazard is defined as:

$$A = p(E1) \times p(E2) \times p(E3).$$

2.5.2 Major events causing instability or changes of state of a coastal system

2.5.2.1 Human activities

For the sake of completeness, we give their classification, as a function of their interactions with the coastal system (Qu  lennec, 1981):

- modification of exchanges with the inland beach: artificial changes in the shoreline, degradation of dunes, extraction of sand and shingle, modification of outlets and river mouths, river damming, mining waste, building polders, etc.;

- modification of longshore exchanges: construction of moles, embankments, jetties, groins and breakwaters, digging and dredging access channels, protection of source zones (cliffs, shores and dunes), reduction of fluvial inputs, etc.;

- modification of the conditions of action of the swell and currents: destruction of marine grasses, algae fields and mangroves, reduction of water volumes oscillating in estuaries and gulfs, etc.;

- modification of the underwater topography: extraction of sediments, dredging, underwater deposits, mining waste, etc.

2.5.2.2 Major natural events

Like most "natural" systems, the coastal system has to tend to equilibrium, that is, a condition which is "stable" on average, on the assumption that exchanges with the ambient environment are "steady state" (Qu  lennec, 1987b).

Seasonal shifts in a beach, or the annual retreat or advance of the line of a coast are "normal" manifestations of the working of the system, to the extent that they are reversible. Under these conditions, the sedimentary balance of the system is in equilibrium over a given reference time period.

Two types of "natural" events are likely to alter the stability of the coastal system, and to generate irreversible changes in the state of the system:

- phenomena involving slow variation, such as land subsidence and rising of the sea level;

- drastic or sudden events: storms and sea level set-up, earthquakes, mass slope movements.

2.5.3 Variations in the sea level

2.5.3.1 Past variations

The numerous periods of glaciation and warming, accompanied by glacier retreat, that the Earth has experienced have caused substantial variations in the sea level, with regressive phases going as low as -110 m to -120 m in the Quaternary (Ogolian), at about -18,000 years, along most coasts (see Fig. 2.9).

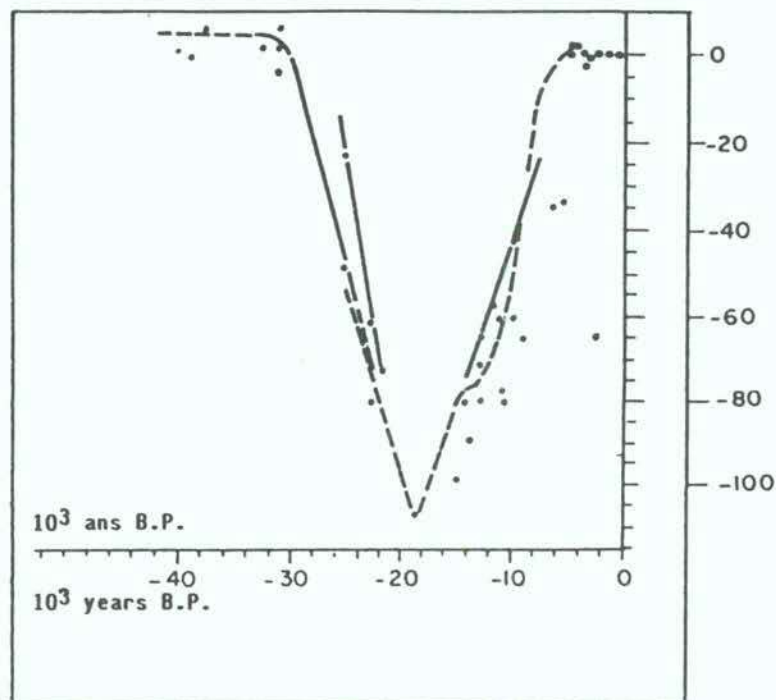


Fig. 2.9. - Variations du niveau de la mer au Quaternaire sur les côtes africaines.

Fig. 2.9. - Quaternary sea level variations on Africa coasts.

(Chateauneuf, 1986)

Since about -16,000 years, the climate has tended to warm, with a progressive "rapid" (8 mm/year) rise in the sea level, which reached or exceeded (by +2 m to +4 m), depending on the region of the world, the present level at approximately -5,000 years, then coming back down again to today's level.

Since the end of the last century, we have been going through a new warming phase, with an average $+0.4^{\circ}\text{C}$ since 1880, and a new phase of marine transgression.

Recent variations in the sea level, estimated from analyses and filtering of tide records, are variable from continent to continent. The countries of Northern Europe, from Denmark to the Scandinavian peninsula, are experiencing an uplifting (glacio-isostasy) of the continent, and hence a relative drop in the sea level of -1 mm to -9 mm/year (Gulf of Botnia). Along Western European coasts, the relative rise in the sea level is estimated to be $+2\text{ mm/year}$, on the strength of good agreement over a long horizon among tide records from Brest in France (2.1 mm/year), from Newlyn (England) and from stations located on the Netherlands coast (1.5 to 2.5 mm/year). Along the American coasts of the Gulf of Mexico, the rise is of the order of $+2.0$ to $+2.5\text{ mm/year}$, with exceptional values of $+9.0\text{ mm/year}$ in the Mississippi delta zone, because of natural and artificial subsidence phenomena. As far as the coasts of West and Central Africa are concerned, tide record data available from Santa Cruz in Tenerife, Dakar and Takoradi, covering the last 30 to 40 years, point to an average rise of the order of 2.0 mm/year (see Fig. 2.10).

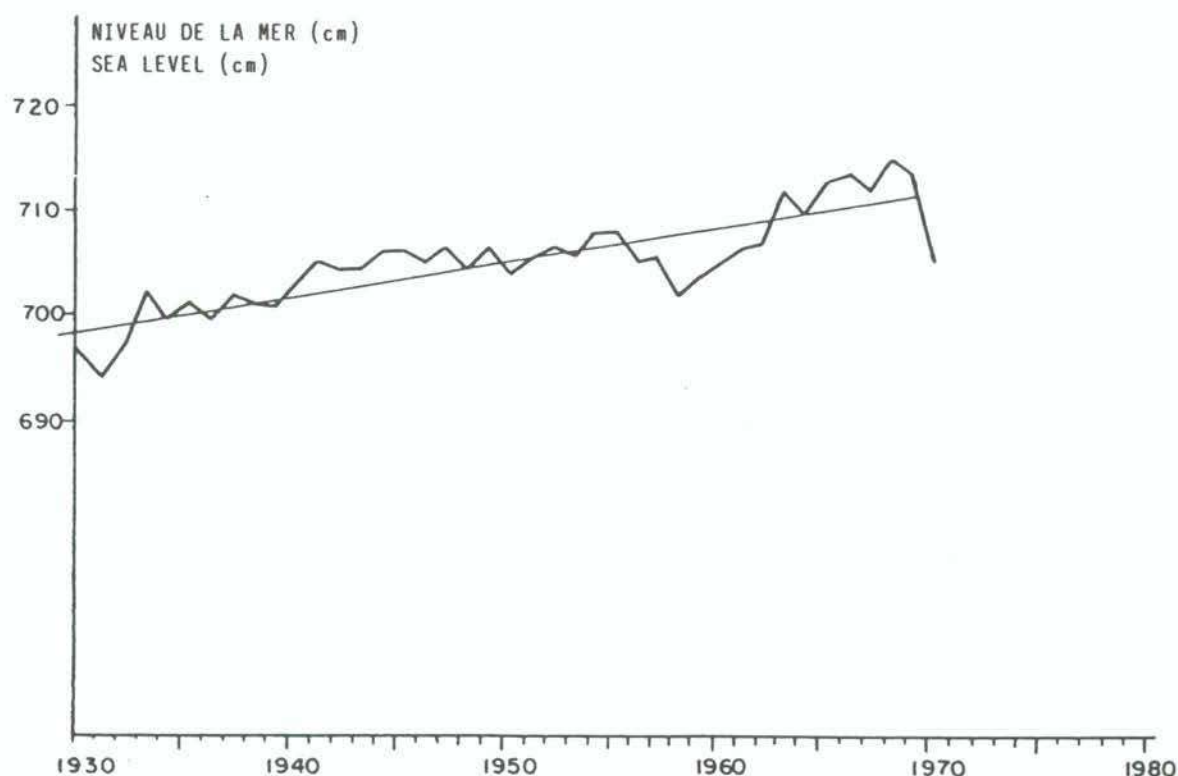


Fig. 2.10. - Variations récentes du niveau de la mer à Takoradi (Ghana)

Fig. 2.10. - Recent sea-level variations at Takoradi (Ghana).

2.5.3.2 Future variations

They are the subject of much international research work connected, in particular, with studies of the consequences of warming of the Earth's atmosphere induced by emissions of CO_2 and trace gases, that is, the greenhouse effect.

Physicists and climatologists believe that a doubling of the emission of these gases could lead to a $+1.5^{\circ}\text{C}$ to $+4.5^{\circ}\text{C}$ rise in the average atmospheric temperature, and that, because of the phenomenon of (thermal, oceanic and social) inertia, an accelerated sea level rise in the short and medium term is "inevitable".

This is an extreme conclusion. The various scenarios most recently developed, on the initiative of the American EPA (Environmental Protection Agency) and NAS (National Academy of Sciences), conclude with the following predicted ranges for the additional average sea level rise (between 1980 and 2025 or 2100), resulting from atmospheric warming:

	<u>1980-2025</u>	<u>1980-2100</u>
Low prediction	+13 to 26 cm	+ 56 to 144 cm
High prediction	+21 to 55 cm	+345 to 368 cm

These estimates of future behaviour have grave consequences for the evolution of the coastal environment, and it is essential to make allowances for them in any coastal development and protection plan.

The most significant consequences, that would probably result from such a regressive evolution, which will tend to accentuate the littoral risk, are of the following types:

- erosion and modification of the coastal morphology with retreat of the line of the coast;
- flooding of humid coastal zone;
- undermining of the effectiveness of coastal defence structures, with higher property damage risks;
- rise in the level of groundwater tables and saline intrusion, especially in estuaries;
- fluvial sedimentary deposits at the level of present river mouths;
- damage to sub-surface littoral networks for drainage, run-off and services.

Thus it would seem to be necessary to take into account, as of the present, this future "sea level rise" factor in any study of the protection, development and planning of coastal zones, without waiting for significant refinements in the predictive models and scenarios, which could make it possible to reduce the ranges of values currently available for average sea level rise.

2.5.4 Subsidence

Subsidence phenomena, be they natural or man-induced, affect a number of coasts, particularly in zones of sedimentary accumulation (deltas, estuaries and swamps), in the neighbourhood of active faults or along the borders of zones undergoing uplifting.

Deltaic zones are particularly susceptible to subsidence phenomena, through settling of sedimentary deposits and isostatic adjustments: 0.6 to 2.0 mm/year for the last 2,000 years in the eastern part of the Rhone delta (France), 0.3 to 1.0 mm/year off the shore of the Mississippi delta (U.S.A.).

In the eastern part of Lake Maracaibo, in Venezuela, as a result of oil extraction, shorelines have subsided by as much as 4 m in 50 years of drilling, that is, an average of 80 mm/year in a given sector. The oil fields of the North Sea and the Niger delta are subject to the same problems of subsidence: values of 25 mm/year have been quoted for the Niger delta (Ibé, 1987).

The combination of the phenomena of sea level rise and subsidence has a very significant impact on humid coastal zones: for example, approximately 1/2 million hectares of the coasts of Louisiana (U.S.A.) have been covered by the sea or eroded since the beginning of the century, that is, about $130 \text{ km}^2/\text{year}$, under the combined effects of these two factors.

2.5.5 Storms and sea level set-up

2.5.5.1 Swells and storms

Waves and swells generated by the wind are the main vector of energy exchange between the "coastal system" and the surrounding environment. At a given point and for a given period of time, this energy can be represented by a directional spectrum which takes into account the origin and the direction of propagation of the swell.

The total energy transmitted by the swell, per unit of crest length "off-shore" from a given coastal site, is proportional to (H^2T) . The energy flow transmitted by the swell along a coast varies from region to region.

Moreover, the distribution of the swell energy when it is transferred from the open water to a given coastal sector (refraction) is a function of the underwater topography, which favours concentration and discharge of this energy in particular coastal "segments".

Thus coastal morphology can be viewed as the result of a progressive evolution, which makes allowances for, in particular, the geological and sedimentary history, and the distribution of this energy with respect to space and time. An "isolated" littoral sector (for example, a beach separated by rocky points) is composed of coastal segments, whose morphology (orientation, profile) and granulometry are variable characteristics in "equilibrium", at a given point in time, with the swell conditions.

One of the problems that naturally crops up is that of knowing whether strong storm swells can "destabilize" a littoral sector (system) in an "irreversible" manner. In order to try to provide an initial answer to this question, we shall consider the following main factors: transmitted energy, distribution over time and space, and induced phenomena.

Transmitted energy

Comparing an "annual" and a "centennial" swell of the same period, the ratio of transmitted energies is only 3.2, which means that this ratio varies only from 1 to 10 depending on the period (T) under consideration.

Distribution of the swell energy

The propagation of the swell towards the coast, after refraction, has the effect of amplifying the above ratio in the event that the orthogonals converge: thus this ratio can theoretically be multiplied by a factor of 1 to 5 for certain coastal segments, while other neighbouring sectors are more protected, because of the fact that the swell discharges there (Fig. 2.11).

In this case, it is understandable that because of longshore transport, in particular, sedimentary exchanges among these neighbouring segments are intensified during high storms. Such drastic variations in flow can induce variations in the mobile sedimentary stock (dmss), which is a possible cause of localized instability of the littoral system.

Induced phenomena

The transitory average rise in the sea level on a beach, due to the breaking of swell during a storm, can be expressed in first order approximation by $R - 0.19 H_b$, where H_b is the

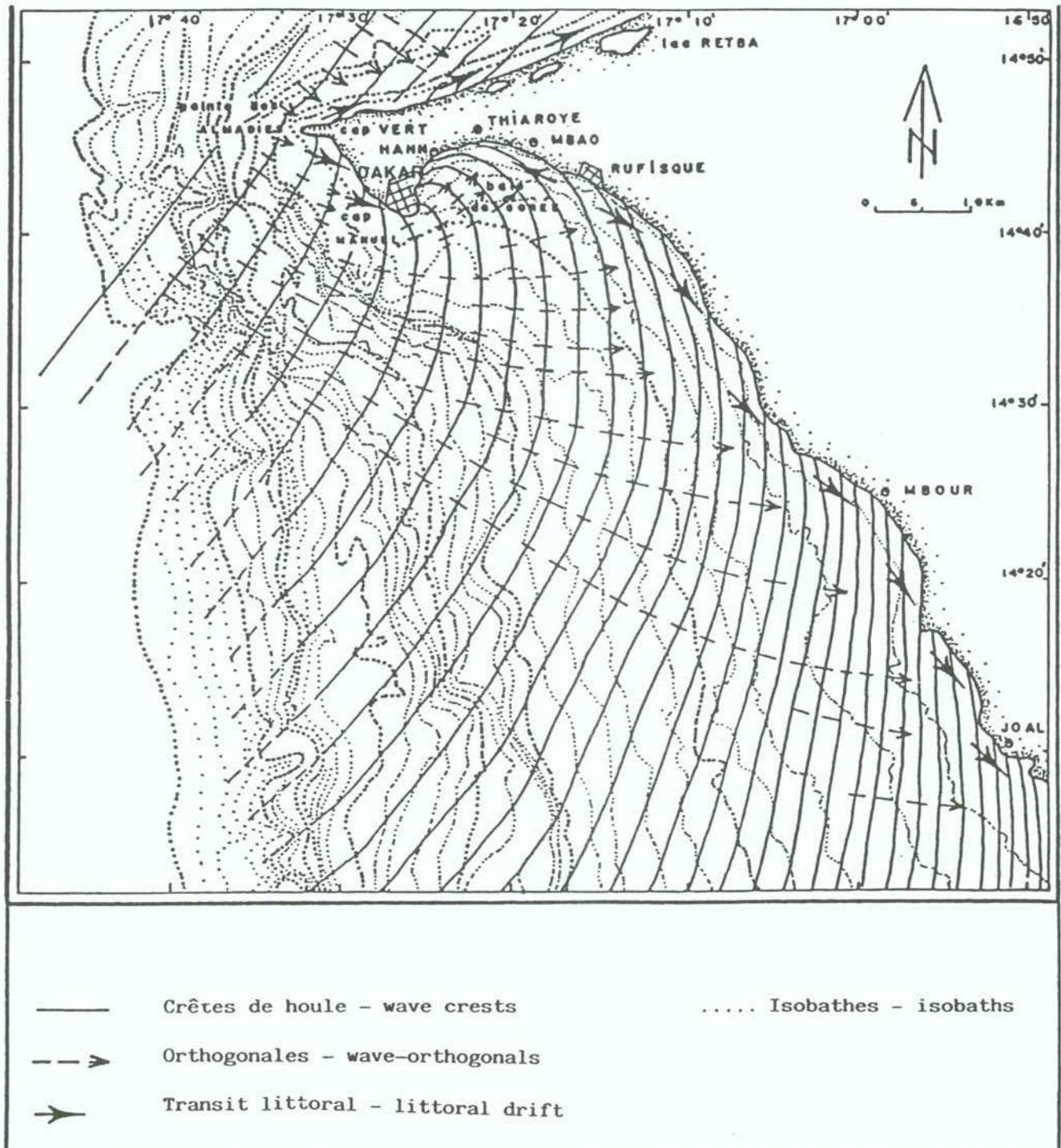


Fig. 2.11. - Réfraction de la houle sur la côte au Sud de Dakar (Sénégal).

Fig. 2.11. - Wave refraction on the coast south of Dakar (Senegal).

(Riffault, 1980)

height of the swell at the breaking point. For a beach with a 5% slope, and a swell characterized by $H_0 = 3$ m and $T = 10$ s, and a refraction coefficient equal to 1, $R = 0.8$ m. This suggests that the rise in level (wave run-up) "activates" an additional slice of the exposed beach of about 16 m in width, which is rarely subjected to the direct influence of the swell. This phenomenon is amplified even more by the sea level set-up due to barometric conditions.

2.5.5.2 Sea level set-up

The set-up is defined as the difference in amplitude between the theoretical tide and the observed tide. It is especially dependent on the barometric and morphological conditions of coastal sites.

Excess sea levels, due to barometric depressions and to water inflows to the shoreline as a result of large scale transfers, are all the greater the shallower the bottom of the sea. They can reach values of 1 to 2 m along European coasts, with exceptional values greater than 2.5 m (Fig. 2.12). In the West and Central African region, there is a dearth of statistical data on excess sea levels.

We note then that the total sea level set-up (barometric excess level and sea level rise due to the swell) at times of storms is one of the most significant risk factors in littoral erosion. For the occurrence of excess sea level facilitates violent action by storm swells on those parts of the "exposed" beach (or on the inland beach), which do not have an initial "equilibrium" morphology that would allow them to "resist" the action of the swell. The consequence of this action is destabilization and/or erosion of sedimentary structures on the high and inland beaches, which are "virtually irreversible" phenomena in the short and medium terms.

2.5.5.3 Long waves: seiches

Lakes, closed bays, roadsteads, narrows, coastal lagoons and ports may, under certain conditions, be the site of long oscillating waves (barometric influences, winds, underwater slumping) or seiches.

Such oscillations of bodies of water can be the cause of substantial damage to ports, as well as to coastlines.

2.5.6 Earthquakes

2.5.6.1 Tsunamis

Tsunamis are gravity waves with a long period which form in the ocean, as a result of earth tremors or underwater slumping, and propagate rapidly in deep water, at a speed $V = (gZ)^{1/2}$ where Z = depth. For $Z = 200$ m:

$$V = 45 \text{ m/s or } 162 \text{ km/h.}$$

The amplitude of tsunamis in deep water is small (H between 0.1 and 1 m), but their period and their wavelength (L) are very long: L can vary from 50 to 150 km on the continental shelf.

Despite the relatively strong seismic activity prevailing in some parts of West and Central Africa (Guinea, Ghana), there are no direct references in literature to damage associated with tsunamis.

2.5.6.2 Coastal mass movements and underwater slumping

Apart from the impact of tsunamis, seismic events directly or indirectly induce other modifications in the morphology of the coastal system (Qu  lennec, 1987b):

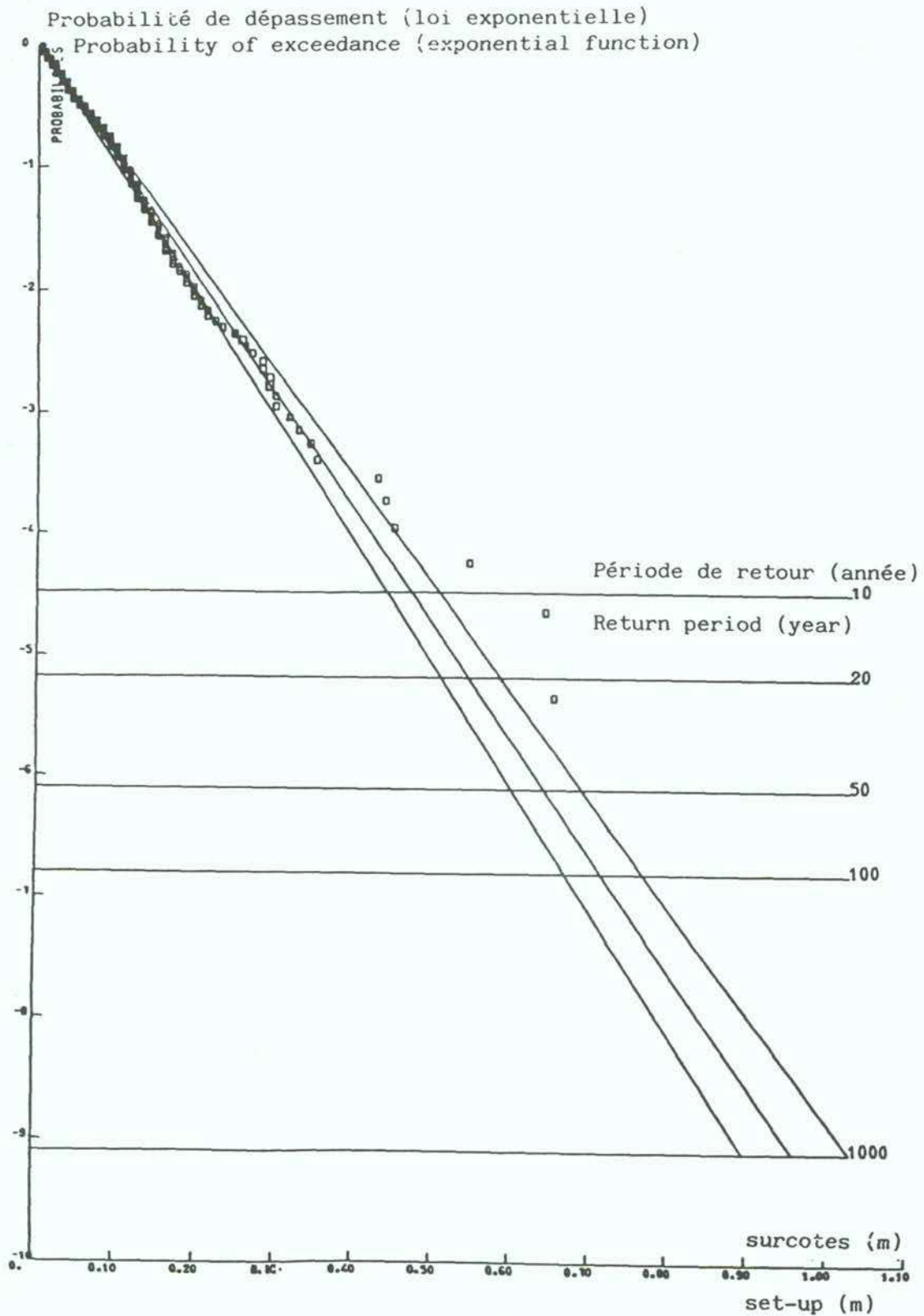


Fig. 2.12 - Estimation statistique des surcotes marines à Granville, France (E.D.F./L.N.H.)

Fig. 2.12 - Statistical estimates of sea-level set-up at Granville, France (E.D.F./L.N.H.)

- coastal foundering and mass displacements: as recent famous examples, one might point to that of the Alaska earthquake in March 1964, with particular impact at Valdez (75 Mm^3), at Seward and at Anchorage (a 3 km long strip of width 200 to 400 m), and also to that of the uplifting of marine and coastal terraces, by as much as 4 to 8 m, on the island of Middleton in the gulf of Alaska. Numerous other examples of such phenomena have been reported from coastal regions with strong to medium seismic activity, such as Japan, the U.S.A., Chile, the Mediterranean and the English Channel;

- underwater slumping: in Western Africa, the strong and virtually permanent seismic activity, centred in the proximity of the major tectonic "Akwapin fault" and the "coastal boundary fault" (5,000 m of upthrow) in Ghana (Bellion, 1984), does seem to be the cause of coastal margin foundering and underwater slumping, which have affected the deltaic zone of the Volta, as well as the coasts of the neighbouring countries of Côte d'Ivoire and Togo. Seismic tremors induce phenomena of liquefaction of saturated and unstable fluvial or marine sediments, accumulated on littoral and underwater slopes (deltas), and on the rims of underwater canyons.

2.5.7 Liquefaction of sediments under the action of swell

Under the combined effect of excess sea levels and of cyclic load stresses, due to high amplitude swells, the sedimentary masses stocked on underwater slopes (deltas, canyon rims) can lose their resistance to shearing, and produce density flowages. This slumping or liquefaction risk can be even higher when the marine sediments imprison pockets of gas, or when they are subjected to additional loads, due especially to artificial construction of poorly drained coastal embankments.

This sort of slump potential makes it possible to provide an explanation for the drastic shoreline retreats observed at Port Bouet in Côte d'Ivoire, across from the "Trou-sans-fond" canyon, in 1905, 1959 and 1984 (Quélenec, 1984c), and at Cape Lopez in Gabon in July 1971 (UNEP, 1985).

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3. FACTORS INFLUENCING COASTAL EROSION IN WEST AND CENTRAL AFRICA

In general, the factors affecting the character of the coastlines in the region can be grouped into natural and man-made.

The natural factors include the work of hydrodynamical factors (winds, waves, tides, currents, sea level changes, etc.) as well as the geological nature of the coastline whether the land margin is low-lying or elevated, stable or mobile, the width of the continental shelf, the occurrence of submarine canyons and gullies, etc.

The effects due to the intervention of man in the natural environment derive notably from civil engineering constructions and also through devegetation, sand mining, dredging, etc.

3.1 HYDRODYNAMICAL FACTORS

3.1.1 Wind

Wind is a particularly significant factor in the evolution of open beaches the world over. The prime function of wind in relation to beach erosion is in the generation and propagation of swells and seas, the effects of which are discussed in Chapters 2 and 3.

Wind also plays an important role in the generation and translation of coastal dunes. This is particularly so in the extreme northern and southern parts of the region where the Sahara and Kalahari deserts respectively present easily remarkable reserves of loose sandy sediments. Lepple (1975) estimated that 600,000 to 2,500,000 m³ of eolian dust of Sahara origin per km of northwest African coast are carried annually to the sea. Fig. 3.1 depicts some eolian dust concentrations in marine sediments off the coast of Mauritania, Senegal and Guinea, but similar figures of the area of southern Angola are lacking.

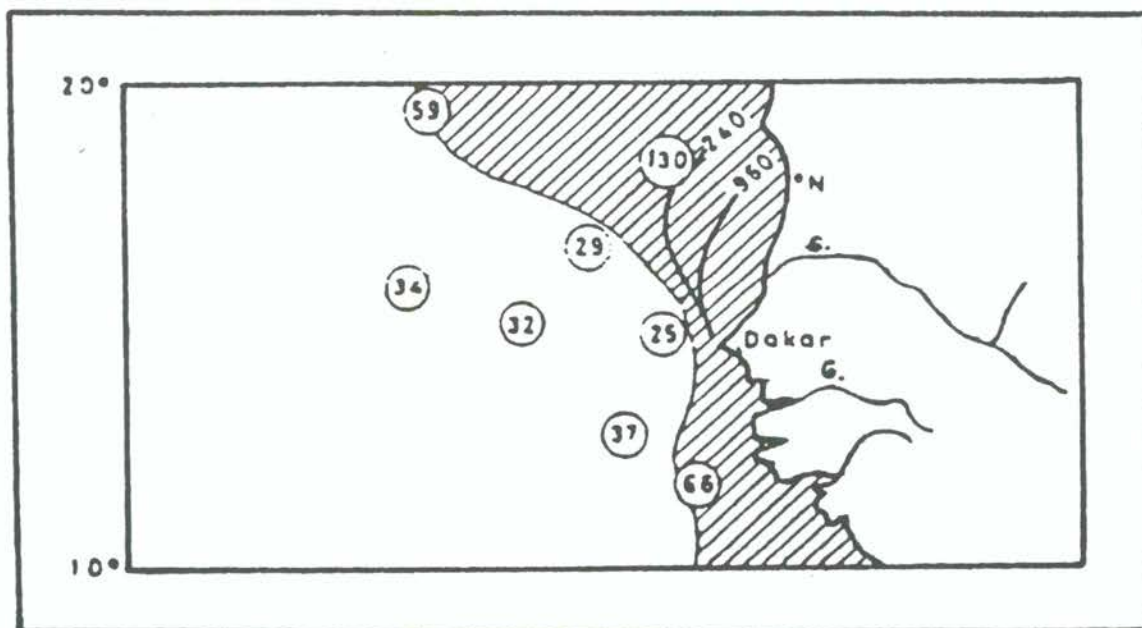


Fig. 3.1. - Concentration de poussières éoliennes (μ/m^3) en suspension sur le plateau continental sénégalais.
In Sall, 1982.

Fig. 3.1. - Eolian dust content (μ/m^3) over the Senegal continental platform.
In Sall, 1982

It has been argued (Pugh, 1954; Allen, 1965) that wind action in the rest of this region and in particular along the humid tropical coastlines is virtually non-existent because air moisture and wetness of the beach favour the cohesiveness of beach sand and its rapid fixing by vegetation.

However, the presence of more or less vegetated coastal dune systems in the backshore area of several sectors of the region (Gambia, Benin, Ivory Coast, Cameroon) indicates past or present active eolian beach sand transport due to high insolation rates which ensures a quick drying out of the beach sand (Ibé et al., 1984; Ibé, 1985, 1987).

Dramatic erosion of coastal land with significant and brutal changes in coastal morphology can occur with strong winds and storms which in this region are associated with tropical weather disturbances. Their effect is enhanced when they coincide with exceptional tides (spring tides, and atmospheric depressions).

Ibé et al. (1984) have described one situation in October 1983 when unusually strong winds coincided with high spring tides and caused a large pile up of coastal waters 1 m above normal average levels, which flooded extensive areas all along the low lying Nigerian coastline. At Victoria Island, a retreat of 3 m occurred on the beach for 3 days (Photo Fig. 3.2). At Escravos, on the Niger delta, a long existing and heavily built up spit near the Gulf Oil company base at Escravos was breached and erosion has been gnawing away at both the resulting island and the remaining main spit (Photo Fig. 3.3).

Similarly, Quélennec (1984c) reported a storm in mid-July 1984 in Cote d'Ivoire, that caused retreats of 10 to 20 m to the shore of the Port Bouet community accompanied by destruction of housing. The summer 1984 storms that hit the Ivoirian shoreline left erosion micro-cliffs from Moumouzou to Grand Jacques, particularly around Toukouzou and Addah. These storms also wrecked havoc in the Gbamble-Azuretti-Grand Bassam area. Here, the narrow coastal bar is subjected to submersion or temporary cuts during storms occurring at high water level. In a striking case during the summer 1965 storm, severe submersions and cuts with resulting beach retreat of 10 - 15 m occurred at Grand Bassam, 1 to 3 km westward of the "Taverne Bassamoise" restaurant, as well as eastward of the France District. Coastal habitation (Apatams) and 7 rows of coconut in the Taverne vicinity were destroyed and the Grand Bassam town hall and south district were flooded. The impact of periodic storms in the coastal zone between Assouinde - Assinie, which houses two major world renowned hotel complexes, was no less severe.

In Angola, strong storms in 1955 caused a new break in the southern part of the Ilha of Luanda, thereby isolating a 1.5 km long spit, which has since then been rapidly eroding (Guilcher et al., 1974).

According to an account in UNEP (1985), the Sangomar Spit in Senegal undergoes catastrophic retreats during storms but the induced cuts remain occasional and calm weather conditions favour the rebuilding of the spit.

On the Togolese coast, storms caused a beach retreat of 25 m within one week between Kp 29 and 31, the retreat measuring 15 m in May 1984 over 2 days at Kp 37 (Kpeme wharf). This storm induced retreat laid partially bare the wharf piles and extended to Aneho (Oliveros, Quélennec, 1985).

The town of Grand Popo (Benin) situated on a low and very long sand bar was subjected to sea attacks during storms and was particularly flooded during the storm of August-September 1984.

The erosion normally observed in the volcanic islands of Sao Tome or Principe occur during the season of heavy storms.



Fig. 3.2. - Erosion côtière à Victoria Island (Nigéria) après 3 jours de tempête (Ibé).

Fig. 3.2. - Coastal erosion at Victoria Island (Nigeria) after a 3 days storm (Ibé).

Fig. 3.3. - Flèche sableuse à Escravos (Nigéria) coupée par la tempête de 1983 (Ibé).

Fig. 3.3. - Sand spit cut at Escravos (Nigeria) by the 1983 storm (Ibé).



3.1.2 Waves and swells

Waves and swells, which are essentially wind generated, and wave induced currents are the most important forces which shape and determine the dynamic behaviour of beaches. Waves result from kinetic energy transfer from the wind to the sea. The mechanism of this energy transfer which is beyond the scope of this manual has been variously described by Jeffreys (1923), Sverdrup and Munk (1947), Phillips (1957) and Miles (1965, 1967) among others. The characteristics (H,T) of waves are determined principally by wind velocity and duration as well as by the extent of open water across which the wind is blowing known as the fetch (Fig. 3.4).

Waves have dual functions in sediment transport on the beach: (a) oscillation and setting up of the beach sediments in suspension preparatory to transportation and (b) generation of currents which affect the dispersal of sediments.

The littoral drift of sediment under wave action is directly proportional to wave energy (H^2T) and wave steepness (H/L) (see Para. 3.4.3).

The majority of the beaches of the region are strongly beaten by high energy swells which are generated by winds originating from Atlantic storm centres and blowing over long fetches. Fig. 3.5 summarizes the main characteristics of swells that prevail off the Atlantic coast of Africa. Two dominant systems are observed north of the area, from Mauritania to Casamance, the swell is northerly to northwesterly, in the central part and towards the South, from Guinea-Bissau to Angola, the swell is south-south-westerly to south-south-easterly. According to Ibé et al. (1984), typical wave energy along the Nigerian coast sometimes reaches 80k joules per metre of crest with a wave steepness varying between 0.023 and 0.070.

Due to the narrow tidal range over much of the region, the wave energy liberated when breaking is concentrated on a narrow strip of shore face. The UNEP report (1985, pp. 79, 103 and 113-167) is replete with accounts of the destructive impact of storm swells which break on the coasts of the region.

More importantly perhaps is the fact that swells, especially of short periods, strike the coast obliquely, thereby generating long-shore drift and rip currents responsible for transporting large quantities of sediments alongshore and offshore.

3.1.3 Longshore currents

The quantities of sediment (littoral drift) transported alongshore by wave induced currents is a function, more particularly of the angle (α) between the wave crest and the shoreline and of the wave amplitude (H_b). Between Mauritania and Senegal, estimates of longshore drift reach up to 1 Mm^3 per year. In the area of Cape Palmas to Cape Three Points, littoral drift is about 0.8 Mm^3 per year. Between Cape Three Points and Lagos, estimates of longshore transport vary between 0.25 Mm^3 in Ghana to 1.5 Mm^3 in Nigeria per annum. From Rio del Rey (Cameroon) to Cape Lopez (N. Gabon) longshore drift is thought to drop to 0.2 Mm^3 per year in a dominantly northerly direction (Fig. 3.6).

The interruption of the littoral drift due to the presence of outlets, estuaries, canyons, and of man-made structures built in the nearshore area (jetties, groins), plays an important role in the sediment budget and in the equilibrium of littoral units (see Para. 2.3.2.3).

3.1.4 Rip currents

Another effect of the breaking waves in the nearshore region is the setting up of rip currents, with water flowing back through the breakers in sectors up to 30 m wide and attaining velocities of up to 2 m/s before dispersing seaward. These cauliflower-shaped, sediment-laden waters transport enormous amounts of sediments offshore and therefore play an important role in offshore sediment transport and coastal erosion processes.

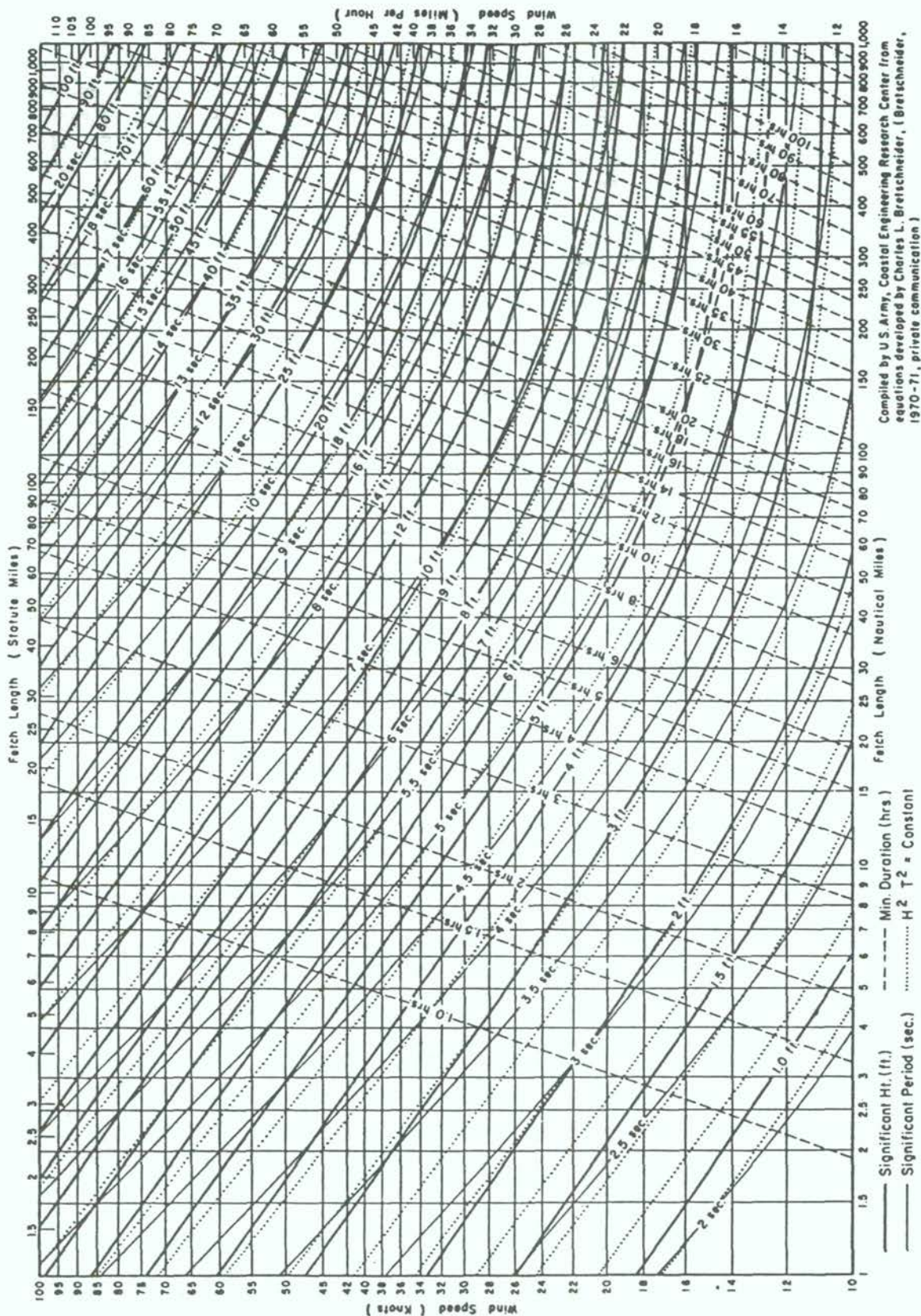


Fig. 3.4. - Estimation des caractéristiques des houles au large en fonction de la vitesse du vent, de la longueur du fetch et de la durée d'action du vent (pour des fetches de 1 à 1000 miles)

Fig. 3.4. - Deepwater wave forecasting curves as a function of wind speed, fetch length and wind duration (for fetches 1 to 1,000 miles)

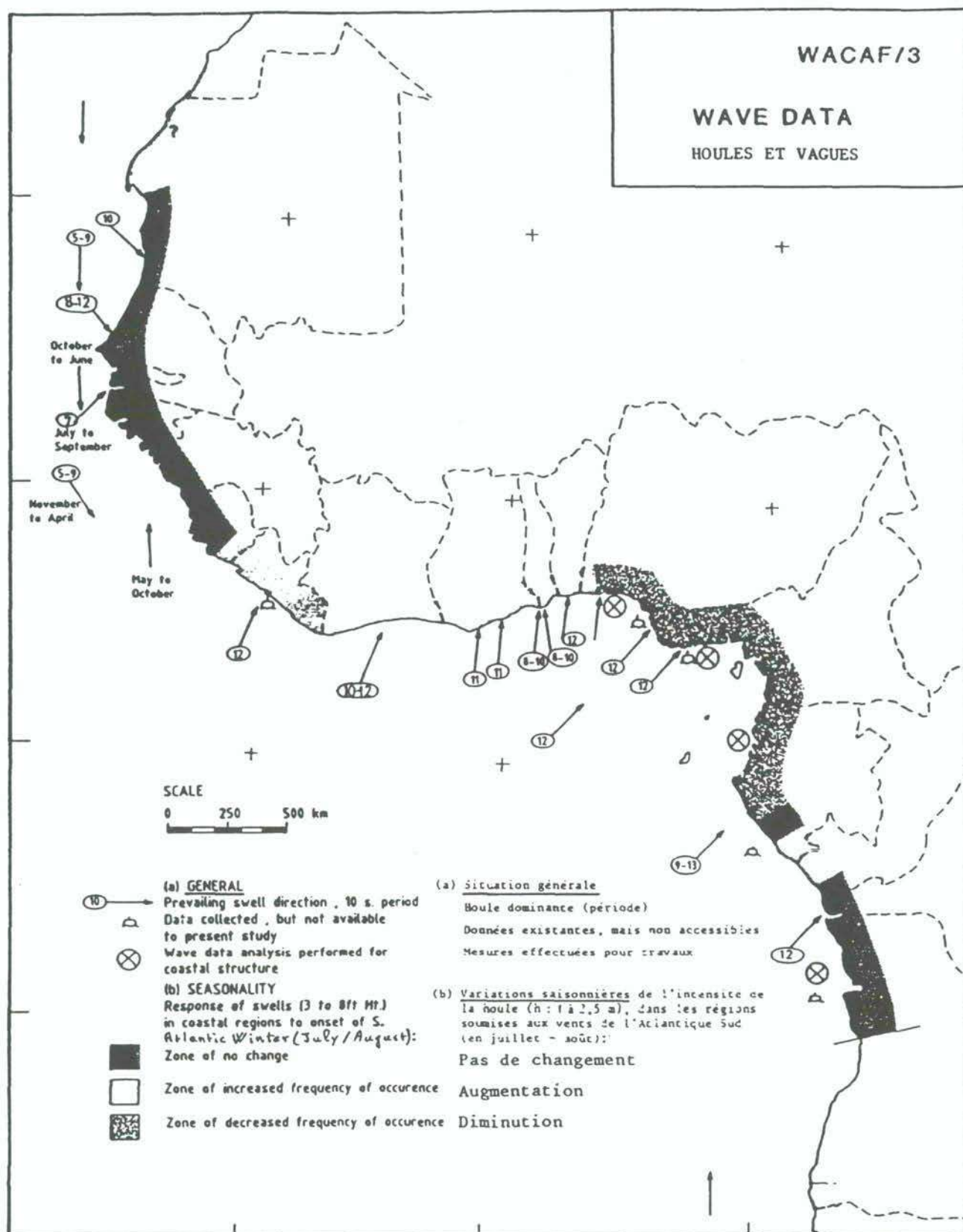


Fig. 3.5. - Caractéristiques des vagues dans la région.

Fig. 3.5. - Wave characteristics in the region.

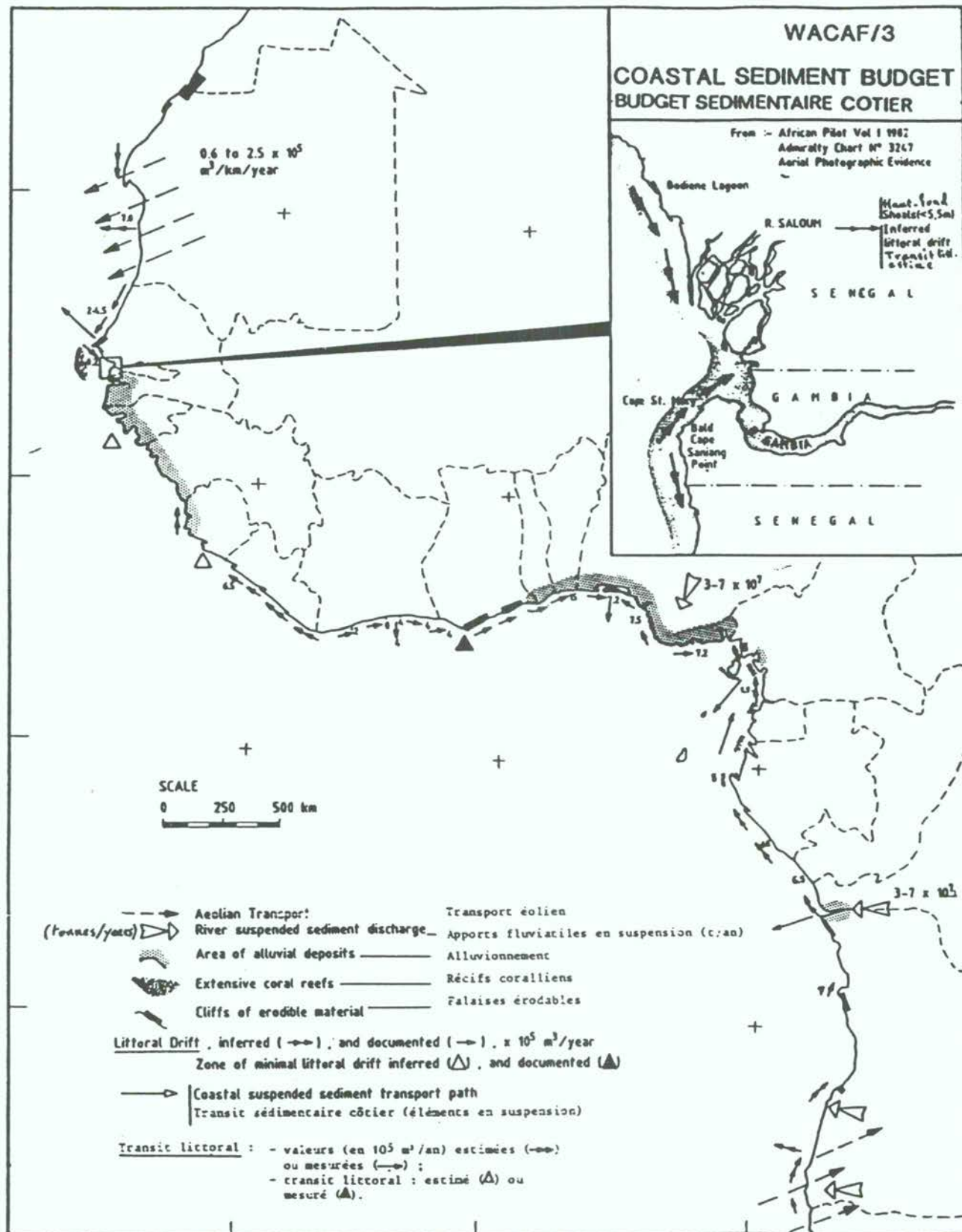


Fig. 3.6. - Elements du budget sédimentaire côtier dans la région.

Fig. 3.6. - Elements of the coastal sediment budget in the region.

According to preliminary dye experiments carried out by Ibé (1985) along the Nigerian coast, velocities reaching 1 m/s have been measured in rip currents.

There is very little available information on the sediment transport capacity of rip currents elsewhere within the region.

3.1.5 Tidal currents

Off the West and Central Africa coast, the tide is mainly of a semi-diurnal type, with two daily maxima and minima.

The tidal range varies within the region (see Table 3.1) but is generally less than 2 metres except in the areas of Guinea Bissau and Gambia where ranges of 3.2 and 5.1 respectively occur. Owing to the low tidal range, it is thought that tidal currents are generally weak (UNEP, 1985). While this may be generally true for straight coastlines with little indentations, the situation in coastal areas grooved with deep bays, estuaries or tidal inlets is different.

For example, studies along the Niger delta (Nigeria) with its numerous inlets show that the semi-diurnal tides which approach the coast from a southwesterly direction create reversible semi-permanent currents which occur at high angles to the coast, carrying sediments away from the shore out to sea in foam bounded plumes of turbid water which can be seen as far as 15 km from shore (Nedeco, 1961); Allen, 1965; Ibé et al., 1984).

The tides generate strong currents of between 0.4 - 1.8 m/s in the tidal inlets strong enough to shift gravel as well as sand (Nedeco, 1961) but maximum velocities ranging from 0.6 - 2.8 m/s are attained at mouth bars during ebb tides. The flood tides which are of shorter duration have lower velocities of between 0.3 and 1.5 m/s. According to Allen (1965) maximum current velocities calculated by Fleming's (1938) formula and which tail off with increasing depth and distance from shore, indicate a competence to erode and transport as bed load the coarsest silt and finest sand over large areas of the inner continental shelf. In Cameroon, tidal currents at the estuaries attain speeds of 1.25 - 1.4 m/s while in the Gabon estuary immediately north of Libreville tidal currents of 2 - 2.5 m/s play a significant role in the nearshore sediment dynamics.

3.1.6 Eustatic sea level rise

A long term process important in the consideration of coastal erosion is the worldwide post glacial eustatic rise in sea level, accelerated in the present day by the increasing green house effect (see Para. 2.5.3). This global rise in sea level has initiated a slow but persistent transgression of the sea which has clear effects along the coastline of West and Central Africa in terms of erosion (Fig. 3.7).

The seriousness of the rise in sea level with respect to erosion can be deduced from the data of Bruun (1977) which showed that even a rise of 0.3 m (1 ft) may cause shoreline recession of more than 33 m (100 ft) with the possibility of much higher recessions (sometimes hundreds or even thousands of times the vertical distance) in marsh and other low shore areas such as are common in the region. According to Fig. 2.10 (Verstraete and Picaut, 1983), the recent mean sea level trend at Takoradi (Ghana) is consistent with global trends.

Specific data related to sea level rise is also available from studies on the Nigerian coast. For example, Allen and Wells (1962b) used a sequence of dead coralline banks in shallow water off the Nigerian coast to indicate subsidence stages over the last four thousand years. All the observed subsidence (approximately 80 m about every 15,000 years) in the southwestern Niger delta has been proposed by Burke (1972) to have resulted from the eustatic sea level rise and the associated isostatic adjustments to water load.

Tableau 3.1.

<u>COUNTRY</u> - PAYS	<u>PORT</u>	<u>TIDAL RANGE</u> (m) MARNAGE
Mauritania	Bahia de Villa Cisneros	1.9
	Nouadhibou	1.8
Senegal	St. Louis	1.2
	Dakar	1.3
Gambia	Banjul	1.6
Guinea Bissau	Bissau	5.1
Guinea	Conakry	3.2
Sierra Leone	Pepal	2.9
	Freetown	2.6
Liberia	Monrovia	1.1
Côte d'Ivoire	Buchanan	1.0
Ivory Coast	Abidjan	1.0
Ghana	Takoradi	1.3
	Accra	1.3
Togo	Lome	1.4
Benin	Cotonou	1.2
Nigeria	Lagos (Bar)	1.0
	Forcados Bar	1.2
	Bonny Bar	1.8
	Calabar Bar	2.0
Cameroon - Cameroun	Douala	2.0
Equatorial Guinea	Bata	1.6
Gabon	Libreville	1.6
	Cap Lopez	2.0
Congo	Pointe Noire	1.3
Zaire	Banana	1.3
Angola	Cabinda	1.8
	Luanda	1.2
	Lobito	1.2
	Mocamedes	1.2

- Tableau des marées (vive-eau) dans les principaux ports de l'Afrique de l'Ouest et du Centre

- *Western and Central African coastline tidal ranges*

(PNUE/UNEP, 1985)

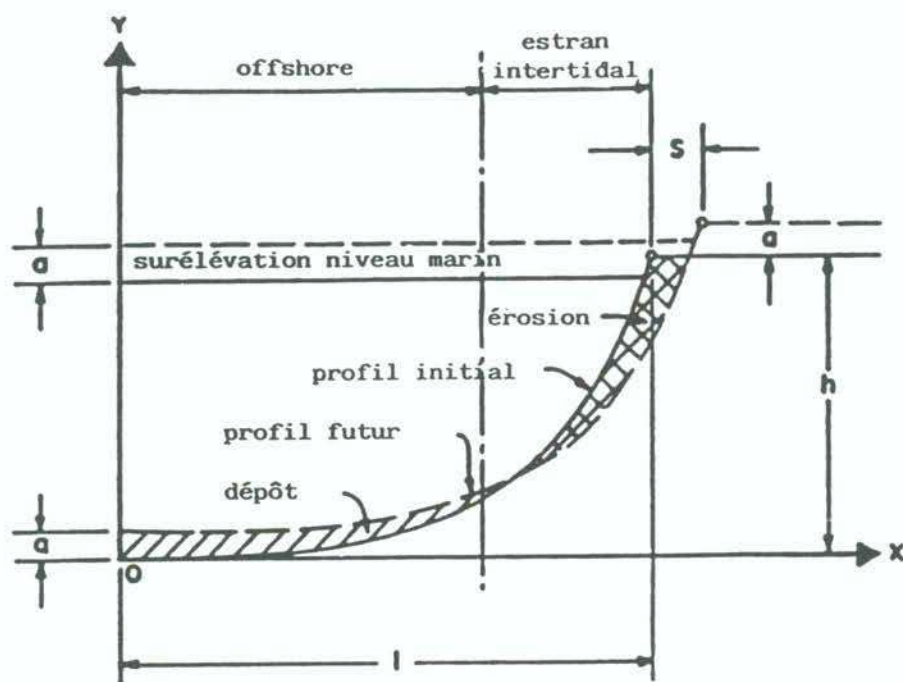


Fig. 3.7. - Evolution du profil de plage sous l'effet de la surélévation du niveau marin.

Fig. 3.7. - Beach profile evolution due to sea-level rise.

(Bruun, 1979)

3.2 GEOLOGICAL AND GEOMORPHOLOGICAL FACTORS

Some large-scale geological and geomorphological features like the coastal relief, the continental shelf width, the occurrence of submarine canyons, the presence of tidal outlets, but also the possibility of subsidence or reworking of sediment stocks, play an important role in the occurrence of littoral hazards (see Para. 2.5).

3.2.1 Coastal relief

Cliffs occur in some parts of the coasts of Senegal, Gambia, western Cote d'Ivoire, Ghana, Cameroon and Angola. The rest of the West and Central Africa coastline is characterized by low plain sandy beaches sometimes backed by mangroves.

Photo Figs. 3.8 (A & B) show two typical beaches, one muddy, the other sandy along the Nigerian coastline that emphasize the low plain nature of a majority of the beaches in the region. Ibé et al. (1965) reported topographic heights of between 0.8 m and 1.8 m above mean sea level, in the Awoye/Molue area shown in Fig. 3.8/A. With a tidal range of about 1.5 m, it means that even at normal high tides, a large expanse of coastal land is flooded by seawater. According to Ibé et al. (1984), typical slopes for beaches in the Arcuate Niger Delta (Nigeria) are 1:15 to 1:20.

The implication of low relief in the region is that any elevation in the ocean surface close to shore would manifest as a landward translation of the shoreline many orders of magnitude compared to the vertical rise. The land surface close to shore is thus degraded and shoreline retreat occurs.

3.2.2 Continental shelf width

The coast of West and Central Africa is bordered by a narrow continental shelf that is only some 10 km wide off the Cape Vert peninsula (Senegal) and off Cape Lopez (Gabon). Although isolated sectors of great width occur (200 km off Guinea Bissau and 100 km off Mauritania and Central Ghana), it is established that, generally, the width of the continental shelf off West and Central Africa is relatively narrow in comparison with the other continental shelves of the world. This platform is rarely 80 km wide, being mostly between 30 and 40 km.

A narrow continental shelf allows waves to break on the coast at greater angles because the waves do not shoal or refract as much. Thus the wave sediment transport capacity is much higher.

Another implication of the narrow shelf in the region is the likelihood that sediment carried from the shore is lost more easily to deeper waters especially in periods of high hydrodynamic activity.

3.2.3 Submarine canyon

The continental shelf and slope of the region is often notched with submarine valleys or canyons. Some of the better known canyons include:

- the Cayar (Senegal),
- the Trou-sans-Fond (Cote d'Ivoire),
- the Congo-Zaire (Congo-Zaire),
- the Avon, the Mahin and the Calabar (Nigeria).

It is known that the heads of most of these canyons, or valleys leading into them, begin in the vicinity of the coastline and therefore act as chutes down which sediment, carried along by longshore and rip currents, is channelled and lost to deeper waters.

For example, the head of the Congo-Zaire Canyon even extends several dozen kilometres inshore towards the inner part of the estuary and therefore exerts considerable influence on the loss of coastal sediment.

In Cote d'Ivoire, the Trou-sans-Fond Canyon in front of the Vridi Canal acts as a "sediment trap". Based on the 1958 assessment of Varlet (in Hinschberger, 1979), approximately 800,000 m³ of sand pass annually in front of Vridi meaning that over 35 years, about 30 million m³ of material has been diverted by the canyon, instead of continuing along the coast towards Port Bouet and beyond.

In Nigeria, more than 1 million m³ of sand transported by littoral drift from two different directions towards the mud coast are lost respectively down the Avon and Mahin Canyons (Fig. 3.9) and this has been cited as being responsible for the lack of sand and the muddy nature of the coast in this sector of the Nigerian coast (Burke, 1972; Ibé et al., 1984). Similarly, the muddy nature of the Calabar coastline and the continued erosion of the eastern extremity of the Nigerian coastline has been attributed to the negative impact of loss of longshore drifted sand into the Calabar Canyon off the coast there (Ibé, 1987).

In Mauritania, the Tiouillit Canyon in front of Cape Timiris has its head close to the shore (Einsele et al., 1977) and therefore serves as a sediment trap. Chen et al. (1983) have attributed the coastal erosion observed 30 km north of Nouakchott to the existence of this canyon.

Fig. 3.8. (A - B) - Plages vaseuses (A) et sableuses (B) à faibles pentes sur les côtes du Nigéria et du Cameroun.

Muddy (A) and sandy (B) beaches, with small slopes, on the Nigerian and Cameroon coastlines.



Delta du Niger
(Nigéria) - (Ibé)

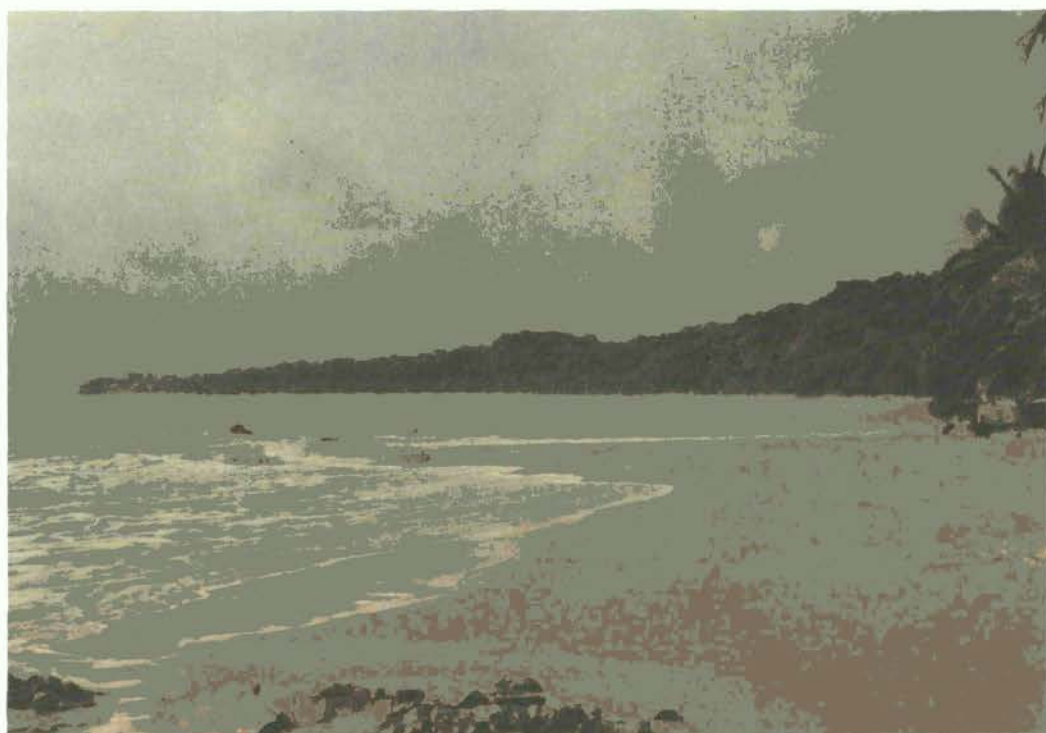
A

Niger delta
(Nigeria) - (Ibé)

Côte sud du Cameroun
près de Campo
(Quélenec).

B

Southern Cameroon
coastline near Campo
(Quélenec).



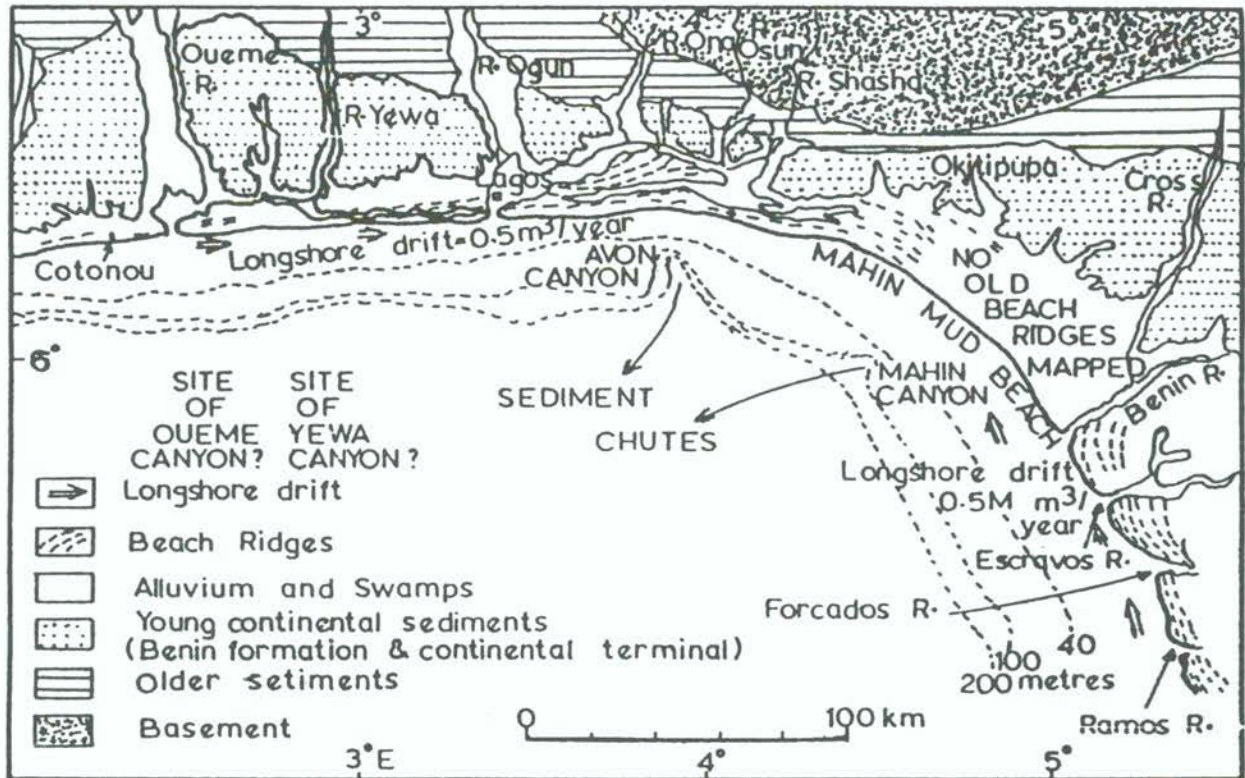


Fig. 3.9. - Transit littoral et canyons sur la côte du Nigéria.

Fig. 3.9. - Littoral drift and canyons on the Nigerian coast.

(Burke, 1972)

The Cayar canyon (off Senegal) represents a major feature influencing sedimentation in the area as it abruptly stops the alongshore sediment transport on the Mauritania-North Senegal margin by trapping a major part of the sandy littoral drift (Diets et al., 1968; Horn et al., 1974; Ruffman et al., 1977).

3.2.4 Tectonics, subsidence

The West and Central African region is marked by the development of sedimentary basins. In all cases their basement outlines are concave and their main axis always coincides with the presence of a major river which has often indicated the development of deltas (some like the Niger are enormous).

In most of these deltas, the coastal geosyncline is subsiding not only because they were formed in a tectonic setting, but because of natural dewatering and compaction processes. This trend is typical of most large deltas that have formed rapidly in a tectonic setting.

In the Cote d'Ivoire basin, it is known that the eastern part of the basin is subsiding (UNEP, 1985). In the sedimentary basins of Gabon, Congo, Zaire and Angola, important subsidence phenomena occur. In the Nigerian coastal geosyncline, a sequence of dead coralline banks in shallow waters off the coast indicate stages in subsidence and/or rise in sea level during the past four thousand years (Allen and Wells, 1962). Present day measurements in the Niger delta show that this subsidence may reach 2.5 cm/yr (Awani, in Ibé, 1987). Ibé (1984) has suggested that the extraction of oil and gas from the porous reservoirs of the Niger delta may be accelerating this subsidence in the present day.

3.2.5 Sediment characteristics

Apart from the cliffed coasts present in Senegal, Gambia, Western Cote d'Ivoire, Cameroon and Angola, the preponderant sectors of the West and Central Africa coast are made up of loose, sometimes friable, sand and silt. Much of the sand beaches are composed typically of well sorted, fine-grained quartzose sands with characteristic heavy minerals like zircon, epidote, sillimanite, kyanite, hornblende, etc. (Allen, 1965; Ibé, 1982).

Fine-grained beaches have gentler slopes permitting greater uprush of waves.

The unconsolidated muddy beaches are even more vulnerable to wave attack and tidal inundation on account of their inherently weak mechanical nature due to a high moisture content, a low density, high plasticity and high organic matter content.

3.3 HUMAN IMPACT

The intervention of man in the natural environment can have a direct negative impact on the erosion problem in the region. Such human intervention includes port construction, sand and gravel mining, river dam construction, developments in the coastal zone, devegetation of watersheds and of littoral zones (mangroves), dredging, petroleum exploitation, etc.

3.3.1 Port construction

The construction of coastal harbours is a major cause of erosion at various locations on the West and Central Africa coast. According to a survey by UNEP (1985), there are 84 ports including wharfs and ore terminals in the region.

Most of the port structures lie perpendicular, or nearly so, to the littoral drift and therefore act as littoral barriers to sedimentary drift estimated generally to be between 0.2 and 1.5 mm³/yr in the directions shown in Fig. 3.6.

Thus, accretions take place updrift, while on the downdrift phenomenal erosion occurs. This is a classic situation. Everywhere in the world where the construction of breakwaters, groins or some other artificial structures have been constructed on a sandy beach to interrupt littoral drift, as, for example, at New Haven (England), South Lake Inlet (Florida), Durban (South Africa), Madras (India), Santa Barbara (California) and Salina Cruz (Mexico), downdrift erosion has resulted (Bird, 1967). The erosion east of the Ports of Lome, Cotonou and Lagos is due to this effect.

The construction of breakwaters for the Port of Lome started in October 1964, and even during the construction, accretion of the coastline started west of the port and erosion at the eastern side. According to Nedeco (1975, 1978) the shoreline progradation 2 km from the pier amounted to 60 m/yr during 1964-1969, 28 m/yr from 1969 to 1973 and 18 m/yr from 1973 to 1975.

In contrast, the entire eastern part of Lome Harbour measuring more than 15 km is being eroded, erosion rates being less as the distance from the harbour increases. 5 km east of the harbour, the beach retreat averages 20 m/yr near the Tropicana Hotel (Oliveros, Quélenec, 1985; UNEP, 1985).

At Cotonou, the harbour jetty built in 1960 has created a deposition zone west of the harbour with a growth of 700 m in 1976 (Sireyjol, 1977) and an erosion zone east of it. In 1976, a retreat of about 250 m was measured downdrift of the jetty.

At Lagos, the construction of the breakwaters between 1907 and 1912 has, since 1913, induced accretion on the lighthouse beach of the harbour and a phenomenal retreat of Victoria Beach on the downdrift side (see Fig. 3.10 after Webb, 1960). The present rate of erosion at Victoria Beach is between 20 and 30 m/yr (Ibé, 1985).

Severe erosion also occurs at Keta (Ghana) lying in the downdrift of the Tema Harbour as well as east of the Vridi Canal, the entrance to the Port of Abidjan (Cote d'Ivoire).

One other effect of the construction of ports along the coast arises from the dredging of access channels from the sea into these ports. The deepening of the channels allows waves to travel further up the inlet thereby increasing the risk of erosion. Deepening of such unprotected channels has the same effect on longshore drifted sand as shore perpendicular structures. It also alters the pattern of wave refraction and may cause a refocussing of wave energy which can lead to the acceleration of erosion at some locations.

3.3.2 River dam construction

The sedimentary input of rivers constitutes one of the main sources of natural sand replenishment for beaches. If therefore the hydrologic characteristics of a river are altered, e.g. through dam construction, the column of terrigenous sediments reaching the coast could be notably reduced.

Fig. 3.11 shows that the West and Central African region is well endowed with rivers which presupposes that copious amounts of sediments would normally reach the coastal zone through these large drainage systems. However, nearly all the major rivers and their main tributaries are dammed for hydro-electric power generation and agricultural practice irrigation and fisheries (see Table 3.2 and Fig. 3.11). The list and figure are far from comprehensive. Some of the rivers boast several dams along their course (e.g. more than 20 on the Congo-Zaire River). In fact, it is known that with the present emphasis in the region on boosting agricultural output, more dams are being constructed or planned.

It is estimated (UNEP, 1985) that the construction of dams in this region of Africa has drastically reduced the catchment areas as effective sources of sediment; an appreciable quantity of fluvial sediment which would otherwise have been transported to the coastal areas is now trapped behind the dams. Consequently, the beach sediment budget is affected and beach retreat results.

Although quantitative information on the effect of dams in the region is now readily available, the order of magnitude of fluvial change caused by dams in this region is indicated by the data of Olofin (1985) from a study in Nigeria. He reported that the mean discharge of the Kano River since 1974-1975 after the construction of the Tiga Dam decreased during the humid months from a pre-dam $101.9 \text{ m}^3/\text{sec}$ to an immediate postdam $14.3 \text{ m}^3/\text{sec}$ increasing to $25.4 \text{ m}^3/\text{sec}$ after 1980. The mean flood discharge of the river also decreased from $383 \text{ m}^3/\text{sec}$ to an immediate postdam $56 \text{ m}^3/\text{sec}$ and increased years later to $76.9 \text{ m}^3/\text{sec}$.

Ibé and Antia (1983) and MacDowell et al. (1983) have reported coastal erosion in the Niger Delta of Nigeria due to dam construction. Ibé (1985) has also attributed the worsening erosion problem in the barrier lagoon coast of western Nigeria partly to the construction of agricultural

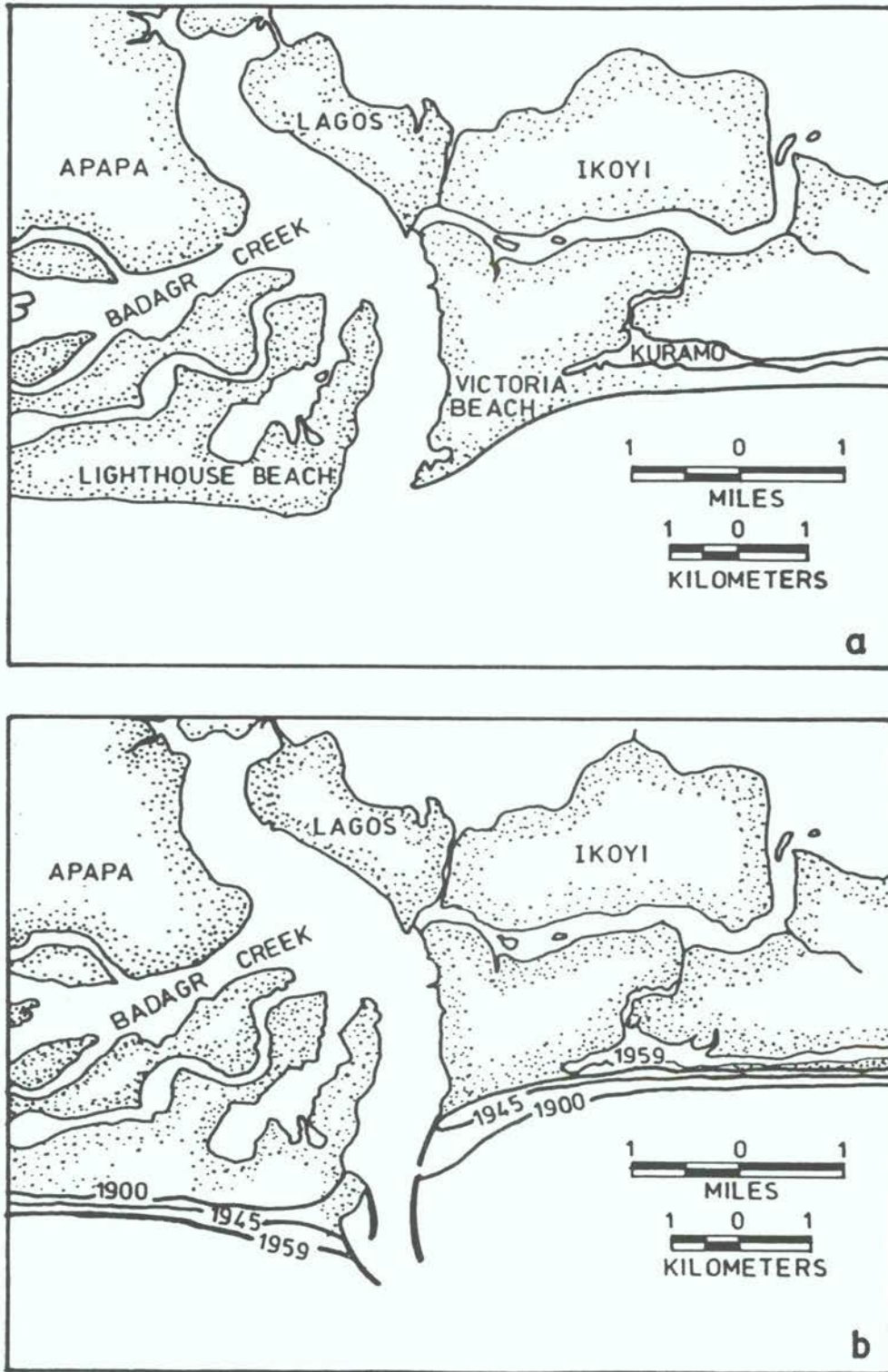


Fig. 3.10. - Le littoral de Lagos (Nigéria) avant (a) et après (b) la construction des jetées à l'estuaire.

Fig. 3.10. - The Lagos (Nigeria) coastline before (a) and after (b) the construction of jetties on the estuary.

(Webb, 1960)

dams in rivers like Ogun and Oshun that hitherto brought sand to the coast. Also, Ly (1980) has identified the Akosombo Dam on the Volta River in Ghana as inducing or accelerating a general erosion in central and eastern Ghana, east of the river mouth.

In Mauritania, the reservoir-dam planned on the Fouta-el-Geita site will partially prevent the sediment of the Gorgol River from reaching the coast (Water Power, 1981). The Diama Dam under construction in the inner delta of the Senegal River has already resulted in a diminished sediment supply to the coast. In Togo, the Nangbeto Dam project on the Mono River could produce the same effect (UNEP, 1985). In Cameroon, the north-west end of the Sanaga Delta is subjected to an erosion process attributable to the construction of the Eden Dam (1965), 70 km inshore of the Sanaga mouth. In Sierra Leone, the damming of many rivers in the 1960's brought about a significant reduction of the rivers' discharge and enhanced erosion sensitivity of coastal segments influenced by river sediment inputs.

3.3.3 Mining of sand and gravel in the coastal zone

Mining of sand and gravel in the coastal zone for building purposes is a common practice in the region. Such construction materials are derived either from estuaries, or from the beach itself or from the nearshore continental shelf.

The mining of sand and gravel from coastal rivers and particularly from estuaries tend to diminish the amount of fluvial sediment input to the coastline, thereby accelerating beach retreat. A slight erosive trend of the coast in the Gabon estuary, immediately north of Libreville, is traceable to illegal sand dredging there (UNEP, 1985). In Nigeria, the dredging of sand from coastal rivers and estuaries has been cited by Ibé (1986) as being responsible for the erosion-prone nature of the estuary shores.

Sand extraction directly from the beach seriously depletes the sediment pool available on the beach and beach retreat is either induced or accelerated. In Liberia, industrial development has encouraged the mining of beach sand with concomitant erosion around major industrial towns like Monrovia and Buchanan.

An appreciable tonnage of sand is mined in Sierra Leone on the coasts of the Freetown peninsula and induces destructive coastal erosion (UNEP, 1985). Observations near Cotonou led to estimates of mined sand of 150,000 m³/yr at one location and, compared with an annual littoral drift of 1 million m³, this activity could induce beach retreat (Nedeco, 1984). Ibé et al. (1984) have reported sand mining operations at various beaches along the Nigerian coast particularly at Brass, Forcados and Ibino-Eket. In Cote d'Ivoire, the erosion east of the village of Jacksonville is thought to be related to beach sand mining. Also in Cote d'Ivoire, large scale sand mining on the beach and the coastal bar in the Janfoli-Gonzagueville-Dieudonne area for several years produced a significant beach retreat (Quélennec, 1984c). Beach sand mining has since 1982 been banned in this area.

Dredging of sand from the nearshore continental shelf is an obvious cause of beach erosion in the region. The gigantic building projects including land reclamation schemes that were undertaken in Nigeria, particularly around Lagos, in the heady oil boom 1970's, would have been next to impossible but for colossal quantities of the sand (and some gravel) dredged from the nearshore area (Ibé, 1982) and has been considered by Ibé (1987) as being partly responsible for the accelerated erosion (25-30 m/year) on the beaches in the Lagos area.

A major shortcoming of such dredging efforts is the failure to understand the beach system in a regional context. On a coastal plain shoreline such as characterizes this region, the beach exists in equilibrium with the inner continental shelf. Therefore, pumping sand for beach replenishment, land reclamation or other civil engineering construction from the foreshore or, for that matter, anywhere else within the dynamic system (see Para. 2.3.2.3) inevitably affects this equilibrium and enhances shoreline retreat (Quélennec, 1981; Ibé and Antia, 1983; UNEP, 1985).

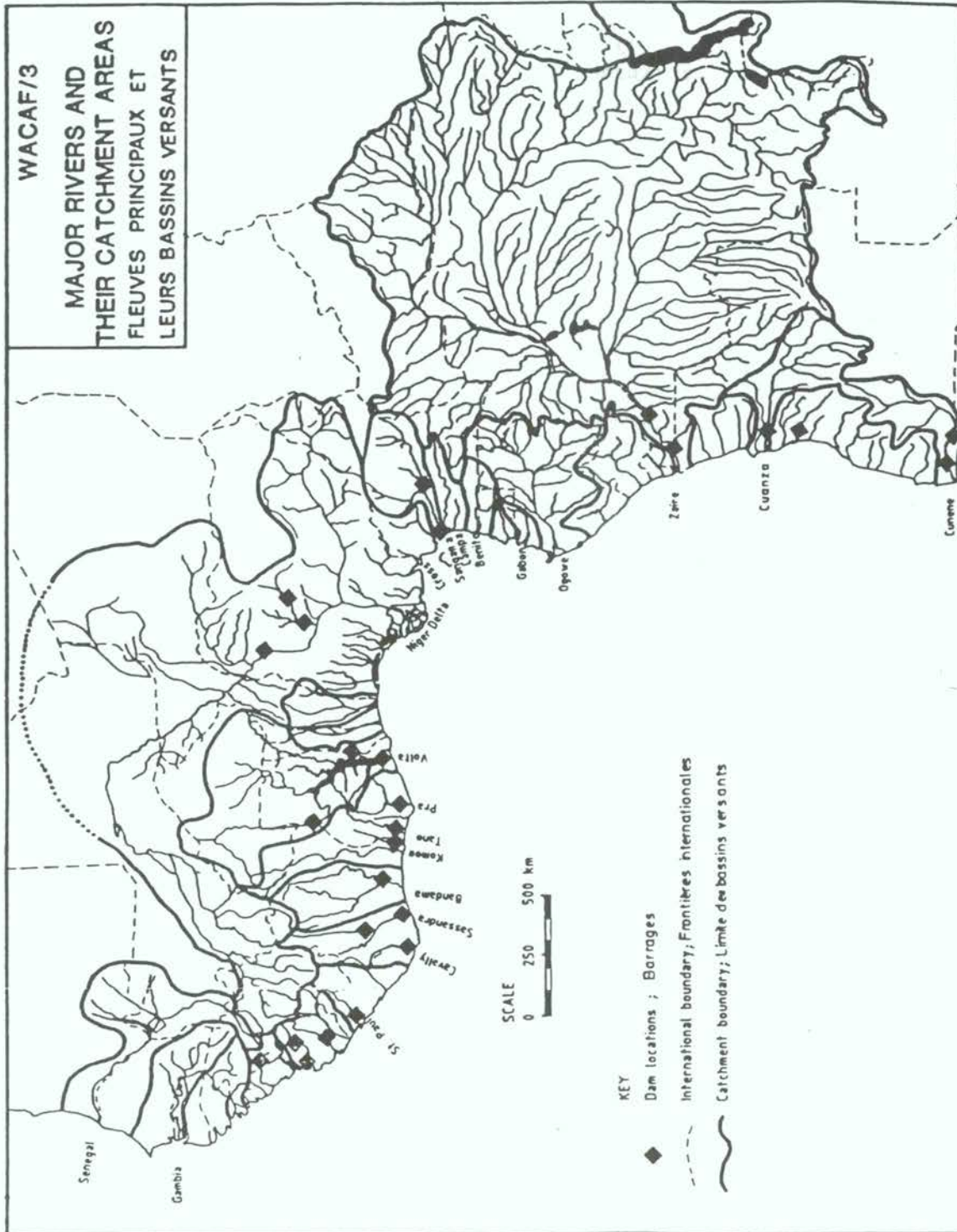


Fig. 3.11. - Principaux barrages sur les fleuves de la région.

Fig. 3.11. - Main dams on major rivers of the region.

(PNUE/UNEP, 1985)

Tableau 3.2.

PAYS COUNTRY	N°	NOM NAME	ANNEE YEAR	FLEUVE RIVER	SOURCE REFERENCE
Angola	9	Cambambe Gove Matala Queve	1962 1970 1969 1968	Cuanze Cunene* Cunene* Queve	A, Sarmiento and Alfonso (1962) B B B
Cameroun Cameroon	4	Sangana Mbakou Bamendjin Edou III	1965 1971 1971 1971	Sangana* Sangana Mbam Sangana	B, Rubin (1968) A A B
Congo	3	Inga I Shongo	1973 1970 1983	Congo Congo Le Fini R	B B B
Eq. Guinea	07				
Gabon	0				A
Ghana	9	Nauranga Hemang Akosombo Kpong	1978 1967 1961 1981	Tano* Pra* Volta* Volta	B B Mackintosh (1965), Ly (1980) Quartey and Allen (1981)
Guinea	2	Grandes Chito	1982	Konkoure	Rubin (1968)
Ivory Coast Côte d'Ivoire	11	Kolotalli Bouake Ayame I Ayame II Kossou Tabbo Buyo Soubre Bandama Cavally Ticbisson	1959 1964 1972 1975 1972 1965(?)	Nzi (Bandama) Kan* Bia* Bia* Bandama* Bandama* Sassandra* Sassandra* Bandama Cavally Kan*	Rai (1974) Rai (1974) A A B B A A Chan (1973) Rubin (1968) Rai (1974)
Liberia	1	Mt. Coffee	1966	St. Paul	A
Mauritania	1	Foum el Gelta	198(?)	Gorgol	B
Nigeria	18	Bakolori Ejigbo Gusau Ikere	1975	Niger* Aro Sokoto Ogan	A, E Sargent (1979) A A A A

A = World register of dams (1977)

B = Water power (1966-1983)

x = Fleuves possédant plusieurs barrages

xx = Tous les barrages ne concernent que le fleuve Congo-Zaire et ses affluents

All dams concerned were constructed on the Zaire (Congo) and its tributaries

Barrages de l'Afrique de l'Ouest et du Centre

West and Central African dams

(PNUE/UNEP, 1985)

3.3.4 Construction on the beach

The coastline is subject to natural fluctuations due to variations in sediment transport, both in terms of quantities and direction.

The location of roads or buildings or facilities very close to the shoreline, interferes with these natural fluctuations especially in areas in the more arid northwestern and southern fringes of the region where normally mobile dunes are formed. This may lead to decreased sediment supply to the shore and consequently erosion is either induced or accelerated.

Throughout the region, coastal towns are the most developed because of the history of early Arab and European contact and the still relatively easier access to and from the outside world afforded by their location on the coast.

As a result, the location of residential, commercial, educational and military buildings and installations on or near the beach is high. The situation is the same whether in Dakar and Rufisque (Senegal) (Photo Fig. 3.12), Monrovia (Liberia), Banjul (Gambia), Port-Bouet (Cote d'Ivoire), Lagos (Nigeria), Lome (Togo), Keta (Ghana), etc.

In the oil producing countries such as Nigeria, Cameroon, Gabon and Angola, most oil export handling facilities, e.g. tank farms, pipelines, etc. have been constructed on the coast and constitute artificial perturbations in a natural dynamic system. In these countries also, a network of canals for hydrocarbon exploitation and transportation, on or near the coast, constitute a visible structural modification of the coastal zone that has negative effects on coastline migration (Ibé, in press).

One offshoot of the erosion engendered by these constructions on the coast is the attempt at protecting them with a variety of coastal defense measures such as stone and concrete revetments, seawalls, etc. (Photo Fig. 3.13). Very often, such longitudinal protective structures increase wave reflection and scouring effects and therefore exacerbate rather than ameliorate the erosion problem they were designed to solve.

3.3.5 Devegetation

Vegetation cover plays a very important role in the protection of coastal sediments by physically binding and colonizing them. Increased clearing of coastal vegetation at construction and mining locations or for establishment of settlements or agricultural farms leads to increased surface run-off and makes the exposed area more vulnerable to mass movement and to erosion by winds, currents and waves.

In a study of this impact in the Awoye and Molume areas of the Niger Delta in Nigeria, Ibé et al. (1985) found that the progressive decimation of the primeval mangrove forest along the shorelines as well as the overgrazing of the derived grassland, have accelerated the erosion rate in these areas. In Guinea, erosion is gnawing away at areas where mangroves are being destroyed (UNEP, 1985a).

Salt extraction in mangrove areas has promoted erosion as it results in a large-scale destruction of the vegetal cover. According to Paradis (1979), this salt mining started in eastern Ghana during the 17th century and is still in progress today. Among coastal vegetation, the mangrove provides a very effective defense against erosion of the sediment in which they grow. This is because the mangrove builds itself a stabilizing raft to adapt to its habitat in mechanically weak silt. The network of aerial roots is particularly effective in stabilizing unconsolidated sediment, and damping tidal and wave generated currents in addition to trapping sediments which would otherwise be transported away from the shore.

There is, however, very big pressure on the mangrove forest. The trees are felled for wood construction and for a variety of purposes: staking out fish traps, tying up boats, cooking, building traditional ovens, etc. Erosion therefore results wherever the mangrove has been cleared.



Fig. 3.12. - Constructions sur le haut estran à Rufisque (Sénégal)
(Quélenec, 1984).

Fig. 3.12. - Constructions on the bach-shore at Rufisque (Senegal)
(Quélenec, 1984).

Fig. 3.13. - Revêtement en gabion d'un haut estran de plage au Libéria
(Ibé).

Fig. 3.13. - Revetment with gabions on the upper beach face in Liberia
(Ibé).



In Mauritania, Guinea, Sierra Leone, Liberia, Togo, Angola, etc., open peat mining in littoral zones also contributes to destroying vegetation and concomitant coastal erosion.

3.3.6 Oil and gas exploitation

A new factor that is fast becoming important in the erosion problem of the region is the exploitation of petroleum. This effect will be more so in those countries that have produced oil for some time.

Nigeria, Cameroon, Gabon and Angola are recognized oil producers. Other countries such as Ghana, Cote d'Ivoire and Benin have joined the league and geophysical indications from other countries in the region indicate other prospective producers. By far a greater percentage of present production comes from oil fields either on or very near the coast as well as on the nearshore continental shelf, both of which are fragile zones.

The impact of oil exploitation is mostly through the initiation or exacerbation of subsidence in the fragile coastal zone. The subsidence phenomenon associated with the withdrawal of fluids has been described by Cooke and Doornkamp (1974, pp. 170-171) among others. The main effect of fluid extraction is the reduction of fluid pressure in the reservoir thus leading directly to an increase in the "effective stress" (or grain to grain stress) in the system. Compaction results and the sedimentary basin subsides. The subsequent progressive inundation of the coastline results in accentuated erosion.

In a study of this impact in Nigeria, Ibé (1985, 1986) and Ebisemiju (1985) consider the withdrawal of oil and gas from the porous and largely unconsolidated reservoirs in the Niger Delta as contributing to an acceleration of natural subsidence of that delta and to the significant erosion problems experienced there.

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4. COASTAL INVENTORY, MONITORING AND CONTROL OF COASTAL EVOLUTION

Because of the very great diversity of morphological formations to be found along the coasts of West and Central Africa, and because of the variety of natural and human parameters that condition coastal changes at the local level, it is virtually impossible to propose a list of detailed operations that could be applied directly to the study of a specific stretch of coast.

Consequently, what follows is no more than a general guide of priority measures, some of which will have to be modified, in order to take account of local environmental and developmental conditions.

The proposed methodology (Quélennec, 1988b) should make it possible to gradually constitute a data base about the coast and its evolution, to acquire the basic data needed for a good understanding of the processes involved, and to pave the way for decisions about coastal protection measures in the most sensitive sectors of the coast.

4.1 COASTAL INVENTORY

4.1.1 Objectives

The WACAF/3 project has made it possible to draw up an inventory of coastal erosion problems in West and Central Africa. The phenomena that were identified pertain especially to coastal zones of major socio-economic importance, where data were available and where immediate protection measures seemed necessary (UNEP, 1985).

Other non-identified littoral sectors of the region are or will be subject to coastal erosion. The preparation of land development policies and of investment plans is a stimulus to continue the effort undertaken by national and international teams on the occasion of the WACAF/3 project.

A logical sequel to this effort would be the drawing up, within each country, of a coastal inventory. Such an inventory would have as its main objectives:

- the description of the sedimentary environment (morphology, sedimentology) of the coast, and of its evolution;
- the identification of sensitive zones, and the evaluation of consequences of erosion;
- the preparation of coastal development and protection decisions.

The dynamism generated by the WACAF/3 project speaks in favour of opting for an inventory methodology common to all countries of the region.

This kind of regional approach was accepted by consensus by the countries of the European Community: in connection with the "CORINE coastal erosion" project, set up for the purpose of providing a scientific base of information for assessment of problems connected with the risk of coastal erosion, the 11 coastal countries of the European Community (from Denmark to Greece) decided to adopt a common methodology, based on the following principles (Quélennec, 1987a):

- breakdown of the shoreline into coastal segments;
- characterization of these coastal segments according to two groups of criteria: morphology/sedimentology and evolutionary trends;
- more detailed characterization of the environment of coastal segments subject to erosion, and evaluation of the causes and consequences of regressive evolution.

Application of this methodology to the countries of West and Central Africa would require a number of modifications, which are suggested below (Quélenec, 1988b).

4.1.2 Identification of coastal segments

This first phase consists in breaking up the coast of each country into a continuous sequence of contiguous and homogeneous littoral segments, in accordance with a morpho-sedimentological classification (Para. 4.1.3).

In the countries of the European Community, this phase, which was prepared by compiling the available data and information (aerial photographs, annotated maps, theses, reports) and then filling in the gaps by field surveys, ends with the coastal segment extremities being plotted on 1:100,000 topographic survey maps.

In West and Central Africa, in view of the scale disparities of the topographic maps available in the various countries, it would very probably be impossible to adopt the same cartographic scale for all the countries of the region: the choice would have to be made in the range 1:50,000 to 1:200,000 country by country, depending on the scales of existing maps of littoral zones.

4.1.3 Classification of morpho-sedimentological units

The following classification, which was inspired by that used by the European Community countries, allows for rapid identification, with no measurements, and for codification of the type of littoral environment, segment by segment.

Facies:

- (A) Solid rocks and/or cliffs made up of material not prone to erosion.
- (B) Conglomerates and/or solid cliffs made up of material prone to erosion.
- (C) Pocket beaches separated by rocky points.

(D) to (F) Extended beaches, with shores consisting mostly:

- (D) of coarse sediments: from gravel to shingle;
- (E) of sandy sediments: fine to coarse sands;
- (F) of cohesive sediments: silts and muds.
- (G) Sandy sedimentary structures of the littoral strand or sandy spit type.
- (H) Tombolo.
- (I,J,...) To be defined.

Shores:

- (a) Presence of a rocky flat on the intertidal shore.
- (b) Presence of beach-rock on the intertidal shore.
- (c) Presence of mangrove on the intertidal shore.
- (d) Presence of dense vegetation on the upper shore.
- (e,f,...) To be defined.

Human intervention:

- (0) Natural undeveloped coastal segment.
- (1) Coastal segment protected by longitudinal defensive works.
- (2) Coastal segment protected by transversal defensive works (groins).
- (3) Artificial beach.
- (4) Coastal embankment.

- (5) Polder.
- (6,7...) To be defined.

Thus each coastal segment can be characterized by the appropriate combination of the above three codes. For instance, a segment coded E/a/0 represents an extended sandy beach, with a rocky flat on the intertidal shore, and with no coastal protection works (natural beach).

4.1.4 Evolutionary trend of the coast

The evolutionary trend is a fourth family of codes, which supplements the codification of each coastal segment, as follows:

- (1) Lack of information about the evolution of the coastal segment.

Stability:

- (2) Evolution not evident on the human time scale.
- (3) Occasional small variations about a point of equilibrium.

Erosion:

- (4) Probable but not documented: data not available.
- (5) Confirmed: data available.

Accretion:

- (6) Probable but not documented: data not available.
- (7) Confirmed: data available.

Thus a segment coded Ea0/5 represents an extended sandy beach, not developed (no protective works), with a rocky flat on the intertidal shore and subject to erosion (data available).

4.1.5 Practical execution of the inventory

The coastline is broken up into homogeneous coastal segments, on the basis of the classification of morpho-sedimentological units (para. 4.1.3). Each coastal segment is identified on the reference topographic survey map by a number. The numbering of segments is continuous and progressive, with the numbers increasing from right to left as one looks at the sea.

The identification of a coastal segment on the reference map (for example, 1:100,000) is carried out by positioning the extremities of the segment on the trace of the line of the coast. This positioning can be done, at least on a provisional basis, by interpreting aerial photographs, maps (topographic, geological) and other available documents.

The definitive positioning of the endpoints of coastal segments is obtained after a field trip, which also makes it possible to determine the morpho-sedimentological code to be attributed to each coastal segment. The first two parts of this code (facies, shore) are essentially definitive in the short term for a given segment. It is only the third part of the code (human intervention) that may change with time, as development and protection works are carried out.

The codification of a coastal segment's evolutionary trend is strongly dependent on the availability of data:

- in the first stage of identification, the "evolution" code of a segment that has not previously been studied can be determined only after an expert has visited and surveyed the area, and rendered his judgement;

- in the case of inhabited littoral zones and/or zones with difficult access, it will be necessary to compare aerial photographs taken on different dates;

- a preliminary study of such photographic documents, when they are available, leads to better preparation of field visits and surveys, and to concentration of such efforts in the field on the most sensitive zones;

- it is only at a later stage (Para. 4.3) that additional surveys and measurements will be taken, with a view to understanding the processes involved, assessing their causes and consequences, and proposing protection and development works.

4.1.6 Littoral data base

The methodology described above allows for the gradual constitution of a littoral data base, which can be entered and managed on a micro-computer, like the "CORINE coastal erosion" data base prepared for the European Community by BRGM (*).

In fact, each coastal segment:

- bears a unique identification number (e.g. 034);
- is located on a reference topographic survey map, so that its endpoints are known in (X, Y) co-ordinates;
- is characterized by two attributes (e.g. Ea0/5).

Digitization of the line of the coast, after it has been broken up into coastal segments, makes it possible to associate with each coastal segment:

- a cartographic representation of the coastline;
- the previously defined attributes: morpho-sedimentological code and evolutionary trend code;
- additional attributes to be defined later.

There are many advantages to having such a computerized littoral data base:

- it can be easily displayed and updated;
- it can be built up gradually by adding new attributes that are characteristic of coastal segments and their environments: numerical data on the slope of the beach, the granulometry of sediments, changes in beach profiles, etc., factual data on land utilization in the inland beach zone, on damage caused by storms, etc.;
- in conjunction with appropriate software, it facilitates drawing thematic maps and computing statistical information: coastline lengths, percentages of coasts that are rocky, sandy, being eroded, etc.

(*) BRGM: Bureau de Recherches Géologiques et Minières (France)

Moreover, a littoral data base acts as an incentive tool for the teams carrying out the coastal inventory, and a management tool for developers and decision-makers: in order for it to fulfill this dual role, it is desirable that the data base be simultaneously available at the level of national management and decision structures (ministries), and decentralized to the level of administrative regions.

When the data base is being established, it is desirable to draw up, at the same time as the coastal inventory, a national inventory of data and information sources contributing to characterization of the coast and its evolution: aerial photographs, maps, measurement campaigns, town planning documents, study reports, theses, scientific publications, etc. This inventory must include summary descriptions of the contents of the documents, their location, and also identification of the coastal segments covered by the documents.

4.2 NETWORKS FOR MEASURING TIDES AND SWELLS

Knowledge about level variations and the state of the sea is an essential component of management and development of coastal areas.

Information gathered in connection with the WACAF/3 project has shown that available tide and swell records are insufficient for a good understanding of the marine hydrodynamic balance on the coasts of West and Central Africa, and that access to measured data is often difficult.

Hence it is important to improve the measurement networks, as well as the data storage and processing procedures.

4.2.1 Tidal measurements

4.2.1.1 Measurement networks

Measurements are taken at some thirty major ports in West and Central Africa.

In these ports, since the beginning of the observation period, the tide has been measured by various means: graduated tidal staffs, and floater, bubble or pressure tide recorders.

Many of the series have been interrupted for several years in a row, because of absence of observers, mechanical breakdown of recorders, or transformation and enlargement of port areas, resulting in displacement of the recorders.

For all these different reasons, port authorities are not very interested in pursuing tide record measurements, once an analysis of sea level records over several months or years has made it possible to estimate the tide's harmonic constants, needed to predict the astronomic tide and to publish tide tables.

As a result, tide record series available in the region do not lend themselves to a regional statistical analysis of secular variations in the average sea level, or an analysis of level rises caused by atmospheric factors (pressure and wind), which are essential components, that must be taken into consideration in coastal development and protection projects.

The tide recording station at Takoradi (Ghana) is the only one in the region providing long data series; regular measurements have been taken since 1929, with just a few interruptions (Fig. 2.10).

Hence it is very important to ensure, in each of the region's large ports, unbroken tide records measured by means of reliable and modern equipment, if possible including storage in memory. The GLOSS (global sea-level observing system) project of the Intergovernmental

Oceanographic Commission (IOC) recently proposed (Unesco, 1987) that a permanent network of tide recording stations be established in the region (Fig. 4.1).

In addition to this quasi-permanent basic network, designed especially for the study of long-period components, it would be of interest to establish and to maintain a network of tide recording stations located at stable points in secondary ports, coastal lagoons and estuaries. This second order network would be aimed at allowing for regional extrapolation of data from the basic network, and local estimation of short-period components due to atmospheric and oceanographic factors; if automatic tide recorders are not available for this second order network, the tide can be observed visually by means of graduated staffs.

4.2.1.2 Setting tide gauge datum

Tidal observations must be referred to some fixed datum to be of full use. For this purpose, a bench mark is used as the primary reference point. For illustration let us consider the simplest type of tide gauge, the visual tide pole.

Depending on the location of the bench mark (BM), the number of instrument stations can be determined, e.g. if the BM is far, more stations are required.

The instruments required are an engineers level with tripod, a steel chain and two levelling staffs.

In a situation where the BM is very close to the erected tide pole as shown in Fig. 4.2.a, the following stages are followed while levelling the tide pole.

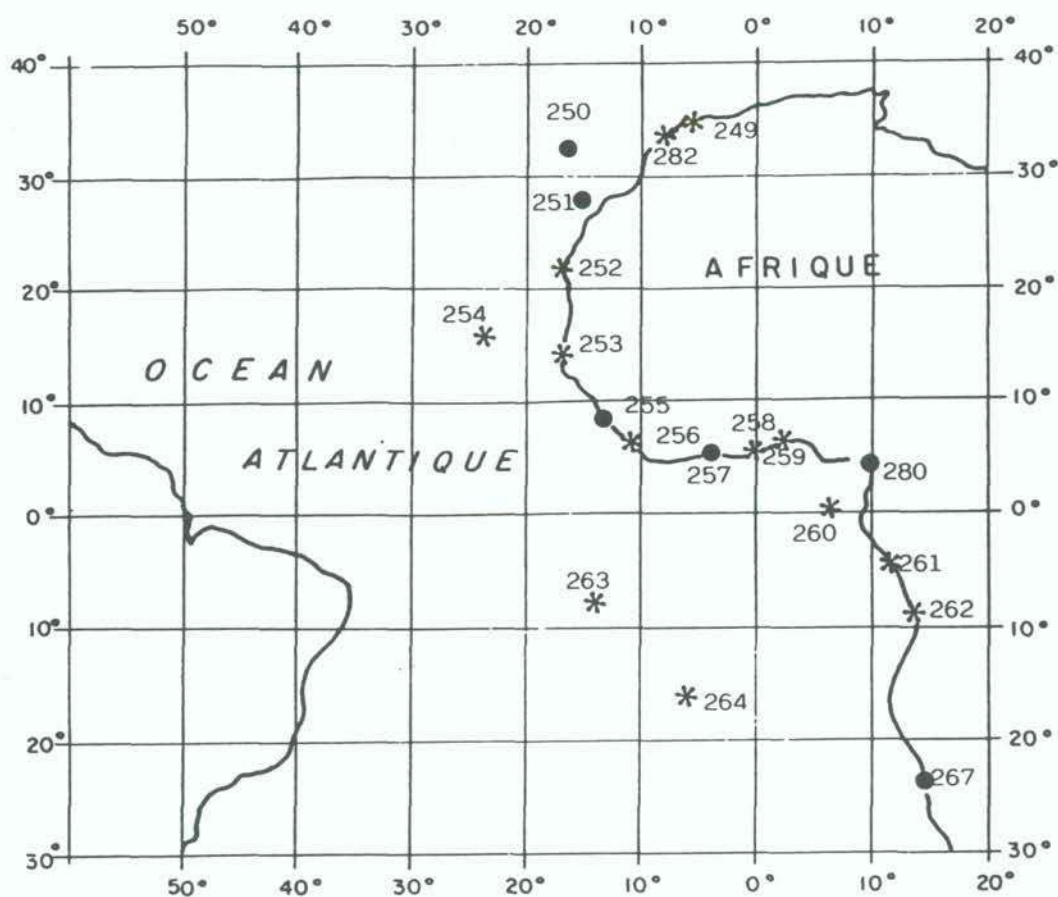
- 1 - Set up and level the instrument close to the bench mark,
- 2 - Put a levelling staff on the BM as well as on the erected tide pole,
- 3 - Read off levelling staff on BM, as a_m ,
- 4 - Read off levelling staff on tide pole, as b_m .

The computational procedure based on Fig. 4.2.a is as follows:

- 1 - Elevation of top face of tide pole (i.e. from top of BM upward)
 $= a - b$
- 2 - Elevation of BM with respect to ordnance datum
 $= x$
- 3 - Elevation of BM with respect to chart datum
 $= x + y$
- 4 - Height of tide pole with respect to ordnance datum
 $= x + y + (a-b)$
- 5 - Zero of tide pole = $[x + y + (a-b)] - \text{length of tide pole.}$

Result (5) must be subtracted from readings obtained on the pole. If the BM is a considerable distance from the tide pole, then the levelling between the two points will need to be done in a number of stages (see Fig. 4.2.b). The procedure is to:

- 1 - Set up and level instrument between BM and first staging point, i.e. position 1
- 2 - Set up levelling staff on BM and position 1
- 3 - Read off staff on BM as backsight, say a



* stations proposées - proposed stations
o stations en opération - stations in operation

<u>GLOSS n°</u>	<u>GLOSS station</u>	<u>Données marégraphiques disponibles</u> <u>Sea-level data holdings</u>
249	Ceuta (Espagne)	1944-1964
282	Tan Tan (Maroc)	1957-1959
250	Funchal (Portugal)	1093-64 1976-78 1981-82
251	Las Palmas (Espagne)	
252	Nouakchott	
253	Dakar (Sénégal)	1942-45 1952-53 1958-66
254	Porto Grande (Cape Verde)	1947-1950
255	Conakry (Guinée)	
256	Aberdeen Point (Sierra Leone)	Freetown 1926 (new gauge expected soon)
257	Abidjan (Côte d'Ivoire)	1971 1974-76
258	Tema (Ghana)	Takoradi 1929-1985
259	Lagos (Nigéria)	
260	Sao Tome (Sao Tome and Principe)	
261	Pointe Noire (Congo)	1959-60 1977-79
262	Luanda (Angola)	
263	Ascension (U.K.)	
264	St Helena (U.K.)	
280	Douala (Cameroun)	

Fig. 4.1. - Stations marégraphiques proposées pour le projet GLOSS

Fig. 4.1. - Proposed gloss sea-level stations

(UNESCO, 1987)

- 4 - Read off staff on position 1 as foresight, say b
- 5 - Move (transit) the instrument to a new position forward (as shown on the diagram)
- 6 - Chose a new staging point, say 2, ahead of the instrument
- 7 - Repeat (3) and (4) above
- 8 - The above is repeated along the route to the tide pole until the forward staff is on the tide pole

The elevation of the tide pole with respect to the BM is
$$= (a-b) + (c-d) + (e-f)$$

All other computational procedure is the same as in Fig. 4.2a.

For other types of tide gauges the procedure is basically the same except that one has to carry out additional observations, e.g. for float operated tide gauges; it is necessary to accurately determine the level of the water in the stilling well referred to the datum (BM) and then set the gauge to this reading.

4.2.1.3 Extraction of levels: statistics

A typical strip chart showing 24-hour gauge drum recordings for 7 days at a tidal station is shown in Fig. 4.3.

The extraction of the heights of low water and high water each day, and averaging the findings over a month and year, ensuring equal numbers of each, produce "mean tide levels" (Unesco, 1985).

The extraction of hourly heights and averaging the results over a period of a month and a year, produce "mean sea level values" (Unesco, 1985).

The extraction of hourly heights fully corrected for gauge time and height errors over a long period, can be used for:

- full tidal analysis,
- mean sea level statistics,
- tidal regime studies.

Alternatively, the same result can be achieved through a filtered average of 3-hourly readings (Z0 filter) or filtered average of hourly readings (X0 filter).

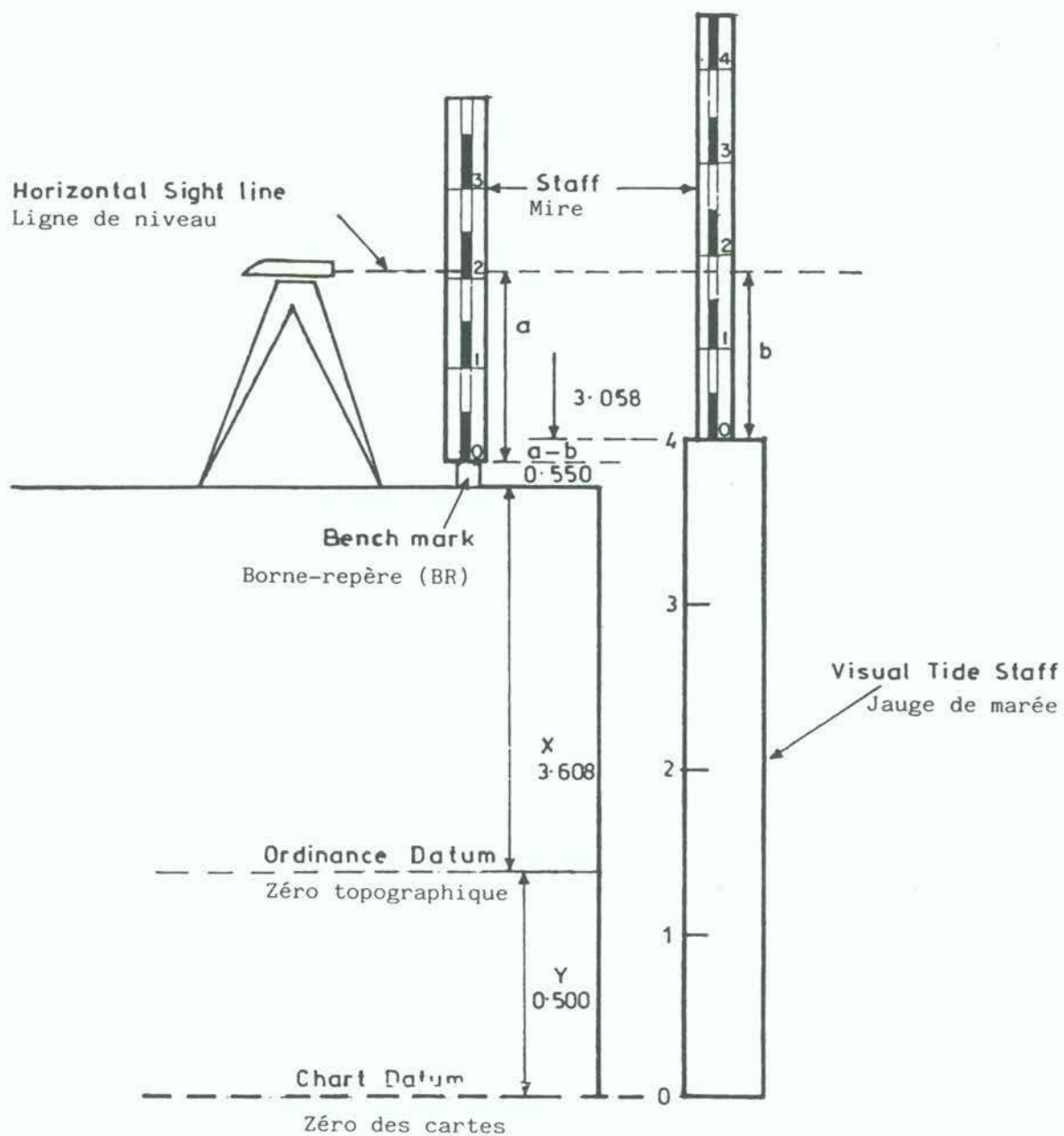
These alternative methods of obtaining sea level statistics normally require some form of computing facility for easy application. The most commonly used filter to compute mean sea level is the Doodson X0. The reader interested in these techniques is referred to the Manual on Sea Level Measurement and Interpretation (Unesco, 1985).

4.2.1.4 Processing tide record data

Among the main factors responsible for sea level variations at a given station, we list the following, in order of importance:

- the astronomic tide: periodic components,
- atmospheric effects: pressure, wind,
- oceanographic effects: currents, temperature, salinity,

(a)



(b)

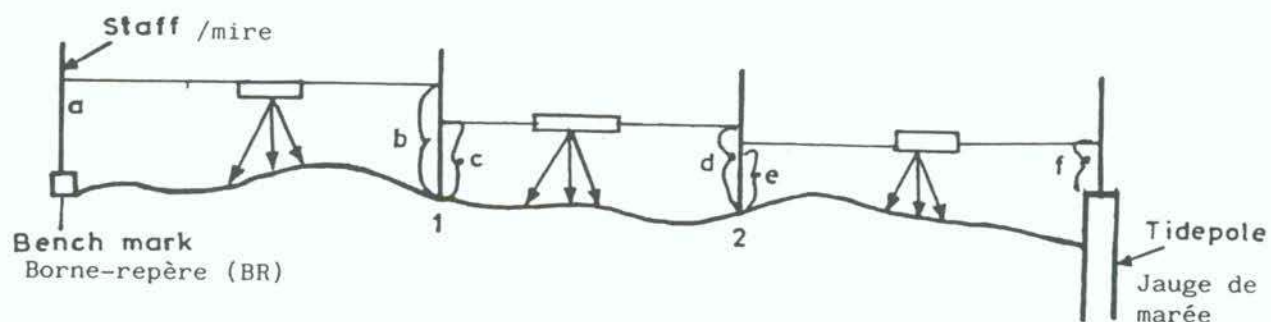


Fig. 4.2. - Détermination de l'altitude d'une jauge de marée
a/ quand la BR est à proximité
b/ quand la BR est éloignée

Fig. 4.2. - Determining the altitude of a visual tide pole
a/ when BR is close
b/ when BR is far away

- eustatic effects: variation in the volume of seas and oceans,
- tectonic effects: uplifting, subsidence.

Eustatic and tectonic effects result in variations of small amplitude (several tenths to several mm per year), which can be brought to light only by analysing long series of tide record data, available over several decades, after filtering out the short period and large amplitude components.

Among the latter components, sea level rises due to atmospheric effects (sea level set-up) are of prime interest to the designer of coastal works.

On a tide record, the excess sea level (set-up) at time (t) can be estimated, as a first approximation, by the positive difference between the amplitude of the observed tide and that of the theoretical astronomic tide.

By analysing a long series of tide record data by this method, one obtains a sample of excess sea levels as estimated. By selecting levels above a given threshold, one extracts from this sample a sub-set of values of independent (not self-correlated) excess sea levels. One then looks for the statistical law that fits these values best, in order to deduce from it statistical estimates for annual, decennial and centennial excess sea levels (Fig. 2.12).

Since the amplitudes of atmospheric excess sea levels vary significantly from one littoral site to another, as a function of the site's morphology and bathymetry, it is easy to understand why it is necessary to have many tide record observation locations along the coast.

4.2.2 Swell measurements

4.2.2.1 The importance of understanding the swell

Off-shore swell is characterized by 4 basic parameters: amplitude (H), period (T), wavelength (L) and direction of propagation (a).

Since the natural swell is often complex, consisting of trains of successive waves with different periods and amplitudes, it is generally characterized by means of the following parameters, estimated on the basis of swell measurement records:

$H_{1/3}$ or H_s = significant amplitude (or height): average of the upper third of recorded heights;

$T_{1/3}$ or T_s = significant period: average of the periods of the upper third of recorded heights;

H_{max} , T_{max} = maximal recorded amplitude and period.

The transfer of swell energy characteristics from the open water to the coast is done on the basis of refraction models. This transfer can only be done if one knows the directional distribution of the energy in open water, which implies knowing the frequency distribution of amplitudes and periods by direction of propagation.

The design and sizing of coastal protection works and harbour infrastructures presupposes knowledge of the swell characteristics previously defined (H, T, a).

The risk of a work being ruined is a function of the maximal characteristics of the swell (H_{max} , T_{max}), but also of the duration of action of maximal swells for a given direction.

It is usually the last two parameters that are least well known (direction, duration of action), because they are not available from conventional swell recording systems.

4.2.2.2 Methods for measuring the condition of the sea

Visual observations of the condition of the sea are generally made from lighthouses, signal stations, harbour master posts or selected ships. One of the main points of such observations is to obtain information about the swell direction. The drawbacks include the following:

- estimates of the swell amplitude and period are approximate;
- observations are rarely made at night;
- the reliability of observations, which is a function of the observation site and the observer;
- underestimation of strong swells when using statistics drawn from observations made by selected ships, because such ships often seek shelter when storms are high.

The main types of recording instruments used to measure swell (H, T) are the following:

- swell rods, usually installed close to shorelines or in harbours, and based on the principle of the resistive or capacitive effect;
- ultrasound swell recorders lying on the sea bed, which determine the height of the water by measuring the time of propagation of a wave between the surface and the bottom;
- pressure swell recorders lying on the bottom of the sea, which make it possible to estimate pressure variations due to the swell;
- floating buoys, such as DATAWELL, ENDECO, NBA, NEREIDES, which make it possible to estimate swell characteristics from the accelerations induced by oscillating movements of the surface.

Pressure and ultrasound swell recorders, lying on the bottom of the sea, have the advantage of not being visible, which shelters them from acts of vandalism, and of not being greatly influenced by storms. On the other hand, as they are usually installed at depths of 10 to 20m, and connected with the land by cable for transmission of information, they run the risk of being caught up in fishermen's nets.

Floating buoys for measuring the swell are, by contrast, exposed to the action of high storms and to vandalism. The information can be transmitted to a land-based receiving station by radio link or through a satellite link (ARGOS, METEOSAT) (Quélenec, 1984).

The conventional measuring systems enumerated above provide no information whatsoever about the swell's direction of propagation. This parameter is available only from directional swell measuring buoys (such as WADIBUOY or WAVEC), when the swell direction is estimated from the course of the buoy and the slopes of the water surface.

4.2.2.3 Measurement networks

Most of the harbour projects carried out in West and Central Africa have been associated with swell measurement campaigns, employing quite different methods and equipment. In most cases, the duration of such campaigns has not exceeded several months to one year: see, for example, Fig. 4.4, which presents the results of measurements at Rio Nunez (Guinea), by means of a pressure swell recorder.

The main disadvantages of such measurement campaigns are the following:

- short duration of the observation period, which does not provide grounds for an accurate estimate of swell characteristics (H, T) for long return periods: 20, 50, 100 years;

- non-observation of swell propagation directions, which leads to considerable imprecision in the result of simulations of the swell energy transmitted to the coast.

The advantages of gradually setting up such measurement networks should not allow one to forget the usefulness of visual swell observation campaigns carried out from the shoreline (para. 4.3): when there is a dearth of swell recorders, such campaigns are the only way of acquiring data on the coastal swell balance, and of drafting preliminary plans for coastal protection projects.

The above considerations show that it is necessary to encourage and to assist the maritime authorities of each country to acquire, in particular when harbour development and renovation works are being carried out, non-directional swell recorders to be implanted for 3 to 4 years off the shores of sensitive coastal zones, in order to add to our knowledge of the swell's balance and characteristics (H, T) in the region.

4.3 PROGRAMME FOR ACQUIRING DATA ON SENSITIVE LITTORAL ZONES

4.3.1 Objectives

The coastal inventory exercise described in Paragraph 4.1 makes it possible to identify a set of coastal segments that are considered, on the basis of a first analysis, as subject to erosion, and hence representing sensitive littoral zones.

The decision to invest in protecting these zones from the action of the sea, or in developing them, is generally taken only after more basic data have been obtained, and have made it possible to determine the causes, characteristics and consequences of the processes involved, and to design protection solutions and development projects that are well suited to the littoral zone in question.

The objective of the monitoring programme proposed below is to provide designers of coastal engineering works and decision-makers with a front line data and information base, in order that they be in a position to appreciate the degree of sensitivity to erosion of littoral zones, and to choose a coastal protection policy, with actual works as required.

The priority aspects of the programme involve techniques that are simple and well suited to the monitoring of erosion-prone coastal zones in the West and Central African region. Naturally, it will have to be adapted to make allowances for the specific characteristics of each littoral site, and for the human and technical resources available for studies.

The design and the detailed sizing of coastal protection works may require, depending on the circumstances, collecting supplementary (geotechnical, hydrodynamic, bathymetric, seismic, etc.) data, as a function of the complexity of the processes involved, and of the type and size of the works to be carried out.

4.3.2 Preliminary surveys

Their objective is to identify, when prior measured data are not available, the littoral segments that are most prone to erosion: it is along these coastal segments that the measurement campaigns proposed in the following paragraphs will be carried out on a priority basis.

In order to achieve this objective, one tries to obtain from users of the coastal area, from the local population and authorities, information about the causes, the extent and the consequences of coastal erosion processes identified on a given littoral segment.

PERIODE DU 13-10-56 AU 24-10-57

80 JOURS D OBSERVATION - 0 JOURS DE CALME PLAT ($H_{max} < 0.25m$)

PERIODES ANALYSEES

13-10-56 AU 16-10-56

25- 8-57 AU 12- 9-57

1- 7-57 AU 16- 7-57

18- 9-57 AU 19- 9-57

19- 7-57 AU 30- 7-57

11-10-57 AU 24-10-57

30- 7-57 AU 23- 8-57

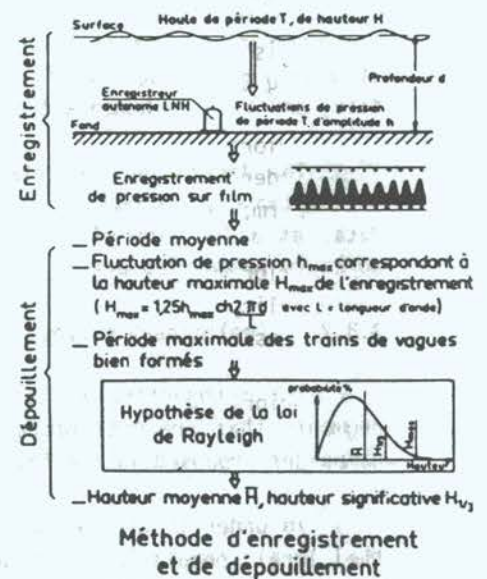
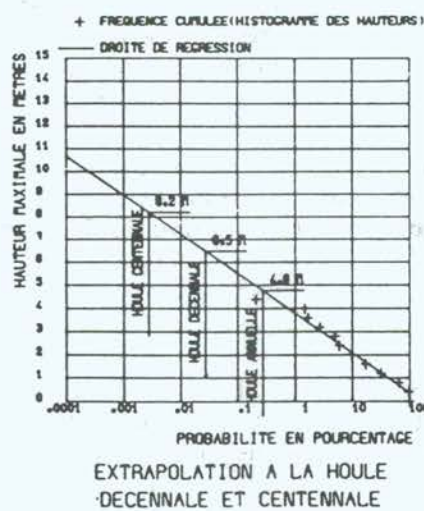
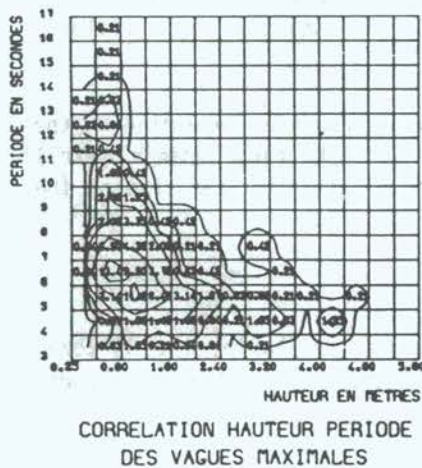
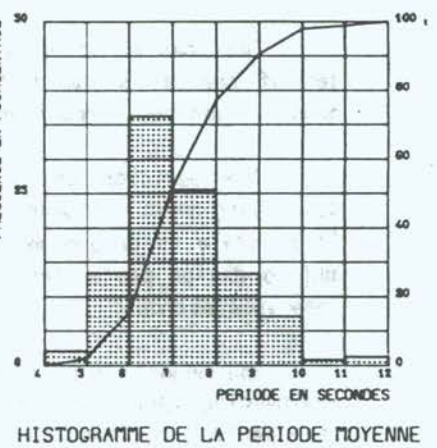
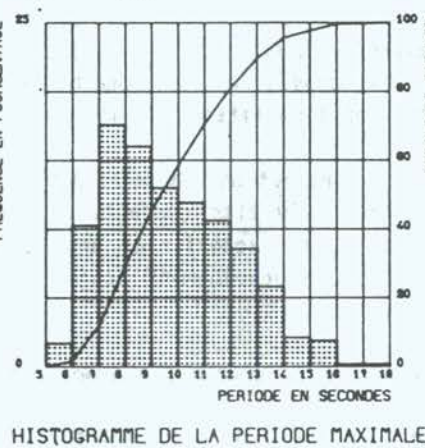
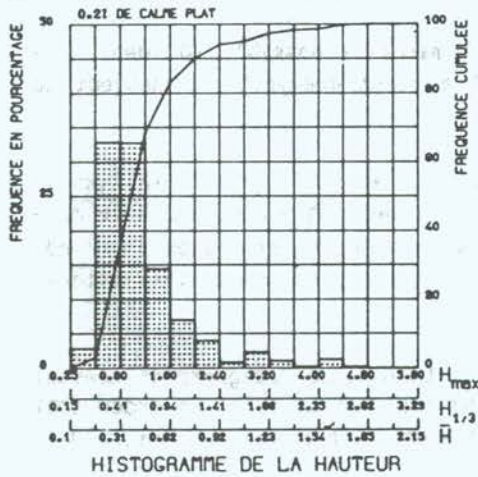
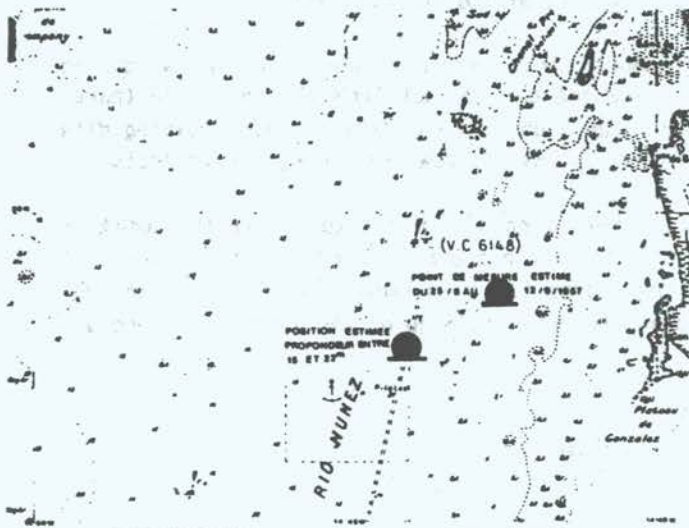


Fig. 4.4. - Statistiques de la houle mesurée à Rio Nunez (Guinée)

Fig. 4.4. - Wave statistic at Rio Nunez (Guinea)

In the course of field surveys, one tries to obtain answers to the following questions from different sources:

- Since when has coastal erosion been evident?
- What objective data (facts) can be used to assess the occurrence and the significance of erosion phenomena?
- Is the regressive change in the shoreline slow and gradual, or does it manifest itself in a drastic way, for instance at times of high storms?
- What are the known dates and characteristics of the highest storms recently observed, and what damage did they cause?
- Are there cyclical phases of shoreline advance and retreat?
- What is the average shoreline retreat, as an order of magnitude (m/year)?
- Is any information available on human intervention in the coastal segment under study and in neighbouring segments: extraction of marine sand, construction along the coast, opening or closing of outlets, etc.?

The information collected through such surveys is marked on separate data sheets for each sensitive coastal segment, with the expert adding his own field observations. Photographs of remarkable phenomena and sites noted in the coastal segment in question are appended to the file, in order to serve as reference documents for subsequent comparisons.

On the basis of this preliminary information, which will vary greatly in quantity and quality from one coastal segment to another, the expert will try to answer the following questions:

- Is it likely that the regressive trend of the littoral segment will continue in the future? Possible responses: not probable, probable, impossible to judge without additional data.
- In the event that the regressive trend does continue with the same order of magnitude of average shoreline retreat (m/year), what would be the possible socio-economic consequences (estimate of cost of damages) in 1 year, 5 years, 10 years?

This new information is then used to classify erosion-prone littoral segments into the following 3 main categories, according to the urgency of intervention:

Priority 1: coastal segments where coastal defence works must be carried out rapidly, in order to protect socio-economic property viewed as important and threatened in the short term;

Priority 2: coastal segments whose evolution must be better understood before a protection policy decision is taken, because the risk of occurrence of significant damage due to erosion is considered low or acceptable in the short term;

Priority 3: coastal segments where the regression of the shoreline is reversible or slow, and where significant damage is to be feared only in the medium or long term.

This provisional classification of sensitive coastal segments allows for more efficient deployment, over a given administrative district or country, of the effort involved in conducting data collection and coastal monitoring programmes.

4.3.3 Study of the shoreline's historical evolution

By comparing old and more recent maps of coastal regions, when such documents are available, it is possible to estimate the historical evolutionary trends of the shoreline.

For the most recent historical period, this evolution can be assessed through a comparative study of aerial photographs of the same littoral zones taken at intervals of several years or decades.

Such photographic documents are generally available for most of the coastal zones of the region of West and Central Africa (UNEP, 1985).

A convenient way of assessing the evolution of a shoreline, from a temporal sequence of aerial photographs of the same littoral zone, is to work with paper prints that have been blown up to the same scale. The practical enlargement factor, which depends on the quality of the original aerial shots, varies from 3 to 5, which means that one can generally work with photographic documents that have been blown up to a scale of 1:5,000 or 1:10,000.

In littoral zones where the tidal range is considerable, and where the slope of the beaches is gradual, it is preferable to follow the evolution of one of the characteristic morphological features of the inland beach (offset, line of vegetation, etc.), rather than that of the sea-beach interface, which varies as a function of the tide and the condition of the sea.

By transferring these morphological features from one document to another, after correcting any residual distortion factors of the enlarged photographs, it is possible to obtain objective grounds for estimating the evolution over time of the shoreline of a coastal segment, which adds to the information obtained through field surveys.

4.3.4 Measuring beach profiles

4.3.4.1 Objectives

Through regular measurement of a series of (transversal) beach profiles in a given coastal segment, it is possible to assess the segment's behaviour under the influence of hydrodynamic agents (waves, currents, tides, winds).

Provided such measurements are continued for a sufficiently long period of time (one to several years), and provided there is a simultaneous programme for measuring the hydrodynamic agents (see Para. 4.3.5), one obtains the basic information needed to do simulation on (mathematical or physical) models of sedimentary exchange processes, and to decide on appropriate protective works.

For a good understanding of longitudinal and transversal sedimentary exchanges in a given coastal segment, it is recommended:

- that profile measurements simultaneously encompass the entire exposed and underwater parts of the beach (see Para. 2.3);
- that distances between profiles be as short as possible;
- that the frequency of measurements be high;
- that the coastal segment be defined in such a way that the lateral sedimentary exchanges at the segment's extremities are known or non-existent.

In practice, one strives to respect these principles as much as possible, depending on the means available.

4.3.4.2 Exposed beach profiles

Each beach profile, oriented at right angles to the shoreline, must be marked by two fixed reference posts or staffs (Fig. 4.5), related (through X and Y co-ordinates and altitude Z) if possible to the local geodetic and topographic system.

Depending on the lateral extension of the segment and its morphology, the distance between profiles can vary from several dozen to several hundred metres.

Measurements are generally taken every week or every month, with additional measurements, in the latter case, after each storm whenever possible.

To the extent possible, beach profile measurement campaigns are conducted with the help of topographic instruments such as a distance metre, a theodolite (Photo Fig. 1.14) or a level, which allow for rapid and accurate measurement by a team of two: a beach profile can be measured in less than half an hour.

4.3.4.2.a Beach profiling with a level

For profiling with a level, the following are required:

- engineers level with tripod,
- 1 levelling staff,
- 100 m steel tape.

The levelling is carried out along a profile line. The profile line should be a straight line at right angle to the coast and should be controlled from a fixed station (bench mark) whose height has been determined. The levelling procedure for the profile line is as follows:

- 1 - Place the level approximately half-way between the backsight staff (which is on the bench mark whose height is known) and the foresight staff (ahead of the level).
- 2 - Level the instrument using the appropriate knobs.
- 3 - Read off backsight staff (backsight = a on Fig. 4.5);
- 4 - Transit to foresight and read off staff (as b on Fig. 4.5);
- 5 - Measure the distance between A and B using steel tape;
- 6 - Keeping the foresight staff on the same position, move the instrument ahead of it so that position B now becomes backsight while a new foresight position is established;
- 7 - Repeat steps 2 to 4;
- 8 - This procedure is continued along the same straight line until the last profile point is reached - which is usually some safe distance into the water.

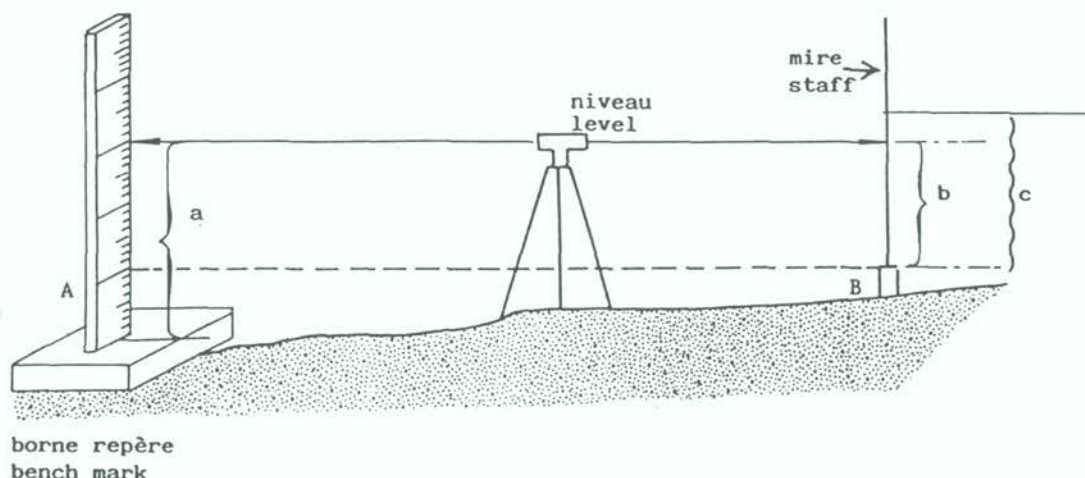


Fig. 4.5. - Mesure du profil de plage à l'aide d'un niveau

Fig. 4.5. - Beach profiling with the aid of a level

It is pertinent to note the following:

- In order to eliminate collimation error, the level should preferably be at equal distance to the forward staff and backward staff.
- The instrument should always be levelled along the profile line before any reading is taken.
- Features along the profile line should be noted, e.g. berm, high water line, low water line.

There are basically two booking and computational methods, viz: "rise and fall" method and height of collimation method, the simplest being "rise and fall" method which is described below.

Station	Backsight	Foresight	Altitudes	Remarks
A	a		H_a	bench mark
B	c	b	$H_a + (a-b)$	berm
C	e	d	$H_b + (c-d)$	rock

The known altitude (i.e. fixed bench mark which is control point of profile = H_a .)

To determine altitudes of B, C etc., the general rule is to subtract the foresight reading from backsight reading and add the results to the altitude of the station at backsight (backsight station). From Fig. 4.5:

$$\text{Altitude of B (H}_b\text{)} = H_a + a - b$$

where H_a = altitude of A
 a = backsight reading of staff on station A
 b = foresight reading of staff on station B

The above procedure is followed for subsequent points whose altitudes are to be determined.

4.3.4.2.b Beach profiling without topographic instruments

When such topographic instruments are not available, profiles can be measured by means of one or the other of the following methods:

- The levelling instrument is replaced by a 1.50 m surveyor's staff placed vertically on the bench mark BR, with the observer sighting the horizon from behind the staff. The line of sight intercepts a height H on a graduated staff, which is displaced along the profile of the beach, as in classical levelling (Fig. 4.6). The distance from the stake to the observer is measured by means of a graduated tape. This simple levelling method is relatively accurate (± 10 cm for ΔH), when the measured distances and the slope of the beach do not force the observer to change position several times along a single profile, in order to be able to estimate the height of interception on a 4 to 6 m long stake, with graduations every 20 or 50 cm;

- Another solution is to materialize the profile of the beach by means of a row of galvanized steel tubes, driven vertically into the sand to a depth of 2 to 3 m, at intervals of 5 to 10 m, and protruding from the sand to a height of 2 m. The tubes can be driven into the sand with a pneumatic hammer on the exposed beach, or with a pneumatic water gun on the underwater beach. Topographic variations are then measured by direct reading of the distance between the sand level and the top of the tube. Such readings can be taken regularly by a single unqualified observer, on the exposed beach, but they require an equipped diver for the underwater readings. The major drawback to this simple observation system is the risk of accidents, caused by the protruding metal tubes, to users of the beach, fishermen and tourists; it can only be used with the permission of the public authorities, and with posting of very conspicuous warnings.

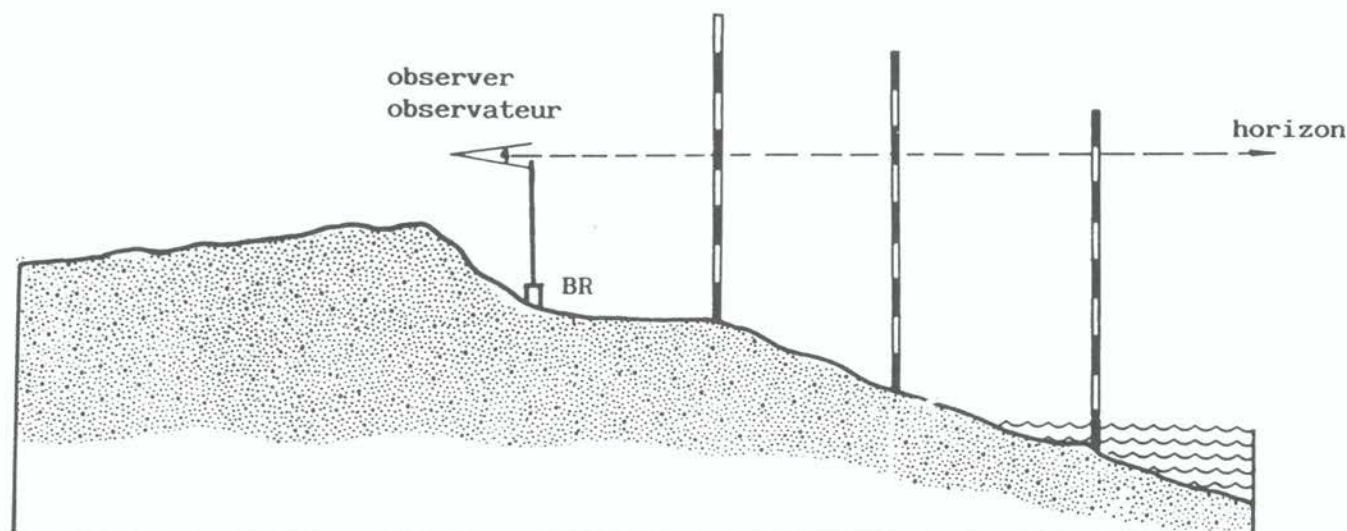


Fig. 4.6. - Mesure du profil de plage par visée sur l'horizon à partir d'un point fixe

Fig. 4.6. - Beach profiling by sighting the horizon from a fixed point

4.3.4.3 Computation of volumes

The ultimate objective of beach profiling is to enable the calculation of volumes of beach materials lost or gained over a period of time. For computation of volumes, a graph of elevation (reduced heights) against distance is plotted for each day of observations for the total number of observations (profiles). The Z scale is usually exaggerated.

The end areas method (Garner et al., 1976) can be used in computing the volume of sand between adjacent profiles and progressively for the whole beach, that is:

$$V = D (A_1 + A_2) / 2$$

where V = Volume

D = Distance between adjacent profile

A1 & A2 = Cross sectional areas of the two adjacent profiles 1 & 2.

4.3.4.4 Profile of the underwater beach

In order to understand the nearshore dynamics and how they affect beach erosion, it is necessary to continue the beach profiling under water to at least the limits of the breaking waves and better still, deeper than that. This can be achieved by fixing a portable echo-sounder on a

small boat or dinghy (preferably a rubber type), with the transducer mounted under or on the side of the boat. An echo-sounder is a simple sonar system device used for recording depths in water bodies. The echo-sounder sends a pulse through the water to the sea bed; this pulse returns to the receiver where conversion of the speed and time is made to achieve a result termed 'depth' based on the formula:

$$D = 0.5 VT$$

where V = Velocity of the pulse and is known ($V \approx 1500$ m/s)

and T = Time of travel of pulse and is known.

A portable echo-sounder can operate on a digital basis if it is so manufactured or can operate by drawing depths graphically on an echo roll.

When an echo-sounder is mounted and is ready for use, the following tests should be carried out:

- transmission error (for graphical echo-sounder);
- bar check.

To check for a transmission error, switch on the echo-sounder and watch the stylus which should just touch the stylus setting stud run down the echo roll plate. By now, pulses have been transmitted to the sea bed and back to the receiver, and conversions have taken place and have been printed out on the echo roll as depths.

The printing on the roll, i.e. depth, must start from the zero (vertical) line otherwise known as the transmission line to show that the roll was properly fixed. The printing on the roll must be sharp enough. The gain knob can be increased until the stylus draws a sharp straight line down the echo roll.

To check if the echo-sounder is recording the correct depth (i.e. bar check), a long iron of about 1 to 2 m with a diameter of about 5 cm and having graduated lengths of ropes at both ends, is lowered under the transducer to a required depth, say 1 m. Now, switch on the echo-sounder and watch the printing on the echo roll. The printed depth must be 1 m if the echo-sounder is truly okay. Repeat the test for different depths up to 2 m. If the depths measured by the bar agree with the printing on the echo roll, the echo-sounder is ready for use.

The digital echo-sounder can also be calibrated with a bar check. Whether the echo-sounder is going to be used for sounding or not, the user should know:

- a true depth will always be neat when printed;
- a false depth will always blot.

False depths are caused usually by shoal of fish, weeds under the water, bubbles of water due to noise from the exhaust pipe of the boat if the echo-sounder's transducers are close to it and, in some cases, if a transducer is partially blocked. Sometimes, there is no printing on the roll if the depths in the area are more than the set basic range of the echo-sounder. In that case, a new range must be selected to accommodate the increased depths.

Finally, when the echo-sounder is certified good and ready for use, the boat is steered along the sounding line, oriented in line with the bench mark or heighted marker ashore or along a steady course on the compass, as the echo-sounder measures and prints out the depths. Note that a steady speed of the boat should be maintained and that the transducer must always remain submerged, even when the boat is rolling, pitching or up on a plane at high speed.

The sounding line should be continuous with the line of profile on the aerial beach. Simple two-way communication systems like walkie-talkies and a more sophisticated electronic distance metre positioned on the beach with the reflecting prism on the boat, are also useful for keeping

the boat on a preferred profile line. The latter will in addition give the distance of the boat from the shore at intervals.

The surveyor may choose to fix the position of the boat at intervals of, say, 2 minutes; in this case, the fix button is depressed every 2 minutes and the stylus prints a straight line down the echo roll, signifying the position of the boat at the fixed point with additional comments written on this line. This procedure provides the surveyor with additional controls for the plotting of the results.

The result of the operation described above, is an echogram such as that in Fig. 4.7 which was a run across from the Badagry Creek through the Yelwa Lagoon, in the western extremity of Nigeria (Ibé et al., 1987; Ibé et al., in press). The recording is made up of a series of vertical scan lines, one line for each transmission. Each line represents a 'snapshot' of what has occurred beneath the boat. The series of snapshots are accumulated side by side across the paper and the resulting contours of the bottom are recorded.

The depth to be read off depends on the basic range setting selected. For example, the echo roll in Fig. 4.7 has provision for four-range readings (corresponding to settings), i.e. 1-16 m, 16-31 m, 31-46 m, 46-61 m which, depending on the capacity of the equipment, can be extended. The range selection is based on prior exploratory sounding or foreknowledge of depth ranges to be encountered.

If possible, bathymetric surveys should be completed with seismic surveys which bring useful information concerning the nature and characteristics of sea-bottom sediment layers (Lenotre, 1984 - see Fig. 4.8); seismic reflexion survey instruments are embarked on the boat used for bathymetric surveys.

When echo-sounding instruments are not available, bathymetric profiles are surveyed point by point from a boat, by measuring the depth of the sea bed with a simple sounding line, consisting of a graduated rope or tape and a ballast.

In these methods which use the surface of the sea as a reference level, it is necessary that the tide be observed on a tide recording marker, installed at the measurement site, at the same time as the measurements are taken, and that the measurement campaigns be conducted in calm seas.

The precision of bathymetric profile surveys using such methods depends both on the condition of the sea, and on the precision with which the ship's position in the profile is known: it is generally of the order of ± 10 to ± 20 cm.

The measurement system based on tides driven into the underwater beach (Para. 4.3.4.2) ensures better single-point accuracy with just one observer involved.

4.3.5 Evaluation of the littoral hydrodynamic regime

Estimates of swell characteristics at the shoreline and of longshore sedimentary transport can be made from off-shore swell measurements with the help of mathematical or physical models. In order to use these models of swell energy transfer to the coast, it is necessary to know, in particular, the cartography of the sea bed and the direction of propagation of offshore swells.

In the absence of such information, it is possible to conduct, on a given coastal segment, a series of visual measurements of the main hydrodynamic littoral characteristics, by simple and inexpensive means that can be applied by one trained observer.

Such measurement programmes with varying contents have been implemented in various countries, including the U.S.A., where they are termed "LEO" (Littoral Environment Observations) (Bruno, 1973).

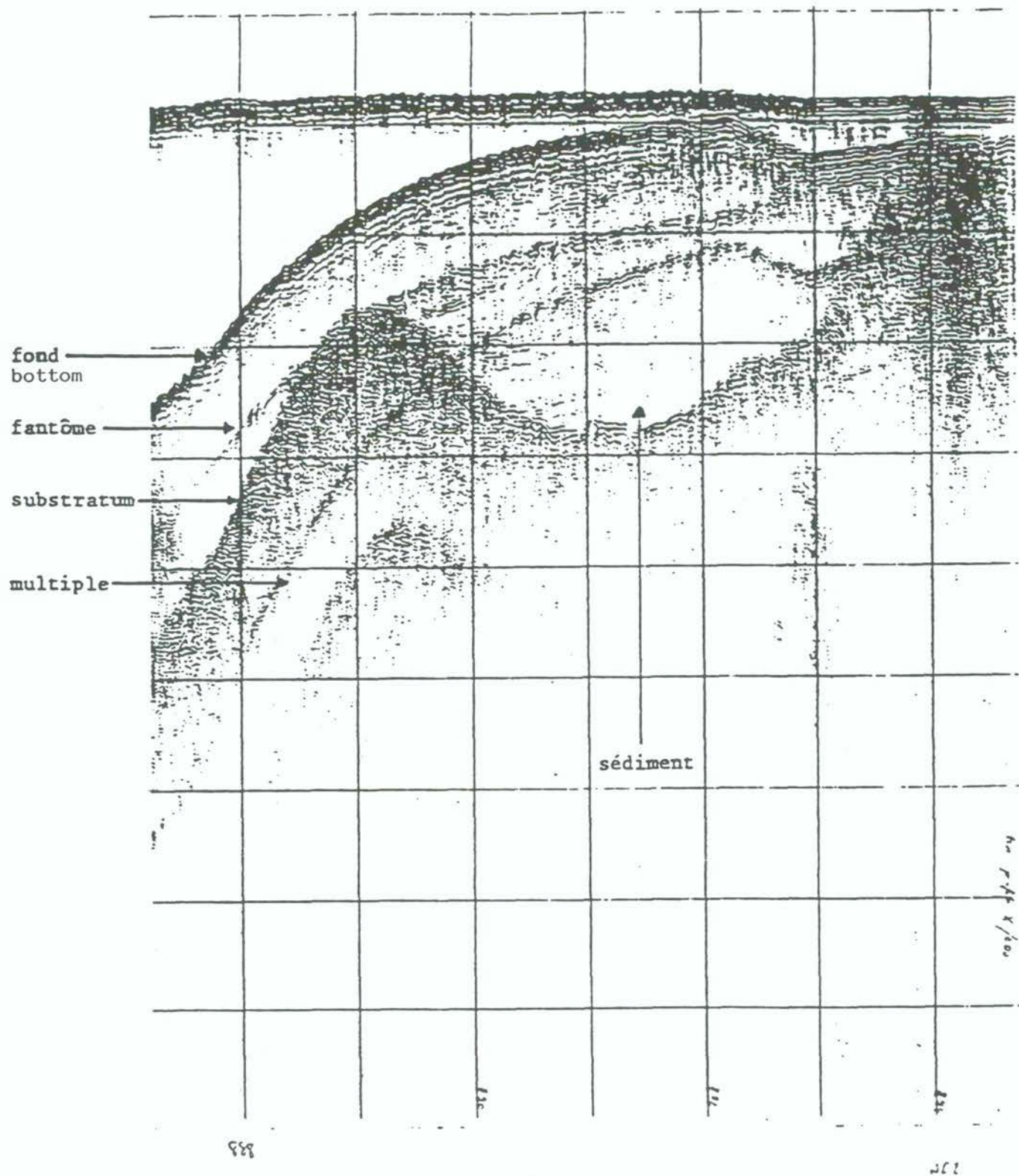


Fig. 4.8. - Exemple de coupe sismique réflexion

Fig. 4.8. - Seismic reflexion diagram

A form commonly used to record littoral environment observations data is shown in Fig. 4.9. This type of format permits the storage of data and analysis of long term effects.

These observation programmes are generally accompanied by sediment sampling and analysis campaigns on exposed and underwater beaches, with the objective of determining the granulometric and mineralogical characteristics, and the physical and chemical characteristics in the case of cohesive sediments (Para. 2.2.2), of beach sediments. Five to ten sediment samples are needed to determine the transversal granulometric variation in a beach profile. The sampling of several profiles leads to the plotting of a sedimentological map of the littoral zone in question, with representation of iso-lines of average sediment particle granulometric diameters. This map is generally drawn only once.

The main hydrodynamic variables that are measured along a coastal segment under LEO-type observation programmes are the following:

- characteristics of the waves at breaking point: amplitude, period, direction, type of breaking wave;
- speed and direction of the longshore current;
- width of the breaking zone;
- sea level.

The following may also be observed as additional parameters:

- speed and direction of the wind;
- average slope of the intertidal shore;
- the position of rip currents;
- the dimensions of beach crescents.

Depending on the availability of observers, the frequency with which these measurements are taken usually varies from twice a day to once a week. Each coastal segment must be observed for a period of at least one year, in order to obtain a significant time series.

The characteristics of the selected hydrodynamic variables are usually estimated by means of the following methods:

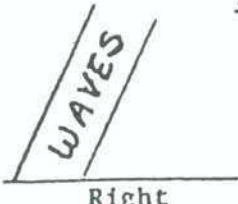
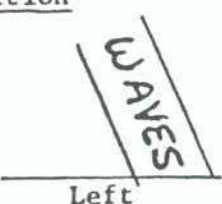
- amplitude of waves at breaking point (H_b) = average of 10 to 20 visual estimates of the amplitudes of successive waves, these estimates made, if necessary, with a swell measuring rod graduated every 0.5 m and permanently fixed in the breaking zone: a trained observer can estimate wave amplitudes to within ± 10 cm;

- period of the waves (T): it is deduced from the times separating the breaking of 10 successive waves;

- direction of the waves at breaking point (θ): it can be estimated visually by means of a simple angular protractor fixed horizontally to a post, and with its base running parallel to the shoreline (Fig. 4.10). Taking the average of 10 consecutive visual estimates yields the direction of propagation to within a few degrees;

- type of break: one generally differentiates three main types - plunging, surging and spilling or collapsing (see Fig. 4.11);

- longshore current: for the direction of the longitudinal current that is generated between the breaking zone and the shoreline, it suffices to note whether this current runs to the right or to the left as one looks at the sea. The average speed (V) is estimated by measuring the displacement of a float or coloured stain, formed by injecting a colouring agent (rhodamine, fluorescein), over a period of one minute;

<u>BEACH DATA</u>				<u>Observer's Initials:</u> _____																			
<u>Station</u> _____ / / /	<u>Time</u> (24-hour system) _____ / / / / / 3 4 5 6	<u>Date</u> (day/mo./year) _____ / / / / / / / 8 9 10 11 12 13	<u>Tide</u> (for office entry) _____ 15																				
<u>Spill</u> (percent spilling waves) _____ / / / / / 17 18 19	<u>Plunge</u> (percent plunging waves) _____ / / / / / 21 22 23	<u>Period of Waves</u> (for "significant" or highest one-third of waves) _____ / / / / / / / 25 26 27 28																					
<u>Height</u> (of breaker) _____ / / / / / 30 31 32	<u>Angle</u> (of breakercrest with shore) _____ / / / / / 34 35	 Right  Left																					
		(circle) <u> 2 </u> / <u> 37 </u>		<u> 1 </u> / <u> 37 </u>																			
<u>Depth</u> (depth of water in which wave breaks) _____ / / / / / 39 40 41	<table border="0" style="width: 100%;"> <tr> <th style="text-align: left;">Time (seconds)</th> <th style="text-align: left;">Distance (meters)</th> <th style="text-align: left;">Velocity (cm/sec)</th> <th style="text-align: left;">Dir (N/S)</th> </tr> <tr> <td>1. _____</td> <td>_____</td> <td>_____</td> <td>_____</td> </tr> <tr> <td>2. _____</td> <td>_____</td> <td>_____</td> <td>_____</td> </tr> <tr> <td>3. _____</td> <td>_____</td> <td>_____</td> <td>_____</td> </tr> </table>							Time (seconds)	Distance (meters)	Velocity (cm/sec)	Dir (N/S)	1. _____	_____	_____	_____	2. _____	_____	_____	_____	3. _____	_____	_____	_____
Time (seconds)	Distance (meters)	Velocity (cm/sec)	Dir (N/S)																				
1. _____	_____	_____	_____																				
2. _____	_____	_____	_____																				
3. _____	_____	_____	_____																				
<u>Wind</u> (velocity, mph) _____ / / / / / 51 52	<u>Wind Direction</u> (0° - 360° bearing) _____ / / / / / 54 55 56	<u>A. Temp</u> (air temp. °C) _____ / / / / / 58 59	<u>W. Temp</u> (water temp. °C) _____ / / / / / 61 62																				

NOTES: (describe general weather conditions)

Fig. 4.9. - Formulaire OEL (observations sur l'environnement littoral).
 Fig. 4.9. - Littoral environment observation form (after RPI)

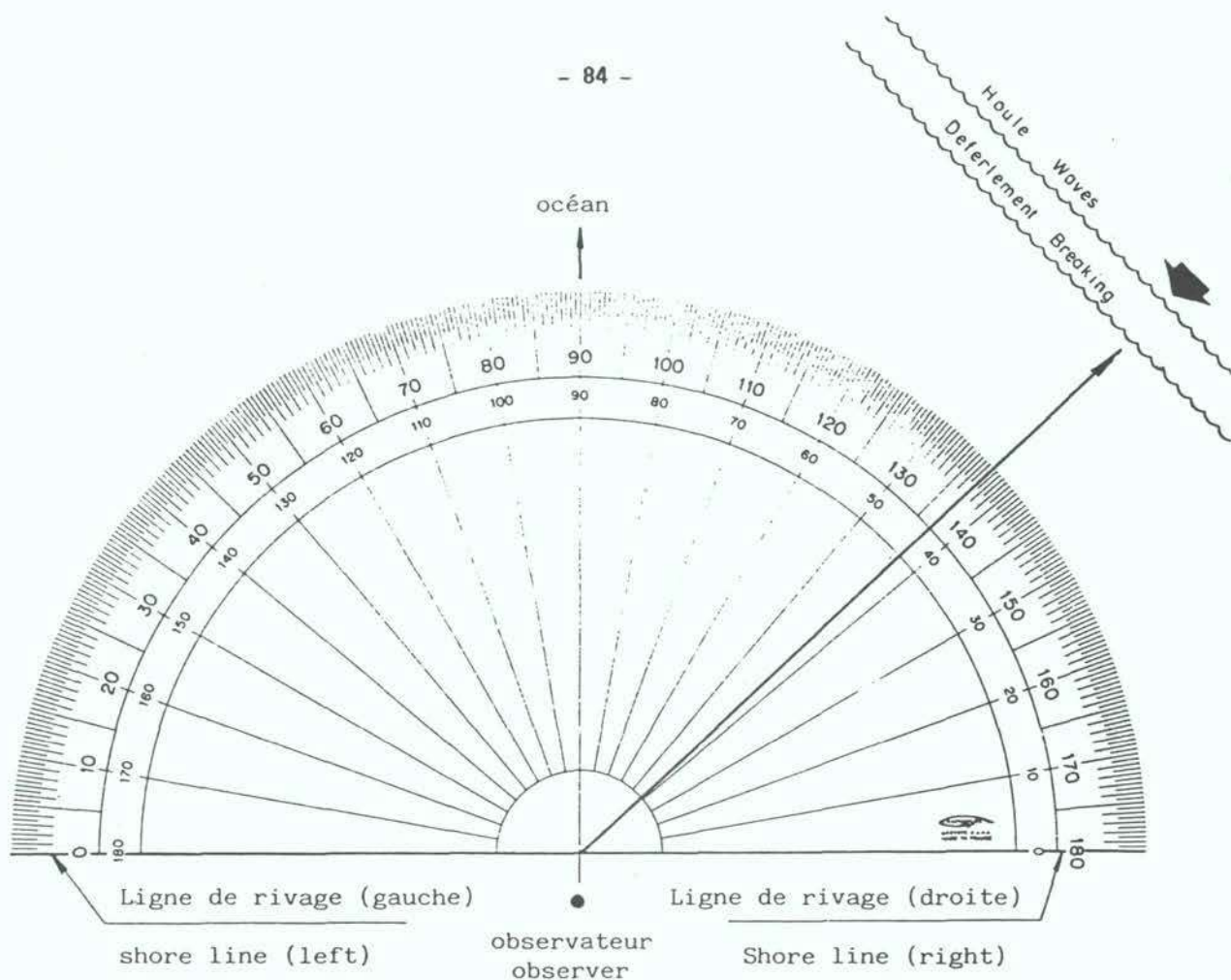


Fig. 4.10. - Détermination visuelle simple de la direction de propagation de la houle à l'aide d'un rapporteur

Fig. 4.10. - Simple visual estimation of the direction of the wave propagation by using a protractor

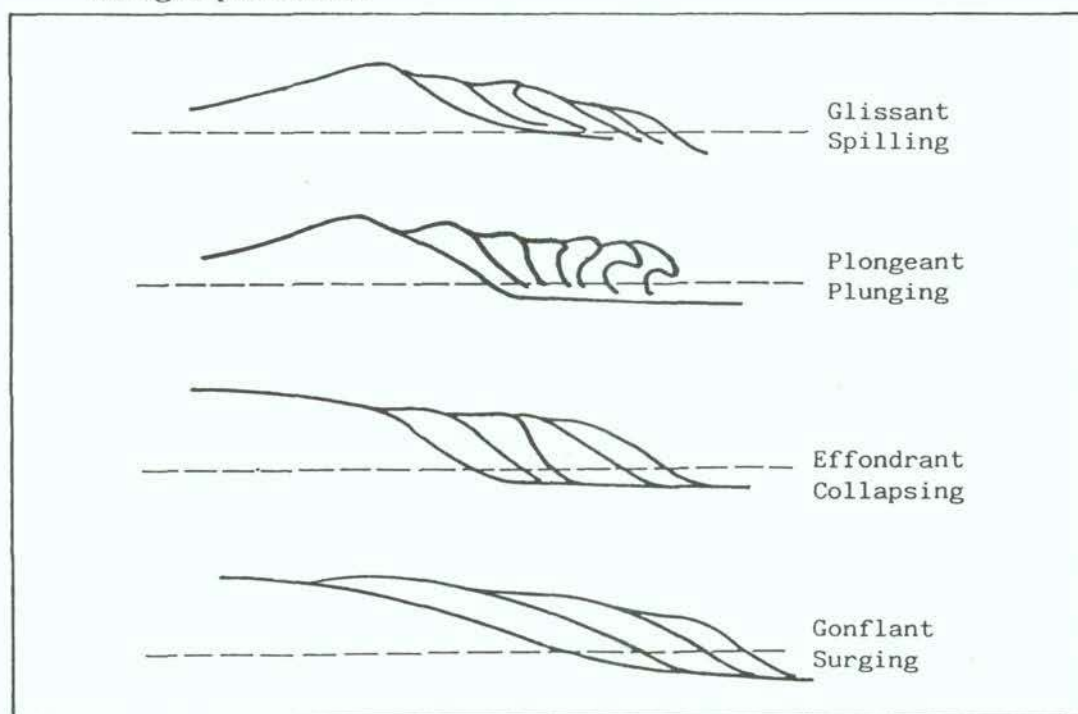


Fig. 4.11. - Différents types de vagues déferlantes

Fig. 4.11. - Different types of breaking waves

- width of the breaking zone (W): it is measured or estimated visually, as the distance between the breaking line and the shoreline;
- sea level: it is observed by visual estimation of the average level on a graduated rod fixed in the sea near the shoreline; the same rod can also be used to estimate the swell characteristics.

The measured parameters are recorded for every day of observations on a littoral environment observation form such as that shown in Fig. 4.9.

From these estimates of hydrodynamic characteristics, it is possible to deduce an estimate of the longitudinal energy flux (PIs) transmitted by the waves after breaking, and of the longshore transport (Q), by applying the following empirical formulae (Vitale, 1980), expressed in metric (SI) units:

$$\begin{aligned} \text{PIs} &= f(\text{Hb})^{5/2} \sin 2\alpha_b \\ Q &= 12.6 \cdot 10^3 \text{PIs} \end{aligned}$$

with Hb in m,
 PIs in kg/s
 Q in m³/yr

A second estimate of the longitudinal energy flux (PIs) can be obtained from longshore current measured data (V), and from the width of the breaking zone, by applying (Walton, 1980):

$$\text{PIs} = 1.28 \text{Hb.W.V (V/Vo) in kg/s}$$

with $V/Vo = 0.2 (X/W) - 0.714 (X/W) \ln(X/W)$

where X = distance with respect to the shoreline where the littoral current was measured.

These empirical formulae are only valid for extended beaches consisting of sandy type sediments. The longshore transport estimates obtained by means of these formulae depend on the duration of the observation programme, and on the frequency and accuracy of measurements taken. They are very much influenced by the observer, and therefore should not be viewed as anything more precise than orders of magnitude of longshore sedimentary transport capacities for the given coastal segment.

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5. A RATIONAL APPROACH TO COASTAL PROTECTION IN THE WACAF REGION

5.1 CONSIDERATIONS UNDERLYING THE CHOICE OF COASTAL DEFENCE MEASURES

Coastal erosion is a prevalent problem in West and Central Africa. The degree of seriousness of the problem and the attempts made to mitigate the nuisance and negative economic consequences vary. In some places, the problem has reached worrying proportions. Retreat of the coastline with the concomitant flooding causes hazards by uprooting settlements, destroying agricultural and recreational lands, disrupting harbour and navigational structures and dislodging economic facilities located along coastal towns.

Natural factors for erosion include: storm wave regime with sea level set-up, orientation and nature of the coastline, low relief of the coastal plain, vulnerable sediment budget, narrowness of the continental shelf, presence of offshore canyons and gullies, global eustatic rise in sea level, etc.

In many cases, man's intervention in the natural environment, by the construction of artificial structures on the coastline, the mining of beach sand, the location of dams on rivers that normally would supply sediment replenishment to the coastline, the haphazard withdrawal of fluids from coastal aquifers and reservoirs, the destruction of mangroves etc., has served to exacerbate the impact of natural forces.

A review of some of the above factors shows that some of the erosion-inducing processes are inevitable and, in a few cases, may even grow in intensity. For example, a recent United Nations projection of global sea level will jump from 1-2 mm per year to 7 mm per year over the next century, because of the increasing atmospheric carbon dioxide budget (also nitrous oxide methane, water vapour, etc.) which would accelerate the melting of the great ice caps the world over.

On cliffed coasts with natural vertical and near vertical barriers, a tripling of the present rate in sea level rise may not be dramatic, but according to the well known Bruun principle, on low lying coastlines such as are widespread in the region, even a few millimetres rise in sea level manifests as a landward translation of shoreline many orders of magnitude compared with the vertical rise. The implication is that coastal erosion in the region would continue, maybe at ever increasing rates.

The recent awareness created by the UNEP regional programme on Control of Coastal Erosion in the West and Central African region (WACAF/3), has brought into focus the need to react timely and appropriately to coastal erosion problems.

Paragraph 5.2. summarizes the different options available to a decision-maker faced with coastal erosion problems. The variety of options applicable to any one erosion problem are linked with the causes and consequences of erosion and the socio-economic environment of the coastal site.

It is not enough to point to defence measures that have proved successful elsewhere particularly in Europe, Japan and the U.S.A. and to seek to transplant such solutions to the region. This is because coastlines differ both in their geomorphology and in the nature and intensity of the hydrodynamical forces that exist on site. Erosion control measures that are appropriate in one place may prove an abysmal failure in another. In the U.S.A. for example, solutions applied to erosion problems on the cliffed Pacific coast differ from those applied in the Gulf and the eastern coast. Even on the only Atlantic east coast of the U.S.A, the erosion control measure applied for a developed island like New Jersey would differ from that of a pristine barrier island in Texas or Miami (Pilkey et al., 1981).

Experience from various parts of the world where coastline stabilization measures have been applied without adequate understanding of the coastal sedimentary processes, show that these measures have generally performed poorly in protecting the coastline from short term beach retreat

and destruction. In several cases, such structures had served to aggravate the very problems they were designed to solve because they have caused reduction in beach width and steepened nearshore slopes. The numerous submerged and stranded jetties, multiple seawalls and groins now detached from the shoreline are visible testimonies to the failure of stabilization schemes applied without due regard to coastal processes and coastal engineering background.

Attempts to modify coastal changes to halt erosion require an appreciation of the factors at work in the coastal morphogenic system, the pattern of change, the sources of the sediments, the paths of sediment flow, and the possible local impacts of protection works.

In the WACAF region today, the knowledge of shoreline processes and dynamics is often so rudimentary that it would be inappropriate and extremely unwise to base the design and construction of costly stabilization measures without prior littoral data acquisition and monitoring programmes such as those described in Chapter 4.

The UNEP/Unesco sponsored project on Control of Coastal Erosion in West and Central Africa (WACAF/3) was designed to fill this yawning gap in knowledge both at the national and regional levels.

The regional level was emphasized because it was recognized that some of the physical ocean processes are large scale and cut across national boundaries. For example, the powerful swells that afflict much of the region's coastline originate from common storm centres out in the Atlantic ocean. Again, the longshore drifted sediments that pass the western Benin coast originate from the Togolese coast. Part of the sediments transported along the Togolese coastlines were brought down to the sea by the Volta River before the Akosombo dam was built.

The overall objective of the WACAF/3 project is to make a scientific input into large scale and long term coastal management planning in the region. The target is to build progressively a solid background (data base) of such fundamental coastal data as the force and direction of prevailing winds relative to shoreline alignment, the characteristics of meteorological situations which can generate storm activity, the wave climate, the tidal regime, the sediment characteristics, the coastal and offshore topography, etc., that are absolute prerequisites for meaningful study of shoreline phenomena and the measures to be considered to combat them. Other factors that merit investigation include the behaviour of mean sea level (MSL) in relation to the global rise in sea level, the local subsidence and other geomorphological characteristics of the coast and ocean that bear on the erosion problem.

5.2 STRUCTURAL METHODS OF COASTAL PROTECTION: SELECTION CRITERIA AND FUNCTIONS

These methods are an alternative to non-structural methods, which essentially consist in deciding:

- not to act at all: the risks of erosion and their consequences are viewed as acceptable in the short and medium terms;
- to move and to reconstruct the works in danger on a withdrawal line further inland;
- to manage the situation: regulations governing town planning, extraction of sand from the beach, etc.

5.2.1 Selection criteria

Structural methods can be classified according to three main categories:

- passive protection methods;
- active protection methods;
- restoration methods.

Each of these methods gives rise to erosion risk prevention or coastal protection works and structures, whose technical characteristics are highly varied, and therefore cannot be presented in detail in this manual (Fig. 5.1).

When confronted with a situation in which a coastal erosion risk has been identified, those responsible for littoral management and protection must be able to choose, from among the available structural methods, those which meet the needs of the given problem, in order to be able to compare the costs and advantages of the possible alternative solutions.

The criteria for selecting these methods depend, in particular, on the answers to the following questions:

- morphological and sedimentological characteristics of the site to be protected?
- hydrodynamic balance?
- type of erosion process?
- urgency to complete the works?
- current and future uses of the site?
- objectives assigned to the defensive works?
- lifetime of the works and ease of maintenance?
- technical means (materials, equipment) and financial resources available?

5.2.2 Passive protection methods

These methods involve works built longitudinally along the shoreline, the objective being to fix the shoreline in the position currently occupied, by protecting it from the direct action of storm swells with artificial structures erected at the top of the beach, without seeking to maintain or to enlarge the beach by affecting sedimentary processes.

The most commonly used longitudinal coastal defence works are of three types: sea-front walls, revetments and embankments.

Sea-front walls are generally made of masonry or concrete (thick walls), or put together by assembling components made of wood, steel sheet or prefabricated concrete, held in place by vertical pillars (thin walls). These works must be solidly anchored to make sure that they are not laid bare. Thin retaining walls are generally almost vertical, which often has the effect of accelerating erosion phenomena at the foot of the works, as a consequence of wave reflection.

Revetments also make it possible to protect the upper part of beach shores, after they have been re-profiled. Such aprons are generally made of prefabricated concrete slabs, of layers of rip-rap stones or gabions, placed on a re-profiled bank with a variable slope (Photo Fig. 5.2). The roughness and the flexibility of the revetment make it possible to limit the risk of damage to the works when the beach level occasionally falls.

Longitudinal embankments are substantial works of trapezoidal shape, consisting of a core (earth, sand, quarry run) covered by several layers of blocks. These works are costly, because of the volume of material to be put in place, and are generally used only to protect low coastal zones against the risk of submersion under the sea.

Bulkheads and rubble-mound embankments can also be used to protect the foot of erodable cliffs against direct attack by the waves.

COMMONLY USED METHODS FOR CONTROL OF BEACH EROSION

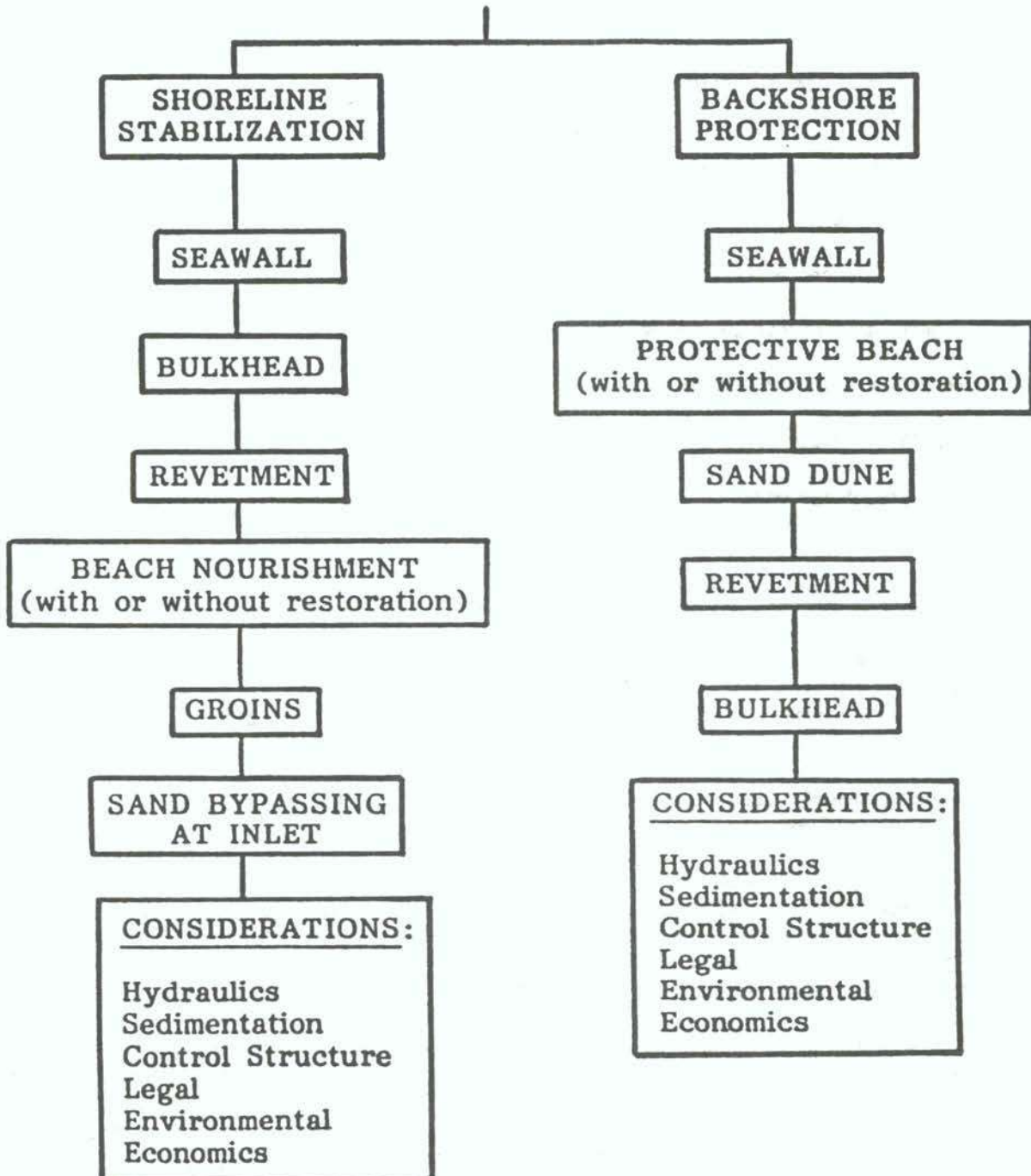


Fig. 5.1.

(C.E.R.C. manual)



Fig. 5.2. - Revêtement en gabions du haut estran d'une plage en recul près d'Accra (Ghana) - (Ibé).

Fig. 5.2. - Gabion revetment of the foreshore face of a retreating beach near Accra (Ghana) - (Ibé).

Fig. 5.3. - Protection de la plage de Cape St. Mary (Gambie) par des épis en bois (Quélenneq, 1988).

Fig. 5.3. - Beach protection at Cape St. Mary (Gambia) by using wooden groins. (Quélenneq, 1988).



In summary, longitudinal protection works are not to be recommended for mobile coasts, in a state of sedimentary disequilibrium and subject to rapid shoreline retreat, because the gradual drop of the beach altitude will tend to destabilize the works.

Longitudinal works may promote erosion of the adjacent coast, in the event that they protect sectors which are sediment source zones.

5.2.3 Active protection methods

As opposed to passive protection works which protect only that part of the shoreline where they are built, active protection works (groins, breakwaters) affect the characteristics of the swell and of littoral sedimentary transport, in order to trap and retain mobile sedimentary stocks on the coasts.

Groins are works built perpendicularly to the shoreline, in the zone where the swell breaks. They are generally constructed in series, at intervals of anywhere from 2 to 3 times their length. Their dimensions and their degree of permeability vary, depending on the type of construction and the desired effectiveness in trapping sediments being moved by longshore transport. This trapping occurs on the upstream side of the groin, with respect to the direction of longshore transport, which results in thickening of the shoreline, while at the same time the shoreline retreats on the downstream side, where there is no sedimentary input, and tends to become oriented parallel to the crests of predominant swells between two successive groins. Various materials are used to build groins: quarry stones, prefabricated concrete blocks, piles and sheets of impregnated wood, steel sheet pile, sheet pile cells, etc.

The choice of characteristics and of construction type must depend, in particular, on the energy of the swell, on the availability of construction materials, and on the lifetime of the works.

Groins can only function properly if there is a significant longshore transport of sediments (Fig. 5.4). The design of a system of groins is not an exercise to be taken lightly, for it must allow, among other things, for ways of reducing erosion induced by insufficient sedimentary input to the adjacent shoreline, because of all or part of the longshore transport being trapped by groins. The groins are not effective when most of the sedimentary transport takes place either transversally in the profile of the beach (frontal swells predominating), or in suspension as littoral silts or muds.

Breakwaters are emerged, submersible or floating works, built off the shore in a direction that is generally parallel to the bathymetric curves. The objective sought by breakwaters is dissipation of the energy of the swell, and hence of its amplitude, as it is propagated towards the shorelines, which reduces both longshore transport and transversal sedimentary exchanges in the profile of the beach, in the littoral zone sheltered behind the breakwaters. As a result, sediments accumulate in this zone, in the form of an embryonic tombolo (Fig. 5.5).

This tombolo plays the role of a groin vis-à-vis longshore transport, which tends to favour sedimentary input deficiency, and hence erosion, in the littoral zone located downstream of the works, with respect to the direction of longshore transport.

The designing and sizing of breakwaters are delicate tasks, requiring coastal engineering expertise. In zones where the swell energy is high, breakwaters are built of large quarry stones, or prefabricated reinforced concrete blocks or caissons. In zones with low to moderate energy and with shallow bottoms, they can be constructed by means of sheet pile cells, sacks of sand, rows of impregnated wood piles reinforced by stone blocks or used tyres, etc.

The third type of active protection in frequent use is artificial sedimentation of the shoreline by bringing in sediments taken from the sea by dredging or pumping. By so doing, one re-establishes the sedimentary equilibrium of a coastal segment suffering from a sediment deficit,

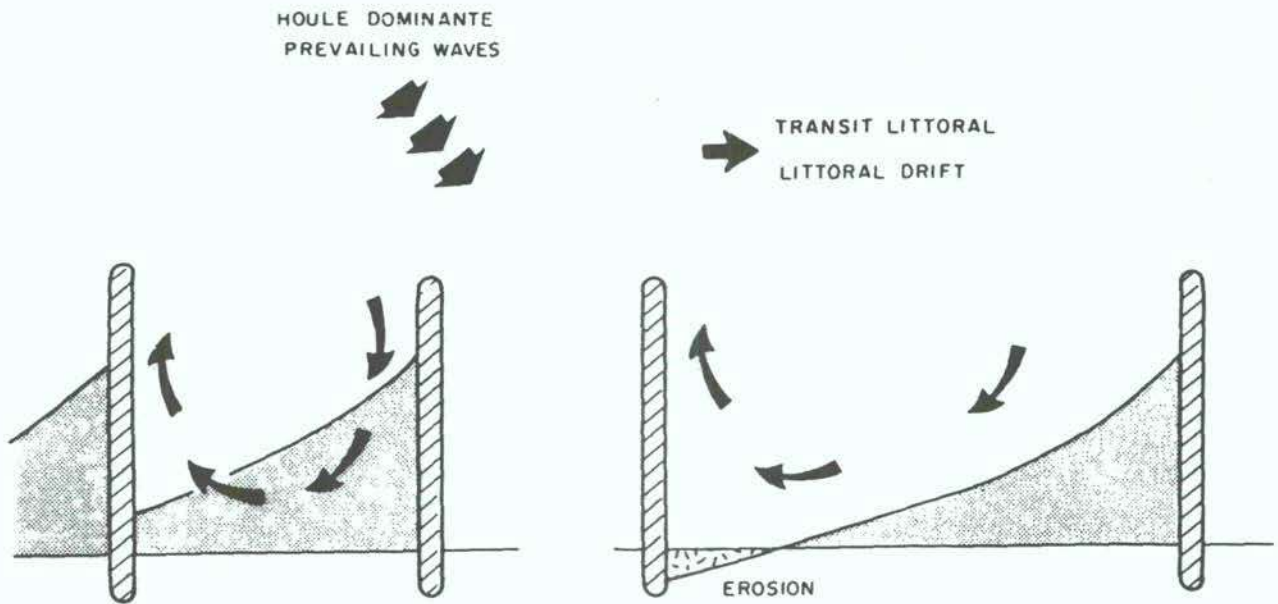


Fig. 5.4. - Principe de fonctionnement des épis

Fig. 5.4. - Principle underlying groynes

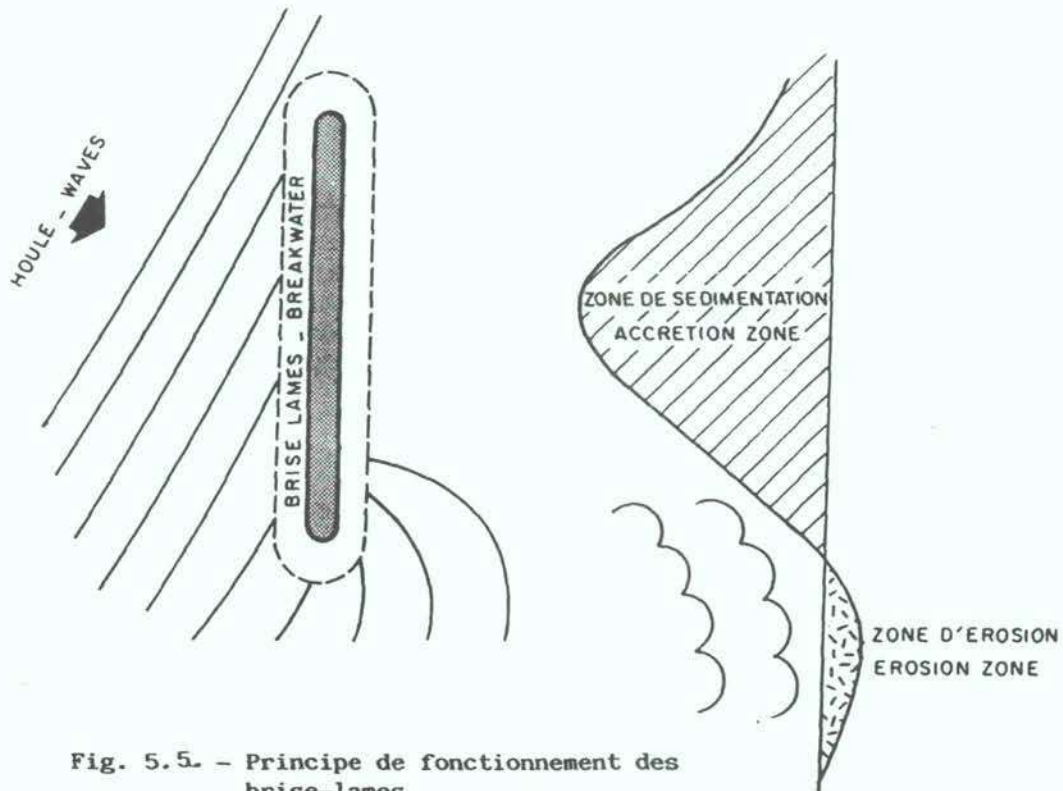


Fig. 5.5. - Principe de fonctionnement des brise-lames

Fig. 5.5. - Principle underlying breakwaters

because of, for example, the construction of works such as jetties, breakwaters or port embankments.

Artificially adding sediments to a beach results in the creation of a buffer sedimentary stock, which favours the dissipation of swell energy, allows for saturation of longshore transport and reduces the risk of shoreline retreat. This sedimentary stock generally has to be reconstituted on a periodic basis, because of longshore transport, and because of granulometric sorting by the swell, which moves the finer sedimentary particles towards the open sea. The choice of granulometric characteristics of the sediments determines the frequency with which beach nourishment has to be repeated, and the morphology of the beach.

The zones from which these sediments are taken must be located away from the shore, and at sufficient depths (usually more than -10 m) to avoid littoral erosion due to changes in the profile of the underwater beach.

Active protection methods involving both groins or breakwaters and artificial beach fill are often used to combat coastal erosion or to create new protective beaches.

Before applying such methods, it is necessary to carry out detailed preliminary studies of the hydrodynamic and sedimentological characteristics of the coastal sites to be protected.

5.2.4 Restoration methods

Unlike the preceding methods, these do not aim to restrict or to change the direct action of swells, but rather to re-establish equilibria destroyed by man, or to reinforce the stability of natural systems. They are applicable basically to three types of littoral facies: erodable cliffs, dunes and maritime marshes.

The stability of coastal cliffs subject to slumping can be reinforced by works aimed at combating infiltration of rainwater, and by draining operations. In urban zones, a rise in the piezometric level of groundwater tables due, for example, to an increase in the number of individual sewerage networks, or to leaks in collective sewerage systems, can favour slumping in littoral cliffs.

Littoral dunes constitute sedimentary stocks, which serve both as source zones for longshore transport during storms, and as natural embankments that protect inland beach zones against flooding during sea level set-up periods. There are two types of actions that can increase the trapping of beach sand on dunes, protect them against deterioration due to trampling, and restore them: erection of wind-breaking screens that act as sand traps, and planting with carefully chosen species of grasses. Such measures make it possible to significantly increase dune dimensions in coastal areas with considerable eolian transport.

Maritime marshes become established in sheltered littoral zones, where one generally finds mangroves, in the case of the West and Central African region. Mangrove barriers enhance sedimentation by limiting the action of residual swells on the shoreline, and by fixing sediments. Such natural protective barriers must be protected themselves, because their disappearance raises the probability of shoreline retreat.

5.3 DECISION FRAMEWORK FOR COASTAL PROTECTION AND MANAGEMENT

The choice of appropriate coastal defence techniques requires a broad experience in coastal engineering works. It is sensible to make such choice within a coastal management decision framework, a solution which would ensure that all appropriate alternatives, resources and factors are considered.

Such framework provides a logical procedure to estimate the costs and benefits of alternative techniques and measures for coastal protection (Kerns et al., 1980). One way of

achieving this is through the use of "utility theory" (Oguara and Ibé, under press). Under this scheme, the approach is to first identify the various possible coastal defence measures and thereafter to define appropriate sets of objectives. These objectives are part of the framework of a "regional sediment management" (Quélenec, 1981) which allow taking into account interactions between natural sedimentary processes and human activities in watersheds and their associated littoral zones.

The best erosion control measure is one that minimizes costs and environmental damages, and provides maximum short and long term efficiency to decisions and operations. The proposed framework thus provides a procedure for making decisions on whether a set of structural or non-structural control measures should be recommended for a given stretch of coast, or whether decisions should be postponed to a date when new data are available.

It is essential that a proposed solution lead to a minimum impact on the socio-economic and cultural texture of the region.

5.4 COASTAL ZONE MANAGEMENT POLICY

It is necessary to draw attention to the need for countries in the region to end the past and recent approach consisting of a set of local and short term actions.

As has been emphasized by several authors, the littoral zone is not only an endangered patrimonial resource composed of various fragile ecosystems, but is also a zone of conflicting uses. For example in the Niger Delta (Nigeria), the coastline is a scene of conflicting use between agriculture (including fishing) and oil exploitation.

Resulting conflicts are sometimes difficult to solve especially when institutionalized management frameworks do not exist. In this regard, inspiration and lesson should be drawn from prevalent practices in most countries in the western world where, despite a wide variety of already existing governmental controls to reduce causes and importance of conflicts linked with the use of the littoral zone, specific coastal legislations have been passed. The "Coastal Zone Management Act" of 1972 in the U.S.A, and the recent decree No. 86-2 of 3 January 1986 in France are particularly instructive.

There is urgent need, therefore, for countries of the WACAF region to define and apply, after a regional concerted action, equivalent national legislations adapted to the characteristics of the coastal environment and the socio-economic development of the region.

To be efficient, such specific legislations must favour concrete supporting measures like national and regional programmes of research, of training and of public information (audio-visual), on the specificity and resources of the patrimonial coastal zone which is one of the key elements for the development of the region.

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