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Changing Climate and the Coast

Volume 2: Western Africa, the Americas, the Mediterranean Basin, and the Rest of Europe

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from the Miami Conference on Adaptive Reponses
to Sea Level Rise and Other Impacts
of Global Climate Change

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CHANGING CLIMATE AND THE COAST

VOLUME 2: WESTERN AFRICA, THE AMERICAS, THE MEDITERRANEAN BASIN, AND THE REST OF EUROPE

REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE FROM THE MIAMI CONFERENCE ON ADAPTIVE RESPONSES TO SEA LEVEL RISE AND OTHER IMPACTS OF GLOBAL CLIMATE CHANGE

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The opinions expressed herein are solely those of the authors and unless noted otherwise do not necessarily represent official views of any of the sponsoring agencies or the Intergovernmental Panel on Climate Change.

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WEST AFRICA

ADJUSTMENTS TO THE IMPACT OF SEA LEVEL RISE ALONG THE WEST AND CENTRAL AFRICAN COASTS

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ABSTRACT

The coasts of West and Central Africa, stretching from Mauritania to Namibia, are mostly low plain, sandy, surf beaten, and in many places, subsiding. The region has population of about 269 million, of which a large percentage live along or near the coasts. All but 4 of the 21 countries presently have their capital cities on the coast. The lopsided history of urban development in the region has meant that most economic and social infrastructures are located in these cities. At present, erosion and concomitant flooding are prevalent along the coasts and have assumed disturbing proportions, putting life and property continually at risk.

These problems would be exacerbated by an accelerated rise in sea level that would virtually cripple most economic structures and activities such as ports, coastal roads, air fields, rail lines, fishing, farming, oil and mineral production, manufacturing, etc. Settlements would be dislocated. Surface and groundwater as well as flora and fauna of the region would be profoundly affected as a result of increased salinization and added load of sediment and pollutants. Increased incidence of heat-related diseases occurring with rising temperatures would mean a drastic reduction in the well-being of humans, livestock, and crops. The enormity of the various expected impacts dictates that significant measures be taken to make the coastal zone habitable. Given the financial disabilities of countries in the region, only well-planned anticipatory actions by these countries, acting preferably in concert, can help avoid or minimize stress, hazards, and resource losses from the expected changes.

West Africa

INTRODUCTION

Recognizing that the impact of the expected accelerated rise in sea level along most low-lying coastlines of the world would lead to a disruption of life and dislocation of socioeconomic structures and activities in such places, the Ocean and Coastal Areas Programme Activity Center (OCA/PAC) of the United Nations Environment Programme (UNEP) set up Task Teams in 1987 to study the implications of climate change on the coastal and marine environments of six of the regions covered by UNEP's Regional Seas Programme, namely the Mediterranean, Caribbean, South Pacific, Southeast Pacific, South Asian Seas, and East Asian Seas regions. In 1989, two more Task Teams were assembled for West and Central Africa and Eastern Africa. Other Task Teams (for the Black Sea and Kuwait region) are in the process of being established. The ultimate objective of these Task Teams is to advise governments in the various regions on how to respond appropriately to the expected impacts of increased atmospheric temperatures and sea level rise. The West and Central African Task Team convened for the first time in Lagos, June 7-9, 1989. This paper combines the author's personal views on the problem with those expressed by team members during that meeting.

SETTING

The West and Central African (WACAF) region, comprising 21 countries between Mauritania and Namibia, stretches approximately for almost 7,000 km between latitudes 23° N and 28° S (Figure 1) with a total area of 9 10^6 km^2.

Climatically (and by implication, in terms of vegetation) the WACAF region falls within three main zones (Figure 1):

1. North arid zone (semiarid and arid zones);

2. Equatorial humid zone (humid and subhumid zone); and

3. South arid zone (semiarid and arid zones).

GEOLOGICAL EVOLUTION AND GEOMORPHOLOGY

The evolution of the continental margin of West and Central Africa is linked with separation of South American from Africa. The dating of this separation is inexact as it consisted of a series of overlapping events.

According to Emery et al. (1974), the earliest of the events in the region was the development of small basins and troughs (the 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 at the south and proceeded northward occupying a time span of about 165 million to 135 million years. The general date of separation is indicated by the general continuity of Precambrian and Paleozoic strata and structures in Africa and South American and the disruption of Jurassic and younger structures. This separation

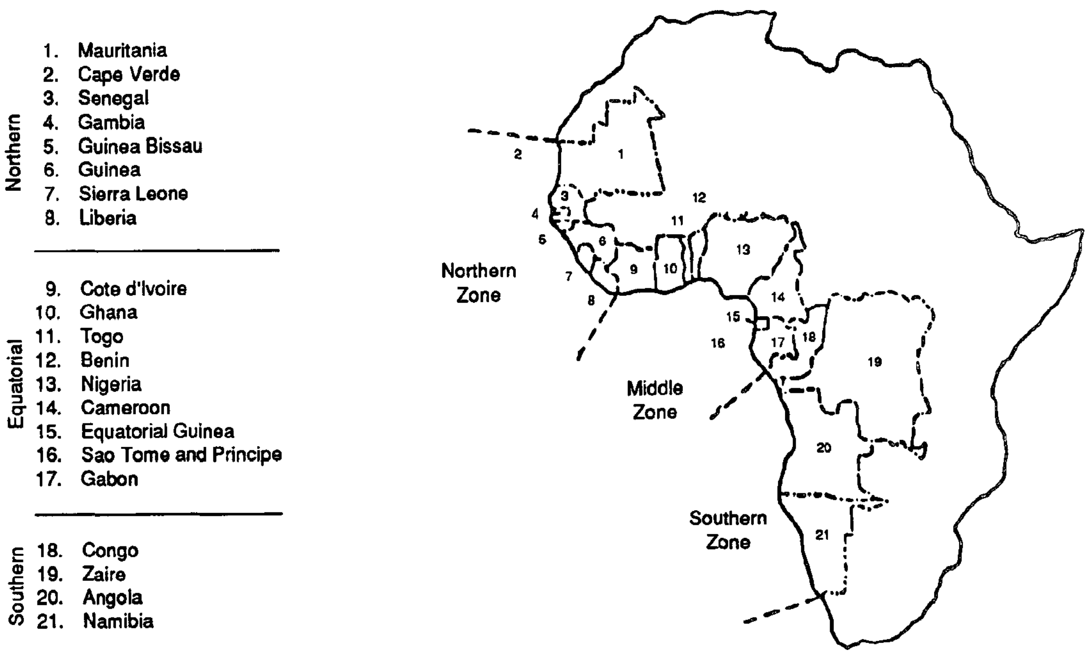

Figure 1. Countries and zones of the WACAF region.

led to the formation of the basins farther south (the Mossamedes, Cuanza, Congo-Cabinda, Gabon, Cameroun, Nigeria, Dahomey, and Ivory Coast Basins). Continued separation of South America from Africa produced easily recognizable ocean-floor provinces (see Emery et al., 1974 for details).

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 area; 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; and coasts with sand spits (and tombolos) formed by accumulation of longshore transported sand in bays found in the southern parts of Angola.

From the point of view of their geological evolution and present geomorphology, the coasts in the region are clearly vulnerable to sea level rise, not only because they are low-lying but also because the sedimentary basins that dominate the coasts are areas of subsidence. These basins, formed by the rapid deposition of sediments in a tectonic setting, are even in present times, still undergoing dewatering and compaction. In recent times, human intervention by fluid extraction (including oil and gas) in the coastal zone has had the effect of accelerating the subsidence due to natural causes.

SOCIOECONOMIC SETTING

Settlement and Population

The WACAF region has a population of about 269 million and with a rapid annual growth rate of about 2.9%, the population will most probably double itself within the next two and a half decades.

Due to the history of early contracts with Europeans, most important cities in the region are located on the coast. Of the 21 countries, only 4 do not have their capital cities in the coastal area. These coastal cities are nearly always synonymous with centers of commerce, industry, and politics and have thus attracted very large populations. For example, Lagos (Nigeria) is reputed to have a population of over 8 million out of an estimated national population of 100 million. The story is much the same for Dakar, Abidjan, Freetown, Banjul, etc.

Communication

Ports and harbors as transportation access facilities for maritime activities provide the lifeline for socioeconomic development of the region and are all located in the coastal zone. Most of these ports and harbors are linked by intricate road, rail, and air transport routes that complete the network for the export-import trade that is the linchpin of most economies in the region. Coastal roads, some of which are presently under threat from marine erosion, provide particularly easy access between the countries in the region, while air transport offers a means of rapid movement of goods and peoples between the countries.

Industries

When compared with Europe or America, the West and Central African region is poorly industrialized, but the pertinent issue is that the industries that do exist are concentrated mainly on or near the coast, most often around the capital cities. Such industries include mining, oil and gas, petroleum products, textiles, paper and pulp, timber, brewing, pharmaceuticals, plastics, leather, lumbering, and various manufacturing outfits.

Agriculture

Agriculture is the most important industry in the West and Central African zone. About 70 to 80% of the population is engaged in agriculture, and the economies of most countries in the region depend on it. The coastal areas are becoming increasingly important to this industry and have the potential of increasing substantially their contribution to agricultural production. About 60 to 80% of the food production of this zone comes from small farms.

The crops and produce from agriculture of this zone may be classified as follows (UNEP, 1984):

1. Tree and horticultural crops (oil palm, coconut, citrus, avocado, pear, rubber, kolanuts, sheanut, cocoa, coffee, pawpaw, banana, plantain, mango, pineapple);

2. Cereals (maize, rice, sorghum, millet);

3. Root crops (cassava, cocoyam, yam, sweet potato, ginger, tigernut);

4. Vegetables and beans (groundnuts, cowpea, phaseolus bean, melons); and

5. Other crops (sugarcane, tobacco, and cotton).

Apart from crops, the coastal and forest areas have a low livestock population. The main categories of livestock are large ruminants (cattle and camels), small ruminants (sheep and goats), equines (asses, mules, and horses), pigs, and chicken. The distribution of livestock is uneven. It is governed by natural factors such as the presence of tse-tse fly and historical and cultural factors as well as vegetation types.

Mariculture and aquaculture are becoming increasingly popular in the coastal zone of the West and Central African region. Captive breeding of economically important species such as Chrysicthy spp., Megalops spp., Clarias lazera, as well as oyster culture, are widely practiced in Nigeria and Ghana with varying degrees of success. In Angola, the culture of mussels, Perna perna, is popular.

NATURAL RESOURCES

Forestry and Wildlife

The West and Central Africa region is the home of the tropical rain forest and mangroves of great biological diversity, but the density and variation of the forests are greatly influenced by climate, especially rainfall. The rain forests and mangroves form the basis of an extensive lumbering industry.

The region is rich in wildlife, which is an important source of protein and are hunted intensively, but several species are on the endangered list as a result of uncontrolled harvesting and poor management. The most important wildlife include elephants, lions, buffalos, hartebeests, smaller antelopes of different kinds, warthogs, aardvarks, civet, cats, chimpanzees, baboons, birds of all types, and reptiles.

The animal species found in the mangroves are also found in other brackish water, salted waters, and nearby forests. The fauna consist of invertebrates, molluscs, crabs, prawns, and fish, reptiles, birds (e.g., herons, storks, and ibises), reptiles, and mammals (monkeys, bush pigs, and manatees). Most of the reptiles, birds, and mammals are semi-aquatic.

In addition, the mangroves provide important spawning and breeding grounds for a variety of finfish and shellfish that are the targets of artisanal and industrial fishery in the coastal zone.

Fisheries

Despite deficient statistics, several resource surveys in the different countries of the region show that respectable quantities of fish are harvested in the region. According to UNEP (1984), production figures show high harvests in Angola, Cameroon, Ghana, Ivory Coast, Nigeria, Namibia, Senegal, Sierra Leone, and Zaire. Namibia, with 761,000 metric tons in 1978, has the highest figures.

The existence of upwelling zones in the region (both permanent and seasonal) is known to be the basis of the rich fishery of the region. Major permanent upwelling zones occur near Mauritania and Senegal as well as off the Congo, Angola, and Namibia, whereas seasonal upwelling occurs in the Gulf of Guinea between Cote d'Ivoire and Nigeria. The lagoons, creeks, and bays along the coasts are also areas of high productivity.

Fish and shrimp are the major resources of the region, although in some countries such as Senegal, Sierra Leone, Nigeria, and others, edible molluscs from near-shore areas are harvested in considerable quantity. The shrimps, prawns, and oysters are now the targets of export trade in the region.

Minerals (Including Oil and Gas)

A variety of minerals ranging from commonplace sand and gravel to gold, diamonds, and petroleum are mined from the coastal zone of this region. According to UNEP (1984), the extent of mined resources, particularly if revenues from petroleum products are considered as part of this grouping, is significant in countries such as Nigeria, Gabon, Liberia, Guinea, Angola, and Sierra Leone; their economies are best described as mineral economies. For example, the export of petroleum accounts for over 90% of the export and foreign exchange earnings of Nigeria. Except for Gabon and Nigeria, nonfuel minerals still dominate the economies of the other countries listed above.

Water Resources

The West and Central African region is well-endowed in terms of rivers. It is also blessed with heavy precipitation (reaching 2,000 mm in the south), which means that the recharge potential of groundwater aquifers is very high. Water balance maps depict areas of high rainfall, high humidity, and low temperature, i.e., Liberia, Sierra Leone, and southeastern Nigeria, which have the greatest water surplus (amounting to the equivalent of more than 1,000 mm of rainfall). In the more arid conditions of the north, however, rainfall decreases to 50 mm and, under such circumstances, aquifer recharge is very low.

PRESENT CLIMATE EFFECTS

The West and Central African coasts are the scenes of high wave intensity. This fact, along with other adverse geological conditions (e.g., erodibility of sediments, subsidence), and detrimental human interference in the natural environment, have meant that erosion and concomitant flooding are prevalent along the coasts of the region (Ibe and Quelennec, 1989). In some places, the flood rates are so rapid that whole towns (e.g., Grand Popo in the Benin Republic and Keta in Ghana) have virtually disappeared. Elsewhere, life and property have been put to risk with resultant economic losses and social misery.

The region in recent times has witnessed a prolonged scourge of drought and desertification with all its attendant dislocation of population and destabilization of socioeconomic activities. Hunger and disease have afflicted the populace as a result of crop failures and losses in livestock.

PREDICTED CLIMATE CHANGES

Different scenarios of climate change have been put forward and defended by various authors, but the Task Team adopted as the basis for its deliberations the assumptions accepted at the UNEP/ICSU/WMO International Conference in Villach, October 9-15, 1985, i.e., increased temperature of 1.5-4.5°C and sea level rise of 20-140 cm before the end of the 21st century. (For the purpose of the meeting, temperature elevation of 1.5° and sea level rise of 20 cm by the year 2025 were accepted with the understanding that these estimates may have to be revised on the basis of new scientific evidence.)

IMPACTS FROM EXPECTED CLIMATIC CHANGES

The problems of erosion and flooding presently experienced along the coasts of the region will be exacerbated by the predicted acceleration in global sea level rise. In fact, worldwide evidence points to erratic jumps in the rates of shoreline retreat that suggest sea level rise as a contributory factor (Pilkey et al., 1981). Although the accepted predicted values may seem small, its impact along the low-lying and, in many cases, subsiding coasts in the region would be immense, particularly when viewed from point of view of the Bruun (1962) rule, which predicts that a rise of 0.3 m (1 ft) of sea level will cause a shoreline recession of more than 30 m (100 ft) on low-lying coasts. Subsidence phenomenon, known to be active in major coastal sedimentary basins in the region, would aggravate the situation.

With the increase in ocean temperature, tropical storms are likely to extend into some humid areas, and with rising sea level, the periodic flooding presently being experienced in vast coastal areas will become more frequent and devastating. This will virtually cripple most economic structures and activities in the densely populated and highly urbanized settlements proximal to the sea. Ports, coastal roads, and rail lines will be knocked out of action; fishing, farming, oil and mineral production, and manufacturing will be interrupted; people and businesses will be forced to relocate, etc.

As a result of increased sea level rise, surface drinking water and groundwater aquifers would be rendered unusable as sources of potable and irrigation water because of increased salinization and added loads of sediment and pollutants.

The fragile ecosystems of the coastal zone will be adversely affected by inundation from the sea and may not be able to perform their traditional roles as the spawning and breeding grounds of most finfish and shell fish that are the targets of artisanal and inshore industrial fishermen.

A rise in sea level will also profoundly affect the flora and fauna of the region as well as the agriculture and livestock production. Vegetation kill due to salinity stress would result, as is presently being witnessed in the Mahin area on the northwestern flank of the Niger Delta (Ibe, 1988a,b). The distribution and composition of the coastal vegetation would be affected with salt-loving species increasing. This may decrease suitable forage for livestock, resulting in a depression of this occupation among coastal populations. The areas of saline soils would increase, making them unsuitable for cultivation of crops like maize, banana, pineapple, etc. Coastal plantations would also suffer from salinization. Hunger, already a problem in the region, would worsen.

Apart from the impacts due to sea level rise, other impacts derived from a rise in temperature would result. Increased humidity and temperature would favor rapid multiplication of insects such as mosquitoes and the tse-tse fly, resulting in diseases such as malaria and trypanosomiasis reaching epidemic proportions. Temperature-sensitive plant diseases and weeds would also increase and cause greater damage to crops. Increased incidence of heat-related diseases with rising temperatures would mean a reduction in the well-being of humans and livestock. The general level of discomfort and misery would be high.

ADJUSTMENTS TO IMPACT OF SEA LEVEL RISE AND OTHER EFFECTS DUE TO CLIMATE CHANGES

It is imperative that countries in the region make some adjustments to cope with the adverse conditions that would accompany the rise in sea level and higher atmospheric temperatures. Given the financial disabilities of countries in the region in the face of these serious threats, well-planned anticipatory and, in some cases, reactive (including adaptive) actions need to be pursued by the countries acting individually or in concert to avoid or minimize the stress; hazards and resource losses would be likely to occur with the expected changes.

In relation to sea level rise, there will be a need to protect heavily built-up areas having high-value installations where the option of relocation is not a reasonable economic proposition. But while many of the engineering countermeasures are feasible for shoreline protection in the face of sea level rise, they are economically impractical in view of the financial position of most countries in the region. The approach here should be toward the adoption of low-cost, low-technology, but effective measures such as permeable nonconcrete floating breakwaters, artificial raising of beach elevations, installation of rip raps, timber groins, etc., from locally available materials. Fortunately, outside the urbanized centers, the coasts are almost in pristine condition and largely uninhabited except perhaps for small fishing settlements which, in any case, are highly mobile. In such situations, resettlement of existing populations and the enforcement of set-back lines for any new developments on the coast should be applied. Where coasts are deemed highly vulnerable, total ban of new development is necessary.

Designs of new buildings and other facilities should take into account the predicted and continuing rise in sea level as well as increased heat. For instance, houses should be concerned with increased use of natural ventilation modes. Afforestation of coastal lands would provide some measure of damping of wave energy as well as relief from increased heat.

Other adjustments would involve the protection of arable land, improved management of water resources, introduction of new agrotechnology to cope with new realities, controlled land use policies, maintenance of food reserves, and the introduction of emergency disaster relief measures.

For protecting arable lands, some of the low-cost, low-technology measures mentioned above would be applicable. Improved water management techniques would involve the building of dams (after environmental impact assessment), aqueducts, reservoirs, irrigation systems, and river diversions with the objective of husbanding water in times of drought. The adoption of new agrotechnology should aim at introducing more salt- and heat-tolerant crops, developing adaptive irrigation systems aimed at reducing salinity stress, and so on. Although the region is far from being self-sufficient in its food needs at present, there will be a need to stockpile food and institutionalize other disaster relief measures to cope with emergencies that may arise from sudden flooding or drought.

Other adjustments would require the setting up of environmental monitoring and early warning systems, providing flood vulnerability and land use maps for coastal areas, and perhaps above all, providing public information and education. This calls for extensive information-gathering, analysis, and utilization. Public information and education would drive home to the populace the seriousness of the anticipated impacts from increased atmospheric temperatures and sea level rise and thus better prepare them for the implementation of certain protective, preventive, or adaptive measures that would necessarily have to be put in place.

CONCLUSION

Higher atmospheric temperatures and increased sea level rise are realities that humanity has to cope with now and in the future. Even if all suggested measures to stop the introduction of greenhouse gases were put in place now, the world would still experience many of the anticipated impacts due to "sins of omission or commission" already committed by man toward global warming.

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The application of most of the protective, preventive, or adaptive measures suggested above will be imperative but it is important that proposals for adjustments to the expected impacts be embodied in a coordinated and enforceable regional development plan. UNEP's Regional Seas Programme for the West and Central African region affords a vantage platform for discussing and institutionalizing such a plan. It is hoped that governments in the region, while pursuing policy options at the national level, would now appreciate, even more than ever before, the distinct advantages for a regional approach to the problems associated with global warming.

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BIBLIOGRAPHY

Bruun, P. 1962. Sea level rise as a cause of shoreline erosion. Am. Soc. Civil Eng., Proc. V.88 Waterways and Harbours Div. Journ. WW1:117-130.

Emery, K.O., E. Uchupi, J. Phillips, C. Bowin, and J. Mascle. 1974. The Continental Margin of Western Africa: Angola to Sierra Leone. Contribution No. 3481. Woods Hole, MA: Woods Hole Oceanographic Institution.

Ibe, A.C. 1988a. The Niger Delta and the global rise in sea level. In: Proceeding of the SCOPE Workshop on Sea Level Rise and Subsiding Coastal Areas, Bangkok, Thailand, November 7-14, 1988. Pergamon Press.

Ibe, A.C. 1988b. Coastline Erosion in Nigeria. Ibadan, Nigeria: Ibadan University Press, 217 p.

Ibe, A.C., and R.E. Quelennec. 1989. Methodology for assessment and control of Coastal Erosion in the West and Central African Region. UNEP Regional Seas and Reports and Studies No. 107. Geneva: United Nations Environment Programme, 112 p.

Pilkey, O.H., et al. 1981. Old solutions fail to solve beach problem. Geotimes 26:18-22.

UNEP. 1984. Environmental management problems in resource utilization and survey of resources in the West and Central African Region UNEP Regional Reports and Studies No. 30. Geneva: United Nations Environment Programme, 83 p.

THE GULF OF BENIN: IMPLICATIONS OF SEA LEVEL RISE FOR TOGO AND BENIN

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INTRODUCTION

The coastline of West Africa in general, and the Gulf of Benin in particular, has witnessed sea level variations of great dimensions in the past. The present configuration of the coast is the product of the oscillation of sea level that took place 20,000 years ago. Short-term as well as seasonal oceanic fluctuations (tides, waves, storm waves) linked to atmospheric disturbances are sometimes spectacular on the West African coasts, but the greatest dangers are long-term changes that could result from a change in the world's climate. Global warming is probably the cause of the rise in sea level that we have been witnessing since the beginning of the 20th century.

Accelerated sea level rise -- which is already 2 cm per year along some coasts -- will bring about important natural, socioeconomic, and cultural disruptions in the coastal plain of the Gulf of Benin. The coastal areas are the most densely populated and contain the economic heart of both Benin and Togo, including the main towns, the port and airport infrastructure, and the majority of the countries' industries.

The coast of the Gulf of Benin is a low and even coastal plain stretching nearly 500 km from the Cape of the Three Headlands (Takoradi Region in Ghana) to the Delta of Niger (Nigeria). This paper focuses on the approximately 175 km that constitute the coastal zone of Benin and Togo, examining (1) the possible effects of future sea level rise on the coastal ecosystems such as deltas, estuaries, lagoons, mangroves, and human activities of the coastal plain; (2) the reactions of the different research institutes and decision-makers in the face of these impacts; and (3) the present characteristics of the coastal environment.

IMPACTS OF ACCELERATED SEA LEVEL RISE

Rising sea level is always accompanied by inundation and erosion. The Gulf of Benin coast will be very sensitive and catastrophes may result if appropriate precautions are not taken in time. We discuss the effects and damages of three possible scenarios:

Sea Level Rise of 50 cm

As Figure 1 shows, the shore could retreat considerably, particularly between Anecho and Grand-Popo. A retreat of about 100 meters may be foreseen, which will be a big blow to the Cotonou-Lome interstate road, which would be dangerously threatened and would have to be moved inland. Nearly half the beaches and coconut-tree plantations would disappear in this region, although some of the agriculture would not suffer serious damage. We can be certain that Grand-Popo and Agoue graveyards would be periodically washed by the waves.

If urbanization is checked, particularly in the east of Cotonou, the risks would be less, but there is little hope that this will happen. The swampy areas would increase considerably, especially in the estuary of the Mono River, which would bring about a loss of nearly 25% of the existing upland, especially in the city of Cotonou where the situation is already highly critical. The ecological imbalance caused by the oversalinization of the coastal lagoons would surely be disturbed; the degradation of the mangroves which was already persistent will be aggravated.

Protective measures would continue to aggravate the problems downstream, but they can protect the very sensitive strategic places on the coast. However, the protection would be short-lived and would lead to other management problems.

Sea Level Rise of 100 cm

All the damages from the previous scenario would be aggravated. The retreat of the shoreline would provoke the displacement of all hamlets built on the crest of recently formed barrier islands. Two-thirds of the town of Cotonou would be submerged and the town would be depopulated since there is no possibility of extension; by contrast, the town of Lome could be stretched farther north on the plateau. The towns of Grand Popo, Agoue, Aneho and Kpeme would be seriously threatened and may disappear. A high salinization of the coastal plain would render life conditions more precarious. Protective measures would not be feasible, and people would instead think of controlling the migration toward the plateau.

Sea Level Rise of 200 cm

Because their elevations are only 3 m, all recently formed barrier islands will come close to complete submergence; the portions not inundated will almost surely erode (cf. Figure 2). Only a few small "islets" of lesser importance will remain. All human settlements of the coastal plain wwould disappear. Only the part of the town of Lome on the plateau would be able to resist destruction. The Lome-Cotonou-Lagos interstate road would be partly submerged. The settlement patterns in this part of the world would have to be reconsidered. In any case, if this rise of the sea level persisted, people would surely not wait before considering relocation toward the plateau and new modes of life.

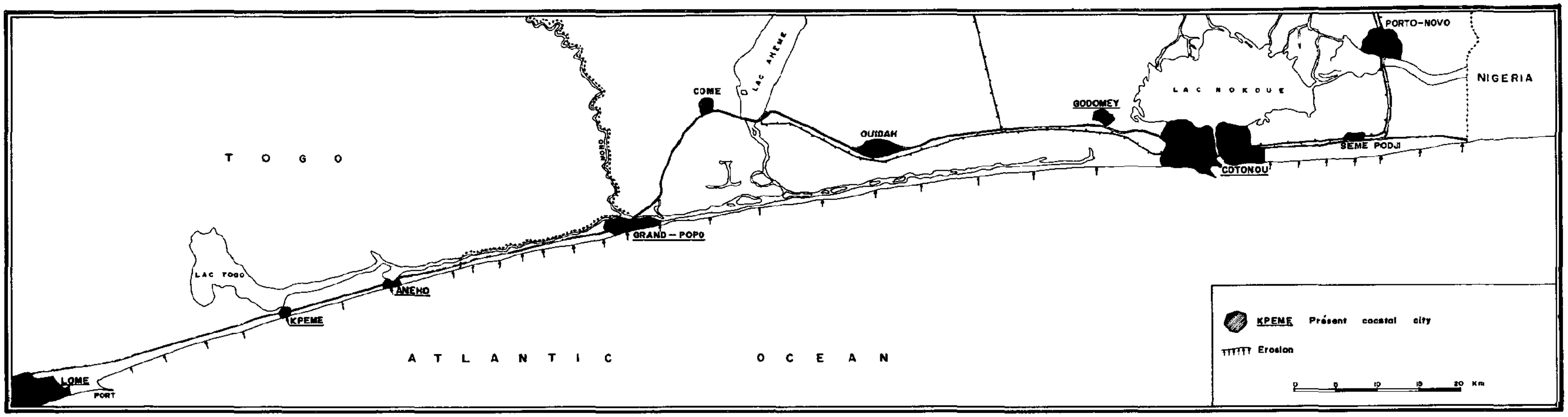

Figure 1. Areas vulnerable to a 50 to 100 cm rise in sea level.

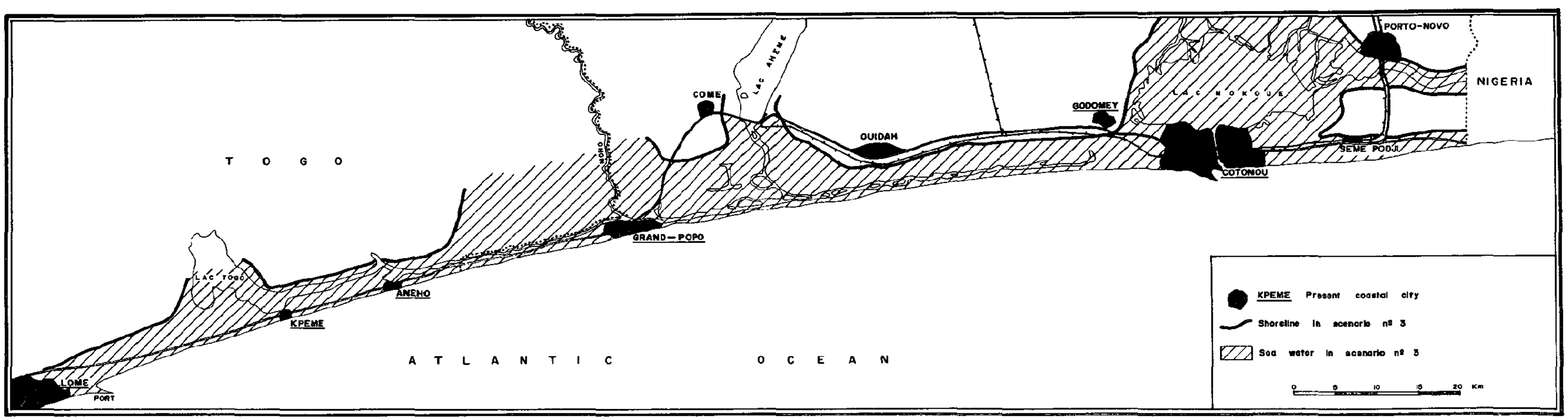

Figure 2. Land loss from a 2-meter rise in sea level.

POSSIBLE RESPONSES TO SEA LEVEL RISE

There are two solutions to safeguard the coastal zones of Togo and Benin along the Gulf of Benin: (1) coastal defense and the artificial nourishment of the beaches; and (2) respect for the littoral dynamics which requires avoiding, as much as possible, development that sets up an unavoidable confrontation between humanity and the sea.

The evolution of research in the region appears to support a gradual shift from the former to the latter approach. Still, most proposals for addressing erosion are short-term and do not consider sea level rise. The overall theme of most proposals is a natural protection of the littoral zone by using beach rock. But the characteristics of the Gulf of Benin coast suggest that the effectiveness of this natural protection would be limited, particularly if sea level rise accelerates.

In both Togo and Benin, survey offices and university Applied Research Laboratories are responsible for management of this coast. The labs are studying the possibilities of safeguarding nature according to its evolution from the field and the laboratory's research. The survey offices are studying the cheapest methods of protecting certain elements of the environment by fighting against some natural forces.

Given the prohibitive costs of some solutions and the lack of resources in these difficult times, the majority favor measures that control the littoral dynamics. The authority of the researchers is limited because it is the decisionmakers who have the final word. Sometimes, they neglect the advice of the nationals and turn to proposals made by foreign survey offices. But policies are changing. Public opinion is obliging decisionmakers to enter into dialogue with researchers, planners, and town developers. Nowadays, few people perceive the rise of the sea level as an important factor in the management of the coastal zone. But over time, the various scientific and policy reports on the subject will probably be able to convey the importance of such a phenomenon.

THE COASTAL ENVIRONMENT OF BENIN AND TOGO

On the coasts of the Gulf of Benin, the tide is semidiurnal, with two highs and two lows of nearly equal amplitudes that succeed each other at regular intervals. The spring and neap tidal ranges are 1.6 and 0.6 meters, respectively.

Along the shores of Benin and Togo is a coastal strip whose width increases from the west (2 km in Lome) to the east (10 km at the Benin-Nigerian border). It is a contact zone between many old and new barrier islands, lagoons, and swamps that separate the coastal features from the inland slopes (yellow and claylike sands). This body is limited in the north by a scarp of the red-clayed plateau. There are numerous barrier islands with elevations of 3 to 5 meters.

Table 1. Evolution of the Coast

SECTORS	1959–64	1964–69	1969–75	1975–81	1981–84	1984–89
ESTUAIRE VOLTA–KETA	*	–	–	–	–	–
ZONE W KETA	+	+	+	+	+	+
KETA VILLE–AFLAO	–	–	–	–	–	–
W PORT – LOME	*	* / +	+	+	+	+
EST PORT – LOME	*	* / –	–	– / *	*	*
TROPICANA	*	* / –	–	–	–	*
TROPICANA–KPOGAN	*	*	–	–	–	–
KPOGAN–AGBODRAFO	*	*	*	–	–	–
AGBODRAFO–GUMUKOPE	*	*	*	–	–	–
GUMUKOPE – ANEHO	*	* / +	* / +	–	–	–
ANEHO–HILLA–KONDJI	*	*	*	* / +	* / +	* / +
HILLA–KONDJI – GRAND POPO	*	*	*	* /	* / +	* / +
GRAND POPO VILLE	*	*	–	–	+	+
GRAND POPO – OUIDAH	*	*	*	*	*	*
OUIDAH–AEROPORT–COTONOU	*	*	*	*	*	*
W–PORT – COTONOU	*	+	+	+	* / +	*
PORT – P.L.M.	*	+	+ / *	+ / *	+ / *	*
P.L.M. — SOBE PRIM	*	–	–	–	–	–
SO BE PRIM — KLAKE	*	*	*	*	*	*

+ FATTENING

– EROSION

* STABILITY

– – – APPARITION OF THE BEACH–ROCK

——— EFFICIENT BEACH–ROCK

West Africa

The evolution of the coast has been schematized in Table 1. The offshore barrier islands are mainly occupied by a well-planned planting of coconut trees complemented in the east by the planting of eucalyptus and filao. Mangroves are mainly found along the coastal lagoons, with the western boundary schematized by an Aneho-Glidji line.

HUMAN ACTIVITIES ALONG THE GULF OF BENIN

Since the 16th century, the littoral of the Gulf of Benin, just like the whole of the West African coast, has been the center of many human migrations and the magnet for intense agricultural and commercial activities.

Demography

Although the distribution of the population is uneven, the density of the rural population in the coastal plain of the Gulf of Benin is more than 200 inhabitants per square kilometer. The urban and demographic dynamism is marked by industrial and related activities in Cotonou and Lome. The combined population of the major cities (Lome, Aneho, Grand-Popo, Ouidah, Cotonou, and Seme) is estimated at about 1.5 million inhabitants; the population of the entire coastal plain is about 2 million, about 25% of the total population of both countries. The urban dynamism of Cotonou is of concern, as it is a town in full demographic explosion (600,000 persons) where the only open space for expansion is on barrier islands stretching east of the town where erosion is already very serious.

Economic Activities

The coastal region is the economic hub of both countries, for it harbors the main towns, the ports and airports, and, above all, a number of important industries. The role of the port activities in the present economic development of those countries is unquestioned (despite the scarcity of comparative data to demonstrate its importance). Lome and Cotonou ports play an important role in the import and export trading of landlocked countries of West Africa (Mali, Burkina Faso, and Niger). The steady growth in the port activities, which was more than 500% from 1968 to 1978, even recorded a sudden increase between 1977 and 1980 because of the onset of certain activities (oil refinery in Lome and the role played by Nigerian imports during the time of the oil boom, when Lagos Port was "congested").

Agriculture

Agriculture in this region is a function of the climatic and pedologic conditions, which are not very good. The bars are mainly occupied by well-arranged plantations of coconut trees. Near the coastal lagoons, some grain foodcrops are grown (maize, cassava, cowpeas) as well as vegetables.

Fishing

Just like the Lebou in Senegal, the Akan in Cote d'Ivoire and in Ghana, the Peda and the Pla peoples from Ghana have moved into the coastal strip of the Gulf of Benin, practicing a flourishing fishing economy which nurtured the big trade with the people of the interior. It was mainly the lagoons that attracted the Peda, even though Lake Nokoue and Porto-Novo lagoon are largely exploited by the Tofinu. In general, fishing is a traditional activity (small day-trip fishing) that provides freshwater species (tilapia and crustacea).

Since 1960, with the construction of Lome and Cotonou ports, offshore fishing has developed with the massive arrival of Ghanaians (Fanti and Keta) who introduced gear boats in this business that became semi-industrial. The economic position of fishing in the region is in an average position (66th) in the world, near the Cote d'Ivoire and far behind Nigeria (28th), Senegal (33rd) and Ghana (34th).

Today, offshore fishing is the most important activity practiced by fishermen living at the coast; it provides a considerable quantity of fish (about 50 million tons/year for both countries) to a large part of the population of the capital cities and the coastal towns.

Many of the fish caught in the region depend upon coastal wetlands. Accordingly, the loss of those areas to rising sea level could severely hurt fishing. The ability of the shallow water bodies that replace the wetlands to support fisheries is unknown.

Modifications of the Shore

The demands of the national economy have called for the construction of two deepwater ports in Lome and Cotonou. The protecting jetties of these ports are large and they have accelerated the process of coastal erosion already started by the construction of Akossombo Dam. More recently, the construction of many piers for the protection of some strategic zone (Kpeme factory, Aneho town, P. L. M. Hotel, Hotel da Silva) and the hydroelectric developments on the Mono River (Nangbeto Dam) have added to the sedimentary and ecological inbalance of the coastal zone (see Table 1).

Coastal Management

The general consumption of space all along the Gulf of Benin by hotels and various structures and equipment aiming at the tourist trade is presently a fundamental concern of planners and developers. In light of today's disorderly management, avoiding irreversible choices will require a new policy for the coastal zone. For the past 10 years, a planned development scheme has been under consideration which, taking into account the present land uses, can be summarized as follows:

- to limit the coastwise boundary of the urbanization zones and main development;
- to define the mode of stabilization of the coasts; and
- to plan the zones for recreation and tourism exclusively equipped with mobile facilities.

Up to now, no government decree has considered such ideas; so, for the time being, they remain purely and simply academic reflections.

CONCLUSION

The fragility of the coasts in general and of those of West Africa in particular is of great concern. To try to best preserve this littoral, it is necessary to understand its dynamics better. Sea level rise is an inescapable parameter to reckon with in any approach to the management of the littoral. A systematic inventory of all useful information sources is a foremost task (e.g., topographic maps, general maps, inventory maps, aerial photographs, satellite pictures, oceanographic data, population density maps, historical documents). Certain approaches such as satellite teledetection are indispensable tools today to better understand certain phenomena (e.g., waves, salinity, currents, water temperatures, biological processes of estuaries). All of these elements are the basis for understanding and efficiently managing the coastal heritage.

APPENDIX

THE GENERAL CHARACTERISTICS OF THE LITTORAL OF THE GULF OF BENIN

THE NATURAL SETTING

The Coastal Climate

The climate of the Gulf of Benin is of a beninian type (subequatorial) with two rainy seasons (mid-March/July and September/November) and two dry seasons. The average rainfall is 1,200 mm per year decreasing toward the west (1,400 mm per year in Seme and 850 mm per year in Lome); this decrease is due to the configuration of the coast in relation to the marine winds. The temperature is constantly high (yearly average is 27°C) with the average maximum in March (33°C) and the average minimum in August (25°C) when temperature can go down to 22.5°C. The months of January, February, and March record high thermal amplitudes (12°C). These variations are reduced during the rainy season.

The predominant direction of the wind is southwest with average speeds of 4 to 6 m/s (3 Beaufort). The winds from the south-southeast sector are not frequent and they blow in April and May. Because of the relatively even relief, the pattern of winds does not vary much according to seasons. In dry season, the wind strength is weak to moderate (2 to 5 m/s) in the morning. It is stronger during the day (5 to 7 m/s) and becomes moderate in the evening and in the night (4 to 6 m/s). During the rainy season, a moderate wind blows (4 to 6 m/s) in the morning which becomes stronger in the afternoon (6 to 8 m/s) and remains constantly moderate to strong (5 to 8 m/s) in the evening and at night. The peak speeds are reached during the passage of rain lines (east to west direction) with average speed of 15 m/s, accompanied by harsh winds and rainstorms.

Swells and Waves

Along the Gulf of Benin, one observes a long swell of a distant origin, the wavelength of which can vary between 160 and 220 m. This swell unfurls over the bar at a distance of about 150 to 200 m from the shore (characteristics at the Cotonou wharf). There are also waves due to local winds whose characteristics are changing but have little importance for the morphological phenomena of the coast. Their wavelength is about 50 m. The swell whose primary period is 12 seconds (even though it can sometimes vary between 10 and 16 seconds) has a relatively regular average height between 1.0 and 2.0 m.

Table 1 gives the average amplitude of swell in Cotonou. Using the averages observed in Lome in 1955 and 1961, it is noted that swells are stronger in Cotonou than in Lome by 28% in 1955 and 11% in 1961. This difference is due, according to Sitarz (1963), to the protection offered by Cape St. Paul (Ghana) to Lome port area.

These swells generally travel from southwest to northeast (1980). The most recent surveys give the following distribution:

West Africa

SE - S	135° to 180°	=	10%
S - SW	180° to 203°	=	36%
S - SSW	203° to 225°	=	54%

The breaker line in the region of Cotonou occurs at a depth of 3 m, or at about 150 to 200 m from the shore: This is the locus of important sedimentary movements.

The Coastal Geomorphology

The geomorphological evolution has mainly resulted from the fluctuations of the marine level during the Quaternary, and secondly by the local tectonics (faults of Togbin, of Godomey and Krake determined by J. Land and G. Paradis, 1977). Since 5,000 years ago the series of barrier features have regularized a coastline that was indented with deep rias during the Flandrian transgressive maximum. These are essentially sandy bars; granulometric and microscopic analyses confirm the marine origin of these sands.

One can subdivide this shore into three sections with varying characteristics:

Lome to Grand-Popo

A narrow coast (average width = 1 km and narrows towards the east) with altitudes of between 3 and 5 m. Three types of profiles can be distinguished according to hydrodynamic parameters:

- Profile with straight crest, steep seaward slope, short foreshore (less than 3 m), upper berm at 1 m, even surfaced slope: profile resulting from strong swells.
- Profile of very strong swells: profile with round crest, with basal berm on its seaward slope. The inlandside of the barrier is steeply sloped toward the lagoon.
- The beach profile with straight or rounded crest characterizes the transition between a strong swell and an average one.

Grand-Popo to Godomey

The altitudes of the barriers in this section also vary between 3 and 5 m, and they are modified on the inland margin by the lower course and the mouth of River Mono, the coastal lagoons, and the swamps. The width of the bars is quite narrow (less than 200 m). We see the same types of profiles as in the previous case.

Godomey to Krake

The bars break up into a multitude of successive parabolic crests which are rigorously parallel, of west-east orientation, and of a maximum altitude of 6 m.

The granulometric (medium and fine sands) and morphoscopic (blunted and shining sands) measures are in favor of a marine origin. These fine sands, generally well sorted, have been deposited under homogeneous hydrodynamic conditions even though some local disturbances can be noticed.

Close analysis of sediments along the littoral of the Gulf of Benin shows fine to coarse sands (median diameters between 0.4 and 1 mm) at the foreshore, up to 4 m; from 4 m to 16 m elevation, the sediments are very fine and well sorted. Despite the homogeneity in the distribution of sediments from the west to the east of the gulf, there is a strong variation to the east of the mouth of River Mono; these sediments have medium diameters from 3 to 6 mm in the depths of -12 m, and they are composed of coarse sands mixed with gravel.

The geomorphological cartography carried out with the collaboration of researchers of both universities (Adam, 1986) has made it possible to demonstrate the complexity of the evolution of this coastal strip. One element is durable formation, beachrock, evidence of an old beach consolidated by a carbonate cement. This formation is made of overlying slabs whose thickness varies between 0.5 and 1.5 m and whose width varies between 25 and 50 m. Its position in the littoral profile (sometimes reaching + 3 m altitude) and its mechanical resistance causes beachrock to be a natural protection against coastal erosion. It presently plays a role of wave-breaker, eliminating the actions of the swell in the coast of the eastern part of Lome. This formation exists all along the coast at different altitudes. Its role seems to be efficient under the present hydrological conditions prevailing between Lome and Kperme, between Ouidah and Cotonou, and to the east of Seme. Its efficiency is null elsewhere. Today, the distribution of beachrock is to be considered in any survey aiming at evaluating the littoral of the Gulf of Benin.

Inlets

Three hydrological systems present themselves from the west to the east:

- The system of Lake Togo: Lake Togo gathers the waters from the Zio and Haho Rivers before flowing into the ocean through the lagoon mouth of Aneho. This mouth has a strange evolution; having been long closed by a spit of barely 30 meters, it discharges water collected from brooks into the Mono River through the latter's effluent, the Gbaga. When the water rises, the whole area is flooded and since 1987, with the construction of jetties at Aneho, an opening has been made at Aneho which serves as a permanent mouth for this system of Lake Togo.

- The estuary of Mono is a hydrological complex characterized by the courses of the Mono and Koufo Rivers and the tidal flows. The dynamic behavior of this sector is linked with the variations of the tides and of the flow of the river. During flood time, the flow is enough to push back the saltwater zone beyond the shoreline. Inversely, when the freshwater flow is at a low level, the saltwater contact goes up to Agome-Seva (40 km). This part of the valley (6 m IGN) and Lake Athieme are completely under the influence of the tide.

West Africa

- The Delta of Oueme is the most important hydrological element of this area. It is characterized by the regime of the Oueme-So system, which

  is influenced by the tropical rainfall pattern of the upper basin of River Oueme and the tidal currents.

All these inlets have undergone serious changes since the nouakchottian transgression that put the different barriers in place. First of all, the construction of successive spits has diverted all the inlets toward the east. Such is the case of the valley of Zio and of Lake Togo, which used to run into the sea at the level of Kpeme but today uses the artificial channel, which is the permanent mouth of Aneho. The Mono River used to pour its waters into the ocean at Grand Popo; it currently discharges through the opening at Avlo, which became a permanent mouth only a couple of decades ago. The Oueme River that flowed into the sea at Lagos before the opening of Cotonou channel in 1986, can only be explained by this progressive migration toward the east for 5,000 years. These inlets are often blocked by the construction of different spits, which often provoke catastrophic floods during the rainy season. Such was the case of Cotonou in 1985, which prompted the opening of the channel in 1986; even after this opening, floods were reported in 1907, 1929, 1935, 1942, 1968, and 1987.

Those spectacular floods made it possible to map out marshy regions which are more than 65% of the area in the Gulf of Benin. They are more widespread in the estuaries of the Mono and Oueme where there are only few subaerial islands whose banks are covered with mangroves. In all of the coastal plain, the depressions between the islands are swamps whose landscapes look like littoral meadows.

COASTAL EROSION AND MANAGEMENT ALONG THE COAST OF LIBERIA

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INTRODUCTION

Beach erosion affects all coastal countries of the world, including Liberia.

The environmental consequences have often been devastating. In some cases, whole communities have been displaced -- or worse, wiped out. In addition to extensive personal properties, major losses have included port facilities, building infrastructures, recreational facilities, and agricultural, industrial, and residential land.

As more and more infrastructures are developed along shorelines, erosion seems to accelerate because of the nature of the type of development. For instance, port facilities tend to promote erosion. It is, therefore, essential to keep in mind the interaction of developmental activities with natural factors so that such development is not threatened at a later date. For example, the construction of the Free Port of Monrovia, the Hotel Africa, and the Villas has accelerated erosion, causing loss of beaches and buildings down the coast.

Sea level rise from the greenhouse effect would aggravate all of these problems. Unfortunately the Ministry responsible for assessing erosion has not conducted any studies of the implications, of sea level rise, and we were unable to undertake even a preliminary inventory of the likely consequence -- let alone the appropriate response strategies. Nevertheless, the Ministry of Lands, Mines, and Energy recognizes the increasing importance of global warming and the need to participate in the international process. Given these limitations, this paper discusses Liberia's current thinking on existing erosion problems, with a hope that it will help researchers trying to understand how our country would respond to accelerated sea level rise.

The Importance of Erosion

Coastal erosion is a dynamic process resulting from an imbalance between sand accretion and erosion by the sea or wind. When equilibrium is not established between accretion and removal of sand, erosion becomes inevitable.

Both manmade and natural factors induce shifts in the equilibrium of alongshore transport. General topographic, geologic, and meteorological features constitute natural process components, while the construction of hydraulic structures, such as port facilities, dams, buildings, and beach mining, tends to induce the artificial component.

Control of coastal erosion is very important in the context of the development and management of coastal environments. However, choosing the type of technology appropriate for solving this problem requires an understanding of three essential elements:

- the basic physical processes of coastal erosion, such as wave behavior, currents, and tides;
- human-induced (anthropogenic) changes in the physical coastal process, which also contribute to erosion; and
- the structural and nonstructural solutions to the problem.

While physical factors and the range of appropriate technologies may exist, sometimes for a developing country the decision of which technology to use with regard to cost becomes very complicated because of the relative scarcity of resources needed for the solution -- e.g., equipment, skilled manpower, financial support.

The development along the coastal zone has been dramatic in the last few decades. Construction has included resort settlements, residences, commercial harbors, and a few coastal defense structures. Most of these structures were built in response to a particular situation and with little concern for environmental or downcoast impacts.

COASTAL PROCESSES

The coastal perimeter consists of both landward and seaward portions of the shoreline. Erosion of the shoreline starts when the removal of sediments is greater than accretion. Both of these processes -- erosion and deposition -- constantly occur along the shoreline. Therefore, an assessment of shoreline erosion must consider the difference in the rates of erosion and accretion within a fixed time span.

The sources of the sand we find on the shoreline originate from upland drainage systems -- e.g., rivers, coastal fastlands, and offshore outcropping of landward deposits. These systems are responsible in the long run for secondary sources, such as beaches, sand dunes, and offshore deposits. Any disturbance of these source materials, for example by wind and water, which are the ultimate agents responsible for accretion and removal of coastal material, will lead to erosion.

NATURAL CAUSES OF EROSION

The natural processes of erosion are usually impossible to resist. The natural shoreline is a result of the interaction between the processes of erosion, accretion, and meteorological and oceanographic conditions. Any changes in one of these conditions will result in the transgression or regression of the shoreline. Natural erosion is a geological process that seeks to establish an equilibrium among the natural forces. Examples of natural processes of erosion include the influences of tides, waves, eustatic changes in sea level, storms, hurricanes, tsunamis, coastal characteristics, and loss of sediment supply.

ANTHROPOGENIC CAUSES OF EROSION

A significant amount of erosion is due to improperly planned human interferences with natural coastal processes, such as dam and port construction, beach sand mining, drainage alteration, devegetation and farming, construction near the shore and beach, disposal of solid waste and landfill sludge, inlet stabilization, and dredging.

The coast of Liberia is approximately 600 kilometers (350 miles) long. It includes deltaic plains, fan deltas, coastal plains, and steep slopes produced by faulting and intense erosion. Part of the coastline is characterized by drowned valleys with bays, promontories, and pocket beaches. Portions of the coastline are composed of sand pits, barrier beaches, and lagoonal environments.

Sands of the Liberian coast drift from Harper City in the southeast to Robertsport City in the northwest. It has been estimated that 7.2×10^6 cubic meters are transported from rivers annually, and that some 20% of this volume is redeposited on the coast. A decrease in supply of sand is due to a decrease in the transport of river sediment and the rate of littoral drift, which results from the construction of manmade structures on the coast.

PREVIOUS WORK

Studies and remedies related to coastal erosion are primarily the responsibilities of the Ministries of Lands, Mines, and Energy; Public Works; and Rural Development.

Three organizations have conducted studies on the coastal erosion of Liberia: the Japanese Agency for International Development; the Ministry of Lands, Mines, and Energy; and the LAMCO J.V. Operation Company.

West Africa

Japanese Activities

In 1978, the Japanese Agency for International Development conducted studies for three weeks to identify the various causes of erosion along the Liberian coastline. Their studies took them to Robertsport, Greenville, Harper, Buchanan, and Monrovia. Two principal causes of erosion were identified by the Agency: (1) drifting of river outlets, and (2) changes in the balance of littoral transport caused by blockage of natural sand drifting, which was the result of human activities -- e.g., construction of breakwaters, beach mining, and possible reduction of sand supply from the rivers by the construction of the St. Paul River Dam.

LAMCO J.V. Operating Company

The rate of erosion increased tremendously in Buchanan after erection of the breakwaters, especially within the port area. Although sand was naturally deposited east of those structures, active beach mining has also been intensive, thereby accelerating the process of erosion.

In recognition of these threats to the beaches with regard to coastal erosion, the Ministry of Lands, Mines, and Energy recommended that LAMCO undertake countermeasures, especially north of Buchanan, either by constructing groins or by providing artificial sand nourishment. Dr. Eugene H. Shannon (Director, Liberian Geological Survey) et al. (1979) reported that two groins, each reportedly valued at $35,000 (U.S. dollars) were constructed and proved to be rather effective at the time. Boulder dumping was also instrumental in reinforcing the shoreline against erosion. After this exercise, the Ministry of Lands, Mines, and Energy devised a scheme -- Environmental Monitoring -- to monitor the extent of beach erosion from time to time in Buchanan.

Whereas the degree of protection was adequate in certain areas, other side effects developed, especially along Atlantic Street in Buchanan. While government, through the Ministry of Lands, Mines and Energy, has continuously recommended that LAMCO establish more groin systems, progress has been slow.

The Liberian Government

Realizing the degradation of the country's shorelines by wave action, especially along areas with exorbitant infrastructures, the Government of Liberia set up a special technical committee in 1981, headed by the Ministry of Lands, Mines, and Energy, to investigate and find means of safeguarding Hotel Africa, the adjacent villas, and the beach. Other Ministries included Public Works and Rural Development. After some studies, the committee estimated the rate of erosion as approximately 10 feet (3 meters) per year.

Dr. Ntungwa Maasha, formerly Head of the Geology Department of the University of Liberia, conducted a study between 1980 and 1982 along the Monrovia coastline between Wamba Town and Yatono. Results of his study indicate that 80% of the coastline of Monrovia consists of sandy beaches that erode at a rate of 0.5 to 4 meters per year. The only depositional area identified was West Point beach, south of the Free Port of Monrovia. Natural shorelines were identified in the vicinity of lagoons. Dr. Maasha also reported that the littoral drift is everywhere from southeast to northwest, and that the long-shore current velocity varies between 16 and 31 cm/sec.

A three-man Swedish team consisting of Hans Hanson, Lennart Jonsson, and Bo Broms conducted a one-week study in 1983 along selected areas of the Liberian coastline. Besides substantiating that harbor construction and other forms of human interferences have aggravated the erosion problem, they gave an annual figure of about 50,000-60,000 cubic meters of sand respectively, for deposition and erosion south of the Free Port of Monrovia. They reported the sediment yield of the St. Paul River as 1.5×10^6 cubic meters/year. They also reported that the most frequent waves arrive from south to southwest, and that their heights change seasonally from 1.3 m (highest) in June to 0.6 (lowest) in March. For littoral transport, a wave height of about 1.1 m is said to be representative. A semidiurnal tide is also reported, with a tidal range of about 1-1.5 m. The tide induces long-shore currents with ebb stream directed to the south and north, respectively, flood currents being much weaker (5-15 cm/sec, as opposed to 15-45 m/sec for ebb currents).

BEACH EROSION STUDIES IN LIBERIA

Like most coastal nations, Liberia is faced with serious problems as a result of changes in the configuration of its shoreline due to the activity of the ocean waves. Erosion is causing shoreline recession in some cities -- for example, in Buchanan, Greenville, Harper, and Robertsport. Most recently, alarming incidents of beach erosion along some portions of the Monrovia coastline have resulted in loss of land and shorefront properties.

Because of the economic and environmental problems associated with beach erosion, the Government of Liberia -- through the Liberian Geological Survey, Department of Mineral Exploration and Environmental Research, Ministry of Lands, Mines and Energy, the University of Liberia, other government agencies, and foreign institutions, as mentioned in the previous section -- has endeavored to implement beach erosion studies and recommend possible remedial measures related to the development of shorefront properties. However, all of these studies have been focused on Monrovia as a result of finance.

OAU Village

The beach of the OAU Village area is characterized by more or less horizontal layers of black and brown-white, unconsolidated, medium- to fine-grained sands. In some areas, especially around Fanti Town, diabase and melanocratic gneisses outcrop in the sea and serve as wave barriers. As a result of the change in the balance of littoral transport caused by blockage of natural sand drift resulting from human interferences, the beach of the OAU Village is estimated to be receding at the rate of 3 meters a year.

West Africa

New Kru Town Area

The New Kru Town area is characterized by very fine- to medium-grained sand. The area is separated from the OAU Village by the St. Paul River. At the mouth of the St. Paul River, the beach is flat and broad, and it is composed of poorly stratified white clayey sand, which is dusty and crumbly when dry.

The recession rate around the New Kru Town area is more or less the same as around the OAU Village area. The area is affected by the same phenomena. Away from St. Paul River, toward Point Four, the beach face becomes narrower, gradually developing into a high escarpment about 5-7 meters higher.

West Point - Mamba Point Area

The West Point spit/bar, which lies at the mouth of the Mesurado River, has characteristics similar to those of the area around the St. Paul area, except that in West Point the flat and broad floodplain of the Mesurado River has been destroyed by manmade structures, mainly zinc shacks. The Mamba Point area, however, is characterized by massive diabase outcrops with steep cliffs, which reflect wave energy, induce offshore sediment transport, and prevent the formation of any beach. The diabase is well jointed horizontally as well as vertically. Boulders of diabase that have been undermined by wave action can be seen in the littoral zone. West Point-Mamba Point is the only area that has been identified as a depositional area, especially south of the Free Port of Monrovia.

The strip of shoreline from Cape Mesurado to the OAU Village area is within an embayment. Wave activity is much more complex because of wave refraction at the cape and at the Free Port breakwaters. This human interference has thus created an imbalance in the geomorphic system, and the adjustments in morphology need to be critically investigated.

Mamba Point - Elwa Area

The beach area between Elwa and Mamba Point is mainly characterized by coarse-to-medium to fine-grained sand in alternating black and white layers. With the exception of the area behind the Executive Mansion and near King Gray, where large diabase outcrops are discernible, the rest of the beach area is uniform, with sporadic diabase outcrops in the area.

There is an unusual increase in black sand (heavy minerals) in the Congo Town area, with band thickness ranging from 1 to 2 feet in some places. This area of increased heavy mineral occurrences is low-lying, swampy, and separated from the mainland by small lagoons.

Neutral shorelines were identified in the vicinity of lagoons where sand accretion and san removal are more or less in equilibrium.

METHODOLOGY

The methodology employed by the Liberian Geological Survey in the erosion studies of Liberia includes beach profiling, sediment sampling, and the observation and measurement of the littoral parameters in the field, as well as granulometric analyses in the laboratory. Aerial photographs and maps were also used to establish stations for studying and future monitoring (Figure 1).

Field Methods

A ground survey of the entire 35-km Monrovia coastline between the OAU Village area and ELWA was conducted between May and July 1984. During the survey, activities were mainly geared toward a better understanding of prevailing sedimentary processes and also the dynamics of the Monrovia littoral environment. The following paragraphs provide a complete breakdown of field activities.

Beach Profiling

Permanent features, such as trees, house fences, and electric poles, were used as reference (bench) marks for profile measurements. In the absence of such features, temporary markers were installed for easy location. Profiles were measured along lines perpendicular to the shoreline and extending to the existing water line. Conspicuous morphological features along the active beach face were used as survey points. Measurements were made using a surveyor's level and a stadia rod, and each station included a series of substations adequately spaced along the beach.

Slope Measurement

The foreshore slope angle was measured directly using the clinometer of the Brunton compass leveled on undisturbed portions of beach slope. Angle values given represent an average of readings collected from various places at a given site.

Wave Measurement

The wave periods at various locations were estimated by timing the breaking interval of incoming waves. At each location, the estimate was done in triplicate and the mean was used as the representative value. These mean values were then combined in statistical fashion, and the resulting average was used as the representative value for Monrovia and its environs. The average wave period was subsequently used to empirically calculate other wave parameters, such as length, height, and celerity.

Wind Direction

The direction of wind movement was measured using a flag and a Brunton compass. The flag was placed on the beach, and the compass was aligned with it to give the direction of wind approach. The various directions obtained throughout the study area were combined statistically to give an average value.

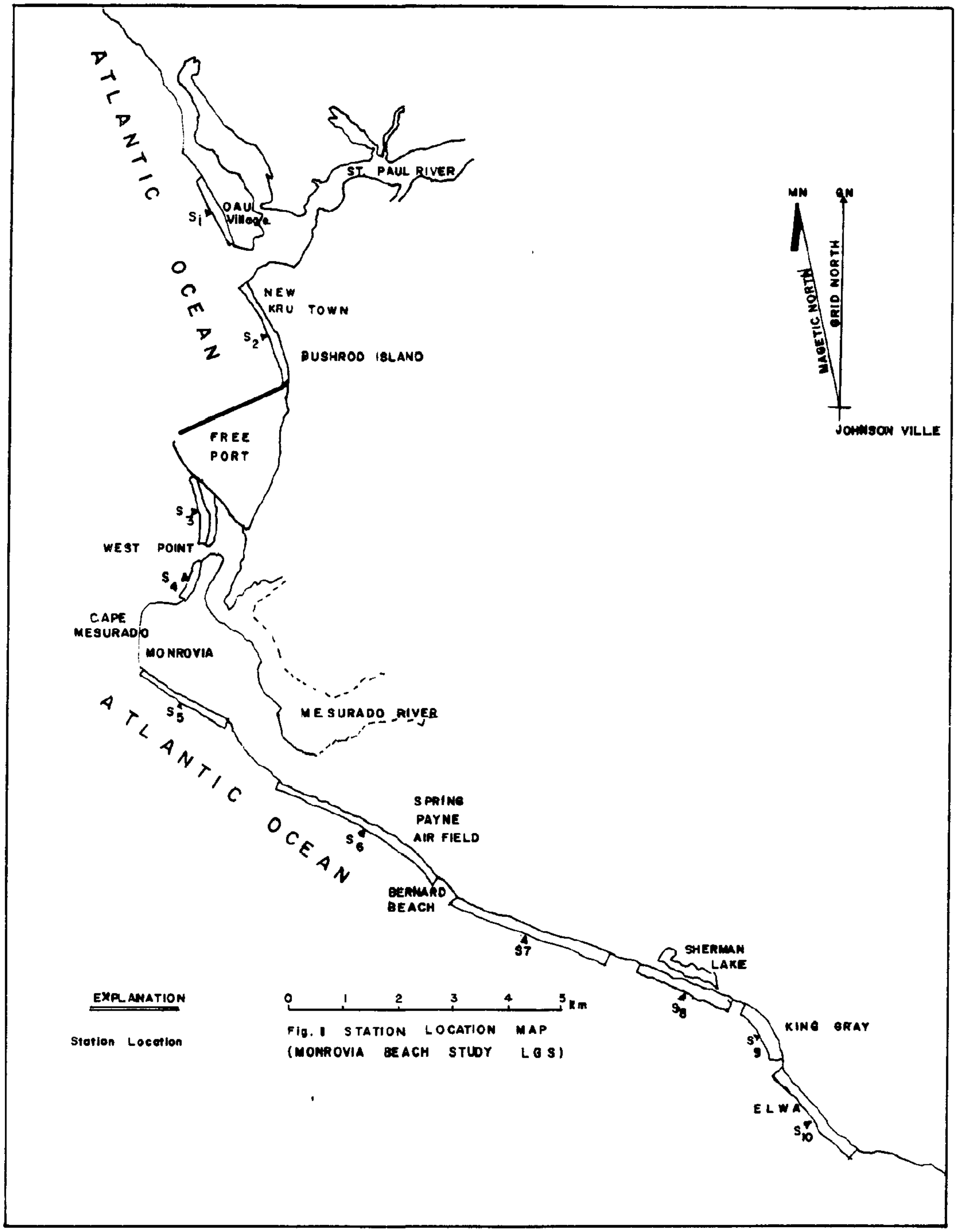


Figure 1. Station location map (Monrovia Beach study).

<u>Sediment Sampling</u>

The width of the beach varies from 9 m to 27 m. Therefore, a single sample taken at a station would not serve as a representative sample of a given station. For this reason, a triangular pattern was used in sampling each station or substation, with samples taken at the three apexes, as shown in Figure 2.

All samples marked A are those taken on the berm or overwash terrace, while those marked B and C were taken at the sea edge and at the midpoint between A and B, respectively.

Each sample was approximately labeled commensurate with the station or substation number. A geologic description of each sample was noted in the field book.

Wave Mechanics of Monrovia and Its Environs

Waves approach obliquely to the shoreline in Monrovia and its environs. The obliqueness increases in the area immediately north of Cape Mesurado, where shoreline orientation approaches parallelism with the apparent direction of wave approach.

Of a total of 40 readings of the direction of wind approach, 28 are toward the southwest, 4 toward the northwest, and 8 toward the southeast (Table 1 and Figure 3). Values to the southwest are more frequent; they have a range of 77 degrees, a mean of 38.3 degrees, and a standard deviation of 25 degrees. This indicates that at the beginning of the rainy season (May-June), the Monrovia coastline receives winds coming predominantly from the southwest (Figure 3). Considering wind-generated waves (sea waves), the estimated average direction of wave approach is South 38 degrees West. This bearing compares closely with wind records at the Spriggs Payne Airfield Meteorological Station.

The mean wave period for the Monrovia coastline is about 12.96 seconds. The statistical analysis is shown in Table 2. Using empirical equations (Friedman and Sanders, 1978), the deep-water wavelength (L_o) and the deep-water celerity (C_o) were calculated as follows:

$$L_o = 1.56T^2$$
$$= 262.02 \text{ m}$$
$$= 1.56T$$
$$= 20.22 \text{ m/sec} \qquad \text{Where } T = \text{wave period.}$$

These values correspond to an initial breaker depth (H_I) of 13.3 m ($L_o/20$), and the associated deep-water weave height (H_o) is found to be 10.22 m (0.039 L_o). Considering transformation due to shallow-water conditions, the wave-length (L_I) and the celerity (C_I) at initial breaking are found to be 139.1 m and 11.33 m/sec, respectively. Wave height at initial breaking (H_I) is found to be 10.4 m, and wave break mainly by plunging, with spilling types being observed in a few places. In the opinion of the authors, the landward limit of the breaker zone will be marked by a water depth equal to about one-half the deep-water wave

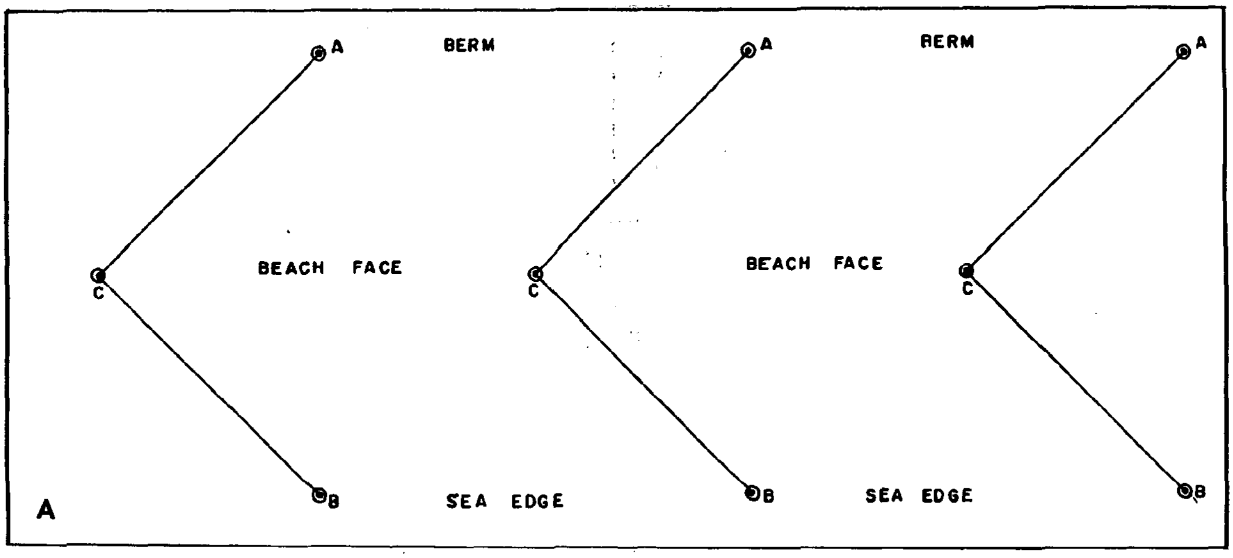


Figure 2(A). Sample pattern in plan view.

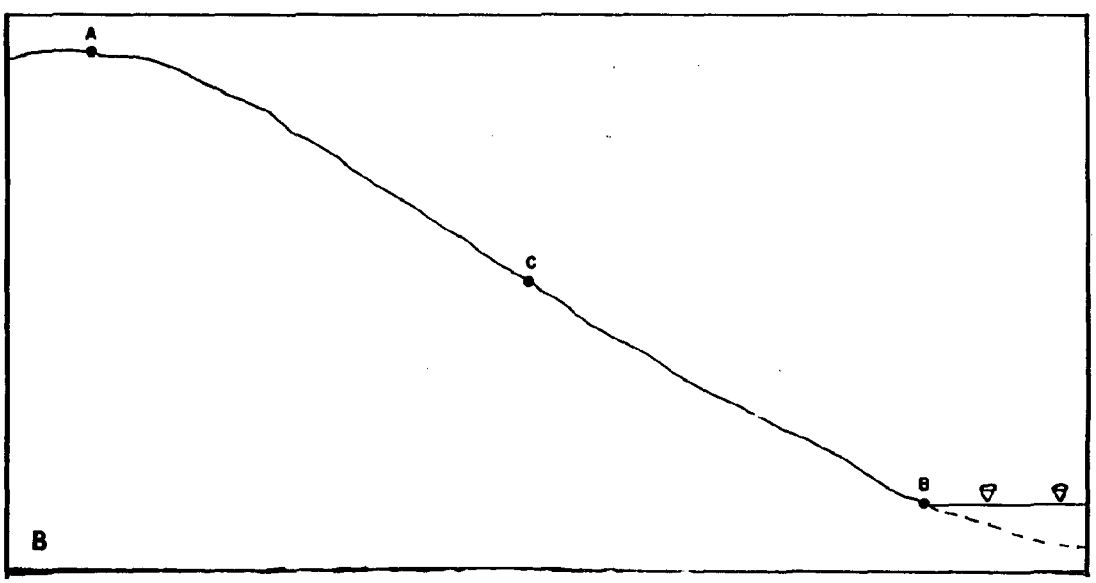


Figure 2(B). Sample pattern in profile.

Table 1. Statistical Analysis of Wind Direction Along the Monrovia Coastline (1984 data)

Measured Direction of wind Approach (Flagging					
Set 1		Set 2		Set 3	
S $X_1°$ W	Frequency (f_1)	S $X_2°$ E	Frequency (f_2)	N $X_3°$ W	Frequency (f_3)
10	3	15	1	80	1
13	1	22	1	83	1
15	1	25	2	75	1
17	1	30	1	85	1
18	1	32	1		$\Sigma f_3 = n_3 = 4$
19	1	37	1		
20	3	45	1		
25	2		$\Sigma f_2 = n_2 = 8$		
27	1				
28	1				
30	2				
50	1				
52	1				
55	1				
60	2				
64	1				
71	1				
75	2				
85	1				
87	1				
	$\Sigma f_1 = n_1 = 28$				

$N = n_1 - n_2 - n_3$

Where : N = Total # of measured values

$N = 28 + 8 + 4 = 40$

$n_1 = 28/40 \times 100 = 70\%$ of N

$n_2 = 8/40 \times 100 = 20\%$ N

$n_3 = 4/40 \times 100 = 10\%$ "

Figure 3. Diagrammatic illustration of dominant wind approach for Monrovia, based on Table 1.

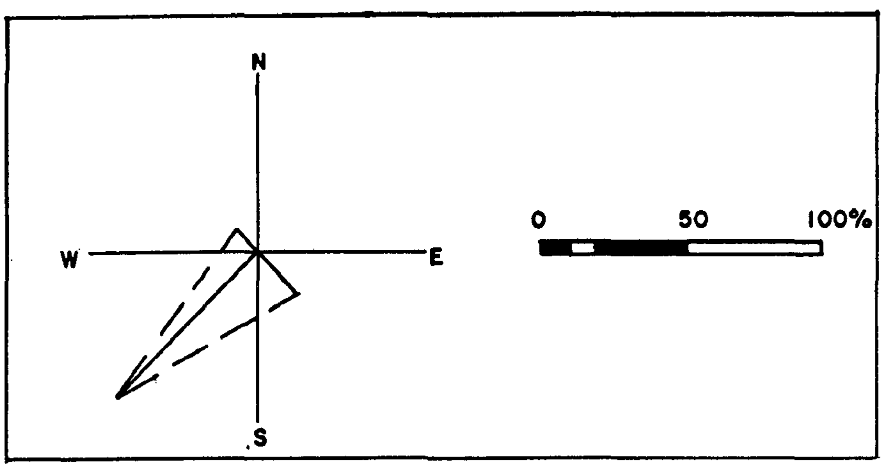


Table 2. Statistical Treatment of Wave Period Along the Monrovia Coastline

WAVE PERIOD (X) SEC	FREQUENCY (f)	(f) (x)	RELATIVE FREQUENCY f/n	DATA GROUPING	GROUPING FREQUENCY
6.6	1	6.6	.016	m	
7	1	7	.016	(7.5)	
8	1	8	.016	6.5-8.5	3
8.9	1	8.9	.016		
3	4	3.6	.065	m	
9.8	1	9.8	.016	(9.5)	
10	3	30	.048	8.5-10.5	9
10.7	1	10.7	.016		
11	3	33	.048		
11.5	1	11.5	.016	11.5	
12	5	60	.081	10.5-12.5	10
13	8	104	.129		
13.1	1	13.1	.016		
13.8	1	13.8	.016	13.5	
14	11	154	.177	12.5-14.5	21
15	8	120	.129		
15.2	1	15.2	.016		
15.5	2	31	.032	15.5	
16	6	96	.097	14.5-16.5	17
17	1	17	.016	17.5	
17.7	1	17.7	.016	16.5-18.5	2
-	62	803.3	1.00		

-GROUPING INTERVALS CONSIDERED are:

	Interval	mid-pt.
1)	4.5 - 6.5	5.5
2)	6.5 - 8.5	7.5
3)	8.5 -10.5	9.5
4)	10.5 -12.5	11.5
5)	12.5 -14.5	13.5
6)	14.5 -16.6	15.5
7)	16.5 -18.5	17.5
8)	18.5 -20.5	19.5

Mode = 14.0 sec.
Median= 13.I "
Mean = 12.96 "

n = 62; $\bar{x}$ = 12,96 s = 2.53 sec.

height ($H_o/2$). At this arbitrary depth of final breaking (h = 5.11 m), the characteristic wavelength (L_f) and celerity (C_f) are found to be 90.92 m and 7.08 m/sec, respectively. The wave height at final breaking (H_f) is also found to be 12.57 m.

COASTAL SEDIMENTS OF THE MONROVIA BEACHES

The beaches of Monrovia are characterized by medium- to coarse-grained sand, consisting of mostly quartz, with iron stains that give a brownish-white appearance. Heavy minerals (black sand) occur in minor amounts throughout, with an apparent increase in the Congo Town and ELWA areas, as evidenced by locally high bulk densities.

Representative histograms of the beach sand are shown in Figure 4 with respect to locality and the dominant size fractions, and a generalized variation line is shown in Figure 5. Local deviations from this general line were observed in the vicinity of rock shorelines where grain size is apparently larger.

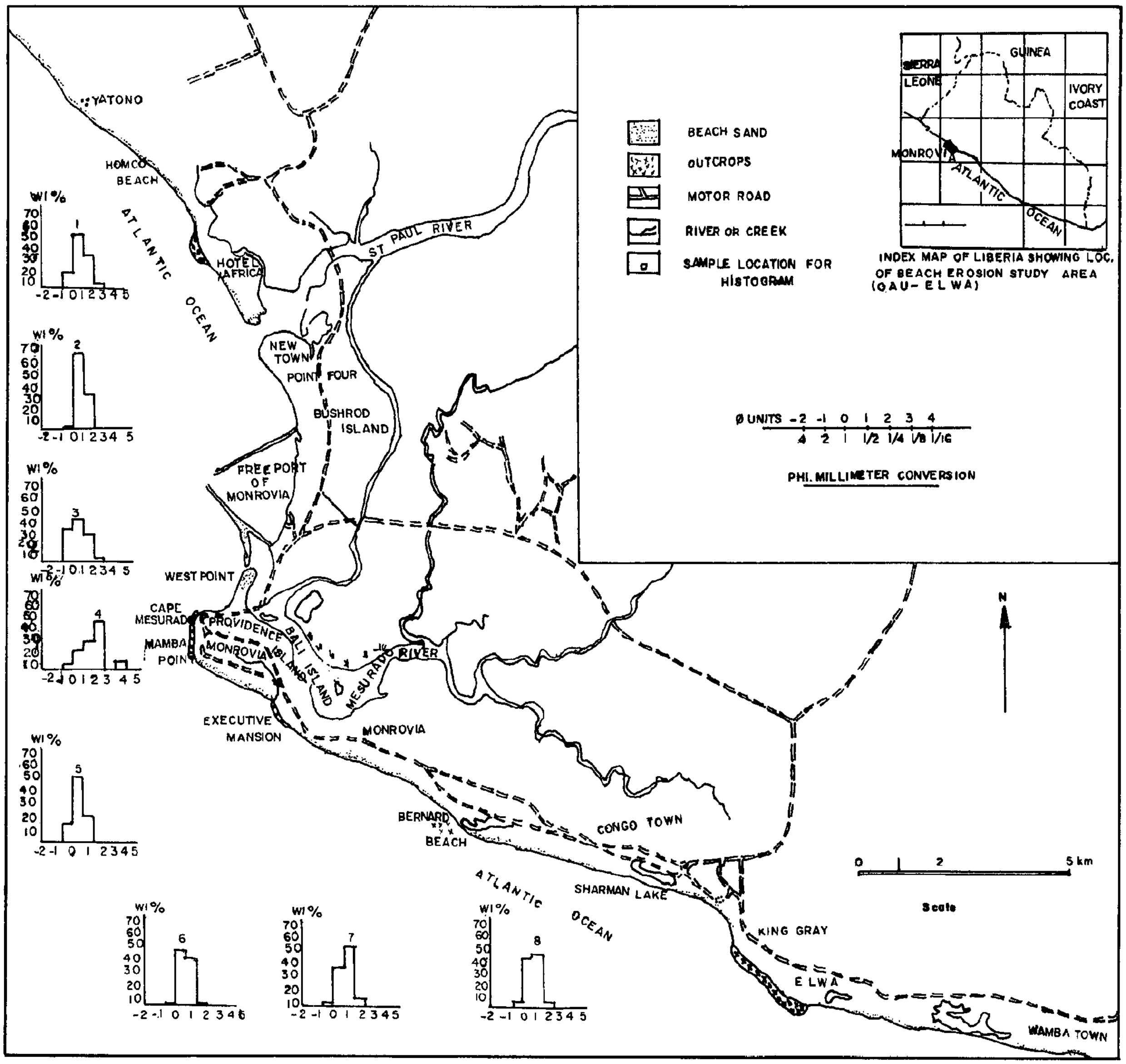


Figure 4. Map showing sediment size variation along the coast of Monrovia (OAU-ELWA).

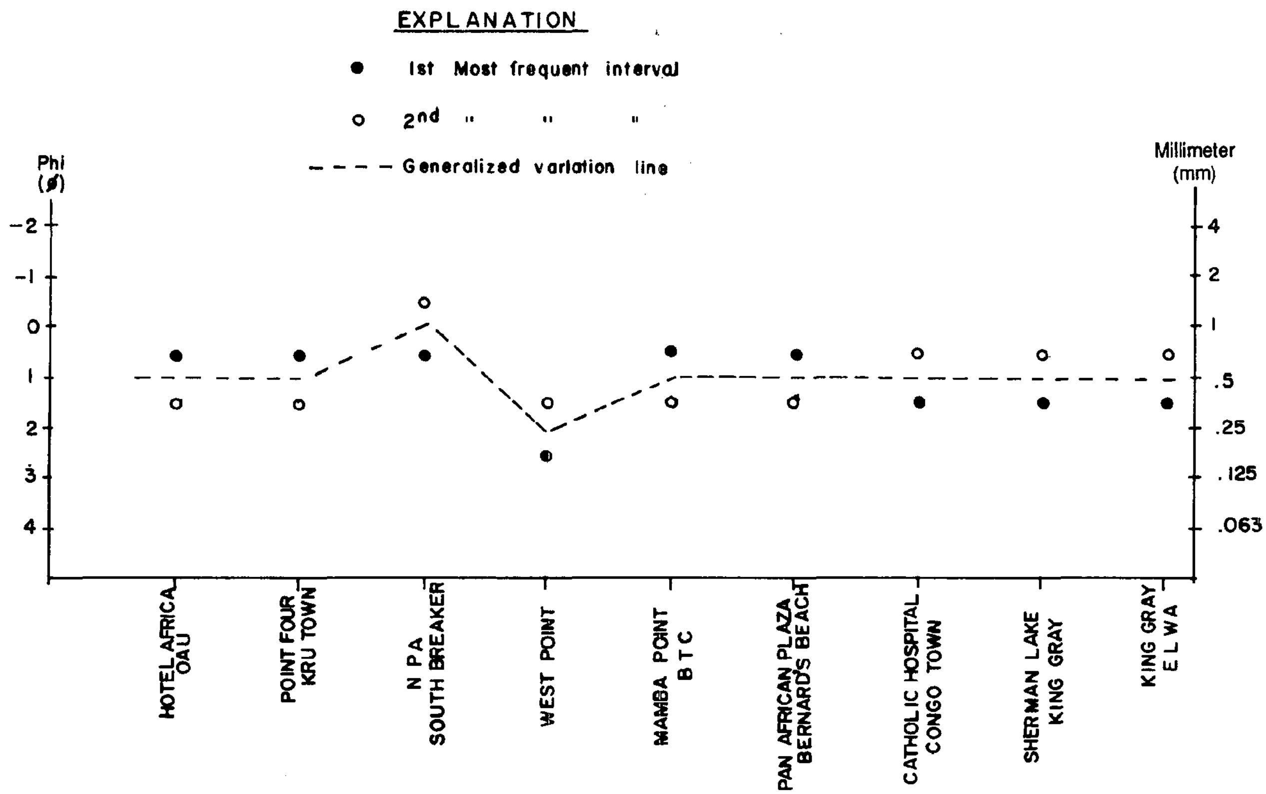


Figure 5. Graphical illustration of dominant grain size fractions along the Monrovia coastline.

Littoral Drift

The littoral drift along the Monrovia coastline is toward the northwest. Using the calculated deep-water wave height (H_o), the potential longshore energy flux (Pls) and the potential longshore sediment transport rate (Q) were calculated using a representative incidence angle of 78 degrees obtained for the ELWA-Cape Mesurado shoreline. According to Sabawa et al. (1981), the calculation is as follows:

$$Pls = 18.3\ H_o^{5/2} (\cos a)^{1/4} \sin 2a$$

$$= 1678 \text{ joules/sec}$$

Where a = angle of wave of incidence.

$$Q = 7.5 \times 10^3\ (Pls)$$

$$= 1.26 \times 10^7\ m^3/yr$$

Within the nearshore zone, littoral transport will be affected by waves of translation. The height of these translatory waves was evaluated from the difference between wave height at various points of breaking and the original wave height (H_o). Hence, the minimum height of the waves of translation along the coast of Monrovia is estimated as 0.2 m (H_i-H_o), and the maximum height is estimated as 2.35 (H_f-H_o). However, a representative height (H_r) of these translatory waves was estimated using the mean of H_i and H_f (H_m), and the calculation is given below:

$$H_m = (H_i + H_f)/2$$

$$= 11.495 \text{ m}^2$$

$$= 11.495 - 10.22$$

$$= 1.275 \text{ m}$$

Therefore, for the littoral transport, a wave height of about 1.3 m is most probably representative of Monrovia. Using this value for H_o in the equation given previously, the longshore energy flux is found to be 9.68 joules/sec, and the longshore sediment transport rate is found to be 7.26×10^4 m^3/yr.

The angle of wave incidence for that portion of the study area immediately north of Cape Mesurado is about 15 degrees. The longshore energy flux along this strip is estimated as 17.47 joules/sec, and the longshore sediment transport rate is estimated as 1.31×10^5 m^3/yr.

The littoral drift is therefore greater within the vicinity of the Free Port breakwaters. This indicates that waves within this area have a greater capacity to transport coastal materials along the shore.

COASTAL BEACH EROSION CONTROL

Various methods are available to fight the coastal erosion problem, but basically they fall under either structural control or nonstructural control.

Nonstructural Control Methods

Most nonstructural methods only lessen or regulate the problems caused by erosion, rather than prevent, halt, or retard erosion. They are grouped into passive and active methods.

Passive Methods

The passive methods include:

- Land-Use Controls: This means that permission should be granted only for structures that have to occupy waterfront sites. All the structures associated with permitted waterfront should be movable or, at worst, semipermanent and capable of quick, inexpensive repair. They should always be designed to minimize damage.

- Coastal Setback Lines: This requires that all constructions on coastal front should be placed at a safe distance from the shoreline.

Active Methods

- Move Threatened Structures: Threatened structures must be moved a safe distance from the shoreline. This may be less expensive than trying to control the erosion that threatens them.

- Vegetative Methods: These methods serve to slow the rate of erosion, rather than stop it. They include stabilization of sand dunes, and bluff and bank slopes with plantings, as well as the creation of salt marshes to absorb wave energy. These methods are employed with structural methods. For example, where a seawall or revetment is used to stabilize the base of a cliff, bluff, or bank, plantings may be made to control erosion from surface runoff and wave overtopping.

Whenever possible and economically practical, every effort should be made to correct or modify manmade increases in coastal erosion before building what may turn out to be much more costly erosion control structures.

Structural Methods of Erosion Control

Shoreline-hardening structures make the land mass more resistant to erosional forces and protect facilities landward from the effect of wave action. They tend to protect only landward infrastructures and have no beneficial effects on adjacent shorelines or on beaches seaward of them. Shoreline-hardening structures include seawalls, revetments, and bulkheads (see Appendix 2 for diagrams and pictures of these structures). The characteristic design of these structures will depend on the height, length, shape, and degree of differences in texture permeability of porosity.

RECOMMENDATIONS

Because of the extent of beach erosion and its imminent threat to investment, especially along the coastal front, the Ministry of Public Works has proposed a temporary solution for reducing the rate of erosion at the site. The technicians at the Ministry have estimated 125 working days at a total cost of $2.4 million (U.S. dollars). The project includes boulder dumping (with a clay dam on the villas side facing the sea) over an area 1,800 feet long and 50 feet wide. Engineering consultants estimated that 100,000 cubic yards of boulders and 40,000 cubic yards of clay would be required (see Appendix 1).

The Ministry of Rural Development also recommended the following tentative structural measures that are capable of minimizing the erosion problems at Hotel Africa: Appendix 2, a stone revetment ($0.98 million, U.S. dollars); Appendix

2, a curved-face wall ($2.7 million, U.S. dollars); Appendix 2, bulkheads ($1.8 million, U.S. dollars); and Appendix 2, a concrete revetment.

But these structures are just a first step for a small part of the Liberian coast. At this time it is difficult for us to contemplate the nationwide response to a rise in sea level from the greenhouse effect. Nevertheless, we conclude with the recommendations that would help us address both the current problems and the additional problems resulting from global warming.

1. During the dredging of the port by the National Port Authority, all sand removed from the port should be deposited on the beach near the Hotel Africa for nourishment of the shoreline.

2. The National Port Authority should be included on the technical committee for future study of beach erosion.

3. Funds should be appropriated to the Technical Committee for logistics that should be used to monitor the rate of erosion. This would provide data for potential consultants. Also, a soil conservation and pollution control division should be developed and empowered to undertake long-range measures for adequate monitoring.

4. A Beach Erosion Control Commission should be created.

5. Specific beaches should be designated for sand mining.

BIBLIOGRAPHY

Fayia, A.K., J.B. Massah, F.T. Morlu and B.O. Weeks, B.O. 1987. A Survey of the Monrovia Beaches. Monrovia: Liberian Geological Survey.

Friedman, G.M., and J.E. Sanders. 1978. Principles of Sedimentology. New York: John Wiley and Sons, Inc..

Hanson, H., L. Johnson and B. Broms. 1984. Beach Erosion in Liberia: Causes and Remedial Measures. Lund, Sweden: University of Lund.

Japan International Cooperation Agency. 1978. Report on the Beach Erosion in the Republic of Liberia. Tokyo: Japan International Cooperation Agency.

Maasha, N. 1982. Erosion of the Monrovia Beaches. Monrovia: University of Liberia, Department of Research.

GDL. 1981. Government of Liberia. Report on "Seminar of Beach Erosion at Hotel Africa" OAU Village, Virginia, Liberia: Government of Liberia, Lands, Mines & Energy, Public Works & Rural Development, Technical Committee.

Shulze, W. 1971. Notes on settlement research in Liberia. In: Rural Africana, No. 15, Liberia: An Evaluation of Rural Research. East Lansing, MI: Michigan

West Africa

State University.

U.N.D.P. 1972. United Nations Development Program. Heavy Mineral Occurrence Between Monrovia and Marshall. Technical report No. 5. Monrovia: Liberian Geological Survey.

White, R.W. 1972. Stratigraph and Structure of Basins on the Coast of Liberia. Liberian Geological Survey Special Paper No. 1. Monrovia: Ministry of Information Press.

APPENDIX 1

ESTIMATE FROM PUBLIC WORKS
OAU VILLAGE COASTAL EROSION PROJECT
(Temporary Solution)

Subject: To prevent the coastal erosion at the OAU Village by the sea.

In order to start the work on temporary solution, an access road is needed.

1. Mobilization for access road.

   A. Access road 12' wide 6" thickness laterite surface length = 1,800' laterite = 1,000 C.Y.

   Equipment:

   1.4 dump trucks
   2.1 grader
   3.1 front end loader

   Fuel consumption:

4 x 25 gallon per day/trucks	=	100 gallons
40 gallons per day/grader	=	40 gallons
35 gallons per day/front end loader	=	35 gallons
		175 gallons/day

   For 7 working days, all equipment = 1,250 gallons. 1250 gallons of fuel for the access road, and 100 gallons of gasoline.

Total cost for fuel consumption @$1.88 x 1,250	=	$2,350.00
Total cost for gasoline consumption @$2.09 x 100	=	$ 209.00
		$2,559.00

Temporary Solution:

Although this solution is costly, it will delay the rate of erosion at the site. Also, the sand hauling from the beach around the area should be stopped by the authorities.

The attached drawing gives a physical picture of what is needed at the site in question and the following are the descriptions:

1. Rolder Rock -- with clay dam on the Village side and facing the sea will be the Rolder with the length of about 1,800' and 50' wide at the top about 100,000 cubic yards (cu. yd.) of Rolder will be needed and about 40,000 cu. yd. Clay will be needed.

West Africa

Personnel:

1 Engineer	@	$40.00/day	=	$ 40.00
1 Superintendent	@	$30.00/day	=	$ 30.00
20 Truck Drivers	@	$10.00/day	=	$200.00
20 Laborers	@	$ 7.70/day	=	$154.00
10 Operators	@	$12.50/day	=	$125.00
		Sub-total	=	$650.00/day

Equipment:		Fuel Consumption/Day
20 - 12 cu. yd. dump trucks	=	550/day
2 Trexcavators	=	100/day
1 Dozer D/C	=	50/day
1 Front end loader	=	35/day
1 Mobile crane	=	50/day
2 Pick-ups	=	20/day (gas)
1 Man-haul truck	=	15/day
1 Compressor*	=	830/day
2 Tankers*	=	

* Plus 20% contingency fuel for emergency equipment of the total consumption.

Minimum haulage/day:

4 Trips/day = 12 x 4 = 48 cu. yd.
40 cu. yd. Truck/day
Total volume of rock needed = 120,000 cu. yd.
for 20 Trucks = 48 x 20 = 960

$$\text{No.} = \frac{120,000}{960} = \frac{1,000}{8} = 125 \text{ days}$$

Expenditures:

$650.00 x 125 days	=	$ 78,000.00
$15/cu. yd. x 12,000 (cost of B. Rock)	=	$ 1,800.00
Cost of fuel 100 x 125 x $1.88	=	$ 235,000.00
Plus 25% of fuel cost for: Lubricant and fast moving parts	=	$ 60,000.00
Gasoline 2.09 x 250	=	$ 5,225.00
	Grand Total	$2,178,225.00
Plus 10% contingency		$ 217,822.50
	Total	$2,396,047.50

It should be noted that this solution will only delay the rate of erosion, until a permanent solution is to be found.

<u>Permanent Solution</u>:

There should be a comprehensive study by the Engineering Division to find the causes of the erosion and the factors influencing it. The following facts have to be known:

a) Direction of wind
b) Frequency of waves
c) Direction of waves
d) Height of tide
e) Topography of the area
f) Soil test

Submitted by: Emmanuel Oseni
Engineer/CB/MPW

APPENDIX 2

STONE REVETMENT

ITEM	QUANTITY	UNIT RATE	EXTENSION
Ballast (above 400 lba)	16764.50	25.00	$ 419,112.50
Ballast	12573.33	25.50	282,900.00
		Subtotal	$ 702,012.50
Contingency	12%		$ 84,241.50
Transportation	20%		140,402.50
Placement	7.5%		52,650.94
		Grand Total:	$ 979,307.44

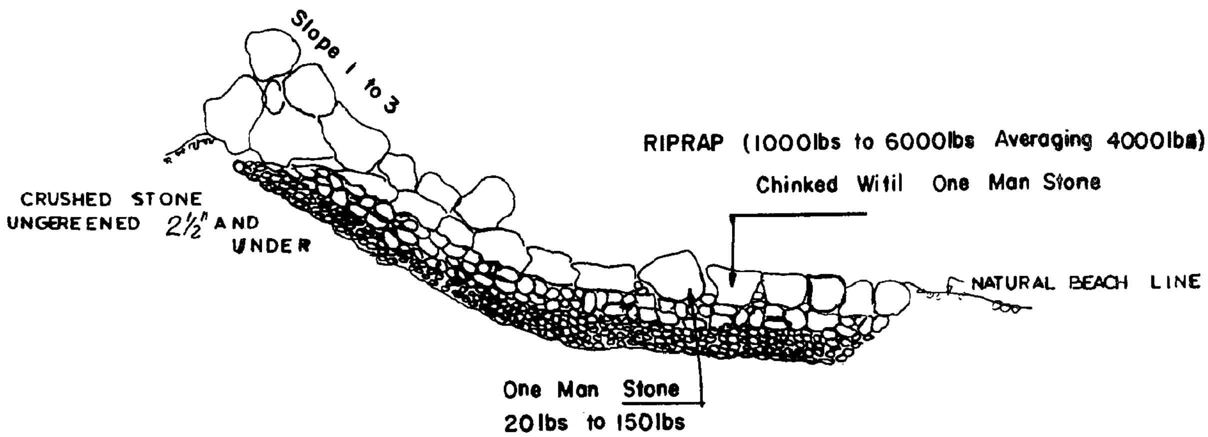
CURVED FACE WALL

ITEM	QUANTITY	UNIT RATE	EXTENSION
Excavation	1955. cu.yd.	25.50	$ 30,315.68
Concrete Work	6286.67 cu.yd.	250.00	1,571,667.50
Form Work	12% of concrete work	5	188,600.10
Pile Work	15% of concrete work	5	392,916.88
Back Filing	8941.04 cu.yd.	12.00	107,292.50
Front Filing	1257.33 cu.yd.	20.00	25,146.70
		Sub-Total:	$2,315,939.40
		Plus 15% contingency:	347,390.90
		Grand Total:	$2,663,330.30

BULKHEAD ESTIMATES

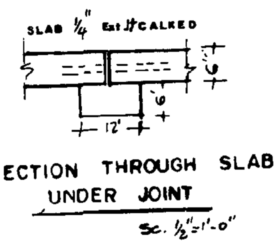
ITEM	QUANTITY	UNIT RATE	EXTENSION
Ballast	50,293.33 cu.yd.	25.00	$1,257,333.30
Contingency	12%		150,879.99
Transportation	20%		251,466.66
Placement	8.5%		106,873.33
		Grand Total:	$1,766,553.30

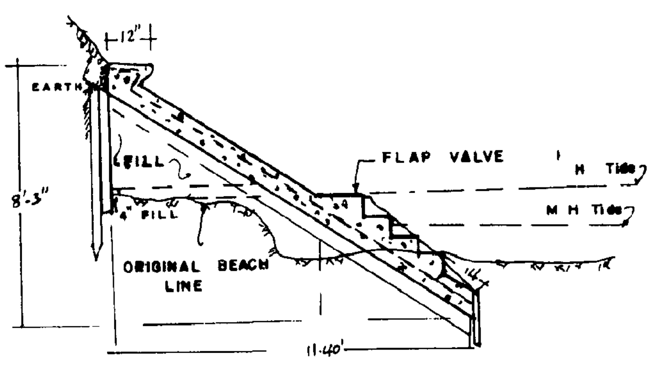
Stone Revetment



Concrete Revetment

These are lighter construction which primarily functions as shore or beach protection against erosion from wave, tide, or current actions.

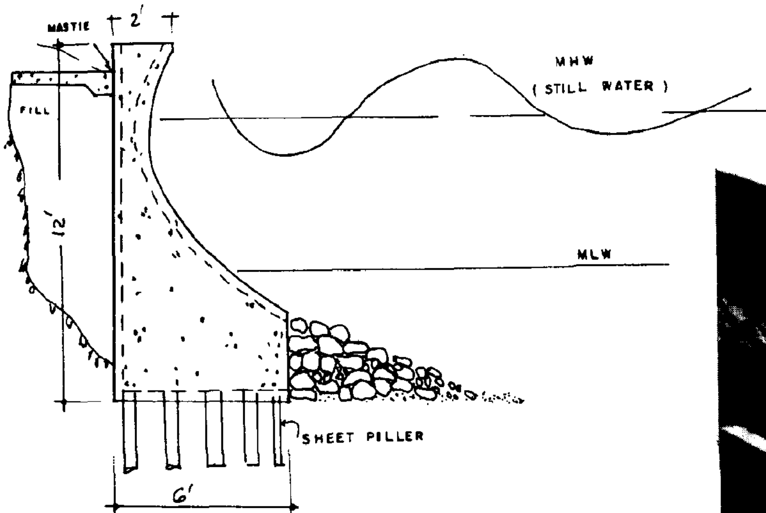


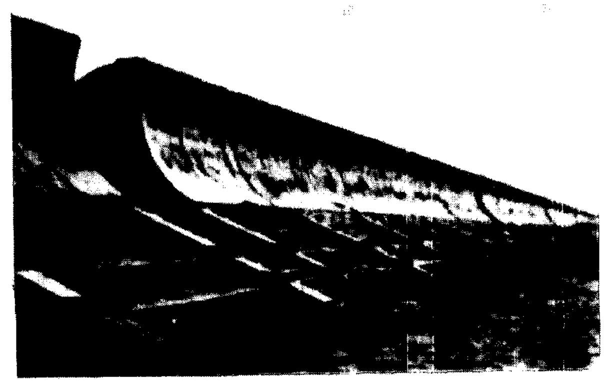


West Africa

<u>Curved Face Wall</u> (Seawall)

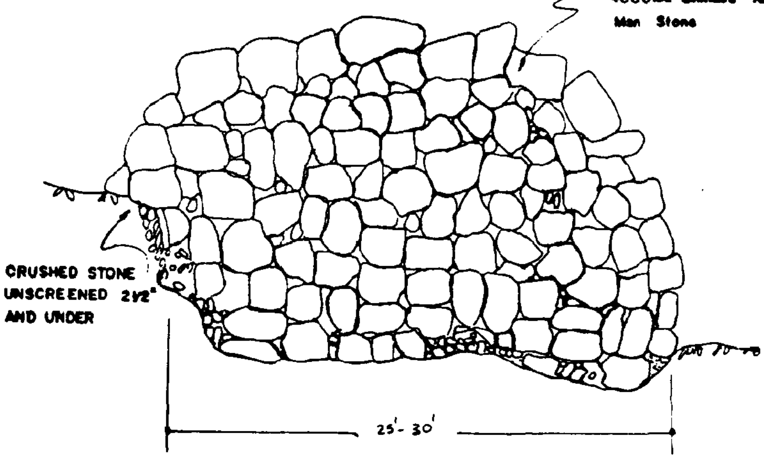
This structure is used for moderately severe wave action where the water level is over the structural base, permitting the full waves to hit the wall. This structure could also be used where poor foundations exist.

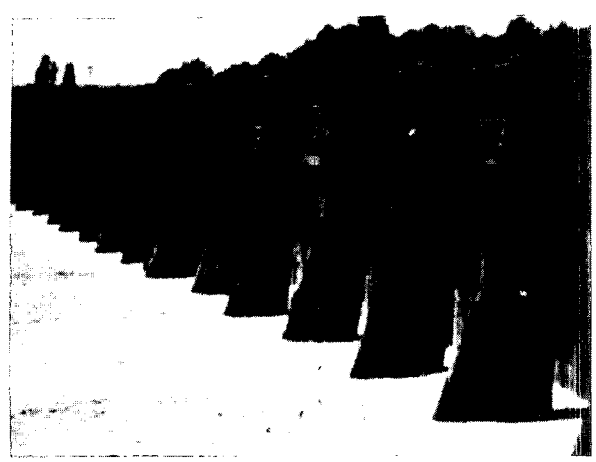




<u>Bulkheads (Breakwaters)</u>

The primary function of bulkheads is to retain fill and secondarily to resist wave action.





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IMPACT OF SEA LEVEL RISE ON THE NIGERIAN COASTAL ZONE

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ABSTRACT

Widespread erosion, flooding, and subsidence are already devastating vast areas of the Nigerian coastline causing severe ecological problems that have compelled the federal government to set up a special relief fund to mitigate the impact. A rise in sea level of approximately 1 m would aggravate the existing ecological problems through accelerated coastal erosion, more persistent flooding, loss of ecologically significant wetlands, increased salinization of rivers and groundwater aquifers, and greater influx of diverse pollutants. Other socioeconomic impacts include uprooting human settlements, disrupting oil and gas production, dislodging port and navigational structures, upsetting the rich fishery, forcing businesses and industries to relocate, wiping out the fledgling coast based-tourism, and generally increasing the level of misery. The several engineering counter-measures being presently proposed for coping with sea level rise are too expensive for a developing country like Nigeria with huge external debts. Responding to sea level rise should consist largely of keeping some steps ahead of the projected rise by slowly "disengaging" from the coast where possible and establishing and enforcing set-back lines in areas of new development. Where this is not possible, as in heavily built up areas, emphasis should be on developing and implementing low-cost, low-technology, but nonetheless effective options.

INTRODUCTION

Along the coastal zone, probably the main consequence of an increase in global temperatures is an accelerated rise in global sea level. This will be due to the melting of alpine and polar glaciers and the thermal expansion of the ocean surface.

West Africa

Estimates of the projected rise in sea level differ, sometimes markedly (e.g., from 0.45 to 3.65 m, according to various estimates), but the following assumptions were accepted at the UNEP/ICSU/WMO International Conference in Villach, 9-15 October 1985: increased temperature of 1.5-4.5°C and sea level rise of 20-140 cm before the end of the 21st century, with the understanding that these estimates may be revised on the basis of new scientific evidence.

This paper examines the potential impact of climate change on the coastal and marine environment in Nigeria and suggests certain suitable policy options and response measures that may mitigate the negative consequences of the impact.

GEOMORPHOLOGICAL SETTING

The Nigerian coastal zone extends for a distance of about 800 km between the western and eastern borders of the country with the Republics of Benin and Cameroun, respectively. It lies generally between 4°10' and 6°20'N latitudes and 2°45' and 8°35'E longitudes adjacent to the Gulf of Guinea.

The coastal zone is mounted on a voluminous, though localized, sedimentary protrusion into the Gulf of Guinea ocean basin comprising a 12-km-thick pile of Cretaceous and Tertiary sediments, close to the juncture of two of the boundary realms of the Guinea basin (Allen, 1964). The origin and evolution of the Nigerian coastal zone are closely linked with the Mesozoic (Upper Jurasic to Lower Cretaceous) opening of the Atlantic Ocean and by different, more recent phases associated with the structural deformation of the East African Rift Systems.

The coast is bounded laterally to the north by an extensive river floodplain (area, 8400 square kilometers), which slopes southward from about 20 m above sea level in the Onitsha gap (Figure 1). This narrow zone is mounted on the Benue Valley and contains the main channel of the Niger River before and after bifurcation. This plain broadens southward with a decrease in slope and subsequent increase in the density of tributaries of the major drainage channels and down to the coast.

To the south is the Continental Shelf characterized by more or less uniform gentle slopes broken at specific points by the recognizable submarine canyons (Avon, Mahin, and Calabar Canyons).

The Nigerian coastal zone is composed of four distinct units with different surficial configurations (Figure 2). A 200-km-long barrier lagoon coast in the western part is followed by 75 km of transgressive mud coast, which tapers into the dominating 450-km-long and beach-ridge-barrier-island-rimmed Niger Delta; farther to the east is an 85-km Strand coast where mangrove fronts the sea in the extreme eastern corner.

A common feature of these geomorphic zones is their low-lying nature. Most areas along these zones are less than 3 m in elevation. The beach ridges on the barrier islands that rim much of the coastline constitute the highest grounds

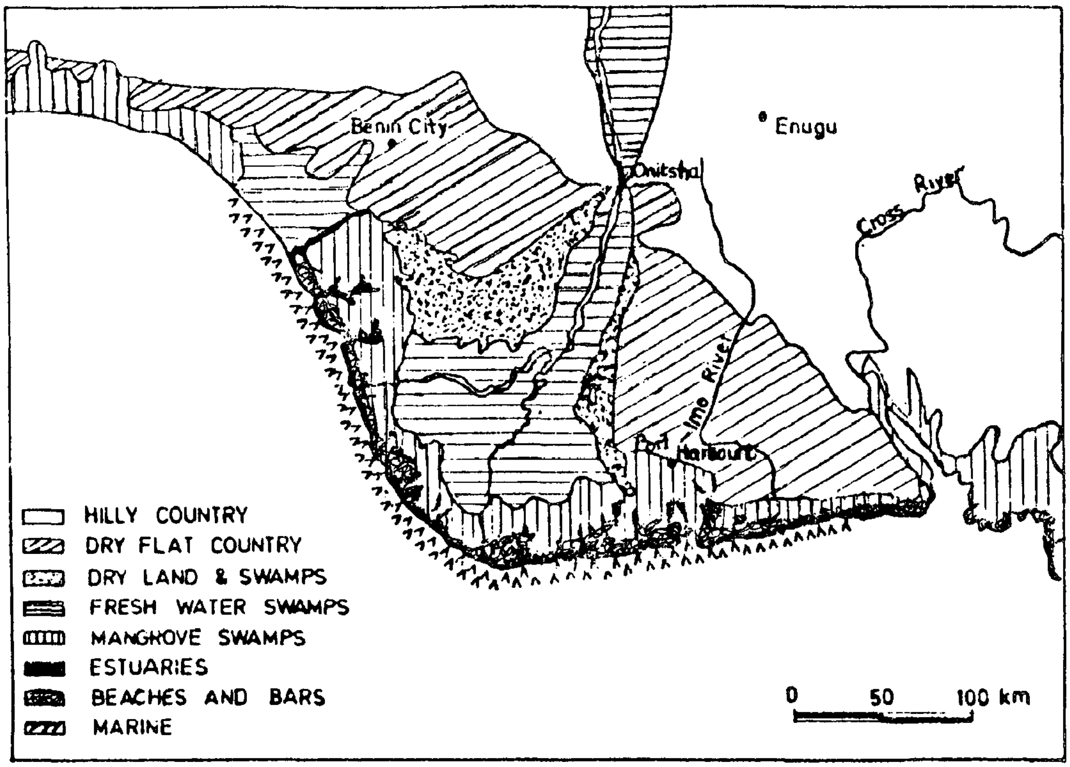

Figure 1. Sketch map showing the main physiographic features of the coastal and adjacent land areas (after Short and Stauble, 1967).

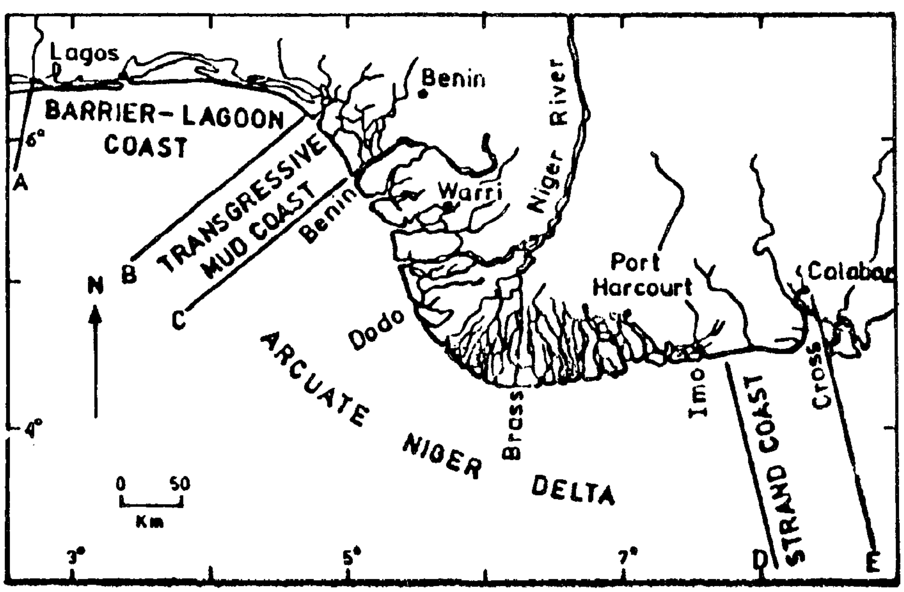

Figure 2. Map of coastal Nigeria showing main geomorphic units (after Ibe, 1988).

with elevation of 2-3 m. In the transgressive mud coast, elevations of less than 1 m are common.

An important feature of the Nigerian coastal zone is that it is part of an actively subsiding geosyncline. A sequence of dead coralline banks in shallow waters off the Nigerian coast indicates stages in subsidence or rise in sea level during the past 4,000 years (Allen and Wells, 1962). More specifically, Burke (1972) has proposed that all the subsidence (approximately 80 m in about 15,000 years in the northwestern flank of the Niger Delta) can be accounted for by eustatic sea level rise and isostatic adjustment to water load. The Nigerian coastal geosyncline is subsiding not only because it was formed in an area of subsidence but also because of the continued dewatering and compaction of its sediments that were deposited rapidly. The present rates of subsidence are being studied by the authors. The only reliable figures available to date reveal subsidence rates of more than 2.5 cm/yr at the site of a tank farm along the deltaic coast, after correcting for loading effects caused by the oil in the tanks (Pender Awani, personal communication, 1987).

Socioeconomic Setting

<u>Settlement and Population</u>

The Nigerian Coastal zone comprises all of the Lagos, Rivers, Cross River and Akwa-Ibom states and the large southern sections of the Ogun, Ondo, Bendel, and Imo states (Nigeria consists of 21 states).

Recent population projections indicate that up to 30 percent of the estimated 100 million people in Nigeria live in the coastal zone with population densities of more than 400 persons per square kilometer in urban centers like Lagos, Warri, Port Harcourt, and Calabar (Nigeria in maps, 1982). Most of these urban centers are also port and industrial cities, which accounts for their teaming populations. Lagos alone is thought to harbour about 8 million inhabitants. Most of those urban centers are literarily bursting at their seams with the continued rural-urban drift of the population.

Apart from the large urban centers, several important historical settlements like Badagry, Forcados, Brass, Abonema, Opobo, and Duke Town, with enduring monuments of early European contacts and trade, are located on or near the coast. Populations reaching 150 persons per square kilometer are typical of these settlements. Oil exploration and exploitation activities in the coastal zone have given rise to sprawling coastal settlements at Escravos, Brass, Bonny, and Ibeno-Eket, and several fishing and trading settlements, smaller in size but no less significant in socioeconomic terms, dot the coastal zone. Some of the fishing settlements now house fishing terminals with a large work force.

Communications

Apart from a fledgling inland port at Onitsha, all other ports and harbors in Nigeria are located naturally in the coastal zone. These ports at Lagos (Apapa and Tin Can), Warri, Port Harcourt, Calabar, Sapele, Bonny, Burutu, Onne, and Koko constitute the economic lifeline of the country supporting a hitherto flourishing import-export trade. Many canals, creeks, and rivers in the coastal zone, particularly in the Niger Delta, provide sometimes the only communication links between coastal towns and settlements on the one hand and between these towns and settlements and the hinterlands on the other hand. This water transportation system is vital to the country's economy in terms of passenger traffic and goods haulage.

Of the four functional international airports, only Aminu Kano International Airport, located at Kano to the north, is outside the coastal zone; the other three airports are at Lagos (Ikeja), Port-Harcourt, and Calabar. These airports constitute a rapid link with the outside world and account for heavy movements of persons, goods, and services to and from Nigeria. Many other local airports and helipads in the coastal zone provide easy links to these large airports.

The terminals of many road and rail systems in the country are located in the coastal zone. Besides very important cross-country roads, transport networks criss-cross the coastal zone; in some cases, these are the only links between the western and eastern regions of the country.

Agriculture

The coastal zone proximal to the sea is not fit for agriculture because of the high salinization of soils and aquifers. Beyond the present limits of direct marine influence are vast agricultural lands afforded by the floodplains of the Niger Delta and its numerous distributaries. The major staples of Nigeria (such as yams, cassava, plantains, and rice) flourish on these lands, earning the coastal zone the nickname "food basket of southern Nigeria"; most of the produce has found a favorable export market in West and Central Africa. A planned World Bank-assisted swamp rice cultivation project will further boost food production from the coastal zone.

The coastal zone has been found to be a highly suitable area for mariculture and aquaculture techniques to enhance natural fish production. Although production from captive breeding currently only modestly contributes to overall fish production from the coastal zone, projections conservatively place the productive potential from future fish farming at a significant 175, 150-525,000 tons annually (Talabi and Ajayi, 1984).

Industries

Nigeria has well over 2,000 industrial establishments, about 85 percent of which are concentrated in the coastal zone. The coastal cities of Lagos, Warri, and Port-Harcourt are centers of heavy industry; products and activities include iron and steel, automobile assembly, textiles, pharmaceuticals, cement, soaps and detergents, paints, refined petroleum products, electronics, tires, plastics, brewing, beverages and tobacco, and wool and wood products. About 75 percent Nigeria's manufacturing industries are located in Lagos and its environs. Warri and Port-Harcourt have two of the country's three petroleum refineries and two of its three petrochemical industries. Warri hosts one of Nigeria's two iron and steel industries.

In both economic terms and physical layout, the oil industry dominates the coastal zone (Figure 3). Oil production and export handling facilities, including structures associated with the ongoing liquefied natural gas project, dot the coastal zone with constellations at Escravos, Forcados, Warri, Brass, Bonny, and Ibeno-Eket.

Elsewhere along the coast, local and small-scale industries like wood works, ceramics, weaving and, boat building flourish around coastal settlements.

Natural Resources

The Nigerian coastal zone has abundant natural resources of great socioeconomic importance. These resources include forests and wildlife, a vast fishery, minerals (including oil and gas), and surface and ground water.

Forests and Wildlife

The natural vegetation along the Nigerian coastal zone consists mainly of strand vegetation consisting of Halophyllons, coastal thickets, and forest in the area immediately adjacent to the beaches. Mangroves grow in the lower Niger and the northwestern flank of the Niger Delta. The mangrove forests alone cover more than 9,000 square kilometers. The mangrove swamps serve as spawning and breeding grounds for most of the finfish and shellfish resources in the coastal zone. Swamp and riparian forests are found along the western region, in the upper Niger Delta, and also fringing the banks of the Niger up to Onitsha. Forest reserves exist on barrier-bar islands between the Benin and Forcados River estuaries and east of the Cross River estuary; these reserves form the raw materials for the timber and plywood industries based in Sapele and Calabar as well as for the paper and pulp industries in Iwopin and Iku-Iboku. Other natural forest products within the coastal zone include thriving wildlife (locally, "bush meat"), which boosts the protein availability , as well as palm oil, fuel wood, and south palm wine and its derivatives. Apart from helping to meet the protein needs of the country, the forest is the home of biologically diverse fauna and flora, including medicinal herbs, that provide a source of scientific interest and tourist fascination.

Fisheries Resources

Nigeria's coastal zone is blessed with lagoons, creeks, estuaries and, of course, the shallow inshore ocean, which constitute a major source of the fish and fisheries products sought by artisanal fishermen.

Before the advent of the oil industry in the late 1950's the coastal zone served as a base for much of the country's artisanal fisheries. Myriad fishing settlements established on protected, better drained land or on stilts in river estuaries and beaches were, and are still, the dominant feature of the well-watered coastal zone. The artisanal fishermen and women who harvest fish,

Figure 3. The lowland muddy coast of the Niger Delta with oil handling facilities in the background.

shrimps, and molluscs in the fresh, brackish, and immediate marine waters with set nets, traps, and other passive gear, use crafts ranging from paddled dugouts to motorized large canoes. Ajayi and Talabi (1984), based on earlier surveys by Tobor et al. (1977) and others, have estimated the annual yield of the coastal and brackish water artisanal fisheries to be between 128,000 and 170,000 metric tons. The coastal zone remains the base for this artisanal fishery.

Bonga (Ethmalosa fimbriata), sardines (Sardinella madarensis = Sardinella eba = Sardinella cameronensis), and shad (Ilisha africana) are the principal pelagic and semipelagic components of coastal artisanal fishery. The demersal component of this fishery targets croackers (Pseudotolithus elongatus, P. typus, and P. senegalensis), catfish (Aurius spp.), sole (Cynoglossus spp.), shinynose (Polydactylus quadrifilis), grunters (Pomadasys spp.) snappers (Lutjanus spp.), and groupers (Epinephelus spp.). Large tarpons (Megalops atlantica), bill fishes, sharks, and rays are also caught. Shellfish harvested by artisanal fishermen include white shrimps (Nematopalaemon hastatus = Palaeinon hastatus), brackish prawn (Macrobrachium machrobrachion), river prawn (Macrabrachium vollenhovenii), and juvenile pink shrimp (Penaeus notialis =Penaeus duorarium). The mangrove oyster, Crassostrea gasar, and other molluscs, e.g., Pachyacllion, are delicacies in high demand.

Artisanal fishery revolving around the above-listed resources not only contributes to the nation's march toward self-sufficiency in its protein needs but also provides, particularly in the case of shrimps and oysters (annual production approximately 48,000 tons, exportable resources with high foreign exchange earning potential. For example, one metric ton of prawns fetches 12,000 U.S. dollars. *The mangrove swamps serve as the breeding and nursery grounds for* most of the finfish and shellfish resources that are the targets of artisanal fishery.

The potential of industural fishery within inshore waters is also very high (Talabi and Ajayi, 1984; Tobor et al., 1977).

Minerals

Nigeria's coastal zone is richly blessed with a variety of minerals. Large deposits of crude oil have been discovered both on land and offshore, particularly in the Niger Delta. Nigeria is the sixth largest producer of crude petroleum oil in the world and the second largest produces in Africa. Nigeria's production capacity reached 2.3 million barrels per day in the late seventies but declined to 1.3 million barrels per day as a result of present OPEC restrictions. Despite this decline, petroleum still accounts for more than 90 percent of the country's exports and foreign exchange earnings.

Natural gas has also been found in the Niger Delta in commercial quantities either alone or in association with crude oil. At present, about much of the gas is flared as there are no large gas utilization projects in the country. Projected investments in the planned liquefied Natural Gas (LNG) project will further increase the importance of petroleum to the national economy.

Other mineral resources such as limestone and valuable mineral concentrations have been reported along the sandy beaches of Nigeria; these provide raw materials for some coastal industries (Ibe, 1982; Ibe and Awosika, 1986). Coal and lignite occur in the eastern sector of the coastal zone, particularly east of the northern tip of the Cross River estuary.

Surface and Groundwater

Some decades ago, based on folklore and meager records at the University of Agriculture and Water Resources, surface water (rivers, creeks, etc.) supplied the freshwater needs of the coastal zone apart from the director impact of the sea. But all that has changed, and groundwater is now one of Nigeria's most important natural resources, especially in the coastal areas. The coastal zone is heavily dependent on groundwater because of the increasing salinization of waters of the lagoons, creeks, rivers, and estuaries. The water table is often less than 9 m near the coast, and varies from 15 m to 39.6 m farther inland. The groundwater potential of this zone is very high (with a yield several hundred thousand gallons per hour), due to generally high permeabilities, considerable thicknesses of the aquifers, and high recharge potentials attributable to heavy rains.

Present Erosion and Flood Situation

Analyses of historical hydrographic charts and aerial photographs, as well as data from ongoing research by the Nigerian Institute for Oceanography and Marine Research, reveal widespread erosion and flooding along the entire national coastline.

Present typical rates established at erosion monitoring stations include more than 18 m at Ugborodo/Escravos, 20 m at Forcados, 16-19 m at Brass, and 10-14 m at the Imo River entrance (Ibe and Antia, 1983 a, b; Ibe, 1984a, b, c, 1985a, b, 1986, 1987a, b, c; Ibe et al., 1985a, b, c; Ibe and Awani, 1986; Ibe et al., 1986a, b; Ibe and Awosika, 1986; Ibe and Murday (In Press); Oguara and Ibe (in press); Stein et al., 1986; Ibe, 1988a, b). Some of these rates are so erratic and out of proportion with historical rates that sea level rise is thought to be a part of the problem (Ibe, 1988). An acceleration of the rise in sea level would further exacerbate the situation.

EFFECTS OF SEA LEVEL RISE ON THE COASTAL ZONE

Increase in Beach Erosion Rates

Although the amount of sea level rise totals a few millimeters per year and may seem small, it plays a big role in explaining erosion processes affecting most of the low-lying coastline in the world, particularly in Nigeria. Though rising sea level does not cause beach erosion per se, other more important causes are waves, winds, longshore currents, tidal currents, low relief, shelf width, subsidence, sediment characteristics, offshore topography, and human impact. The seriousness of sea level rise with respect to increased erosion and flooding can be deduced from the data of Bruun (1977), which showed that a sea level rise of 0.3 m (1 foot) would cause a shoreline recession of more than 35 m (100 feet). This may even translate to higher values on low-lying areas typical of the Nigerian coastal zone.

A rise in sea level of approximately 1 m, which here will be accentuated by the phenomenon of subsidence, would aggravate the existing ecological problem of coastal erosion, resulting in loss of wetland and creating a threat to all installations on or near the coastline.

Flooding

A rise in sea level will result in flooding of the low-lying beaches. This will automatically cause flooding in the adjacent coastal areas. This is expected to become even more threatening whenever storm surges coincide with spring tides.

Many of these barrier islands defend the rich low-lying coastal lands against storms; they enclose and protect the rich low-lying resources of estuaries, marshes, and mangroves, all which are highly vulnerable to flooding resulting from sea level rise.

Many of the barrier island, e.g., Victoria Island, Ikoyi Island, are heavily developed and urbanized, with most state capitals and settlements situated near the coast. Flooding of these urban area will result in destruction of properties and loss of income and lives. Many industries and oil-handling facilities built near the coastline, particularly in the Niger Delta, will also be affected by flooding.

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With rising sea level of approximately 1 m, the potential for flooding and erosion of certain key transportation arteries on barrier islands and others near the coast will increase. This will lead to a degeneration or interruption of emergency and other social services. With higher sea levels, existing fishing facilities, such as jetties, and storage centers built on the coastal fringes only a couple of feet above the mean high tide line will be subjected to more frequent tidal and storm inundation. The growing coast based-tourism will be heavily affected as a result of both increased rates of erosion and persistent flooding (Figure 4).

Figure 4. Tourist and recreational scene on a beach on Victoria Island with hotels in the background.

Subsidence

The effects of sea level rise will increase as a result of ongoing subsidence.

The Nigerian coastal geosyncline, particularly the Niger Delta, is sinking not only because of tectonic subsidence but also because of continued dewatering and compaction of sediments that were rapidly deposited.

The authors are studying the present rates of subsidence. The only reliable figures available to data reveal subsidence rates of more than 2.5 cm/year at the site of a tank farm along the delta coast, after correcting for the loading effects of the oil in the tanks (Pender Awani, personal communications, 1987).

Human intervention in the coastal zone (e.g., fluid extraction) has tended to accelerate the subsidence problem. Subsidence associated with withdrawal of fluids results in the reduction of fluid pressure in the reservoir or aquifer, thus leading directly to an increase in "effective stress" (or "grain to grain stress") in the system. Compaction results, and basin subsides.

Saltwater Intrusion and Higher Water Tables

The depth to water-table in the coastal zone is often very shallow, and the groundwater itself is subject to pollution and saline contamination from seawater. Sweet water in the area is, however, contained in the deeper aquifer, which probably is in hydraulic continuity with the coastal plain sands.

Many towns and cities situated on the coastal lowlands obtain their water supplies from the enormous groundwater resources of this hydrogeological province. Some municipal wells in Port Harcourt yield as much as 90,000 gallons per hour. A global sea level rise is expected to raise the water table along the coast and result in increased salinity of the groundwater.

Deforestation

The Nigerian coastal zone is endowed with an extensive and productive mangrove ecosystem, particularly in the Niger Delta.

Vast and fertile river floodplains have made the delta and other parts of the coastal zone the food basket of southern Nigeria. Rising sea level will increase the salinity of the water and soil. Such plants that are not tolerant to this increased salinity will die. Scenes of dying vegetation are now common along the Mahin mud beach where saline waters have flooded the adjacent low-lying coastal areas.

This has resulted in the complete decimation of the once-flourishing rain and mangrove forests (Figure 5). The lumber industry in Spele is expected to suffer from the deforestation resulting from increased salinity attributable to global sea level rise.

Transportation and Communication

Owing to the booming economic activities, an extensive network of roads (about 4,000 km in Bendel State, 2,500 km in Rivers State, and the new 65-km Lagos to Epe dual highway built on the Lekki barrier island) has been developed, while extensive creeks, channels, rivers, and estuaries provide an excellent water communication and transportation network. Increasing sea level will result in flooding of these transportation and communications networks.

The state government canals linking the numerous settlements along the Mahin mud beach are close to being overtaken by the ocean (Figure 6). This could be disastrous to tertiary institutions, hundreds of secondary schools, commercial houses, hospitals, hotels, and other institutions in which billions of naira have been invested.

Figure 5. Trees dying as a result of saltwater intrusion.

Ocean Dynamics

It has been suggested that sea level rise will cause a continued deepening of the Continental Shelf beyond the depth of closure and will result in an increase of effective wave height due to the reduction in bottom friction as a result of greater depth.

It is hence to be expected that the present ocean dynamics (wave height, period, length, breaker angle, longshore current direction and magnitude, etc.) shaping the coastal zone will change. A change or modification of ocean dynamics, particularly the nearshore dynamics, will affect the sedimentary fluxes and hence sedimentary budget. This controls the coastline evolution through erosion, accretion, or stability. These modifications will vary from place to place, depending on whether the changing dynamics will result in erosion, accretion, or stabilization. These impacts could be further exacerbated if storms become more frequent, or winds and currents change.

POSSIBLE RESPONSES

The possible measures that can be taken to mitigate the impacts of sea level rise on the Nigerian coastal zone can be classified according to whether the measure will attempt to halt the approach of the sea, i.e., "no retreat"; whether the measure will allow the sea to rise while avoiding the impacts, i.e.,

Figure 6. The Niger Delta is already experiencing flooding problems which will only be made worse by sea level rise.

("retreat"); or whether the measure will be an attempt to cope with sea level rise ("adaptation").

"No Retreat" Measures

"No retreat" measures include construction of the following:

1. Levees, seawalls and revetments, which basically protect the shoreline from waves and floods; and

2. Construction of groins and breakwaters to act as a wave barrier; this results in a zone of reduced wave energy, and also helps to trap sediments.

Generally the "no retreat" measures are very expensive for a developing country like Nigeria with huge external debts. Examples from other countries where these "no retreat" measures have been attempted have shown that they have not worked effectively and, in some cases, have exercabated the erosion and flood problem. Again, these "no retreat" measures are not capable of abating other impacts of sea level rise such as higher water tables and saline groundwater intrusion.

"Retreat" Measures

"Retreat" measures are generally soft regulatory and policy measures that generally do not require large and immediate expenditure. These measures are also flexible and can be easily changed in response to new sea level rise data.

However implementation of such of measures results in the loss of land. Retreat measures include the following:

1. Set back line: A set back line is a predetermined limit along the coast seaward to which no settlements or facilities should be located. Ibe et al. (1984) suggested a set back line of 20 times the determined rate of erosion.

2. Beach nourishment program: This method is a popular approach used to protect coastal property and to maintain recreational beaches. However the success of beach nourishment programs depend on correct implementation procedures, i.e., choosing the right grain size, burrow pit, etc. The many beach nourishment programs implemented at the Bar beach during 1974-75, 1981, and 1985-86 have not very successfully checked erosion and flooding. This was partly due to incorrect implementation procedures.

3. Controlled urbanization and capital facilities: The coastal zone of Nigeria has witnessed sporadic urbanization in the 20 years due to the oil boom of the seventies. Efforts should now be made to control this urbanization within the coastal zone. Construction of capital facilities such as roads, buildings, sewers, etc., should be kept beyond the reach of projected sea level rise.

4. Public awareness program: Measures to increase public awareness of the potential impacts of sea level rise should be pursued. Private developers should be enlightened on the foundation and structural codes required for buildings in such unstable zones along the coast. Illegal mining of beach sand should also be discouraged. These san miners should be made aware of the danger they create by their actions.

5. Increase in flood plan elevation: Efforts should be made to increase the elevations of the floodplain or beach ridges around the many barrier islands. This would help to reduce the potential of flooding of the adjacent lowland, but preliminary studies show that this is an expensive option.

6. Afforestation: Limiting deforestation and using reforestation and afforestation to slow or stop the rise in atmospheric concentration of carbon dioxide was first proposed during the 1970's. Today it is accepted as one of the effective ways of slowing down erosion and denudation of the land. Efforts to afforest the coastal zone should be stepped up, while deforestion should be discouraged.

7. Studies: Since rising sea level affects all coastal areas, studies must be initiated with the aim of identifying area that will be very sensitive to impacts of sea level rise. These studies should also include collecting data on water level, rates of erosion, subsidence, groundwater, ocean dynamics, and other facets of coastal management.

Such studies must be viewed by government and other sponsoring agencies as essential and not as an academic exercise.

CONCLUSION

Nigeria does not presently have a well-articulated, concrete and enforceable coastal zone management policy. The lagoon city project, which was intended to create prime real estate on the foreshore of the Lagos lagoon but instead led to enormous ecological damage, took advantage of this lack of a coherent policy. An urgent need exists for national policies with adequate legal provisions for coastwide, coordinated, and effective management and control of the Nigerian coastal zone.

BIBLIOGRAPHY

Allen, J.R.L. 1964. The Nigerian continental margin: bottom sediments, submarine morphology, and geological evolution. Marine Geology 1: 289-332.

Allen, J.R.L. 1965a. Late Quaternary Niger delta, and adjacent areas: Sedimentary environments and lithofacies. A.A.P.G. Bull 49: 547-600.

Allen, J.R.L., and Wells, J.W. 1962. Holocene coral banks and subsidence in the Niger Delta. J. Geol. 70: 381-397.

Ajayi T.O., and Talabi, S.O. 1984. The potentials and strategies for optimum utilization of the fisheries resources of Nigeria. NIOMR Tech. Paper No. 18.

Atlas of the Federal Republic of Nigeria. First Edition 1978. Lagos.

Bruun, P. 1977. Practical solution to a beach erosion problem. Coastal Engineering 1: 3-16.

Burke, K. 1972. Longshore drift, submarine canyons and submarine fans in development of Niger Delta. AAPG Bull. 56: 175-1983.

Ibe, A.C. 1984a. Defending Victoria Island against sea incursion. Special Report, Lagos, Nigeria: Federal Ministry of Education, Science and Technology, 7 p.

Ibe, A.C. 1984b. Protecting Victoria Island against sea incursion. A position paper submitted to the Ad Hoc Committee on the Victoria Island Erosion Problem; August 1984. 5p.

Ibe, A.C. 1984c. A rational strategy for defending Victoria Island against oceanic surges. In: Proc. Conference on the Bar Beach Surge. Federation of Building and Civil Engineering Contractors of Nigeria Ltd.

West Africa

Ibe, A.C. 1985a. Nearshore Dynamics and Coastal Erosion in Nigeria. Paper presented at the UNESCO Expert Workshop on WACAF/3 Project; Dakar, Senegal; March 11-19, 1985.

Ibe, A.C. 1985b. Harbor development related erosion at Victoria Island, Lagos. First International Conference on Geomorphology, University of Manchester, England; September 15-21, 1985. In: International Geomorphology 1986. Gardiner, V., ed. pp.165-181.

Ibe, A.C. 1986. Port development related erosion at Escravos, Bendel State, Nigeria. In: Proc. Man's Impact on the Coastal Environment Barcelona, Spain, 6-13 September 1986. In: Thallasa, Revista De Ciencions Del Mar Special edition. Villas, F., ed.

Ibe, A.C. 1987a. Marine erosion on a transgressive Mud Beach in Western Nigeria. In: Proc. Intern. Symposium on Geomorphology and Environmental Management, Alahabad; India, Jan. 1-20 eds. S. Sighn and R. C. Tiwari (in press).

Ibe, A.C. 1987b. Collective response to erosion hazards along the Nigerian Coastline. In: Proc. Coastal Zone, 1987. Seattle, Washington: pp. 741-754.

Ibe, A.C. 1987c. Human Impact on the coastal erosion problem in the west and central Africa (WACAF) region. In: Proc. International Se Conference, University of Mauritius, Reduit, Mauritius, 7-12 September 1987 (in press).

Ibe, A.C., and E.E. Antia. 1983a. Preliminary study of the impact of erosion along the Nigerian coastline. In: Proc. First International Conference on Flooding, Desertification and Erosion in Africa. Port Harcourt, Nigeria: Rivers State University of Science and Technology, May 2-6, 1983.

Ibe, A.C., and E.E. Antia. 1983b. Preliminary assessment of the impact of erosion along the Nigerian shoreline. NIOMR Tech. Paper No. 17p.

Ibe, A.C., and P.E. Awani. 1986. Erosion management strategies for the Mahin Mud Beach, Ondo State. In: Proc. National Seminar on Flooding and Erosion along the Nigerian Coastline. University of Lagos, May 1986.

Ibe, A.C., and L.F. Awosika. 1986. Sedimentology of the barrier bar complexes in Nigeria. NIOMR Tech. Paper No. 26.

Ibe, A.C., L.F. Awosika, and E.E. Antia. 1984. Progress Report No. 2. Coastal Erosion Research Projects. NIOMR Special Publications; 106p.

Ibe, A.C., L.F. Awosika, A.E. Ihenyen, C.E. Ibe, and A.I. Tiamiyu. 1985a. Coastal erosion at Awoye and Molume, Ondo State, Nigeria. A report for Gulf Oil Company (Nigeria) Ltd. 123p.

Ibe, A.C., L.F. Awosika, A.E. Ihenyen, C.E. Ibe, A.I. Tiamiyu, E.C. Okonya, and T. Orekoya. 1985b. A study of currents and scouring effects at the proposed Davy Banks 'A' Location in OML 14. A report for Shell Petroleum Development Company of Nigeria Ltd. 56p.

Ibe, A.C., L.F. Awosika, C.E. Ibe, A.I. Tiamiyu, F.O. Egberongbe, and S. Orupabo. 1986. The erosion problem at Victoria Island (1900 to Present) and its solutions. In: Proc. National Seminar on Flooding and Erosion along the Nigerian and similar coastlines. University of Lagos, May 1986.

Ibe, A.C., A.E. Ihenyen, and C.E. Ibe. 1985c. A hydrographic Survey of the Proposed Benin Estuary Location OML 43. A report for Shell Petroleum Development company of Nigeria Ltd. 25p.

Ibe, A.C., and M. Murday. 1986. Aerial Photostudy of recent migration of the Lagos shoreline. NIOMR Techn. Paper (in press).

Stein, D., G. Echwebber, and A.C. Ibe. 1986. Investigation on the Bar Beach erosion and a proposal on the maintenance of the coast. National Seminar on Flooding and Erosion along the Nigerian and related coastlines. May 1986, University of Lagos.

Oguara, T.M., and A.C. Ibe. Decision Analysis for the selection of erosion control measures. NIOMR Tech. Paper (in press).

Nigeria in Maps, 1982. Barbour, K.M., Oguntoyinbo, J.S., Onyemelukwe, J.O.C., and Nwafor, J.C., eds.

Tobor, J.G., M.O. Okpanefe, J.O. Oladoye, A.L. Ekwemalor, and O. Oladip. 1977. Fisheries Statistical Survey of Nigeria. Report 1975-1976 NIOMR, Lagos.

RESPONSES TO THE IMPACTS OF GREENHOUSE-INDUCED SEA LEVEL RISE ON SENEGAL

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ABSTRACT

The predicted rise in sea level of 1 m from greenhouse-induced global warming will greatly impact the country of Senegal. The coastline of Senegal is made up of three large estuaries (Senegal, Saloum, and Casamance Rivers), about 400 km of sandy coastline, and approximately 70 km of rocky cliffs. The low-lying estuarine areas will be prone to inundation, and the sandy coasts will most likely experience increased erosion if sea level rises as predicted. The Cap Vert peninsula, where the majority of the population and economic activity are concentrated, will be greatly affected. Furthermore, Senegal relies upon the coast for the income generated from agriculture, fisheries, industry, and tourism. Coastal towns and cities, like Dakar, Saint-Louis, Rufisque, Mbour, and Joal, will be required to retreat and/or stabilize their waterfronts.

IMPLICATIONS OF SEA LEVEL RISE

Senegal would be very vulnerable to a rise in sea level, because low-lying beaches and estuaries account for approximately 90% of its 700-km coast. Increased coastal erosion would be particularly severe in areas that are already eroding, such as Saint-Louis, Rufisque, and Joal, and homes would almost certainly be destroyed. Coastal wetlands, including tidal flats, mangroves, and tannes would be flooded, upsetting fish and wildlife. Saltwater intrusion into both groundwater and agricultural lands would increase. Sand spits would breach more often, and roads and other infrastructure would be lost.

Because two-thirds of the nation's population and 90% of its industry is in the coastal zone, the nation cannot afford to ignore this issue, nor should coastal cities and towns. The authorities are aware of the importance of the coastal zone, but not about the possible acceleration in sea level rise. It will be necessary to coordinate efforts among authorities, scientists, educators, and industry leaders, who should all consider the national well-being to be of highest priority. An action plan is required that would include:

1. Scientific monitoring of the coastal zone (e.g. beaches, estuaries, mangrove, groundwater evolution). No tide data have been recorded since 1964. A network of tide gauges should be established. Swell monitoring and regular morphological and sedimentological profiles should be continued.

2. Education of the entire nation about sea level rise and its consequences through a major public information campaign. This is especially critical in a nation of diverse ethnic groups who have long histories of living and working in ancestral grounds. For example, at Rufisque, the Lebou fishermen refuse to leave even when their homes are inundated, because these are ancestral grounds. In other areas, sand miners need to learn the consequences of their removing sand from eroding coastal areas, but perhaps more important, they need to learn other occupations that would provide an acceptable livelihood for them and would be harmless to the environment.

3. Revision or creation of strong and consistent national policies for use of the coastal zone. This would enhance uses of the coastal zone and would avoid future problems of inappropriate siting of industries or populations.

4. Creation of response strategies to a rise in sea level. Developing countries such as Senegal find it very difficult, if not impossible, to invest in hard coastal protection works, or even those such as beach renourishment. Other options will have to be developed for inclusion in the national policy.

5. Programs to cope with potential relocation of communities, and possible retraining of people for new skills or occupations. For example, artisanal fisheries or even certain agricultural activities might be changed to mariculture or aquiculture. Strong tribal or ethnic ties that exist in some traditional communal villages on the coast will have to be considered in any relocation and retraining activities.

6. Programs to develop and encourage new industries, or agricultural activities to replace others displaced by the effects of sea level rise. For example, in the Casamance River valley perhaps some peanut and millet growing might be replaced by more rice growing, which already exists. Saltworks at Kaolack on the Saloum River have the potential to increase.

In the absence of detailed studies, it is impossible to be any more specific about the effects and responses to a rise in sea level. Nevertheless, considerable knowledge about the coast of Senegal has accumulated. To give the reader an idea of the environments at risk, the following sections describe the nature of the coastal environment, the impacts of current changes in sea level and climate, and the socioeconomic resources of the coastal zone. Geological details about the coast are found in the appendix.

THE COASTS OF SENEGAL

The three main types of coastlines in Senegal (Figure 1) are rocky coasts (about 70 km long), sandy coasts (about 400 km long), and mangrove estuaries (about 250 km).

Rocky Coasts

These coasts are located along the Dakar and Ndiass horsts. Generally, their base is covered by blocks, cobbles, and pebbles, which protect them from wave attack. There are often small bay beaches between adjacent rocky capes.

Sandy Coast

The North Coast or "Grande Cote" (Saint-Louis to Yoff)

Here, the straight sandy beaches are linked with three Quaternary dune systems: (1) the continental "red dunes," which are about 20 m high; (2) the yellow dunes, which form a 250- to 4,500-m-wide field that is often 20-30 m high; and (3) the littoral white dunes, which range from a few to 100 m wide and vary between a few to 25 m high and are still accumulating windblown sand from the beach. The interdunes (known as "niayes") are periodically inundated by precipitation and groundwater, and play an important role in the coastal ecology. Although they are 3 to 10 m above the sea level, they would be affected by any rise in sea level due to the backwater effect.

The beaches are relatively narrow (between 40 m at Yoff and 110 m at Camberene). Sall (1982) suggests that they erode during the dry season and accumulate during the wet season. The Bruun rule suggests that with a rise in sea level, the reaccumulation would be less owing to the need for the offshore profile to rise with sea level. Given the Bruun rule-of-thumb that a one meter rise in sea level causes one to two hundred meters of beach erosion, it is clear that even a relatively small rise in sea level could completely eliminate these beaches.

The South Coast or "Petite Cote" (Hann to Djiffere)

Unlike the North Coast, the South Coast is characterized by rocky capes and the absence of dunes (Demoulin, 1967). Because the beaches are lined with a sandy barrier, however, we consider these areas to be part of the sandy coasts (Figure 2). These barriers are often adjacent to shallow lagoons (wadi). During the rainy season, these lagoons and wadi have much higher water levels, which sometimes causes a barrier to break; this can release substantial organic material into nearby coastal waters.

The beaches are very narrow (30 to 40 m). Beach rocks stick out of the sand at the beaches at Rufisque, Bargny-Sienndou, and along the "Pointe de Sangomar" sand spit.

Because the beaches are very narrow, a rise in sea level could have an even greater impact here than along the North Coast. In cases where rocky capes lie

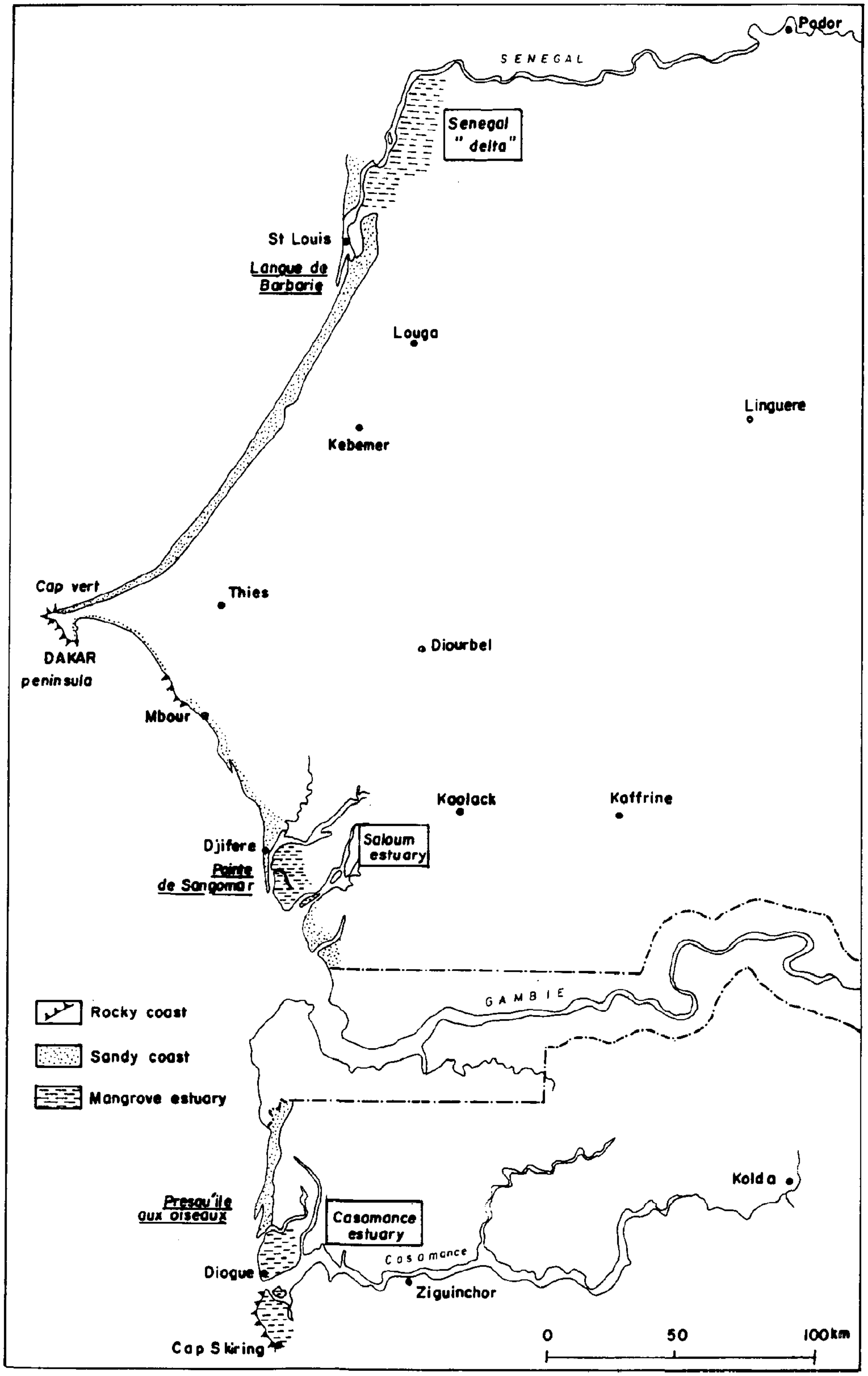

Figure 1. Main coastal types of Senegal.

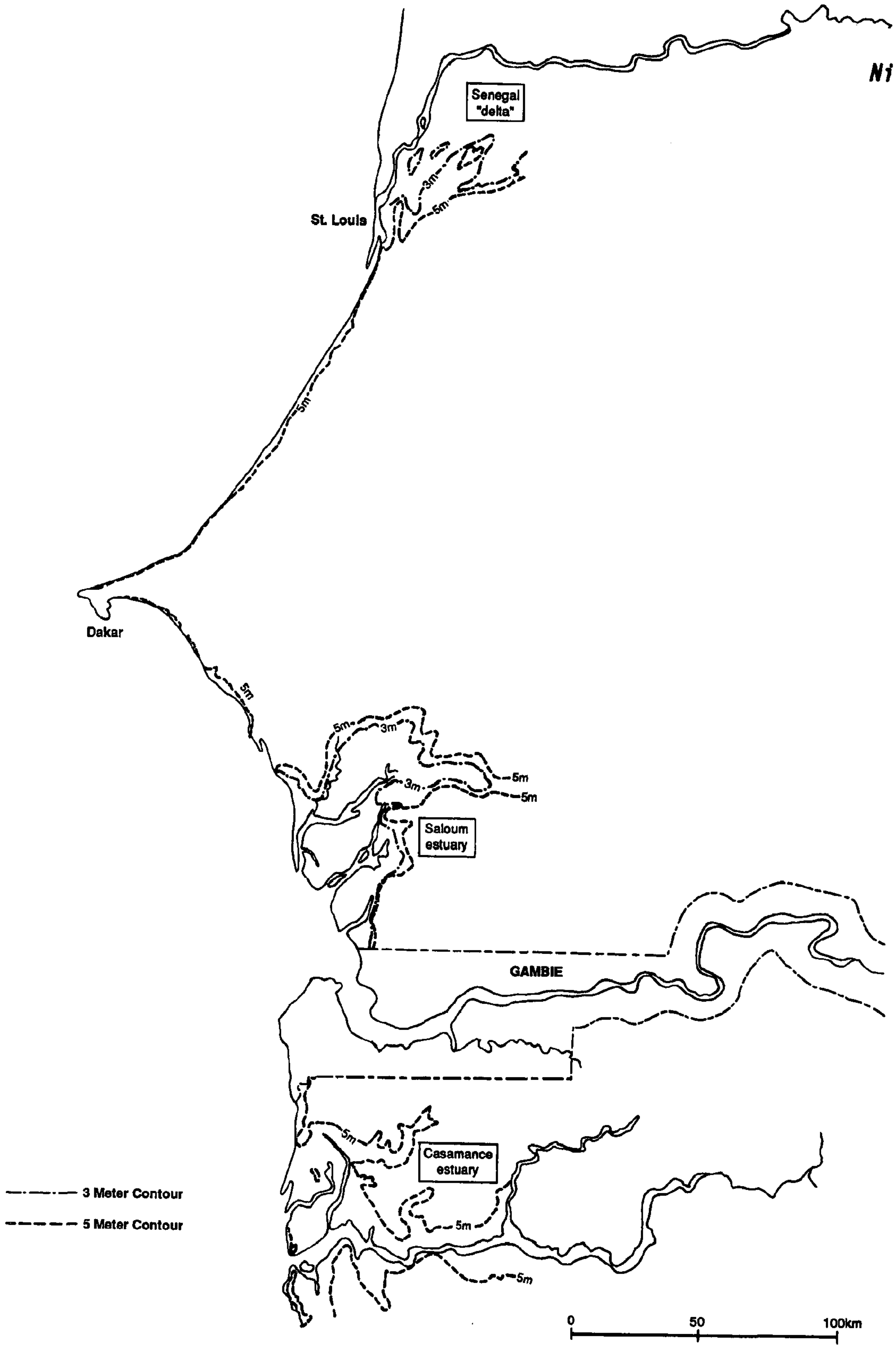

Figure 2. Map of Senegal showing 3- and 5-meter contours.

behind the beach, there would be little opportunity for the ecosystem to shift landward.

Mangrove Estuaries

These estuaries correspond to the three most important rivers: the Senegal, Saloum, and Casamance. All of these estuaries are characterized by tidal flats, mangroves, marshes, and tannes. Moving inland from the tidal channel, one observes first tidal flats, then mangrove marshes with Rhizophora racemosa (5 to 12 m high) replaced by R. harisonnii and R. mangle in the Saloum estuary, then Avicennia africana (1 to 3 m high). From south to north, owing to climatic conditions, we notice a reduction of the mangrove population density and a diminution of the species number (six in Casamance, four in Saloum, and two in Senegal). The bare tanne is limited by the annual tide level, whereas the vegetated tanne is also found above this tide level but can tolerate inundation by freshwater.

These estuaries are also characterized by manmade shell deposits resulting from the trade of Anadara senilis and the Rhizophora oysters (Gryphea gasar) since the Neolithic times. They are present in the three estuaries but are particularly pronounced in the Saloum (Diop, 1986).

Studies on the mangrove population along the Saloum (UNESCO, 1985) have shown that from the mouth to the upstream part of the estuary, there has been a height reduction of Rhizophora, diminution of the area occupied by Rhizophora, reduction of the population density, and augmentation of dead Rhizophora. Finally, the mangrove disappears upstream of Foundiougne. This regression of the mangrove environment will be related to the drought, to the human activities (use of trees for cooking, small-scale exploitation of salt), and to natural diseases.

CURRENT CHANGES IN THE COASTAL ENVIRONMENT

Consequences of the Drought

First of all, there is a renewal of eolian (wind-blown) migration of dunes due to recent droughts. Along the Grande Cote, white dunes are migrating toward the continent (2 m/year to 7.1 m/year), the exception being the "Gandiolais" (south of St-Louis), where the white dunes migrate seaward (11.5 m/year between 1954 and 1980). This phenomenon determines a progressive filling up of the interdunes (niayes). The migration speed of the yellow dunes varies between 4.80 m/year in the Cayar-Tanma lake sector to 1.3-3.8 m/year at Vele and Pikine. If global warming worsens drought conditions, we may see an acceleration in the rate of dune migration.

The lack of precipitations also induces a salinization of the rivers, the groundwaters, and soils due to the weak or absent freshwater input. Saltwater intrusion has led to a decline in the mangroves (in Casamance, 70 to 80% of the mangrove has disappeared since 1969 (Diop, 1986; Marius et al., 1986)). The reduction of the mangrove population is accelerated by human activities such as the use of trees for cooking, construction of dams, the rice culture (responsible for 25% of the destruction in Casamance between 1967 and 1982), and the exploitation of salt (Paradis, 1986). Therefore, tannes are replacing the mangrove swamps (Marius et al., 1986). For example, between 1973 and 1979, in the Casamance estuary, Sall (1982) noted that tannes increased 107 km^2 while mangroves declined by 87 km^2.

Other consequences of the drought are the acidification and oxidation of the soils, well studied in the Casamance estuary (Boivin et al., 1986; Marius et al., 1986). The acido-sulfated soils are characterized by a low pH (<4.5), formation of jarosite (iron sulfate), and salt precipitation with appearance of gypsum unknown in Casamance before 1972.

Last, there is a tendency toward salt contamination of the groundwater due to the lowering of the groundwater table (Boivin et al., 1986).

All of these problems could be made substantially worse if global warming leads to a drier climate in coastal Senegal. Destruction of mangroves would have a particularly severe impact on fishing. The threat to water supplies would be particularly important for communities already struggling with salt contamination.

Coastal Erosion

Cliff erosion

The speed of a cliff's retreat depends on its type. The Cap de Naze cliffs are retreating slowly (5.8 cm/year) at the base owing to accumulation of blocks and pebbles, but five times as rapidly at their summits. The plunging cliffs (Cap des Biches, Fann) are eroding more rapidly, particularly those made of sedimentary rocks (32.9 cm/year for the Cap des Biches and 29.3 cm/year for the Fann cliffs).

Erosion Along the Sandy Coasts

Several parts of the Senegalese coasts are eroding rapidly (DHV, 1979; PNUE, 1985): St-Louis (1.25 to 1.30 m/year), Rufisque (about 1.30 m/year), and Joal in particular. The impacts are important because all of these areas are densely inhabited. Consequently, many coastal defense structures have been built, including seawalls at St-Louis, Rufisque, and Joal, and groins at Rufisque (Murday, 1986).

The causes of coastal erosion are still unclear. According to Masse (1968) and DHV (1979), the erosion between Mbao and Bargny is induced by a predominant onshore-offshore sand transport especially during storms, part of the sands not being recovered by the beaches. This result is consistent with the slow continuous rate of sea level rise (a few millimeters per year, Elouard et al., 1967). In addition, human activities such as the hardening of the coastline by human construction and especially the extensive sand mining along the Cap Vert coast (from Cayar to Bargny) are contributing to the problem. Below Bargny, the littoral drift also contributes to the problem. If sea level rise accelerates, there is little doubt that erosion would increase proportionately throughout much of the coastal zone.

The many sand spits are even more vulnerable, even with current trends. From 1850 to 1980, the "Langue de Barbarie" has seen 24 breaks, which forced the authorities to stabilize the sand spit. Since then, the breaks have occurred only south of St-Louis. With an accelerated rise in sea level, additional protective measures will be necessary.

SOCIOECONOMIC ASPECTS OF THE COASTAL ZONE

About the two thirds of the nation's population (about 6.8 million in 1987) is concentrated along the littoral zone. The population density is between 10 and 20 persons/km^2 along the North Coast, 20-50 persons/km^2 in the South Coast and Casamance, and more than 1,800 persons/km^2 in the Cap Vert peninsula. Most of the big cities and towns are located along the littoral zone: St-Louis (88,404 inhabitants in 1976), Dakar (about 500,000), Pikine (1 million), Mbour (37,896), Joal (15,665), Kaolack (135,473), and Ziguinchor (69,757). Directly or indirectly, a rise in sea level would affect all of these inhabitants.

The most important maritime fishing centers are, from north to south, St-Louis, Cayar, Dakar, Mbour, and Joal. Owing to the seasonal migration of fauna, in relation to upwellings, the fishermen migrate from north during the dry season to south during the wet season. Estuaries are important centers for nonmaritime fishing. The total fish production was approximately 157,000 tons in 1987 with a predominance of maritime and industrial fishing. Part of the production is distributed on the great markets, another part is smoked and/or dried, and a part is exported. Global warming could upset these fisheries both through the loss of wetlands that support estuarine fishing and as a result of changes in ocean currents, which could affect maritime fisheries.

The main farm crops along the coast are peanuts (total production of 946.4 thousand tons in 1987) and millet (total production of 801.2 thousand tons in 1987); the rice culture (total production of 135.8 thousand tons in 1987) has traditionally has been confined to the Casamance estuary, but now is also present in the Senegal and Saloum estuaries (EPEEC, 1983). Along the North Coast, the niayes are used for market gardening, which is also practiced in the different estuaries.

Since 1950, the Senegal estuary has been subject to management of irrigated perimeters; this development program is now enhanced by the Diama and Manantali Dams. These projects will permit the irrigation of 250,000 hectares (Michel and Sall, 1984). Both sea level rise and changes in precipitation could impair the functioning of these new systems.

Tourism is extensive on the South Coast (Saly, Mbour, Joal) and in Casamance (Cap Skiring, Kabrousse), where it contributes 31 billion CFA francs per year in hard currency.

APPENDIX: THE COASTAL ENVIRONMENT OF SENEGAL

EVOLUTION OF THE COAST

The configuration and the evolution of the coastline in Senegal have been controlled by three main factors: climate, geology, and hydrodynamics. We discuss each in turn.

Climate

Senegal's climate is characterized by the alternation of two seasons:

- The dry season: cold, lasting 6 or 8 months during which the N to NW maritime trade winds are dominant all along the coastline, with some incursions of the NE continental trade wind or "harmattan."

- The wet or rainy season: hot, during which the precipitation occurs (80% of the precipitation between July and September with a maximum in August). The wind regime is dominated by SW monsoon winds.

The main characteristic of this climate is the great interannual variability of the precipitation. The recent drought has been in effect since 1968 (Olivry, 1983).

Geology

The lithology and tectonics are responsible for the great morphological subdivisions of the coastline (Sall, 1982). The entire Senegalese coastline belongs to the Meso-Cenozoic Senegalo-Mauritanian passive margin basin (Bellion, 1987) (Figure A-1).

Tectonics

The Cap Vert peninsula is subdivided by N-S to NNE-SSW faults in two horsts (Dakar and Ndiass horsts) separated by the Rufisque graben (Elouard, 1980). The two horsts constitute the higher parts of the coastline (105 m). From Kayar to Mbour three main fault directions (NNE, NW, and NE) have been identified (Dia, 1980; Bellion, 1987; Lompo, 1987), and these faults appear to have been active since the last Pleistocene (Dia, 1980). Furthermore, two subsidence centers are located in the Senegal "delta" zone to the north and in the Saloum-Casamance regions to the south. But recent studies (Faure et al., 1980) have shown a lithospheric rigidity of more importance than predicted.

Volcanism

It is a basic volcanism (Dia, 1980, 1982; Bellion, 1987), subdivided in two periods:

- The Tertiary volcanism (35.5 to 5.3 MA) is fissural (Dia, 1982). In the Cape Verde peninsula, this volcanism determines the "eruptive system of Dakar" (Dia, 1980);

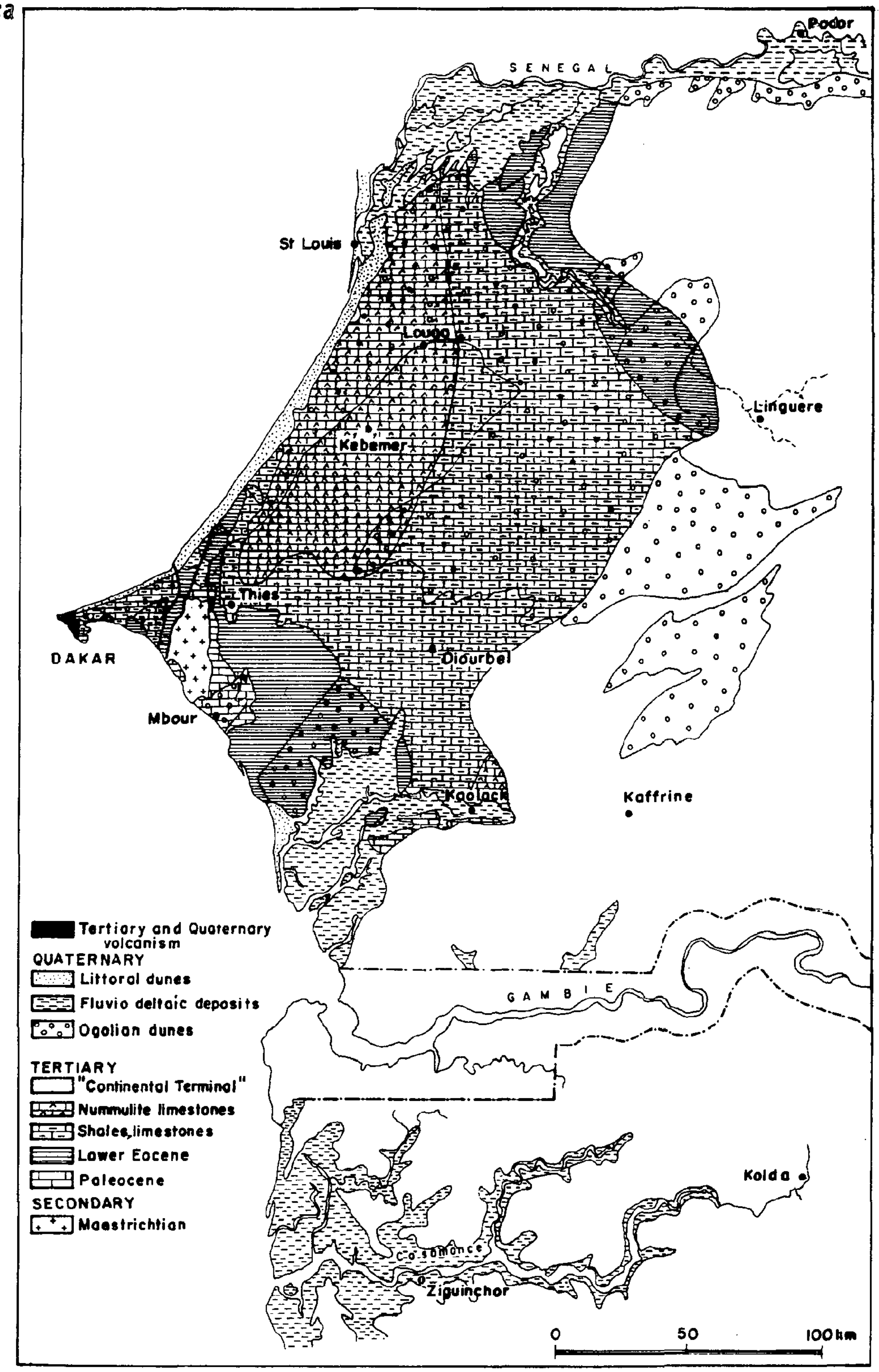

Figure A-1. Geology of Senegal.

- The Quaternary volcanism (2 MA to 500,000 ago) is represented in the extreme west of the Cap Vert peninsula by the Mamelles volcano, secondary eruptive bodies (Mermoz), and also by about five or six lava beds and interstratified tuffs (Dia, 1980, 1982; Lo, 1988).

Hydrodynamics

The tidal range is only about one meter on the ocean coast, and less in most estuaries. The NW swells are dominant and associated with SW swells only during the rainy season (Figure A-2). On the North Coast, the NW swell determines a NE-SW littoral drift (Pinson-Mouillot, 1980). Then, the NW swell is diffracted three times around the Cap Vert peninsula (Riffault, 1980), determining a divergence in the Hann bay and an E-W current between Rufisque and Hann (Masse, 1968). From Rufisque, the swell obliquity increases, generating a NW-SE littoral drift with speeds between 0.8 m/s at Bargny and 1 m/s at the Somone estuary (Demoulin, 1967).

Estimates of volume of sand transport by the littoral drift vary (PNUE/UNESCO/ONU-DAESI, 1985), but all indicate that the sand transport is much more important along the North Coast than along the South Coast.

THE MAIN TYPES OF COASTLINE

Three main types of coastlines are encountered in Senegal (see Figure 1) (Sall, 1982): rocky coasts (about 70 km long), sandy coasts (about 400 km long), and the mangrove estuaries (about 250 km).

The Rocky Coasts

About 70 km long, they are located along the Dakar and Ndiass horsts. The cliffs consist of the following:

- Volcanic rocks along the Cap Vert peninsula. The Tertiary eruptive system of Dakar gives rise to the ankaratrite cliffs of Goree (40 m high) and Cap Manuel (35-40 m) and to the basanite cliffs of Madeleines Island and Fann. The Quaternary eruptive system of Mamelles gives rise to the dolerite cliffs located between Yoff and Fann (10 to 12 m high);

- Paleocene and Eocene marly limestones for the cliffs of Popenguine, Cap des Biches (13 m high),"anse" Bernard and Madeleines;

- Maastrichtian sandstones and shales for the cliffs of the Ndiass horst: Cap Rouge (47 m), Toubab Diallao (12m), and Cap de Naze (about 60 m);

- "Continental terminal" sandstones capped by lateritic crust in Casamance.

These cliffs can be plunging cliffs (Cap Manuel) when they are made of volcanic rocks, or have a straight to convex face when they consist of

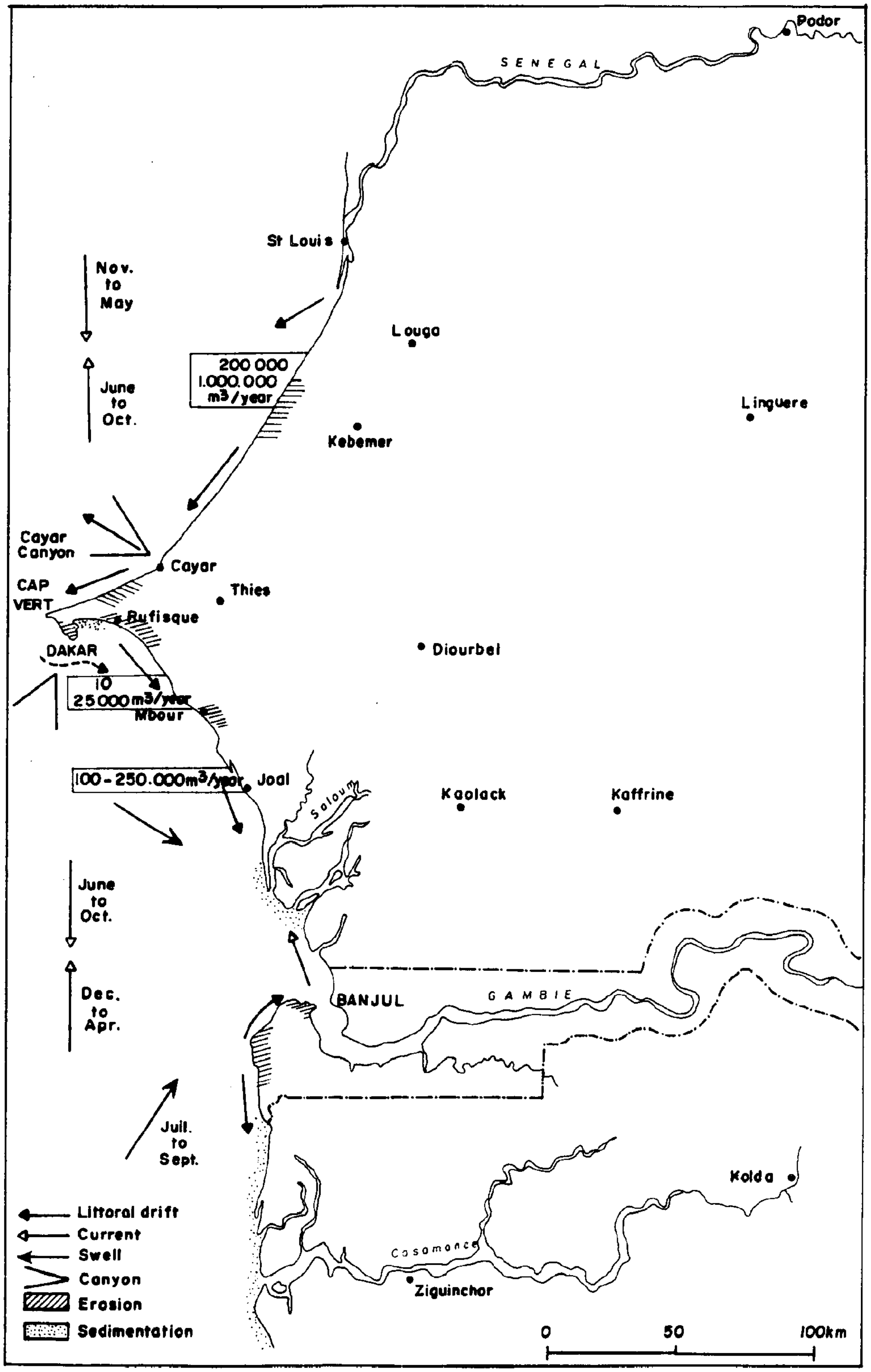

Figure A-2. Hydrodynamics of Senegal.

sedimentary rocks (Cap de Naze) (Sall, 1982). Generally, their base is covered by blocks, cobbles, and pebbles protecting them from wave attack. The abrasion platforms are very rare (Cap des Biches, Cap Manuel, Fann-Almadies). Between two rocky capes, there are often small bay beaches.

The Sandy Coasts

The North Coast or "Grande Cote" (Saint-Louis to Yoff)

Here, the straight sandy beaches are linked with three Quaternary dune systems present above the Eocene shaley limestones (see Figure 1 and Figure A-1). From the land to the sea, we can distinguish:

- The continental dunes or Ogolian red dunes (20,000-12,000 years ago) with first NE-SW flattened longitudinal dunes (about 10 m high) built during the arid Ogolian (18,000 years ago), followed by NNW-SSE to WNW-ESE dunes of about 20 m high that are the result of Ogolian dunes reworking during a short arid phase (8,000 to 6,800 years ago) (Michel, 1969);

- The semi-fixated yellow dunes built during an arid phase (Tafolian, 4,000-1,800 years ago) form a 250- to 4,500-m-broad dune field. They are made of NNW-SSE parabolic dunes, barkhans (Pinson-Mouillot, 1980). Often very high (up to 20-30 m), they are ended by an abrupt upthrow front (30-45° steep, more than 30 m high) above the niayes or the red dunes (Pezeril et al., 1986);

- The littoral dunes or white dunes form a band from a few meters to hundred meters broad. They are parallel to the coast, the typical form being the NNW parabolic dunes. The heights vary between a few meters to 25 m maximum. They began to form during the Subactual and are still supplied by the beach sands.

The main characteristic of this littoral zone are the interdunes' so-called niayes, temporarily inundated by precipitation and groundwater. Three to ten meters above sea level, these niayes are of three different types (Michel, 1969; Pezeril et al., 1986); they can originate from old hydrographic networks or be true interdunes. These niayes are characterized by a relictual subguinean vegetation with the oil palmtree (Elaeis guineensis) bordering them (Fall, 1986; Lezine, 1986).

The beaches are relatively narrow (between 40 m at Yoff and 110 m at Camberere). The average slopes are less than 8°. The characteristic forms of these beaches are beach cusps, with ridges and runnels (Diaw, 1981; Sall, 1982). Sall (1982) proposed a model of the beach cycle, swell controlled with erosion during the dry season and accumulation during the wet season and determining a seasonal balance between the foreshore and the shore face.

West Africa

The South Coast or "Petite Cote" (Hann to Djiffere)

Unlike the North Coast, the South Coast littoral zone is characterized by rocky capes and the absence of dunes (Demoulin, 1967). The beaches are lined with a sandy barrier, however (see Figure 1 and Figure A-1).

The sandy barrier can lean on a shallow lagoon or wadi or on a rocky bedrock. Arid during the dry season, these lagoons and wadi are filled up during the rainy season, sometimes inducing a barrier break with little detrital input to the coast (Masse, 1968).

Very often, we can observe behind the lagoon the Anadara senilis Nouakchottian terrace. This terrace, located between +2.5 and +3 m, is the result of the last important Holocene transgression, the so-called Nouakchottian (max; at 5,500 years ago). This terrace is present at Mbao, Bargny (Demoulin, 1967), between Mbour and Nianing (Elouard et al., 1967), and at Mbodiene (Elouard et al., 1967; Debenay and Bellion, 1983).

The sandy barrier(s), 100 to 150 m wide and less than 5 m high, can present several aspects (Demoulin, 1967). The fixated barrier (the most common type) is covered by Opuntia tuna and limited seawards by a microcliff. In the Mbour sector (Elouard et al., 1977), there is a barrier of several generations, with the first one very rich in heavy minerals (ilmenite, zircon, and rutile). After this barrier, there are successive and more recent barriers up to the beach.

The beaches are narrow (30 to 40 m) with average slopes of 3 to 4° (Demoulin, 1967), the shore face being more steep (5 to 15°). The beach cusps are well developed on this coast (Demoulin, 1967) and sometimes consist of pebbles. The beach sands on this coast are very often titaniferous (amorphous ilmenite), the more important concentrations being found at Rufisque (33,360 to 92,580 ppm) and Tine Dine island near Joal (131,000 ppm) (Dumon, 1981).

One feature of this coast is the presence of Holocene to Pleistocene "beach rocks" (Demoulin and Masse, 1969) outcropping on the beaches at Rufisque, Bargny-Sienndou, and along the "Pointe de Sangomar" sand spit. The first carbon-14 dating made on shells have given an age of 32,500 +2150 years ago (Demoulin and Masse, 1969), which corresponds to the so-called Inchirian. New petrographical and geochemical studies (Giresse et al., 1988; Diouf, 1989) have questioned the previous dating.

Mangrove Estuaries

Representing about 150 km of coastline, these estuaries correspond to the three most important rivers, from North to South: Senegal, Saloum, and Casamance.

General Characteristics

In all the estuaries, the common geomorphological units have been formed during the last Quaternary (Sall, 1982; Diop, 1986).

- Tidal channels. They are sinuous except in the Senegal estuary. These channels present a well-developed hierarchy. The depths are not very important except in the main channels: 8-10 m in the Senegal, 6 m in the Saloum, and 8-9 m in the Casamance. These channels present sandy or clay channel bars, very developed and unstable in the mouth channels. From north to south, the channel sediment granulometry diminishes.

- Tidal flats-mangrove marshes-"tannes." From the tidal channel, we can observe in the intertidal zone, first tidal flats then mangrove marshes with <u>Rhizophora</u> <u>racemosa</u> (5 to 12 m high) replaced by <u>R</u>. <u>harisonnii</u> and <u>R</u>. <u>mangle</u> in the Saloum estuary, then <u>Avicennia</u> <u>africana</u> (1 to 3 m high). The sediments are finer in the inner estuary than on its maritime part. From south to north, due to climatic conditions, we notice a reduction of the mangrove population density and a diminution of the species number (six in Casamance, four in Saloum, and two in Senegal). The bare tanne presents salt efflorescences and is limited by the very high tide level. The herbaceous tanne is developed beyond the tide levels but can be inundated by freshwater. It is colonized by an halophyte vegetation.

- Sandy barriers: with "kjokkenmoddinger" and some "lunettes," they constitute the rare permanent emerged units (+2 to +4 m high) in these estuaries. They are, therefore, favored sites for habitat and fresh groundwater. Well developed in the Senegal estuary, they surround small lagoonal lows. They are also present along the maritime parts of the Saloum and Casamance estuaries but less developed. The different sand spits bordering the main rivers belong to this unit: "Langue de Barbarie," "Pointe de Sangomar," and "Presqu'ile aux Oiseaux." These sand spits, built since 3,000 years ago, are N-S oriented due to the littoral drift.

- "Kjokkenmoddinger" (manmade shell deposits): These are due to the completion and trade of <u>Anadara</u> <u>senilis</u> and the <u>Rhizophora</u> oysters (<u>Gryphea</u> <u>gasar</u>) since the Neolithic. They are accumulations sometimes of huge size marked by the presence of <u>Adansonia</u> <u>digitata</u>. They are present in the three estuaries but are particularly developed in the Saloum (Diop, 1986).

<u>The Senegal Estuary</u>

The estuary is a triangle. First flowing E-W with numerous meanderings, the Senegal River changes direction from Keur Macene, flowing NE-SW then N-S from St-Louis, bordered by the 25-km-long "Langue de Barbarie" sand spit. Before reaching St-Louis, it receives a number of tributaries (Gorom, Lampsar), which are ancient deltaic channels. From Bogue, the Senegal river bed is situated below the sea level (-5 m up to St-Louis).

The Senegal estuary presents normal fluctuations with two seasons (Sall, 1982):

- A high-water season (July to November) during which there is a fluviatile regime. The flood is characterized by an high interannual variability in relation to the precipitation irregularity. For example, at Dagana, the annual module varies between 890 m^3/s during wet years and 490 m^3/s during dry years. Studies by Kane (1985) and Gac and Kane (1986) on suspended matter in the "delta" zone showed that the values are higher than 200 mg/L until the beginning of the flood, then reach maximum values of 686.4 mg/L (1981) and 415.8 mg/L (1982). From November, these values diminish to reach mean concentrations of 10 mg/L during the low water period. The inundated areas fluctuate between 100,000 and 500,000 hectares, depending on the flood quality.

- A low-water season (December to June) during which the saltwater enters the low estuary. The mechanism of the salt intrusion has been described by Gac et al. (1986a,b). The salt front was found around Richard Toll (170 km from the mouth) during wet periods and reached Dagana (217 km from the mouth) during dry periods.

<u>The Saloum Estuary</u>

It opens into the Atlantic Ocean through three distributaries: the Saloum, the Diomboss, and the Bandiala separating three groups of islands (Gandoul to the North, Betanti and Fathila to the South). The three distributaries are connected by a dense network of small and shallow tidal channels, the so-called bolons. The Saloum is bordered by a 20-km-long sand spit, the "Pointe de Sangomar." A mangrove swamp stretches all over the estuary. The main characteristics of the Saloum estuary are the following:

- Hydrodynamic and hydrological regime: several studies conducted between 1981 and 1984 (EPEEC, 1983, 1984; UNESCO, 1985) have proposed for the Saloum and Diomboss a reverse estuarine model (Barusseau et al., 1985, 1986) due to the weak or absent freshwater inflow (water discharges lower than 0.7 m^3/s (Diop, 1986)). The characterized model of the regime is as follows: the flood phase lasts longer than the ebb, with current velocities generally higher during the flood than on the ebb; and the Saloum distributaries receive more water than flows back into the sea (about 66%); the estuarine salinity is always higher than the seawater, even after the wet season. It increases from the mouth (35% in the wet season, 55% in the dry season) to the upstream end of the estuary (respectively, 42 and 88% in Kaolack).

- The Saloum estuary is characterized by the presence of relatively coarse sediments, and, even if the fine fraction is important, it is silt dominated. The percentage of carbonates is low (<5%) due to the mechanical and chemical destruction (low pH) of the shells.

- Studies on the mangrove population along the Saloum (UNESCO, 1985) have shown that from the mouth to the upstream part of the estuary, there has been a height reduction of <u>Rhizophora</u>, diminution of the area occupied by <u>Rhizophora</u>, of the population density and augmentation of dead

Rhizophora. Finally, the mangrove disappears upstream of Foundiougne. This regression of the mangrove environment will be related to the drought, to the human activities (use of trees for cooking, small-scale exploitation of salt), and to natural diseases.

- The great development of "kjokkenmoddinger."

The Casamance Estuary

It is, in fact, a ria dominated by the "Continental terminal" sandstone plateau (30-40 m high) often capped by a lateritic crust (Pages et al., 1987). During the last 240 km, the slope of the Casamance is null. Downstream of Ziguinchor, the Casamance River receives the Diouloulou tributary and there are numerous small tidal channels interconnected ("bolons"). The mangrove marshes are well developed with Rhizophora racemosa and Avicennia nitida, followed by the tannes. There are two types of sandy barriers (TECASEN, 1979). The recent ones, like the "Presqu'ile aux Oiseaux" which is a sand spit, are N-S oriented in the direction of the actual littoral drift; the old ones (since about 4,000 years ago) are oriented NNW-SSE (change of direction of the littoral drift since 4,000 years ago) or NE-SW south of the Casamance mouth (built by the SW swells).

The water discharges are relatively low. During wet years (1962, 1967, 1969, 1975), the annual module was of 6.4 m^3/s with a maximum of 32 m^3/s. But now, with the drought, the annual module is of 1.7 m^3/s with a maximum of 6.8 m^3/s (Pages et al., 1987). Before 1970, the Casamance River had a normal estuarine function, but now it is a reverse estuary like the Saloum (Debenay et al., 1987; Pages et al., 1987). Actually, the salinity increases upstream with values higher than 100% upstream of Sedhiou located 200 km from the mouth (max; of 170% in June 1986) (Pages and Debenay, 1987).

BIBLIOGRAPHY

Barbey, C., and Chamard, P. 1970. Contribution a l'etude petrographique des sables de la presqu'ile du Cap Vert. Bull. IFAN, Dakar, (A), 32-3:569-584.

Barusseau, J.P., Diop, E.H.S., and Saos, J.L. 1985. Evidence of dynamics reversal in tropical estuaries, geomorphological and sedimentological consequences (Salum and Casamance Rivers, Senegal). Sedimentol. 32(4):543-552.

Barusseau, J.P., Diop, E.H.S., Giresse, P., Monteillet, J., and Saos, J.L. 1986. Consequences sedimentologiques de l'evolution climatique fini-Holocene 102-103 ans) dans le delta du Saloum (Senegal). Oceanogr. trop. 21(1):89-98.

Bellion, Y.J.C. 1987. Histoire geodynamique post-paleozoique de l'Afrique de l'Ouest d'apres l'etude de quelques bassins sedimentaires (Senegal, Taoudenni Iullemme-den, Tchad). Thesis, Avignon, 302 p.

Biarnes, P. 1988. Senegal-1988. Marches Tropicaux. Mediterraneens, Paris, 13 p.

West Africa

Boivin, P., Loyer, J.Y., Mougenot, B., and Zante, P. 1986. Secheresse et evolution des sediments fluviomarins au Senegal. In: Symp INQUA/ASEQUA, Changements globaux en Afrique durant le Quaternaire: Passe-Present-Futur. Paris: Orstom, p. 43-48.

B.R.G.M. 1962. Carte geologique du Senegal (echelle 1/500 000, 4 feuilles). Serv. Mines et Geol., Dakar, 36 p.

B.R.G.M. and D.M.G. ed. 1985. Plan mineral de la Republique du Senegal. Min. Dev. Ind. Artisanat, Dakar, 3 volumes, 725 p.

Bruun, P. 1962. Sea level rise as a cause of shoreline erosion. Am. Soc. Civil Eng., Proc. V.88 Waterways and Harbours Division Journal WW1:117-130.

Debenay, J.P., and Bellion, Y. 1983. Le quaternaire recent des microfalaises de Mbodiene (Senegal): stratigraphie, variations du niveau marin. Ass. senegal. Et. Quatern. Afr. Bull. liaison, Dakar, p. 70-71, 73-81.

Debenay, J.P., Ba, M., Ly, A., and Sy, I. 1987. Les ecosystemes paraliques du Senegal. Description, repartition des peuplements de Foraminiferes benthiques. Rev. Paleobiol. 6(2):229-255.

Demoulin, D. 1967. Etude de la morphologie littorale de la Petite Cote de Bargny au marigot de la Nougouna (Senegal). La cote basse de Bargny Guedj a Yene Tode. Dipl. Et. Sup., Dakar, 122 p.

Demoulin, D., and Masse, J.P. 1969. Gres de plage de la presqu'ile du Cap Vert (Senegal). Bull. IFAN, Dakar, (A), 31(3):721-738.

D.H.V. Ingenieurs Conseils. 1979. Rapport sur l'etude de la protection du rivage de la Petite Cote. Min. Equip. Dakar, 92 p.

Dia, A. 1980. Contribution a l'etude des materiaux volcaniques de la presqu'ile du Cap Vert et du plateau de Thies. Inventaire et etude preliminaire des sites. Rapt Dpt. Geol., Dakar, Nlle Ser., 6, 92 p.

Dia, A. 1982. Contribution a l'etude des caracteristiques petrographiques, petrochimi-ques et geotechniques des granulats basaltiques de la presqu'ile du Cap Vert et du plateau de Thies (carriere de Diack-Senegal). Thesis, Dakar, 183 p.

Diaw, A.T. 1981. Etude morpho-sedimentologique de l'estran sur la cote nord du Senegal. Bull. IFAN, Dakar, (A), 43:1-2, 69-78.

Diop, E.H.S. 1986. Estuaires holocenes tropicaux. Etude de geographie physique comparee des "Rivieres du Sud": du Saloum (Senegal) a la Mellacoree (Republique de Guinee). Thesis, Strasbourg, 2 volumes, 522 p.

Diop, E.S., and Sall, M. 1986. Estuaires et mangroves en Afrique de l'Ouest: evolution et changements du Quaternaire recent a l'Actuel. In Symp. INQUA/ASEQUA, Changements globaux en Afrique durant le Quaternaire: Passe-Present-Futur. Paris: Orstom, p. 109-114.

Diouf, M.B. 1989. Sedimentologie, mineralogie et geochimie des gres carbonates quaternaires du littoral senegalo-mauritanien. Thesis, Perpignan, 237 p.

Dumon, J.C. 1981. Comportement du titane dans les phenomenes d'alteration et de sedimentation sous differents climats: Esquisse d'un cycle biogeochimique. Thesis, Bordeaux I, No. 718, 296 p.

Elouard, P. 1980. Geomorphologie structurale, lithologique et climatique de la presqu'ile du Cap Vert (Senegal). Notes Afr., IFAN, Dakar, 167:1-68.

Elouard, P., Faure, H., and Hebrard, L. 1967. Quaternaire de la region de Mbour. Sixth Cong. Panafr. Prehist. Et. Quatern., Dakar, p. 31-33.

Elouard, P., Faure, H., and Hebrard, L. 1977. Variations du niveau de la mer au cours des 15,000 dernieres annees autour de la presqu'ile du Cap Vert. Dakar, Senegal. Bull. liaison Ass. seneg. Et. Quatern. Afr., Dakar, 50:29-49.

E.P.E.E.C. 1983. Atelier d'etude des mangroves au Sud de l'estuaire du Saloum: Diomboss-Bandiala (Senegal). UNESCO/ROSTA, Dakar, 219 p.

E.P.E.E.C. 1984. Etude des mangroves et estuaires du Senegal: Salom et Somone. UNESCO/ROSTA, Dakar, 88 p.

Fall, M. 1986. Environnements sedimentaires quaternaires et actuels des tourbieres des niayes de la Grande Cote du Senegal. Thesis, Dakar, 130 p.

Faure, H., Fontes, J.C., Hebrard, L., Monteillet, J., and Pirazzoli, P.A. 1980. Geoidal change and shore-level tilt along Holocene estuaries: Senegal river area, West Africa. Science 210:421-423.

Gac, J.Y., Kane, A., and Monteillet, J. 1982. Migrations de l'embouchure du fleuve Senegal depuis 1850. Paris: Cahiers Orstom, Ser. Geol. 12(1):73-75.

Gac, J.Y., Carn, M., and Saos, J.L. 1986a. L'invasion marine dans la basse vallee du fleuve Senegal. I.Periode 1903-1980. Rev. Hydrobiol. trop. 19(1):3-17.

Gac, J.Y., Carn, M., and Saos, J.L. 1986b. L'invasion marine dans la basse vallee du fleuve Senegal. I.Periode 1980-1983: proposition d'un nouveau modele d'intrusion continentale des eaux oceaniques. Rev. Hydrobiol. trop. 19(2):93-108.

Gac, J.Y., and Kane, A. 1986. Le Fleuve Senegal: I. Bilan hydrologique et flux continentaux de matieres particulaires a l'embouchure. Sciences Geol. 39(1):99-130.

Giresse, P., Diouf, M., and Barusseau, J.P. 1988. Lithological, mineralogical and geochemical observations of Senegalo-Mauritanian Quaternary shoreline deposits: possible chronological revisions. Paleogeogr. Palaeoclim. Palaeoecol. 68:241-257.

Kane, A. 1985. Le bassin du fleuve Senegal a l'embouchure. Flux continentaux dissous et particulaires. Invasion marine dans la vallee du fleuve. Thesis, Nancy I, 205 p.

Lezine, A.-M. 1986. Environnement et paleoenvironnement des niayes depuis 12 000 B.P. In Symp.INQUA/ASEQUA, Changements globaux en Afrique durant le Quaternaire: Passe-Present-Futur. Paris: Orstom, p. 261-263.

Lo, P.G. 1988. Le volcanisme quaternaire de Dakar (Senegal occidental): particularites petrographiques, caracteres geochimiques. Implications petrogenetiques. Thesis, Nancy I, 143 p.

Lompo, M. 1987. Methodes et etude de la fracturation et des filons. Exemple de la region du Cap Vert (Senegal). Mem. DEA, Dakar, 58 p.

Marius, C., Lucas, J., and Kalck, Y. 1986. Evolution du golfe de Casamance au Quaternaire recent et changements de la vegetation et des sols de mangroves lies a la secheresse actuelle. In Symp.INQUA/ASEQUA, Changements globaux en Afrique durant le Quaternaire: Passe-Present-Futur. Paris: Orstom, p. 293-295.

Masse, J.P. 1968. Contribution a l'etude des sediments actuels du plateau continental de la region de Dakar (Republique du Senegal). Rapp. Lab. Geol. 23:81 p.

Michel, P. 1969. Les bassins des fleuves Senegal et Gambie. Etude geomorphologique. Thesis, Strasbourg, 1169 p.

Michel, P., and Sall, M. 1984. Dynamique des paysages et amenagement de la vallee alluviale du Senegal. Paris: Mem. Orstom, No. 106, p. 89-109.

Murday, M. 1986. Beach erosion in West Africa. Res. Plan. Inst. ed., Columbia, 101 p.

Olivry, J.C. 1983. Le point en 1982 sur l'evolution de la secheresse en Senegambie et aux iles du Cap Vert. Examen de quelques series de longue duree (debits et precipitations). Paris: Cahiers Orstom, Ser.Hydrol. 20(1):47-69.

Pages, J., and Debenay, J.P. 1987. Evolution saisonniere de la salinite de la Casamance. Description et essai de modelisation. Rev. Hydrobiol. trop. 20(3-4):203-217.

Pages, J., Debenay, J.P., and Lebrusq, J.Y. 1987. L'environnement estuarien de la Casamance. Rev. Hydrobiol. trop. 20(3-4):191-202.

Paradis, G. 1986. Role de l'homme dans les changements du paysage tropical: les mangroves ouest africaines. In Symp.INQUA/ASEQUA, Changements globaux en Afrique durant le Quaternaire: Passe-Present-Futur. Paris: Orstom, p. 357-362.

Pelissier, P. 1983. Atlas du Senegal. Paris: Jeune Afrique, 72 p.

Pezeril, G., Chateauneuf, J.J., and Diop, C.E.W. 1986. La tourbe des niayes au Senegal: genese et gitologie. In Symp. INQUA/ASEQUA, Changements globaux en Afrique durant le Quaternaire. Passe-Present-Futur. Paris: Orstom, p. 385-392.

Pinson-Mouillot, J. 1980. Les environnements sedimentaires actuels et quaternaires du plateau continental senegalais (Nord de la presqu'ile du Cap Vert). Thesis, Bordeaux I, No. 1554, 106 p.

PNUE/UNESCO/ONU-DAESI. 1985. Erosion cotiere en Afrique de l'Ouest et du Centre. Rapp Et. Mers regionales Geneve, 67, 248 p.

Riffault, A. 1980. Les environnements sedimentaires actuels et quaternaires du plateau continental senegalais (Sud de la presqu'ile du Cap Vert). Thesis, Bordeaux I, No. 1561, 145 p.

Sall, M. 1982. Dynamique et morphogenese actuelles au Senegal Occidental. Thesis, Strasbourg, 604 p.

Sy, A. 1982. Etude geomorphologique des fleches sableuses du littoral senegalais: Langue de Barbarie (Nord Senegal), Pointe de Sangomar (Saloum), Presqu'ile aux Oiseaux (Casamance). Trav. Et. Rech., Dakar, 103 p.

Sy-Niang I. Littoral ore deposits in Senegal. In International Conference on Geosciences in Development. Nottingham, England: in preparation.

TECASEN. 1979. Teledetection de quelques geosystemes littoraux senegalais. Depart. Geogr. Dakar, E.N.S.J.F. Montrouge, Rapp.1, 83 p.

UNESCO. 1985. L'estuaire et la mangrove du Sine Saloum. Proceedings of a regional UNESCO-COMAR workshop held in Dakar (Senegal) February 28 to March 5, 1983. Rap. UNESCO Sciences de la Mer, No. 32, 139 p.

RESPONSE TO EXPECTED IMPACT OF CLIMATE CHANGE ON THE LAGOONAL AND MARINE SECTORS OF COTE D'IVOIRE

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INTRODUCTION

Since 1985, scientists in the Oceanographic Research Center of Abidjan (Cote d'Ivoire) have been studying erosion. Although the southwest shoreline (Tabou-Sassandra) is stable, the southeast (Fresco-Vridi-Port-Bouet-Ghana) border is very unstable and is eroding at the rate of 1 to 2 m/year. Although part of that erosion results from the Vridi Canal and the Bottomless Pit Canyon, the Fresco-Vridi area appears to be eroding as a natural consequence of current sea level trends.

The potential implications of an accelerated rise for Cote d'Ivoire are similar to those for other nations in West Africa. Erosion would accelerate threatening some structures. Perhaps more important are the implications for the lagoonal systems. If the outer barriers should break up due to erosion and inundation, these lagoons might become exposed to the open ocean; even where the barriers remain intact, rising water levels could drown the intertidal wetland areas. In either event, subsistence fishing in the lagoons would be seriously threatened.

This paper briefly describes the environmental conditions along Cote d'Ivoire and the administrative structure for dealing with coastal management issues.

GENERAL DESCRIPTION OF LAGOON AND MARINE ENVIRONMENTS

Cote d'Ivoire is located in West Africa on the Gulf of Guinea (Atlantic Ocean), between latitudes 4° and 11° North; its surface area is 322,463 square kilometers. Its 500-km coastline is fringed with 350 km of lagoons, which are separated from the sea by a narrow offshore bar and a narrow continental shelf.

Of the nation's 10 million people, about 3 million live along the coast (about 2 million in and around Abidjan).

The climate is warm and humid in the south and tropical dry in the north, which results in two major types of vegetation: guinean (dense forests and pre-forest savannahs) and sudanese (savannahs). The economy of Cote d'Ivoire is essentially based on agriculture: traditional agriculture using slash and burn techniques, and industrial plantations using very extended land areas. The industrial growth rate for the last three decades has been about 7% from 1960 to 1984.

Lagoons

Lagoons are found along 60 percent of the coast and cover about 1200 square km. There are three main lagoons (Grand-Lahou, Ebrie, and Aby Lagoon) connected with the sea and each other by natural or artificial channels. Grand-Lahou lagoon, which covers 190 square km, is the smallest and shallowest (average depth of 3 m). The Bandama River, which drains the largest watershed of Cote d'Ivoire, flows into it. Ebrie Lagoon, in the middle, covers 566 square km and is on an average, 4.8 km deep. It is connected to the sea by the Vridi Canal and Grand-Bassam Channel. Aby Lagoon, near the Ghana border, covers 424 square km.

Lagoonal seasons are determined by riverflow and rainfall. The dry season (January to April) is characterized by marine influence (maximum temperature and salinity). During the rainy season (May to August), heavy rains swell forest rivers. The flood season (from September to December) corresponds to maximum inputs by "Sudanese" rivers (Comoe and Bandama) causing lagoon salinities to approach zero.

A change in climate could affect these lagoons in many ways. The inundation of intertidal vegetation would remove important habitats for fisheries. Erosion and flooding would increasingly threaten establishments along the shore. Rising seas and decreased precipitation would increase the salinity of the lagoons, perhaps leading to increased predation in some cases.

The Open Coast

There are two types of landscapes in the coastal region: (1) cliffs of the southwest (from the Liberian border to Fresco) are characterized by a step-like profile where a narrow quaternary coastline and the contact of the precambrian plinth alternate. These plateau-coasts, cut as abrupt or gently sloping cliffs, are elevated more than 20 m above sea level (more than 65 m in the San Pedro sector); and (2) sandy low coasts (from Fresco to the Ghana border), which have flat landscapes where the quaternary shoreline is more developed (maximal width 4,500 m) and continuous. Low plateaus of the nearby inland areas are generally less than 12 m above sea level. The land adjacent to the sandy shorelines is usually 2-6 meters above sea level -- even lower near Assinie.

There are two major marine seasons: a major warm season (from February to May) during which water temperatures vary from 27 to 28°C; and a major cold season (from July to October) during which the upwelling is more distinct, water temperatures are less than 23°C, and the salinity is near 35%. Beside these two distinct seasons, there is a short warm season (November to December) with the disappearance of the upwelling, and a short cold season (December to January) with a coastal upwelling and water temperature varying from 24 to 25°C.

If sea level rises one meter, the Bruun rule implies that sandy beaches could erode 100-200 meters, which would threaten some establishments along the coast. In addition, upwelling and other aspects of the marine climate have an important impact on fisheries. If climate change alters the seasonal or geographical extent of upwelling, fishing would probably be affected.

PROTECTION OF THE ENVIRONMENT IN COTE D'IVOIRE

Administrative and Institutional Efforts

Environmental protection is a national concern. Among the institutional establishments dealing with this subject are the Oceanographic Research Center, the Tropical Ecology Institute, the National Agency of Meteorology, the National Committee for fighting bush fires, and nongovernmental organizations like the Green Cross. Cote d'Ivoire has also signed several international conventions in environmental protection. Actions against environmental degradation include the monitoring of coastal erosion.

Shoreline evolution and coastal erosion have been studied since 1985 at 18 stations from Tabou to Assinie. The initial results are as follows: (1) the southwest shore (Tabou-Sassandra) is stable because of its geology and steplike formation; and (2) the sandy low coast at the southeast (Fresco-Vridi-Port-Bouet-Ghana border) is very unstable and is eroding at 1 to 2 m/year. This area in turn can be divided into an area with natural erosion (Fresco-Vridi) and an area where erosion is linked both to the presence of the Vridi canal and the proximity of the "Bottomless Pit" canyon (Vridi-Port-Bouet).

The aim of this erosion study is to establish a coastline sensitivity map. This map will include the geology and coastal shapes, erosion and sedimentation rate of the coastline, coastal drift, the topography of the coast, and intertidal zones. This study will help in managing (1) passive measures of coastal protection; (2) the exploitation of quarries (sand and others); and (3) refining a sedimentation model built to predict erosion and the effectiveness of protection options for the Abidjan area.

With respect to the fight against deforestation, Cote d'Ivoire has established a permanent national forest domain in the thick forest and savannah zones (decree no. 78-231 of 3/15/78), which includes a total of 5,921,558 hectares divided into 205 forests and parks. A program of reforestation favoring rapid-growing species of trees is being instituted, which will help slow global warming by providing a natural sink for carbon dioxide.

West Africa

Major Constraints to Environmental Protection

An obstacle to protecting and managing the environment is the antagonism between environmental and developmental forces, which must be reduced to achieve the benefit of an effective equilibrium between the two.

The search for this precarious equilibrium is sometimes difficult because of the ingrained habits of people, which are often detrimental to the environment, and because of financial constraints.

CONCLUSION

The Ministry of Defense and the Ministry of Scientific Research coordinate national activities related to research and monitoring of meteorological and oceanographic surface conditions among all regional institutions with responsibilities for studying climatic variability and its local impact. We need to establish public education projects to promote an understanding of changing climate and rising seas, to assess its potential impacts on society, and to encourage regional scientific centers related to environmental research to establish studies to identify the vulnerability of particular geographical areas.

IMPLICATIONS OF GLOBAL WARMING AND SEA LEVEL RISE FOR GHANA

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ABSTRACT

This paper identifies coastal areas in Ghana subject to erosion and some of the causes of erosion, such as artificial structures along the coast or river barriers. The socioeconomic aspects of sea erosion are also highlighted, including the displacement of people with subsequent destruction of economic activities, and the threat to tourist activities. Some of the studies conducted to evaluate shoreline recession are discussed, as are attempts that have been made to arrest or to contain sea erosion. Finally, this paper addresses sea level rise and ways to assess it with data that could be obtained in Ghana.

INTRODUCTION

The Ghanaian coastline stretches roughly 550 km from Half Assini in the west to Aflao in the east. A substantial number of dwellings, commercial activities, and industries, as well as fishing and tourism, are found within 300 m of the ocean coast. Coastal areas can be grouped into three basic economic categories:

1. Commercial and industrial areas, such as Accra, Tema, Sekondi, and Takoradi;

2. Fishing areas, such as Tema, Keta, and Winneba; and

3. Tourist areas, such as Batianor, Ada, Labadi, Biniwa, Elmina, Winneba, and Busia.

Coastal erosion is experienced in varying degrees; the adverse effects on developments along the coastal zones cannot be overemphasized. The immediate result of shoreline retreat is the loss of land, which in almost all cases results in loss of properties and displacement of people. Erosion greatly affects the social and economic activities of coastal dwellers and users. Lack of economic activities means lack of jobs or forced change of vocation, with a subsequent loss of revenue to the government. New fishing areas must be sought, and tourist sites are threatened. A typical example is Keta, where portions of the population had to seek shelter elsewhere because properties had been engulfed by the sea. The Labadi pleasure beach, until coastal protection measures were carried out, lost its tourist business to other areas. Bortianor, another tourist spot, is being seriously threatened by coastal erosion.

COASTAL ZONE

Most of the coastal areas in Ghana are low-lying and sandy, interspersed with beach rocks and rock outcrops. In some areas experiencing active beach erosion (see Figures 1 and 2, which show shoreline changes for Keta and Ada, respectively), shoreline changes have been monitored; these areas include Axim, Dixcove, Nkontompo, Labadi, Ada, and Keta. Records for periods indicated in Table 1 have been kept for Keta, Ada, Labadi, and Nkontompo.

Table 1. Periods of Shoreline Monitoring

Town	Period	Remarks
Keta	1907-87	Soil logging
	1971-87	Beach profile monitoring
Ada	1941-85	Soil logging
	1980-86	Beach profile monitoring
Labadi	1954-65	Soil logging
	1968-71	Beach profile monitoring
Nkontompo	1956-86	Geological data
(Sekondi)	1971-86	Beach profile monitoring

Studies conducted on these areas indicate the following major causes of erosion:

1. Creation of artificial barriers across some rivers (e.g., the Volta and Densu), which reduce or otherwise interfere with the sediment load to the coast;

2. Creation of artificial harbors (e.g., the Takoradi and Tema Ports), where breakwaters and jetties interrupt littoral transport of sand and other sediments;

3. The mining of sand along the coastline, which removes supply material from the coastal zone so that natural shoreline stability is diminished; and

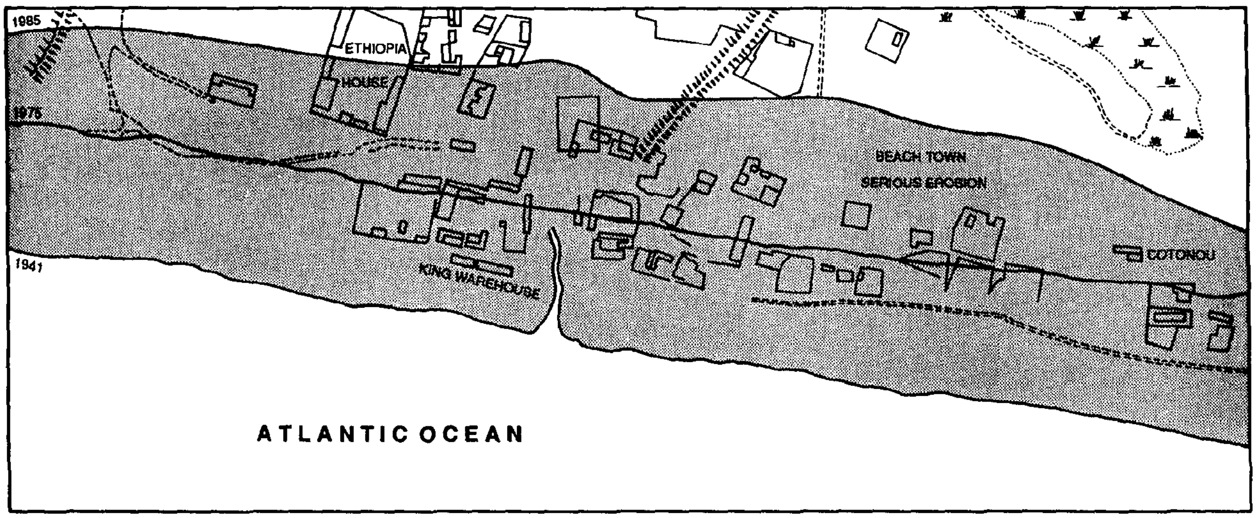

Figure 1. Successive flooding and erosion through the years at Keta.

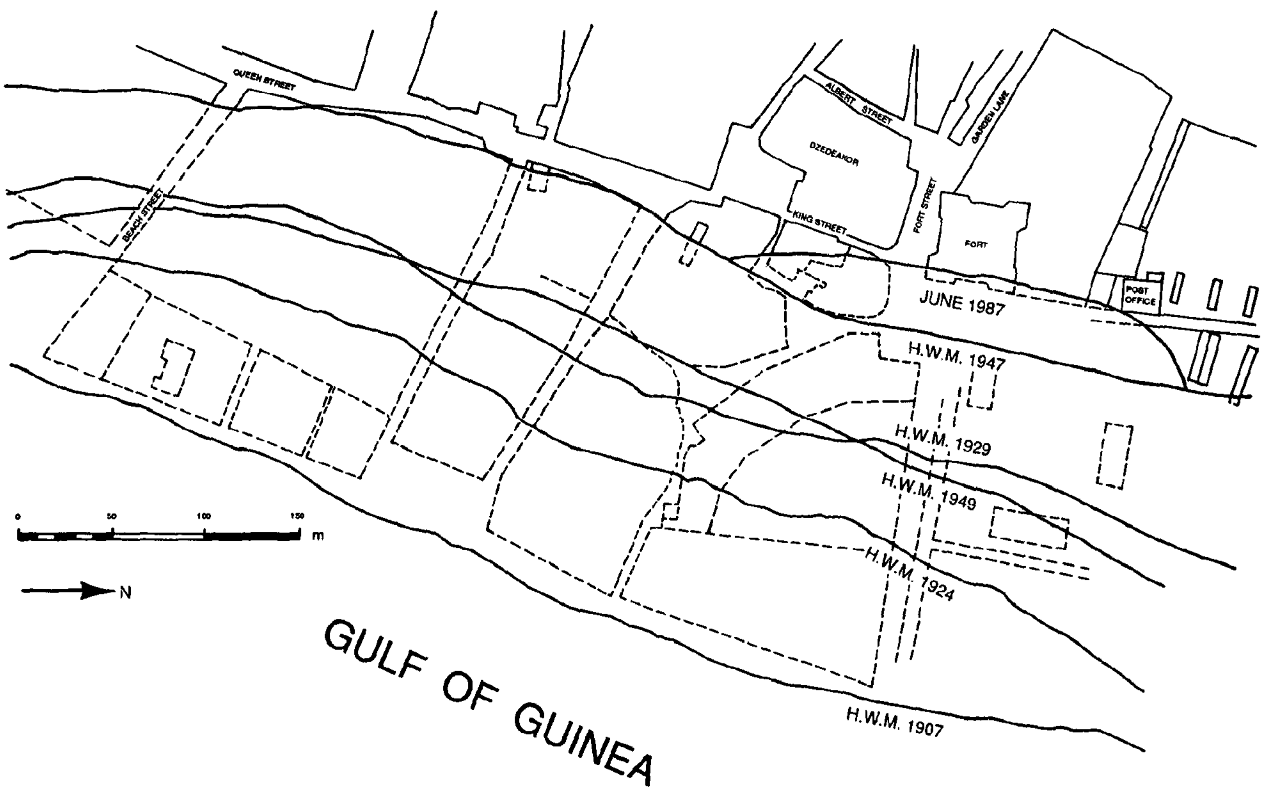

Figure 2. Successive flooding and erosion through the years at Ada.

4. Natural, constant coastal processes (e.g., subsidence, seasonal and interannual wave climate variability, and tectonic movement).

WETLANDS

The Ghanaian wetland ecosystem has not been exhaustively studied in the environmental context, but a few studies have been conducted through the graduate school at the University of Cape Coast. The Environmental Protection Agency of Ghana is generally responsible for the policies developed to protect the wetland ecosystems.

Two types of marsh-ecosystems are found in the West African region:

1. Wet-humid areas dominated by grasses and marshy shrubs (found near small estuaries and lagoons); and

2. Mangrove-type vegetation dominated by almost all types of hydrophilic angiosperms (with monocots of oil palm in plantations near large estuaries).

Human habitation is common in the areas described above, since these ecosystems are also dominated by fauna that form the economic basis of the region. Fishing is the predominant activity in Ghana and the west coast of Africa. Most of the wetlands on the Ghanaian coast are natural, and human habitation and industry have not yet taken their toll. Mangroves generally are not cut, except in cases where land has to be cleared for farming purposes, e.g., rice farming. This is all the more reason why specific policies and research leading to protection of such areas should be initiated now.

SALTWATER INTRUSION

Coastal river estuaries are subjected to saltwater intrusion. Low riverflow allows seawater to intrude farther upstream. This tends to seriously affect the drinking water supply in areas such as Ada and Keta, where the local residents rely on groundwater as a source of drinking water. In some cases, the high salinity of the groundwater has made the water unsuitable for drinking.

FLOODING

Flooding along the coastal areas occurs in Accra, Botianor, and Keta. Floods in Accra are mainly due to improper planning or to the inadequate drainage system. Efforts to desilt and improve the hydraulics of the primary drains (stormwater channels), coupled with various maintenance schemes, have significantly reduced flooding in Accra.

Flooding in Botianor is due mainly to releases from the Weija Reservoir (one of the impounding waters providing Accra with a water supply) during the rainy seasons. This could be controlled by proper regulation of the Weija Reservoir, channeling the river downstream from the dam, and construction of a proper outfall to the sea.

Since the early 1960's, three floods in Keta have been caused by excess water discharged into the Keta Lagoon from the Todzie and Belikpa Rivers during exceptionally wet seasons. The creeks connecting the Keta Lagoon to the River Volta estuary are blocked and, therefore, the excess water is impounded in the lagoon instead of being discharged into the sea.

POPULATION

About 13.5 million people were estimated to live in Ghana in 1987, with a large percentage residing in the coastal zone where most of the major cities are located. Population density in the coastal urban areas exceeds 550 people per square kilometer, 10 times the density of inland areas. The last three population censuses indicate that the Keta area (including Kedzi and Vodza) is being rapidly depopulated, the result of severe erosion coupled with non-availability of land.

COMMERCIAL ACTIVITY

Ghanaian coastal area inhabitants are primarily fishermen, except for those directly in commercial centers such as Labadi, a suburb of Accra (the capital of Ghana), Tema, and Sekondi. Although Keta used to be a bustling commercial center, these activities have dwindled to nothing because of severe waterfront erosion.

TOURISM

Some of the tourist beaches along the Ghanaian coastal zone are Ada, Chemuna, Labadi, Botianor, Biriwa, Elmina, Winneba, and Busia. Erosion of varying degrees has been recorded in these areas.

AGRICULTURE AND FISHING

The most important crop in Ghana is cocoa, which accounts for about 60 percent of the nation's exports. Although the cocoa-growing area is not located in the coastal zone, shipments must pass through the coastal ports. Production of corn and other grains is substantial and is increasing. Data for 1969 indicate that production of corn and rice totaled 305,000 and 61,000 metric tons, respectively; fishing produced 162,800 metric tons. In 1969, salt production totaled 1,700 metric tons in the coastal lagoon area.

Although fishing is the mainstay of the coastal people, some inhabitants move inland to practice arable farming during the off-season. Some of the local farms along the fringes of the Keta Lagoon primarily cultivate shallots, rice, sugarcane, okra, pepper, and maize. These farming activities are disrupted each time the Keta Lagoon is flooded.

COASTAL LAND DEVELOPMENT RESTRICTIONS

No consistent rules seem to limit coastal land development. In the past, coconut trees planted along the coast indicated the off-limit zones for building structures. However, the zones vary from place to place; in some beach areas, structures are very close to the coastline.

In areas of active sea erosion, such as Keta, Vodza, Kedzi, and Labadi, the coconut plantations have been claimed by the sea; thus, development, previously behind the plantations are now close to the sea.

STRUCTURES ALONG THE COAST OR COASTAL WATERS

Four major ports are located along the shores of Ghana: Tema, Elmina, Sekondi, and Takoradi. Sekondi is a naval port, and Tema and Takoradi are commercial ports. Tema has a fishing port attached, and Elmina is purely for fishing. All four harbors are manmade, and their breakwaters protrude into the sea. Elmina harbor has two basins: the inner basin is in the Benya Lagoon, and the outer basin is at the mouth of the lagoon where the lagoon water discharges into the sea.

Apart from Tema harbor, where erosion is occurring on the western side of the breakwater structure, erosion is occurring on the leeward (eastern) side of the harbors.

Takoradi and Tema have tidal gauges. The Takoradi and Tema harbors were opened in 1928 and 1962, respectively. The tidal gauge installations are as old as the ports. Hydrological gauging stations are also located in the Keta Lagoon and on the Volta estuary at Ada. Hydrological gauges were established at Keta and Ada in August 1963 and September 1963, respectively. The mean range of the semidiurnal tide along the Ghanaian coast is a nearly uniform 1.0 meters.

EFFECTS OF A ONE-METER SEA LEVEL RISE

A one-meter sea level rise would have a serious negative socioeconomic impact on the country, causing storm flooding, beach and coastal erosion, and loss of wetlands.

Storm Flooding

A one-meter rise in sea level would create a higher mean water level in coastal lagoons and estuaries. This, combined with high riverflow due to heavy rainfall, would exacerbate the flooding that presently occurs. Such flooding would cause additional loss of property and would very likely require relocating whole communities and industries.

As indicated previously, Accra and Keta are but two examples of areas of constant flooding. Although Accra and Botianor floods are attributed to an inadequate drainage system and improper regulation of Weija Reservoir, respectively, these areas, like many coastal towns, have drainage outlets subject to tidal influence of the sea. Flooding affects industries through inundation of warehouses, which results in damage to equipment, raw materials, and manufactured goods. Some residential areas near natural drainage channels are constantly flooded during the wet season.

The traditional reaction of local people is to move out until the floods subside and then to move back again. Some people, however, tend to find permanent accommodations elsewhere.

The government antiflooding program, especially in Accra and other coastal areas, focuses on improving the drainage system in these areas. The government is also discouraging development of lowland areas.

The projected sea level rise would allow water pushed by coastal storms to surge farther ashore with devastating effects.

Beach and Coastal Erosion

The projected one-meter rise in sea level would exacerbate the erosion already seen along the low-lying sandy coast of Ghana. Loss of these coastal lands would have a far-reaching socioeconomic impact on the nation. Coastal tourist enterprises would be at risk; commercial and industrial sites would need major protection or relocation. Agriculture in the near-shore zone might suffer, requiring inhabitants either to move or to change crops to remain productive.

Loss of Wetlands

The rate of natural growth and migration might not be able to keep pace with the rate of wetland submersion caused by rapid sea level rise. Consequently, valuable wetlands could be lost. A more gradual rise might permit wetlands to survive and migrate. Wetland migration could occur only in areas having no barriers to lateral displacement. Agricultural lands, sharply rising land contours, dams, or other barriers would interfere with migration.

IMPACT ON FUTURE DECISIONS

Sea level rise would certainly influence the development of new settlements and the use of beaches as recreational grounds. Existing laws would have to be enforced or modified, especially regarding restrictions on development of the coastal zone. Decisions would have to be made concerning whether or not to resettle people affected by sea level rise.

West Africa

Response to Sea Level Rise

The country will have to reassess its planning with regard to development along the coastal area once the sea level rise impacts have been identified and quantified.

Historical records of the tidal and hydrological stations mentioned previously, together with studies conducted so far at Keta and Ada and aerial photographs, could form the basis for the study of the sea level rise.

Although dozens of culturally different tribes live in Ghana, the people are well integrated into a whole national fabric. The Ghanaian educational system is one of the best in the West Africa region, with a literacy rate that stands at roughly 30 percent. The government is striving to rehabilitate and strengthen the national economy; therefore, many issues have more immediate concern than sea level rise. Educating and informing everyone at all levels of government and industry, as well as the general public, of the need to plan and prepare responses to rising sea level will be a formidable task.

Preparations also will be formidable. These will encompass the entire spectrum of the nation's business: enhancing education, enacting legislation, establishing government agency responsibility for oversight or regulation, monitoring industry and private sector activity in the coastal zone, carrying out scientific monitoring programs, and conducting research to assess impacts of sea level rise. Such research must address geomorphological impacts and must also provide important information upon which to base appropriate responses to socioeconomic impacts. Cultural impacts must be considered as well.

Property Ownership

In Ghana, land is entrusted to the government (local authorities) or to the "stool" (kings or chiefs as custodians). Land for development can therefore be leased to interested parties by these agencies.

The government could only advise people to move as the sea level begins to rise and areas are threatened. Experience in Keta and elsewhere has shown that people are not very willing to vacate their houses, let alone resettle elsewhere, when being threatened by the sea. In most cases, people move out or migrate only when their houses have been destroyed by the sea. There have been instances where people have built more than one house that has been engulfed by the sea.

COASTAL PROTECTION IN GHANA

Ghana has protected its coast since the 1920's.

Bulkheads

Steel sheet pike bulkhead was tried in Keta in the sixties. The average depth of the pile was 10 m. Even though this form of sea defense wall was expected to last at least 40 years, it started to fail within 6 years after construction and has now collapsed completely.

Stone Revetment

Stone revetment in the form of armor rocks has been successfully tried at Sekondi. About a kilometer of road lined with houses has been saved from sea erosion.

Another successful form of stone revetment is the gabion revetment. Tourist spots such as Labadi and Elmina have been protected since 1981. A gabion armor rock revetment is currently being put in place at kilometer 22 along the Accra-Tema beach road to prevent that section of the road from being engulfed by the sea.

Groins

Wooden groins were tried in Keta several times between the 1920's and 1960's without much success. Pilot gabion groins constructed along the James Town Beach, Accra, about 5 years ago appear to be very promising, and they are being monitored for eventual adoption along some sandy beaches.

Sea Outfalls

A rubble mound outfall structure constructed in the sixties at James Town to help with the runoff from stormwater and sewage had no adverse effect on the coastal morphological changes in the vicinity.

Subsidence

Land subsidence has not been investigated much in Ghana, but there is reason to suspect that subsidence might be contributing to the severe erosion occurring at Keta.

SOCIOCULTURAL IMPLICATIONS OF CLIMATE CHANGE AND SEA LEVEL RISE IN THE WEST AND CENTRAL AFRICAN REGIONS

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ABSTRACT

This paper begins by examining what is presently known about the characteristics of climate and climate variations in the West and Central African (WACAF) regions and then looks at the socioeconomic and sociocultural implications of the environmental impacts of climate change and sea level rise. Also discussed are strategies that could be used to reduce or eliminate the vulnerability of human settlements and environmental systems, as well as socioeconomic and sociocultural systems, to the adverse consequences of climate change and sea level rise.

INTRODUCTION

Since the beginning of time, the world's climate has fluctuated. In the West and Central African region, for instance, there has been a great variation in rainfall, which in turn has affected environmental processes and human activities in the region. The impact on geological processes has influenced and indeed severely disrupted local, regional, and even global socioeconomic and sociocultural systems (for example, natural resources planning and management, food production and agriculture, water resources and energy systems, forestry, marine resources development, transportation, and tourism).

There is mounting scientific evidence that human activity is partly responsible for changing the earth's global and regional climates. Although it is difficult to distinguish between ecological changes due to human activities and those caused by natural processes, there is no doubt that the differences in climate between various parts of the earth has in large measure determined the types of activities people pursue for both recreational and productive purposes.

This paper examines the impact of climate change on the West and Central African regions, with particular focus on the sociocultural implications of the greenhouse warming and the rise in sea level.

WEST AND CENTRAL AFRICA: CLIMATE CHANGE AND VARIABILITY

Future climate changes are likely to have a significant impact on the marine environment and the adjacent coastal areas. The coastal areas of West and Central Africa extend from the coast of Mauritania in West Africa to the coast of Angola. Most of the region is in the tropics and spans the low latitude areas between approximately 30° N and 30° S.

Annual precipitation varies from less than 200 mm in the north and south to over 2,000 mm in the western equatorial regions, most of the area receives between 200 and 1,000 mm of rainfall per year. Of this total, 75% or more of the precipitation falls during the rainy season, which lasts between 6 and 12 months in the central parts of the West and Central African region, and less than 4 months in the extreme north and south. The rainy season is linked to the migratory pattern of the intertropical convergence (ITC), sometimes called the intertropical discontinuity (ITD), which is associated with the apparent migratory patterns of the sun (incorporating a time lag of about a month or two).

The climate in the WACAF region is also influenced by factors other than the ITC, such as atmosphere and oceanic circulation, and land and sea breezes. However, little is known about their relative influence.

IMPACTS OF CLIMATE CHANGES AND SEA LEVEL RISE

Climate change is defined here as the change in the mean values of climate variables. Climate variability is defined as the differences between monthly, seasonal, and annual values of climate parameters and their average values. Clearly, it is possible for climate to change without becoming more variable, and it is possible to become more variable without the average condition changing. Any impact analysis must examine both the long-term climate changes and the short-term climate variabilities. These must be examined over three natural time scales: (1) the short-term periods, which range between daily, weekly, monthly, seasonal, or annual periods; (2) the medium-term scales, which cover a decade or so; and (3) the long-term scales, which span decades or centuries (although in the case of nuclear waste sites the assessments span tens of thousands of years.)

The impacts created by short- and medium-term climate problems have made the governments and people of the West and Central African regions aware of the need to examine their own causative role and to fashion appropriate responses. Droughts and floods in particular have caused so much damage that world attention has been drawn to the socioeconomic consequences in the WACAF regions, particularly over the past three decades. Indeed, there is a growing realization that society is vulnerable.

Ecological and Physical Impacts

The average global rise in temperature is expected to be in the range of 1.5°C to 4.5°C, while sea level rise is expected to be between about 20 and 140 cm. Based on these expectations, it is assumed that both evaporation and precipitation will increase by about 2 to 3% for each degree of global warming.

Thus, it is reasonable to expect that both precipitation and evaporation would increase, possibly between 5 and 20% in the humid, tropical areas of the WACAF regions, which are already too hot and too wet. The increase in both precipitation and temperature could have significant environmental impacts. The increase in average rainfall may be accompanied largely by an increase in the amount of rain per hour during severe storms and shifts in geographical patterns of precipitation and cloudiness. However, since the increase in temperature could increase evaporation and potential evapotranspiration, there would be a tendency toward more droughts in many, if not most, of these humid, tropical areas. With the increase in ocean temperatures, tropical storms (e.g., hurricanes and thunderstorms) are likely to extend into areas of the region where they have been less common. Where tropical storms already occur, more intense winds and rainfall might be expected.

The savanna and semiarid areas of the WACAF region would probably have less rain, which -- coupled with temperature increases -- would reduce soil moisture availability (WMO/TD, 1988). Less soil moisture, in turn, would diminish food production and availability, the availability of water and fuel, and human settlements.

The rise in sea level that would accompany global climate change would result in submergence and inundation of the coastal lowland areas. It would also lead to increased salinity of the estuarine areas and increase the size of the coastal region.

The ecological and physical implications of climate change include effects on geological, geomorphological, and hydrological processes, ocean dynamics, droughts and desertification, and floods and erosion. Decreased precipitation would lessen the water supply and hydroelectric power generation, while decreasing the risk of floods. Increased variability could increase the probability of both floods and droughts.

Forest ecology and the ecosystems would also be affected. For example, changes in ecological conditions might be less favorable to the existing biota. Ecosystems would respond by gradually invading the neighboring areas where the climate is more favorable.

Impacts on Agriculture and Livestock Production and Management

Agriculture and livestock production are the center of life for almost all the peoples in the region. The climate and soil characteristics determine how the land is used for agriculture and livestock production, including which crops are grown.

The impact of climate change and sea level rise on agricultural production would no doubt be significant, as would the socioeconomic and sociocultural consequences. For example, decreased rainfall would reduce the production potential of the crops presently grown in the various ecological zones, increasing hunger in the region and reducing the incomes of farmers and others whose occupation depend on farming. In the extreme, unemployment, starvation, and death could also result. There might also be increased migration to urban centers for alterantive employment; and livestock farmers may migrate to other areas in search of water for their cattle.

Livestock zones are also clearly determined by climate, particularly rainfall. The cattle zone is essentially determined by distribution of the tse-tse fly, which so far has made it virtually impossible to keep zebu cattle in the southern reaches of West Africa. Furthermore, these southern reaches have been unable to develop mixed farming even though their heavily leached soils could greatly benefit from animal manure. The north is the main cattle area in the region primarily because its climate is not hospitable to the tse-tse.

Decreased rainfall and drought would affect livestock production in other ways. The productivity of existing grassland areas, important for livestock production, would be reduced. On the other hand, new grazing lands would emerge, possibly shifting livestock production toward the coast. As with reduced crop production, income would decline, leading to greater financial stress, which could threaten ecoromic survival. There would also be significant impacts on labor, employment, and population distribution.

Along the coasts, where sea level rise may lead to submergence of the lowland coastal areas (e.g., along the coasts of Senegal and Gambia), much of the land currently used for agricultural and livestock practices would be lost. As a result, there would be mass migration out of that area, substantial loss of income and great financial stress, and unemployment. Large-scale resettlement would cause additional problems. In a few cases, farmers may be forced to change their practices. Because most of the coastal environment would be characterized by water surfaces and their associated ecological systems, converting to aquaculture may be a viable response (see Everett, Volume 1, Environmental Implications.)

Impacts on Water Resources and Water Resources Management

Agriculture, industry, and domestic activities depend on water resources. Unfortunately, a large proportion of the population in the WACAF regions lacks access to adequate freshwater supplies, especially because of population growth and rising standards of living which increase water demands.

The changes in the magnitude and timing of water resources would necessitate changes in management strategies toward greater conservation efforts in order to balance water supply and demand. In addition, because most of the water resources along the coast would become polluted by intrusion of saltwater, water resources management would place greater emphasis on desalinization.

In general, the WACAF regions have five types of water supply systems. The first category includes areas that depend mainly upon precipitation; unless storage is available, these systems are only useful during the wet season, usually six months of the year or less. The second category includes water supply systems based on river flows that do not store significant amounts of water for use during periods of deficiency.

The third category of water supply systems is located in coastal areas where precipitation occurs during most months of the year. The impact of decreased regional precipitation on this region may be less than elsewhere since there would be a general tendency for coastal areas to receive more precipitation. However, sea level rise may cause floods and saltwater intrusion, which could contaminate water supplies. This would hurt agriculture and might even disrupt settlements, with all the consequences discussed in the conference report section on social and cultural implications.

The fourth category of water supply systems consist of manmade reservoir systems, which can reduce the effect of intra- and interannual variations in precipitation and runoff. With reservoirs, water is released when it is required for agriculture and other purposes. Examples include such manmade lakes as the Kainji and Akosombo dams. If climate becomes drier, it may be necessary to curtail releases of water to maintain needed storage capacity for later release. Water shortages in these reservoirs could have considerable financial implications and lead to hunger, famine, and death.

The fifth category of water resource systems consists of those based on groundwater resources. In this case, decreased precipitation would lead lower water tables and thus increase the difficulty in obtaining water even if the total amount of water in the aquifer is still sufficient.

Impacts on Other Sectors

Although the impacts on agriculture and water resources are likely to be the most important, other sectors would also be affected, including fishing, energy resources, transportation, manufacturing, and construction.

Upwelling fisheries predominate off the southwest coast of the WACAF region. Increased global temperatures would warm the normally cold upwelling waters, making them unsuitable for the fisheries and causing a reduction in and possible collapse of ocean upwelling fishing activities. Tropical warm water fisheries would be hurt since a rise in temperature would cause a change in the characteristics of the ocean waters and consequently in the habitat of the fish currently found in the area. Any significant reduction in the catch would upset both the economy and culture of the coastal zone. In addition, wetland loss and increased salinity would reduce estuarine fishing.

Energy supply and demand would also be affected. For example, Critchfield (1966) notes that the construction of power lines must always take into account a great number of climate effects on the equipment. Strong gusty winds can down poles and snap lines, or cause trees and other debris to fall onto the lines. An increase in the number of thunderstorms would bring more lightning, which causes at least temporary power failure if it strikes a power line. Temperature fluctuations can also affect the operation of switches, transformers, and other equipment. In warmer weather, lines tend to expand and sag; thus they become susceptible to more damage from strong winds.

Climate change could also have significant impacts on solar energy and wind, two sources of energy that still remain untapped in the WACAF region. Submergence of the coastal areas would make the onshore development and exploration of petroleum more difficult and more expensive.

However, of more immediate concern are the possible impacts on the supply and demand of hydroelectric power and fuelwood, which is the most widely used source of energy in the WACAF region. For example, reduced precipitation would adversely affect the supply of hydroelectric power, which is very sensitive to riverflows. There might also be problems related to the seasonal aspect of riverflows, as well as to the unreliability of rainfall as a source of water supply in many parts of the WACAF regions. Reduced hydroelectric power production would impose economic hardships.

The impacts on the supply of fuelwood could also be important. For example, with a decrease in precipitation, some sources of the fuelwood would be eliminated. Also, more frequent thunderstorms and erosion could cause more damage to the forests. With a rising sea, the increased landward penetration of storms would hurt all but a few (salt-tolerant) tree species, and thus decrease the area of forests. If climate change leads people to migrate to a particular area, the increases demand for fuelwood in some areas would aggravate all the environmental problems commonly associated with deforestation.

There could also be important impacts on energy demand. For example, with increased temperatures, particularly at night, there would be less demand for space heat in the WACAF regions and, consequently, less energy consumption. However, if temperatures were higher during the day, there would be greater demand for energy to cool buildings.

STRATEGIES FOR AVOIDING OR MITIGATING THE IMPACTS ASSOCIATED WITH CLIMATE CHANGE

The above discussion shows that the impacts of climate change and sea level rise are likely to be considerable. The question arises: what are the possible solutions for reducing or, if possible, eliminating the adverse consequences. In general, there are two categories of strategies: (1) avert or reduce the magnitude of climate change and (2) mitigate the consequences.

The following measures could be used to avert or reduce the magnitude of climate change:

- Reduce demand for fossil fuels;
- Adopt technical solutions to collect or control carbon dioxide; and
- Increase biomass production, which includes the reforestation of denuded areas.

Strategies to reduce demand for fossil fuels involve the use of conservation measures and alternative sources of energy. This measure is particularly important for developing areas such as the WACAF regions because the relative contribution of these areas to the atmospheric gases has been increasing since 1950. Reducing energy demand will reduce burning of fossil fuels. Technical solutions, which include the use of mechanisms to control atmospheric concentrations of carbon dioxide, are linked to world, regional, and national energy policies, forest management, and personal and societal values. Such solutions include measures to control the production and use of coal and petroleum and measures to control emissions from power plants or those occurring at the point of combustion. The adoption of such measures, however, could require complete sociocultural change.

Increasing biomass production through afforestation will provide a natural sink that will absorb carbon dioxide. Cooper, for example, noted that an increase of only 1% in the plant life on earth, especially forests, would be sufficient to absorb one year's release of carbon dioxide at the present rate (Kellogg and Schware, 1982). In tropical areas in general, and in the WACAF regions in particular, there is a great need to reduce the rate of deforestation and to reforest deforested areas. However, it is important to note that reforestation implies ecological changes, which in turn may have climate consequences. Marchetti (1979) has pointed out that a change in vegetation patterns could offset the intended cooling by absorbing more solar radiation, thus warming the earth.

Strategies for mitigating the consequences of climate change include those that would help to increase human resilience to the effects. Such strategies include protecting arable soil, improving water resources management, applying agrotechnology, improving land-use policies, maintaining food reserves, and adopting disaster response measures.

In the WACAF regions, there has been a tremendous loss of arable soil through soil erosion and salinization in recent years, and this trend would probably persist with climate change and sea level rise. Largely responsible for this loss are poor agricultural management practices such as overgrazing. Improving water resources management, for example, through effective management of dams, aqueducts, reservoirs, irrigation systems, and diverted rivers, would ensure adequate and reliable water supply in the event of drought and water deficiency.

Another effective measure would be to develop agrotechnologies such as more efficient irrigation systems, saltwater crops, and new forms of nitrogen-fixing plants. Improved coastal land-use policies would also be important and should be considered in sociocultural planning for mitigating the consequences of sea level rise.

Maintenance of food reserves and adoption of provisions for disaster relief now being promoted by international organizations to help the countries adversely affected by the recent climate variations, also could help to mitigate sociocultural impacts. The WACAF regions, like any other part of the world, require a reliable food supply; since any variation or change in climate and consequent sea level rise could adversely affect food production in the region, it would be prudent to develop adequate food reserves.

Other strategies for mitigating the effects of climate change and sea level rise involve access to information and technology, which can lead to better decisionmaking regarding how best to respond to potential climate change. Examples of such strategies include the use of environmental monitoring and warning systems, the collection and use of improved data, public information and education, and the transfer of technology.

CONCLUSION

Climate change and sea level rise would have considerable implications on human cultural systems. We need to plan and implement the measures necessary to either avert or mitigate the consequences. It is important to note, however, that usually the sufferer of the consequences sees the causes and effects of the problem as wholly local, and thus thinks only of local solutions. However, to effectively plan and implement solutions to the problems that could result from climate changes, it is important for local people to base their response decisions on a larger world view.

We need to ensure that solutions are carried out on world, regional, national, and local scales. For the WACAF region, in particular, it is important that cooperation, collaboration, and coordinated efforts occur at the regional and local levels as well as at the national and international levels. To this end, national governments must be ready to do their part as appropriate, for example, by ensuring that their national observing and communication systems function efficiently, and doing more to protect the coastal environment. Scientists, planners, and policymakers must promote research, provide improved access to data and information necessary for effective planning and implementation, prudently use data and information, and support effective public participation in planning and implementation of measures to avert or mitigate the consequences of climate change and sea level rise.

BIBLIOGRAPHY

Critchfield, H.J. 1966. General Climatology. Englewood Cliffs, NJ: Prentice Hall.

Flohn, H. 1979. A scenario of possible future climates -- natural and man-made. In: Proceedings of World Climate Conference. WMO No. 537. Geneva: World Meterorological Organization, pp. 243-268.

Kellogg, W.W., and R. Schware. 1982. Climate and Society: Consequences of Increasing Atmospheric Carbon Dioxide. Boulder, CO: Westview Press.

Marchetti, C. 1977. On geoengineering and the CO_2 problem. Climate Change 1:59-68.

Maunder, W.J. 1970. The Value of Weather. London: Meuthen.

Ramanathan, V. 1980. Climatic effects of anthropogenic trace gases. In: Interactional of Energy and Climatic. W. Bach, J. Bankrath and J. Williams, eds. Dordrecht, Netherlands: Reidel.

Rotty, R.M. 1979. Energy demand and global climate change. In: Man's Impact on Climate. W. Bach, J. Pankrath, and W.W. Kellogg, eds. Developments in Atmospheric Science 10. Amsterdam: Elsevier, pp. 269-283.

WMO. 1979. World Meteorological Organization. Proceedings of World Climate Conference. WMO, No. 537. Geneva: World Meteorological Organization.

WCP. 1986. Report of the International Conference on the Assessment of the Role of Carbon Dioxide and Other Greenhouse Gases on Climatic Variations and Associated Impacts. WMO, No. 661. Geneva: World Meteorological Organization.

MEDITERRANEAN

IMPACTS OF GLOBAL CLIMATE CHANGE IN THE MEDITERRANEAN REGION: RESPONSES AND POLICY OPTIONS

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ABSTRACT

Global climate change is likely to have two major types of negative impacts on the Mediterranean region: (1) changes of precipitation and soil moisture, which will affect water resources, riverflows, irrigation systems, and agriculture; and (2) sea level rise, which will exacerbate coastal erosion and flooding with repercussions on tourism, settlements, communications, and ports. To minimize the adverse impacts of climate change, analyses of these impacts should be incorporated into the planning of new projects and activities along the coast.

In most Mediterranean countries, the use of the coastal zone has increased, especially for agriculture and tourism. Unfortunately, development has progressed in a haphazard way, with little planning or consideration of environmental impacts. This present state of environmental degradation will exacerbate sea level rise impacts.

The large amount of capital investment along the coasts suggests that protective measures will be desired, even though they may not be feasible in many cases; thus, the cost of protection will greatly escalate and difficult political decisions will have to be made concerning when, where, and how the coast should be protected.

In the meantime, preparation is imperative through increased awareness, analysis, regional planning efforts, and regulation in the face of unhindered development based on short-term profitability.

INTRODUCTION

The impact of climate change on soils, hydrology, vegetation, and on two Mediterranean deltaic regions was first evaluated at the European Workshop on Interrelated Bioclimatic and Land Use Changes, in the Netherlands, October 1987

(Imeson et al., 1987; Sestini, 1989). The consequences of temperature and sea level rise for the coastal areas were further examined in 1988 by a United Nations Environment Programme (UNEP) task team of experts in Split, Yugoslavia, which attempted to forecast changes of climate, sea level, hydrology, ocean circulation, marine ecosystems, and vegetation (Sestini et al., 1989, for a review), as well as socioeconomic changes (Baric and Gasparovic, 1989). Six case studies have evaluated impacts on major deltaic areas (Georgas and Perissoratis, 1989; Corre, 1989; Marino, 1989; Sestini, 1989a,b; Hollis, 1989).

The conclusions with regard to climate variables were that doubled CO_2 would result in a temperature increase of 1.5 to 3.5°C; evaporation increases of 15-20%; a possible northward shift of the areas of cyclonic activity, with a probability of a precipitation decrease in the southern half of the Mediterranean; and magnification of interannual variability, with more frequent occurrence of extreme conditions (e.g., heat waves, droughts) (Wigley, 1989).

Soils would be affected in their physiochemical structures, particularly where rainfall is <500 mm/year, with greater salinization and reduction in organic matter. Soil erosion would increase. Higher temperatures would cause a northward and upward shift of vegetation zones, changes in forest composition, and greater incidence of forest fires; desertification would increase in the marginal areas of limited rainfall. Agriculture might be affected by changed water supplies, decreased soil fertility, and especially by the greater incidence of extreme events. Lagoons and salt marsh ecosystems might change as a consequence of greater temperature and salinity fluctuations, with water stratification phenomena becoming more frequent.

A discussion at the September 1987 UNEP Conference in Norwich, England, on the type and magnitude of changes in sea level produced an estimate that sea level will rise 14-22 cm by 2030, 25-40 cm by 2050, and perhaps up to 1 meter by the end of the 21st century (Raper et al., 1990). Nevertheless, the behavior of some of the causal variables (e.g., oceanic thermal expansion and the melting of polar ice) are more uncertain than these estimates would lead one to believe.

The Mediterranean study also emphasized that (at least in some countries) the pressure on the environment from rapid population growth would far outweigh the impact of climate change (Baric and Gasparovic, 1989).

Two principal effects of climate change stand out for their far-reaching consequences and require urgent attention from both scientists and policy makers:

1. Coastal instability due to sea level rise, and its attendant negative consequences for lowlands and wetlands, maritime cities, and harbors (e.g., for lagoonal fishing, reclaimed land agriculture, beach tourism, industries, and communications); and

2. Precipitation and soil changes and their consequences for slope stability, for surface and subsurface waters, and stream and irrigation systems (e.g., for the management of hydropower, irrigation, drinking

and industrial water supplies, inland navigation, and waste disposal systems, especially in a situation of growing water pollution).

THE PROBLEMS OF IMPACT ASSESSMENT

The complex, interrelated nature of the physical-biological systems and the present and future population and economic patterns of the coasts and alluvial plains (Figure 1) makes assessing the impacts of climate change and sea level rise difficult.

The physical impact of sea level rise on low-lying coasts can be predicted, even modeled quantitatively, on the basis of the present parameters of morphology, hydrodynamics, sediment budgets, land subsidence, and the effects of artificial structures. Likewise, the impacts of altered rainfall distribution on surface and groundwater can be modeled, and the effects of increased air temperatures and changed soil-water parameters on biosystems can be estimated at least qualitatively. What is more difficult to quantify, however, is the impact of these physical and biological changes on the future socioeconomic framework of the threatened coastal zones.

Future organization of these regions (Figure 2) depends on an evaluation of the present and future state of the environment; on the side effects of large construction projects with a life of decades; on the necessity to protect unmovable assets such as historical cities, harbors, and industrial centers; and also on the possibility of abandoning threatened areas and/or the redeployment of land uses.

Evaluation of economic impacts must consider not only the present function and value of land uses in the context of local needs and of the importance of the lowland concerned to its hinterland and farther, but also future land functions and values. The primary needs are determined by the present level of population and its trends of growth or decline, by the wider economic role of the region, and by external market forces. Some economic activities and land uses cannot be projected into the future because they are interrelated with "external" -- economic, social, and political -- factors and therefore can evolve independently of local conditions (Figure 2). For instance, the future relevance of local industries, agriculture, and ports will largely depend on worldwide commodity prices and trade trends such as those related to mineral and energy raw materials (with their effects on heavy and chemical industries) and to cereals and industrial crops; and on the demand for consumer goods in a competitive, exchange-oriented international society.

The role of ports may change in response to altered trends of maritime trade (e.g., the Suez Canal after a decline of petroleum transport), and local markets for consumer goods and services could vary in relation to stagnating or reduced urban growth resulting from shortages and pollution of surface and ground waters.

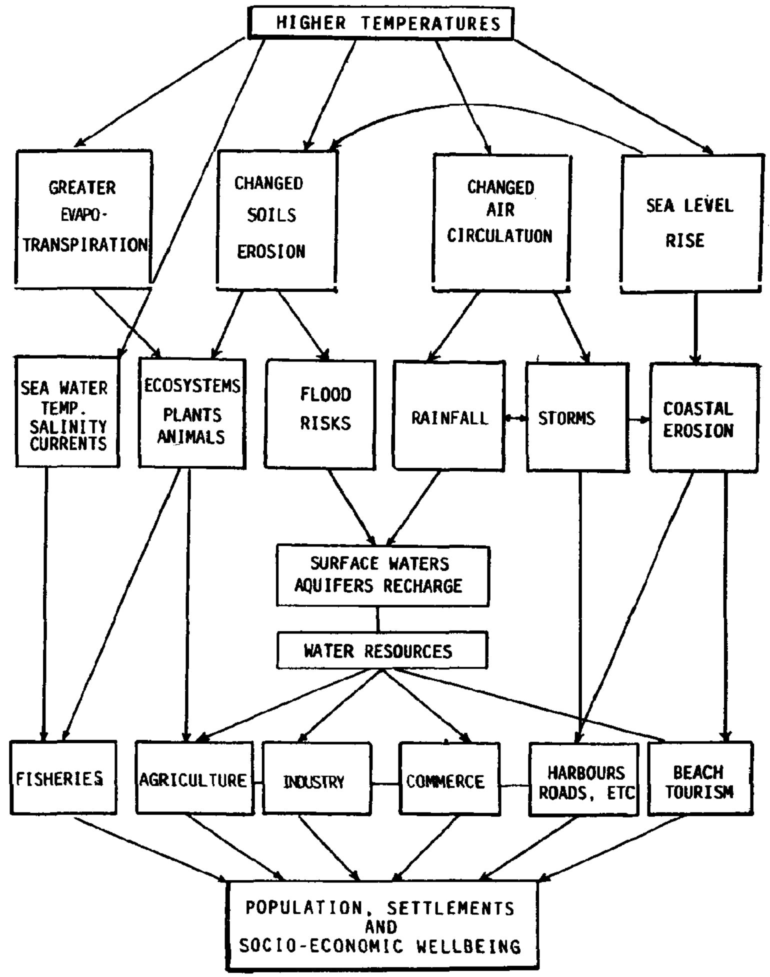

Figure 1. Some of the variables affecting the assessment of the impacts of future climatic changes.

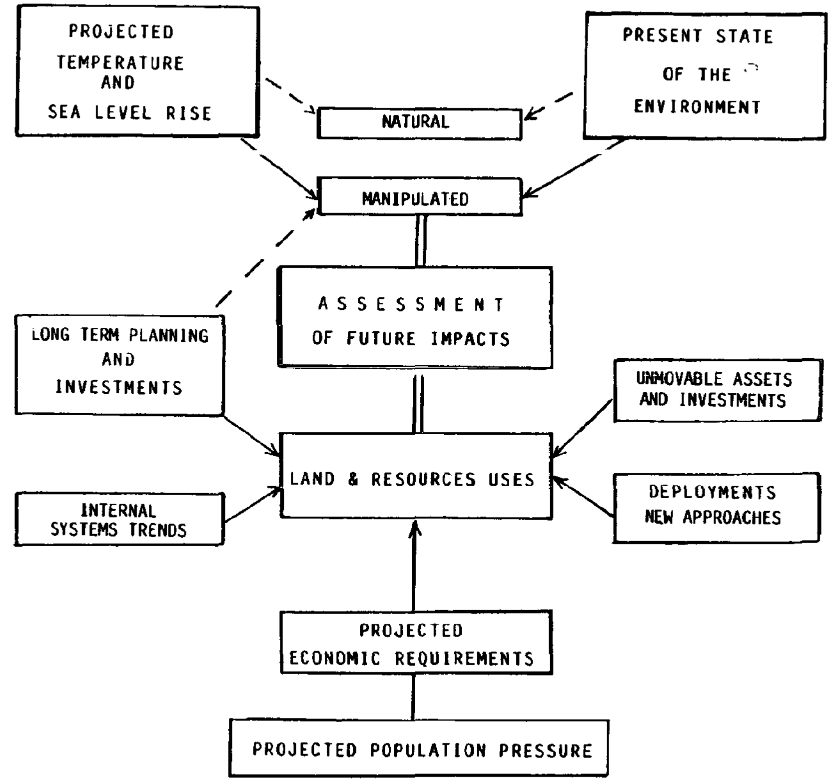

Figure 2. The interrelated nature of physical and biological systems.

THE IMPACT OF SEA LEVEL RISE

Much of the 46,000-km-long Mediterranean coastline rises quickly from the sea. There are many alluvial and coastal plains, but each is fairly small. Nevertheless, they have been important since ancient times as communication pathways for the interior. Deltas have been generally advancing in the past centuries (despite a 1- to 2-mm sea level rise and local geological subsidence), and until early in this century (or a few decades ago in some countries), they were in a fairly natural state with extensive lagoons and marshes.

Today, all coastal plains are intensively used for agriculture, often on lands reclaimed from wetlands, with active fishing and aquaculture in the lagoons. Industrial centers and harbors have been established in some areas (e.g., Ravenna and Porto Marghera, Venice, Italy; Fos de Mer by the Rhone Delta in France; and Abuqir-El Taba by Alexandria, Damietta, and Port Said in Egypt). Considerable portions of the Mediterranean coastlines have become more and more intensively exploited for beach recreation at the edges of coastal plains or between cliffed shores. In fact, in the northern Mediterranean, practically all beaches are presently used (utilization ranges from as low as 25% of total coastline in Yugoslavia to as high as 75% in north Italy and eastern Spain). Tourism development has involved construction of hotels, apartments, pleasure boat harbors, and related permanent infrastructures and services. Some resorts have become very urbanized (high rises), and old towns have expanded with an increase in resident year-round population. Undoubtedly, all these activities and settlements would be the first to be threatened by a rising sea level.

Coastal settlements, from villages to cities, are numerous. However, with a few notable exceptions (e.g., Venice, Siracusa), most major cities have only small portions at sea level with exposed seaside boulevards and some residential quarters at an elevation of 1 meter or less (e.g., Barcelona, Nice, Marseilles, Genoa, Naples, Ancona, Algiers, Pyreus, Alexandria).

The effects of sea level rise must be considered in conjunction with the degree of exposure to storm waves and surges that aggravate coastal erosion with seaward removal of sand, direct attack, or overtopping (with flooding) of seawalls and dikes. The degree of exposure to wave energy varies with coastal orientation in relation to waves (Figure 3). Storms with high waves (2-6 m) are generated in the western Mediterranean (and to a lesser extent in the central basin) causing wave paths to the northwest, west, and northeast (in the west and in the Adriatic Sea), and to the southeast in the eastern Mediterranean. The cold and violent winds that blow in winter from the north and northeast (mistral, bora, etc.) generate waves that attack the Algerian-Tunisian, Sardinian, west Adriatic, central Aegean, and Nile Delta coasts. All other lowlands and cities are more sheltered (e.g., Albania, Turkey, northern Greece) and suffer from a smaller degree of storm wave impact.

Low sandy coasts still in a fairly natural state would probably retreat gradually in response to beach profile readjustment (Bruun and Schwarz, 1985) with some periodic flooding. The breakup of barrier islands and breaching of beach/dune ridges would occur where exposure to storm waves is accompanied by

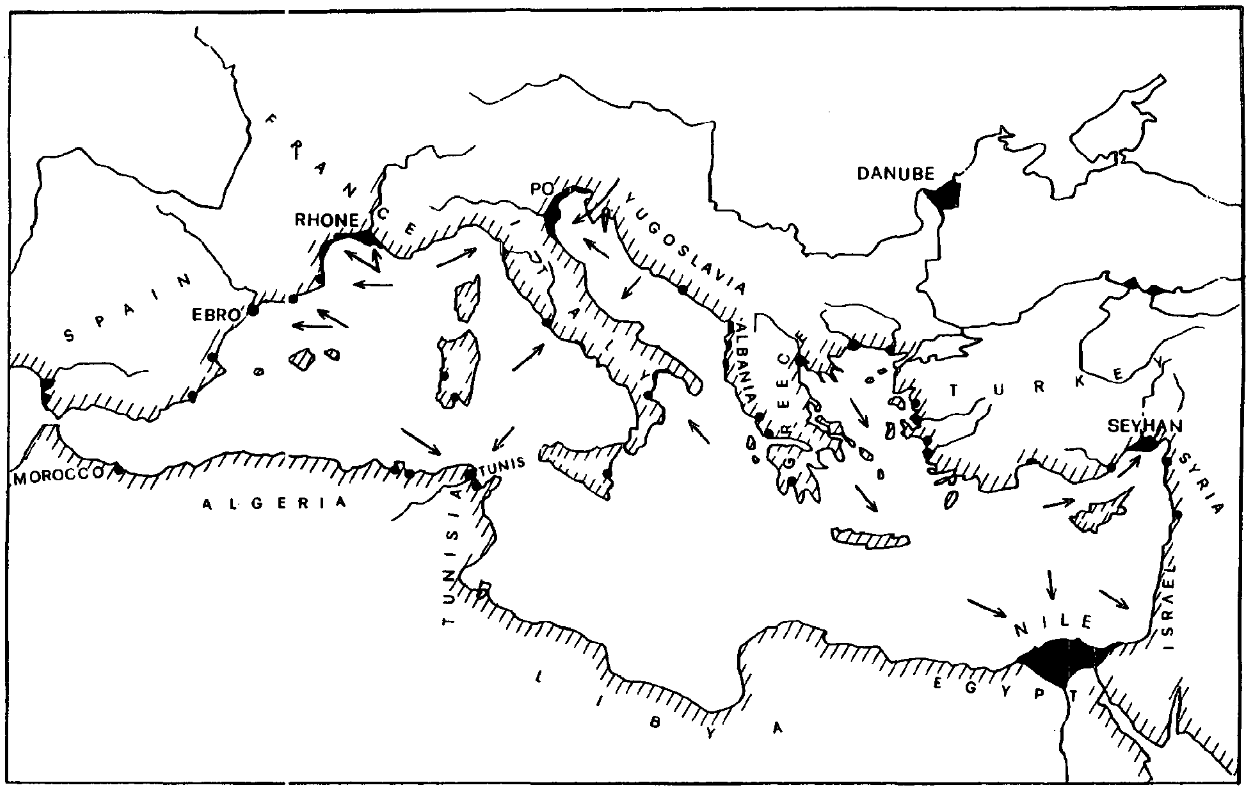

Figure 3. Main deltaic-alluvial lowlands of the Mediterranean region (arrows indicate the predominant directions of winter storm waves).

natural (in some cases also manmade) subsidence or where the coastal sand budget is low or negative. Undoubtedly, well developed, thick ribbons of coastal sand can survive sea level rise, as indicated by the relic dune and beach ridges on the Continental Shelf of the Adriatic Sea and Nile Delta.

Wetlands can move landward and grow upward if the rate of sea level rise is low. However, the persistence of brackish lagoons and marshes would depend on the integrity of the barrier islands, while their ability to move landward is, in fact, generally impeded by dikes, roads, and other structures.

Many stretches of the Mediterranean coasts are, however, no longer in a natural state. Many shores are retreating because dams have sharply reduced (or eliminated) the ability of rivers to supply sand to the coast (Figure 4), or because people are mining the sand in river beds. In addition, dunes have been flattened to make room for beach resorts. The natural beach fluctuations and coast-parallel sand movements are impaired by fixed defense structures, as well as by the jetties that protect the entrances of estuaries, lagoon outlets, canals, and ports.

The most heavily fortified lowland coasts are in the west Gulf of Lions, on the Tyrrhenian and Adriatic side of northcentral Italy, and in parts of Greece and northern Tunisia. The other lowland coasts (e.g., Turkey, Albania) have fewer coastal protection structures; continued shore erosion in conjunction with increased use of the coast will gradually motivate other coastal areas to begin employing these devices as well, as in the Nile Delta. From a local perspective, these measures are justified to stabilize harbor accesses and to protect beach investments; but when one considers the impacts that protecting one area can have on other areas, the wisdom of these measures is not as obvious. All too often, people fail to sufficiently consider the future effects of hard structures on sediment-starved coasts (e.g., the dikes built at the retreating Rosetta and Damietta headlands in the Nile Delta will eventually weaken the lagoon barriers to the east).

A 25- to 30-cm sea level rise would not flood most Mediterranean lowlands, but it would worsen the present situation of beach, delta, and lagoonal instability. Water levels in lagoons, estuaries, and canals would be higher, especially in areas already facing land subsidence (e.g., the Adriatic coast). There would be increased salinity in the lagoons, more extended salt wedges in rivers, and further salinization of reclaimed lands. All protective structures (breakwaters, seawalls, dikes) would have to be raised periodically, and beach nourishment schemes would have to be intensified. The cost of beach and urban seaside protection will threaten the economic viability of some beach resorts and small towns.

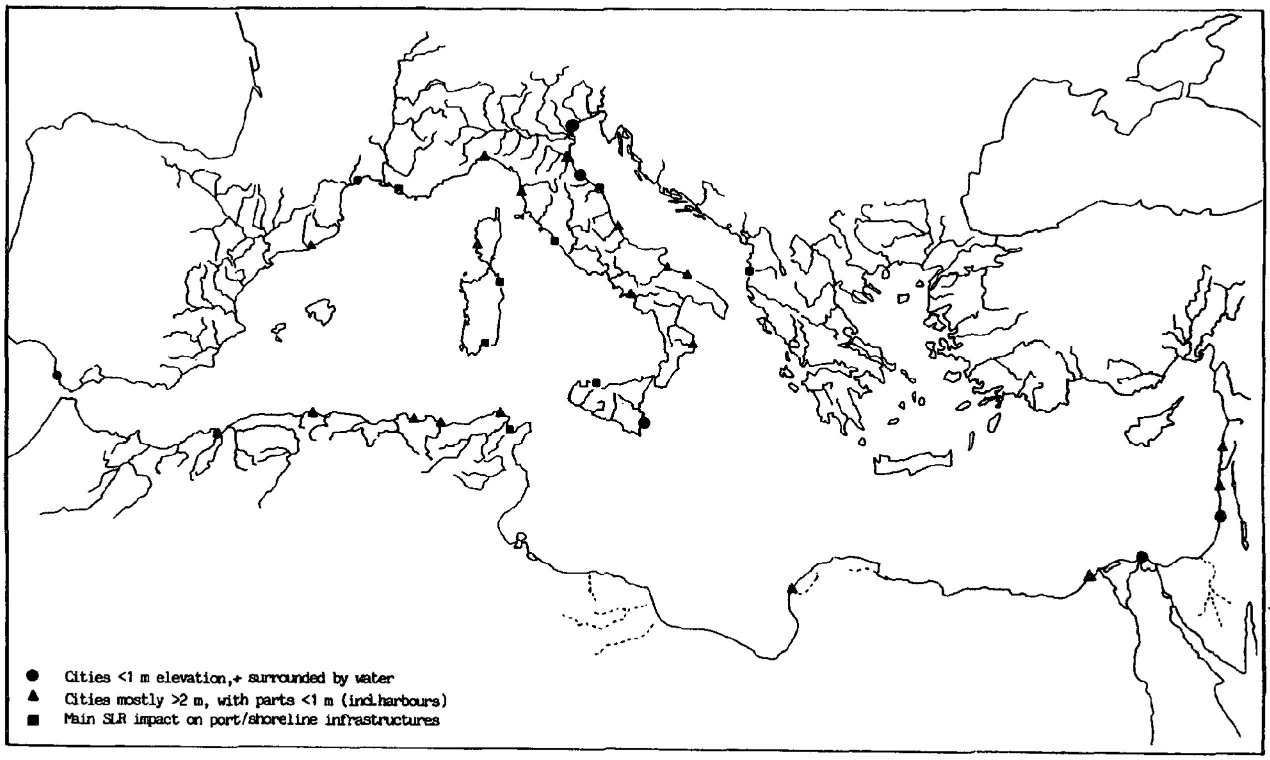

Figure 4. Mediterranean cities that would be most threatened by sea level rise in association with storm surges. Also shown are the main river systems that are dammed.

Mediterranean

A further rise of 30-100 centimeters would have catastrophic effects, unless measures of artificial protection measures are implemented in advance (e.g., raising and stabilizing dunes, erecting more seawalls, and blocking canals/estuaries and lagoonal entrances with sluice systems). Recreational beaches would continue to exist (along coastal plains if not along cliffed coasts), but existing seaside resorts and exposed cities would suffer extensive damage. Higher water levels in the northern Adriatic lagoons would cause the gradual decline of several historical and commercial centers; these impacts could be further exacerbated by other human activities such as withdrawing groundwater.

The socioeconomic impact of sea level rise on coastal lowlands will vary because the degree of land use and development varies -- both in absolute terms and in comparison with nationwide averages (e.g., the Ebro and south Turkey Deltas are relatively undeveloped as compared with the Nile Delta, which contains 45% of Egypt's population). Few people live below the 1-m contour, even in the generally overcrowded Nile Delta. Populations are usually concentrated on ground more than 2 m above sea level, especially on the raised present or past alluvial channels. But there are exceptions, including Venice, and new recreational and port/industrial centers. Moreover, land use will become more intensive because of population growth (probably 550 million by 2025, as compared with 350 million in the Mediterranean countries today), and increased tourism (213 million a year in 1984, perhaps doubling by 2025) (UNEP, 1987). Recent urbanization on coasts has been and will continue to be focused on all available flat ground near the sea.

In the southeastern Mediterranean countries, populations will grow faster and coastal areas will continue to provide focal points for development, mainly in the vicinity of cities. In North Africa, the nature and extent of the economic consequence of sea level rise will depend on the degree and type of coastal development during the next 2-3 decades. In Egypt, for instance, the economic consequences will depend on the uses made of the coastal lagoons (i.e., land reclamation, fishing, or freshwater storage).

In conclusion, the most serious negative consequences for coastal (in some cases national) economies would be the physical impacts on (1) tourist beaches and infrastructure; (2) pleasure marinas; (3) coastal protection structures; (4) towns and cities by the sea, seaside boulevards, and residential areas subject to washovers; (5) ports and industrial installations, especially those built on lowlands and in lagoonal areas; (6) roads, railways, airports by the sea; (7) lagoonal fishing; and (8) reclaimed lands and relative irrigation systems.

RESPONSES AND POLICIES FOR ACTION

Responses to rising sea level would vary from (1) extensive artificial protection, to (2) altered land use (e.g., less urbanized tourist beach centers, the return of some agricultural reclaimed lands back to their lagoonal state), to (3) abandonment. Because the Mediterranean coast is diverse, no single solution is likely.

Nevertheless, the intensity of development and the economic value of coastal activities suggest that abandonment will be confined to isolated localities; however, in many places, public and private investments might gradually become economically unviable as increased physical damages make maintenance too costly (e.g., polders, infrastructures, tourist harbors, power stations by the sea). The Mediterranean coast already has a high degree of coastal defense in many areas; the large number of unmovable features (cities, ports, valuable agriculture, etc.) would make abandonment expensive. But the escalating costs of protection would impose major burdens on state and local governmental budgets, perhaps taking up a large percentage of the income generated by coastal economies.

The maintenance of beach recreation facilities requires a more practical and rational approach than that of today. Is the vision of total protection held by local residents, private investors, and politicians practical in the long run, given the natural processes involved? The present state of degradation caused by the very activities to be protected suggest that it is not. It may be unrealistic to continue occupying a retreating sandy shoreline by maintaining the existing defense structures. A more rational approach would be to establish setback lines and zoning, with less urbanized settlements, and to adopt more "open-space" tourism, wherever feasible, based on the model of the Camargue in the Rhone Delta (Corre, 1989).

With a few notable exceptions of good regional planning (e.g., Gulf of Lion), coastal exploitation has been a local or private investment venture (often with political backing), whereas the ownership and responsibility for coastal use usually are with the state, which has to pay for protection and for the damages caused by natural hazards.

In the face of rising costs of protection, it may be necessary for nations to adopt the approach that coastal investments, if carried out with no consideration for environmental impact, must be accepted as "high risk," and the consequences are to be borne by the investors themselves. (See papers in this volume for a discussion of this principle. The concept is parallel with the spreading attitude and burgeoning legislation that industrial-urban-agricultural polluters must pay for degrading and redressing the environment.)

Given the continued uncertainty about the timing and magnitudes of sea level rise, determining which policies ought to be implemented now is difficult. A low level of awareness persists on the part of the public and authorities alike concerning the consequences of climate change and the seriousness of -- and the need to address -- the present state of coastal degradation.

It would also seem to be reasonable that countries where the coastal zone is still mostly undeveloped should look at the consequences of failing to conduct impact assessments, which can be seen in most nations with heavily managed coasts.

Response strategies will depend on the degree of local impact, physical and financial, according to present and projected land and water resource uses.

Mediterranean

Impacts have, by and large, yet to be evaluated because data bases are, in many cases, limited or nonexistent.

Strategies imply long-term planning based on interdisciplinary approaches. Policy decisions based on these strategies will require political insight and the will to carry out and implement them; that is, they will require a high degree of centralized decision -- in the rather tight timeframe of just a few decades. Even the first stage, that of deciding upon and implementing a phase of rational studies (i.e., to create institutes and/or to coordinate existing ones for environmental impact assessment and planning), is no light task in countries where responsibility for environmental matters is dispersed among different ministries, local authorities, universities, and national research centers.

BIBLIOGRAPHY

Baric, A. and F. Gasparovic. 1989. "Implications of climatic changes for the socio-economic activities in the Mediterranean coastal zone." UNEP/OCA, Nairobi, Rept. WG 2/12.

Brunn, P. and M.L. Schwartz. 1985. "Analytical prediction of beach profile change in response to a sea level rise." Zeitschr. fur Geomorphologi, Suppl. Bd. 57: 33-55.

Corre, J.J. 1989. "Implications of climatic changes for the Gulf of Lion." UNEP, Nairobi, Rept. WG 2/4E.

Georgas, D. and C. Perissoratis. 1989. "Implications of climatic changes for the inner Thermaikos Gulf." UNEP/OCA, Nairobi, Rept. WG 2/9.

Hollis, G.E. 1989. "Implications of climatic changes for the Garaet Ichkeul and Lac Bizerte." UNEP/OCA, Nairobi, Rept. WG 2/a.

Imeson, A., H. Dumont, and S. Sekliziotis. 1987. "Impact analysis of climatic change in the Mediterranean region." European Workshop on Interrelated Bioclimatic Changes, Norwijkerhout Oct. 1987, v.F.

Marino, M.G. 1989. "Implications of climatic changes on the Ebro delta, Spain. UNEP/OCA, Nairobi, Rept. WG 2/3.

Raper, S.C.B., R.A. Warrick, and T.M.L. Wigley. 1990. Global Sea Level Rise. In: Milliman, D.J. (ed.) Rising Sea Levels and Subsiding Coastal Areas.: SCOPE, Bangkok, Nov. 1988 Seminar (in preparation).

Sestini, G. 1989a. "The implications of climatic changes for the Po delta and Venice lagoon." UNEP/OCA, Nairobi, Rept. WG 2/11.

Sestini, G. 1989b. "The implications of climatic change for the Nile delta." UNEP/OCA, Nairobi, Rept. WG 2/14.

Sestini, G., L. Jeftic, and J.D. Milliman. 1989. "Implications of expected climatic changes in the Mediterranean region: An overview." UNEP Regional Seas Reports and Studies, No. 103, UNEP, Nairobi.
Sestini, G. 1990. The impact of climatic change on two deltaic lowlands of the Eastern Mediterranean. In: Jelgersma S. (ed.) Sea Level Rise and European Coastal Lowlands, Basil Blackwell (in press).

UNEP, 1988. The Blue Plan, Futures of the Mediterranean Basin. Executive Summary and Suggestions for Action. Sophia Antipolis, France.

Wigley, T.M.L. 1989. Future climate of the Mediterranean Basin with particular emphasis on changes in precipitation. UNEP/OCA, Nairobi, Rept. G WG/2/6.

IMPACTS OF CLIMATE CHANGE ON THE SOCIOECONOMIC STRUCTURE AND ACTIVITIES IN THE MEDITERRANEAN REGION

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ABSTRACT

This paper examines the possible impacts of climate change on the Mediterranean coastal areas, focusing special attention on human settlements and major economic sectors (agriculture, tourism, fisheries, and aquaculture).

Society's activities depend closely on the existing climate. One can assume that the impact on activities and institutions will be primarily local, with possible important common characteristics for small and large areas or regions. However, the assessment of local impacts is outside the scope of this paper owing to our lack of knowledge on the particular circumstances facing other regions.

Climate change will have a limited impact on the distribution and dynamics of coastal populations. The natural population growth will not be affected by climate changes and will continue to follow the present general trends -- i.e., little natural population growth in the northern Mediterranean countries, with high growth rates for nations along the southern and eastern coasts. The current rate of migration toward the coast will probably not change, although it could accelerate in the south owing to the natural spreading of the deserts. Approximately 5 percent of the population living in coastal zones will be indirectly affected by the impacts of climate changes and sea level rise; about one percent reside in areas that would be inundated by a rise in sea level.

An inherent quality of most institutions is a certain inertness in response to phenomena that are not expected for decades. However, because these changes could begin to occur as soon as the next decade, the governments and the public should begin preparing for them today.

The nations of the world should incorporate the mitigation of climate change into national development and environmental management. This calls for (1) alerting the public (avoiding unnecessary alarm) and all administrative and economic institutions involved in the decision-making process about the possible

effects of the climate changes; (2) studying the local conditions under which these changes will occur; (3) incorporating the implications of climate changes into the integrated planning process for global development and development of individual economic activities; (4) undertaking appropriate cost-benefit and environmental impact analyses within land-use, environmental, and town planning and management; and (5) promoting and developing new technologies for mitigating the impacts of climate change.

Responding to climate change will require considerable funds, which should be anticipated in national, regional, and local plans.

INTRODUCTION

It is no exaggeration to say that climate largely determines the basis of all human activities. Directly and indirectly, climate affects soils, vegetation, water resources, storminess, and most other environmental conditions, which in turn help to determine our productive pursuits and the very institutions by which society organizes itself.

Thus a change in climate would affect the social and economic structures of the entire world in ways that we cannot yet predict. Would the changes be sudden or gradual? Should we view the worldwide impact as simply the sum of all local impacts, or must the socioeconomic impacts -- like the geophysical processes -- be viewed in a global context? Both approaches yield important insights, although predicting regional and local impacts is impossible unless someone has become truly familiar with a particular area.

Reducing the impacts of climate change in the next century will be expensive. New investments will be required for coastal defense and supplying sufficient water to agricultural areas, or for relocating people should such engineering projects be too costly. The need for new investments may affect developing nations in the eastern and southern Mediterranean region particularly severely. New strategies will be necessary for development, technology, and environmental protection.

The changes brought about by the greenhouse effect are chronic, while the sociopolitical and economic institutions react only to existing and impending emergencies. Because the complex network of institutions need 20 to 50 years to adapt, the planning should already be under way. In this paper, we attempt to evaluate the adaptability of the socioeconomic activities to a change in climate.

BACKGROUND INFORMATION ABOUT THE MEDITERRANEAN REGION

Although the coastal zones of the Mediterranean countries represent only 17% of the total area of the countries (Blue Plan, 1988), they are a primary focus in assessments of climate changes, given the risk of a rise in sea level.

The 46,000 kilometer Mediterranean coast is very ragged and indented. More than half of it is rocky, while the rest is considered to be sedimentary (see Table 1). About 75% of the coastline belongs to four countries:

Table 1. Selected Data for the Mediterranean Coastal Zones

Country	Urbanized coastal zones (sq. km)	Population in coastal zones (1,000's)	Percentage of coastal population in urban areas	Population/km of coast	Length of coastal shoreline (km) total	islands
Spain	2,794	13,860	80.64	5,372	2,500	910
France	1,203	5,496	87.52	3,227	1,703	82
Monaco	2	27	100.00	6,750	4	--
Italy	4,981	41,829	66.76	5,260	7,953	3,766
Malta	13	383	85.38	2,128	180	--
Yugoslavia	351	2,582	54.38	422	6,116	4,024
Albania	52	3,050	34.10	7,297	418	--
Greece	1,315	8,862	59.37	591	15,000	7,700
Turkey	371	10,000	53.00	1,926	5,191	--
Cyrus	20	669	49.48	855	789	--
Syria	17	1,155	35.93	6,311	183	--
Lebanon	86	1,668	80.15	11,867	225	--
Israel	154	2,886	90.35	21,250	200	--
Egypt	236	16,511	35.73	17,300	950	--
Libya	85	2,284	62.17	1,290	1,770	--
Tunisia	168	4,965	67.47	3,819	1,300	--
Algeria	276	11,500	48.00	9,583	1,200	--
Morocco	91	3,390	44.89	6,621	51	--

Mediterranean

Greece, Yugoslavia, Italy, and Turkey. The islands in three of these countries account for roughly 40% of the Mediterranean coast: Greece, 7,700 km; Yugoslavia, 4,024 km; and Italy, 3,766 km (Blue Plan, 1987).

Approximately 133 million people live in coastal zones, representing 37% of the total population of the Mediterranean countries. About 87 million people live in the coastal cities. The gross national product in the region ranges from about $700 to $10,000 (U.S.) per capita (Blue Plan, 1988). The distribution of gross domestic product varies among the countries (Table 2). For example, agriculture's contribution ranges from 2% in Libya up to 20% in Syria and Egypt; industry's contribution ranges from 24% in Libya up to 69% in Syria.

IMPACT OF CLIMATE CHANGE ON SELECTED ECONOMIC ACTIVITIES

Agriculture

Agricultural production in the Mediterranean countries is generally oriented toward food, although a few countries also produce tobacco and cotton. Cultivated land is less than 50% of the total area of each country; in north African countries, it is always less than 10%. In recent times Mediterranean agricultural regions have generally remained unchanged, although in Italy and France the total cultivated land has declined (Blue Plan, 1988).

In the northern Mediterranean countries and Turkey, most agriculture is removed from the coast, although the high fertility of coastal soils makes the coastal zone highly productive. By contrast, in the eastern and southern Mediterranean countries, production is concentrated in the coastal zone. In Egypt, agriculture is found both in the Nile Delta and inland along the Nile River.

The expected climate changes in the Mediterranean region (Wigley, 1988) could have very far-reaching consequences on agriculture. Sea level rise will inundate some areas and lead to salinization of others. Other factors could also be important, such as higher temperatures and changes in the amount and distribution of precipitation.

Lengthening of the summer dry period may affect the existence of crops or plantations, the incomes of farmers, and the commercial values of products. Rising temperatures will change growth cycles, harvest times, and the quality of produce; for example, as spring comes earlier in northern Europe, the need for early fruits and vegetables produced in the Mediterranean will decrease. Warmer temperatures will also have indirect effects, such as increased evaporation, lower moisture levels of the soil, and increased erosion.

Most plants require the greatest amounts of water during the spring or summer, which is the period of least precipitation in the Mediterranean. The absence of showers in late spring or early summer may significantly reduce productivity or necessitate increased irrigation. At the same time, warmer temperatures will increase water requirements for plants. Wherever possible,

Table 2. Distribution of Gross Domestic Product (%)

Country	Agriculture				Industry				Services			
	1960	1976	1980	1984	1960	1976	1980	1984	1960	1976	1980	1984
Spain	21	9	8	6[a]	39	39	37	34[a]	40	52	55	60[a]
France	9	6	4	4	48	43	36	34	43	51	60	62
Italy	15	8	6	5	38	41	43	40	47	51	51	55
Yugoslavia	24	15	12	15	45	43	43	46	31	42	45	40
Greece	23	18	16	18	26	31	32	29	31	51	52	53
Turkey	41	29	23	19	21	28	30	33	38	43	47	47
Syria	25	17	20	20	21	36	27	24	24	47	53	57
Israel	11	8	5	5	32	43	36	27	57	49	59	68
Egypt	30	29	23	20	24	30	35	33	46	41	42	48
Libya	14	3	2	2	9	68	72	64	77	29	26	34
Tunisia	24	21	17	15	18	30	35	35	58	49	48	50
Algeria	21	7	6	6	24	57	57	53	55	36	37	41
Morocco	29	21	18	17	24	31	32	32	47	48	50	51

[a] 1982

Source: World Bank, World Development Reports.

it will be necessary to use closed systems of water distribution and ways of supplying water, which will minimize evaporation; it may also be necessary to reuse wastewaters.

Temperature rise may also significantly affect the development of various parasites and insects, which may directly affect agricultural productivity and income.

The investments required for coastal defense, dams, and irrigation systems will make agricultural production much more expensive, which could have far-reaching socioeconomic consequences. The rich northern Mediterranean countries should be able to solve these problems. But the poorer countries in the south, which even today have problems with supplying their inhabitants with food, will have more difficulty coping.

Tourism

The Mediterranean is by far the strongest tourist region in the world. For over 30% of the tourists that vacation outside their own country, their final destination is one or more of the Mediterranean countries. In 1984, about 100 million people visited the Mediterranean,[1] of these, 45 million were domestic tourists. Although France, Spain, and Italy are the most popular destinations, tourism is an important part of the coastal economy throughout the region.

Mediterranean tourism is primarily oriented toward swimming and sunbathing -- activities that directly use the seashore.[2] Therefore, the immediate coast, its slope, climate,[3] and the quality of land and sea are of prime importance. Most tourist facilities, such as hotels, camps, and youth hostels, are located within 200-300 m of the coast. Facilities farther from the shore are found mainly in the developed and luxurious tourist areas.

Tourism will suffer from climate change. Beaches that lie below cliffs and other rocky inclines would be first to disappear. There would also be problems with beaches where infrastructure is within a few meters of the high water mark. It may be necessary to relocate city streets and promenades (e.g., Nice, Cannes)

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[1] This number is probably too low, since most of the countries do not accurately register their domestic tourists (Blue Plan, 1988).

[2] Mediterranean tourism fluctuates seasonally. Depending on location, the number of visitors from June to September is from 50% to 80% greater than other periods of the year.

[3] Mediterranean tourism fluctuates seasonally. Depending on location, the number of visitors from June to September is from 50% to 80% greater than during other periods of the year.

or highways and railway lines (the coastal stretch between Nice and Cannes, and parts of the Italian and Yugoslav coasts).

Even if sea level rises moderately and does not threaten tourist facilities, the loss of beaches would disappear or require substantial investments for reconstruction. Moreover, saltwater intrusion due to sea level rise and increased evaporation from higher temperatures would diminish the availability of water needed for tourism and wastewater drainage. Islands may experience even greater damages than the coast of the mainland.

A special type of tourism, nautical tourism, has stimulated the building of a large number of marinas, sport harbors, and berths. They will be much harder hit than the large freight harbors.

Global warming may lengthen the tourist season in the northern Mediterranean by creating more favorable weather. However, the rise in air temperature and sea level may enhance the attractiveness of the continental lakes and of the coastal tourist areas of other seas (e.g., Baltic, North Sea), thus negating the need for many northern Europeans to travel south for their vacations.

Any attempts to relieve the impacts of climate changes on tourism will encounter great organizational and financial difficulties. The industry has a great number of hotels, restaurants, shops, and tour operators, each of which respond to their own sets of incentives. Moreover, mitigating the consequences would require high public investments in roads, utilities, and other infrastructure.

Fisheries

Foods harvested from the sea have historically provided an important staple in the diets of the inhabitants of the Mediterranean, especially the small islands. With the development of food preservation techniques and faster transport, the consumption of fresh seafoods has spread inland.

About 4 million tons of seafood are produced in the Mediterranean countries every year. The needs of individual Mediterranean countries for seafood are basically satisfied through national fishing. The annual catch on the Mediterranean is approximately 1 million tons.

Although the total catch has remained constant for about the last 10 years, there have been significant changes in the species composition of the catch (Blue Plan, 1988). This change has resulted from the overexploitation of some species, the demands of the market, and the development of specific new techniques in fishing. Looking at individual countries, we find major differences: In more developed northern countries, there has been a significant decrease in the number of average-quality fish (sardines, mackerel) caught and an increase in the number of high-quality fish (mullet, perch, dorade). In the less developed countries, there has been no real change in the catch of poorer quality fish.

Mediterranean

According to some assessments, the present level of fishing is close to the sustainable catch, endangering the existing fish stock. In some regions the catch may not be threatening species survival, while in other areas certain species are clearly overfished. The consequences at first are reduced catches, but eventually the species can disappear (e.g., mackerel in the Adriatic Sea). Because sustainable yields themselves will change, better assessments and regulation to ensure an optimal catch without overexploitation will be even more important in the face of climate change.

It is likely that the expected climate changes will break existing ecological balances and chains, and new ones will be formed on significantly different levels. The Mediterranean region is typical of this problem, because it contains species that are heterogeneous in every individual area, the result of the vastly different biotypes. Generally speaking, the weak primary production limits fish stocks. Cyclonal activity directly affects the dynamics of water-mass movements, especially in shallower coastal regions.

A general decrease of precipitation is predicted for the entire year and for the summer period.[4] The resulting increase in the salinity of the sea, along with sea level rise, could affect the inflow of nutrients from river runoff or from "upwelling" of deep-sea waters. The changes in the physical characteristics also could affect the oxygen solubility in the sea. The changes in the physical characteristics could speed up the physiological processes of marine organisms. They also could accelerate the mineralization of organic matter.

The rise in the sea temperature in the shallow coastal waters could create subtropical or even tropical conditions, which would probably stimulate a greater immigration of numerous plant and animal species from the Red Sea through the Suez Canal into the Mediterranean region. Some plant and animal species indigenous to the Red Sea have already naturalized in the eastern Mediterranean, but in the future they will spread westward. In contrast, the boreal species will be endangered or may even disappear.

These changes could bring about major alterations in the qualitative and quantitative composition of the Mediterranean marine flora and fauna. Economically important populations of marine organisms will also be affected. Climate change also may cause subsequent changes in the migratory habits of fish species that constitute the largest part of the annual catch. Likewise, a shift in the distribution of niches of some other economically important species may require significant modification of existing fishing techniques. This may include new devices and equipment for detecting fish, larger boats capable of fishing in farther and deeper waters, and new fishing equipment. All these changes will require significant financial expenditures that may depress further development of fishing in the economically weaker countries.

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[4] However, in some regions of the Mediterranean, precipitation and/or the inflow of freshwater may increase. Nonuniform changes in precipitation could cause very complex alterations in the physical characteristics of the Mediterranean Sea, especially the shallow coastal areas.

Aquaculture

Some countries have tried to satisfy the demand for high-quality fish by artificial fish production, although it still accounts for a small fraction of total fish consumption. In 1987, approximately 26,500 tons of high-quality fish were produced; by 1992, this number is estimated to reach 44,000 tons (Blue Plan, 1988). About 90% of the present aquatic farming in the Mediterranean occurs in lagoons. Other techniques, for example raising fish in tanks, are being introduced in some countries.

The Mediterranean coast provides great conditions for further development of aquaculture. However, uncontrolled development often endangers the areas suitable for aquaculture. If aquaculture is to be notably increased, measures for the protection of suitable habitats must be taken immediately. Within the framework of the program prepared by the Priority Action Programme of the Mediterranean Action Plan in cooperation with the Food and Agricultural Organization, ecological criteria for the rational development and protection of aquaculture in the Mediterranean coastal regions are being developed, so that the Mediterranean countries can in time legislate the proper protective measures.

Since marine aquaculture is mainly located in the coastal zones, climate changes and their direct consequences (sea temperature rise, salinity rise, sea level rise) will greatly affect its development. Keeping mind the fact that marine culture in the Mediterranean comes from lagoons whose average depths are only 50 cm, sea level rise may make the lagoons completely unfit for production. New lagoons will need to be created or existing ones greatly modified.

A rise in both the salinity and the temperature of the Mediterranean Sea will result in a decrease of oxygen solubility and an increase in the decomposition of organic matter. This may enhance the oxygen depletion and may even create anoxic conditions. On the other hand, warmer temperatures will accelerate the growth of marine organisms in the colder periods of the year, shortening the production cycle.

The changes in climate conditions may alter the effects of pollutants on certain organisms. For example, the expected temperature rise may create major changes in the bioaccumulation of certain pollutants, which may negative impacts on some commercially important species. Regulations on the acceptable levels of water pollution in fish ponds may need to be amended, and some aquacultural activities may need to be relocated (see Titus, Problem Identification, Volume 1, for additional discussion of impacts of sea level rise on fish ponds.)

Community Infrastructure

The discussion here on human settlements is restricted to freshwater supply and wastewater collection, treatment, and disposal. Although little technical data are available on community infrastructure in the Mediterranean region, we can anticipate the general impacts of climate change. However, the impacts will vary by locality.

Mediterranean

When discussing infrastructure along the Mediterranean, we must distinguish between the northern, eastern, and southern areas, and between urban and rural units. Infrastructure is generally most numerous in the cities of the more-developed northern countries. While all northern cities have systems of waterworks, most areas in the south do not and some do not even have running freshwater.

Until recently, most sewage systems in the Mediterranean released their wastes directly to the sea by the shortest possible route. A large number of small systems released wastes immediately under or just at the surface of the sea. It was difficult to control these releases, and consequently coastal waters became polluted.

Recently the philosophy and practice of wastewater management has been changing. The general belief now is that wastewater should be collected, treated to an acceptable degree of contamination, and then released through a long pipeline far into the sea. This method of wastewater disposal also allows for the reuse of wastewater -- a point of great importance to areas with inadequate water sources. Israel has not released any wastewater into the sea for the last several years; after proper treatment it is reused, mainly for irrigating crops.

The expected climate changes will have affect existing community infrastructures and require new infrastructures. Basically, the reduction of available water will exacerbate present-day problems in many areas. It will be necessary to supply some cities and settlements with water from far-away sources, since the local sources will have a lessened capacity and poorer quality.

Due to the temperature rise, the rate of growth of various microorganisms in some water sources will increase, thus increasing possible waterborne environmental health risks. Eutrophication may be intensified in some sources and rivers. All this will require the construction of equipment and facilities for freshwater purification, which will significantly increase the price of freshwater -- the price may even double.

Sea level rise may endanger the sewage systems in some coastal cities, particularly those whose sewage systems also serve as cisterns. Drainage may also be more difficult. After rainstorms, wastewater may flood the lower parts of these cities. Both this situation and the shortage of water will require the construction of completely new sewage systems and facilities for wastewater treatment and possibly reuse.

IMPACT ON THE DISTRIBUTION AND DYNAMICS OF COASTAL POPULATION

The current migration toward the coast will continue in the future, but with less intensity than urbanization. This latter process will be especially intense in the southern and eastern parts of the Mediterranean, where today 40-50% of the population lives in the urban areas. According to the Blue Plan (1988), this figure is expected to reach 70-80% by the year 2025.

Changing climate will have a limited impact on the population in the coastal zone, especially in the initial years of accelerated sea level rise, assuming that coastal defense measures are taken. The natural population growth is primarily affected by other factors, such as the growth of the standard of living, the growth of the economic vitality, the level of medical care, and cultural and religious customs. Nevertheless, migration to the coast may be accelerated in the south if global warming increases desertification.

Urbanization probably will be slower than predicted by the Blue Plan (1988). Reduced water supplies, poorer water quality, the need for more purified drinking water, transport of water from distant sources, plus a greater level of wastewater treatment and recycling will require greater expenditures for urban infrastructure. The resulting rise in the cost of urban living will slow the migration toward cities. The temperature rise will make living in crowded cities less pleasant during the summer. The hot exhausts of air-conditioning systems, which probably will be increasingly used, also add to the warming in cities. A reduction of their use would occur only with a drastic rise in energy prices, which may be necessary to limit fossil-fuel emissions.

Our preliminary calculations suggest that at least 5% of the coastal population -- some 6,700,000 inhabitants -- would be affected by the impacts of sea level rise. Some of these people would be directly threatened with inundation, but probably not more than 10-20% of the total number affected. The repercussions will include the need to remove structures and construct new one for the eventual relocation of the inhabitants.

CONCLUSIONS

Inertia is inherent to economic, social, and political institutions, particularly for phenomena that will not manifest themselves in the near future. But because recent information indicates that these changes could happen as early the next decade, the public and the governments should start preparing for them now. Our recommendations are as follows:

1. Information should be disseminated to the public as well as to all levels of economic and political decision-making entities about the possible consequences of gradual changes in the climate and the need for measures to mitigate the impact. This should be a national action, not be left to the local authorities or to coastal zones.

2. Local inventories should be made of the coastal zones, and data should be collected on the expected local impacts of sea level rise and temperature rise on water, soil, precipitation, and individual socioeconomic activities.

3. A strategy should be developed that can react to changing climate conditions, keeping in mind the accumulative nature of these changes. Calculating expenditures for a given change or given time horizon ignores any additional changes in subsequent years.

4. The effects of changing climate should be incorporated into the methods of integrated planning, including integrated, economic, land-use, environmental, and town planning issues.

5. The cost-benefit analyses and environmental impact assessments should be used to evaluate the feasibility of every expenditure for alleviating the impacts of climate changes.

6. Technology should be developed for the alleviation of these impacts on local, regional, and general levels.

7. All these activities ultimately should be integrated and coordinated on a regional level.

BIBLIOGRAPHY

Blue Plan. 1987. Data Base of the Mediterranean. Belgrade: Sophia Antipolis.

Blue Plan. 1987. Mediterranean Basin Environmental Data (Natural Environment and Resources). Belgrade: Sophia Antipolis.

Blue Plan. 1988. Futures of the Mediterranean Basin - Executive Summary and Suggestions for Action. Belgrade: Sophia Antipolis.

Blue Plan. 1988. Futures of the Mediterranean Basin - Environment Development 2000-2025. Belgrade: Sophia Antipolis.

Wigley, T.M.L. 1988. Future climate of the Mediterranean Basin, with particular emphasis on changes in precipitation. Geneva: United Nations Environment Programme/OCA/WG. February 6.

VENICE: AN ANTICIPATORY EXPERIENCE OF PROBLEMS CREATED BY SEA LEVEL RISE

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ABSTRACT

This paper discusses the social, cultural, and other impacts of increased flooding in Venice. It briefly describes Venice's physical, ecological, social, economic, and cultural framework and the characteristics and evolution of flooding phenomena. It then analyzes the short-term impacts of the increased floodings and discusses the response of the city (and the country) at the social, technical, and political levels. The paper next describes the special projects being undertaken to prevent floodings, with particular emphasis on the mobile gates at the lagoon entrances (whose construction will soon be started), on the impact of this project, and on the reactions of the city. Finally, the paper attempts to interpret the Venice experience, identifying the features that can be considered as representative of generally expected impacts and the reactions to sea level rise in seafront cities.

INTRODUCTION

Although it is necessary "to consider with great caution casual connections (to the earth's climate evolution) often proposed" (Puppi and Speranza, 1988), a large number of studies indicate that there is credible evidence for an accelerated rise of sea level in the next century.

The current trend is characterized by an increase of about 10 centimeters per century (Gormitz et al., 1982). With respect to this trend, all scenarios forecast by different researchers indicate a significant increase. Most of the studies forecast a rise in global sea level of between 25 and 75 centimeters by the year 2050 and between 50 and 225 centimeters by the year 2100 (Titus, 1986).

Mediterranean

The many consequences expected in coastal areas as a result of sea level rise can be classified into three categories: shoreline retreat, flooding, and salt intrusion (Titus, 1986). These consequences would affect urban and rural areas differently, but in both cases they would have significant economic, social, and cultural impacts. All of these have been extensively investigated by many authors in recent years. Previous assessments have been based on a priori estimates of the impacts, since experience on this topic has not yet been acquired. However, few cases exist worldwide that can provide a valuable insight into the phenomenon. Among them, Venice represents an extremely significant experience.

Since the beginning of this century, the relative mean sea level in Venice has risen by about 25 centimeters, and the mean number of floodings of the city has increased from less than 10 to more than 40 per year. Catastrophic floodings, having a return period of 800 years at the beginning of the century, presently have a return period of 200 years; that is, a 25-centimeter rise quadrupled the risk of serious flooding. For these reasons, the problem of protecting the city from the sea has taken an increasingly urgent priority, and in such a way Venice represents the likely economic, social, and cultural impacts that sea level rise would have on an urban environment.

This paper illustrates the Venice experience in order to provide some indication for future, possibly more generalized situations. It first briefly describes Venice and its environment and provides a short history of sea level rise. It then analyzes the perception of the problem, discusses the short- and long-term reactions, and presents the course of action that officials have selected. Finally, it illustrates future perspectives and critically reviews the Venice experience, outlining the most prominent aspects likely to be experienced by coastal communities in general as sea level rises.

VENICE AND ITS ENVIRONMENT

The Venice lagoon is the most important remnant of a series of lagoon formations that, thousands of years ago, occupied all the northern bow of the Adriatic. It is made up of a basin of 550 square kilometers, and is connected to the sea by three openings at Lido, Malamocco, and Chioggia (Figure 1). The basin has an oblong and arched shape and extends about 50 kilometers along the Adriatic coast, varying from 4 to 15 kilometers in width, with an average depth of about 1.5 meters.

One portion of the lagoon (420 square kilometers) is permanently submerged by water (shallows); another is permanently above the water (islands and urbanized areas). Of the remainder, one part (the "barene") is submerged only by normal tides, while another part (the "velme") is generally submerged and is above water only during very low tides. At the edge of the lagoon, 90 square kilometers of water are reserved for fish farming. Figure 2 illustrates various parts of the Venice lagoon.

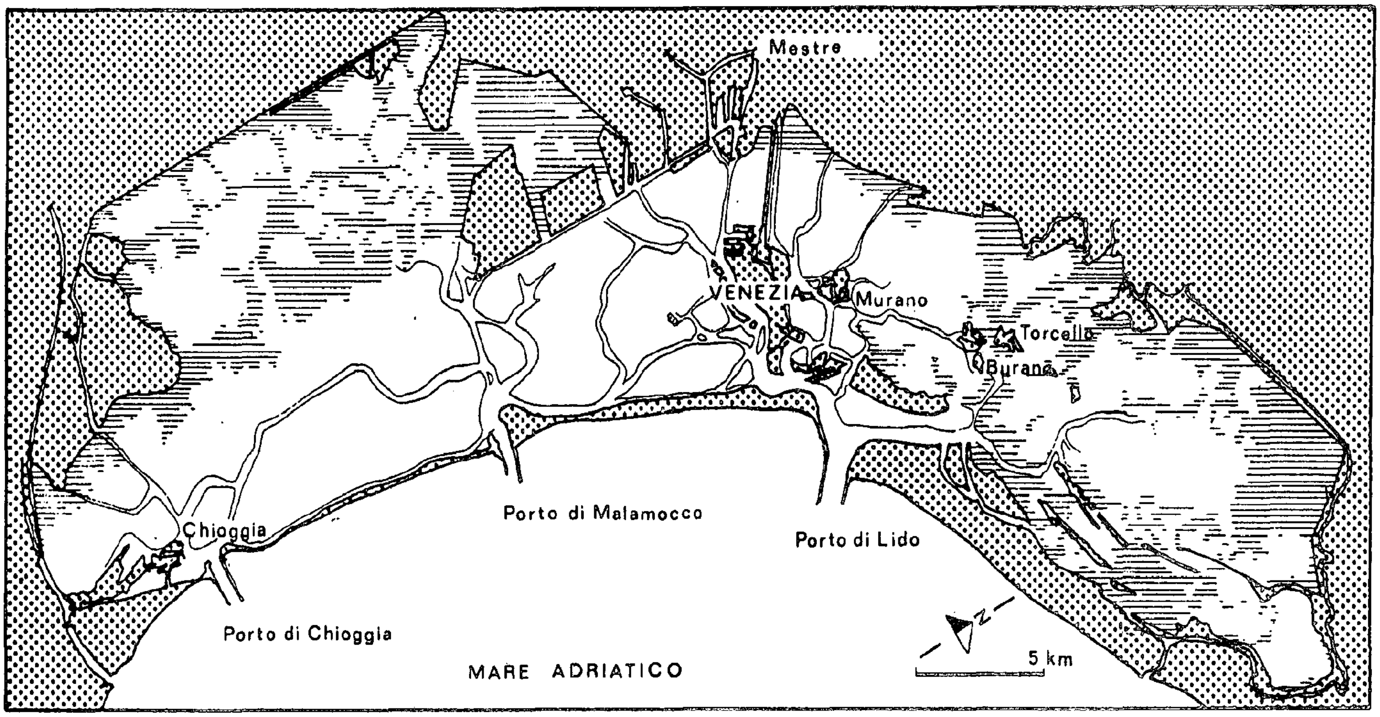


Figure 1. Map of the Venice lagoon.

The evolution of the Venice lagoon has been reconstructed on the basis of geological studies. About 10,000 years ago, the sea level began to rise and the coastline migrated north from the lower Adriatic. When it reached approximately the present location (about 6,000 years ago), an intense and prolonged alluvial phase took place. Sediment flowed into the sea and was distributed along the coast by the wave motion and the sea currents, forming the littoral line that delimited the primitive Venice lagoon (albeit with a smaller extension than the present one).

Among the factors affecting the lagoon's morphology during the ages, the activity of the lagoon's tributaries was dominant. They kept the water brackish (rather than salty), but they also threatened to make the entire lagoon a marshland and eventually to fill it completely.

The lagoon is an extraordinary environment to be conserved and protected, with a balance between the natural beauty of the place and the needs of the communities living there. Several hydraulic works have been carried out to preserve it, particularly the diversion of major tributaries into the sea, the location of the sea entrances, and the dredging of channels for inland navigation.

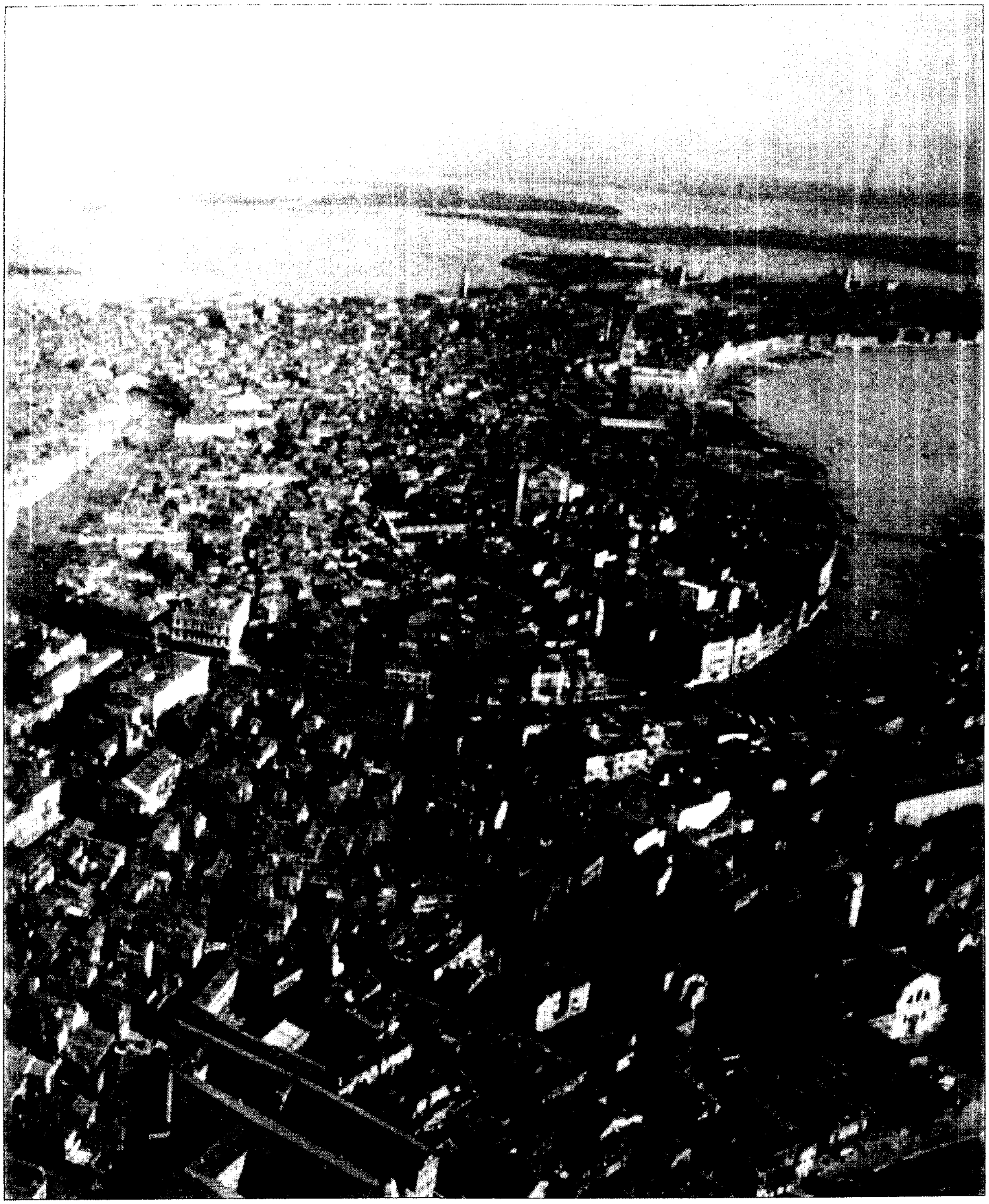


Figure 2 (A). Historic Venice.

B

C

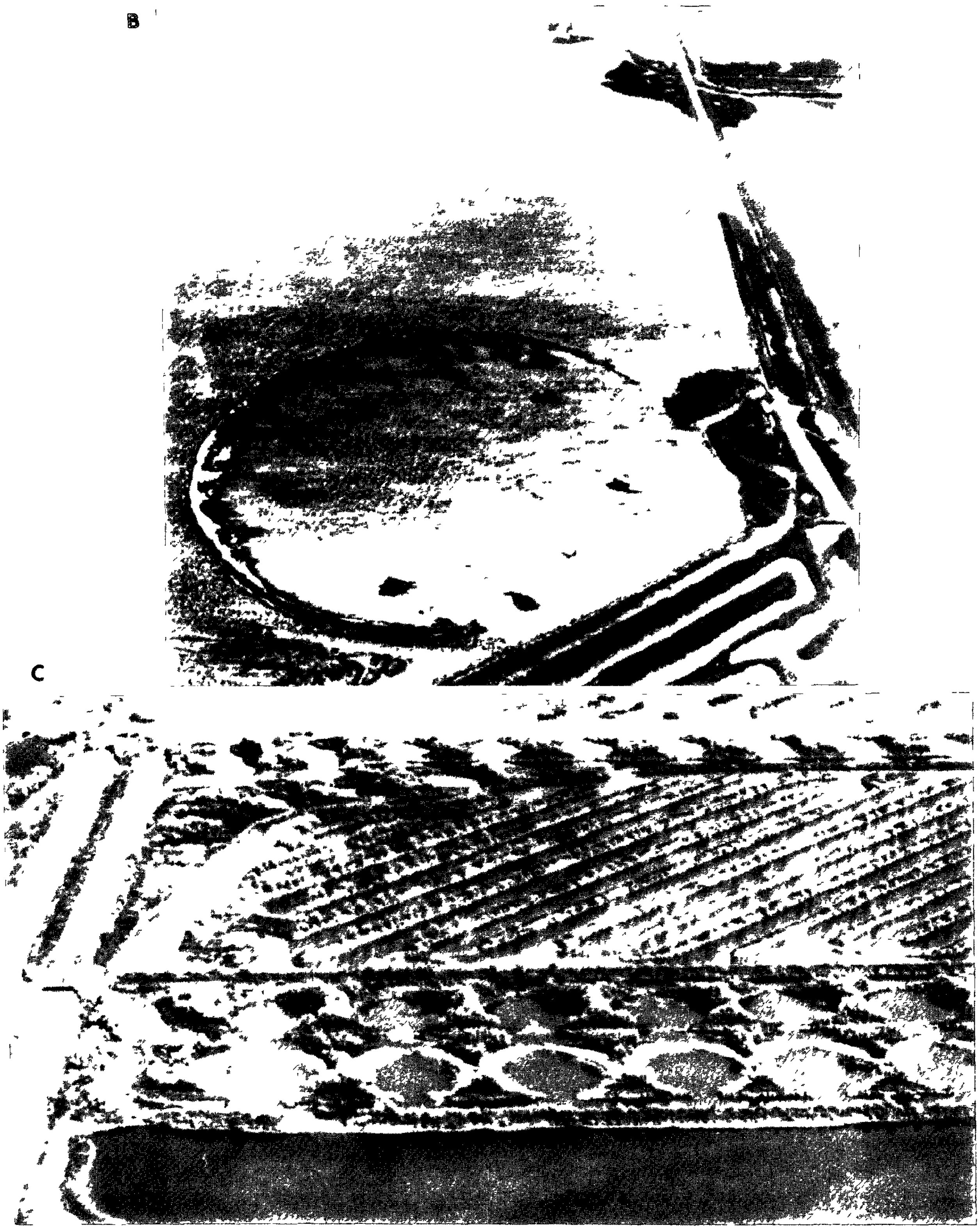


Figure 2 (B and C). Aerial view of a fish farm in the Lagoon of Venice. Conditions in the lagoon are particularly favorable for this type of fish farming. This had led to the construction of numerous dykes which isolate the farms that are now part of the Venetian landscape.

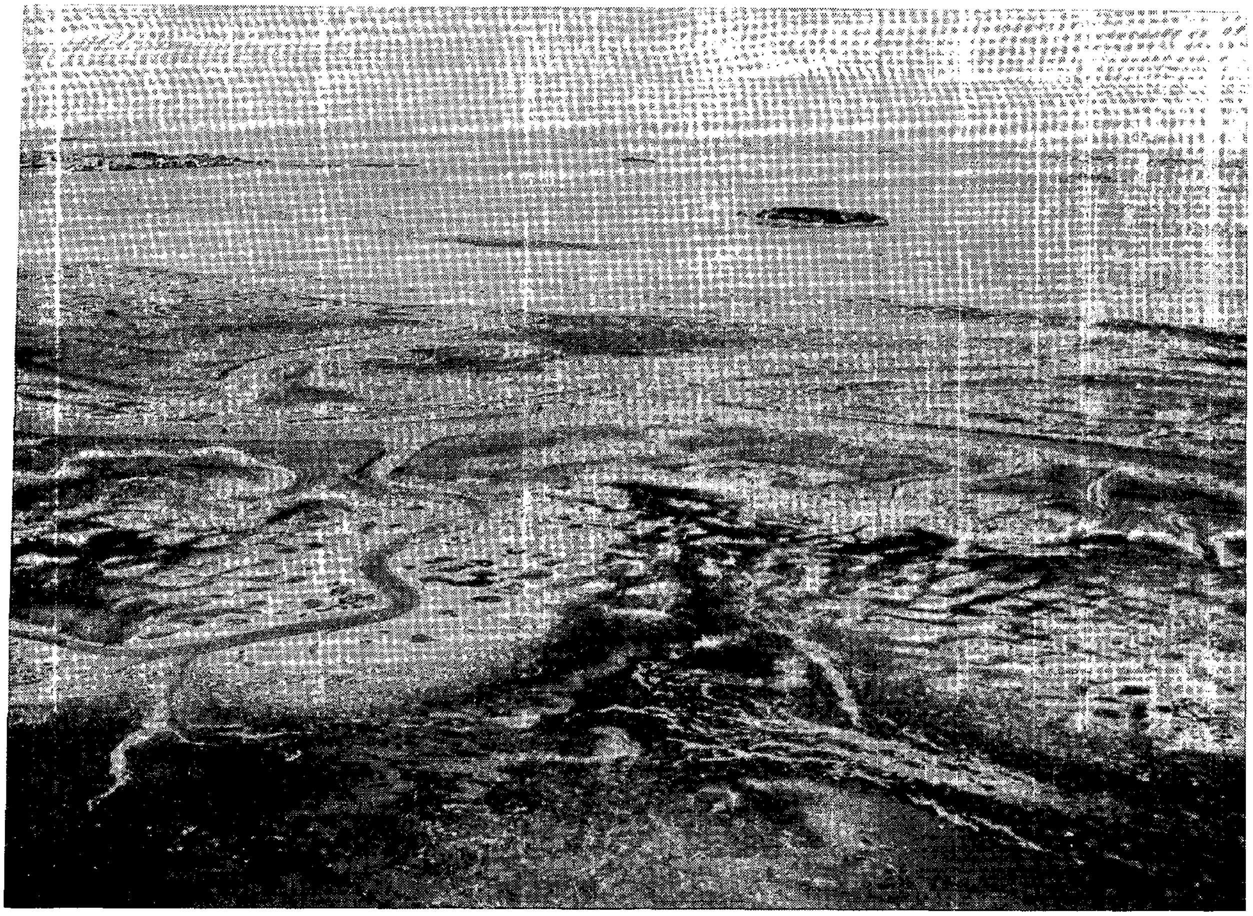


Figure 2 (D). Aerial view of a low-tide inlet of the Lagoon of Venice. The strips of land that emerge at low tide are a distinctive feature of the lagoon. They have a very important hydraulic and ecological role; they can attenuate currents and wave motion, and so help to control two of the causes of the city's decay.

The Venice lagoon is characterized by networks of deep natural channels to the mainland, which branch out of the three openings. Other manmade channels have been operated over the centuries to improve navigation within the lagoon, and two large channels have been created in recent times to house shipping to the industrial Port of Marghera: the Vittorio-Emanuele Channel (1926) from the Lido opening, and the San Leonardo Channel (1968) from the Malamocco opening. Tides propagate primarily along these natural and manmade channels.

To allow ships of increasing tonnage to enter the lagoon (for military and commercial reasons), as well as to avoid the frequent malaria caused by stagnant water, the Venetians carried out, between the 16th and 19th centuries, a complex series of works to redirect the course of rivers such as the Brenta, Piave, and Sile, so that they came out into open sea rather than within the lagoon. In this way, the flow of freshwater into the lagoon was reduced, and the rivers no longer carried sediments into the lagoon, which in the long run would have caused the basin to silt up.

Other internal defense measures were undertaken against the major external threat represented by the sea. In the 18th century, the "Murazzi," massive seawalls performing their function even today, were built to protect the shores from flooding by high tides. Between the 19th and 20th centuries, breakwaters were also built to prevent the silting up of the three openings to the sea. As a result, the tidal flow between the sea and the lagoon was increased along with the speed of the tides in the internal channels, leading to noticeable changes in the physical characteristics of the lagoon. These changes were further emphasized by the two large shipping channels opened during this century. For the Venetian lagoon, therefore, the problem has always been one of maintaining the equilibrium between the natural and human environments.

The presence of human settlements in the lagoon has made the ecological balance even more complicated, and so the search for an equilibrium between the various needs of the environment is becoming increasingly difficult. The movement of the sea is essential to the renewal of the lagoon's waters, removing human, industrial, and agricultural waste, but stronger tides must be controlled to avoid both flooding of inhabited areas and erosion of the "barene," which would silt up the channels.

SEA LEVEL RISE IN VENICE

From the hydraulic point of view, the complex system of the Venice lagoon can be subdivided into (1) the basin of Lido, or the northern lagoon; (2) the basin of Malamocco, or the central lagoon; and (3) the basin of Chioggia, or the southern lagoon. Each of these three basins is connected to the northern Adriatic by inlets, known as port openings. The three port openings have a total cross-sectional area of approximately 18,000 square meters, and for each tidal cycle about 330 million cubic meters are exchanged.

Approximately 430 square kilometers of the lagoon are open to tidal expansion, which flows into the lagoon through the three openings along the 800-kilometer network of channels. These channels wind across shallow waters and "velme" (areas of the lagoon usually covered with water), islands, and "barene," and their depth and width gradually decrease as they reach upland to the extreme borders of the lagoon. Excluding fish farms, 75 percent of the area subject to tidal expansion is between 0 and 2 meters deep, whereas only 5 percent exceeds 5 meters, as is the case of the deepest channels.

In this natural environment, with largely urbanized areas, the phenomenon of exceptionally high tides is taking place with an increasing frequency, thus becoming a real threat to Venice and its lagoon. High tides are often determined by the coincidence of various factors: the normal astronomical tide, the scirocco wind that drives waters of the Adriatic to the north, the sea level fluctuations due to different atmospheric pressures at each end of the Adriatic (seiche), rain on the catchment basin drained by the lagoon, and finally the seasonal variations in the level of the Mediterranean Sea.

Mediterranean

The frequency and severity of tidal floods increased in this century as a result of sea level rise due to the melting of world's glaciers, and as a result of land subsidence due to natural settling and the drawing of water from artesian wells.

Land subsidence, which is also caused by natural factors, played a major role in the origin and evolution of the lagoon, and has become a determining factor affecting the city and lagoon environment after human intervention. Anthropogenic subsidence initially started with the heavy groundwater pumping used mainly for industrial purposes. Intense pumping of groundwater resources, which is the main cause of Venice's sinking, mainly occurred between 1950 and 1970. Since the progressive reduction in artesian water consumption started in 1970, the piezometric levels have moved back to their original values, and by 1978 the natural aquifer pressure had been reestablished.

Aquifer depletion and subsidence ran parallel courses between 1950 and 1969-70. Both reached their peak values in 1969, when subsidence was reported to be 12 centimeters in the industrial zone and 10 centimeters in Venice. With the reduction in consumption and further natural recovery of aquifers after 1970, the land survey of 1973 showed subsidence to be slowing. A small rebound (of the order of 2 centimeters) in the historical center was measured during the 1975 survey.

However, human-induced subsidence was not the only factor causing more tidal floods in the lagoon: natural subsidence and global sea level rise (eustacy) also contribute to the diminishing land surface level of the city with respect to the sea level, thus increasing the impacts of high tides (Carbognin et al., 1984).

Leveling measures from before and after groundwater exploitation -- i.e., between 1908 and 1980 -- suggest that the present natural subsidence is about half a millimeter per year. This annual average rate is appreciably lower than the average rate of about 1.3 millimeters per year estimated with reference to the last millennium.

Eustacy has affected the water level of the lagoon due to its connection to the Adriatic Sea. From the beginning of this century, the sea level has been rising 1.27 millimeters per year.

These three factors (human-induced subsidence, natural subsidence, and global sea level rise) and their effects on the Venetian environment are depicted in Figure 3. The period 1908-80 includes the different stages of land sinking. The aforementioned anthropogenic subsidence lowered the land an average of 10 centimeters, netting out any rebound.

In conclusion, these three factors have lowered the surface level with respect to sea level by about 22 centimeters from the beginning of the century. Today the mean elevation of the land surface of the city is about 110 centimeters above mean sea level, while 80 years ago it was nearly 130 centimeters. This loss of 22 centimeters has caused Venice to flood more frequently.

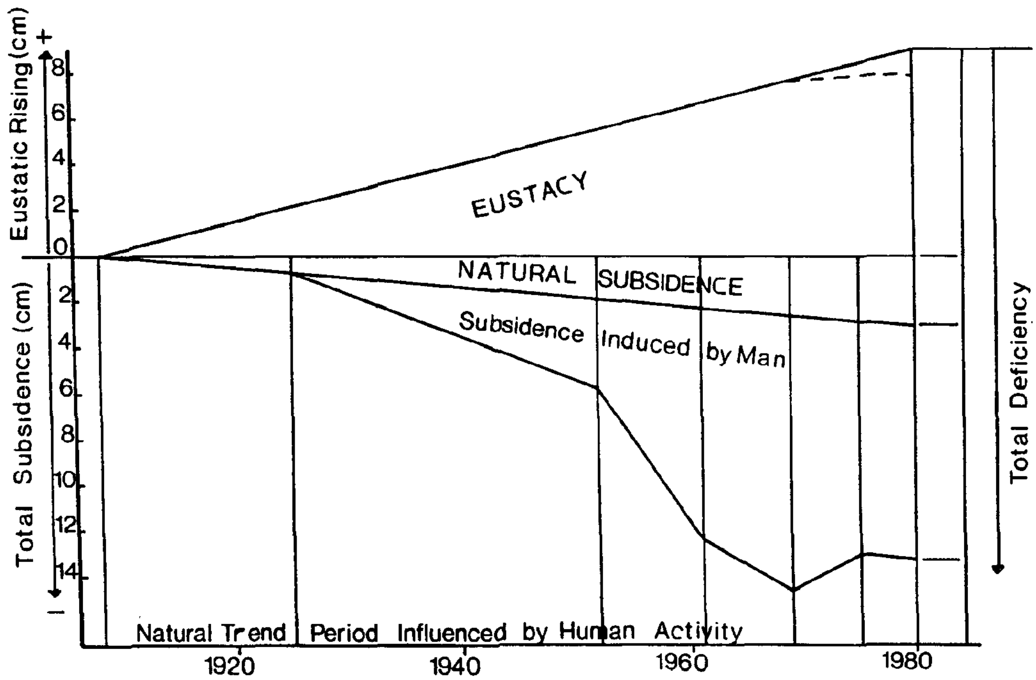


Figure 3. Eustacy and subsidence trend.

Parallel to the rise of relative mean sea level, high tides have increased as well. Figure 4 shows the increase of the annual mean level of high tides (as well as of low tides) from 1920 to 1980. In Figure 5, the number of high tides for height classes (for each 10 years from 1955 to 1985) is presented. The increasing number of exceptionally high tides is clearly indicated. For instance, between 1931 and 1945, eight exceptionally high tides took place, reaching or exceeding 1.10 meters above the average sea level; whereas between 1971 and 1985, with the increased subsidence due to human interventions subsequently interrupted, forty-nine high tides were recorded.

As Figure 6 shows, Venice is extremely vulnerable to sea-induced flooding. When water levels are 70 centimeters above zero (relative to the Punta della Salute hydrometer), St. Mark's cathedral is flooded; at 80 centimeters, water pools appear in St. Mark's square; at 90 centimeters, the square cannot be walked through any more and begins flooding the lowest streets ("calli"); at 140 centimeters, more than 60 percent of the city is flooded. In the period 1920-50, the tidal level exceeded the "critical threshold" level of 80 centimeters 15 times a year. This threshold has been exceeded, on the average, 25 times a year in the period 1950-60, and 50 times a year since 1960. Exceptionally high tides (e.g., greater than 140 centimeters) have become more frequent as well. Looking back to history, during the preceding seven centuries the Republic of Venice was

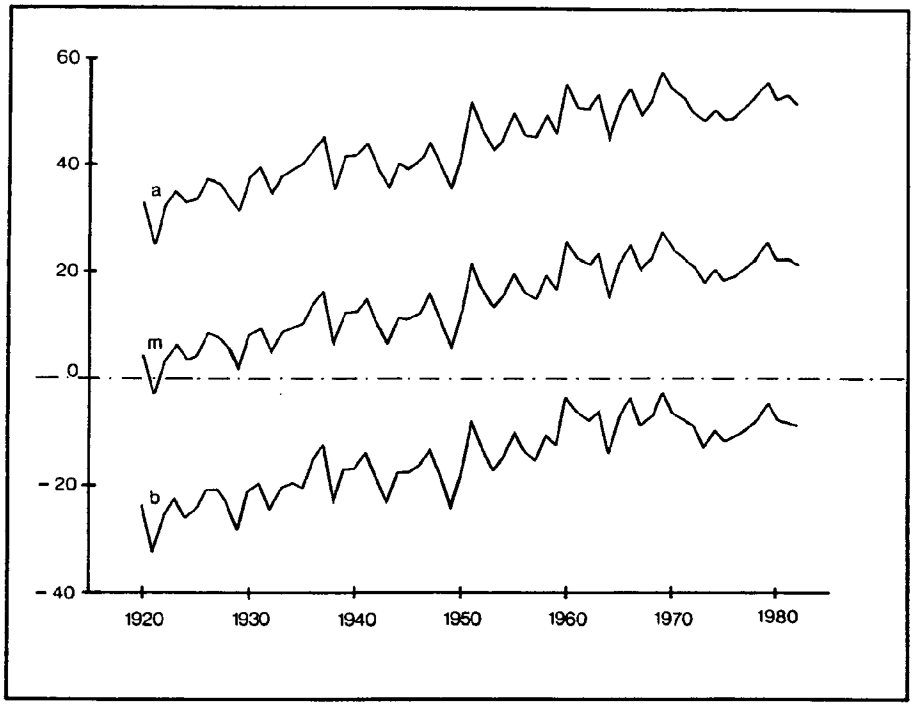


Figure 4. Annual average high (a), mean (m), and low (b) tides.

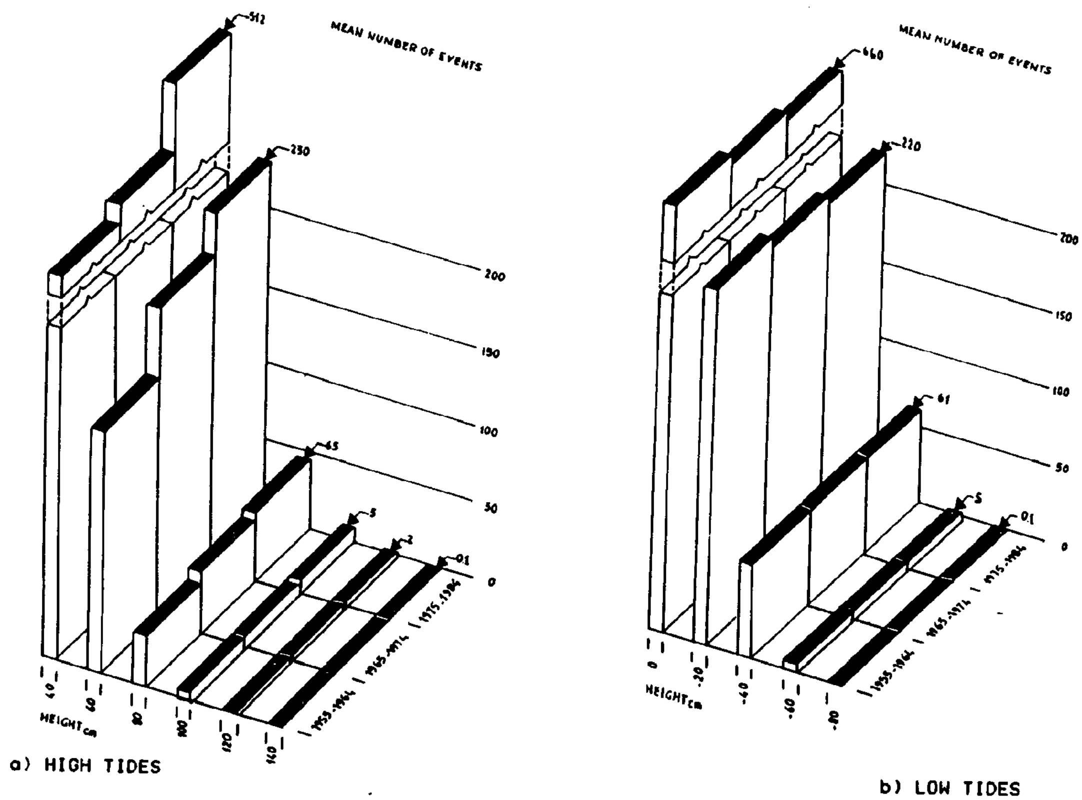


Figure 5. Number of high tides for height classes.

subjected to fewer exceptionally high tides (51) than in the 52 years between 1914 and 1966, when it experienced 53. Figure 7 illustrates the area flooded by tides of 1 to 1.9 meters.

PERCEPTION AND SHORT-TERM EFFECTS

Venice has always been a sea-town, organized and subordinated to the lagoon environment. Its economy was based mostly on shipping. Water was an essential factor of life. It simultaneously meant refuge, safety, nourishment, income, and prospects for development. As an example, until 1300 there were no streets in Venice: its channels were the only transportation system, and the boat was the only transportation facility in town.

Though Venetians became allied with the lagoon water to build their "living environment" on the archipelago, practically in every age calamities have been reported periodically affecting the town. An exceptionally catastrophic event occurred on November 4, 1966, at the time of a big flooding of the Padana Plain by the Po River and of the city of Florence by the Arno River: a tide 194 centimeters above average sea level was recorded. More than 4,000 ground-floor apartments were inundated, and more than 13,000 people lost their homes. The tide devastated shops and storerooms, caused an electric blackout, and cut off gas supplies and telephone connections.

Although the problem of rising sea level was already studied and discussed by a few specialists in the fifties and early sixties (e.g., Miozzi, 1960), at that time the problem was basically ignored by public opinion and the political groups. The main issues at the beginning of the sixties were the industrial and urban development of the city and the surrounding area.

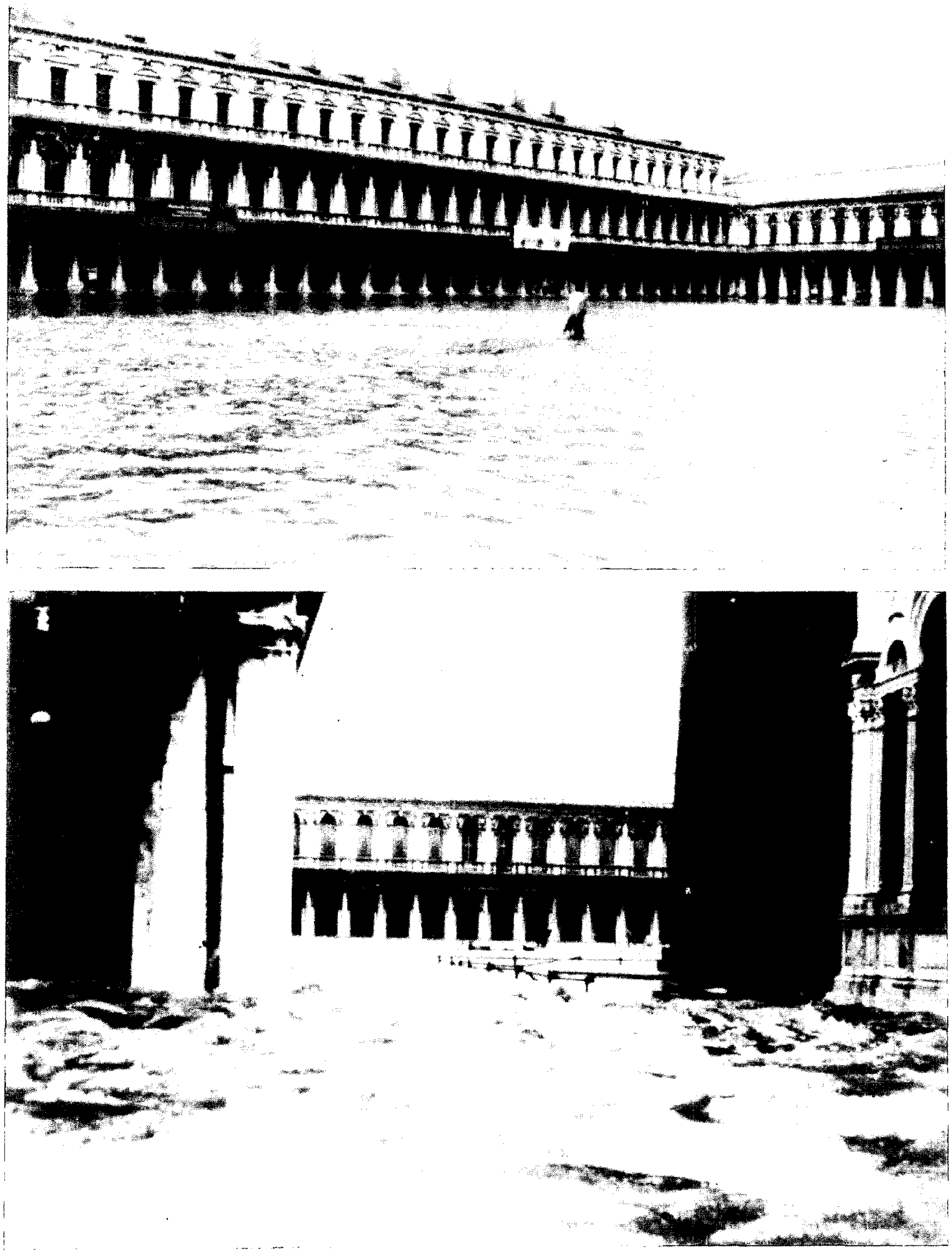
The situation suddenly changed after the catastrophic 1966 event. The high tides ("acque alte") immediately became the central problem of the public debate. The impact was enormous, not only in Italy but worldwide, and committees to "Save Venice" grew up all over the world. The event, defined by an author as being "cruelly beneficial" (Miozzi, 1968), also gave a substantial impetus to the work of the interministerial committee "Per lo Studio dei Provedimenti a Difensa della Citta di Venezia," set up in 1963 and practically inactive until then.

The high tides continued in the years after 1966 (basically at the same level as during the years immediately prior), and the press gave them extensive attention. In 1970, a public body was set up to predict high tides.

Meanwhile, the program for protection proceeded slowly. The slowness of the interministerial committee that was supposed to coordinate the operations exasperated the citizens. The Venetians protested and organized symbolic demonstrations of disapproval of the city's administrators.

In 1971, seven proposals for a special law for Venice were presented within eight months. Finally, after endless discussions and a large number of amendments, on April 16, 1973, the Special Law (Law 171/73) was approved. It

A



B

Figure 6. Flooding in Venice: (A) San Marco Square under flood water in 1987, (B) and during the exceptional flood tide of 1966.

C

D

Figure 6. Flooding in Venice (continued): (C) Venice during the exeptional flood tide of 1966, (D) damage to buildings produced by the combined action of high tides and wave motion.

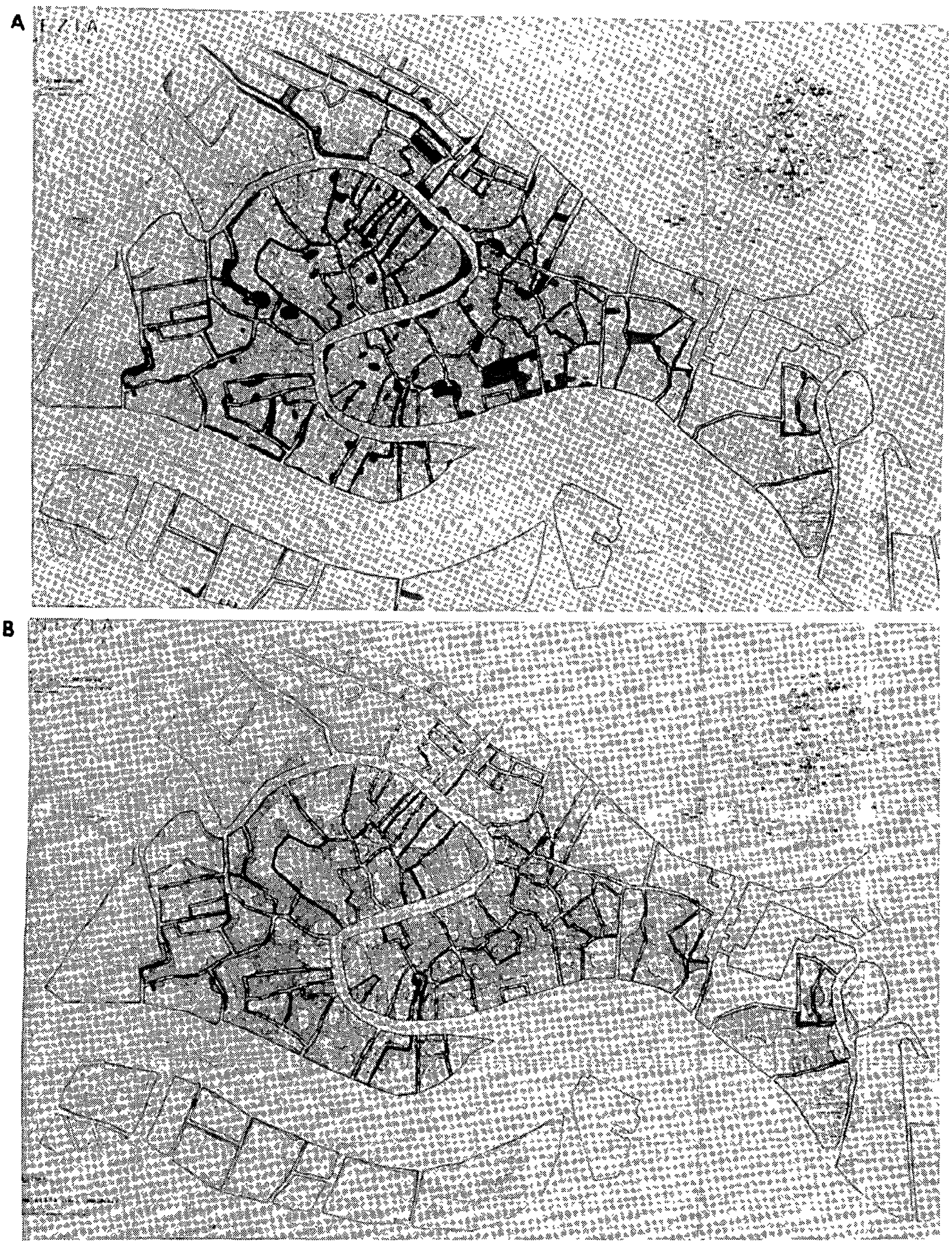


Figure 7. The shaded areas show the portion of Venice flooded by tides of (A) 1 m, (B) 1.1 m, (C) 1.2 m, and (D) 1.9 m. Assuming no change in storm frequency, these areas will be underwater 50 times a year for rises in sea level of 20, 30, 40, and 110 cm, respectively.

C

D

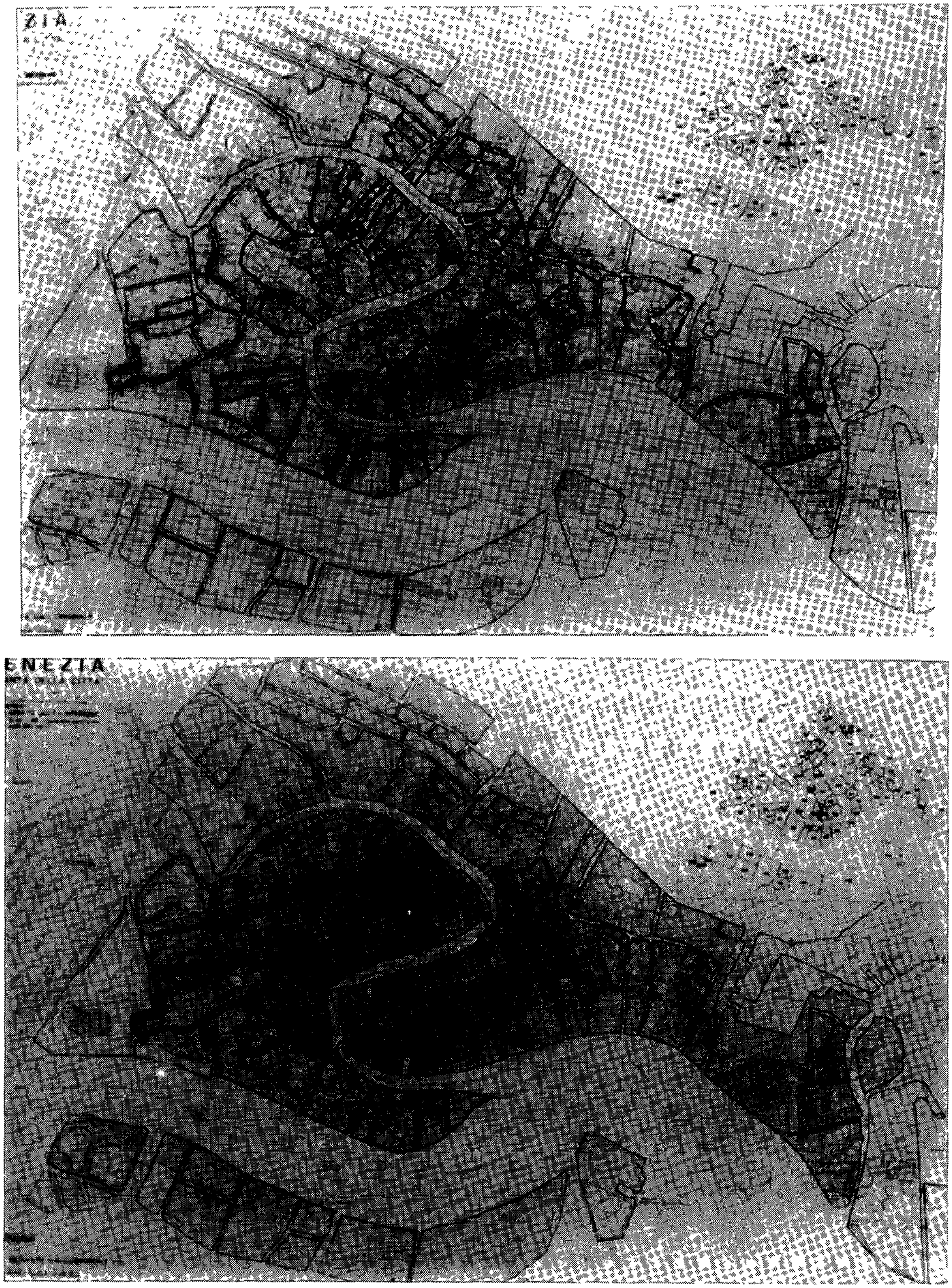


Figure 7 (C and D).

established that the national government should take care of the physical safeguarding of the lagoon and urban areas; the regional government would be in charge of planning activities; and the city government would manage the restoration of the historical center. The planned response measures have four objectives: the physical safeguard of the lagoon, decontamination, the restoration of monumental and smaller buildings, and the economic development of the Venetian area. The law also provided financial support of 300 billion lire (about 3 billion U.S. dollars). At that time, many people believed that most of the problems were over. However, the long path toward the protection of Venice from high tides was just beginning.

LONG-TERM REACTIONS

Since the Venice program started in 1973, the people became more and more accustomed to the periodic flooding of the city, intensifying public commitment to a solution.

To carry out the 1973 Special Law, an international bid was issued (Law 404/75) to solicit proposals for implementing the Special Law. Five groups of well-recognized companies submitted their proposals, but none was considered adequate (March 1978). Then the Ministry of Public Works was authorized to buy the projects submitted (Law 56/80). The Ministry commissioned a group of internationally recognized experts to draw up a plan of action to protect the city from high tides. The plan was based mainly on the idea of temporarily closing off the lagoon at the three openings, using barriers that were in part fixed, in part mobile. These would normally be left open and closed only when necessary.

The project drawn up by the experts was approved in 1982 by the Supreme Council of Public Works, which established that the work should aim, above all, to achieve these primary objectives:

- the reduction of flood tides in the lagoon;
- the guarantee that a sufficient renewal of the lagoon water would be maintained to prevent a worsening of the water pollution;
- the maintenance of the three openings at Lido, Malamocco, and Chioggia as viable port entrances, limiting closures to a minimum.

To carry out intensive studies of the area, test possible solutions, and then plan and carry out a complex series of measures that should meet the needs of both the environment and the tourist, commercial, and industrial activities that are now part of it, the Italian Government has entrusted the Venezia Nuova Consortium.

The project drawn up by the experts in 1981 suggested, as a solution to the problem, the installation of mobile gates set in fixed barriers. The barriers made it possible to reduce the effects of excessively high tides, but they also permanently reduced the exchange-flow between the sea and lagoon.

The "Venice Project" has as its primary objective the conservation and development of the city of Venice, and of its lagoon, which is a unique ecosystem. This obviously requires controlling the high tides. The difficulty arises from the impossibility of closing off the lagoon from the sea for long periods of time. The tides have a fundamental role in maintaining the life of the lagoon environment. Even a simple reduction in the exchange-flow could have consequences that should not be underestimated (see Park, Volume 1).

The series of operations to safeguard Venice was given its clearest definition in Law 798 of November 29, 1984.

In 1982, the Magistrato alle Acque charged the Consortium with the task of carrying out studies and producing mathematical models of the lagoon. These studies were to focus on reestablishing the hydrogeological equilibrium of the lagoon; arresting and reversing the process of decay within the lagoon by eliminating its causes; reducing the level of the tides in the lagoon; defending, with specific local measures, the islets that make up the city center; and safeguarding the urban areas of the lagoon from flooding by means of mobile gates at the three openings to regulate the tides. The work of the Consortium actually started in 1986.

To finance this first stage of operations, the law set aside 234.5 billion lire (almost 2 billion U.S. dollars). The funding for the following studies was to be guaranteed by the budgets from the fiscal year 1987 onward. An updated estimate of the cost of the work is 3,300 billion lire.

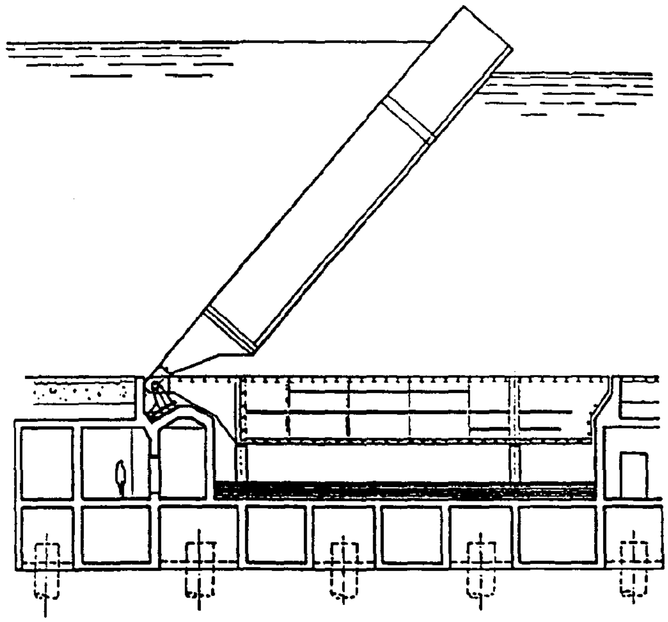
THE PROJECT AND THE PROBLEMS

To protect Venice and its lagoon from sea level rise, the only possible solution is the control of tidal flow at the port openings. In compliance with Law 798, the solution that has been found most suited to the conditions and needs of the lagoon environment consists of a system of mobile structures for the regulation of tidal flow.

The project envisions the use of specially designed gates, respecting the typical conditions of the lagoon system from the viewpoints of both the environment and socioeconomic development. For each port opening, a set of rectangular flap gates will be installed; these will be hinged to a foundation structure made of cellular-reinforced concrete caissons.

Each gate -- i.e., each module -- is 20 meters wide (Figure 8). In their "off" position, the gates are flooded and lie horizontally in a recess in the foundation structure. If necessary, by expelling part of the water they contain, the gates are lifted to their operating position (at an angle of 45 degrees with the horizontal) to stop the tidal flow. The gates have no intermediate piers to hold them in their operating position and, therefore, oscillate freely under

A



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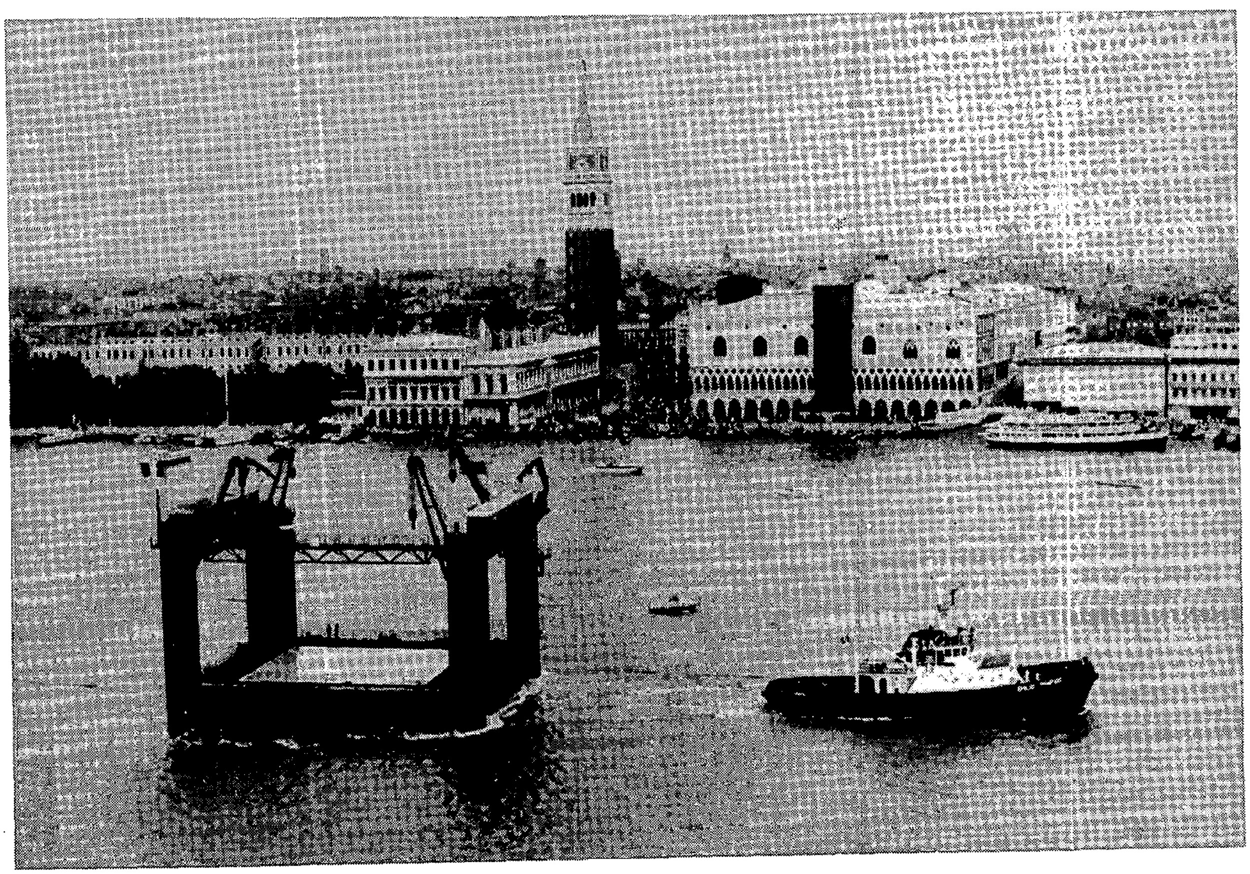

Figure 8. (A) Schematic illustration of the mobile gates and (B) gate being towed past San Marco.

the action of the waves, which are transmitted, practically unaltered, to the lagoon. The compliance of the gates with the waves drastically reduces the forces transmitted to the foundation structures, thus simplifying their construction and reducing costs as compared with more traditional solutions.

In normal conditions, when the gates are open, the port openings are free from any structure. Therefore, there are no obstacles to either water flow or navigation. There will be no aerial superstructures, either temporary or permanent, since these would alter the landscape and could hinder the transit of ships.

Although strongly requested after the 1966 event, the project for the temporary closing of the lagoon has encountered increasing public opposition. A strong environmental concern grew, fed by the tremendous environmental degradation of the lagoon. Fear was expressed that the closing of the lagoon could reduce the water exchange and further worsen the environmental problems. In view of the rise of the "green movement," increasing attention was devoted to those concerns, and a number of additional detailed studies were performed by the Venezia Nuova Consortium to investigate these problems. However, a final approval of the project is still pending.

In the same period, the interministerial committee, set up by the Law 798/84, recognized the pollution of the lagoon as a major problem and started a restoration plan. The guidelines for the restoration plan were approved by the Committee in October 1989.

Updated estimates indicate that the total financing needed for safeguarding and restoring Venice and the lagoon will most likely reach some billions of dollars.

CONCLUSIONS

During this century, Venice has experienced a significant increase in both the frequency and the magnitude of periodic floodings. This is due to a number of different simultaneously occurring causes (particularly mean sea level rise in the Adriatic Sea and land subsidence due to uncontrolled exploitation of the water table). The experience of Venice has many similarities with the expected effects of the sea level rise on other seafront cities, at least in a first stage.

However, although the Venice situation represents a very interesting case study, some of its peculiarities must be carefully considered:

- its physical characteristics -- i.e., the presence of the lagoon between the sea and the inland environments;
- its sociocultural implications, since the sea-town of Venice always tried to manage the lagoon environment not only by integrating itself with the element "water" but also by developing its organization "on the sea"; and

- its political and economical peculiarities, being a "unique" town worldwide and having available large financial resources.

Some interesting conclusions can be drawn from the Venice case study:

- sea level rise (although of limited extent) represents a critical problem for the town;
- the problems were recognized for a long time by the scientific community and were outlined to the public administration, but interventions were started only following a catastrophic event;

- the definition and implementation of remedial measures required a very long period of planning and study, and after 20 years real work still has to start;

- some years after the catastrophic event, Venetians started to accept the floodings as an unavoidable phenomenon in its particular habitat;

- as time passed, other issues started to be considered essential for the remedial measures (environmental conservation, city development, etc.), slowing down the initial rate in the development and implementation of the remedial measures; and

- remedial measures need very large financial resources, that in general can be collected only from the national government.

From a more general point of view, the Venice case can provide some guidelines on the following:

- the need to focus in advance public attention on both the primary and secondary effects of the sea level rise phenomenon;

- the need to consider the environmental, urban planning, and socioeconomic impacts of the safeguard projects from their inception; and

- the need to clearly evaluate the project's financial requirements and to assign priorities.

In particular, we believe that it is not generally possible to rigidly maintain the "ante quo" situation. Rather, when a sea level rise effect is forecast, it is necessary to develop a new environmental strategy, (1) with adequate human, urban planning, and aesthetic characteristics; (2) with limited social and cultural impacts; and (3) that is achievable with available financial resources.

BIBLIOGRAPHY

Carbognin, L., P. Gatto and F. Marabini. 1984. The City of the Lagoon of Venice - A Guidebook on the Environment and Land Subsidence. Venice.

Gormitz, V., S. Labedeff and J. Hansen. 1982. Global sea level trend in the past century. Science 215:1611-1614.

Miozzi, E. 1960. La Conservazione e la Difesa dell'Edilizia di Venezia, il Minacciato suo Sprofondamento ed i Mezzi per Salvarla. Proceedings of the Conference for "La Conservazione e Difesa della Laguna e della Città di Venezia".

Miozzi, E. 1968. Venezia nei Secoli, Vol. III: La Laguna. Venice: Libeccio Publishers.

Puppi, G., and A. Speranza. 1988. The physical problem of global climate on Earth. Alma Mater Studiorum 1:1-14.

Titus, J.G., ed. 1988. Greenhouse Effect, Sea Level Rise and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G. 1986. Greenhouse effect, sea level rise, and coastal zone management. Coastal Zone Management Journal 14:3.

IMPLICATIONS OF SEA LEVEL RISE FOR GREECE

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INTRODUCTION

Many parts of coastal Greece will be seriously affected by a rising sea level. If drastic measures are not taken soon by state and local governments, it will be much more difficult and more costly to face this problem later.

Consider the delta of the Sperkhios River. If sea level rises 2 meters in the next century, this deltaic plain could lose about 40 square kilometers of land. A rising sea level would also cause serious problems to coastal urban areas, industries, settlements, harbor facilities, tourist complexes, coastal communication networks, airports, and other infrastructure. The areas that will probably be most threatened are the big harbors of the country: Pireas, Thessaloniki, Patra, Volos, Iraklio, Alexandroupoli, etc. Many airports like Kerkyra, Alexandroupoli, and Thessaloniki are almost at sea level and will certainly be threatened. Coastal highways in northern Peloponnessos, Thessaloniki plain, Sperkhios delta, Porto Lagos, etc., will have problems too (Figure 1).

The incursion of the sea will create another very serious problem to the coastal environment, that of erosion. This process will most certainly affect densely populated coastal zones on low to intermediate slopes. In recent decades, more than one million cottages have been constructed on or near the coastal zone. Many of these already face erosion problems, since they were constructed without prior knowledge of the conditions that prevailed in the environment. Thus, a sea level rise of just a few decimeters would be destructive to all these structures. Unfortunately, nothing has yet been done to put some limitations on coastal construction.

Correspondingly, similar problems are expected to occur in coastal cultivated areas like the deltaic plain of the Sperkhios, the plain of Thessaloniki, the Argolis plain, Akheloos plain, and the Louros-Arakhthos plain. It is believed that parts of the extensive drainage and irrigation networks of these areas will be rendered useless. The groundwater table will also be affected by rising seas. The underground saltwater wedge in the water table will certainly shift inland, affecting cultivated land.

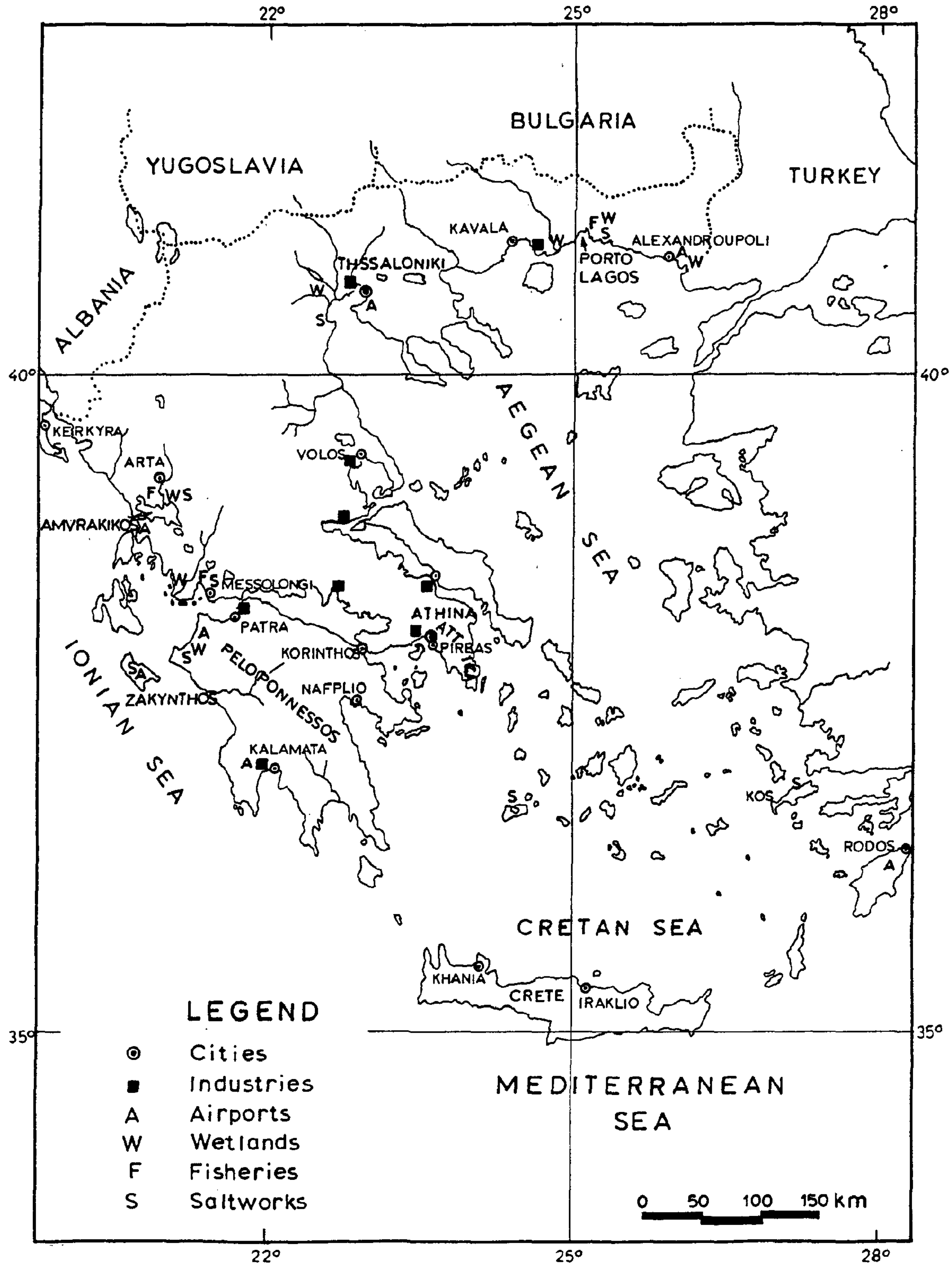


Figure 1. Map of Greece.

Finally, coastal wetlands will be covered by the rising sea level and an important natural resource of the environment of Greece will cease to exist. The lagoons of Messologi, Amvrakikos, and Porto Lagos, which are important fishing grounds, will become shallow bays or gulfs. The extensive saltworks of Messologi and other areas of Greece will have to move farther inland.

Despite these problems, the prospect of sea level rise does not seem to concern officials from government or private organizations in Greece. In recent meetings with high ranking officials of the Ministry of Environment, Physical Planning and Public Works (the main agency responsible for the management and protection of the Greek Coasts), they agreed that they would eventually need to take measures to confront the problem, but they felt that there is no urgency today. They generally encouraged me to assess in more detail the likely consequences of global warming and sea level rise, and to come back and suggest to them options that could be rationally implemented today, given the uncertainties.

This initial response made me realize that the most fundamental barrier to responding to sea level rise in Greece will probably be similar to the barrier that has confronted the world in general since Svante Arhenius warned us of the greenhouse effect in 1896: the information gap between researchers and policy makers. This gap is more than a failure to communicate often enough: between our respective fields of scientific and policy expertise lies a conceptual "no man's land" into which both scientists and policy makers are reluctant to tread.

As I left the meeting, my initial reaction was that the policymakers seem to unrealistically expect me to have all the answers on a "silver platter." But on the other hand, perhaps I was unrealistic to expect that if I presented them with scientific information on an environmental risk, they would be able to give me the response options on a silver platter. Scientists feel comfortable describing observable facts, but are hesitant to speculate about future impacts of new phenomena, and are even less qualified to recommend policy actions. Yet by the same token, policy makers that feel comfortable making decisions when all the options have been laid out feel less qualified--and often lack the time--to develop planning and structural responses that have not been thoroughly assessed. To properly respond to sea level rise, scientists and policymakers must work together to answer questions that are interdisciplinary in the broadest sense of the word.

But the necessary collaborative effort has not yet gotten under way in Greece, so it is not possible to provide a detailed examination of the impacts and responses to sea level rise. The remainder of this paper describes the environment and the resources at risk.

THE NATURAL ENVIRONMENT

Climate and Tides

The coastal climate of Greece can be characterized as Mediterranean with warm to hot dry summers and moist cool winters. Storms are not a common phenomenon in Greece. Storm winds usually blow from the northern or southern quadrants. Those from the east or west are rare and of short duration, no more than one or two days.

The tidal range around Greece, as in all of the Mediterranean Basin, is small. The greatest tidal range is observed at the Strait of Evripos where the northern and southern Evvoikos Gulfs join. The maximum tidal range is 1.20 m in the northern port of Khalkis and the mean is 0.42 m.

Although the Greek region has numerous earthquakes, tsunamis are rare. Nevertheless, it is very likely that the great explosion of the volcano of Thera (Santorini) around 3,400 years ago was followed by a catastrophic tsunami that reached all the shores of eastern Mediterranean Sea. According to Galanopoulos (1960), from 1801 to 1958 there occurred 170 earthquakes with a range fron I to VIII on the Mercalli-Sieberg scale, but only 6 tsunamis were destructive.

The low tidal range and absence of frequent storms implies that it has been safe to build one to two meters above sea level. As Titus (this volume, Problem Identification) points out, this situation potentially makes low areas more vulnerable to inundation than areas with frequent storms or large tidal ranges.

Types of Coasts

Fortunately, Greece does not have a particularly flat coast, except for deltas. About 31% of the coasts are rocky with slopes greater than 50%, generally along the northern portion of the western coasts of Greece, the northeastern coasts of the Gulf of Corinth, the western coasts of the Aegean, and some parts of Khalkidiki (Figure 2). Another 25% of the coasts have slopes between 10% and 50%; these shores are often easily erodible, e.g., the southern Korinthiakos Gulf.

Despite the predominance of steep coasts, about 45% of the coast has slopes less than 10%. These include the deltaic plains of Arakhthos-Louros, Akheloos, Pinios (Peloponnessos), Sperkhios, Pinios (Thessalia), Aliakmon-Axios, Evros, and the fan delta of Nestos; the barrier beaches of northwestern Peloponnessos, Akheloos-Messologi, Amvrakikos, and Nestos; the lagoons of Messologi, Amvrakikos, and Vistonida; and all the pocket beaches, accretion beaches, and coastal plains. Figure 3 shows a number of low-lying areas in Greece.

The sediment size of most of the depositional features is in the sand range, but in many parts the presence of pebbles and stones is not uncommon. Although the presence of sand dunes is not rare in many parts of Greece, they are located along the coast without extending inland because of the short duration of the high intensity winds.

A final feature typical of warm seas is the presence of beachrocks. They all seem to be eroding today and are found mostly in the central and southern part of the country, usually in sandy beaches. Most of them date from the Late Holocene age and are located a couple of meters above or below present sea level.

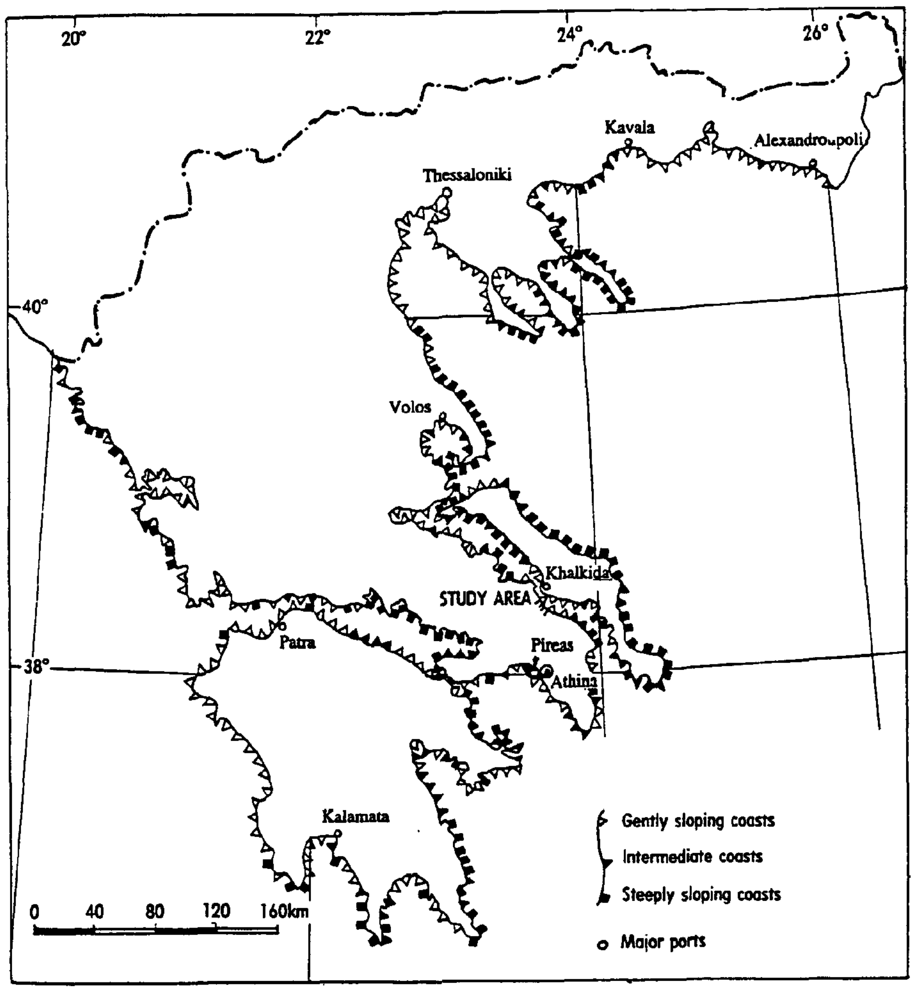


Figure 2. Distribution of slopes along the coasts of mainland Greece.

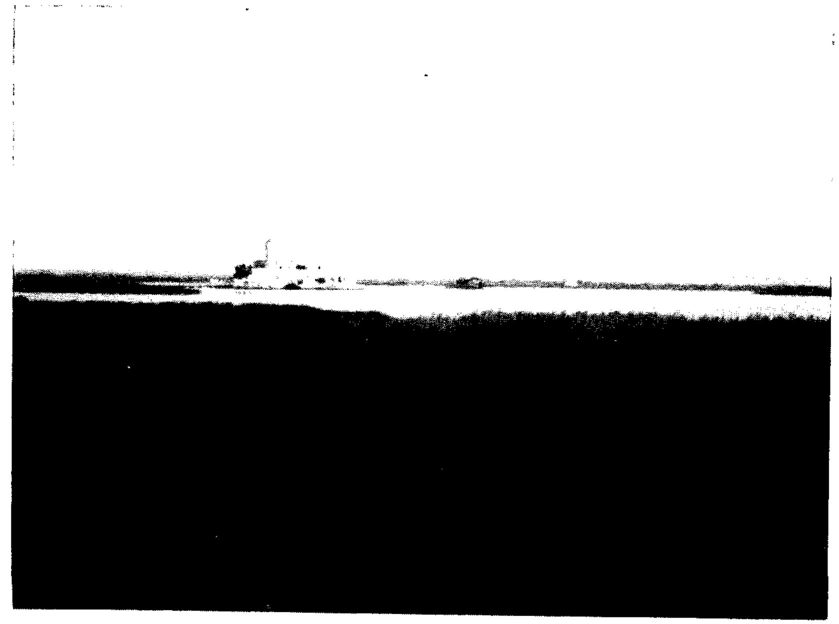
There are five major deltaic plains (Evros, Axios-Aliakmon, Sperkhios, Akheloos, and Louros-Arakhthos) and four regions with barrier beaches, barrier islands, and spits (Amvrakikos, Akheloos-Messologi, northwestern Peloponnessos, and Nestos). There are also numerous pocket beaches, accretion beaches, and fan deltas (the largest at Nestos).

Wetlands

The Ramsar Agreement, concluded in Iran in 1971, called for each country to delineate the wetlands that were environmentally significant. For Greece these are the following:

A

C



B

Figure 3 (A-C). Low-lying areas of Greece.

(A) Southwest Attica. Eroding coastline with newly built hotel in the backgound.
(B) West Peloponnessos. There is a road sign in the middle of the picture but the road is gone.
(C) Vulnerable church along the Porto Lagos Lagoon in northeastern Greece.

D

F

E

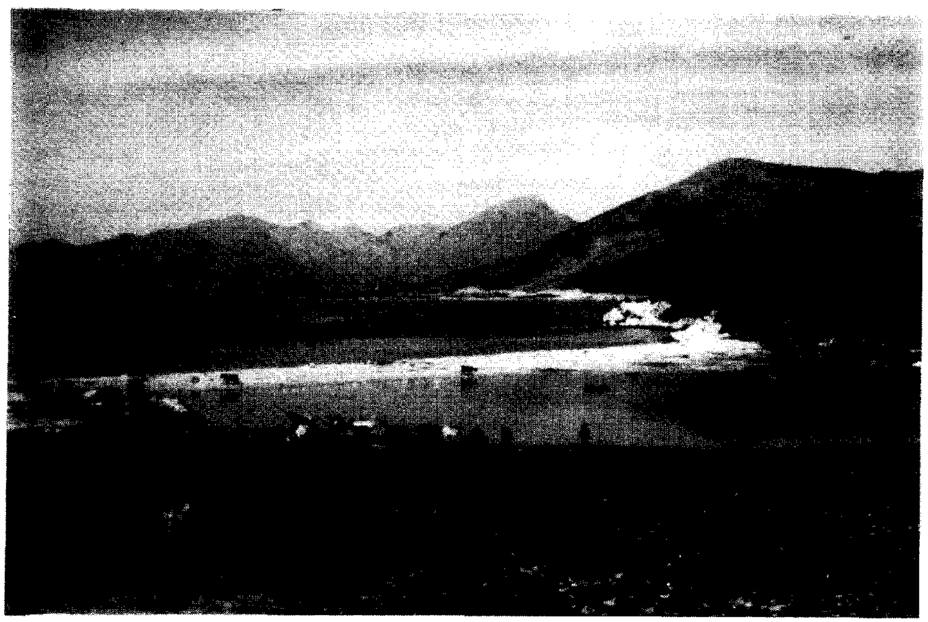


Figure 3 (D-F). Low-lying areas of Greece.

(D) Saltworks in Zakynthos island, western Greece.
(E) Astakos, west-central Greece. Barrier beach.
(F) Amvrakikos Gulf, western Greece. Barrier beach with lagoon on the right.

Mediterranean

The Evros Delta Wetland

The River Evros is one of the largest rivers of the Balkan peninsula and is characterized by high discharge and sediment transport rates, particularly during the winter and spring months. There are four lagoons and at least three barrier islands of limited size. Until 1950, human interference in the natural environment was minimal. Since then, various artificial drainage systems control to a large degree the flow of the river.

The Vistonida-Porto Lagos Wetland

Lake Vistonida is located in central Thrace and is the extension of the bay of Porto Lagos. It has an area of 4500 hectares (11,120 acres) and forms a shallow lagoon with an average depth of 2.0-2.5 meters and a maximum of 3.5 meters. The average height of Vistonida is 0.10 meter. The deterioration of the surrounding lowlands has led to their increased erosion and sedimentation deposition in the lake, which has resulted in a rise of the lake bottom by 0.40 meter from 1976 to 1982.

The Nestos Delta Wetland

The Nestos River is the natural boundary between Macedonia and Thrace. Its source is in Bulgaria and its length in Greece is 130 km. The main wetland area comprises the main channel, the bank zones, and the coastal zone of lagoons (Nea Karvali-Nestos mouth - Cape Baloustra). The general area of the coastal zone (a length of about 45 km and width of 1.5-3 km together with the Nestos Delta) is characterized by a great variety of biotopes with various plant colonies and zones of vegetation. The present cultivation of the land has worsened the conditions in the Nestos wetland.

The Aliakmon-Loudias-Axios Delta Wetland

This region covers the lower deltaic plain of three rivers (Aliakmon, Loudias, and Axios) and has an area of about 200 square kilometers. The largest part has been apportioned to the local peasants. The coastal parts of the deltaic plain are drained today for cultivation purposes. This process, together with water and soil pollution, has turned this wetland into a very unstable and endangered environment.

The Messologi Lagoon Wetland

This wetland is found in the middle of western Greece next to the Akheloos Delta. It is composed of three lagoons (Aetoliko, Messologi, and Klisova) and has a total area of 25,800 hectares (63,752 acres). The natural biotope has deteriorated in the last twenty years owing to the draining of some areas and the conversion of others to salt-works.

The Armvrrakikos Wetland

Found in northwestern Greece, the wetland forms a closed sea with a total shoreline length of 256 km and a maximum depth of 60 m. The Louros and Arakhthos

Rivers flow into the gulf where the Logarou, Tsoukalio, Rodia, and Mazoma Lagoons are located as well as the Bay of Koprani. The wetland is burdened by human and industrial effluents as well as agricultural and cattle by-products.

The Lake Koukhi Wetland

This wetland is located in northwestern Peloponnessos facing the Ionian Sea. It connects to the sea through a very narrow inlet having a width of only 8 m. The deepest part of the lake is 40 cm and the mean is 30 cm. Its area varies seasonally from 710 hectares (1,754 acres) to 850 hectares (2,100 acres). It is one of the largest lagoons in Peloponnessos. It is rapidly deteriorating, mainly as a result of human activities (agriculture, hunting, and pollution).

Because of the low tidal ranges in Greece, these wetlands are barely above sea level and hence would be mostly lost with a one-meter rise in sea level.

SOCIOECONOMIC FEATURES

Demography

A large part of the Greek population has lived near the coast since ancient times. Many ancient city-states flourished along the Greek coast and in many cases their very existence depended on their coastal colonies in the Mediterranean Basin. The population of ancient Athens, for example, could have been a few hundred thousand people. In Roman and Byzantine times and the ensuing period of Turkish occupation between the fifteenth and nineteenth centuries, life deteriorated and inhabitation in coastal areas decreased considerably. In the early nineteenth century, Athens was just a village of 5-6,000 people. Today, greater Athens has about 3.5 million inhabitants.

Table 1 gives a general picture of the proportion of inhabitants on or near the coast of mainland Greece. This number is 52% of the total population of 7,083,000 living in the above-mentioned departments. If we consider the seasonal migration of the Greek population toward the coasts in summer, then this percentage could easily reach the 65% mark. Furthermore, if we include the millions of tourists who visit Greece during the summer months, then it is safe to say that for a considerable time of the year, about three quarters of the population live along the coasts.

Harbors, Ports, and Other Coastal Structures

Various types of artificial structures are found along the coasts of Greece. They may be classified into three main groups:

1. harbor and other ship-related structures,
2. coastal defense structures, and
3. water intake/outfall structures.

Table 1. Number of Inhabitants Who Lived On or Near the Coast of Mainland Greece (by department in 1981)

Department	Population (x 1,000)
Aetoloakarnania	99
Argolis	49
Arkadia	9
Arta	28
Attiki	1,947
Akhaia	190
Evros	48
Evvia	116
Ilia	71
Imathia	3
Thesprotia	1
Thessaloniki	597
Kavala	83
Korinthia	60
Lakonia	21
Larissa	11
Magnissia	135
Messinia	72
Xanthi	5
Pieria	29
Preveza	25
Rodopi	3
Fthiotida	63
Fokis	9
Khalkidiki	23
TOTAL (includes rounding)	3,697

Greece has a total of 444 commercial harbors of various sizes and importance, of which 284 have sea defense structures (these numbers do not include small harbors for local ferries). The first group of structures is by far the most important. It includes, among other types, such structures as moles, breakwaters, bulkheads, jetties, and trestles. Moles and breakwaters have either vertical or sloping faces. The most commonly used materials are quarry stones and concrete. In many cases, especially in the smaller harbors, jetties serve several purposes including those served by moles and quays. The most common type of quay walls are gravity walls of concrete blocks. Jetties are usually formed with a surrounding bulkhead and backfilling.

Coastal defense measures usually consist of revetments, groins, and, more recently, artificial nourishment. Coastal revetments and groins are built almost exclusively with quarry and concrete blocks.

In Table 2, the most important harbor installations are shown together with passenger and cargo movement.

Pireas shows the greatest domestic movement of passengers and cargo, most of it being car-ferries (ferry boats). Pireas together with Rafina serve to a great extent the Aegean islands. The high cargo movement of Thessaloniki is due to the transport of goods to neighboring countries (Yugoslavia and Bulgaria). The increased cargo movementin Volos is due to the transport of goods from Europe to the Middle East (Syria). The high number of passengers arriving in Patra and Igoumenitsa is due to the increased arrivals of tourists from Italy with car-ferries during the summer months.

Land Use

A large proportion of the Greek coast with steep slopes and cliffs has not been developed. The remainder is composed of deltaic plains, narrow coastal plains, and pocket beaches. In many cases, these coastal zones were developed in a very disorderly fashion before the state could intervene. As a result of this anarchic development, construction in the coastal zone has, in many instances, upset the equilibrium that exists in the coastal environment.

In several coastal lowland areas, particularly in the Messologi region, there are extensive salt works. In other parts of Greece, like the plains of Thessaloniki, Sperkhios, Amvrakikos, Evros, and southern Peloponnessos, there are large areas with rice fields. In the Argolida-Messinia-Lakonia area, northern Peloponnessos, Volos, and Crete, there is extensive cultivation of fruit-bearing trees and horticulture. Olive trees are found everywhere in Greece, but the main producing areas are in Amfissa-Itea, western and southern Peloponnessos (Kalamata), and Crete.

The often thoughtless exploitation of water resources in coastal areas with water pumps and wells has led to a serious drop of underground water tables and simultaneous advance of saltwater. This has led to the degradation of underground waters which, in turn, has affected the quality and quantity of agriculture in the coastal zone. This problem will only be exacerbated with rising sea level and more frequent droughts resulting from global warming.

Fisheries

Aquaculture is a very important activity in Greece. The indented coastline and its great length complement aquaculture development. Important areas of coastal fisheries are the lagoons of Messologi, Amvrakikos gulf, and Porto Lagos. Fishing boats are usually of small displacement and the production is intended for domestic consumption (Table 3). Exports are minimal.

In recent years, a great effort has been directed to the reorganization and modernization of fisheries in the various lagoons of Greece to make them profitable, in both quality and quantity.

Table 2. Number of Arriving Boats, Passenger and Cargo Movement in Selected Harbors of Greece (1986)

Harbor	Arrivals of vessels	Passengers: Embarking (1000s)	Passengers: Disembarking (1000s)	Cargo: Loaded (10^3 tons)	Cargo: Unloaded (10^3 tons)
Pireas	17,600	2,701	2,664	2,125	4,825
Thessaloniki	2,400	11	10	2,452	8,024
Patra	2,250	492	584	219	349
Iraklio	2,030	382	385	428	1,313
Rodos	1,980	128	124	213	394
Kerkyra	2,180	114	147	19	165
Alexandroupolis	830	44	42	335	115
Kavala	880	15	16	1,662	645
Volos	3,330	107	105	3,714	2,837
Kalamata	200	--	--	16	156
Igoumenitsa	2,080	86	108	3	254
Khania (Souda)	200	180	182	141	318
Khalkis	800	--	--	1,635	818
Syros	2,100	110	110	37	103
Rafina	1,700	330	328	77	81
TOTAL	140,000	9,256	9,297	38,703	46,203

Table 3. Fishing Vessels and Fish Caught in Greece (1986)

	Total	Coastal Fisheries	%
Number of fishing vessels	6,380	5,500	89.7
Fish caught (tons)	112,700	35,700	31.7

Fishing could be vulnerable to sea level rise both because the fishing ports and other activities are located in low areas, and because the loss of wetlands would reduce fish populations.

Coastal Development

Human intervention in the deltaic plains, the lagoons, and the wetlands is not very extensive. Shore alignment and protection structures are found in some lagoons like those of Amvrakikos, Messologi, and Porto Lagos (Vistonida).

Important shore protection structures (against erosion) are found only in the area of Messologi and the deltaic plain of Thessaloniki.

The state has spent very little on the development and protection of the coastal environment. Beside harbor works in various locations of Greece and the construction of some coastal roads, state assistance that addresses coastal problems is of only local significance.

Private investment in the coastal region, however, is at high levels. In the last decades, thousands of summer cottages have been constructed in many parts of the Greek coasts. This rapid settlement development is frequently accomplished without any planning and is many times done illegally. Another important development along the Greek shores is the construction of big vacation complexes with hotels and all kinds of sports and recreational facilities.

Finally, a variety of industrial complexes, like oil refineries, aluminum smelters, steel works, shipyards, and dockyards, are located in coastal zones. All of these activities will be vulnerable to a rise in sea level unless some remedial actions are taken.

CONCLUSION: THE NEED FOR A GOVERNMENT POLICY

The first attempt at a comprehensive solution to the question of coastal management and protection was made with Law 2344/1940. There followed many amendments and additions, mostly relating to land use and management of the coastal zone.

Following the increasing interest in the protection of the environment in recent decades, a national coastal management program was started in 1980. The implementation of this program was entrusted to the Ministry of Physical Planning and Environment. The primary aims were as follows:

1. To prepare a uniform and complete program for the development and management of the coastal zone; and

2. To study the following:

   - Settlement patterns and deterioration of the coastal zones;
   - The frequent irreversible destruction of the natural ecosystems and landscapes;
   - The reduction of productive agricultural land;
   - The exhaustion of marine resources due to pollution and overexploitation; and
   - The inaccessibility of the beach due to continuous land ownership along the beach.

Unfortunately, this program never had the financial resources necessary to carry out its original mandate. Recent administrations have shown little interest in spending additional money on the project, and there has not been a large outcry from the public to revive this initiative. Nevertheless, the wave of concern for the environment sweeping across Europe is beginning to be felt in Greece, and the protection of our coastal heritage is an obvious priority.

Clearly, any new national research, planning, or management efforts to protect the coastal environment should estimate the likely impacts of sea level rise; calculate the costs of alternative response strategies such as retreat and holding back the sea; and compare costs for alternative policy implementation dates between today and 2020, particularly in the case of land-use restrictions. Such an assessment will require a technical panel including coastal geologists, engineers, planners, economists, and public works officials.

In the narrow sense, we can afford to ignore accelerated sea level rise for a while, because the consequences are a few decades away, and a culture that has survived as long as ours is hardly likely to perish at the hands of a changing climate. But, by the same token, since we know that there will be a Greece for centuries to come, is it proper to ignore the adverse impacts that our actions today may bequeath to future generations? Compared with the potential environmental, cultural, and economic losses that could result from a rise in sea level, the cost of developing a national response strategy would be small.

APPENDIX: DETAILS OF COASTAL CLIMATOLOGY, CURRENTS, TIDES, AND TSUNAMIS IN GREECE

PRECIPITATION

The general characteristic of the geographical distribution of mean monthly temperatures is a decrease with higher latitudes. July and August are exceptions because they present great temperature homogeneity. Generally, the western coasts of Greece are a little warmer than the eastern coasts during the winter months. The opposite is true during the summer months. Both the temperature difference and the summer duration increase with higher latitudes. The eastern coasts experience a more continental climate.

The precipitation system that prevails all over Greece is of the Mediterranean type and is characterized by winter precipitation and summer drought (Table A-1). During the warm period of the year, rainfall increases from south to north because of the increasing continentality of the climate. The mean annual precipitation is 706.8 mm.

Table A-1. Mean Monthly Precipitation in Greece (mm)

Month	Amount	Month	Amount
J	112.5	J	12.4
F	80.9	A	10.4
M	70.4	S	29.8
A	41.5	O	77.4
M	33.9	N	92.8
J	21.4	D	123.4

The maximum 24-hour period precipitation occurs during autumn and winter months and rarely during the remaining months of the year, e.g., Lefkas 248.0 mm in November, and Rodos 320 mm in January. The largest number of days of precipitation are observed during the month of January.

The greatest snowfall occurs in January and February, followed by December and March. The mean number of days with snow increases with increasing latitude, distance from the sea, and from west to east.

When a low-pressure storm arrives from the west, the weather over Greece becomes cloudy with a tendency toward rain and storms over the Aegean Sea while wind intensity abates. Finally, storms from the south occur when a low pressure from the west passes over the Balkan Peninsula, north of the Aegean Sea.

Mediterranean

WINDS

In general, the most prevalent winds blow from the northern quadrant. The highest wind speeds occur in the open seas, mostly in the central Aegean Sea, in the Ionian sea, and between Crete and Peloponnessos. In the summer, the Etesian winds blow from the north.

The direction, intensity, and duration of the winds, along with the fetch length, determines the height of waves. The general circulation of winds in the Greek seas depends on the distribution of the atmospheric pressure, which is affected to a great extent by the local influences of the distribution of the seas and the uneven setting of the mountain masses.

In winter, we have northerly winds, which are the result of high-pressure cells covering the Balkans and northern Russia. These winds become very intense if a storm occurs over Greece when cyclonic depressions move over or move north of the Greek seas. This results in very intense southerly winds.

In summer, the prevailing winds over the Greek seas are northerlies, called Etesian. They are seasonally very constant, being northernly and northeasternly in the Aegean and northwesternly in the Ionian and western Greece. Their dominance is interrupted in fall when southerly winds start becoming more and more frequent, thus keeping coastal temperatures high long after summer is over.

The temperature of the surface of the Greek seas presents a normal annual fluctuation with a minimum in February and a maximum in August (Figure A-1). The annual temperature range of the surface water fluctuates between 9.8°C in the south Aegean Sea and 11.5°C in the north Aegean Sea. The warmest seas of Greece are found in the north Aegean and the Ionian Seas all year round.

According to observations by the Hydrographic Service of Greece, the highest mean annual sea surface temperature is located around Rodos (19.7°C) and the lowest near Alexandroupolis (15.5°C).

CURRENTS

The currents in Greece are of three types:

- Local currents,
- Tidal currents, and
- General currents of the open sea.

Local currents are directly dependent on the configuration of coasts, depth, the bottom relief, and the direction and intensity of winds.

The main tidal currents occur at the Strait of Evripos, the Corinth Canal, the Strait of Lefkas, at the entrance of Amvrakikos gulf, and at Rio-Antirio Narrows.

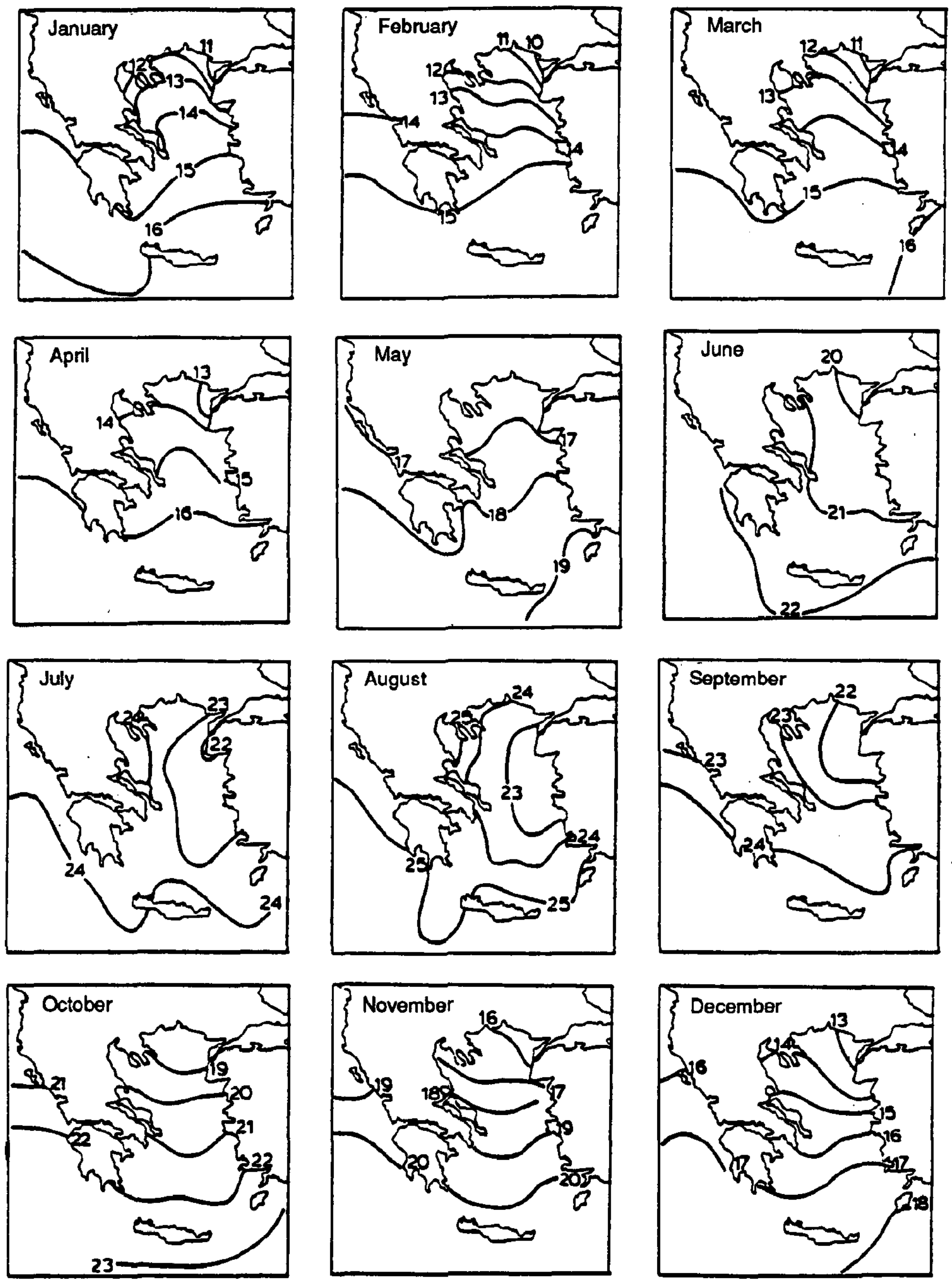


Figure A-1. Mean monthly sea surface temperatures (°C) of the Greek seas.

Mediterranean

The open sea currents generally follow an east-west direction. The current originating from the Black Sea determines the motion of the north Aegean currents giving a general east-west direction and a north-south direction in the western Aegean. The Black Sea current, as it comes out of the Dardanelles, has a speed of up to 2.5 knots and is directed to the south.

In the central Aegean, there is an anticlockwise motion, while in the southern Aegean there is a clockwise movement around the island of Crete. Along the east Aegean, there is a south to north current. In the Ionian sea, the general motion of the currents is from south to north except near Kerkyra (Corfu) and Lefkas, where the current near the coast runs from north to south.

TIDES

Most stations use automatic tide gauges, and the remainder use tide poles (Table A-2).

Table A-2. Tide Stations in Greece

1.	Aedipsos	12.	Kavala+	23.	Posidonia+
2.	Alexandroupolis	13.	Kalamata+	24.	Preveza+
3.	Aliverion	14.	Katakolon	25.	Rodos
4.	Amfiali	15.	Kerkyra	26.	Skiathos
5.	Argostolion	16.	Leros	27.	Souda (Khania)+
6.	Volos	17.	Lefkas+	28.	Stylis
7.	Gythion	18.	Limnos	29.	Syros+
8.	Igoumensitsa	19.	Mytilini	30.	Khalkis (north)+
9.	Iraklion+	20.	Salamis	31.	Khalkis (south)+
10.	Thessaloniki+	21.	Patra+	32.	Khios+
11.	Isthmia	22.	Pireefs+		

Note: Stations with a cross use automatic tide gauges; all others use tide poles. Stations 4 and 11 have been discontinued. Source: Zoi-Morou (1981).

During their installation, the leveling of the stations is linked to the national geodetic system of the country by the Greek Army Geographical Service. It is possible to divide the Greek seas into three large areas (Table A-3).

1. The north Aegean Sea with tidal ranges between 0.11 and 0.25 m;
2. The south Aegean Sea with tidal ranges between 0.05 and 0.08 m; and
3. The Ionian Sea with tidal ranges between 0.05 and 0.18 m.

TSUNAMIS

Tsunamis in Greece are rare. Their zones of origin coincide with the seismogenic zones of the external island arc of the Greek microplate (Ionian islands, Crete, Rodos) as well as with the internal volcanic arc (Corinth-Megara, Aegina, Milos, Santorini, Nisyros, Kos).

Along these zones there occur numerous earthquakes which every few years reach an intensity of ≥6 on the Richter scale. Owing to the highly irregular sea bottom terrain, there is a possibility of submarine landslides which can sometimes produce tsunamis.

The tsunamis have not been systematically studied in Greece. The first study was done in 1956 by seismologist Galanopoulos when a tsunami-like phenomenon occurred in the southeastern Cyclades, following a great earthquake on July 9, 1956 (36.9°N, 26°E, H = 03:11:38, M = 7.5). The tsunami owed its genesis to a submarine landslide on the steep slopes of the southeastern shores

Table A-3. Maximum, Mean, and Minimum Tidal Ranges (in Meters) at Tide Stations in the Ionian and Aegean Seas

Station	Maximum Range	Mean Range	Minimum Range
<u>Ionian Sea</u>			
Preveza	0.28	0.05	0.01
Lefkas	0.30	0.11	0.01
Katakolo	0.67	0.08	0.01
Patra	1.05	0.18	0.01
Kalamata	0.58	0.11	0.01
<u>South Aegean</u>			
Syros	0.32	0.05	0.01
Khania (Souda)	0.25	0.06	0.01
Iraklio	0.58	0.08	0.01
Leros	0.52	0.06	0.01
<u>North Aegean</u>			
Thessaloniki	0.94	0.20	0.01
Kavala	0.96	0.25	0.01
Alexandroupolis	0.65	0.13	0.01
Limnos	0.60	0.11	0.01

Source: Zoi-Morou (1981).

of Amorgos Island (36.8°N, 26.2°E). The seismic sea wave caused sea level to fall up to 3 meters and rise 2.5 meters. The wave train affected almost all the harbors of the south Aegean. Galanopoulos prepared a map with the sources of known tsunamis which proved to be destructive in historical times (Figure A-2).

A second tsunami was generated by an earth slump, set in motion without shock, in the area of Aegion in northwestern Peloponnessos when a massive slumping, estimated to have a mass of 57,000 cubic meters, subsided 5-44 meters below the sea level and the coastline in some parts receded up to 500 meters inland (Comninakis et al., 1964). Even though there was no earthquake at the moment, the slump occurred (7 February 1963), it was preceded by seven local earthquakes west of Aegion on 2 February 1963.

Figure A-2. Sources of tsunamis that have affected the coasts of Greece from 479 B.C. to A.D. 1956.

BIBLIOGRAPHY

Comninakis, P., N. Delibasis, and A. Galanopoulos. 1964. A tsumami generated by an earth slump set in motion without shock. Annales Geologiques des pays Helleniques 16: 93-110 (in Greek).

Dagre, D., and Lambrou, D. 1981. Study of the legislation about "aegialos" and "paralia." Athens: Technical Chamber of Commerce, (in Greek).

Galanopoulos, A.G. 1957. The Seismic sea wave of July 9, 1956. Praktika Akadimias Athinon 32: 90-101 (in Greek).

Galanopoulos, A.G. 1960. Tsunamis observed on the coasts of Greece from Antiquity to present time. Annali di Geofisica, 13 (3-4): 369-386.

Hydrographic Service. PILOT (Ploigos), Athens (in Greek).

Volume A. Western coasts of Greece 1971, with announcements in 1983 and 1986.

Volume B. Southern coasts of Greece 1976.

Volume C. Northeastern coasts of Greece 1947, with announcements in 1983 and 1987.

Volume D. Northern and eastern coasts of Greece, 1987.

Kamkhis, M. 1981. The development and protection of the coastal zone in Greece. Proceedings of the Conference on the Development (Growth) of Greece, Athens, III. pp. 152-156.

Kotini-Zabaka. 1983. Contribution to the Study of the Climate of Greece by month. Doctoral dissertation. Thessaloniki, Greece: University of Thessaloniki (in Greek).

Maroukian, H. 1989. Sea level in the past, present and future. Proceedings of the First Panhellenic Geographical Conference, 2, 1987, Athens.

Ministry of the Environment, Physical Planning, and Public Works. Program for the delineation of wetlands of the RAMSAR agreement. 1986. Athens: Ministry of the Environment, Physical Planning, and Public Works (in Greek).

i. Evros delta
ii. Lake Mitrikou
iii. Lake Vistonida-Porto Lagos
iv. Axios-Loudias-Aliakmon delta
v. Nestos delta
vi. Kotyhi lagoon
vii. Messologi lagoon
viii. Amvrakikos gulf

Moutzouris, C., and Maroukian, H. 1988. Greece. In: Artificial Structures and Shorelines. H.J. Walker ed. New York: Academic Publishers, pp. 207-215.

National Statistical Service of Greece. 1982. Actual population of Greece according to the April 5, 1981 census, Athens: National Statistical Service of Greece (in Greek and French).

Zoi-Morou, A. 1981. Tide data of Greek harbors. Oceanographic Study no. 13, Athens: Hydrographic Service (in Greek).

IMPACTS OF SEA LEVEL RISE ON TURKEY

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ABSTRACT

The low coastal belt of Turkey is occupied by intensive agricultural land use, and most of the cities, towns, and villages are found along the lowland coasts. But most of the population is settled on the high cliff sections of the coast. The ports are principally established at a point where the stretches of sedimentary coastline meet the relatively higher bedrock ground. Some parts of the harbor cities and industrial establishments have extended onto the low coastal plains, especially during recent years. Because they are not wide areas, these parts may be subject to disruption as sea level rises. Artificial coastal protection is not present along this low coastline because there is mainly no need for it at present.

The common assumption in Turkey that sea level is constant is not shared by the scientists, and for good reason. The Turkish shores have fluctuated several times during the Holocene, and sea level has been rising at least for the past 4,000 years. But because the rising sea has been balanced by sedimentation and tectonic uplift, for most practical purposes it has been reasonable to assume that sea level is constant. But if global warming is likely to cause a 50- to 100-cm rise in the next century, the time is now to recognize this issue in the coastal decisionmaking process. In Turkey, some government offices are responsible for planning and construction of harbors and other coastal establishments. Some municipalities of coastal cities are also responsible for managing low coastal plains, but none of them is yet dealing with a future sea level rise. Will it take a dramatic event to draw the attention of policymakers, or can they respond to scientific information?

INTRODUCTION

When one asks "What will happen on the Turkish coastline if the sea level rises?", the answer at first seems simple: not much, because the Anatolian Peninsula is a tectonically uprising block, and, except in the deltaic areas, there are no extensive lowland areas around it. But if sea level rise accelerates, the hidden dangers will emerge. Because tides and storms are small, many coastal establishments and settlements have been built within 2 meters of sea level and will eventually be inundated unless dikes are built. But many fishing villages, such as Meset Limani illustrated in Figure 1, could not afford dikes, and an inland migration would not be feasible if traditional activities were to continue.

In the past, the main causes of shoreline changes have been sea level fluctuations due to tectonic uplift and subsidence, alluviation, and human activities (Erol, 1983, 1988). The most important recent changes have been in deltas (Erol, 1983; Bird, 1985), which in some cases have advanced 40 kilometers seaward (Erol, 1976). Because of changes in river courses, Ephesus, Priene Miletus, Kaunos, and many other ancient harbors have been abandoned. Nevertheless, tectonic uplift -- often associated with earthquakes -- has also been important in some cases. For example, the city of Seleukeia Pieria in Hatay was completely abandoned after Byzantine times (Erol, 1963; Pirazzoli et al., 1989).

No one has assessed the impacts of a 50- to 200-cm rise in sea level. Nevertheless, a number of expectations seem reasonable. First, in the high rocky cliff coasts, the rising sea level will not cause great changes or shifts of the coastline, but the rate of cliff recession will accelerate, increasing the frequency and extent of landslides and destroying portions of many coastal roads. Second, along low, eroding, soil cliffs, there may not be immediate changes, but erosion will eventually result. Because these areas are already densely populated narrow terrace strips, displacement of destroyed coastal establishments will become a serious problem, and protecting them from the sea will cause erosion elsewhere. Finally, along deltaic coasts that are advancing seaward today, rising sea level will reverse the shoreline change, and coasts will begin to retreat. The geomorphological result of this will be a thick alluviation that may bury relatively new deltaic soils and perhaps interrupt agricultural activity on the deltaic plain as much as droughts do today.

Many coastal establishments would be displaced as a result of these changes. In the high rock cliff areas, the increased activity will influence the settlement points, roads, etc. Since the places at the top of the cliffs are already scarce, rebuilding settlements elsewhere will be difficult if not impossible. In the narrow strip of low soil-cliff terrace areas, the displacement of ruined coastal establishments, especially tourist places, will be several times more expensive. In the low deltaic areas, which are already overcrowded, displacing the populations may be politically impossible, necessitating expensive coastal protection. Even where it is feasible, it will encroach upon important agricultural areas, which is already happening due to population growth. In Turkey, the art of life may have to change.

Many cultural sites would also be at risk. Besides the modern settlements, most of the ancient harbors and cities would be covered by seawater. Because of sedimentation, they would be buried, and access to these ruins would be much more difficult. Some of them would be destroyed by increased wave activity. Because of their great number, moving the ruins would be practically impossible, and in any event, it would change their character.

Figure 1. A typical Turkish fishing town. While towns like this clearly lack the resources to hold back the sea, retreat is not a viable option either.

In Turkey, the State general directorates and offices responsible for planning and constructing airports and harbors are connected to the Ministry of Construction and Settlements. In addition to these General Directorates, the State Planning Department and some municipalities of the coastal cities have interests in the low coastal belt of Turkey.

None of these agencies is dealing yet with the issues and problems that will accompany future sea level rise. When asked about the problem, they generally minimize its significance. Even coastal engineers, who would seem more predisposed to incorporate technical information, are designing coastal establishments without regard for future changes.

In the Turkish law for coastal protection, sea level is accepted as an "unchanging" boundary between the land and sea. Even without the greenhouse effect, we know that such a definition is technically inaccurate, but in the past it has not mattered as other processes offset rising sea level. But in the future, keeping this definition in our coastal policy will yield irrational results, as the United States and other countries with higher current rates of relative sea level rise have already seen (Titus et al., 1985).

The remainder of this paper summarizes the natural environment of Turkey and human activities along its coasts.

THE NATURAL ENVIRONMENT OF TURKEY

Climate and Waves

Turkey lies between the middle latitudes and the Mediterranean macroclimatic zones and has a transitional character. The climate of the Black Sea is mainly under the influence of northerly winds that usually blow as gales. Because of the long fetch of the Black Sea and the absence of intervening islands, large waves strike the shore; hence high coastal cliffs and shingle beaches at the mouths of short mountain rivers are eroding. Details of wave heights and water temperatures are in Appendix 1.

Coastal Geomorphology

The coast of Turkey has developed under the influence of (1) the geomorphology of the mainland -- that is of the Anatolian Peninsula and especially of the North Anatolian and Taurus folded mountain chains and the belt of faulted central plateaus; and (2) the submarine relief of the sea basins surrounding the peninsula. The coastline of Turkey may be divided into three main groups: (1) retreating cliffed coastlines on rocky and soil material (5,752 km), (2) advancing sandy depositional soil (1,546 km), and (3) advancing, partly swampy deltaic soils (1,035 km).

High Rocky Cliff Coastlines

High rocky cliffs are found mainly on the north and south Anatolian coastlines, which run parallel to the folded mountain chains. There are, however, some shorter stretches of similar coastline on the faultline coasts of the Aegean and Marmara Seas. This type of high rocky cliff rises sometimes a hundred meters above the sea. These cliffs are interrupted by river mouths with limited shingle beaches on the north and south Anatolian coastlines. On the Aegean coastline, on the other hand, the rocky cliff coasts of fault mountains are relatively short and are interrupted by several deltas.

Generally, the high rocky cliff coasts are slowly eroding. At the foot of the cliffs, the coastal platform is usually very narrow or absent. Therefore, building highways along the coastline is extremely difficult, and the roads are located on the top of the cliffs if possible. Because of the humid climate during all seasons of the year, landslides are common on the Black Sea coastal strip. However, because of the minor drop in sea level following the Climatic Optimum of the middle Holocene, narrow sandy beaches have developed at the foot of these cliffs. In the event of a future sea level rise, these narrow sandy beaches will be covered by water again, exposing cliffs to waves, which will accelerate their erosion.

The Low Soil Cliff Coastlines

Low (2-meter elevation) and medium-high (10- to 20-meter elevation) cliffs composed of soft sediment are found at the base of many Pleistocene terraces. For the most part, the coastal belt is a narrow strip between the sea and the mountains. Because these coastal belts have been ideal for settlement, tourist and industrial establishments, and road construction, they are densely populated. Although this narrow strip has a few meters of relief, the increasing exposure to waves will cause erosion, and shorefront establishments will be ruined at an increasing rate.

The Low Unconsolidated Coastlines

These low stretches are found especially on the deltaic coastlines. They include wide sandy beaches, beach rock, lagoons, tidal flats, and coastal dunes. Because rivers are supplying large amounts of sediment, these shores are advancing into the sea today. Accelerated sea level rise, however, would reverse this process.

Especially on the north and south Anatolian coastline, the small deltaic unconsolidated coastlines consist mainly of gravel and shingle beaches. This is the result of the influence of the strong waves and coastal currents. Although there are no barrier islands in Turkey, some coastal spits have developed at the mouths of rivers and bays; some have formed along the foots of cliffed coasts. These low areas are very vulnerable to both inundation and erosion due to sea level rise.

Coastal Dunes, Wetlands, and Lagoons

Turkey has well-developed coastal dunes, especially along the western Black Sea coast and in the deltas of the Aegean and Mediterranean Seas. These natural barriers to storms would provide some defense against the consequences of sea level rise, at least in the short run. Elsewhere, beach rock has developed along numerous low soil cliffs.

Wetlands are mostly confined to relatively narrow areas in the Kizilirmak, Yesilirmak, Seyhan, and Ceyhan Deltas and in other low coastal reaches along the Aegean Sea, most of which are associated with lagoons. There are no coral reefs, mangroves, or saltmarshes in Turkey.

Lagoons are found mainly behind the coastal spits of the deltaic areas of Turkey. There are, however, lagoons in some inlets with high- and low-cliffed coasts, too. The lagoons of the Turkish coastline are used partly as salt pans and fish ponds. The former lagoons of Kucukcekmece and Buyukcekmece have recently been converted to water reservoirs for the city of Istanbul.

Genuine tidal estuaries are not found in Turkey, although some ria-type inlets are present. The ancient harbor of Istanbul, which is called Halic, is an example of this type of ria.

LATE PLEISTOCENE AND HOLOCENE SEA LEVEL CHANGES

Recent sea level changes have played a very important role in the coastal geomorphology of Turkey. The influence of young tectonic subsidence and uplift phenomena are observed at several points of the coastline. Alluviation, deltaic subsidence, and climate changes must be added to this group. These kinds of coastal processes are controlling the prograding and retrograding stretches of the coastline.

Finding some unchanging coastline stretch in Turkey is really difficult. Generally, the upper Pleistocene (Tyrrhenian) terraces with their fossils are less than about 250,000 years old, and they are found at elevations between 10 and 80 meters in different coastal places. Some coastal terraces and their fossils at about 6 to 10 meters must belong to the last interglacial period -- that is, about 100,000 years ago. Moreover, on the recent coastline of Turkey, except prograding deltaic coastline stretches, there are traces of elevated former sea levels of 200 cm (about 6,000-8,000 years ago), 100 cm (about 2,000-2,500 years ago), and 50 cm (about 1,400 years ago) (Kayan et al., 1983; Laborel, 1989; Pirazzoli et al., 1989). If we reconstruct these former traces, we may determine what will happen in the future. These kinds of studies must be extended for all the Turkish coastline.

CULTURAL AND ECONOMIC FEATURES

Demography

Most of Turkey's population of 50 million is well out of danger from a rising sea. Of the 399 cities and towns in Turkey, more than half the population lives less than 100 meters above sea level. Unfortunately, the lack of vertical resolution on topographic maps makes it impossible to estimate the portion of the population that lives within a few meters of sea level.

Ports

During ancient times, there were several harbors and cities on the coastline of Turkey, generally at the point where the main trade ways of the country ended, usually on a deltaic plain next to a low soil-cliff (Erol, 1976, 1983, 1989; Akurgal, 1970). The presence of lagoons facilitated the establishment of primitive landing places that were later converted to harbors. Many of these harbors and cities had to be abandoned because deltaic alluviation, sea level changes, earthquakes, and tectonic uplift shifted the shorelines (c.f. Erol, 1963, 1983; Kraft et al., 1977, 1980a,b, 1982; Kayan, 1981, 1987).

In modern times, the ports have expanded and situated on much broader grounds. In addition to the historical ports, several smaller fishing harbors and shelters with breakwaters have been built. According to Erol (1988), the total number of the artificial structures of Turkey is as follows:

Large commercial harbors	12
Small harbors	115
Shelters with breakwaters	9
Abandoned ancient harbors	44
Major coastal protection works	6

In the building of all these coastal establishments, unfortunately, sea level and other environmental conditions are assumed to be constant. In reality, even some of the new harbors have been destroyed or covered by sediments, often within a period less than 10 years. Warning the policy makers in Turkey has been extremely difficult. In some cases, sea level rise may help to offset the sedimentation processes that have forced port abandonments. However, this would be merely a fortuitous coincidence.

Other Land Uses

The coastal zone has Turkey's most fertile agricultural lands and a mild, humid climate. In recent times, coastal tourism and yachting have experienced explosive growth. The tourist establishments were first built on the narrow beach strip, but now they are backing up to the country's most valuable inland agricultural fields. The land has also been expanded toward the sea with walls, embankments, quays, etc. But as noted previously, the coastal lowland strip of Turkey is narrow at the base of inland mountains. A rise in sea level would force the nation either to give up agricultural lands to facilitate landward resettlements or to spend large amounts of money on erecting coastal defenses.

Fisheries

Fishing has been an attractive livelihood for the people who have lived on the Turkish Mediterranean coastline since historic and even prehistoric times. For example, in 1923, there were about 30 fish ponds on the Anatolian coastline with a yearly production of 9,000 tons of fish products. However, in the area of the Marmara Sea and Straits, the local character of fishing developed somewhat differently. This is because fish from the Black Sea migrate toward the Marmara and Aegean Seas during the autumn and winter months, as the Black Sea waters become cooler. In the early years, the migrating fish were staying partly in the Marmara Sea during the winter season. But in recent years, because of water pollution and other hostile conditions, they prefer to continue their migration to the north Aegean Sea. Those fish return to the Black Sea during spring and summer seasons. So fishermen are following the fish and are catching them, especially in the Anatolian coastal waters of the Black Sea, at the entrance of the Bosphorus, and in the Marmara and north Aegean Seas. Under these circumstances, fish production has increased yearly from 79,000 tons (1952) to 532,000 tons (1985). The percentage of this production is distributed as follows:

	(%)
Black Sea	80
Marmara Sea and Straits	12
Aegean Sea	5
Mediterranean Sea	3

Climate change could affect the fisheries in many ways. Although Turkey does not have extensive wetlands, many of the fish caught there spend part of their lifetimes in the marshes found elsewhere. Warmer temperatures could encourage some of the fish that migrate out of the Black Sea during the winter to remain there longer. On the other hand, warmer temperatures might amplify pollution problems. The unknown impact of global warming on seasonal precipitation, river flow patterns, and currents also could be important.

CONCLUSION

An evaluation of the implications for Turkey leads one to realize that worldwide, sea level rise would be a serious problem. Turkey would appear to be one of the countries least vulnerable; yet even here, the consequences could be severe.

Clearly, policy makers need to take sea level rise into account. Even in the short run, doing so would help to ensure that new development is consistent with current environmental changes. In the long run, it is important both because our valuable coastal strip is very narrow and because it would help introduce policy makers to the other consequences of the greenhouse effect, such as hotter summers and more droughts, which in Turkey could be far more devastating.

APPENDIX: CLIMATOLOGY AND CURRENTS OF TURKISH WATERS

The climate conditions that control the recent phenomena are determined by the main physiographic features. The country lies between the middle latitude and Mediterranean macroclimatic zones and has a transitional character. The Middle European and Mediterranean climates alternatively dominate in the Black Sea region, whereas only the Mediterranean climate dominates south of the Taurus Mountains and in the Aegean Sea region. The climate of the Marmara region is transitional between the Black Sea and Mediterranean types. In the central part of the Anatolian Peninsula, which is between the North Anatolian and Taurus Mountains, a continental plateau type of Mediterranean climate is characteristic. The types of coastal regions found in Turkey are shown in Figure A-1.

Black Sea

The climate of the Black Sea coast of Turkey is mainly under the influence of northerly winds (air masses) that usually blow as gales called Karayel (black winds) in Turkish. Because of the long fetch (i.e., distance over which waves can form) in the Black Sea and the absence of islands along this somewhat straight coastline, the wave energy is considerable. Thus, rapidly retrograding high coastal cliffs and shingle beaches at the north of the short mountain rivers are predominant along this coastline. The sandy beaches and their related dunes are also developed under the influence of these strong northerly winds.

The heavy rainstorms and strong northerly winds that dominate the winter climate (temperature 0 to 7°C) of the Turkish Black Sea coasts yield to mild winds during the summer. Except for some rare winds in the eastern part of the coastline, the influence of the southerly winds is extremely rare in the Black Sea coastal strip of Turkey. Therefore, the summers are also mild (19 to 23°C), cloudy, and rainy in this area. The temperature of the seawater is cool (15 to 16°C), and the surface of the Black Sea is mainly rough.

Marmara Region

The North Anatolian Mountain chain usually prevents the penetration of the marine climate influences inland--that is toward the main plateau of Central Anatolia, especially in the middle and eastern parts of the country. But in the west, toward the Marmara Region, the climatic influence of the northerly winds and air masses can easily penetrate to the south during the winter and summer seasons. But usually these northerly weather conditions alternate with southerly conditions. In Istanbul, for example, the southerly gales alternating with northerly winds have an important effect. The Maramara Region with cold (1 to 6°C) rainy winters and cool (22 to 23°C), windy summers is a transitional area between the Black Sea and the Mediterranean environments. These climate characteristics as well as sea currents in the straits are also controlling the physical properties of the water masses in the Marmara Sea.

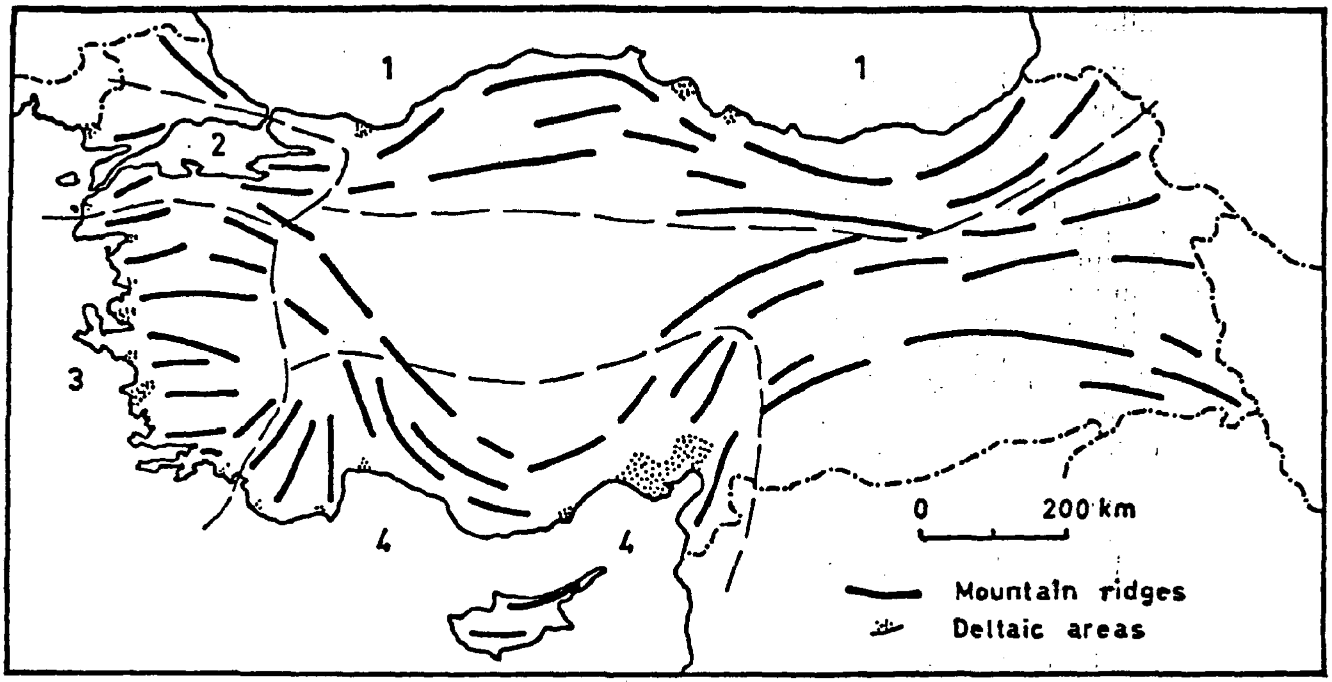

Figure A-1. Types of coastal regions of Turkey: (1) Black Sea type; (2) Maramara type; (3) Aegean type; and (4) Mediterranean type.

Aegean Sea

The climate in the Aegean Sea is a transitional blend of the climate between the Black Sea and the Mediterranean Sea. But there the Mediterranean climate dominates mainly during the summer, whereas the Black Sea conditions dominate during the winter in the Marmara region. However, because of the northerly cool to warm (26 to 28°C) summer winds in the Aegean Sea, the summers are cooler than the eastern Mediterranean area, and this climate characteristic also controls the summer seawater temperatures (16 to 19°C) of the Aegean Sea.

Along the Mediterranean coast of Turkey, the Mediterranean climate dominates. Warm (24 to 29°C), dry, and calm weather conditions are very conducive to the development of biogenetic coastal forms as well as dunes and beach rock. The rainy, cool to warm (9 to 11°C) winters and wave activity cause the formation of wide, sandy beaches. The excessive summer evaporation causes cementation in the beach sands or calcite concentrations in the coastal to inland soils. Investigations have shown that similar conditions were prevalent in this part of the coastline during the Holocene and even during the upper Pleistocene (Erol, 1983; Kayan et al., 1983; Laborel, 1989).

Marine Hydrology

Water Masses

The Black Sea in the north and the eastern Mediterranean in the south are Turkey's two main sources of water masses. The water masses originating from the Mediterranean Sea are principally warm (21.54°C on the surface) with high salinity (39.15 parts per thousand), and the water masses in the Black Sea are cool (8 to 15°C on the surface) with low salinity (18.36%). In the area of the Marmara Sea and Straits, there are transitional conditions between the Black Sea and Mediterranean masses. Indeed, the warm and saline Mediterranean water flows on the surface along the Anatolian coast toward the north in the Aegean Sea (Figure 3) and meets the cool and less saline Black Sea water. There the lighter, less saline Black Sea water flows on the surface toward the south, and relatively heavy saline Mediterranean water flows under it toward the north into the Dardanelles Strait. These layered surface and deep-water masses also occur in the Marmara Sea and Bosphorus Strait.

The mean surface temperature in the Marmara Sea is 15 to 17°C. The surface temperature of the seawater is 8 to 9°C in January and 24 to 26°C in August. The salinity of the surface waters is 23.47%, and that of the deep waters is 38.64%.

The characteristics of deep seawaters are also influenced by the surface conditions. In the eastern Mediterranean, there are four layers of water masses (Yuce, 1987): (1) surface waters of Atlantic origin (temperature 21.54°C, salinity 39.15%); (2) intermediate eastern Mediterranean waters (temperature 15.5°C, salinity 39.15%); (3) deep water (temperature 12.6°C, salinity 38.4%); and (4) Bottom water.

In the Black Sea, there are three layers of water masses: (1) surface water in the upper 200 m (temperature 8 to 15°C, salinity 18%); (2) transitional water layer; and (3) deep water (temperature 9°C, salinity 22.5%).

The surface temperatures drop below the freezing point, especially in the north and western coasts of the Black Sea, and ice masses may penetrate through the Bosphorus to the northern Marmara Sea (Erinc, 1985).

Currents

The characteristics of the currents in the straits and Marmara Sea are principally influenced by the salinity and temperature differences between the Black and Mediterranean Seas. The water volume brought by rivers into the Black Sea Basin is great, and because of this, the surface level of the Black Sea is 50 cm higher than that of the Marmara Sea. This is another reason for the currents in the straits.

The winds are a significant influence on the currents in the Bosphorus. Normally, the surface current in the Bosphorus is from north to south. Its velocity is directly under the control of the dominant northerly winds, and it may reach up to 9-10 km/h. But it may decrease or completely disappear when the southern winds blow persistently for a few days, especially during the southerly gales. In this case, the warm and saline Mediterranean deep water may rise to the surface. This kind of unusual sudden change causes mass mortality of fish that live in the upper, less-saline, cool waters and also of fish that live in the deeper, saline, and warm water layers.

Because of the strong underwater currents, the bottom of the Bosphorus is partly bare of fine sediments or is covered in some places by larger particles of sands and even shells. The water exchange between the Black and Mediterranean Seas has been studied by several authors since the 19th century (e.g., Makarov, 1885; Wharton, 1886; Ullyott and Ilgaz, 1946; Pektas, 1953; Yuce, 1985, 1987b). The influence of the currents in the area of the straits and Marmara Sea has also been discussed by Stanley and Blanpied (1980). According to these authors, the sea level changes during the late Holocene was the most important factor controlling the currents in this area.

In the Marmara Sea, the surface currents are directed from the Bosphorus toward the Dardanelles Strait with a maximum speed of 2.5 km/h, and a minimum speed of 750 m/h (Figure A-2). In the Dardanelles Strait, similar to the Bosphorus, the Black Sea water flows on the surface from north to south, and the Mediterranean water flows as an undercurrent toward the north. Because of the strong mixing on the boundary of these two counter-currents, the salinity of the surface water increases rapidly here. It is 18% in the north Marmara Sea, it becomes 25% in the Dardanelles, and 37.52% in the north Aegean Sea. There, the surface temperature is at a maximum of 24.11°C in August and a minimum of 13.33°C in March. Toward the southern Aegean Sea, the surface waters coming from the Black Sea gradually disappear.

Dissolved Oxygen

The amount of the dissolved oxygen, especially in the surface water masses, plays an important role in the biologic properties of the sea. The boundary of this dissolved oxygen surface layer is 150-300 meters in the Black Sea. Below this level is an anaerobic (due to high levels of H_2S) water body, as in the Marmara Sea. This deep layer is not found in the Aegean and Mediterranean Seas.

Wave Conditions

The wave conditions on the surface of the seas surrounding Turkey is under the control of wind direction and its velocity and the fetch distances. But, since satisfactory studies on fetch are missing, only the conditions of wave heights and directions will be explained here.

In the Black Sea, northerly and northwesterly winds are dominant especially in winter months. Because the fetch distance is great in this direction, waves are high and they strongly erode the foot of high cliffs on the coastline of the North Anatolian Mountain chain. The strong southwesterly winds in the Marmara Sea blow sometimes as gales and they alternate with northern winds. In the Aegean and Mediterranean Seas, the southwesterly winds influence the coastline during the winter, whereas the moderate northerly winds prevail during the summer, especially in the Aegean Sea.

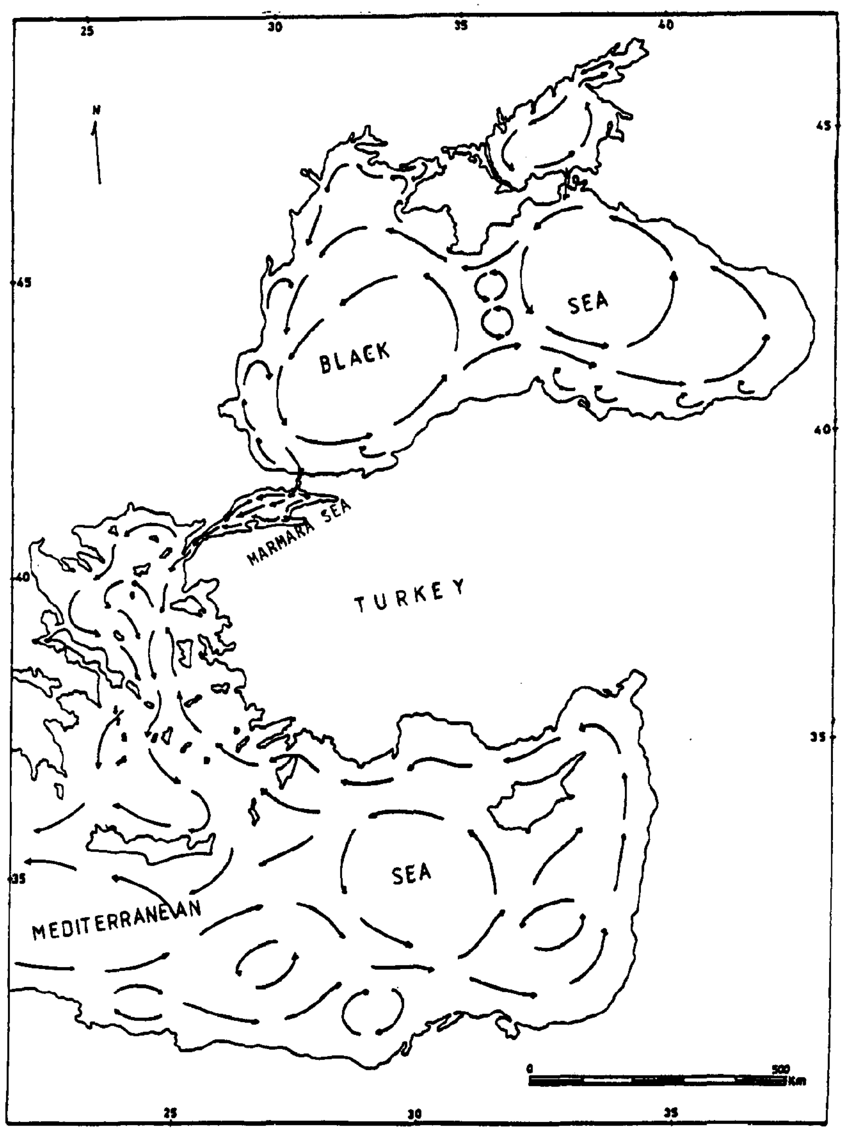

Figure A-2. Surface currents in the seas surrounding Turkey.

The height of the waves and related wind directions are as follows:

	Mean	Maximum
Black Sea	N 3-4	Up to 13 m in winter
Bosphorus	N 1	
Marmara Sea	SW 3-4	Up to 4-6 m in winter
Dardanelles	SW 1-2	
Aegean Sea	SW 3-4	
Mediterranean Sea	SW 3-4	Up to 8-9 m in winter

The tides and other sea level fluctuations are small along the Turkish coastline. The daily periods of the tides are as follows:

Mediterranean

Black Sea	maximum	10 cm
Bosphorus	maximum	2.5 cm
Marmara Sea	maximum	2.5 cm
Aegean Sea	maximum	30 cm
Mediterranean Sea	maximum	30 cm
Izmir Gulf	maximum	50 cm
Iskenderun Gulf	maximum	50 cm

The pattern of storm surges (compared to mean sea level) are as follows (Aykulu, 1952):

Marmara Sea	maximum 101 cm
Aegean Sea	maximum 122 cm in Izmir
Black Sea	maximum 65 cm in Eregli

According to historical records in Turkey and surrounding countries, tsunamis and other rapid sea level changes were frequently observed (Soysal, 1985). The waves may not be very high, but they are destructive. Some of them may be only storm surges, but the others must be tsunamis. This kind of wave was especially destructive at the Izmit Gulf and at the estuary of Istanbul-Halic Harbor in the Marmara Sea, at the Izmir Gulf and Islands in the Aegean Sea, and at the Fethiye Gulf in the Mediterranean Sea.

BIBLIOGRAPHY

Akurgal, E. 1970. Ancient civilization and ruins of Turkey, 2. Ed. Istanbul.

Bener, M. 1974. Beachrock formations on the coastline between Alanya-Gazipasa, southern Turkey. No. 75, 95. Istanbul: Geographical Institute of the University of Instanbul.

Bird, E.C.F. 1980. Sea Level Curve. Monde. 24 e Congr. Intern. Geogr. Japan. IGU-CCE Project One.

Bird, E.C.F. 1985. Coastline Changes: A Global Review, 219 pp. John Wiley Sons Ltd.

Erinc, S. 1985 Relationship between the ice formation and meteorological conditions in Black Sea. Istanbul Univ. Deniz Bilimleri ve Cogr. Enst. Bulteni 2:11-16. Istanbul.

Erol, O. 1963. Asi Nehri deltasinin jeomorfolojisi ve dorduncu zaman deniz-akarsu seki leri. Die Geomorphologie des Orontes Deltas und der anschliessenden Pleistozaenen Strand- und Flussterrassen, Provinz Hatay, Turkei. Ankara Univ. Dil ve Tarih-Cografya Fak. Yayini. No. 148, 11 s. Ankara.

Erol, O. 1969. Observations on Anatolian coastline changes during the Holocene. Cogrefya Arast. Derg. 2:89-102. Ankara.

Erol, O. 1972. Beachrock formations on the western coasts of the Gelibolu Peninsula, Dardanelles, Turkey (S). Cogr. Arast. Derg. 3-4:1-12. Ankara.

Erol, O. 1976. Quaternary shoreline changes on the Anatolian Coasts of the Aegean Sea and related problems. Bull. Soc. Geol. France 18, 2:459-468, coll. Internat. CNRS Paris No. 244:263-272. Paris.

Erol, O. 1981. Heotectonic and geomorphologic evolution of Turkey. Neve Folge Suppl. Bd. 40:193-211. Berlin-Stuttgart.

Erol, O. 1982. Geomorphological Map of Turkey. 1:2 million. Ankara: Mining Research and Exploration Institute of Turkey.

Erol, O. 1983. Historical changes on the coastline of Turkey. Bird, E.C.F., Fabri, P. (eds). Coastal problems in the Mediterranean Sea. Proceedings of a symposium held in Venice 10-14 May 1982. Int. Geographical Union, comm. on the Coastal Environment:95-108. Bologna.

Erol, O. 1985. Turkey and Cyprus. In Bird, E.C.F., Schwartz, M.L. (eds). The Worlds Coastline:491-500. Van Nostrand Reinhold Co., New York.

Erol, O. 1987. Quaternary sea level changes in the Dardanelles Area, Turkey. Ankara Univ. Dil ve Tarih-Cogarfya Fak. 60. yil armagani:179-187. Ankara.

Erol, O. 1987. Turkey. IGCP Project 200:Late Quaternary Sea Level Changes: Measurment, Correlation and Future Applications. Summary Final Report. Ed. by P.A. Pirazzoli. Nivmer Information No. 14:38-40. Paris.

Erol, O. 1988. Turkey. In Walker, H.J. (ed) Artificial Structures and Shorelines:241-252. Kluwer Academic Publishers.

Erol, O. 1989a. Holocene development stages of the Ceyhan and Seyhan river deltas, southern Turkey. (Baskida, in print).

Erol, O. 1989b. Anatolia, Turkey. Encyclopedia of Geoarcheology. (In print).

Erol, O. 1989. Anatolian historical harbours. Encyclopedia of Geoarcheology. (In print).

Erol, O. 1989. Geomorphological Map of Turkey. 1:1 million. Publ. of M.T.A. Ankara. (In print).

Erol, O. 1989. A geomorphological approach to the application of the Laws for the coastal protection in Turkey. Istanbul Univ. Deniz Bilimleri ve Cografya Enst. Bulteni 6. Istanbul. (In print).

Evans, G. 1971. The recent sedimentation of Turkey and the adjacent Mediterranean and Black Seas: A review. Campbell, A.S. (ed). Geol. and Hist. of Turkey:385-406. Tripoli.

Mediterranean

Evans, G. 1975. Recent sedimentation of the southern Turkish coast and adjacent Mediterranean between Cyprus and Turkey. Imperial College, London. (Unpublished)

Flemming, N.C. 1968. Archeological evidence for sea level changes in the Mediterranean. Underwater Assoc. Report:9-12.

Flemming, N.C. 1971. Cities in the Sea. Doubleday and Co., 222 p., New York.

Flemming, N.C., Czartoryska, N.M.G., Hunter, P.M. 1973. Archeological evidence for eustatic and tectonic components of relative sea level change in the South Aegean. Blackmann, D.J. (ed). Marine Archeology. London: Butterworths.

Gozenc, S., Gunal, N. 1987. Urban and rural population in Turkey and the distribution of urban population according to the altitudes on a map of 1:200 000 scale. Istanbul Univ. Deniz Bilimleri ve Cogr. Enst. Bulteni 3:27-38. Istanbul.

Kayan, I. 1981. Effects of natural environment on changing Aegean civilization (Abstract). Ankara.

Kayan, I. 1987. Late Holocene sea level changes along the western Anatolian Coasts. Late Quaternary sea level correlations and applications. Dalhousie Univ. Halifax, Canada. July 19-30, 1987. Abstracts: 15.

Kayan, I., Kelletat, D., Venzke, J.F. 1983. Morphogenetic and geodynamic evolution of the coastal strip between Karaburun and Figla Burnu in the west of Alanya, south coast of Turkey. Torkiye Jeologi Kurultayi 163-165. Ankara. (Abstract)

Kraft, J.C., Aschenbrenner, S.E., Rapp, G. 1977. Paleogeographic reconstructions of coastal Aegean archeological sites. Science 195:941-947.

Kraft, J.C., Kayan, I., Erol, O. 1980a. Geographic reconstructions in the environs of ancient Troy. Science 209.4458:776-782.

Kraft, J.C., Aschenbrenner, S.E., Kayan, I. 1980b. Late Holocene coastal changes and resultant destruction or burial of archeological sites in Greece and Turkey. Proc. CCE Field Symp. Japan. IGUComm. Coast. Env.:13-31. Bellingham USA.

Kraft, J.C., Kayan, I., Erol, O. 1982. Geology and paleogeographic reconstructions of the vicinity of Troy. In Rapp, G., Jr., Gifford, J. (eds). Troy. Supplementary Monograph 4:11-42. Princeton Univ. Press.

Kraft, J.C., Belknap, D.F., Kayan, I. 1983. Potentials of discovery of human occupation sites on the continental shelves and nearshore coastal zone. In Masters, P.M., Flemming, N.C. (eds). Quaternary Coastlines and Marine Archeology:87-120. Academic Press.

Kraft, J.C., Kayan, I., Aschenbrenner, S.E. 1985. Geological studies of coastal change applied to archeological settings. Rapp, G., Gifford, J.A. (eds). Archeological Geology. Yale Univ. Press.

Laborel, J. 1989. The oyster-vermetid formations of the southeastern coast of Turkey (Region of Samandag-estuary of the Orontes River). In Biogenic Constructions in the Mediterranean, a review. Scientific reports of the Port Cros National Park. (In print).

Makarov, S. 1985. On the water exchange between the Black Sea and the Mediterranean Sea. Proc. Sci. Imp. Acad. St. Petersburg 51:6. (In Russian).

Neumann, W. 1954. Natural causes of mass-mortal of fishes in the Bosphorus. Hidrobiologie Mecm. Seri A. 2.2:74-77. Istanbul.

Pektas, H. 1953. Surface currents in the Bosphorus and Marmara Sea. Hidrobiologie Mecm. Seri A. 1.4:154-169. Istanbul.

Pirazzoli, P.A., Laborel, J., Saliege, J.F., Erol, O., Kayan, I. 1989. Holocene raised shorelines from Hatay (Turkey): paleoecological and tectonic implications. (In preparation).

Soysal, H. 1985. Tsunami and Tsunamis that effect Turkish coasts. Istanbul Univ. Deniz Bilimleri ve Cografya Enst. Bulteni 2:59-66. Istanbul.

Stanley, D.J., Blanpied, C. 1980. Late Quaternary water exchange between the Eastern Mediterranean and the Black Sea. Nature 285:537-541.

Sengor, A.M.C., Canitez, N. 1982. The North Anatolian Fault. Alpine Mediterranean Geodynamics, Geodynamic Series 7:205-216.

Titus, J.G., Leatherman, S.P., C. Everts, D. Kriebel, and R.G. Dean. 1985. Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, D.C.: Environmental Protection Agency.

Ullyott, P., Ilgaz, O. 1946. The hydrography of the Bosphorus. the Geographical Review 36:44-46.

Wharton, W.J.L. 1886. Report on the currents of the Dardanelles and Bosphorus. Admirality. London.

Uslu, T. 1977. A plant ecological and sociological research on the dune and Maquis vegetation between Mersin and Silifke. Sommunications de la Fac. des Sciences de l'Univ. d'Ankara. Serie C. Botanique 21.1:1-60. Ankara.

Yuce, H. 1985. Change of deep water salinity in Black Sea. Istanbul Univ. Deniz Bilimleri ve Cogr. Enst. Bulteni 2:93-98. Istanbul.

Mediterranean

Yuce, H. 1986. Water level changes in the Bosphorus. Istanbul Univ. Deniz Bilimleri ve Cografya Enst. Bulteni 3:67-78. Istanbul.

Yuce, H. 1987a. Characteristics of mean surface temperature-salinity and dissolved oxygene variations in the Aegean Sea. Istanbul Univ. Deniz Bilimleri ve Cogr. Enst. Bulteni 4:105-116. Istanbul.

Yuce, H. 1987b. Formation and distribution of the water masses in the northeastern Mediterranean Sea. Unpublished Doctorate thesis. Istanbul Univ. Deniz Bilimleri ve Cografya Enst. Istanbul. 151 pp.

THE INFLUENCE OF SEA LEVEL RISE ON THE NATURAL AND CULTURAL RESOURCES OF THE UKRAINIAN COAST

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INTRODUCTION

The Union of Soviet Socialist Republics has a larger mainland coastline than any other nation. However, concerns about global warming have not focused on sea level rise as much as on other implications of global warming. This relative emphasis is reasonable when one realizes that most of the Pacific, Arctic, and Baltic coasts are sparsely developed and that much of this coastal area is currently experiencing uplift. Aside from Leningrad, the most important exception is probably the Ukrainian Black Sea coast. Unlike most other parts of the U.S.S.R., this is a warm coast with a low barrier appropriate for tourism and substantial fishing that depends on natural systems that are sensitive to sea level.

Because no research has been done on the subject, we are unable to present any quantitative estimates of the impacts of accelerated sea level rise, and the lack of policy assessments makes it impossible for us to discuss response strategies. With those limitations, this paper briefly describes the activities along the Ukrainian Black Sea coast that seem vulnerable to a 50- to 200-cm rise in sea level, characterizes the coastal environment, and summarizes existing research on sea level trends and related coastal processes. We hope that this paper helps to encourage officials in the Ukrainian Republic to begin considering the implications of global warming and sea level rise.

RESOURCES AT RISK TO A RISE IN SEA LEVEL

The Black Sea coast of the Ukranian Republic is heavily developed and is one of the most populated coasts in the U.S.S.R. Fortunately, most of the development is concentrated on the highlands. Nevertheless, some coastal barriers and low terraces with elevations between 1 and 5 meters are completely occupied with buildings, including port facilities, sanatoriums, holiday homes, and camping establishments. The barriers along the Sukhoy and Adjalyk Lagoons, for example, have considerable port facilities. All of these economic resources would be at risk from a 50- to 200-cm rise in sea level.

The Sasyk Lagoon near the mouth of the Danube has been transformed into a freshwater basin, with river water used for irrigation. To prevent seawater from encroaching during heavy storms, a 12-kilometer-long, 4-kilometer-high dike was built; however, sea level rise could threaten the dike unless additional protection is constructed.

Along the Sasyk (near Eupatoria) and Dniester Lagoon, the coastal barriers have railroads and highways. For almost 40 years, the retreating shores have created difficulties for these critical transportation links, especially on the Dniester barrier. As a result, the Dniester barrier has been protected with a 5,000-foot-long concrete structure and rip-rap. On some parts of the Sasyk barrier the highway has been rebuilt somewhat inland. On the Tiligul and Kujalnik barriers, the highway is about 200 meters inland on a dike with an elevation of about 5 meters.

Because the coastal barriers are only 1 to 5 meters above sea level, future sea level rise threatens the aquaculture in the lagoons behind them. To prevent problems in the Usunlar, Burnas, and a few other barriers, the dunes have been artificially elevated. Because the Shagany, Alibey, Budaki, Tiligul, Usunlar limans are important for fish breeding, stabilizing barriers in front of the lagoons is important.

The natural conditions of the Black Sea coast encourage erosion and cliff retreat; average annual cliff erosion rates range from 0.1 to 4.5 meters per year (Shuisky and Schwartz, 1988). More than half of all the coastal protection structures attempt to retain artificial beaches, mainly groins and breakwaters. Seawalls are less widespread, and there are very few rip-rap structures. An accelerated rise in sea level would clearly diminish the effectiveness of existing structures, and probably necessitate increased artificial replenishments of beaches, as has already occurred in other countries.

The largest portion of the shoreline protected from landslides is along the Crimea coast, where 50 kilometers (almost 15% of the coast) -- mainly from Sarych Cape to Alushta -- is protected by short concrete groins with artificial gravel beaches between them. On the western Crimea coast, 5 kilometers are protected near Eupatoria, Saky, and Nikolayevka. Around Skadovsk the shore is protected by a one-kilometer-long seawall and an artificial beach, and there is a seawall of about 2 kilometers (concrete and rip-rap groins with an artificial sand beach) near Port Zhelezny. All of these structures will have to be fortified.

In a number of cases, artificial beaches have been used. The District of Ochakov, Koblevo, and along Odessa Bay each have about 2 kilometers of protected shore (solid concrete and stabilized slopes). In the City of Odessa, the shore is strengthened for 12 kilometers from Langeron Cape to Bolshoy Fountain Cape. Coastal protection structures were built near Illichevsk and on the Dniester barrier. All of these artificial beaches would require additional fortification as sea level rise accelerates.

Neither the U.S.S.R. nor the Ukraine has a single organization to deal with research on and exploitation of the natural and cultural resources of the Black Sea coastal zone as a whole. Instead, several regional organizations are responsible for part of the problem, for example, the Ukrainian Institute of Communal Building (Odessa) in the Ukraine, the Sea Coast Protecting Concern (Krasnodar) and the Sea Hydrotechnical Construction Institute (Sochi) in Russia, and the Sea Coast Protecting Concern (Tbilisi) in Georgia. Some aid is rendered by other organizations, such as the Sea Institute in Odessa, the Geological Station in Yalta, and the Hydrological Station in Vilkovo. Scientific research is carried out by laboratories and scientific groups in the Universities of Odessa, Rostov, Kuban, Moscow, and Kiev.

No administrative or economic organization on the Black Sea coast is concerned with solving the sea level rise problem. The lack of concern is caused by a number of factors, including the following: (1) the lack of reliable data about the disastrous effects of the rise on the natural and cultural resources of the Ukranian coast; (2) the relatively low rate of the rise of the Black Sea; (3) the economic system of the Ukraine, which does not encourage research on possible future disastrous consequences of the sea level rise; and (4) the low prestige of the scientists, whose opinion is usually ignored by state and economic institutions.

THE COASTAL ENVIRONMENT

Climate

The average air temperature at the coast varies from 9°C in the Odessa region to 16°C in the Yalta region. The mean temperature during the warm season, which lasts from April to October, is 22-24°C. Maximum temperatures occur in August when some days reach 30-35°C, the absolute maximum being 40°C.

The winter is fairly mild; in January, the average air temperature is -2.5°C in Odessa and about 6.5°C in the Yalta region. The temperature often falls below -10°C, but rarely below -20°C. The absolute minimum is -28°C. A severe winter happens once in 14-15 years, and a warm winter occurs once in 12-13 years.

Rain and fog prevail during the cold half of the year, and snow falls every year. The precipitation reaches 300-400 mm per year in the Odessa region, 200-300 mm in the Tarkhankut and Kerch peninsulas, and 500-600 mm in the southern coast of the Crimea.

The Black Sea water is warm; in the open sea its temperature is never lower than 6°C, reaching 19°C to 26°C in July and August and up to 28°C in shallow bays. In the winter, the temperature falls to 2-3°C at the shore; in narrow areas along the shores between the Danube delta and the Crimea, sea ice can appear, on the average, every 3-5 years. The sea freezes annually only at the Danube and Dnieper outfalls, and in small bays (Egorlyk, Tendra, Djarylgach, Perekop, and in the Kerch Strait).

Mediterranean

Geology

It is known (Shuisky, 1982) that the northern Black Sea coasts are characterized as classical liman coasts. Sediments in the limans and lagoons contain chemical elements and organic salts that can be used for medical treatment. Deposits of medicinal mud were found in the limans of Burnas, Budaki, Hadjibey, Mojnacki, Saky, and especially the Kujalnik liman. Those medicinal sediments have led to the establishment of numerous medical and sanatorium institutions.

The districts of the Danube delta, Shagany, Burnas, Kujalnik, Saky limans, Yalta, Theodosia, Kerch, and Skadovsk towns are the sites of mineral water baths. Their contents are varied including carbonates, hydrocarbonates, potassium and sodium, sodium and magnesium, and chalybeate waters. These deposits, too, serve as the basis for many medical institutions.

The Black Sea coast within the Ukraine borders also contains deposits of certain nonmetallic minerals, such as building stone, sand, gravel, pebbles, and sedimentary ores. The largest deposits are located near the Danube delta, near Odessa city, Sevastopol and Theodosia towns (building stone and raw cement materials), on the shores of the Jebrijan cove and Dnieper, and the Sasyk limans (sand and shells).

Among the natural resources of the Black Sea coast, the recreational resources are the most important. Warm water and a long warm season are the main factors that make the Black Sea a popular tourism and recreational area. In addition, coastal sediments contain important deposits used for medical purposes.

Sand and pebble sediment exploitation (removal) is forbidden within the coastal zone. The nearshore zone is the traditional location for the fishery industry. It is most intensive in the Danube, Dniester, Dnieper outfalls, Karkinit and Kalamit Bays, and Kerok Strait. The biggest seaports are Illichevsk, Sevastopol, and Kerch. Fish-breeding farms are situated on the shores of the Sasyk, Shagany, Budaki, and Tiligul limans.

There are many nature reserves on the Ukranian Black Sea coast. Their purpose is to save the gene banks and protect flora and fauna. The largest of them, the Danube reservation, is situated in the Danube outfall. It is oriented to ornithology and botany, as well as research on freshwater fish. In addition, there are important bird reservations in Chernomorsky (in Egorlyk and Tendra Bays) and Lebiashiy (on Lebiazhiy isles), and the Kalanchak Isles in Djarylgach Bay were declared reserve areas. The Martian Cape reserve on the southern coast of the Crimea Seas has a botanic orientation. The Kara-Dag reserve protects volcanic landscapes and relief shapes, and also the precious and semiprecious mineral and rock deposits.

SEA LEVEL MEASUREMENTS

There is a general awareness that the Black Sea has been rising for at least the past 200 years. This phenomenon was discovered by instrumented measurements at many locations in the U.S.S.R. and in other countries (Bulgaria, Romania, Turkey) on the Black Sea.

Although the measurements of the sea level changes began in Odessa in 1803, the first gauging rods turned out to be unreliable, and the data from 1870 are now the earliest used. In that year, controlled gauging stations were established in Odessa, Ochakov, Sevastopol, and Poti, which are now sources of precise data about the changing level. During 1916-23, measurements were begun in other places, generally in seaports. The data from those observations have been analyzed by many researchers (Blagovolin and Pobedonostzv, 1973; Pobedonostzv, 1972).

The direct observations with gauging staffs indicate a relative rise of sea level. On the Black Sea coast it consists of the two constituent phenomena: (1) the eustatic rise and (2) tectonic sinking of the littoral areas. The correlation of the eustatic and tectonic factors can differ, however, among various parts of the Black Sea. The level can rise, but also the littoral areas can rise, sink, or be stable, and the rates of these phenomena can be equal or unequal. It has been determined that there are 16 combinations of eustatic (E) and tectonic (T) factors (Shuisky, 1978).

1. +T>-E - very strong, relative sinking, never rises
2. +T<-E - strong, relative sinking, never rises
3. +T4>+E - weak, relative sinking, usually does not rise
4. +T<+E - weak, relative sinking
5. -T>-E - very weak, relative sinking
6. -T<-E - weak, relative sinking
7. -T>+E - moderate, relative sinking
8. -T<+E - strong, never turns into sinking
9. +T=+E - the level state is relatively stable
10. -T=-E - the level state is relatively stable
11. +T=-E - strong, relative sinking
12. -T=+E - strong, relative rising
13. Stable T with +E - rising
14. Stable T with -E - sinking
15. Stable E with +T - relative sinking
16. Stable E with -T - relative rising

This pattern of the T and E correlation should serve as a basis for the coastal zone dynamics analysis. (For the most part, the coastal zone is indifferent to the causes of both stability and changing with various rates. It is the stability, rising, or sinking at various rates that is important. The actual rates of positive and negative long-term changes in different physical and geographic conditions of a sea coast are of particular significance.)

Mediterranean

There is a lack of practical information in connection with sea level rise. Although scientific research on the process is under way, there is still no interest on the part of industrial, economic, and financial organizations despite the important natural and cultural resources on lowlands (Stepanov and Andreev, 1981). The most serious reports of the researchers on the natural processes connected with the sea level changes were published in collections such as "Sea Level Fluctuations" (Kaplin et al., 1982a) and "The Sea and Oceanic Level Fluctuations" (Kaplin et al., 1982b).

The analysis of the modern data on Black Sea level change within the Ukraine led to the conclusion that there is a relative rise at 26 stations and sinking at only one (Kherson, situated in the Dnieper outfall). The relative rising rates vary considerably from place to place -- from +5.10 to -1.50 mm/year (Table 1), with an average of 1.40 mm/year. The higher rates prevail between the Danube Delta and Dophinovka Lagoon and in the Dnieper outfall. The information on modern relative changes referred to here were verified by other geomorphological and geological research methods (Melnik and Mitin, 1982; Ivanov and Shmuratko, 1982).

SEA LEVEL RISE AND COASTAL PROCESSES

The influence of multicentennial sea level change on coastal development in different seas has been studied quite extensively. Much research was carried out to define the curve of sea level rise in the Holocene period using stratigraphic, radiocarbon, oxygen, palynologic, and archeologic methods. These studies led to the construction of Black Sea coast maps and the distribution maps of the abrasive and accumulative relief shapes for the last 50,000 years. In Odessa University, the climate-stratigraphic method is being worked out, based on the astronomic climate theory of M. Milankovich. Transferring a radiation curve into a climate (or eustatic) curve, we use the sea level as an integral index.

As far as the annual and centennial changes (algebraic sum of E and T) and their influence on coasts, the study of this question in the U.S.S.R. is inadequate at present.

The methods for calculating the nearshore bottom abrasion rates have almost been completed. These methods also take into account the T and E correlations. Finally, we will be able to quantitatively estimate the impact on the shore processes of the sea level change rates and figures.

But it is already obvious that a more rigorous analysis of such a phenomenon -- its nature and its impacts on coastal systems -- is extremely urgent. Such an analysis should address sea wave activity and the eustatic factor interaction. It is also necessary to carefully check the benchmark tidal gauges, and their steadiness, where especially high relative rising rates are noticed. We know (Klige, 1981) that about 14.3% of the general world ocean shoreline has been rising at more than 2 mm/year.

Table 1. Average Relative Fluctuations of the Black Sea Level Along the Shores of the Ukraine (mm/year)

Coastal points	Duration years	Rates of sea level fluctuations (mm/year) Average	Precision
1. Sulina (Romania)	1896-1988	+1.60[a]	±0.13
2. Primorskoje	1951-1975	+1.80	±0.78
3. Lebedevka	1950-1987	+1.59	±0.51
4. Bugaz	1945-1987	+2.01	±0.66
5. Illichevsk	1958-1987	+1.51	±0.48
6. Odessa	1875-1988	+5.10	±0.32
7. Yuzhnij	1974-1988	+1.26	±0.43
8. Ochakov	1874-1985	+0.97	±0.27
9. Nikolayev	1916-1983	+0.52	±0.19
10. Stanislav	1925-1970	+0.85	±0.25
11. Kasperovka	1916-1970	+2.10	±0.14
12. Kherson	1916-1987	-1.50[b]	±0.54
13. Gerojskoye	1951-1986	+3.70	±0.79
14. Tendra Spit	1885-1987	+2.26	±0.35
15. Lazurnoye	1964-1988	+1.10	±0.18
16. Skadovsk	1923-1985	+0.82	±0.16
17. Khorly	1923-1985	+0.95	±0.11
18. Chernomorskoye	1927-1986	+1.04	±0.41
19. Tarkhankut	1878-1986	+1.21	±0.23
20. Yevpatoriya	1917-1986	+0.72	±0.14
21. Sevastopol	1875-1986	+0.91	±0.15
22. Balaklava	1951-1985	+0.60	±0.63
23. Yalta	1928-1988	+1.10	±0.22
24. Alushta	1928-1987	+1.30	±0.33
25. Sudak	1931-1987	+0.68	±0.28
26. Feodosiya	1923-1987	+0.35	±0.18
27. Kerch	1882-1970	+0.45	±0.15

[a] + = Sea level is rising.
[b] - = Sea level is sinking.

By drawing analogies from storage lakes and from the Caspian Sea in the U.S.S.R., we can propose the following steps to respond to intensive sea level rise expected as a result of the greenhouse effect:

- A survey of both the most and the least valuable natural and cultural resources states, and of their locations along the Ukranian coast, is needed. An assessment of the morphology and coastal dynamics is also important. The results should be used to identify the places requiring protection from the seawater invasion -- in the first phase, second phase, third phase, etc. The financial and material resources to accomplish the necessary measures must also be identified.

- Some of the cultural resources can be relocated to secure areas. Others can be dismantled because their work is complete. The remainder may need protection from the advancing sea when the level rises. Various combinations of these approaches are possible.

- The protection of the most valuable natural and cultural resources on the lowlands can be realized by using protective seawalls or dikes, following the example of the Netherlands, Belgium, Great Britain, and China. The lowland in the State of New Jersey (U.S.) is also protected and we have taken such experience into account here in the Ukraine -- not, however, as protection from the eustatic level rise, but as protection from heavy storms.

- Elevation of artificial sandy dunes can be used where the appropriate conditions exist, especially in the areas of active wave and eolian accumulation of sandy sediments. Dune formation should precede the sea level rise.

- The long-term effect on the coastal zone of artificial placement of sediments usually promotes the increase of beaches and accumulative forms. In the Holocene period of the Black Sea shelf, during the periods of coastal zone sediment activation, the areas of accumulative forms increased, and in the periods of sediment deficit, these areas decreased, down to an entire washout. In the modern stage of the Black Sea coast development, most of the barriers and spits developed following a sea level rise, especially where the sediment reserves are sufficient. Accordingly, we cannot rule out the possibility that the coastal zone is artificially saturated with sediments that will also promote the rise of the accumulation forms after the accelerated sea level rise in the following decades.

- Since the Black Sea coastal zone structure is very complicated, there is no single step that will resolve the sea level rise problem. A combination of measures is necessary.

It is unclear whether the disastrous sea level rise is something certain and unavoidable. But in the last year, the idea of such a rise caused a tide of new research, which widely discussed various causes of the world ocean level's changing nature, including the influence of the anthropogenic factor.

Hoffert and Flannery (1985) came to the conclusion that the nonstationary impact of CO_2 on the climate (in the time scale of 10-100 years) is conditioned by simultaneous influence of several external factors (outer-atmosphere insolation, volcanic aerosols, concentration of CO_2 and the other greenhouse gases, and also by internal changeability of the climatic system (first of all, the internal oceanic dynamics).

In the U.S.S.R., many scientists have also come to such conclusions. For instance, on the basis of the analysis of the latest comprehensive observations, results, and climate numerical modeling, Kondratiev (1986, 1987) concluded that existing information is insufficient for elucidation of global climate trends and the complicated changeability and causal conditionality of climate. The tendency to ascribe observed climate temperature to CO_2 influence encounters has been rejected by some for a number of reasons, including the character of the atmosphere and ocean interaction.

Long-term observations of the abrasion and accumulative shore dynamics cause me to make other correlations with the latest Black Sea level relative changes. The connections are not significant. The causes are still unknown, the nature of such interaction is not clear, and the complex analysis of the results has not yet been carried out. But still, the results received are sufficient to offer a series of theoretical theses, which can explain the causes of the modern seashore retreat.

Although the Ukraine has no policy to address sea level rise, long-term research on the winds, waves, currents, and changing level is continuing. In this case, it is important to carry out the synchronic observations of the cliffs, beaches, barriers, spits, and changing longshore drifts. We have already received such data, but laboratory work and theoretical analysis, which will be completed in 1990, are also required to demonstrate the connections between the sea level changes and the changing storm strength, and the changing sea level and cliff abrasion rates. We will look at the shoreline accumulative forms, retreat rates, drift distribution, and the interrelationships between the destructive and accumulating processes.

CONCLUSION

Before we can sensibly specify or implement policies to protect the Ukranian coast from rising sea level, we must understand the implications. To do so, scientists will need the enthusiastic encouragement of policy officials, who have much of the information necessary for meaningful assessments.

Scientists will also have to cooperate better with policy officials and with each other. The issue is clearly interdisciplinary, which means that the issues that professionals in one field prefer to study may not address the questions that people from other fields are -- or at least should be -- asking. In the case of sea level rise, policy makers need coastal scientists to determine which land would be inundated or eroded, or which would experience increased flooding or salinization, and to assess the ecological implications; they need engineers to estimate the cost of protecting all the coastal areas, as well as recommendations for incorporating sea level rise into current infrastructure planning; and they need economists to estimate the costs of protection versus allowing the sea to advance. In turn, the researchers need policy makers to provide continual guidance on the type of information most useful for decision making.

BIBLIOGRAPHY

Blagovolin, N.S., and S.V. Pobedonostsev. 1973. Recent vertical movements of the shores of the Black and Azov seas. Geomorphology 3:46-55 (in Russian).

Mediterranean

Hoffert,. M.I., and B.P. Flannery. 1985. Model projections of the time-dependent response in increasing carbon dioxide. In: Potential Climatic Effects of Increasing Carbon Dioxide. MacCracken, M.C., and F.M. Luther, eds. Washington, DC: U.S. Department of Energy, p. 149-190.

Ivanov, G.I., and V.I. Shmuratko. 1982. Oceanic levels during the Pleistocene. In: Sea Level Fluctuations. Moscow: Moscow State University Publishing House, p. 60-75 (in Russian).

Kaplin, P., R. Klige, and A. Chepalyga, eds. 1982a. Sea Level Fluctuations. Moscow: Moscow State University Publishing House, 310 p. (in Russian).

Kaplin, P., R. Klige, and A. Chepalyga, eds. 1982b. Sea and Oceanic Level Fluctuations for 15,000 Years. Moscow: Nauka Publishing House, 230 p. (in Russian).

Klige, R.K. 1980. The Ocean Level During Geological Time. Moscow: Nauka Publishing House, 145 p. (in Russian).

Klige, R.K. 1981. Estimations of Contemporary Seashores Vertical Changing in Connection with Ocean's Level/Coastal Zone of the Sea. Moscow: Nauka Publishing House, p. 11-17 (in Russian).

Kondratiev, K.Y. 1986. Natural and anthropogenous changing of climate. Heral of Acad. Sci. U.S.S.R. 10:30-39 (in Russian).

Kondratiev, K.Y. 1987. Carbonic acid gas and climate: Data of observation and numerical modelling. New All-Union Geogr.Soc. 119(2):97-105 (in Russian).

Melnik, V.I., and L.I. Mitin, eds. 1982. Geology of the Ukrainian Shelf: Environment, History, and Methods of Investigations. Kiev, Naukova Dumka Publishing House, 175 p. (in Russian).

Pobedonostsev, S.V. 1972. Contemporary vertical changing of the seashores around the European part of the U.S.S.R. Oceanology 12(4):460-469 (in Russian).

Shuisky, Y.D. 1978. Types of Coasts of the Earth Globe. Odessa: Odessa State University Publishing House, 75 p. (in Russian).

Shuisky, Y.D. 1982. Limans and liman's coasts. In: Encyclopedia of Beaches and Coastal Environment. Schwartz, M.L., ed. Stroudsburg: Hutchinson Ross Co., p. 516-518.

Shuisky, Y.D., and M.L. Schwartz. 1988. Human impact and rates of shore retreat along the Black Sea coasts. Journal of Coastal Research 4(1):405-416.

Stepanov, V.N., and V.N. Andreev. 1981. The Black Sea -- Resources and Problems. Leningrad: Hydrol.-Meteorol. Publishing House, 157 p. (in Russian).

COASTAL MORPHOLOGY AND SEA LEVEL RISE CONSEQUENCES IN TUNISIA

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INTRODUCTION

The consequences of sea level rise are already evident on the 1300-km Tunisian coast (Oueslati et al., 1987). Almost the entire landscape of beaches, rocky low coasts, salt marshes -- and particularly cliffs -- is retreating (Oueslati, 1989). In many cities, erosion is threatening hotels, dwellings, salt pans, industrial establishments, and the public infrastructure; the nation's archeological heritage is also at risk. The few sections of the coast not yet suffering erosion are generally in undeveloped areas at the mouths of rivers and the bottom of some bays.

The vulnerability of the Tunisian coast has been particularly evident in the aftermath of storms. For example, a January 1981 storm in the Gulf of Tunis caused severe damage and completely removed beaches along many stretches of coast, especially the suburbs of the capital. With a stable sea level, the waves could have rebuilt these beaches after the storm. But the Bruun Rule shows that when sea level rises, offshore portions of the beach system must gradually rise as well, implying that much of the sediment deposited offshore during storms will remain there. The experience in Tunisia after the 1981 storm has been consistent with this theory.

Water tables are also rising, with a resulting salinization of low-lying areas, particularly in subsiding areas such as those along the Gulfs of Tunis and Gabes (Oueslati, 1989). Rising seas have also transformed many occupied (in ancient times) areas into wetlands, and may soon do the same to the cultivated areas of antiquity (Oueslati, 1989; Paskoff and Oueslati, in press).

In response to these problems, coastal defense structures are becoming increasingly common on the Tunisian coast. Seawalls are most common, with dimensions scaled to the size and value of the buildings being protected. Along the Gulf of Tunis and at Mahdia, the structures are very large. On the other hand, many human activities are increasing the vulnerability of the coast: extraction of beach sand for construction and the loss of marine vegetation as a result of pollution directly weaken the coast. Dams for managing water resources and jetties at harbor entrances diminish the natural supply of sediment, which might otherwise offset some of the erosion (particularly in cases where the littoral drift is mostly in one direction, such as Bizerte and Ghar el Mebah, where beaches downdrift of the jetties are eroding rapidly).

The next two sections briefly summarize the likely impacts of an accelerated rise in sea level on the Tunisian coast and the possible responses. Although Tunisians have not studied in detail the implications of sea level rise for each particular coast, the reader can better understand our vulnerability by considering the environmental conditions of the coast in more detail; this information is provided by the final sections of this paper.

IMPACTS OF ACCELERATED SEA LEVEL RISE

About half of Tunisia's population and most of its major cities are on the coast (Figure 1). The many ports range from industrial-sized harbors to those servicing small fishing or pleasure villages. Most of the nation's industrial and tourist establishments, and all of its salt production facilities, are very close to the shore. The remainder of the coastal lowlands are cultivated -- mostly for cereals, although fruits and vegetables are also profitable in the Medjerda River Delta and around urban areas where they can be sold to local residents. All of these activities are at risk.

A rise in sea level of 50 to 200 centimeters would almost undoubtedly result in a great retreat of the entire coast, the extension of salinized areas, and the disappearance of some natural systems. Along the Gulf of Tunis, important parts of the Medjeida delta (Figure 1) and the Milian plain would be inundated; most lagoons either would disappear or would be shifted substantially landward; and Tunis and its suburbs would be seriously threatened. Along the Gulf of Gabes, coastal systems could probably shift landward. New wetland ecosystems may form on the alluvial plains where the current ecosystems are inundated. Figure 2 illustrates the Kerkna archipelago, where the outer parts of Sfax and Gabes may be seriously damaged -- perhaps even more than Tunis, given current subsidence trends. Sea level rise at sfax is estimated to be 5.7 mm/yr, a rate almost four times higher than the worldwide average (Pirazzoli, 1986).

In the central part of Hammamet Gulf, the most important impact would be saltwater intrusion into cultivated alluvial plains. Meanwhile, the wetlands behind the foredunes may be converted into open-water lagoons. Cities in the northern and southern parts of this gulf may be severely damaged, especially the large tourist complexes of Hammamet and Sousse Monastir. Along the eastern coast of the Cap Bon peninsula and at Dimass, the lagoons seem likely to be completely lost, because rocky high ground (a consolidated Tyrrhenian bar) immediately inland would preclude a landward migration. Similarly, in the Sahel, the narrow alluvial plain would be squeezed between an advancing shore and the rocky high ground.

Rising sea level also threatens fishing, a major occupation and an important Tunisian tradition. The two largest fisheries are located at the inlets of the

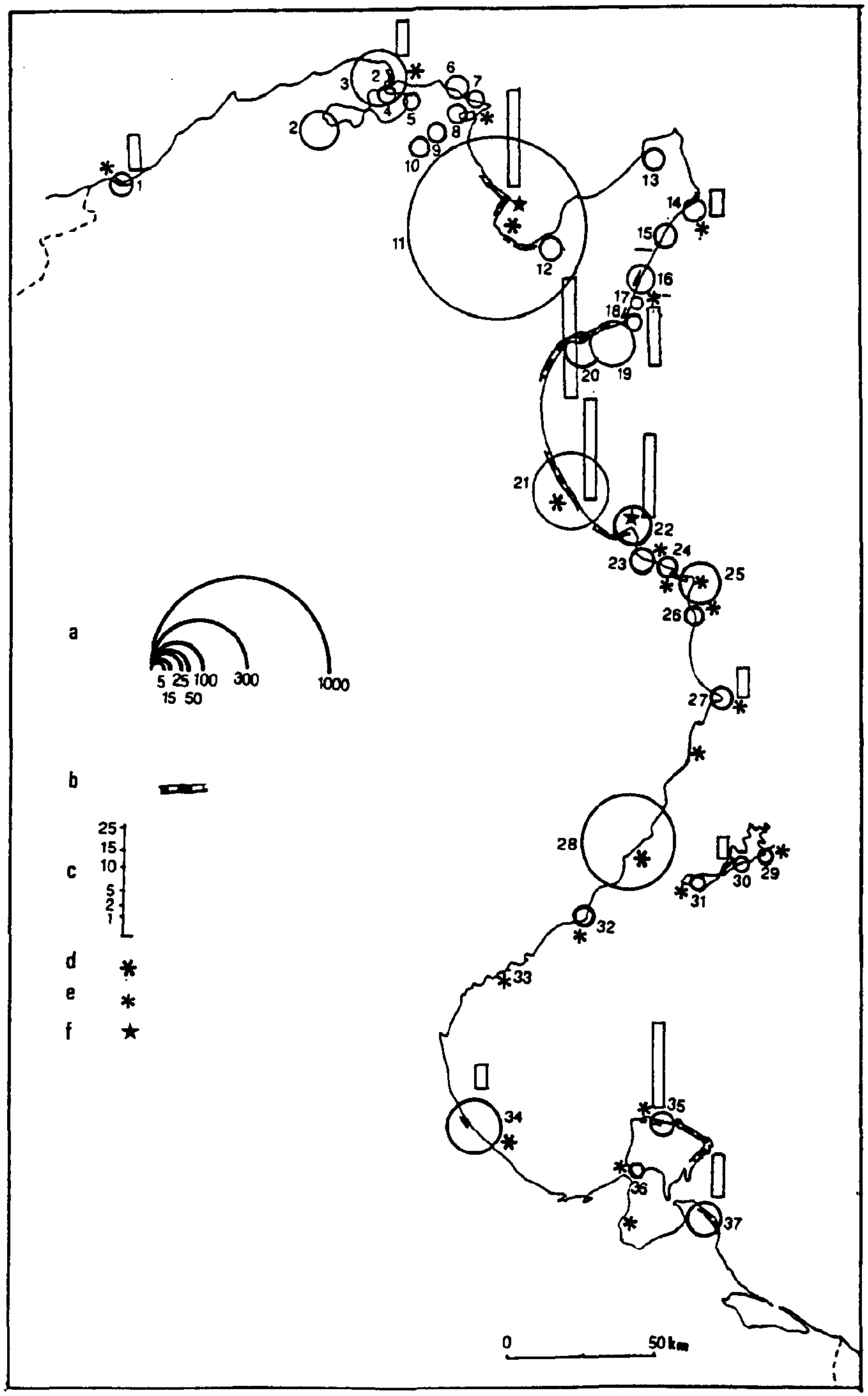

Figure 1. Cultural and economic features (urban population, hotels, and ports) [Legend: a = towns wholly or partly installed on unconsolidated lowlands - 1,000s of inhabitants; b = zone occupied by important tourist area; c = hotel capacity - 1,000s of beds; d = ports; e = fishing ports; f = marina]

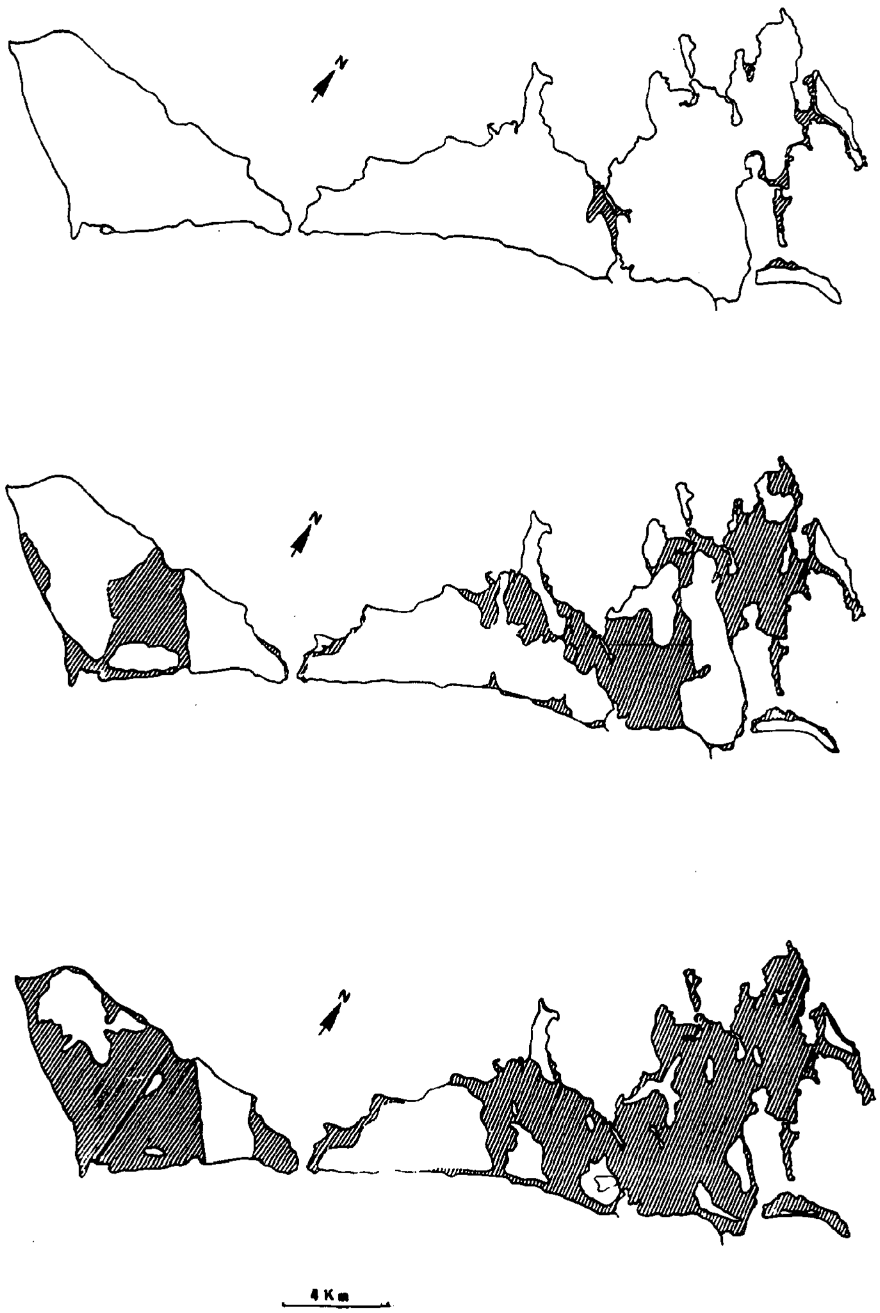

Figure 2. Kerkna archipelago -- possible consequences of 50, 100, and 200 cm rise in sea level (hatched areas would be invaded by sea water).

Ichkeul and Bhiret el Biban Lagoons, which would be drastically altered by sea level rise. Along the Gulf of Gabes (particularly Jerba and Kerkna Islands) fishing is still conducted by the traditional method of using palm fronds stuck into tidal flats to trap fish brought in by tidal currents; along other parts of the gulf, many families feed or support themselves by gathering cockles in the tidal flats. But sea level rise would inundate most of the tidal flats. Breeding facilities for fish (Monastir), oysters (Lagoon of Bizerte) and other shellfish would also be at risk.

Finally, we could expect the erosion and loss of a major portion of the many archeological sites that are among the most important constituents of Tunisian culture.

RESPONSES

Like other nations discussed in this report, Tunisia could respond to sea level rise either by holding back the sea or by retreating landward. Most of the structural approaches described by Pope (Adaptive Options, Volume 1) would be appropriate for some part of the coast, and in many cases, the necessary structures would not have to be erected for several decades. By contrast, although shores will retreat and settlements will be relocated in many (if not most) parts of the coast, the anticipatory strategies presented by Titus (Adaptive Options, Volume 1) would be difficult to implement, because they presuppose that (1) officials are willing to modify current activities to protect against crises not likely to occur for several decades, and (2) that environmental protection is sometimes important enough to prohibit construction. Neither of these assumptions yet applies to coastal management in Tunisia.

The inhabitants of the coast are somewhat aware that erosion and salinization threaten their fields and dwellings, but they generally are not aware that rising sea level is causing the problem. Similarly, it would be obvious to mudflat fishermen that if sea level rise inundated the flats, their livelihood would be threatened. Because their ancestors have pursued this traditional occupation for centuries, the fact that the crisis would confront their grandchildren (instead of them) would not substantially reduce their concern. But no one has informed them about this problem.

Currently, only two state agencies are even concerned about current beach erosion problems. Although they have tried solutions, the projects have been arbitrary, scattered, and poorly studied. They have been mostly ineffective and in some cases have made the problems worse. Managers almost never consider the relationship between sea level rise and current problems. There is a complete lack of legislation and policies to protect the coastal environment. When coastal areas are developed, no one is considering the argument by Everett (Environmental Implications, Volume 1) that in the long run, a hectare of mudflats might feed more people than a hectare of agricultural land, and that we should therefore set development back farther from the shore.

THE COASTAL GEOMORPHOLOGY

Cliffs

The most important and extensive active cliffs are characteristic of the northern coasts (characterized by relatively deep water and exposed to strong northern and northwestern swell) of the country where they generally average 15-30 m in height. In rare contrast, such as at the extremity of the Cap Bon peninsula, they are higher than 50 m.

For the most part, these cliffs consist of sandstone and clay and rarely are composed of rocks, limestone, or marls. Rocky cliffs (eolianites and marine quaternary limestones) that alternate with fluvial layers often show remarkable differential erosion rates. However, such cliffs are usually only a few meters high (5-10 m).

Along the entire northern coast, the cliffs are retreating, sometimes quite rapidly, under the attack of north and northwesterly swells. Measurements taken during 1982-87 on cliffs 7 to 15 m high, formed in the Numidian flysch, showed them retreating at rates varying from 1.5 to 8 m/yr. Because of the very humid atmosphere and steep coastal slopes, landslides are frequent wherever clays dominate. Landslides along the northern coasts are also threatening human dwellings. Fortunately, this area is not yet densely occupied.

There are fewer eroding cliffs on the eastern coasts. For the most part, they are a few meters (2-5 m) high and are formed in Pleistocene materials (especially alluvium, eolianite, and marine limestone). The only important cliffs there are along the Gulf of Gabes and its surroundings, where they are formed in gypsum-rich clays covered by a strong calcrete (attributed to the lower Quaternary) or a gypsum crest (late Pleistocene). These latter cliffs, generally averaging 7 to 15 m in height, are sometimes prone to high rates of erosion, despite the small waves. There is severe erosion of the important archeological sites that are visible in the upper part of the cliffs (e.g., on western coast of the Kerkna archipelago and at Nadhour between Sfax and Gabes Town).

Unconsolidated Low Coasts

Unconsolidated low coasts are extensive in Tunisia and are found primarily at the inland margin of wide gulfs (Tunis, Hammamet, Gabes) and bays (Tabarka and Bizerte). They are especially developed and predominant along the eastern portion of the coastal landscape. They generally consist of alluvial plains formed by fine material dating back to the late Quaternary, mainly the Holocene and the historic times. The seaward margin of these lowlands is characterized by sandy beaches, small cliffs, or salt marshes. These are found in the Gulf of Gabes and its surroundings where tides are high and may reach 2 m at spring tides.

Careful observations reveal significant regional differences in these lowlands because of physical conditions, human activities, and the orientation of the coast. This section describes several distinctions:

- A narrow alluvial plain situated at the inland portion of a bay bordered by sizable cliffs and intersected by small but active wadis. The shoreline is characterized by a large sandy beach favoring the formation of extensive dunefields and important human settlements inland.

This is the case of the Tabarka and Zwaraa coasts, which are situated near the Algerian border. The plain, averaging 4 m in height, is made of sand and clay sometimes containing more or less well-rounded pebbles. It covers about 5 km^2 and is partly occupied by the Tabarka agglomeration.

This area boasts one of the best sandy beaches of the country. Extending over 10 km, this beach stretches to 50-70 m in width, especially around the mouth of wadis. It benefits from two important sources of sediments: (1) wadis that cross in their higher courses steep slopes formed in the Numidian flysch, and (2) rocky active cliffs situated at the borders of Tabanka Bay. Well exposed to the ambient winds, this beach formed an important source of sand to be blown inland to create an extensive and thick dunefield (Ouchtata field) that is today largely stabilized by a planted forest. The system must have been repeated in the geologic past, because recent dunes cover Pleistocene eolianite. The assemblage of forms is crossed by active wadis that in turn supply the shoreline with sand.

- A narrow, largely alleviated plain, occupying the inner margin of a bay and devoid of active wadis. The shoreline is also characterized by a sandy beach favoring the formation of large dunes.

In Bizerte, situated on the northern coast, the plain is 200-700 m wide and covers about 3.5 km^2. Its altitude, which rarely exceeds 10 m above sea level, is sometimes lower than 2 m. This is especially the case in the outer section, which is often characterized by a swampy landscape. Sediments are mainly composed of sand and silt, except in the northern part where clay predominates. The sediments are locally quite thin (50 cm-1.5 m) and cover marine consolidated deposits inherited from the Tyrrhenian stage. The beach covers about 12 km. At its eastern part, well exposed to the northwest winds, is a large field of sand dunes (Rmel's field), now almost wholly colonized by a planted forest.

- A wide deltaic plan formed by a large wadi and situated in a gulf. The shoreline of this plain is characterized by sandy beaches and lagoons.

The deltaic plain of the Medjerda, the largest and most important river of the country, covers about 600 km^2. It is generally 1-10 m above sea level, but in some parts it may be less than 30 cm above sea level. Its sediments are mainly composed of sand and clay. Swamps occupied a very large portion of the area before the draining operations undertaken since the French colonization. Today the swamps are found only in the lowest section of the delta, especially near the shore.

The formation of this deltaic plain dates back mainly to the Holocene. But its progradation was significant during historic times because of the increased sediment carried by the river following deforestation. The ancient archeological site of Utica illustrates such a history of alluviation. This site is today more than 10 km inland, whereas it was a harbor in ancient times.

The coast is characterized by a relatively wide (10-15 m) sandy beach and a low (2-3 m) and narrow (30-60 m) foredune. The northern part shows a typical spit at the location of a former mouth of the Medjerda River, which was abandoned following the 1973 flood when the river shifted southward to occupy an artificial channel originally designed to drain the excess water during floods. The southern part of the coast is well exposed to the northwestern winds, which favored the formation of a dunefield (Raoued Gammarth) now almost entirely wooded. The coast is also characterized by a lagoonal landscape (see the paragraph describing lagoons).

- An alluvial plain at the mouth of a major river and situated at the inland margin of a deep bay. The coast is characterized by a densely occupied sandy beach.

This is the case of the coast of the bay of Tunis, which is largely occupied by the southern suburbs of Tunis, the capital of the country. The alluvial plain is an accumulation mainly of the Miliane wadi, Tunisia's second largest river. Relatively wide (approximately 36 km) and low (2-10 m), this coastal plain was created essentially during historic times because its material covers marine deposits dated from about 2,750 years ago and certain antique ceramics. The alluvial deposits are generally fine (sand and clay), but can locally contain some coarse layers of mixed and more or less well-rounded pebbles.

The beach is about 10 m wide and is generally accompanied by a small foredune (1-2 m high and 10-30 m wide). Dunes are much more prevalent on Tunis's eastern coast than on its northern coast. An example is the small dunefield of Borj Cedria-Soliman, which is partly covered by a planted forest. The land immediately behind the foredune, is almost everywhere, swampy and colonized by salt plants.

- A straight coast with active streams, narrow alluvial plain, broad sandy beaches, extensive dunefields, and absence of major human settlements.

These characteristics are prevalent along the coast between Wadi el Abdi and Wadi el Mgaiez on the northwestern face of the Cap Bon peninsula. The plain, averaging 800 m wide and 5-10 m high, is limited landward by a dead cliff. Its deposits are generally made of sand and silt and often lie on a bedrock platform inherited from the Tyrrhenian transgression. This coastal type is prominent only around the mouth of wadis that in their higher and middle courses drain steep slopes across Miocene marls and sandstones. The beach is generally 10-15 m wide, but can stretch 50 m wide in some river mouths. The dune fields are sometimes very extensive and often cover late Quaternary eolianites.

- An alluvial plain at an inland margin of a large gulf intersected by active wadis. The shore is characterized by a broad sandy beach, with localized development, and a lagoonal landscape.

This is the case of a large part of Hammamet Gulf, especially northern Hergla and southern Sousse. The plain covers about 150 km^2; its height varies from 2 to 10 m. The seaward parts of the coast are often swampy and saline. The beach is generally well developed, stretching into 40 m wide in many places. But foredunes are large in only two cases: in Skanes and between Hergla and Selloum, where it is largely wooded. Lagoons characterize segments of the northern Hergla and southern Sousse coasts. Except for the area between Hergla and Bou Ficha, the Hammamet Gulf coast has been subjected to extensive human development, particularly hotel construction in Hammamet, Monastir, and especially Sousse.

- A relatively straight coast devoid of active wadis and characterized by a narrow coastal plain and wide sandy beach. The human installations vary from one region to another.

In four main regions -- Mahdia, Chebba, northeast Jerba, and Zarzis -- the coastal plain is sometimes only a few hundred meters wide. Its altitude may be, such as at Mahdia, less than 3 m above sea level, where there is extensive swampland. Generally this plain is situated downdrift from a consolidated coastal barrier or a dead cliff dating back to the Tyrrhenian stage.

At Mahdia the beach is about 10-15 m wide, and the foredune is always small (2-3 m high) and discontinuous. The coast is partly developed, especially in the segment next to the city of Mahdia (residences, industries, and hotels). At Chebba the beach is wider and is sometimes punctuated by Pliocene sandstone outcrops. It is also has an extensive dunefield inland, now artificially fixed, and the coast is still unoccupied.

The beach of Jerba, extending almost 20 km, is frequently wide (7-20 m) and is also punctuated by rocky outcrops (marine limestones, eolianites, and calcretes). It is not continuous, forming elongated spits at three sites. The foredune is locally well developed. Sand dunes, sometimes covering large areas are often occupied by orchards and dwellings. The major part of this coast is occupied by hotels often built close to the shoreline.

At Zarzis, the coast is largely developed, especially with tourist facilities. The beach resembles that of Jerba in its width and its outcrops of rocky material. But the foredune is relatively smaller.

- A coast marked by a sebkha landscape fringed by a microcliff or a sandy beach, especially at the mouth of active wadis.

These characteristics predominate along a large part of the coast of the Gulf of Gabes. The lowlands, composed mainly of fine sandy and silty materials, are generally 5-10 m high. The most important of them are linked to relatively large wadis and are 2-10 km wide. In some cases, such as at Kerkna and Jerba, the sandy and silty material is thin (50 cm-1 m) and covers a marine limestone dating back to the Tyrrhenian.

Mediterranean

Sebkhas[1], salt marshes found in northern Africa, are a major feature of the coastline. The largest sebkhas are inherited from Holocene eustatic sea level oscillations and occupy the position of ancient lagoons or bays that have been filled by continental deposits.

Beaches occupying the mouth of wadis are relatively wide (10-20 m) and are accompanied by small (2-5 m) but sometimes well-defined foredunes. In some cases the beach forms a spit. Except for the coasts at Gabes and Chaffar, these beaches are still unoccupied.

Wetlands

Wetlands occupy the seaward parts of the alluvial plains (Medjeida, Miliane, Gulf of Hammamet, Mahdia) and can be associated with sebkhas. The most important wetlands exist along the southern coast (Gulf of Gabes and its surroundings) and correspond to typical tidal marshes favored by the low energy of the coast and the high tides. Such tidal marshes occupy different positions (behind spits and capes, bottoms of creeks, mouths of wadis) and have a low vegetation dominated by Salicornia. They also present some particularities in comparison to tidal marshes of other climate zones. They are always characterized by the existence of dunes and plants adapted to the aridity, and they often extend landward into the sebkhas and alluvial plains.

Lagoons

Lagoons are numerous and varied along the Tunisian coasts. But according to their morphology, hydrology, and position in comparison with the sea, they can be classified into two main categories: (1) wide lagoons with continued communication with the sea and (2) those isolated from the sea with a sandy bar, and lagoons invaded only during the stormy season.

Four main lagoons belong to the first category:

- The Lagoon of Bizerte covers about 15,000 ha and connects to the sea through a large channel, now partly developed.
- The Lagoon of Ichkeul (12,000 ha) is linked to the Bizerte Lagoon through the Tinga emissary and responds to an important seasonal variation. It is occupied by marine water only during the dry season. In the winter it is the recipient of considerable continental discharge because of the large wadis that divert into it.
- The Lagoons of Ghar el Melah (3,000 ha) and Tunis (4,000 ha) are cut off from the sea by a sandy coastal bar, but connected to the sea by dredged inlets.

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[1]An arabic term for a flat area, close to the water table and characterized by a salt material.

- The Lagoon of Bhiref el Bibane, situated near the Libyan border, has a surface of about 30,000 ha. It is bordered on the seaward side by a consolidated littoral bar dating back to the Tyrrhenian. Connection with the sea is possible through some natural inlets, among which the inlet of S. Mohamed Chaouth is the most important.

Lagoons of the second category are connected to the sea only through natural inlets that generally open only during storms. These lagoons are numerous and exist in the Gulf of Tunis (St. Sidi Bakhoun, St. Ariana), in the eastern coast of the Cap Bon peninsula (St. Bouzid, St. Klibia), in the Gulf of Hammamet (St. Assa Jiriba, St. Halk el Mungil), and in the Sahel (St. Skanes, St. Dimass).

In all of these situations, the inland area is often swampy. The salinity of the lagoons and the temperatures are often higher than in the open sea. They also increase toward the south. In the Bhiret el Bibane Lagoon, for instance, the temperature can climb as high as 40°C, and the salinity increases in the summer when sirocco winds blow.

CONCLUSION

Given our inability to effectively address problems due to current relative sea level rise, one might pessimistically assume that coping effectively with accelerated sea level rise will be close to impossible. But there may be a positive aspect: As late as 1983, for example, the United States was failing to address current trends of sea level rise, but widespread public attention to the greenhouse effect prompted officials to look into the issue of sea level rise and to direct their staffs to at least take current trends into account. As the paper by Klarin and Hershman (Legal and Institutional Implications, Volume 1) illustrates, five years later officials were preparing for an accelerated rise. The same thing could happen here. In Tunisia, there is sufficient technical expertise to begin preparing for a rise in sea level, but neither the public awareness nor the official recognition necessary to start the process.

APPENDIX: ADDITIONAL DETAILS ON THE CLIMATE OF COASTAL TUNISIA

Some very important regional differences can be observed between the northern and the eastern coasts, particularly in the rainfall volume and wind characteristics. The mean annual rainfall is often higher than 500 mm and sometimes reaches 1 m in the northern coast, whereas it is generally less that 300 mm in the major part of the eastern coast. Moreover, the rain average diminishes rapidly toward the south. Near the Libyan border it is only about 100-150 mm/yr. Rain is often torrential and falls in concentrated patterns of a few days.

During the summer, the mean monthly temperature everywhere is greater than 20°C. The average daily maximum temperature during July and August is always higher than 30°C and can reach 40°C when southern winds, the sirocco, are prevailing. During the winter, the mean temperature of the coldest month (January) is higher than 10°C almost everywhere along the coast. The mean minimum temperature generally oscillates between 6° and 8°C. Temperatures are rarely below 0°C.

The strongest and most frequent winds generally blow from the northwestern direction and occur mainly in winter. Nevertheless, differences exist according to seasons and the coastline orientation. On the northern coast, western and northwestern winds prevail occurring approximately 35% of the time. On the eastern and especially on the southern coasts, the gentler eastern and northeastern winds dominate.

The contrast between the northern and the eastern coasts of Tunisia appears also in the hydrodynamic and the marine water characteristics. Because of its exposure to northern winds and its relatively deep water, the northern coast has cooler, less saline, and rougher and larger waters than the eastern coast. At the end of the hot season, water temperatures are about 21-22°C, and the salinity is about 37 0/00 (parts per thousand). At the end of the winter, the temperatures vary between 15 and 16°C, but the salinity is still almost unaltered (36 to 37 0/00) except in the inner portion of the Gulf of Tunis. Unless there is an exceptional storm, wave height along the northern coast rarely exceeds 6 m. In the Gulf of Tunis, waves of 1.5 m and higher represent only 6% of the observed cases. Tides constitute a secondary phenomenon as their range is, at spring tides, about 0.20 to 0.30 m.

Along the eastern coats, waves are mainly generated by the eastern and the northeastern winds. They are generally characterized by a low energy. The most important waves rarely exceed 1.20 m in height. From 1954 to 1961, the largest wave registered at Sousse was only 3.5 m in height. The eastern coasts have a broad shelf. The southern part (Gulf of Gabes) is characterized by important tides. Here, the tidal range is often higher than 0.70 m and may reach 2 m at spring tides. Water temperatures of the eastern coasts are always more than 16°C and increase southward, where they are about 16-19°C and 22°C, respectively, at the end of winter and summer. However, the salinity change is less perceptible -- 37.1 and 37.2 0/00, respectively, at the end of the cool and the hot seasons.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

Oueslati, A. 1986. Jerba et Kerkna (iles de la cote orientale de la Tunisie): leur evolution geomorphologique au cours du quaternaire. Publ. Univ. Tunis, 210 p.

Oueslati, A., R. Paskoff, H. Slim, and P. Trousset. 1987. Deplacements de la ligne de rivage en Tunisie d'aprea les donnees de l'archeologie a l'epoque historique. Coll. Intern. C.N.R.S. Paris, 67-85.

Oueslati, A. 1989. Les cotes de la Tunisie, recherches geomorphologiques. Th. d'Btat, University of Tunis, 680 p.

Paskoff, R. 1985. Les plages de Tunisie. BDITEC, Caen. 198 p.

Paskoff, R., and A. Oueslati. Modifications of coastal conditions in the gulf of Cabes (southern Tunisia) since classical antiquity. In: Journal of Coastal Research (in press).

Pirazzoli, P.A. 1986. Secular trends of relative sea level (R.S.L.) changes indicated by tide gauge record. In: Journal of Coastal Research, Special Issue 1:1-26.

RESPONSES TO THE IMPACTS OF GREENHOUSE-INDUCED SEA LEVEL RISE ON EGYPT

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ABSTRACT

The projected sea level rise of 1 meter in the next century from greenhouse-induced global warming is a serious concern to deltaic countries such as Egypt. Deltas are particularly susceptible to sea level rise because the delicate balance at the river-ocean interface produces land that is inherently just above sea level. Deltas depend on new sediment delivered by rivers to enable them to keep pace with sea level rise. Sea level rise will exacerbate the erosion already present in the Nile River delta caused by dams upstream that have reduced the sediment supply.

The population of Egypt is clustered along the banks of the Nile River and within the delta. Only 3.5% of the one million square kilometer area of the country is cultivated and settled (Quarterly Economic Review of Egypt, 1985). The nation's coastline has experienced severe erosion in the last 100 years. Reduction in the supply of sediment to the delta started with the construction of delta barrages in 1881. Since then, the situation has become progressively worse with construction of new dams. The 1964 construction of the Aswan High Dam has completely stopped the supply of sediment to the delta; since that time, many areas on the delta coast have been eroding 1 meter every year. In some areas, erosion rates have jumped to more than 100 meters per year.

The impacts of global warming on the Nile delta are taken seriously by concerned authorities in Egypt. A basic survey of available information and implications has been compiled by Broadus et al. (1986) and Sestini (1989). Sestini and others anticipated that a relative rise of 1 meter could submerge lowlands 30 km inland of the coast or more, which accounts for 12-15% of Egypt's arable land, 8 million people, and 10-15% of the country's gross national product. Salt intrusion will also contaminate water used for drinking and agricultural purposes. Many people have called for a national policy of response to these anticipated changes.

Responding to sea level rise in Egypt will be difficult because most of the arable land is along the Nile River or within the Nile delta. Therefore, when this area becomes uninhabitable, moving to higher ground will not solve all the problems, because this land will be inadequate for growing enough food to support the displaced population. Other possible responses include building a dike along the delta coastline or bypassing sediment around Aswan High Dam. This study investigates the impacts of a 1-meter sea level rise on Egypt, assesses what is at risk along Egypt's coastline, and discusses possible responses.

INTRODUCTION

Technological developments and the conversion of agricultural communities to industrial communities have resulted in excessive use of energy resources. As energy use is necessarily associated with waste in the form of materials and heat, this waste has increased dramatically in the last few decades to the extent that it has become a major threat to the environment. In particular, a gradual increase of greenhouse gases (CO_2, CFCs, O_3, CH_4, and OH) in the environment has resulted in a measurable warming of the atmosphere with anticipated changes in climate, and additional effects such as sea level rise and changes in precipitation patterns.

The impact of these climate changes on the ecosystem, human activities, health, and welfare should be carefully assessed before a policy for countering those impacts is developed. National and international organizations have coordinated efforts to develop measures to adapt to these climate changes.

Models have predicted that the temperature rise associated with accumulation of greenhouse gases may range from 2.5°C to 5°C by the middle of the next century. The associated rise in sea level, due to both ocean thermal expansion and melting of polar glaciers and ice caps, is anticipated to range from 30 cm to 150 cm (Titus, 1986; UNEP, 1987, 1989).

Egypt's Nile delta, in particular, will be adversely affected because its northern region is entirely less than 1 meter above sea level. It is already subject to a great deal of environmental changes due to severe reduction of sediment delivery after construction of the Aswan High Dam.

This paper outlines the impact of various environmental changes over the northern Egyptian coasts, directs attention to areas of potential risk from the effects of climate change, and recommends a policy by which government agencies could reduce losses and help Egypt adapt to global warming.

IMPACTS ON THE NORTH COAST OF EGYPT

No formal multidisciplinary team has investigated the detailed impacts of climate change on the Egyptian delta. However, a number of research centers have studied one aspect or another of the problem and have accumulated valuable information. These groups include the Institute of Coastal Research, the

Institute of Oceanography, the Suez Canal Authority, the Environment Affairs Authority,a nd the University of Alexandria research groups. A number of United Nations Environment Programme meetings have also stressed the seriousness of the impact of global warming, especially sea level rise.

An assessment of the impacts of climate changes on the northern Egyptian coasts requires the documentation of detailed information on land use, topographic variations, population distribution, soil characteristics, coastal erosion, and socioeconomic distribution parameters. Unfortunately, the information already available is outdated, intermittent, and, in many cases, inconsistent. In addition, large uncertainties exist regarding the accuracy of important variables, such as regional subsidence rates, elevation, and the distribution of economic activities. Nevertheless, available information provides a general account of the likely impacts.

A 1-meter interval elevation contour map of the Nile Delta and vicinity (Figure 1) shows that the area below the 1-meter contour extends inland as much as 30 km south of Alexandria city and south of Lake Manzala (Sestini, 1987). Because about 40% of Egyptian industry is located near and around Alexandria, we can infer that serious damage could result from a 1-meter rise in sea level. In addition, because of the sandy and porous nature of the soil in this area, waterlogging resulting from saltwater intrusion may affect the fertility of the arable land below the 2-meter or perhaps the 3-meter contour. Considering the relatively high population density and extensive resources of the area, a tremendous socioeconomic impact would be likely.

Recent analysis of erosion and accretion patterns (Frihy et al., 1989) has also shown large changes over the northern Egyptian coasts. Hence, many tourist, recreational, and economic sites will be subjected to considerable stress. In addition, this area is generally subsiding. Based on these results and on consideration of economic development axes in both vertical and horizontal directions on the north coast (ARICON, 1988), we conclude that sea level rise will pose major risks to three areas: the Alexandria region west of the Rosetta branch, Lake Burullus and vicinity, and the Lake Manzala region.

1. Alexandria region: The region at risk includes residential areas in several localities, in addition to industrial sections west and east of the city. A large part of the area south of Alexandria city (Amerya) is also below the 1-m contour level. These areas are presently under extensive development. Plans for development in this area should be carefully revised. Some tourist sites west of Alexandria are also built between the first ridge and the sea (at localities below the 1-meter contour), which puts them at risk. This region hosts about 40% of Egypt's industry, as well as many historical and tourist sites.

2. Lake Burullus: This area is already subject to serious erosion and accretion problems. Rising sea level will increase this rate and destroy beaches and resort villages in the area. In addition, the lake is under consideration for a water storage project. The environmental

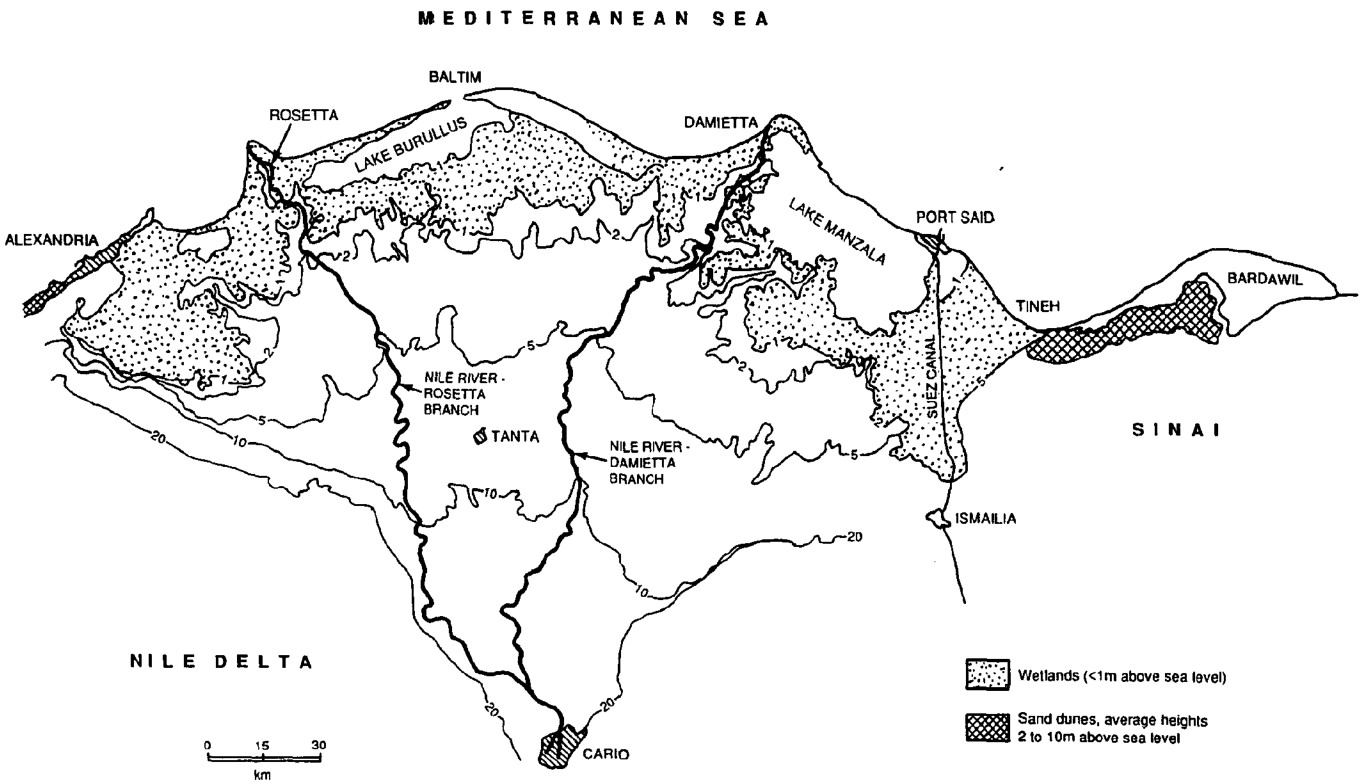

Figure 1. Contour map of the Nile delta and vicinity (Sestini, 1989). In addition to inundating land below 1-meter elevation, a 1-meter rise in sea level would waterlog land up to 2 and possibly 3 meters.

impact assessment of this project should take sea level rise into consideration.

3. <u>Lake Manzala region</u>: The area at risk is extensive and includes the cities of Damietta and Port-Said, and extends south of Lake Manzala to include a large part of the Suez Canal on both sides. This area hosts a large harbor at Damietta in addition to many fishing and industrial centers.

A question may also arise here on the discharges of the Nile River necessary to counter the effects of sea level rise at the promontories. Although such discharges would assist land creation, they would adversely affect bridges, water supply, and perhaps some land along the Nile.

A detailed quantitative environmental impact assessment should be carried out based on use of geographical information systems, making use of the information on the northern coasts already existing at the University of Alexandria and other research centers. A multistage technique in which the impact could be calculated by an interaction matrix for each 0.25 meter of sea level rise is suggested. An interaction matrix with elements of the "magnitude" and "importance" of the impact should be calculated for each area. The elements of such a matrix could be estimated from accurate analysis of geographic information systems based on recent data of the area.

ADAPTIVE OPTIONS

If sea level rises, Egypt has only three options:

- Withdraw from coastal areas;
- Build walls around limited areas to protect valuable lowlands or industrial complexes from inundation; or
- Adjust to expected changes, and perhaps take advantage of them by appropriately changing land use (e.g., shifting to crops that tolerate flooding).

Because of the variable environmental and economic conditions in the vulnerable areas, the choice of any of these options will greatly depend on the area under consideration. A detailed study of each area is, therefore, necessary.

Alexandria city is built over a number of relatively high hills or dunes separated by narrow "tunnels" (Figure 2). It may be possible to protect the urban and industrial areas against rising seas by building a number of walls to protect the southern parts of the city. However, such a response must await accurate analysis of data and studies of geological structure and elevation of these hills.

In general, any policy that would be of interest for future development in the area must be of the type that will help whether or not climate changes -- i.e., it must a two-sided policy. Conserving energy and water resources and converting to salt-tolerant agriculture are policies of this type. Broadly speaking, response strategies fall into two categories: limiting global warming and adapting to its consequences.

Limiting Global Warming

This approach is intended mainly to buy time:

1. Limit the production and emission of CO_2, CFCs, and other greenhouse gases. Enforce air pollution control measures. Apply the Clean Air

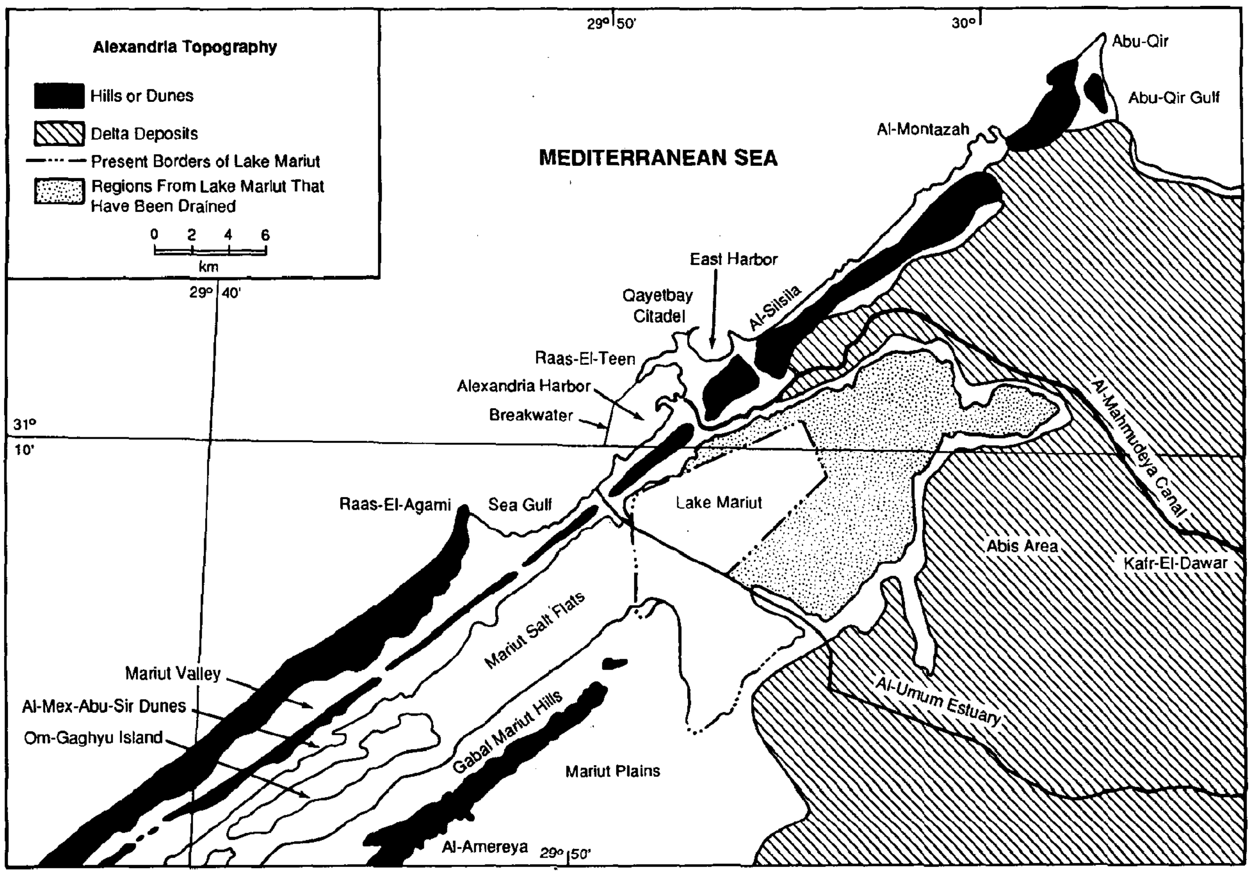

Figure 2. Alexandria outskirts showing ridges over which the city is built.

Act in Cairo, Alexandria, and Tanta, at least, and enforce it by efficient monitoring networks.

2. Develop and enforce the operation of more energy-efficient engines. Increasing engine efficiency is found to be one of the most important factors in reducing greenhouse emissions (Lashof and Tirpak, 1989). Include a social impact tax in the price of polluting fuels to limit their excessive use.

3. Work on planting greenbelts, and increase the awareness and perception of the public concerning overuse of fertilizers. Encourage and support programs for environmental education and research.

4. Increase the proportion of solar energy use and/or other renewable energy sources, such as wind energy. Support programs for studying and implementing energy conservation techniques.

Adaptation

Adapting to global warming involves long-range planning. For instance, one of the most important problems developing countries are expected to face in the near future, with special reference to Egypt, is the availability of freshwater. With a population growth rate of 2.8% per year, future domestic water use is expected to consume a large part of Egypt's fixed water budget (55 million cubic meters per year). In view of the projected global warming, water conservation programs must start -- the sooner the better -- whether we have climate changes or not. Other adaptation policies for Egypt include the following:

1. Adopting new agricultural practices with improved efficiencies for using freshwater resources.

2. Encouraging and developing multidisciplinary institutions concerned with the reallocation and use of scarce freshwater supplies, such as groundwater resources. Developing techniques for rainfed (as opposed to irrigated) agriculture. Supporting projects based on rainfall along the north coast.

3. Strengthening mechanisms for converting land and other resources into and out of agriculture in response to climate change.

4. Adopting a new policy for urban development of coastal regions based on predicted sea level rise for the next 40 or 50 years. For instance, resort villages with massive foundations are currently built on ridges parallel to the shore. In the future, only transportable wooden cabins should be allowed near shores.

Special policy recommendations for the northern coastal region include the following:

1. Plans for building an international road along the north coast consider enforcing road foundations to act as a wall for protecting the Nile delta in case of sea level rise. The same could be extended to vulnerable areas west of Alexandria.

2. Reevaluate the Alexandria and Damietta master plans, based on new predictions. Build future massive beach resorts on the ridges at least 1 meter above sea level.

3. Launch a socioeconomic program directed toward increasing public awareness that rainfall patterns may change. Use recent biotechnological capabilities of saltwater-tolerant plants.

4. Develop and implement techniques for reducing water table levels over existing lowlands and human settlements near the coastal regions. Develop windmill techniques of water pumping, and test capabilities in pumping already waterlogged areas in Agamy west of Alexandria.

5. Control the overexploitation of quarries along the coasts west of Alexandria.

6. Relocate waste dumping to suitable sites to reduce future risk of water pollution.

7. Investigate the technical and economic possibilities of protecting Alexandria city by building a number of discontinuous walls over "tunnels," and using local natural rocks, such as granite, basalt, dolomite, and diorite.

8. Delineate and study regions of erosion and accretion for better evaluation of conditions along the northern coasts and identification of areas most vulnerable to sea level rise.

9. Encourage the reclamation projects to take place in areas with greater elevation. Extend public services to newly developing communities in the highlands, giving first priority to people from vulnerable areas to move to these newly developed lands.

10. Explore the technical and economic feasibility and impact assessment of bypassing Nile River sediments from Aswan High Dam.

As a first step, a multidisciplinary team of experts should be formed to carry out a detailed environmental impact assessment of the effects of sea level rise and to recommend specific measures to counter these effects. The same exercise should then be carried out for other effects of climate change.

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BIBLIOGRAPHY

ARICON. 1988. Master plan for development of the north delta region and international road. Cairo, Egypt: Ministry of Reconstruction, New Communities and Infrastructure.

Broadus, J., J. Millman, S. Edwards, D. Aubrey and F. Gable. 1986. Rising sea level and damming of rivers: Possible effects in Egypt and Bangladesh. In: Effects of Changes in Stratospheric Ozone and Global Climate, Vol 4: Sea Level Rise. J.G. Titus, ed. Washington, DC: U.S. Environmental Protection Agency and United Nations Environment Program.

Frihy, O.E., S.M. Nasr, M.H. Ahmed, and M. El-Raey. Long term shoreline and bottom changes of the inner continental shelf off the Nile Delta, Egypt. (Submitted).

Lashof, D.A., and D.A. Tirpak. 1989. Policy Options for Stabilizing Global Climate. Washington, DC: U.S. Environmental Protection Agency.

Quarterly Economic Review of Egypt. 1985. Annual Supplement. London: The Economist Publications Ltd.

Sestini, G. 1989. The implications of climatic changes for the Nile Delta. Report WG 2/14. Nairobi, Kenya: United Nations Environment Program/OCA.

UNEP. 1987. United Nations Environment Program. Environment Library No. 1. Geneva: United Nations Environment Program.

UNEP. 1989. United Nations Environment Program. The Full Range of Responses to Anticipated Climatic Change. Geneva: United Nations Environment Program. April.

IMPACTS OF SEA LEVEL RISE ON PORTS AND OTHER COASTAL DEVELOPMENT IN ALGERIA

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INTRODUCTION

More and more, the public is recognizing that global warming due to the "greenhouse effect" will increase the mass and volume of the water in the oceans and will thereby accelerate the rate of sea level rise during the next few decades. Such a rise would increase coastal erosion and other hazards of coastal life.

Due to the seaward advance of deserts and rising sea level, the coastal zone of North Africa is becoming narrower. At the same time, population growth is causing rapid urbanization. Thus, it is important today to create strategies for adapting to the global warming of tomorrow.

SEA LEVEL TRENDS IN THE MEDITERRANEAN SEA

The Mediterranean shore has been populated since the beginning of recorded history. Ancient civilizations have left a great number of remains on the coast, which can be very helpful in addressing the impacts of sea level rise. As early as 1934, His Highness Prince Omar Toussoun ordered a study to determine how much the sea level had risen in the port of Alexandria, Egypt.

Most people along the Mediterranean coast have not noticed the sea rising, but that does not mean it is not occurring. Tidal gauge records in Marseilles show that the sea level has been rising 1 mm per year there for the last century (Bruun, 1987). This rise may be limited by the region's climate. For example, the Mediterranean Sea is already an area of net evaporation, which tends to lower sea level. Moreover, seasonal variations may obscure the sea level. As Figure 1 shows, seasonal variations can be 100 times the annual rise.

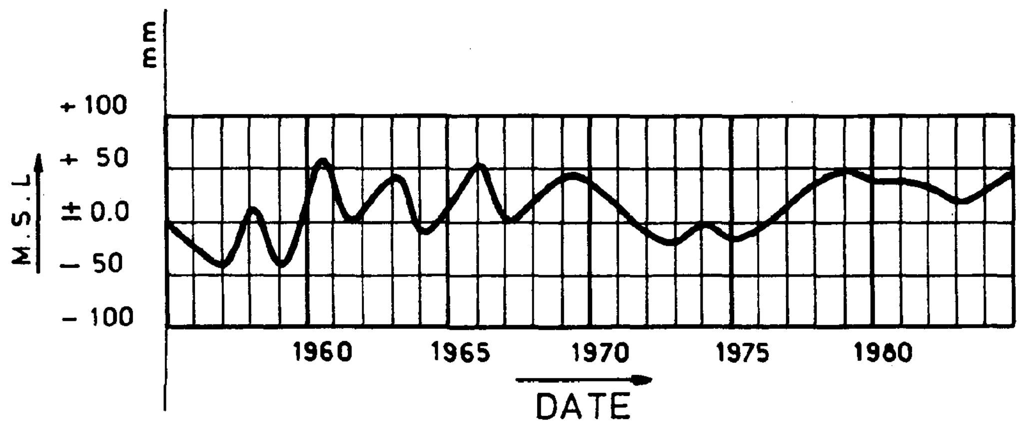


Figure 1. Yearly evolution of mean sea level in Trieste, Italy, which is a good approximation of trends on the Algerian Coast.

POSSIBLE IMPACTS ON ALGERIA

For Algeria, the most important problems resulting from sea level rise are likely to be the loss of usable land, damage to port facilities, and pollution of groundwater.

Loss of Usable Land

The continental shelves in the western part of the Mediterranean Sea are rather narrow -- less than 25 miles wide -- and are cut by numerous canyons. Along the Moroccan and Algerian coasts, the shelf slopes an average of approximately 10%.

Above the sea, the limited width of the vital belt confined between the desert and the sea implies that national population growth will increase the urbanization of the coastal zone. In Algeria, more than 50% of the population lives within 50 kilometers of the sea (Figure 2).

Park et al. (1986) forecast that 40 to 75% of existing U.S. coastal wetlands could be lost by 2100. A similar impact can be expected in Algeria.

Quays and Port Facilities

Given the low tidal range (less than 50 cm) in the Mediterranean Sea, port facilities have been designed with levels close to sea level. In Algeria, ports are designed with quays up to 2.0 m above sea level. A rise in sea level would flood these structures as well as the operational land behind.

Because of the importance of maritime trade, which represents more than 90% of the total amount of the Algerian trade exchange, port designers should bear in mind the possible effects of sea level rise in future port construction. Fortunately, existing structures can be elevated as the sea rises.

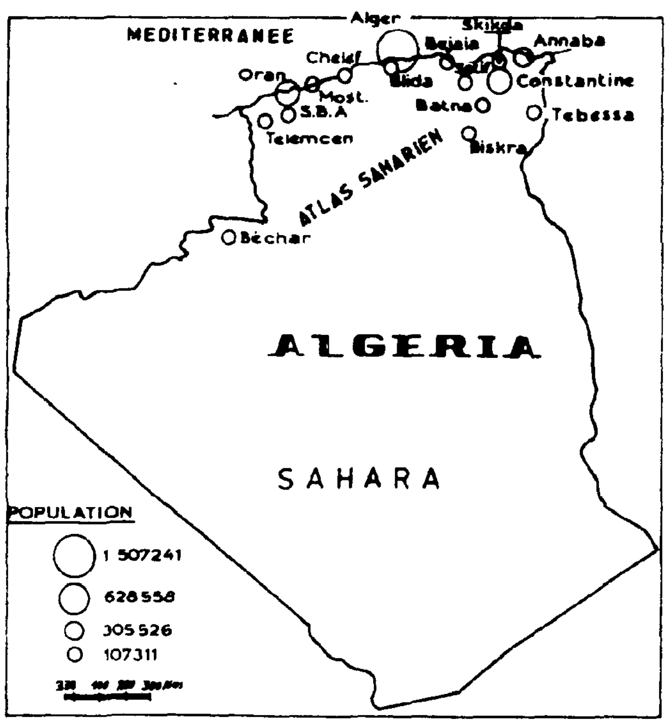
Groundwater Pollution

Most of the cities on the North African coast are supplied by groundwater. A rise in sea level will cause saltwater to contaminate the groundwater. Regarding soil permeability and smooth groundwater table slope near the shore, large quantities of freshwater will be lost, proportional to the rise in sea level.

WHAT CAN BE DONE

Along the North African coast, both structural and planning measures will be necessary.

Rigid structures, such as breakwaters, seawalls, and groins, can protect urban areas. However, given their high cost, these structures would be appropriate only where there are valuable buildings or land. If structures are destroyed by storms or other phenomena, they should not be rebuilt.



STATISTIQUES O.N.S N° 21 – ALGERIA

Figure 2. Algerian cities with more than 100,000 inhabitants.

Mediterranean

In rural areas, rigid solutions would not usually be justified economically. More flexible measures may be appropriate such as setback lines that prohibit construction in areas likely to be inundated within a specified period of time (up to 100 years). New construction criteria should be defined. However, the difficulty will be to convince officials to accept the loss of precious land today to prevent the consequences of something that will happen in the 21st century.

BIBLIOGRAPHY

Bruun, P. 1987. The effects of changing the atmosphere on the stability of sea level and shore stability. PIANC 58:129-132.

Bruun, P. 1989. Coastal engineering and the use of the littoral zone. Ocean and Shoreline Management 12(5) and (6).

Lamy, A., and C. Millot. 1981. Bottom pressure and sea level measures in the Gulf of Lions. Journal of Physical Oceanography 11:394-410.

Park, R., T.V. Armentano and C.L. Cloonan. 1986. Predicting the effects of sea level rise on coastal wetlands. In: Effects of Changes in Stratospheric Ozone and Global Climate. Volume 4: Sea Level Rise. J.G. Titus, ed. Washington, DC: United Nations Environment Programme and the U.S. Environmental Protection Agency. October.

Sharaf el Din, S.H., and Z.A. Moursy. 1977. Tide and storm surges on the Egyptian Mediterranean coast. Rapp. Comm. Inter. Mer Medit. 24:2.

Vignal, J. 1935. Les changements du niveau moyen des mers le long des cotes en Mediterranee. Annales des Ponts et Chaussees 28.

Weaver, D.F., and D.L. Hayes. 1989. Proposed response to sea level rise by a local government. In: Coastal Zone '89. New York: American Society of Civil Engineers, pp. 2490-2501.

NORTH AND WEST EUROPE

THE VULNERABILITY OF EUROPEAN COASTAL LOWLANDS ALONG THE NORTH SEA AND ATLANTIC COASTS TO A RISE IN SEA LEVEL

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ABSTRACT

The European coastal lowlands comprise deltas and plains including wetlands and natural areas at low altitudes that encompass extensive zones of densely populated, intense economic and agricultural activity. Around the southern North Sea Basin alone, the coastal plains area is the home of more than 200 million people who live close to present sea level and are already at risk from inundation as a consequence of coastal erosion, storm surge, and the current trend of sea level rise of 1 to 1.5 mm per year.

During a session on the impact of a future rise in sea level, part of the European Workshop on Interrelated Bioclimatic and Land Use Changes, 12 papers presented case histories on the present situation of the shoreline. The consensus was that European coastal lowlands are already experiencing damage from erosion, inundation during storm surges, storm waves, subsidence, and saltwater intrusion as the consequence of sea level rise, increased incidence of storminess, and human activities.

Moreover, many human activities are increasing the vulnerability of coastal areas to a rise in sea level. These activities include sand extraction from beaches and offshore areas for reclamation and the construction industry; the destruction of natural shoreline defenses, such as sand dunes, to provide hotel accommodations and amenities for the tourist industry; the interruption and diversion of longshore sediment transport by groins, jetties, and harbors; the reduction of the sediment load of rivers by water management in drainage basins and the construction of dams and reservoirs, cutting sediment supply to nourish beaches and deltas; the canalization of rivers for navigational purposes; the reclamation of coastal lowlands for agricultural, industrialization, and residential development; and the extraction of groundwater for drinking water and irrigation, which has led to subsidence and the penetration of saltwater.

North and West Europe

The maximum rise of sea level during the recent geological past did not exceed 2.2 m/100 years. During the past 4,000 years, when the rate of rise was considerably less, sedimentation has kept up with and locally exceeded sea level rise. In natural areas, where human activities are not pre-eminent, such as the Dutch, German, and Danish Wadden Sea, sedimentation has kept up with the present rise of sea level of 10 to 15 cm/100 years. Investigations of the sediments of the coastal lowlands indicate that, given a natural sediment budget, these areas responded and adjusted to a range of rates of sea level change and climatic change in the past.

The coastal lowlands of Europe have a good infrastructure. Accordingly, they will be able to address future sea level rise more easily than countries that have none, e.g., the Third World. Nevertheless, in both rich and poor nations, the socioeconomic impacts of a future sea level rise will be profound and widespread.

INTRODUCTION

As the report of the Miami conference notes, people have always been concentrated near the coast. Although the general lack of topographic information has made it impossible so far to estimate how many people live within one or two meters of sea level, we do know that about half of the world's population lives in deltas and other coastal lowlands. In most cases, deltas are entirely less than ten meters above sea level; and in many cases at least half the delta is within one or two meters of sea level. Even for the portions with greater elevations, life is affected by sea level because the heights of river and storm surges are influenced by the base level of the sea.

For purposes of this paper, we define coastal lowlands as areas that are within coastal floodplains or would be without manmade coastal protection structures. Besides flooding, most of these areas are already subject to erosion and saltwater intrusion because of rising sea level and, mainly, as a result of human interference with the natural flow of rivers to the sea and sediment along the coast.

Even a large part of relative sea level rise stems from subsidence induced by human activities, such as withdrawals of groundwater, oil, and gas, and drainage of land and the resulting compaction of peat and clay underlying it. In some cases -- such as the Netherlands -- the fact that relative sea level rise and its consequences are already being faced would make communities less vulnerable to global warming because physical and political infrastructures to address the problem already exist. In other cases, existing subsidence has eliminated the safety margin that might otherwise have allowed communities to tolerate the projected rise in sea level over the next 50-100 years.

This paper summarizes the implications of sea level rise for low-lying coastal areas around the North Sea and the Atlantic coast of Europe.

ENVIRONMENTAL CONDITIONS

Coastal lowlands comprise the lands where sediments are deposited by tides, storm surges, and some areas flooded by river water -- namely, those in which flooding results because of the backwater effect from the sea. The sediment deposited includes peats, clays, silts, and sands generally lying below the present spring tide level; at slightly higher altitudes, they also lie along the inland margins of the coastal lowlands. Although coastal lowlands are usually within a few meters of sea level in the case of coastal dunes they can accumulate to several tens of meters above sea level.

The coastal lowland itself shows a great variety of morphology and lithology. Rivers entering the sea can have deltas that show great variation due to dominant processes of waves, currents, and fluvial input. If river input is low and/or the tide ranges are relatively great, estuaries are found instead. Inland from the shoreline, there are generally coastal wetlands, with zonations primarily dependent on the vegetations' tolerance of salinity and frequent flooding.

Along certain coasts, coastal barriers with dunes on top of them and barrier islands can occur with coastal wetlands in the hinterland. During the Holocene rise in sea level, these zones of different environments have shifted landward; if sea level rise accelerates, their landward migration will do likewise.

There are no important deltas in northern and western Europe. Most of the rivers end in estuaries, like the Elbe, Weser, and Ems estuaries in Germany; the Rhine and the Meuse Scheldt estuary in the southwestern Netherlands; the Severn and Thames in England; the Somme, Seine, and Gironde estuaries in France; the Tajo estuary in Portugal; and the Guadalquivir estuary in Spain.

In large measure because of the configuration of the southern North Sea Basin, storms from the north and west can produce extremely high tides, which have caused severe flooding many times throughout the last several centuries. This configuration also contributes to large tidal ranges: macrotidal (>4 m) conditions prevail along the English Channel, along the Strait of Dover, and in the Bristol channel. The highest tidal range of Europe can be found in the Bay of Mont-Saint-Michel (12 m) in France. Figure 1 roughly indicates the coastal lowlands, the river estuaries, and the delta.

LAND USE

For centuries, Europeans have drained and reclaimed wetlands for agriculture, industry, and housing of large cities. The draining has caused land subsidence through compaction of peat and clay soils; moreover, land surfaces have also been lowered because the compaction of unconsolidated sediments -- which would be occurring even without human interference -- is no longer offset by the deposition of sediment from floods. In many areas, compaction has been so great that these soils are now lying below mean sea level. Accordingly, they have to be drained by pumping, and many areas are protected by dikes against storm surges and high tides. The only extensive natural areas left are the tidal flats of the Dutch, German, and Danish Wadden Sea.

An important side effect of this intense drainage is the intrusion of saltwater. The damming of rivers diminishes the freshwater flows that would otherwise push saltwater back toward the sea. Dredging in the estuaries and deltas in the interest of port development has also caused saltwater intrusion farther upstream. This shift of saline water has affected the intake of water from the river for irrigation and other water supplies. Yet another side effect is saltwater intrusion in coastal aquifers (see Titus in the section on Problem Identification).

The coastal lowlands of Europe, especially the river estuaries and deltas, are areas of dense population and heavy industrial activity. More details about human activities, land use, and vulnerability to flooding, especially by a rise in sea level, should be given on smaller scale maps by the European countries involved. An example is the maps of the southern North Sea Basin. In the region, about 20 million people live below the high-tide level. The economic value of these low-lying areas is enormous. These areas are also gateways to industrial areas in the hinterland as well as oil and gas fields; there is a heavy concentration of pipelines, refineries, and oil harbors in the southern North Sea. The population density and important industries in the coastal lowlands surrounding the southern North Sea Basin make them very vulnerable to sea level rise.

EFFECTS OF A FUTURE RISE IN SEA LEVEL

An accelerated rise in sea level would (1) increase the risk that reclaimed lowlands will be inundated; (2) accelerate coastal erosion, threatening both structures and recreational beaches; (3) increase the risk of flood disasters; (4) impair the effectiveness of drainage systems; (5) increase saltwater intrusion into groundwater, rivers, bays, and farmland; (6) damage port facilities; (7) threaten the wetland habitats of birds, fish, and wildlife; (8) shift sedimentation in rivers farther upstream, hampering shipping; and (9) alter tidal ranges, which might exacerbate many of the other effects.

Other impacts of global warming could also be important. If wind patterns and climate change, the runoff from rivers will increase in winter and decrease in summer. The increased runoff can create problems for the embankments, and a decreased runoff can cause extensive saltwater intrusion upstream. Increased storminess could be even more important: the most significant damages on coastlines occur during storm surges at the time of high tide. If this increase in storminess should occur along the coasts of the southern bight of the North Sea, the highly populated, industrialized coastal lowlands would suffer disastrous losses.

RESPONSE TO SEA LEVEL RISE

How can the coastal lowlands of Europe respond to the predicted rise in sea level? They can either try to defend the lowlands or move present activities and development landward. The land can be protected by dikes, seawalls, beach nourishment, and other engineering solutions, but economic and environmental impacts can make such a protection strategy unacceptable. On the other hand, moving present activities landward also will have serious economic and social effects. Well-developed countries such as a united Europe will have the organization, the technology, and the resources to make these tradeoffs, unlike less developed countries, which lack the above-mentioned infrastructure.

Sea level rise and the implementation of response strategies will have serious effects on individual, regional, and national economic levels. Impacts on real income include the loss of production from land and seas as well as the effects of employment changes from reconstruction. Migration of people and enterprises will disrupt existing economic and social structures.

Many European coastal lowlands are in critical balance with the present sea level and are in great danger of flooding if storm surges occur. Important parts of the shorelines are affected by erosion, especially during storm surges. At places where shorelines are eroding, stone jetties and concrete or wooden groins are built to lessen sand draft. This method is disputable because it seems to be causing more erosion on the rest of the unprotected shoreline. Beach nourishment seems to be a more successful method of protection.

But a strategy is more than a set of physical structures or laws governing what and where people can build. We need to systematically analyze which areas are vulnerable, as well as the legal, environmental, economic, and cultural implications of each of the possible responses. Only then will it be possible to rationally respond to the risks of accelerated sea level rise.

IMPACT OF A FUTURE SEA LEVEL RISE IN THE POLISH BALTIC COASTAL ZONE

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ABSTRACT

About 3,645 square kilometers of land (1.2% of the total area) in Poland are less than 20 feet above mean sea level. The area at greatest risk, located below 1 m above sea level, is 1,550 square kilometers, of which 70% lies in the delta of the Vistula and 12% lies in the lower Odra valley and around Szczecin Bay. The remaining 18% below 1 m elevation is in a 300-km section of the coast between Wolin Island Hel (at the end of the Hel Spit). These areas have 1.8% of Poland's population.

In the area at risk, there are four large shipyards with capacity equal to 2% of world production, a large chemical plant at Police, an oil refinery in Gdansk (processing 6 million tons/year), railway junctions, plants of the machine-building industry, the lower Odra power plant, and the whole of the old city of Gdansk, a priceless cultural center. Within the low-lying area, there are 28 holiday resorts and sandy beaches. Eighteen holiday resorts are situated above the cliffed coast and are exposed to erosion rates of 40-150 cm/yr.

At present, the awareness of the impacts of sea level rise is low, both in society in general and in the administrative units.

INTRODUCTION

Intensive emission of CO_2 induces the so-called greenhouse effect. This will increase global temperature, which will bring about a faster melting of glaciers and inland ices, as well as thermal expansion of the ocean water. Forecasts indicate that during the next 100 years, these factors may cause sea level to rise from 50 to 200 cm. This rise will pose a number of threats to the natural and cultural environments of the coastal zones of maritime nations.

NATURAL FEATURES OF THE POLISH COASTAL ZONE

Sea Level Changes and Storm Surges

Changes in coastal water levels in Poland have been recorded by 21 marigraphic and gauging stations (Figure 1), many of which have been operating for the last century. A clear cycle of changes in the sea level can be observed in periods of 19-20, 7-11, and 3-5 years. The first two are connected with changes in the activity of the sun; the origin of the last cycle is obscure (Jednoral, 1984; Dziadziuszko and Jednoral, 1987). The regression lines and equations show that there has also been a gradual rise in sea level over the last hundred years (Figure 2). The tendency has accelerated markedly in recent years. The mean annual sea level rise over more than a hundred years amounts to +0.7 mm/yr in Swinoujscie, +1.1 mm/yr in Kolobrzeg, and +1.2 mm/yr in Gdansk. For the last 35 years (1951-85), the rate of rise is generally higher, reaching +1.4 mm/yr in Swinoujscie and +2.9 mm/yr in Gdansk.

Poland experiences severe storm surges. Surges greater than 570 cm have a probability of 0.75% in any given year. From 1951 to 1975, storm surges occurred very irregularly, from none to seven in a year (Majewski et al., 1983) (Figure 3). Over the last 700 years, 82 storm surges have exceeded 1.2-1.5 m. In 31 of these cases, sea level rose by more than 2.5 m (maximum <3.0 m), exceeded 600 cm, and none was higher than 650 cm (Jednoral, 1984). During the period of systematic observations, the highest intensity of storm surges took

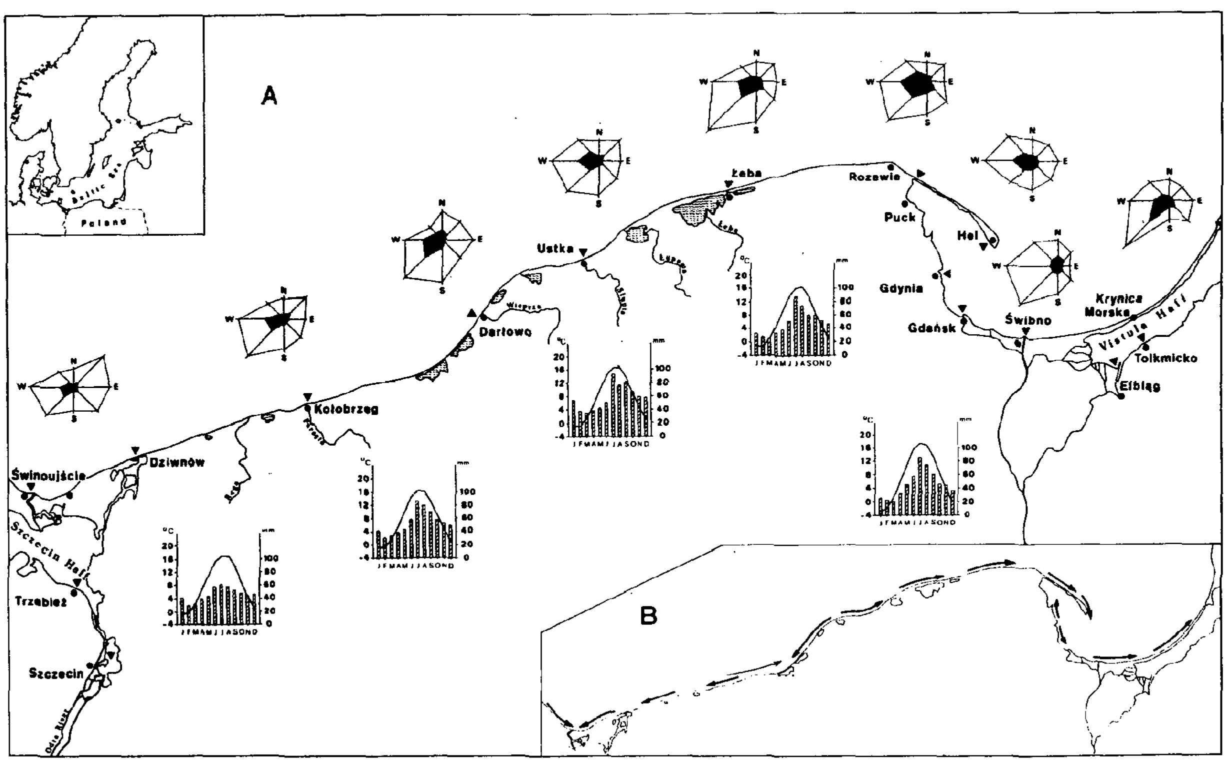


Figure 1. Wind conditions, air temperature and precipitation (A), directions of longshore currents (B) along the Polish coast.

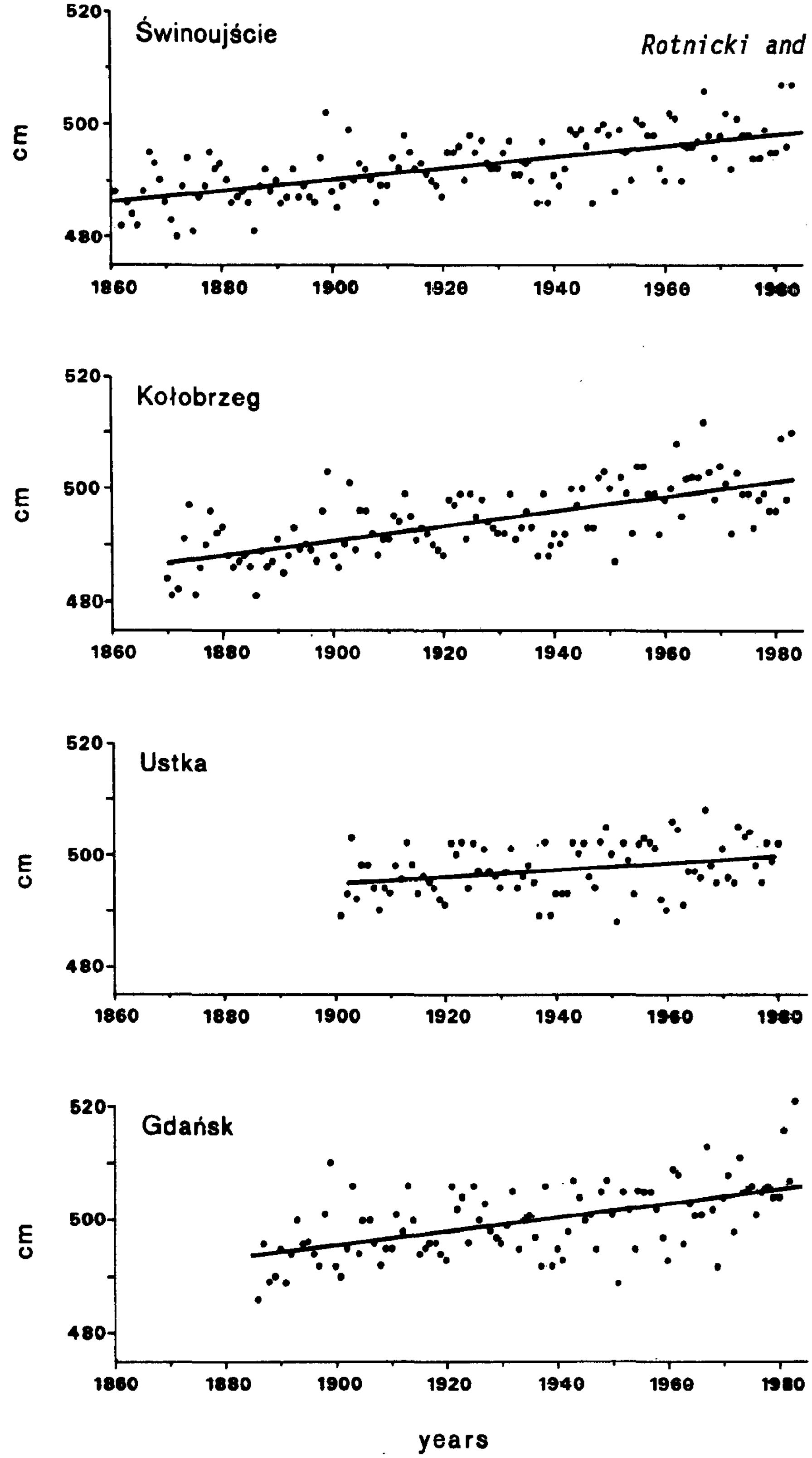


Figure 2. Sea level rise during the last century in the Polish coastal zone. (Czekanska, 1948). From 1951 through 1980, 88 storm surges occurred; 15 of these

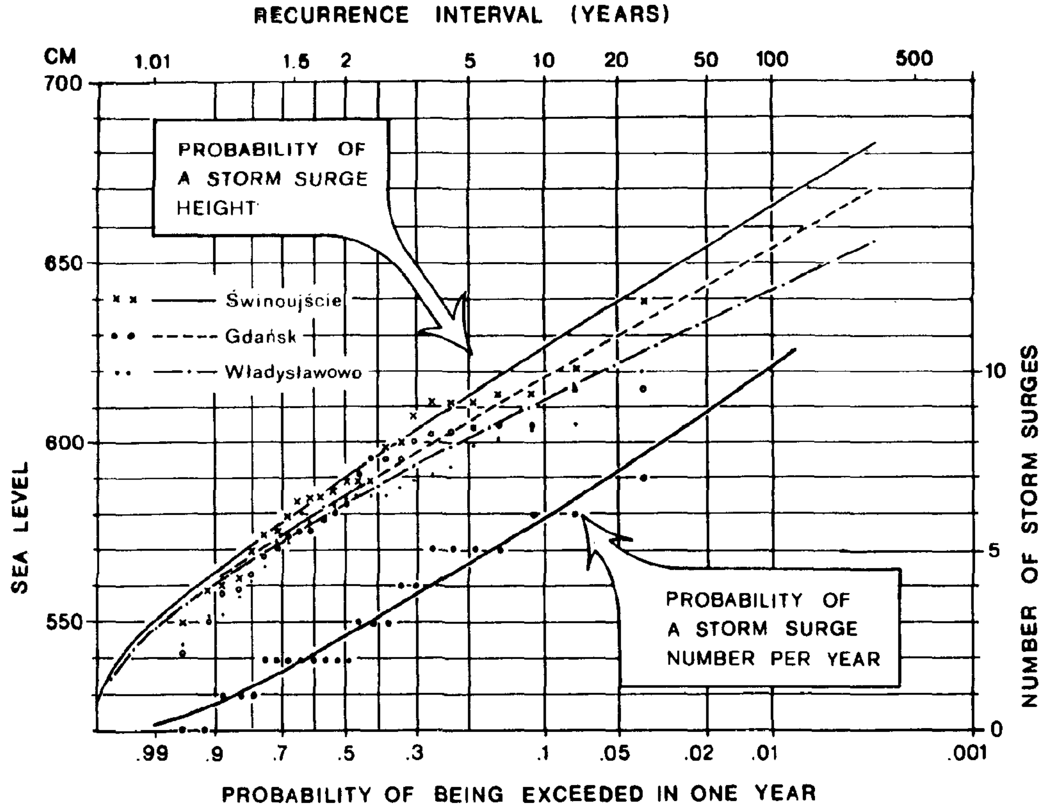


Figure 3. Probability of storm-surge height and of number of storms per year in the Polish Baltic coastal zone. Probability curves counted on the ground of data published in Majewski et al. (1983).

place at the turn of the 19th century. About 55% of storm surges develop withwinds from the north, 31% from the northwest, and 14% from the northeast. The northeast wind creates the highest and most dangerous storm surges.

River mouths are important sources of longshore material and are also zones of discontinuity in the dune belt. Therefore, they are places where storm surges can penetrate the coastal barriers onto usually low-lying areas behind them. On the Polish coast of the Baltic are the mouths of two rivers with drainage basins exceeding 100,000 km^2 (the Vistula and Odra Rivers) and six rivers with basin areas of 1,000 to 3,000 km^2 (Figure 3).

Geomorphology

The 493-km Polish coast consists of alternating cliffed (105 km) and barrier beach sections (373 km). Swampy coastal sections occupy about 15 km (Figure 4). The cliffs are 15-40 m high, with a maximum of 90 m; 45 km of cliffs are retreating between 0.4 and 2.3 meters per year. At the cliff base one can observe low beaches (0.4-0.8 m) with one or no submerged sandbars in the breaker zone (Rosa, 1984). A striking example of coastal erosion is the ruins of the church at Trzesacz, which was built in the 12th century about 1,800 m from the

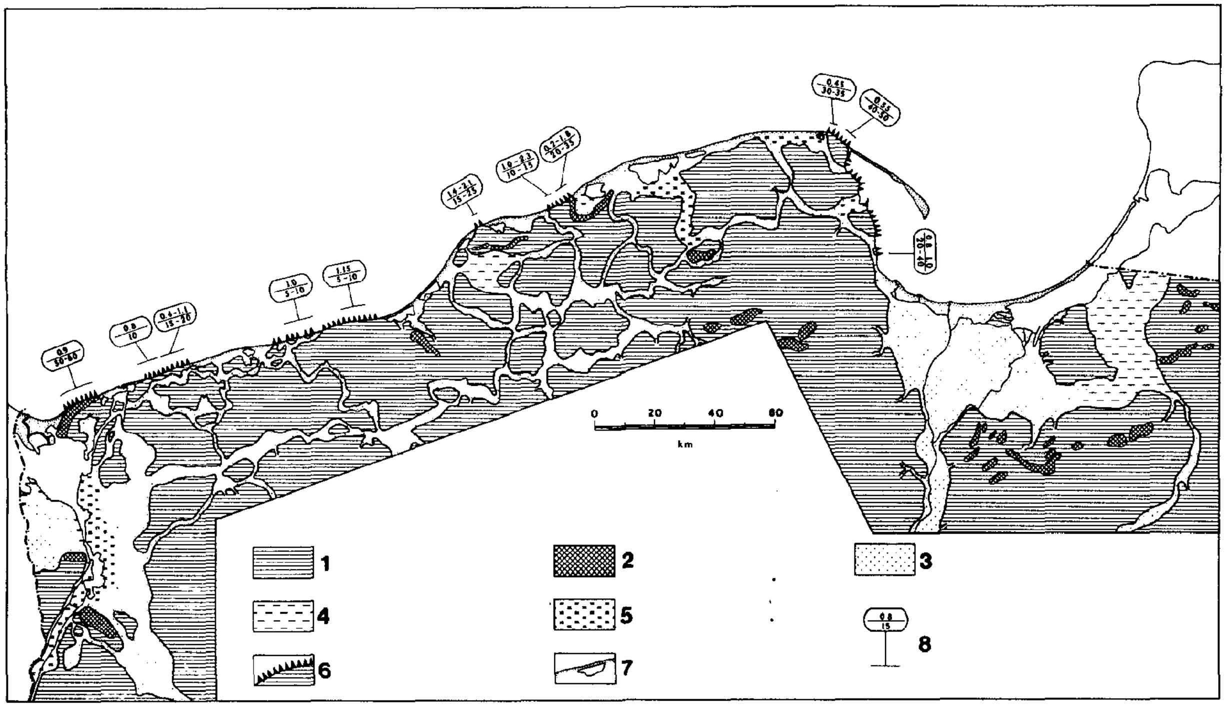


Figure 4. Geomorphology of the Polish coastal zone. 1 - ground moraine plateau, 2 - end moraine hills, 3 - alluvial and glaciofluvial plains, 4 - glacio-lacustrine plains, 5 - swampy plains, 6 - cliffed coasts, 7 - barrier coasts, 8 - mean annual rate of the cliff abrasion (meters per year - in numerator) and cliff height (in meters - in denominator).

coast. Figure 5 shows the church and other areas threatened by erosion. Figure 6 illustrates structural response to this erosion.

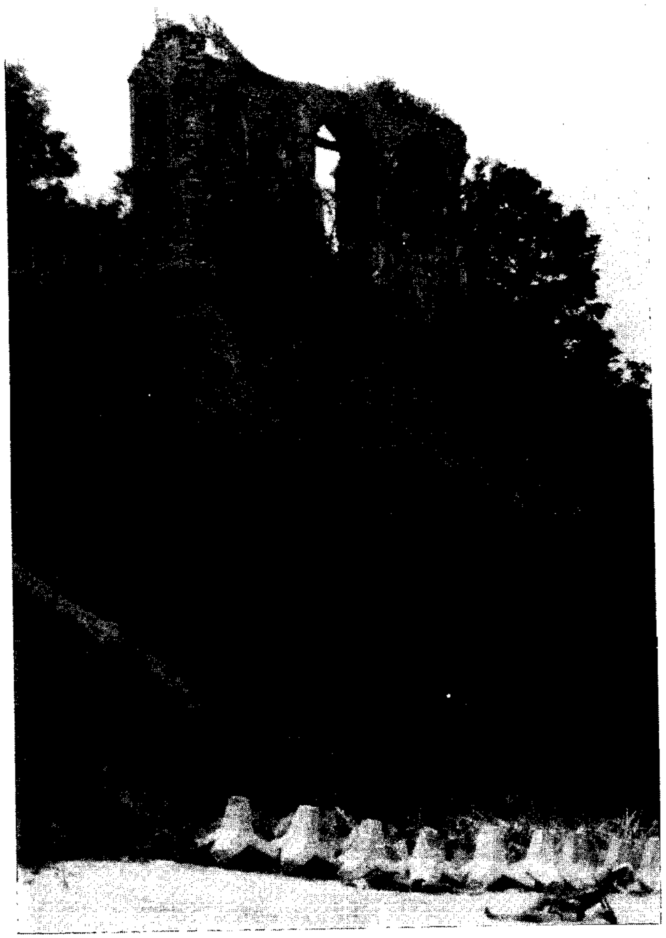
Coastal barriers are especially well developed in the eastern and middle parts of the Polish coast. They separate old marginal valleys and terminal depressions of the last inland ice from the sea, allowing coastal lakes and swampy plains to form. On the Polish coast three types of barriers can be distinguished:

1. Barriers of a modest width (<0.5 km) occupied by a single row of dunes 3-6 m high. They are already susceptible to destruction by storm surges, especially because the adjacent beaches are low (0.6-0.8 m).

2. Wide barriers (<2.0 km) occupied by several rows of dunes with heights up to 20 m. Beaches extend up to about 1.0-1.2 m above sea level.

3. Wide barriers (about 2 km) occupied by complexes of parabolic and barkhan dunes that are 20-50 m high. Foredunes can be found only near the beach, and their heights vary from 3 to 10 m. On the Leba Barrier, for example, there are also fields of migrating dunes with barkhans shifting east by about 10 meters per year.

A

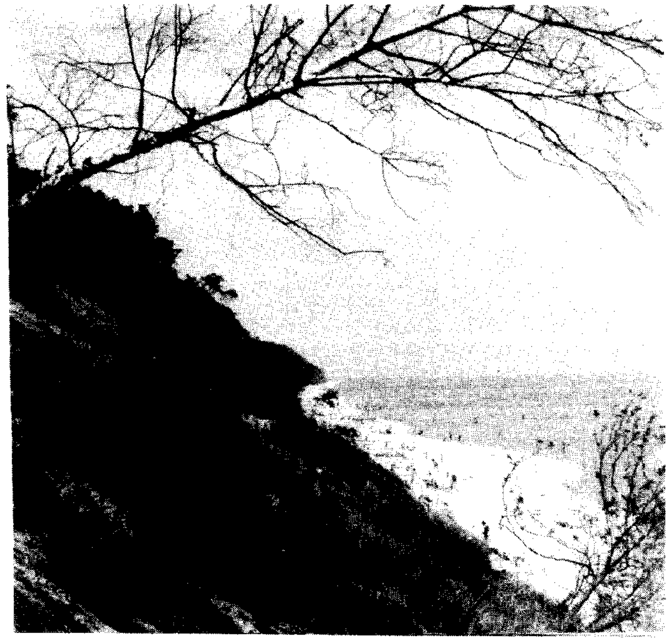


B

Figure 5. Coastal erosion in Poland.

(A) Ruin of the church at Trzesacz (middle coast), which was 1.8 km from the Baltic coast when it was built in the 12th century. Tetapads have subsequently been installed to slow cliff erosion.

(B) The town of Ustronie Morskie (middle coast) is also threatened by cliff erosion.



(C) Swimmers and sunbathers at Wolin Island (western coast) where the cliff has been cut into glacial and fluvial glacial Pleistocene deposits.

(D) Leba Barrier (middle coast) when erosion of foredunes has exposed underlying peat.

A

B

C

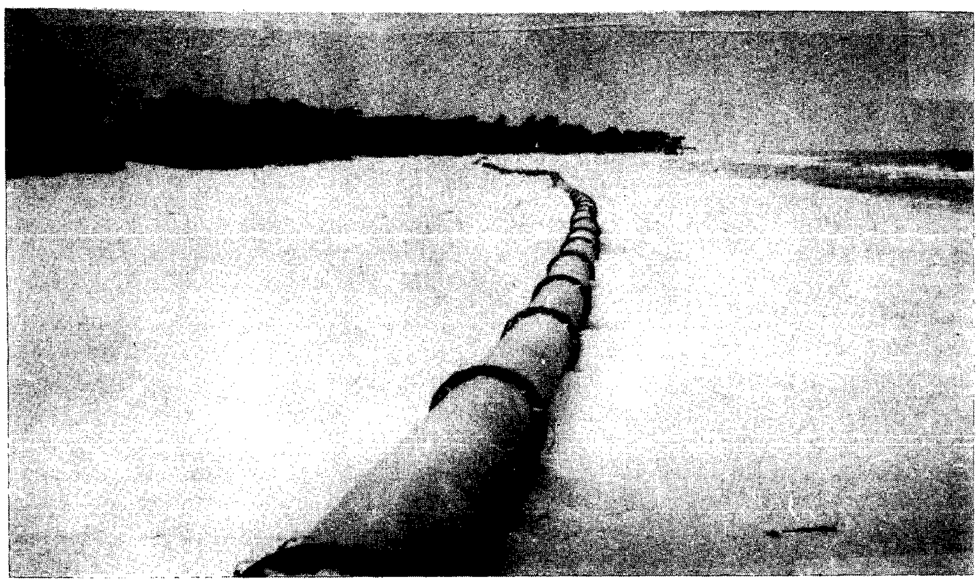


Figure 6. Erosion protection in Poland.

(A) Sarbinowo (middle coast). Concrete block and concrete band protect the cliff against erosion.

(B) Fishing village Kuznica on the Hel spit (eastern coast.) Boulder and clay ridge and piles of concrete sleepers protect the coast where foredunes have been destroyed by storm surges.

(C) Hel Spit near village Kuznica. Artificial beach built of sand pumped from the bottom of the Puck Bay.

There are also well-developed spits. Hel Spit is being intensively destroyed by erosion at present, especially in its western part. This process started with the construction of the harbor breakwaters of Wladyslawowo in 1938, located at the base of the spit.

Along the Polish coast are two large estuaries: Szczecin Estuary (687 km^2), the Vistula Estuary (838 km^2), and some coastal lakes with a total area of about 196 km. Low-lying wetlands behind barriers are commonplace (Figure 4), particularly in the deltas of the Vistula (ca. 1,650 km^2) and Odra Rivers (ca. 300 km^2) as well as numerous late glacial marginal valleys. A substantial part of these areas, especially on the Vistula Delta, are depressions with an elevation of -1.8 m below sea level. Since the 15th century, people have controlled the hydrologic conditions of the wetlands; hence a rise in sea level would not necessarily inundate them, but it would require increased pumping.

CULTURAL AND ECONOMIC FEATURES OF THE POLISH COASTAL ZONE

Land Use of the Low-lying Areas

The Szczecin Estuarine area and the lower Odra valley areas lie less than 1 m above sea level. These areas are mainly wet meadows and grazing land, similar to areas on Poland's middle coast. Areas between 2 and 5 m above sea level are mostly arable land. In the Vistula Delta (1,653 km^2), embracing 47% of the low-lying areas of the Polish coastal zone, agricultural land takes up 77%, and nonagricultural land, 23%. Of the agricultural land, 62.5% is in cultivated fields and 37.5% is in meadows and pastures (Matusik and Szczesny, 1976).

The Vistula Delta has very good soils that have facilitated the development of intensive agricultural production. A substantial part of the low-lying areas of the Polish coastal zone (1,835 km^2) is in polders, of which 555 km^2 are in depressions (Cebulak, 1976, 1984). About 67% of the polders are in the Vistula Delta, 18% on the middle coast, and 15% in the Szczecin region. The polders are protected by a system of dikes: 975 km of dikes in the Vistula Delta, 22 km on the middle coast, and about 250 km in the Szczecin area (Cebulak, 1984).

Population

The Polish coastal zone comprises 28 towns, which in 1985, were inhabited by 4.2% of the total population of Poland (i.e., 1.6 million people); of this total, 83% live in six towns: Gdansk, Szczecin, Gdynia, Elblag, Swinoujscie, and Sopot (Figure 7). In 13 of these towns, 50-100% of the land is 0-5 m above sea level. Only 5-40% of the remaining towns lie less than 5 meters above sea level.

Jointly, the low-lying areas of the Polish coast are inhabited by about 680,000 people -- i.e., 1.8% of Poland's population. Approximately 52% live in the Gdansk-Gdynia-Sopot agglomeration, 23.5% in the Szczecin region, and 13.6% in the Vistula Delta. The remaining 11% are dispersed along a 300-km-long coast between Wolin Island and the tip of Hel Spit. The density of the population of the coastal belt lying less than 5 m above sea level is 193 persons/km^2, of which 25-26 persons/km^2 live in rural settlements.

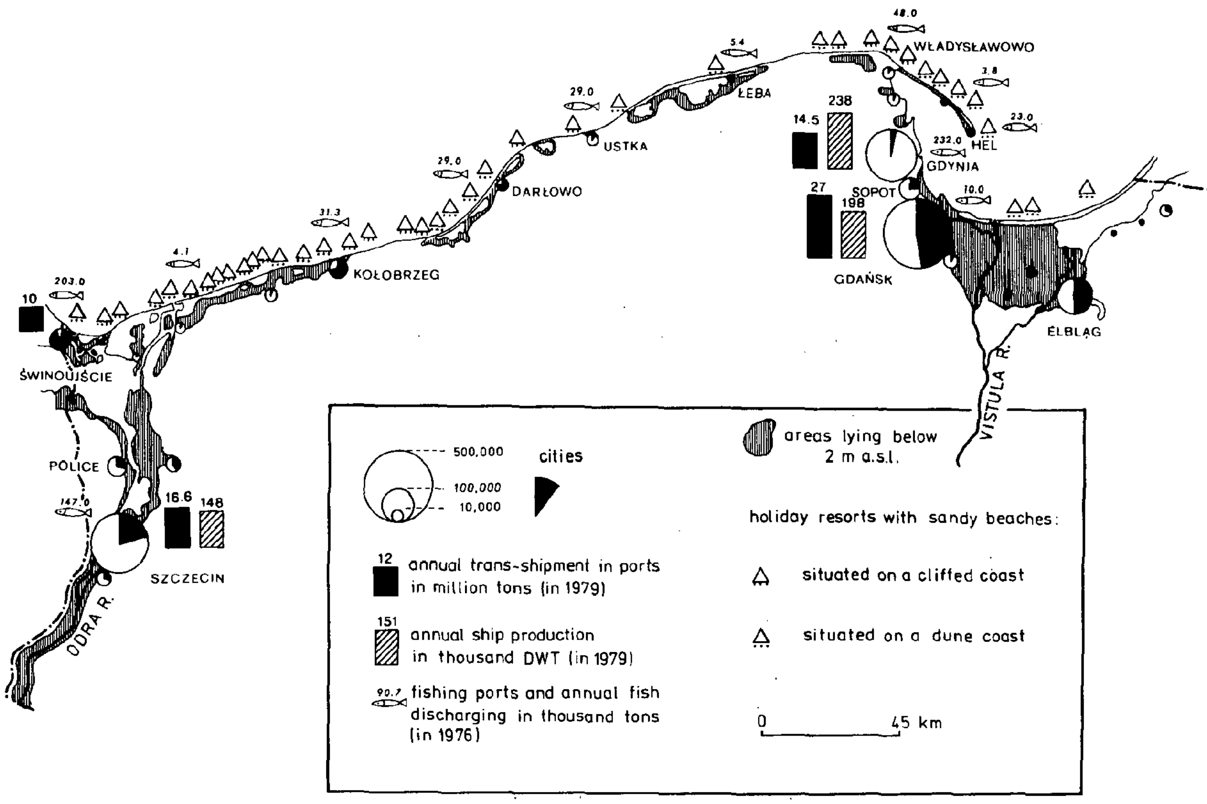


Figure 7. Cities, ports, shipyards, and holiday resorts at the Polish Baltic coast. Black sector in the circle marks the part of the city threatened by a future sea level rise.

Ports and Industry

The largest Polish port is Goteborg, which lies on the Baltic. Poland has four other large ports: Szczecin and Swinoujscie on the west coast, and Gdansk and Gdynia on the east coast (Figure 7). The joint annual transshipment of the four smaller ports amounted to 60 to 70 million tons in 1979. The old harbor in Gdansk and those in Szczecin and Swinoujscie are natural, situated in the river mouths; the Gdynia harbor and the North harbor in Gdansk are artificial. In addition, three small natural harbors are situated in the river mouths on the middle coast.

The coastal zone has a well-developed shipbuilding industry. There are several shipyards, including three large ones in the ports of Gdansk, Gdynia, and Szczecin with an annual productive capacity of about 2% of the world production. The harbors and shipyards have a developed industrial hinterland, which also is the location of the electromechanical, electronic, and food industries. Also located in this area are the Lower Odra power plant, an oil refinery in Gdansk, a large chemical plant at Police with a new harbor for handling chemical cargo located on the Odra River, railway junctions, and numerous architectural monuments (e.g., the Old Town in Gdansk, a priceless monument of culture).

Tourism

Almost the entire coastal zone has spectacular landscapes, which are valued by tourists. It has two national parks, on Wolin Island and on the Leba Barrier, and a coastal landscape park at Hel Spit. The coastal zone boasts a combination of sandy beaches (3 ha/km of beach), cliffs, forested and partly active dunes, large coastal lakes behind narrow barriers, and architectural monuments (Andrzejewski, 1984).

In 1980, 14.5 million tourists visited the Polish coastal zones, which has 138,000 beds for tourists, mostly in small localities of up to 1,000 inhabitants. There are also accommodations at camping grounds, of which about 50% are up to 500 m from the beach (Andrzejewski, 1984).

Shore Protection

Of the 39 holiday resorts and sandy beaches (Figure 7), 16 are on cliffed coasts that are eroding 0.4-2.3 m/yr. As a result, a variety of shore protection structures have been erected on the Polish coast. The most expensive concrete seawalls protect about 20 km of the shoreline. Wooden and concrete groins are located along 58 km of the coast, but they often do not really protect the shore against erosion; they merely slow erosion and in so doing, create a problem elsewhere. Most of the low unconsolidated dune coast is only protected with the help of low fences.

In recent years, especially after storms of the 1980s when erosion caused the shore of the narrow Hel Spit to shrink by 50-80 m at some places and the water washed over in other places, boulder-and-clay ridges are being built, and piles of concrete sleepers are being dumped along a 4-km section of the shore. However, these are destroyed too. In 1989, at two points of Hel Spit, the sand from the bottom of Puck Bay was pumped onto the seashore to create a 50-m beach belt 2-3 m in height.

The entrances to all the harbors are protected against storm waves by jetties, usually running parallel to each other and confining the navigable channels. There is sand accumulation on the updrift (western) side of the jetties, and erosion and landward shoreline movement on the downdrift side.

IMPACT OF A FUTURE SEA LEVEL RISE

Accelerated rise in sea level will pose direct and indirect threats to the low-lying areas. Direct inundation will confront the lowest areas, which will be below the new sea level. Indirect threats such as flooding will face the adjoining, slightly higher, areas. The natural, economic, demographic, and cultural resources of Poland's coastal will be seriously jeopardized.

Impacts of a 0.5-m Sea Level Rise

The areas lying less than 0.5 m above sea level will be inundated by a number of processes: (1) the narrow, sandy coastal barriers separating the low-lying areas from the sea could erode, exposing inland areas to the sea; (2)

river valleys will drown; and (3) groundwater tables will rise. Several other effects will be evident with a 0.5-m rise in sea level. Other impacts include cliff erosion and higher lake levels.

Increased Cliff Erosion and Landward Movement of the Beach

With a 0.5-m rise in sea level, the probability of particular levels of the sea being exceeded during storm surges will increase markedly. Flood levels that today occur only once in a hundred years will recur every 3.5 to 5 years. Based on the cliffs that are currently exposed to similar levels of wave attack, we estimate that most cliffs will erode 2.3 m/yr.

Accelerated Sediment Transport by the Longshore Current

The higher levels attained by storm surges will destroy foredunes and erode barrier islands and spits. The lowered barriers will then be susceptible to storm washover, which will lead to inlet breaches and sedimentation on the backside of barriers. The sedimentation will encroach either upon coastal lakes or upon the meadows and pastures of peat plains. As a result, the coast will recede and the barriers will shift landward. Especially threatened are the narrow barriers of the middle coast separating Lakes Jamno, Bukowo, and Kopan from the sea and Hel Spit.

Higher Coastal Lake Levels

Coastal lakes are connected with the sea through canals or rivers. The coastal barriers along the Polish coast have enclosed depressions and valleys of the late glacial age, forming coastal lakes and peaty marsh plains. Theoretically, a sea level rise of 0.5 m should increase the area of these lakes by 10-30%. This, however, depends on (1) how fast sea level rises, and (2) whether other geological and biological processes adjust to the rate of the rise.

Over the last few decades, no increase in the area of these lakes has been observed, despite the accelerated rate of sea level rise. On the contrary, because of their intensive eutrophication, the lakes tend to be overgrown, and their area is dwindling. The rise in water level would have to be very rapid to change this tendency. Hence, a rise in the level of the lakes will probably enlarge the area of swamps and young peat bogs surrounding the lakes and situated on valley floors and low-lying plains. The sediment transported by rivers into the lakes, the shift of coastal barriers southward through overwash and inlet-fan sedimentation, the rapid growth of vegetation on the lake sides, and biogenic sedimentation controlled by eutrophication are all likely to transform the coastal lakes to land, thus gradually destroying a zone of great landscape value. However, theoretically the whole of the lacustrine-barrier zone could shift south.

Expanded Depression Areas and Higher Groundwater Levels

A sea level rise of 0.5 m will enlarge the area of depressions from 555 km^2 to 1,720 km^2, with 63% of the increased area in the Vistula Delta, 23% in the Szczecin Haff region, 13% on the middle coast, and 1% in the Gdansk-Gdynia-Sopot agglomeration (mostly in Gdansk). These areas will probably be inundated by the groundwater level rise; however, this too depends on the adjustment of natural processes to (1) the rate of sea level rise and its ingression through the valleys, and (2) the rate of groundwater level rise. Most probably this sea level rise will make these areas swampy and will cause the development of peat bogs and the accumulation of phytogenic layers. Thus swamps and wet grassland will greatly increase in area. The rise in sea level may even affect areas situated 1-2 m above sea level today. The range of this process will depend primarily on (1) the intensity of the inflow of groundwaters from morainic plateaus onto the low-lying areas, and (2) the initial depth of the groundwater level.

In polders, primarily in the Vistula Delta (1,135 km), (1) groundwater will rise more rapidly; (2) the probability of particular areas being flooded will increase, as will the breaching of dikes due to increased infiltration of water during high stages; and (3) the dikes already built will be too low for the new hydrological conditions. The probability that the dikes already built in the Vistula Delta will be unable to protect polders against water is today less than 0.1% (i.e., a recurrence interval of 1,000 years). However, dikes can be disrupted because of their excessive permeability or by an ice jam at the mouth of a river.

The height of the dikes is 2.2-2.3 m because Polish regulations require them to be 70 cm higher than the 50-year storm (i.e., annual probability of 0.02), although sea level has risen 10 cm since some of them were built (Krzesniak, 1976). If the sea rises another 50 cm, then the water level during the 50-year storm will only be 10-20 cm below the dikes, 50-60 cm too low for comfort.

Thus, it will probably be necessary to (1) upgrade the capacities of intermediate pumping stations; (2) rebuild and increase the height of dikes; and possibly (3) raise polder bottoms. These problems would face polders with a combined area of 1,500 square kilometers, their surrounding dikes (some 1,300 km long), and 120-200 intermediate pumping stations. It is possible that new polders will have to be built on waterlogged land that will keep expanding in area. Given the possibility of a one- meter rise in sea level, the new dikes should be 3.2-3.3 m above sea level.

<u>Inundation of the Lower Reaches of River Valleys</u>

Several changes will take place in the lower reaches of river valleys, depending on the ability of a particular river to adjust to the rate of the anticipated sea level rise.

In the Odra valley, a sea level rise of 0.5 m would increase the frequency of flooding over an area 3-4 km wide that extends 50 km upstream, due to both higher storms surge levels and the backwater effect on river surges. Near the coast, flood levels will generally rise 50 cm; upstream, the rise in flood levels will be somewhat less but still significant. In some cases, the increased flooding may be mitigated if global warming reduces ice jams, which currently are responsible for some floods. Sedimentation from floods will tend to shift upstream, perhaps increasing the ability of a few undeveloped areas to keep pace with the rising sea -- at the expense of increased inundation downstream.

These effects will necessitate rebuilding the facilities currently protecting the polders, such as dikes and possibly also intermediate pumping stations. In the lower Odra valley, harbor facilities and low-lying industrial plants in Szczecin and in Police will be threatened. Similar threats will emerge in the lower Vistula valley and the valleys of the lesser rivers (the Rega, Wieprza, Parseta, and Slupia), at the mouths of which are located harbors, industrial buildings, and parts of residential buildings.

Increased Estuarine Salinity

The lakes will grow more saline as a result of more frequent inflows of Baltic waters into them through river mouths and overwash breaches of barriers. Moreover, a rise in sea level will facilitate contact between the Baltic and Atlantic through the Danish Straits. We may anticipate more frequent and massive storm inflows of the more saline and oxygenated Atlantic waters into the Baltic, which will benefit the biological life of this sea.

Increased Groundwater Salinity

Higher sea level will hinder the seaward flow of groundwater and allow the water table to rise in the coastal zone. Higher groundwater levels will also increase seawater infiltration. This will be reinforced further by an accelerated water circulation in polders and an excessive exploitation of fresh waters on barriers, where the drawing of freshwater from near-surface lenses may cause a rise in the saline water table.

Summary of the Impacts of a 0.5-m Rise

Because of physiographic conditions, the zones of the contemporary landscape and land use probably could not shift inland. It is imperative to keep the present agricultural use of the Vistula Delta and the lower Odra Valley, especially in the polder areas. Giving it up would mean tremendous economic losses.

All the ports and shipyards as well as a part of the industry and railway junctions located in the low-lying areas will suffer damage with a future rise in sea level. The extent of the danger will vary from port to port, depending on the following factors:

1. The degree of exposure of the ports and their facilities and infrastructure to waves and storm surges. Thus, the North Harbor in Gdansk and the fishing harbor in Wladyslawowo, both projecting into the sea, will be most threatened by exposure, whereas the harbor in Swinoujscie, situated on the west coast, will be more threatened by higher storm surges in this part of the Baltic.

2. The altitude above sea level of wharves, jetties, breakwaters, and other facilities.

3. The probability of simultaneous impacts of the rising sea level and floods caused by ice jams at the mouths of the rivers on which some

harbors are located -- e.g., in Szczecin, Police, Darlowo, Kolobrzeg, and Ustka.

4. An increase in sediment transport by longshore currents. This, in turn, will cause a more intensive alluviation of the entrances to the harbors in Swinoujscie, Ustka, Darlowo, Kolobrzeg and Wladyslawowo, as well as of the fairways leading to the harbors -- e.g., the 30-km long fairway in the Pomeranian Gulf leading to the harbors in Swinoujscie and Szczecin.

5. The kind, height, strength, and technical condition of the storm protection structures in the harbors. They are built to accommodate the probability of storm surges of various heights. However, the rise in sea level will increase the probability of storm surges that will be higher than those currently planned for. As a result, various technical equipment in the harbors and their storm protection structures may prove to be too low and too weak. They may stop fulfilling their function and may suffer more rapid destruction. A general answer to the question of whether harbor facilities and storm protection structures would suffer destruction in case of a sea level rise is impossible at this stage of the analysis of the problem. It requires detailed analyses for each of the harbors.

Impacts of a 1- to 2-Meter Rise in Sea Level

Such a rise would inundate another 1,200 km^2 of land (Figure 8); a much larger area would experience increased flooding. The processes and phenomena triggered by the rise of 0.5 m will continue and intensify, but their spatial range will expand, and the threat they will pose to urban, industrial, and agricultural areas with a high capital investment level will be greater. The

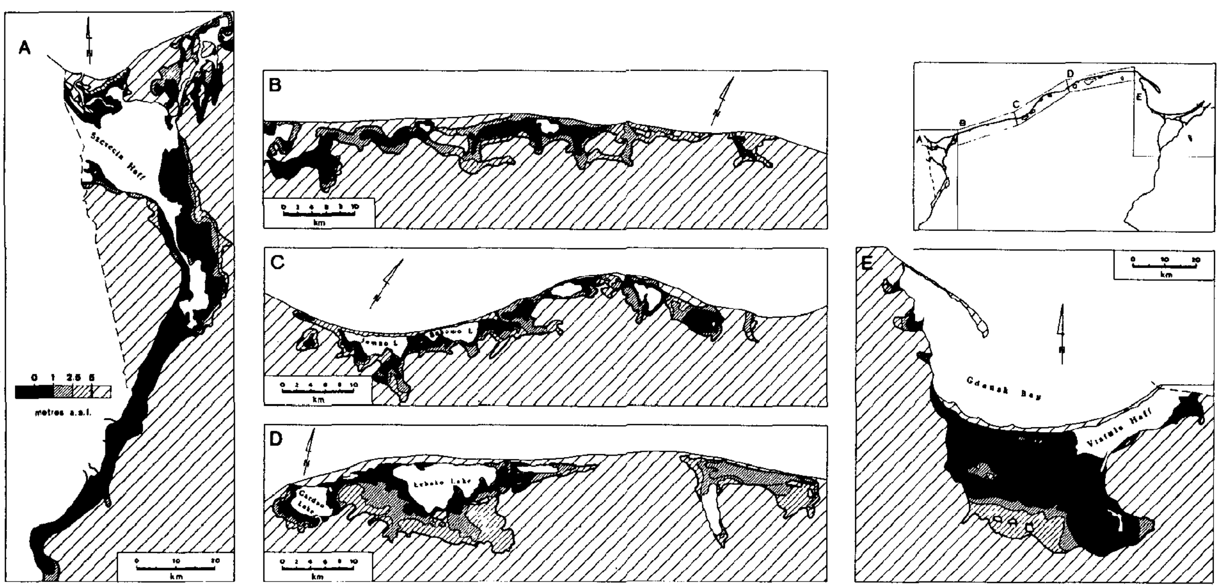


Figure 8. Location of low-lying areas along the Polish Baltic coast.

steep slopes along the morainic plateaus would prevent the beach-barrier-lake zones from shifting inland by more than 1 to 4 km.

Lakes will change shape, unless peat formation and sedimentation accelerate. Some lakes will unite; and cultivated fields, with the exception of polders, will practically disappear from the low-lying areas of the coastal zone. There will be an increase in the area of peat bogs and water-logged meadows. In the Odra valley, the narrow strip of the floodplain in danger stretches 80 km south of Szczecin; in the Vistula delta, the endangered area includes 1,560 km, or 94% of the delta area less than 5 m above sea level.

Rural settlement will have to be moved to altitudes higher than the 2-m contour lines. Agricultural use of this land will be possible only through the building of polders in an ever-increasing area. A part of the settlements and tourist accommodations on the low sandy coast will be destroyed or will have to move onto newly developed accretionary lands on the inner parts of barriers. Threatened with direct inundation will be parts of towns located less than 2 m above sea level and inhabited today by about 360,000 people -- mainly parts of Gdansk, Szczecin, Swinoujscie, and Elblag. Higher situated areas of towns will be threatened indirectly by flooding.

CONCLUSIONS

It is difficult to make a complete list of threats to urbanized, harbor, industrial, and historical areas. We can only draw attention to the main sources of danger. The danger starts today and will grow with the rise of sea level. Its main sources are (1) the insufficient height and strength of harbor protection facilities; (2) the increased filling up of the entrances to harbors and navigable channel ways; (3) the destructive action of storm surges of a higher frequency of given stages and ever higher; (4) a rise in groundwater level posing a threat to (a) the strength of foundations and grounds under houses, industrial buildings, railway junctions, and communication routes, and (b) the functioning of the urban underground infrastructure with such installations as stormwater drains, telecommunications, and power cables; (5) the appearance of groundwater on the surface of low-lying parts of towns; and (6) the insufficient height of artificial dikes and the possibility of a flood.

The Central Marine Office is responsible for planning and implementing the protection of Poland's seashores. The existing plans consider current erosion rates but would not accommodate an accelerated rise in sea level. Also, they concern only the shoreline, not the entire coastal zone. Awareness of the dangers from future rise in sea level is low, both among the public and within the administrative units. It is highly probable, however, that with the changes taking place in Poland today, the message of this report will get through to the new decisionmakers and managers in the state administration.

The processes already started by the rising sea will require town planners, designers, planning offices, economists, engineers, and decisionmakers to adopt a totally different approach and philosophy that will accommodate the analysis of the costs, risks, and effects of sea level rise. They must learn to view the coastal zone as a dynamic system that undergoes continual adjustment.

BIBLIOGRAPHY

Andrzejewski, E. 1984. Turystyka (Sum.:Tourism). In: Pobrzexe Baltyku. Augustowski, B., ed. Wroclaw: Ossolineum.

Cebulak, K. 1976. System wodno-melioracyjny (Sum.:The water and drainage system). In: Xulawy Wislane. Augustowski, B., ed. Wroclaw: Ossolineum.

Cebulak, K. 1984. Gospodarka polderowa (Sum.: Polder economy). In: Pobrzexe Baltyku. Augustowski, B., ed. Wroclaw: Ossolineum.

Cieslak, K., and W. Subotowicz, eds. 1986. Stan wiedzy o hydrodynamice i litdynamice oraz ochronie brzegu morskiego.

Czekanska, M. 1948. Fale burzowe na poludniowym wybrzexu Baltyku (Sum.: Flood raised by storm on the southern shores of the Baltic Sea), Badania Fizjograficzne nad Polska Zachodnia 11:58-96.

Dziadziuszko, Z., and T. Jednoral. 1987. Wahania poziomow morza na polskim wybrzexu Baltyku (Sum.: Variation of sea level at the Polish Baltic coast), Studia i Materialy Oceanologiczne 52:215-238.

Jednoral, T. 1984. Spietrzenia sztormowe wzdlux polskiego wybrzexa. Slupsk: Instytut Morski, Archives Reports., Jednoral, T. 1985. Fale wiatrowe Morza Baltyckiego w swietle badan empirycznych. Slupsk: Instytut Morski, Archives Reports.

Kwiecien, K. 1987. Warunki klimatyczne (Sum.:Climatic conditions). In: Baltyk Poludniowy. Augustowski, B., ed. Wroclaw: Ossolineum.

Majewski, A. 1987. Charakterystyka wod (Sum.: Characteristic of the Southern Baltic waters). In: Baltyk Poludniowy. Augustowski, B., ed. Wroclaw: Ossolineum.

Majewski, A., Z. Dziadziuszko, and A. Wisniewski 1983. Monografia Powodzi Sztormowych 1951-1975, Warszawa: Wydawnictwa Komunikacji i Lacznosci.

Matusik, M. 1984. Gospodarka rolna (Sum.: Agricultural economy). In: Pobrzexe Baltyku. Augustowski, B., ed. Wroclaw: Ossolineum.

Rosa, B. 1984. Rozwoj brzegu i jego odcinki akumulacyjne (Sum.: The development of the shore and its accumulation sections). In: Pobrzexe Baltyku. Augustowski, B., ed. Wroclaw: Ossolineum.

Slupsk: Instytut Morski, Archives Reports., Costa, J.R., and V.R. Baker. 1981. Surficial Geology Building With the Earth. Chichester: John Wiley and Sons.

Subotowicz, W. 1982. Litodynamika brzegow klifowych. Gdansk: Ossolineum.

APPENDIX: CLIMATE AND HYDRODYNAMICS OF POLAND

Climate

The climate of the Polish coast is characterized by highly variable weather conditions because the southern Baltic is on the path of very active cyclones. Moreover, it is an area of a frequent exchange of air masses advancing almost freely from different directions. The prevailing masses are polar-maritime air from the west (60.4%). Much less frequently the area comes under the influence of polar-continental air masses from eastern Europe (15.5%) and arctic air from the Norwegian Sea (9%). The least frequent are tropical air masses (1.5%) (Kwiecien, 1987). The mean annual temperature of the Polish coast varies between 7.1°C at Cape Rozewie and 8.0°C in Swinoujscie. The coldest months are January and February, with mean temperatures from -0.6°C in the west to -2.4°C in the east (see Figure 1). The warmest months are July and August (16.1-17.2°C). The mean precipitation depends on the degree of exposure of the coastline to rain-bringing westerly winds. Thus, the highest mean annual rainfall is recorded on the middle coast between Darlowo and Leba (650-700 mm), while the remaining areas receive much less rainfall (550-570 mm). The highest mean monthly wind velocities (5-7 m/sec) are characteristic of the autumn-winter months, whereas the lowest are recorded from May to August (2.5-3.5 m/sec). The autumn-winter season contains the greatest number of days with strong winds (29 days: 6-7°C) and storm winds (18 days: >8°C).

Hydrodynamics

The direction of the longshore current is controlled by prevailing winds, and sediment in the littoral zone is generally transported from the west to the east (see Figure 1). It is only between Kolobrzeg and Swinoujscie that westward sediment transport can sometimes prevail. During storms, rip currents 50-200 m apart appear that are almost perpendicular to the coastline. In the deep-water zone, about 85% of waves are not higher than 3 m or longer than 7 sec. As much as 95% of the waves are not higher than 4 m or longer than 8 sec. In the offshore zone, storm waves attain a height of 1 m above the current mean sea level, and reach 2 m only in the zone of a steeply sloping coast (Jednoral, 1984).

ADAPTIVE OPTIONS AND IMPLICATIONS OF SEA LEVEL RISE IN ENGLAND AND WALES

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ABSTRACT

On July 10, 1989, the National Rivers Authority was established as the major flood defense agency for England and Wales, with the regionally based staff transferred from the regional Water Authorities. One of the Authority's principal roles is to coordinate and plan flood defense strategies and to undertake appropriate defense programs.

As an island nation, the United Kingdom has a significantly high percentage of low-lying land already at risk; rising sea levels will increase that risk. Coastal land use is a mix of rural, urban, residential, commercial, and industrial zones. This paper identifies the location of flood-prone areas and refers to some of the socioeconomic aspects of those unprotected areas. Reference will be made to the storm of 1953 and the defense systems constructed subsequently around the coast and along the river networks.

The principles used to develop the design defense level for the Thames Barrier is also summarized. We review the present policies for flood defense and the short-term interim approach needed to respond to any additional threat from sea level rise.

Long-term strategies cannot be developed until predictions from global circulation models become more reliable. This paper refers to current research programs to analyze the effectiveness of the present generation of defense structures and identifies some of the constructional adaptations that would increase their effectiveness.

Some reference is made to the implications for agricultural lands if the rainfall patterns deviate from those of the present day. Rising sea levels may preclude the use of gravity outfalls and low-head pumping stations.

The United Kingdom has an extensive data-gathering network to aid the monitoring of rainfall, river flows, and river levels in real time. Tidal and

storm-surge forecasts can be undertaken with a considerable degree of accuracy. The tidal gauge network can be monitored, again, in real time, to check these predictions. This paper shows that the United Kingdom's ability to issue reliable flood warnings to inhabitants in urban and coastal areas is well advanced.

Finally, this paper comments on the use of benefit/cost analyses to support policies, as well as the effects of the new European Community Directives for environmental and wildlife protection as a component of the flood defense policies.

INTRODUCTION

Legislation

The government departments responsible for flood defense policy are, in England, the Ministry of Agriculture, Fisheries, and Food, and, in Wales, the Welsh Office. The 1989 Water Act established the National Rivers Authority. This act transferred to the new Authority from the former regional water authorities responsibility for supervising all matters relating to flood defense, and for undertaking functions set out in the 1976 Land Drainage Act. Among other things, the new act gave the National Rivers Authority responsibility for safeguarding the water environment; for improving water quality and resources; for enhancing the environment, amenities, and recreation facilities; and for developing, in conjunction with the Ministry of Agriculture, Fisheries, and Food, strategies for flood defense and flood warning systems. The act also provided for the establishment of utility companies to deal with water supply, sewer systems, and sewage treatment. (Scotland and Northern Ireland have separate legislation, so policies and practices in these two countries are excluded from this paper.)

The powers to deal with problems of erosion of coastal land not subject to flooding are exercised by 88 Maritime Councils in England and Wales under the Coast Protection Act of 1949. As in the case of flood defense, the government departments that have overall responsibility are the Ministry of Agriculture, Fisheries, and Food in England and the Welsh Office in Wales. The National Rivers Authority has no responsibility for this area of activity; thus, no further reference will be made in this paper.

The National Rivers Authorities exercises its functions through nine regions in England and one region in Wales (Figure 1). Before the new act's passage, ten regional water authorities managed all aspects of the water cycle.

As the principal flood defense agency in England and Wales, the National Rivers Authority not only has powers to construct all types of flood defense works and land drainage works, both on statutory main rivers and on the coast,

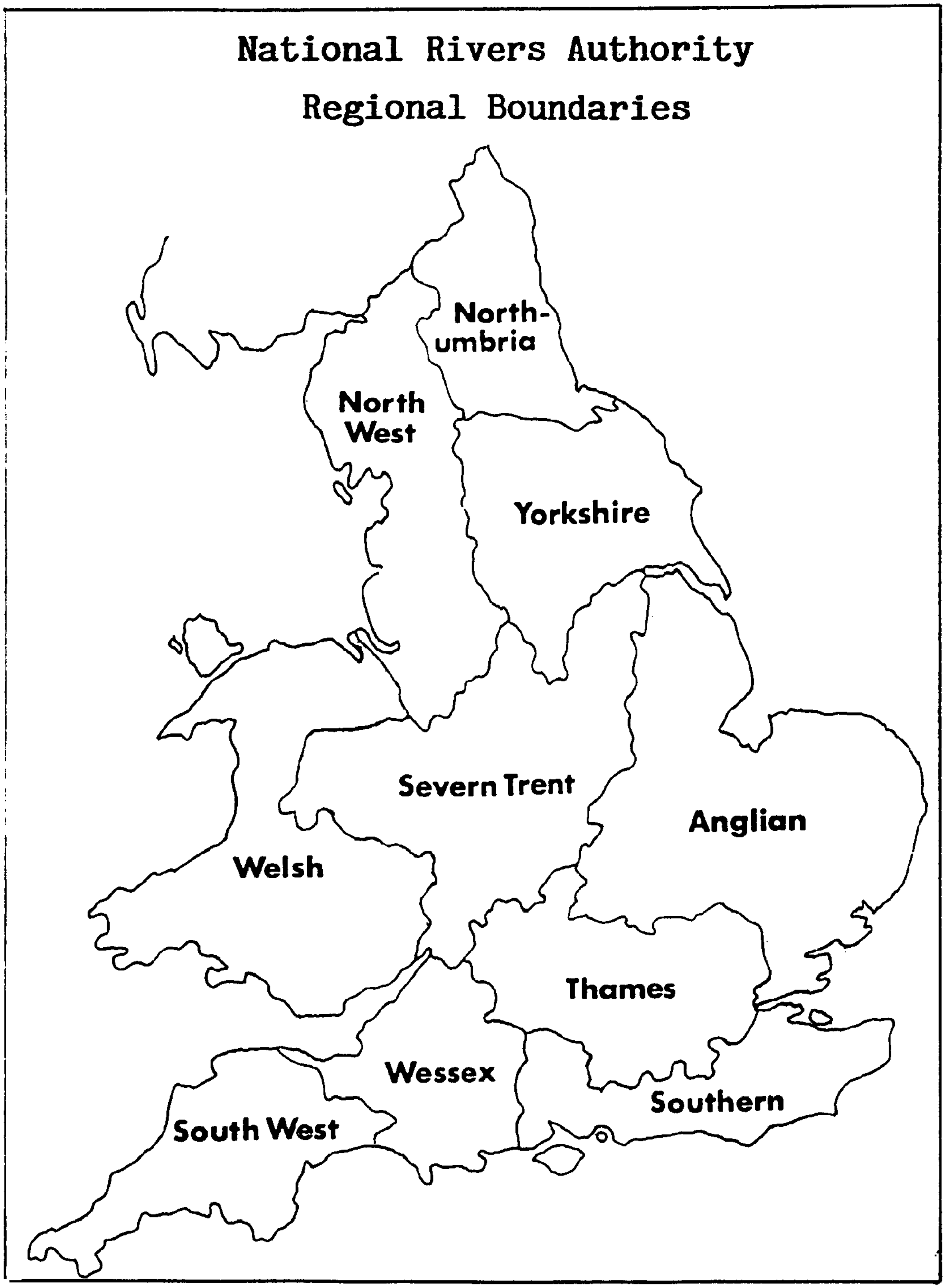


Figure 1. The ten regions of the National Rivers Authority.

but also has general oversight of 250 Internal Drainage Boards and the county, district, and metropolitan borough councils.

Within the ten regions, flood defense functions are carried out by Regional Flood Defense Committees, each under a chairman appointed by the Minister of Agriculture, Fisheries, and Food. Four of the regional committees have developed their functions to local flood defense committees. The boundaries of the areas of regional and local committees are "river catchment based" and have evolved over a 50-year period as a consequence of the various land drainage acts preceding today's statutes. These four regions share a total of 18 local districts.

Funding of Flood Defense Works

Any of the above flood defense agencies undertaking improvement works that can be regarded as a capital investment may be eligible for funding from the national government. The level of the grant may range from 15 to 55%, with the actual rate depending on the type of flood defense agency and, in the case of the National Rivers Authority, the scale of local district programs and the ability of the local population to pay for them. Sea defense works or river works to protect against tidal flooding attract a 20% supplement added to the above rates.

The balance of the cost of the capital works, together with the costs of all maintenance works, staff costs, all overhead costs, equipment costs, etc., are met out of revenue raised individually within the local districts.

The National Rivers Authority is currently spending some £67m (over 100 million U.S. dollars) per annum on capital works. The majority of this amount goes toward building or reconstructing flood defenses. This level of investment is expected to increases, in real terms, over the next decade by as much as 50%. Through grants, the Ministry of Agriculture, Fisheries, and Food provides approximately 30% of the cost of the capital works program; this contribution also will increase. Finally, almost as much is being spent on the maintenance of existing structures, defenses, and water courses.

SEA LEVEL RISE - PROTECTIVE MEASURES

Historical

Until some 8,000-10,000 years ago, much of Great Britain was covered with a deep ice sheet. The northern part of England and Wales was covered by thick ice, while land to the south of this sheet suffered varying intensities of ground freezing. At this time, the sea level would have been up to 100 meters (330 feet) lower than today, and the present sea bed of the English Channel and southern North Sea was exposed as dry land. Thus, Great Britain was apparently part of the European continent (Brunsden, et al., 1989).

As a consequence of a gradual rise in global temperature, this ice sheet melted and sea level rose. Over time, the ancient deep river valleys and lakes gradually silted up and the layers of the superficial deposits became interspersed with layers of vegetation, resulting in a complex, stratified arrangement of organic and inorganic materials.

Despite the silting processes, much of this land still lies below present-day sea level. Some of it is as low as 7 meters below the sea, but the majority lies between 0 and +5 meters (Figure 2). These areas have a high level of natural fertility, and, over many centuries, inhabitants have raised embankments to exclude either seawater or riverwater. These embankments were constructed at what was the edge of the sea. Gradually, the lower lying land that was seaward of the defenses was covered and raised by further deposits of marine sediments. As the resulting salt marsh grew, new defenses were constructed at the new seaward limit. Each of these successive embankments was constructed to a much larger cross-section and to a higher level than the earlier ones.

These progressively larger defenses were needed because the sea and river levels were rising relative to the land and because higher standards of defense were required to protect the increasingly larger areas of land carrying the ever-increasing valuable agricultural and horticultural industries.

England and Wales cover an area of approximately 15 million hectares. Agricultural land is graded using a five-category land classification system. The Ministry of Agriculture, Fisheries, and Food has conducted some work on identifying areas at risk, and a paper on this subject was presented at the 1989 Loughborough Conference (Whittle, 1989). About three-quarters of a million hectares of land lie below +5 meters Ordnance Datum Newlyn (ODN). (Note: ODN, similar to NGVD in the United States, refers to a fixed elevation that was at sea level when the datum was established.) Within this lie some 640,000 ha of land, (8%), Grades 1-3, of which nearly 200,000 hectares are classed as Grade 1 land.

In the early days, these lowlands were frequently inundated and, consequently, not conducive to occupancy by settlers. So for the most part, settlements developed along river estuaries, especially where a high-level spit or area of land was free from frequent inundation. Today, many of these early settlements alongside rivers have become established as major commercial and industrial zones supported by the necessary infrastructure and residential areas. Progressively, demand for developable land has meant extension into zones where risk of flooding is high. Thus, higher standards of defense have been demanded. In common with many developed countries, the United Kingdom now has billions of pounds of real estate investments in rural and urban zones--to say nothing of the hundreds of thousands of people, protected from sea and tidal flooding, all of which will require continued protection against a rising sea level.

Post-1953 Tidal Surge

A major tidal surge struck along the east coast of England in 1953. Some 300 people died, thousands of hectares of land were inundated with saltwater,

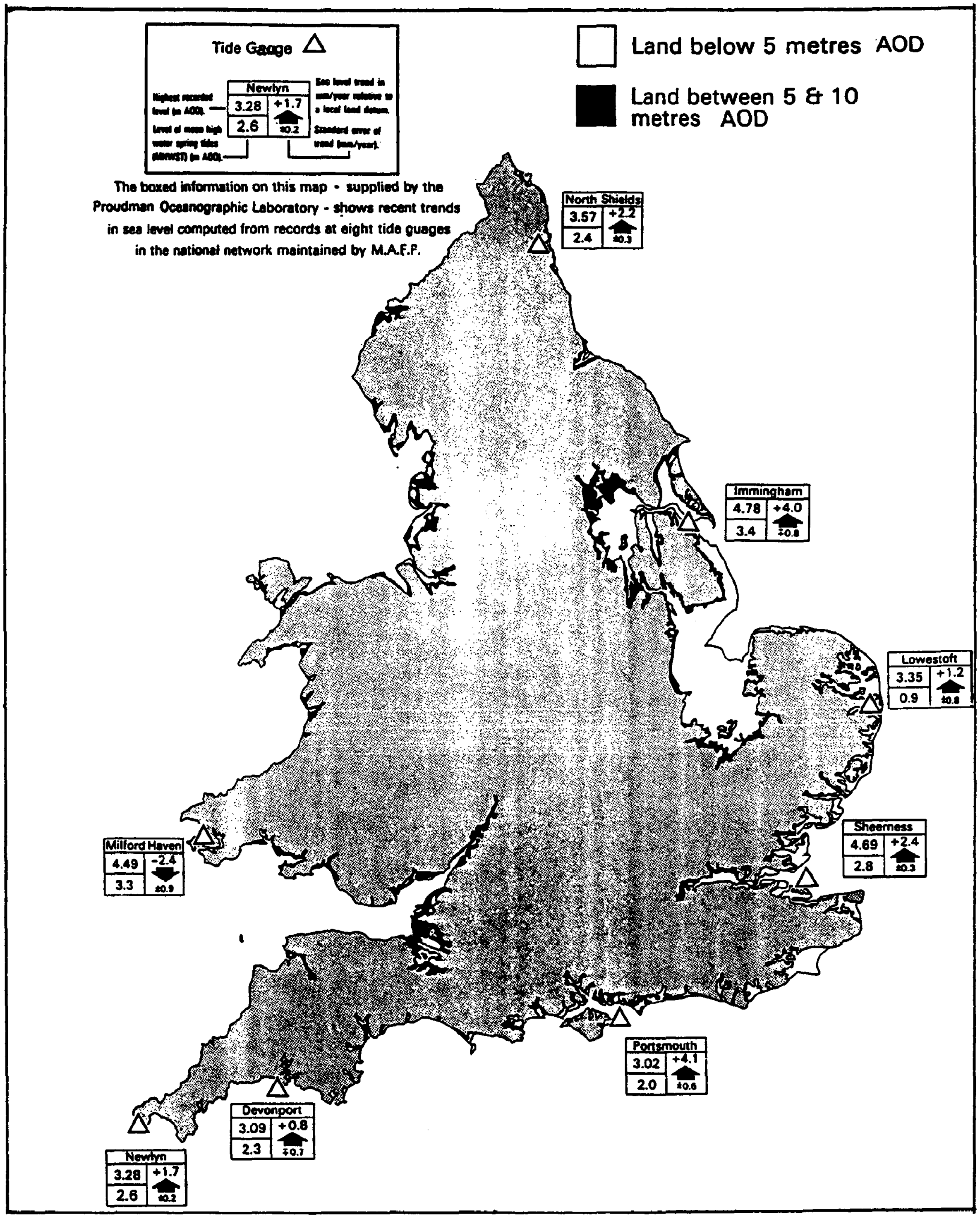


Figure 2. Low-lying land in England and Wales.

and vast urban areas were demolished or seriously damaged. Many kilometers of sea defense were breached, demolished, washed away, or overtopped. The surge caused a tide-lock condition in many rivers, causing them to overflow their banks and flood low-lying lands.

Since that storm, at that time the worst recorded in living memory, the catchment boards and their successors (river boards, followed by river authorities, water authorities, and the National Rivers Authority) have reconstructed, raised, or constructed most of the 1,000 km of sea defenses and the many thousands of kilometers of tidal defenses. However, many of those defenses have reached the end of their useful lives. Earthen embankments may have a life of only 25 years and are being reconstructed, and some hard sea defenses, which appear to have led to increased beach erosion, need either complete reconstruction or, at least, a new and deeper foundation at the front toe.

The surge of 1953 threatened the center of London (Figure 3). The decision was taken then to implement a long-standing proposal to protect London: the Thames Barrier.

The Thames Barrier

The Thames Barrier is unique in concept. It consists of a series of gates that are rotated upwards out of cills set into the river bed (Figure 4). The Barrier has been designed to afford a standard of protection against a one-in-one-thousand year storm surge, including sea level rise expected through the year 2030.

The level of the top of the gate was determined as follows:

1. Tide levels at Southend, the mouth of the estuary, were analyzed to determine the one-in-one-thousand year return period.

2. The hydrodynamics of the river were analyzed to translate the Southend data of tide levels to the Barrier site.

3. The trend line of the rise in river levels at a location near the Barrier site was analyzed to establish the relative rise in water level, and then extrapolated to the year 2030 (i.e., 50 years following the completion date of the structure).

4. The Barrier structure and gates are designed to resist a static force from some 9 meters (29 feet) of water.

The Barrier has been designed to permit water to spill over the top of the gates. Upstream of the Barrier, the river extends for a tidal length of 40 kilometers (28 miles). If the Barrier is operated sufficiently early in the tidal cycle, a "reservoir" of this length, and 9 meters deep, has little chance of being filled on any one extreme event. Furthermore, the gates could be rotated further to gain another 2 meters (6.5 feet) in height, provided that

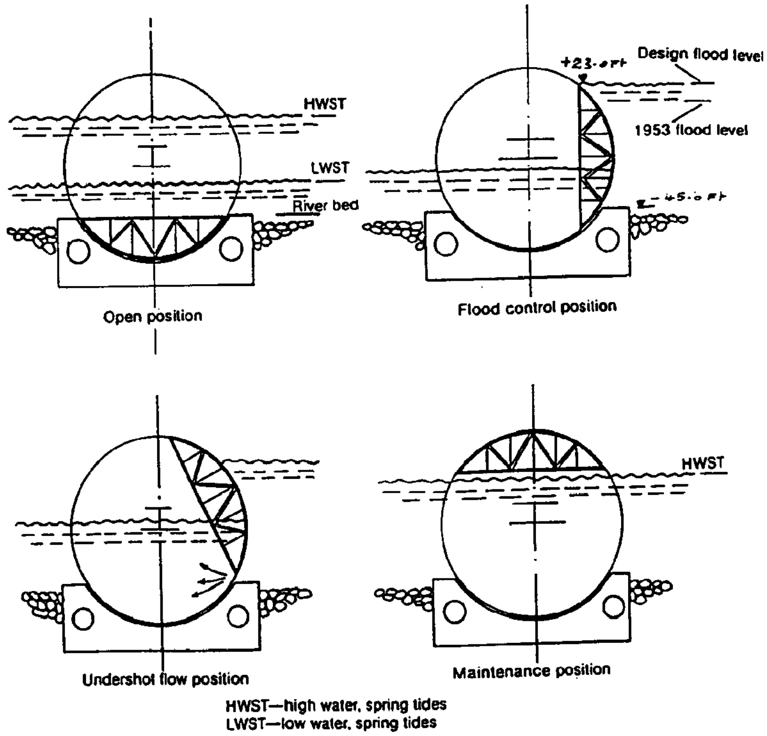
Figure 3. What London would have looked like if the flood had been just a bit higher.

minor alterations are made to the cills (Figure 4). Thus, the Barrier is capable of modification to effectively protect London well into the next century against the worst case predictions of sea level rise (at least given current storm severities) (Kelly, 1989). In 1982, the Barrier and associated riverside defenses from Southend, at the river mouth, to Teddington, at the tidal limit, were tested when the Barrier, although not quite complete, was closed against a high-surge tide. The Barrier has been operated against adverse conditions on four occasions.

Other Structures Along the Thames

Besides the Thames Barrier itself, other rivers and creeks have been given protection by new barrier structures. Most of these consist of drop-leaf gates set between towers. Those and other gated structures along the Thames would probably need structural reanalysis to determine their suitability for modification.

A



B

Barrier gate in four positions

Figure 4. (A) The Thames Barrier concept and (B) barrier in place on Thames River.

Barriers apart, many of the remaining defenses along the Thames consist of conventional hard defenses of varying design. Some may have adequate foundations and stability to receive an additional crest to gain extra height. Other defenses, such as soft earthen embankments with protected front face, may also be capable of being raised merely by the addition of extra material. Elsewhere, however, where the foundations and subfoundations consist of soft alluvial soils, it is unlikely that additional weight can be added to these structures. An extensive program of geotechnical investigation will be required to find the optimal solution.

Other Defenses in England

The areas of land in England and Wales at risk are protected by a variety of defenses. In the main, these defenses have been constructed from soft materials excavated from adjacent lands, but some occur naturally, such as sand dunes. Soft, artificial defenses have a short life, and many of those built since 1953 are now showing signs of stress and are being rebuilt, often by substituting a concrete or stone structure to meet the higher standards needed for the future.

Some navigable rivers within the United Kingdom have been supplied with barrier structures, particularly the river at Hull and the Fosse River at York. These structures have been designed with significant "air draught" to permit navigation.

Lowering Beach Levels

The United Kingdom, in common with other parts of the world, is experiencing a general lowering of beach levels and, frequently, loss of the protective foreshore and salt marsh in front of the soft defenses. The cause of this decline is alleged to be inability of the surf zone to move shoreward because of the presence of some obstructing defense. Accordingly, it has been shown that foreshores are becoming steeper (Halcrow, 1989), which will aggravate problems associated with defense management policies.

It can be shown through experimental work that the rate at which the beach level is being reduced is affected by the type of obstructing defense. A vertical profile wall creates reflective waves, which aggravate beach scour, although these damaging effects may be reduced by a "stepped" profile. An alternative profile to combat the adverse effect of walls is to use an embankment that permits waves to "run up" the face of the structure and thus dissipate wave energy.

OPTIONS FOR COMBATING SEA LEVEL RISE

Allowances in Design of Sea Defenses

It has been recognized for many decades that as a result of the retreat of the ice sheet, northern England is rising and southeastern England is sinking.

This isostatic change has contributed to a relative rise in sea level in southern England. An overall allowance on the order of 3 millimeters per year has, therefore, been included in the recent designs for sea defenses.

Most of the defenses along the east coast of England are open to a long fetch to the Continent and can experience severe wave action. An allowance of up to 2 meters may be provided. Soft defenses built from marine alluvium and clay soils suffer from shrinkage in the upper drying zone. An allowance of up to 1 meter for this effect is added to the design still-water level. Obviously, concrete walls do not have this component of safety, so crest levels of such defenses are lower. These allowances, together with any additional allowances that appear pertinent, are added to the basic still-water level (tide plus surge). The base still-water level is that for 1953 or any later event that resulted in a higher level.

It is appropriate to consider the allowances that should be included in the design of new flood defense works for sea level rise. There is so much uncertainty about future storm patterns, rainfall changes, and evapotranspiration changes that any allowance must be regarded as a "first guess." Some have suggested that an allowance of about 6 millimeters per year, including the existing isostatic change, could be prudent for short-life structures pending improved estimates of the consequences of climate change. Design concepts of structures should ideally permit easy modification to meet longer term needs.

The Ministry of Agriculture, Fisheries, and Food has estimated that the cost of constructing a defense suitable for currently projected sea level rise in England and Wales could amount to between 5 and 8 billion pounds (7 and 12 billion U.S. dollars). Within this budget figure is an allowance for new and replacement pumping stations, new drainage outfall systems, and at least two new tide-exclusion barriers.

Alternative Solutions

The opportunity for reconstructing soft defenses is diminishing. In many instances, this may be due to the need to provide increasingly large structures, the difficulty of obtaining a cheap supply of material from nearshore or inland sources, or the need to avoid damage caused to the environment by digging "borrow pits." Similarly, hard defenses are becoming more expensive, costing 3 to 5 million pounds per kilometer. With an appreciation of the damage that the hard structure can cause to the environment, there is a gradual change in the engineering attitudes toward seeking equally efficient alternative solutions.

Engineers in Great Britain are gaining experience with schemes that involve raising beach levels using material dredged from sources in stable, offshore zones. The specification for this material is usually for a coarser grading than that already on the beach; thus, longer term stability is anticipated. This material may be further stabilized and protected by the construction of large terminal groins built from imported rock.

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The design of these structures is complex. A core of lighter weight material is protected by layers of rock of increasing mass. Further, in an attempt to overcome the adverse effect associated with terminal structures, the "plan shape" is built to resemble a "fish tail," and it may be curvilinear on plan; the crest level at the seaward end may be higher than that at the landward connection to encourage the littoral drift processes (Barber, 1988).

Thus, if the "soft" solutions being constructed to date are shown to be reasonably stable, we may see an extension of this engineering concept for future capital schemes. In engineering terms, the choice of this solution is sound, and it really only represents a reversal of natural trends through the use of energy-dissipating structures.

A natural feature to which much attention is being paid is the salt marshes found frequently to the seaward side of defenses. These marshes are often found at a level of about high spring tide. In addition to their environmental benefits, they are able to dissipate wave energy and allow only small, depth-limited waves to reach the defense structure.

Many of these marches are in decline because the seaward edge is being eroded or the vegetative cover is dying back, thus leaving only mud patches. Engineering solutions are being sought to reverse these trends so as to preserve these valuable components of a defense system.

The behavior and performance of marshes outline in other recent papers (e.g., Titus, 1988) confirms that experienced in the United Kingdom. There is a need, therefore, for an international approach to optimize the ability of this natural type of defense to respond to future sea level rise.

RESEARCH

Bodies Commissioning Research

The National Rivers Authority is continuing research previously carried out by water authorities and will be expanding its program to complement research already undertaken by the Ministry of Agriculture, Fisheries, and Food. Other complementary research is commissioned by organizations such as the oil industry, firms of consulting engineers, or intergovernmental agencies in conjunction with other government departments using research facilities at the numerous universities, research laboratories, and specialist consultants.

One area of research of specific interest to the National Rivers Authority is the work undertaken by the Ministry of Agriculture, Fisheries, and Food on the collection and analysis of tidal data from its system of tidal gauges around the coast of the United Kingdom (Figure 5). Data from some of these gauges are used in connection with the Storm Tide Warning Service (see the following section). The program of analysis feeds into other worldwide scientific programs.

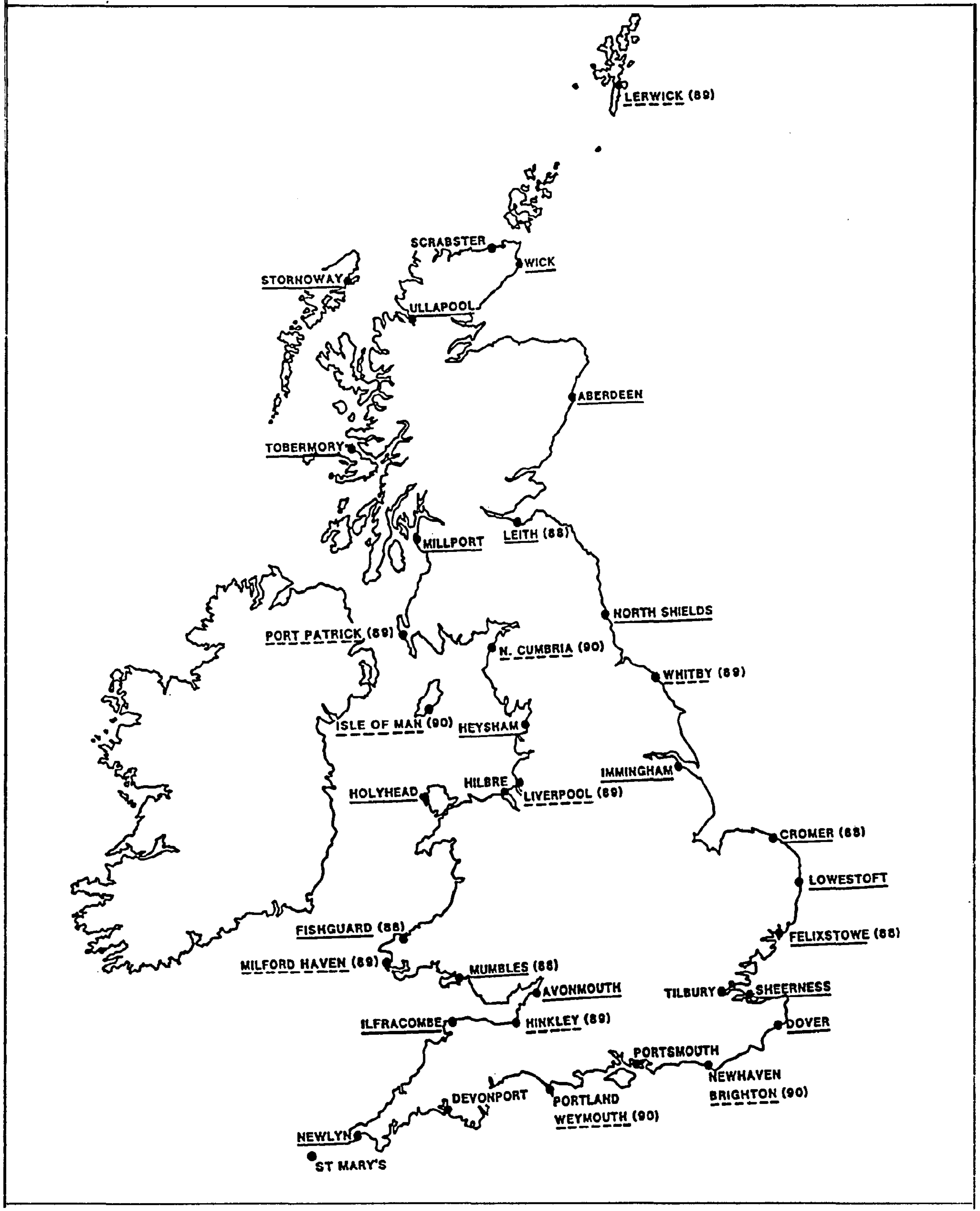

Figure 5. Tide gauges of the national network - December 1988 (modernized installations are underlined).

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Another strategic research effort is being directed toward finding ways in which existing defenses can be modified to improve their effectiveness. The findings from this program are equally important when considering designs for new defenses. At present, there is much uncertainty about both the timing and the extent of sea level rise. Until some of these uncertainties are removed, it is prudent to build defenses to deal only with known situations but, equally so, to build in provisions for easy modification when the need arises.

Research Programs

For many years, the Ministry of Agriculture, Fisheries, and Food has been funding applied research and development programs. The principal areas of marine research have centered around the interaction of tides, surges, and waves. These dynamic forces have effects on sediment transport processes which greatly affect the foreshore, surf zone, and stability of estuaries. Many other aspects of the program are set out in the annual report (MAFF, 1988).

The former water authorities and now the National Rivers Authority also undertake complementary research programs. At present, the Authority is concerned with developmental research into the performance of embankments. The Authority will also include some research into the use of new materials and systems to facilitate a rapid response to be made to structures should the need arise.

STORM TIDE FORECAST SERVICES

East Coast Storm Tide Warning Service

Following the 1953 storm event, the government set up a review committee to report on the event and to make recommendations. The Waverley Committee recommended the establishment of a warning service for the east coast. Today, the service is administered by the Ministry of Agriculture, Fisheries, and Food and is run from the United Kingdom's Met Office.

Atmospheric and tidal data are fed into a numerical surge model to provide hourly sea level forecasts up to 36 hours ahead. If it appears that a critical level could be reached at any of the reference ports (Figure 6), checks are made about 12 hours before high water, using real-time tidal and wind data. This critical level, known as Danger Level, is predetermined and related to some crucial defense within the relevant Division. The Met Office will issue preliminary warning notices to the relevant police force, the National Rivers Authority region, the local authorities, the Ministry of Agriculture, Fisheries, and Food, and other interested parties during this period, and it will issue a metric confirmation or cancellation of that preliminary warning some 4 hours before expected high water.

The National Rivers Authority will open up its relevant flood control center, either upon receiving a warning or whenever it perceives that meteorological conditions could lead to a storm. The Authority has access not only to this principal tidal gauge network but also to local gauges, and it will monitor all of these as part of its flood forecasting procedure.

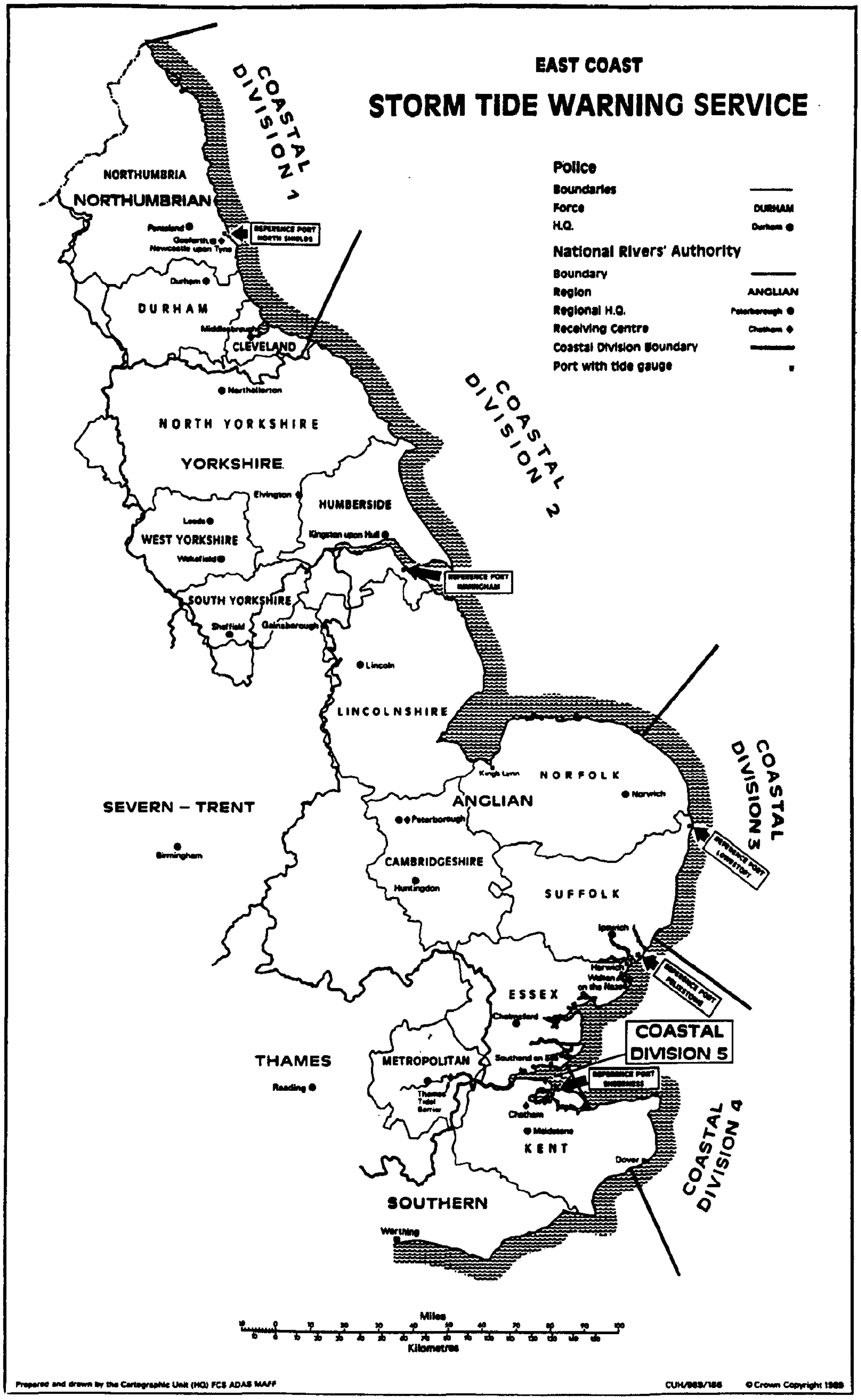

Figure 6. The Storm Tide Warning Service and the east coast reference ports.

Throughout any event, the Authority maintains close liaison with the police forces and local emergency services and others as needed. The National Rivers Authority work force and other private and public work forces, including military personnel, may be called on in an extreme event. The police, as the law and order enforcement agency, will, in liaison with the National Rivers Authority, issue any notice to the public. They will coordinate the evacuation of the public from any threatened zone. Following any event that entailed the issuance of a warning, there is an intense inquiry both to validate the quality of the warning and, if necessary, to evaluate the return period of the event.

The performance of the warning service has been progressively improving. This has been made possible by the new computers that can handle greater inputs of data; by improvements funded by the Ministry of Agriculture, Fisheries, and Food to the data-gathering systems at the tidal gauges; and by modifications to the numerical models. The detailed analysis of the tidal data is undertaken by the Proudman Oceanographic Laboratory at Bidston, near Liverpool, under contract to the Ministry of Agriculture, Fisheries, and Food.

The warning service outlined above applies only to the east coast. The remainder of England and Wales receives only the output from the numerical surge model on a twice-daily basis. A full warning system depends on refining the models for the south and west coasts and on having better real-time data from the eastern Atlantic and Western Approaches to the United Kingdom. Much of these data are exchanged with similar agencies on the Continent, thus ensuring their optimum use within international forecasting systems.

SUMMARY

Land in England and Wales lying less than 5 meters above sea level must be protected from flooding. Some of this land is below the sea level and has to be pump drained. In the main, this low-lying land is backed by a scarp-face, with land rising rapidly up to the +10.0 meter contour. Much of the lowest lying land is used for agricultural production, but the higher ridges have been developed for urban, commercial, and industrial use.

A rise in sea level will necessitate a review of present defense design standards. In the absence of a definitive statement on timing or amount of rise, designers in the National Rivers Authority are contemplating increasing the defense allowances and are adopting designs that are flexible enough to permit easy modification. Through close contact with research bodies, the National Rivers Authority will develop strategies appropriate to the needs to meet changing circumstances.

It has been suggested that defenses that may have only a short life, approximately 25-50 years, be designed to incorporate an allowance of not less than 6 millimeters per year, which includes 3 millimeters per year for the isostatic movement in southeast England (Figure 7) (Whittle, 1989).

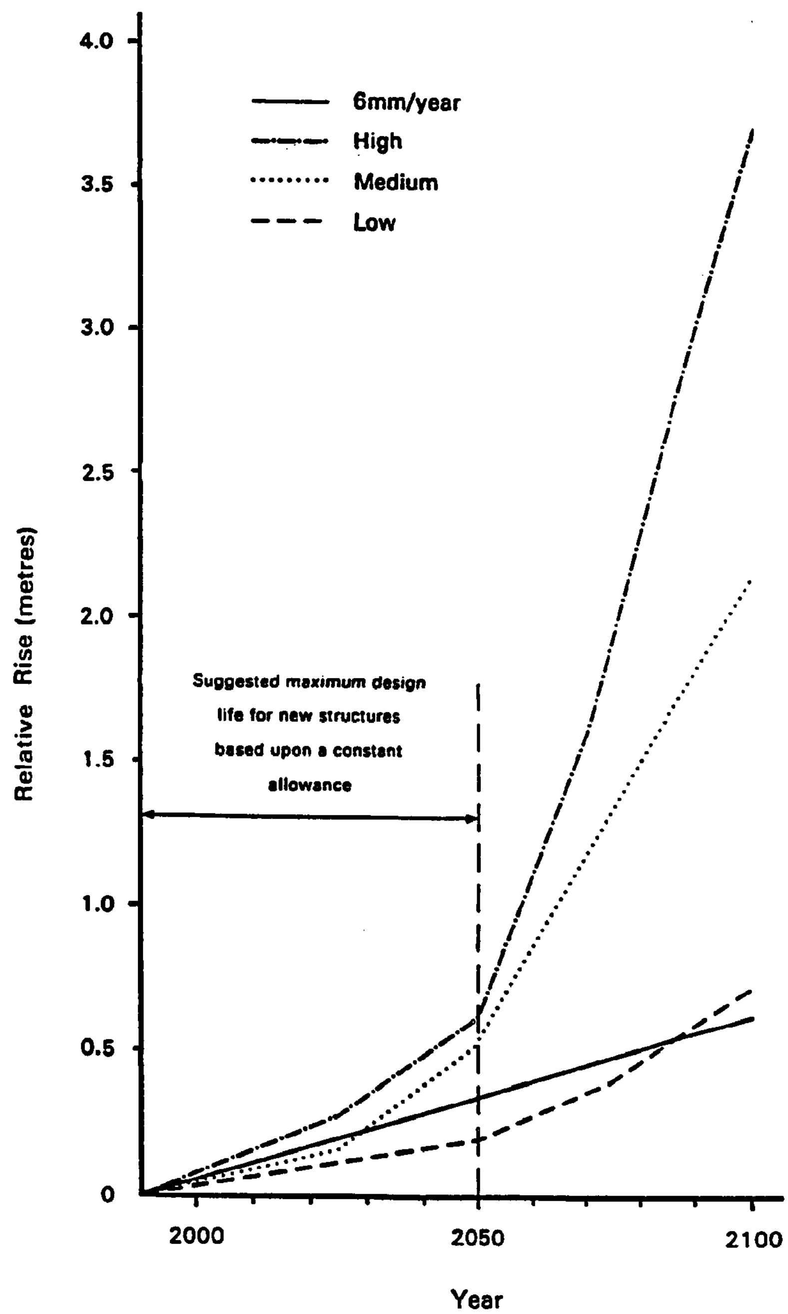

Figure 7. Range of predictions for an east coast port and compared to an allowance of 6 mm per year.

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Options for raising defenses should not be implemented unless they are cost effective. Decisions, however unpalatable, may have to be taken not to reconstruct some defenses. Present-day solutions favor the environment by artificially raising the beach levels. The evaluation of benefits for coastal defense includes components for environmental, recreational, and amenity benefits. It may be appropriate to include within the benefits assessment those benefits that will accrue to planned future development, so that developers are prepared to make appropriate contributions.

Research into climate change, global warming, and sea level rise is essential to develop financially sound defense and land drainage strategies. The National Rivers Authority is conducting research on the use of newer materials and new proprietary systems to protect defenses.

ACKNOWLEDGMENT

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BIBLIOGRAPHY

Brunsden, D., E. Gardner, and A. Goudie A. 1989. Landshapes. London: David and Charles.

Barber, P. 1988. Sea Defense at Jaywick. Report to Anglian Region, National Rivers Authority.

Halcrow, Sir William and Partners. 1989. Report on Coastal Management for Anglian Region. London, England: National Rivers Authority.

Kelly, P.M. 1989. Global Warming and the Thames Barrier. London, England: London Emergency Planning Information Center, University of East Anglia.

MAFF. 1988. Ministry of Agriculture, Fisheries, and Food. River and Coastal Engineering Report. London, England: MAFF.

Titus, J.G., ed. 1988. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Whittle, I.R. 1989. The Greenhouse Effect: London at Risk. Conference of River and Coastal Engineers. Loughborough, England: Ministry of Agriculture, Fisheries, and Food.

POLICY ANALYSES OF SEA LEVEL RISE IN THE NETHERLANDS

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INTRODUCTION

In the Netherlands, politicians are becoming more and more aware of the potential problems that could be caused by climate change. Rijkswaterstaat, a part of the Ministry of Public Works and Transport, started some smaller studies on this topic in 1985 (De Ronde, 1989; De Ronde and De Ruijter, 1986).

THE COASTAL PROTECTION STUDY

In 1989, an extensive policy analysis was completed on the future management of our sandy coast with regard to present erosion problems and the expected increase in sea level rise (Rijkswaterstaat, 1989). The analysis was based on morphological predictions of coastal development (erosion and accretion) for every kilometer of the 254-km length of our dune coast. The total length of the Dutch coast without estuaries is 353 km. The predictions were made for the years 2000, 2020, and 2090 for three scenarios:

Scenario A -- present sea level rise of 20 cm per century,
Scenario B -- sea level rise of 60 cm, and
Scenario C -- sea level rise of 60 cm plus an increased wind velocity of 10%.

Impacts like loss of safety and loss of (dune) area were compared with such measures as beach nourishment, groins, and dikes. An inventory was made of the whole coastline with a width of 500 m, and this was entered into a GIS system. The grid used was 1,000 by 50 m; the 50 m was perpendicular to the coastline. The predictions of coastal erosion/accretion together with the GIS system could be visualized, and totals could be made of lost areas. The areas can be subdivided into different types, such as nature, nature with a high ecological value, housing, industry, and areas used for drinking water.

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Figure 1 gives an example of the results, showing the predicted total losses of dune area in hectares up to the year 2090. The lower line depicts the predicted losses if the present sea level rise of 20 cm per century were to continue, and the upper line depicts the predicted losses if the expected sea level rise of 60 cm up to 2090 were to occur. In the case of scenario C, the lost area in 2090 is expected to be about 5,000 hectares. It can be concluded from these predictions that, in the case of the sandy coast of the Netherlands, the expected future sea level rise is worsening the erosion problems, but present erosion is the main problem.

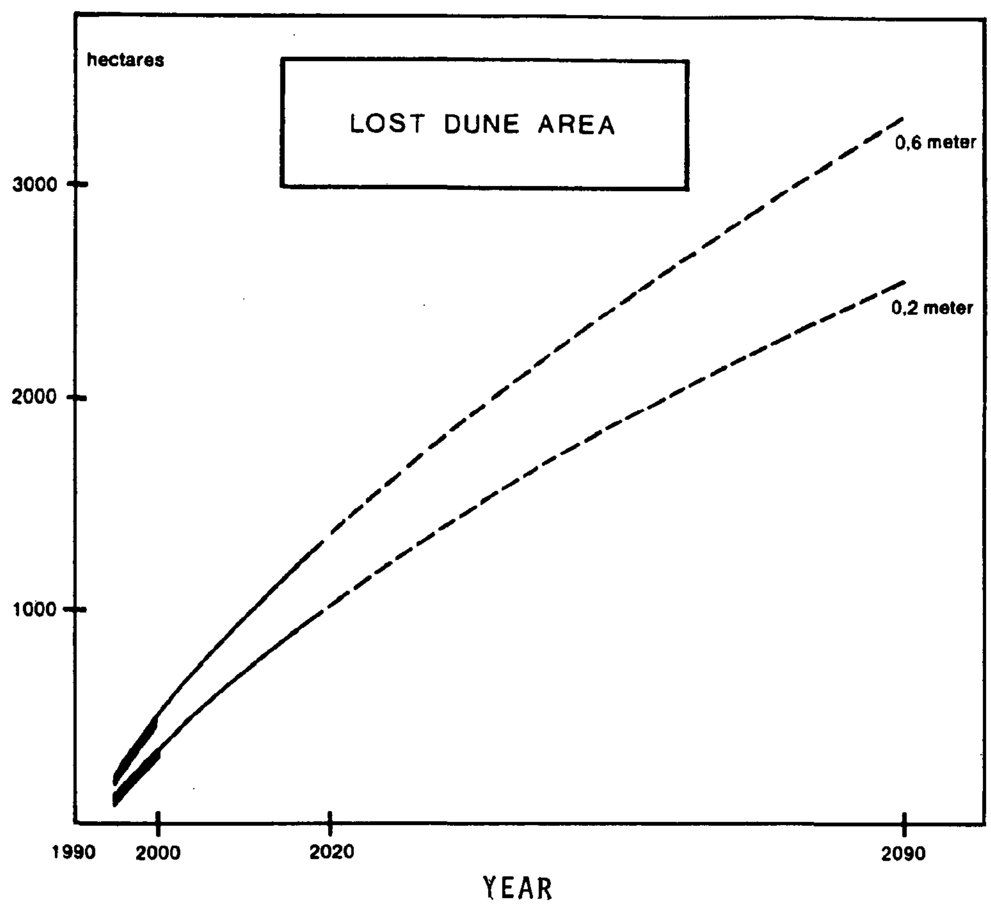

Figure 1. Predicted loss of dune area up to 2090 in the case of present sea level rise of 20 cm per century (scenario A) and in the case of the expected sea level rise of 60 cm for the next 100 years (scenario B).

It is believed that present sea level rise is only a minor cause of this present erosion. It is thought that this erosion is partly a late coastal response to more severe sea level rise in the past and partly due to sediment moving from the coast into the estuaries.

Concerning dikes, the story is of course different. Here, present problems consist of just maintenance plus minor adaptations, while in the case of future sea level rise, the necessary adaptations are much greater.

The length of dune coast where measures like beach nourishment are necessary, in the case of scenarios A and B, can be found in Figure 2. The large increase in the beginning is due to the fact that up to 1990, many beaches already will have been nourished. So in 1990, the length of "unsafe" dunes is zero. If nothing is done, this length will increase rapidly in the beginning until the effect of past nourishments will have been diminished after roughly 10 years. At present, about 15 km of beach needs to be kept in place by beach nourishment. This area will increase to 45, 60, or 80 km (of a total of 254 km) up to 2090 for scenarios A, B, and C. At other parts of the coast, where safety is not at stake, erosion will still occur.

Future Policies

During the coming year, politicians will have to decide what kind of policy will be followed in the near future. This study describes and compares four possible future policies:

- RETREAT -- At all places where safety is not a problem, nothing will done, and these parts of the coastline may retreat. Everywhere where safety is at stake, the coast will be defended.
- SELECTIVE DEFENSE -- In addition to the actions described above, the most valuable areas (e.g., dunes with a high ecological value) will also be defended as well.
- TOTAL DEFENSE -- No retreat at all will be tolerated.
- SEAWARD DEFENSE -- "Weak parts of the coast" will be strengthened.

Examples of the necessary measures for retreat and selective defense are shown in Figure 3. Here the planned beach nourishments are given over the period 1990-2000 in the case of present sea level rise of 20 cm per century.

The expected costs for the four possible policies over the coming 10 years are given in Table 1. Especially during the first 10 years, seaward defense is very expensive. The "cheapest" policy is, of course, retreat. The costs for scenario B are nearly the same as those for scenario A. For scenario C, the costs are again a lot higher, due to the 10% increase of the wind, with great effect on dike height and dune strength. In the long run, however, seaward defense is only a bit more expensive than the other policies. In the case of

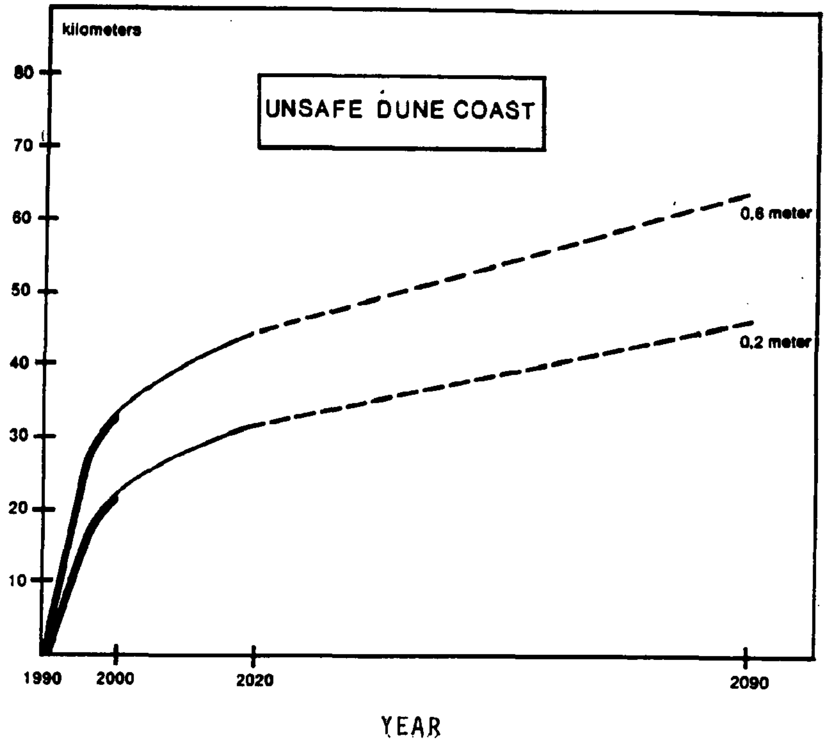

Figure 2. Predicted length of unsafe dune coast in the case of present sea level rise of 20 cm per century (scenario A) and in the case of the expected sea level rise of 60 cm for the next 100 years (scenario B).

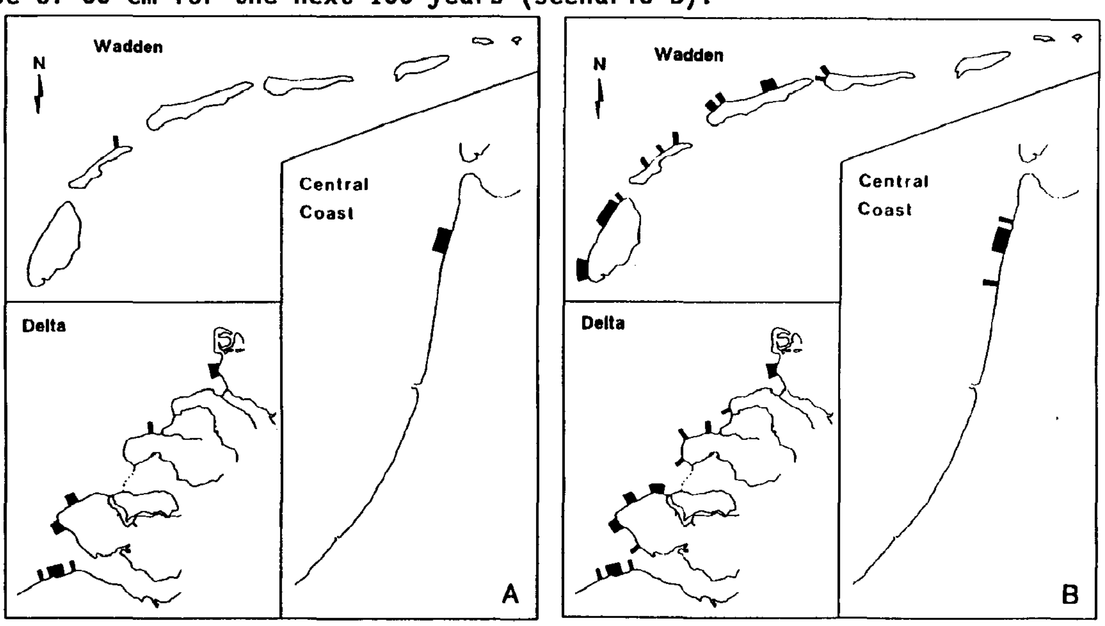

Figure 3. Parts of the coast where beach nourishments are planned during the period 1990-2000 with policy RETREAT (A) and with policy SELECTIVE DEFENSE (B) in the case of present sea level rise.

Table 1. The Expected Costs Over the Coming 10 Years for Four Policies and Three Scenarios (millions of U.S. dollars per year)

Policy	Sea level rise scenario: A 20 cm	B 60 cm	C 85 cm (plus 10% wind)
Retreat	15	17	26
Selective defense	19	20	31
Total defense	25	28	43
Seaward defense	30	33	55

a sea level rise of 20 cm per century, the average costs over 100 years are 16, 18, 21, and 23 million U.S. dollars per year, respectively, for the four policies.

The Minister of Transport and Public Works recently advised policy makers to use the policy of total defense.

THE ISOS STUDY

Another policy analysis will be finished at the beginning of 1990. This so-called Impact of Sea Level Rise on Society (ISOS) study is being conducted in cooperation with the United Nations Environment Programme and Delft Hydraulics.

This study focuses on the impacts of and possible responses to sea level rise. It also examines other effects of climate change, including shifts in storms, river discharges, precipitation, and evapotranspiration. Storms may become more severe or more frequent, having great consequences for the design of coastal structures. River discharges may increase and cause more frequent flooding during the winter season, or may decrease during summer and cause shortages of water needed for agriculture or drinking. These impacts and the possible measures against them will also be studied, but more along the lines of a sensitivity analysis.

The ISOS study will include the entire Netherlands. Besides the coast, it will look at 3,000 km of dikes along estuaries, rivers, and lakes. Further, it will analyze the impacts of sea level rise on the ecology and water management of the Netherlands. Table 2 shows some of the scenarios that will be used in this study.

Of course, looking at only impacts is insufficient when discussing sea level rise. Equally (or even more) important are the possible measures to be taken and when they should be taken.

Table 2. Main Scenarios of the ISOS Study -- Changes Between 1990 and 2090

Parameter	Favorable Scenario A	Mean Scenario B	Unfavorable Scenario C
Mean sea level rise	+ 35 cm	+ 60 cm	+ 85 cm
Wind force	- 10%	0%	+ 10%
Wind direction	- 10°	0°	+ 10°
Mean rise of design level	- 20 cm	+ 65 cm	+ 150 cm
Precipitation			
Summer	+ 20%	+ 10%	0%
Winter	0%	+ 10%	+ 20%
Evapotranspiration			
Summer	+ 0%	+ 10%	+ 20%
Winter	+ 0%	+ 10%	+ 20%
River discharge			
Summer	+ 10%	0%	- 10%
Winter	- 10%	+ 0%	+ 10%

First of all, impacts with the so-called T_0 alternative (no measures taken) will have to be quantified, starting with the changes in hydraulic conditions; the effects on morphology; and the consequences for safety, water management, environmental management, and costs. With this knowledge, alternative measures and constructions can be designed. Given a certain measure or set of measures, the impacts on hydraulic conditions, morphology, etc., must be studied. When this has been done, the different alternatives can be evaluated and compared.

With the ISOS study for the Netherlands, it will be possible to answer questions such as the following:

- Depending on the rate of acceleration of sea level rise, what measures should be taken, and when should we initiate them? (or: How long can we wait before we have to do something?)

- If not only relative sea level rise is changing, but also storm frequency as well as river discharges, then how important are the various impacts compared to each other? In other words, should we not be as worried about these other changes as we are about sea level rise? For example, in the case of the Dutch coast, a 10% increase in wind force has about the same influence as a 60-cm rise in sea level.

The results of the first phase of the ISOS study, with an inventory of all important relations between -- on the one hand -- sea level rise, changes of storm surges, and changes of river discharges, and -- on the other hand -- the impacts, were published in 1988 (Rijkswaterstaat and Delft Hydraulics, 1988). The second phase of the study is not yet finished. Here, though, some preliminary results will be given for dikes only.

The 3,000 km of primary dikes in the Netherlands were divided into about 50 so-called dike-rings, each with its own safety standard and subdivided into about 150 dike-parts. For each dike-part, cost functions were calculated, depending on the amount of heightening of the dike, the dike's construction, and the extension of buildings along and on the dike. The raising of a dike within a town with many houses in and on the dike is many times more expensive than the raising of a simple dike in the countryside. On the other hand, the model can calculate for every dike-part the necessary raising, depending on sea level rise, changes in storminess, changes in river discharges, and changes in management (e.g., the management of the IJssel Lake).

In the case of the expected sea level rise of 60 cm for the coming 100 years, total costs for dikes will amount to about $7.5 billion U.S. dollars (Figure 4). In the case of the unfavorable scenario, where besides the 60-cm sea level rise an increase of the wind of 10% and an increase of winter river discharges of 10% were considered, the total costs increase to $14 billion U.S. dollars.

Within the model, the number of dike heightenings during the coming 100 years and the amount of heightening can be differed. When the dikes are raised in small steps, the costs will be incurred as late as possible in time, but the total costs will be greater because of the initial costs that occur at every step of raising. On the other hand, when they are raised in one or two big steps, the initial costs will occur only once or twice, but the relatively high costs of the first raising will occur early in the heightening. These different strategies can be worked out with the model, and an optimal strategy can be found.

Given a certain scenario (e.g., 60-cm sea level rise), finding an optimal strategy will not be difficult. The target in the ISOS study will be to find an optimal strategy, given all possible scenarios with their chance of

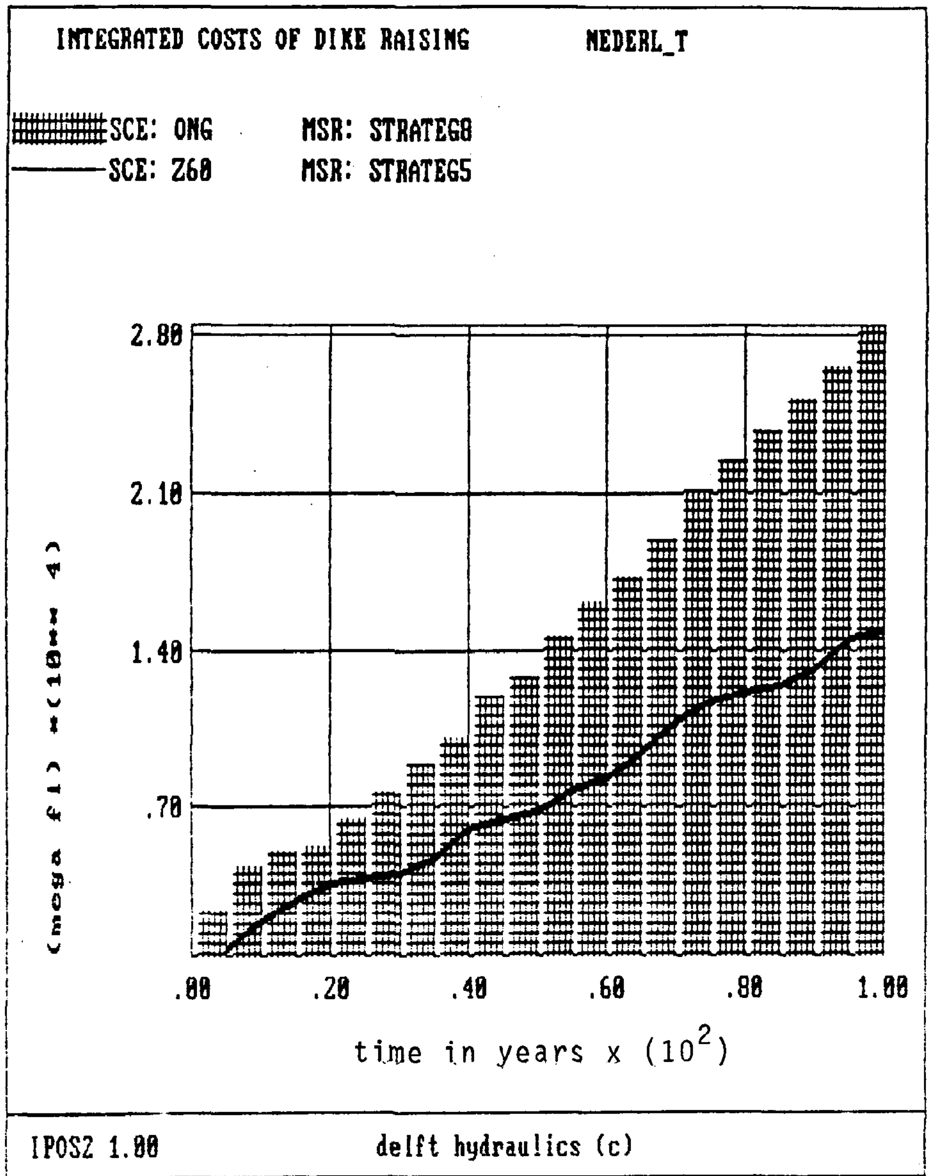

Figure 4. Integrated costs of dike raising for the scenarios. Expected sea level rise of 60 cm and the unfavorable scenario with 85-cm sea level rise plus 10% wind and 10% river discharge.

occurrence. This will be much more difficult. On the one hand, one will try to minimize the chance of being in an unsafe situation (when real changes will be greater than expected), while on the other hand, extensive measures might be overdone when changes will be smaller than expected.

BIBLIOGRAPHY

De Ronde, J.G. and W.P.M. De Ruijter, eds. 1986. Zeespiegelrijzing, worstelen met wassend water. Report GWAO-86.002. The Hague, the Netherlands: Rijkswaterstaat, Tidal Waters Division (in Dutch).

De Ronde, J.G. 1989. Past and future sea level rise in the Netherlands, Proceedings of the Workshop on Sea Level Rise and Coastal Processes, Florida, March 9-11, 1989.

Rijkswaterstaat and Delft Hydraulics. 1988. Impact of Sea Level Rise on Society: A Case Study for the Netherlands, phase I. The Hague, The Netherlands: Rijkswaterstaat.

Rijkswaterstaat. 1989. Kustverdediging na 1990, discussienota. (In Dutch, an English version of this report will appear in 1990.)

IMPACTS OF AND RESPONSES TO SEA LEVEL RISE IN PORTUGAL

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ABSTRACT

Because of the physiographic characteristics of the Portuguese coast and its population distribution, the main potential impacts of sea level rise will occur in the estuaries and coastal lagoons, on the barrier islands, and along the active sandstone cliffs. The large estuaries and coastal lagoon systems will be the most severely affected areas because they are densely populated and are the sites of extensive economic activity. Approximately 70% to 95% of their intertidal areas, 0.5 m to 2.0 m in elevation, are reclaimed or used in their natural capacity. These reclaimed lands are occupied by salines (salt pans) and aquacultural ponds (40%), agricultural fields (34%, primarily rice) associated with extensive pasture land (2%), port development (12%), urban and industrial development (8%), and airports (1%).

Among the impacts already being observed as a result of sea level rise are damage to several artificial coastal structures, beach erosion, retreat of sandstone cliffs, salt marsh retreat, and salinization of the reclaimed agricultural soils. The first two and the last of these impacts require immediate responses from the responsible central and local government agencies.

Wherever harbors and tourist beaches are affected by erosion, the institutional reaction has been, and will be in the near future, to rely on technology to repair or reinforce the existing development.

Regarding the impacts on the agricultural soils (rice fields), the responses of the agencies to the current situation have been to build freshwater reservoirs along the freshwater fluvial systems to assist in flushing the fields. Future responses to the increasing salinity in the soils and in the water table, and also to the submergence (up to 2 m), will need to be different from current responses. The initial reaction by central governmental bodies to the soil salinization probably will be to shift the main crop from rice to more salt-tolerant plants (e.g., barley or sugarbeets), or more probably to shift the use of these reclaimed areas from agriculture to some sort of development. At the

municipal level, agencies will probably rely on technological improvements and will continue to produce rice.

INTRODUCTION

This paper briefly lays out the climate, hydrology, and coastal geomorphology of Portugal. It then discusses potential impacts of sea level rise and summarizes our discussions with officials of Portuguese agencies that must respond to sea level rise.

Climate and Hydrology

The Portuguese coast is in the subtropics, on the boundary between the Atlantic temperate climate and the Mediterranean climate (Figure 1). This geographical position explains the different climate regimes that can be found along the coast, which contributes to the different local geomorphological processes.

All of the western coast is exposed to the influence of the Westerlies that dominate the annual and the seasonal wind regime blowing from the north, northwest, and west. Strong storm winds blow from the southwest in the winter, associated with tropical depressions.

Wave heights vary: the annual mean wave height is 2.9 m on the northern sector (Leixoes), 2.3 m on the central sector from Aveiro to Cabo da Roca, 1.0 m on the southwestern sector, and 1.1-1.4 m on the southern coast of the Algarve

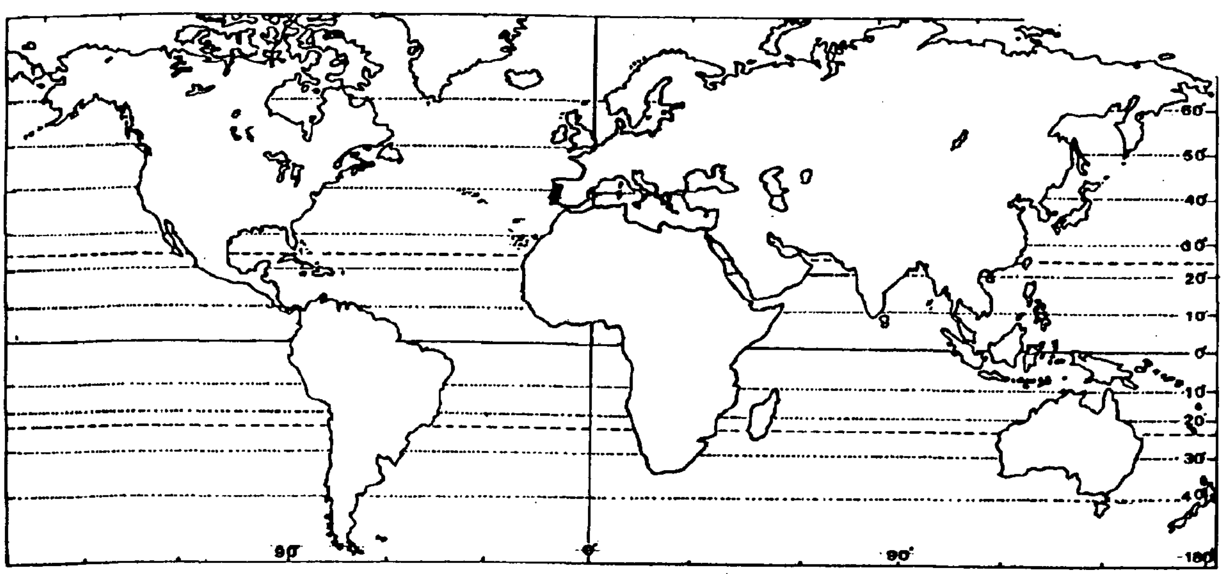

Figure 1. Location of Portugal in the subtropical zone.

(Figure 2). The greatest wave heights, observed in Sines on the western Portuguese coast in 1978, were around 16-17 m; they originated from the southwest during a 100-year storm that destroyed the jetties of the harbor of Sines (Feio, 1980). On the southern coast, the calm seas dominate and the infrequent high waves very seldom reach 5 m. They occur when the strong Levante wind blows from the Gulf of Gibraltar, usually in winter but also in spring or in autumn.

On the western coast, calm seas (wave height less than 1 m) are infrequent, as are extreme storm waves (higher than 6 m, Figure 2). The storm waves do not occur every year, but they are more frequent in the northern region, occurring every winter.

As a consequence of the wave regime, a general longshore current is generated from north to south on the western coast (Ferreira, 1981; Ribeiro et al., 1987). Deflected and refracted by the capes, the current can reach the coast from opposite directions, from the west, the west-southwest, and the southwest. A strong littoral current from the southwest also occurs when the waves run from the southwest. The morphodynamic effects of both of these littoral transport directions can be seen on the growth and migration of the spits and barrier islands along all of the coast.

The tidal regime on the Portuguese coast is semi-diurnal and mesotidal. The tidal range is around 3.8 m along the western coast, 3.4 m on the southern coast during the spring tides, and between 0.9 m and 1.2 m during neap tides. In the estuaries, the tidal range is 60-80 cm higher during spring tides. In time of the fluvial floods, or even during the high fluvial water flow, these values can increase a few centimeters. The spring tide level reaches 2 m above mean sea level on the open coast, if the sea is calm.

THE COASTAL GEOMORPHOLOGIC CHARACTERISTICS

The Portuguese coast (excluding the islands) is around 870 km long and presents a great variety of geomorphologic features, as shown in Figure 3. According to the published geomorphologic map (Ferreira, 1981) and measurements taken from the 1:50,000 national topographic maps, sandy beaches occupy 37.5% of the total length of the coastline; coastal wetlands, 36.9%; and cliffs, 25.6% (Figure 3).

Excluding the beaches located near the main estuaries, which are nourished by the fluvial sediments, the beaches of the western coast are narrow (70 to 150 m) -- even those with dunes. The widest beaches have gentle slopes and are located along the spits, or on the coastal sectors sheltered from the waves by prominent capes.

On the southern coast, the beaches are narrow with gentle slopes. On the western side, there are pocket beaches interconnecting through the karst caves and galleries cut into the calcareous sandstone of the cliffs. Along the eastern sector, there are linear beaches extending along a cliff face or in the form of barrier islands and barrier spits.

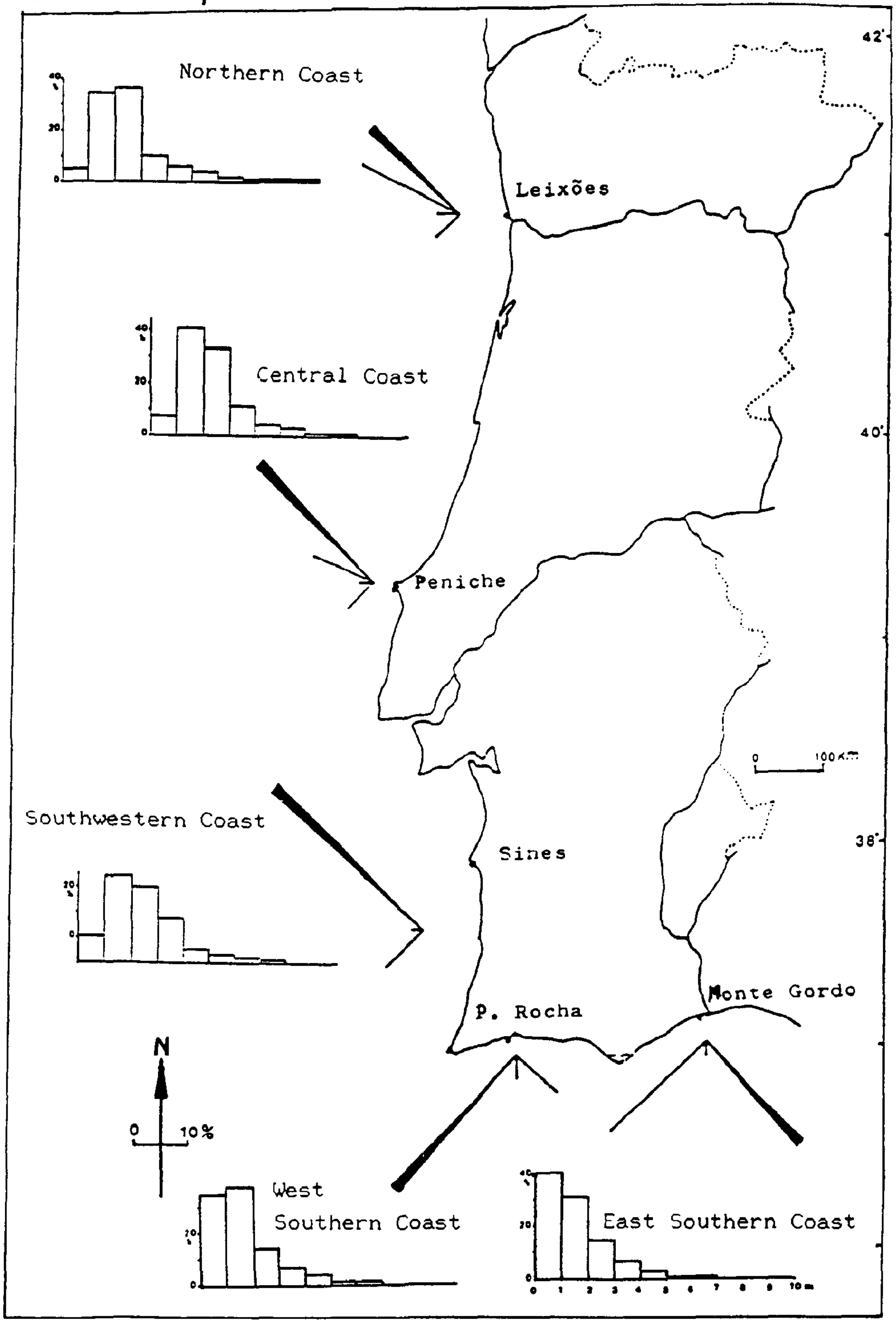

Figure 2. Spectra of the annual mean wave directions along the Portuguese coast (1974-1978). Frequency distribution of the annual mean wave height. Data from I.N.M.G.

A

B

C

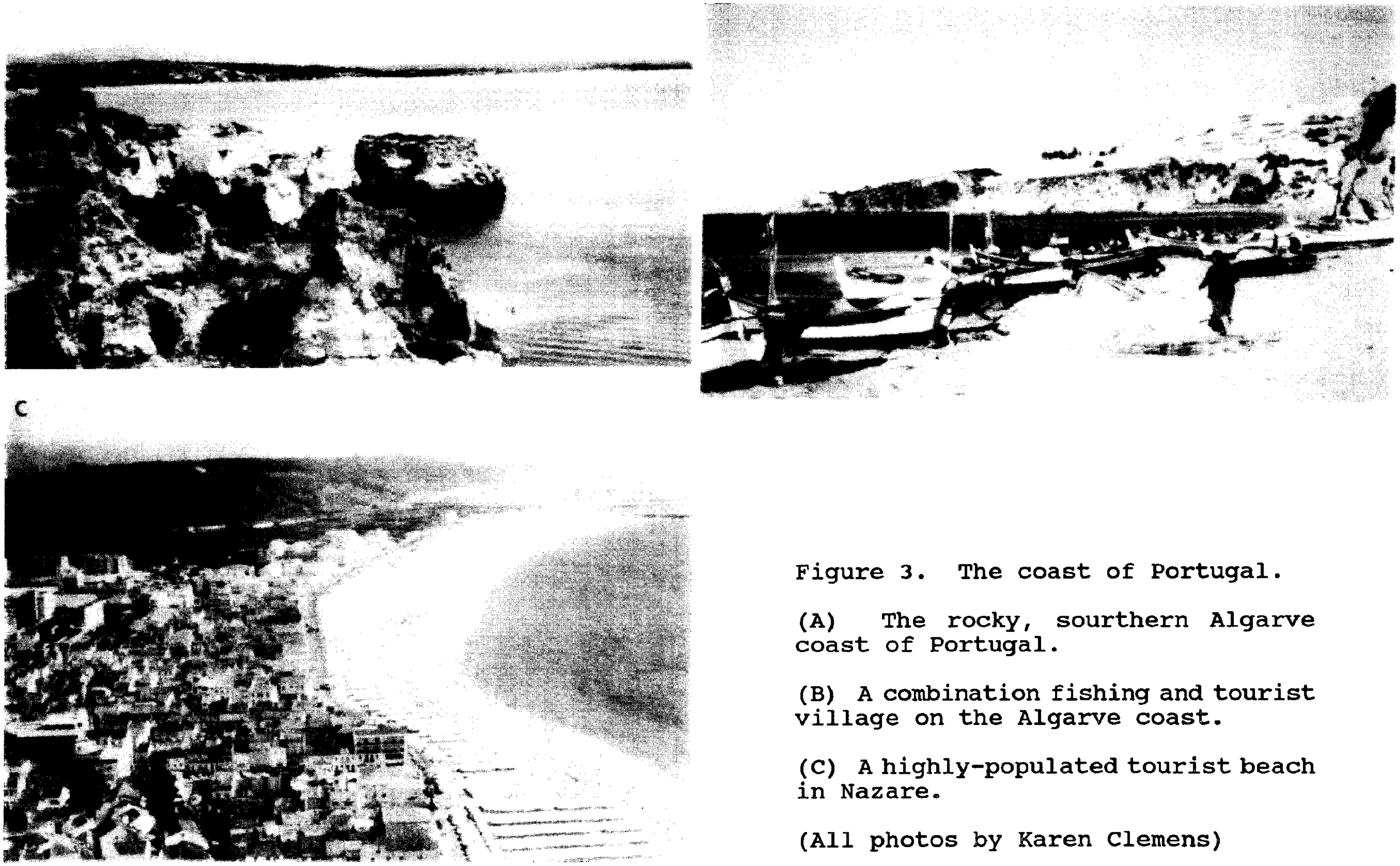

Figure 3. The coast of Portugal.

(A) The rocky, sourthern Algarve coast of Portugal.

(B) A combination fishing and tourist village on the Algarve coast.

(C) A highly-populated tourist beach in Nazare.

(All photos by Karen Clemens)

North and West Europe

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Most of the western Algarve beaches are almost completely submerged during the high spring tides. This feature and the retreat of the cliffs (Dias, 1988) are already serious problems to the tourist industry there.

The coastal wetlands include the low tidal platforms, which are sandy or muddy, and the upper tidal platforms covered by salt marsh vegetation. They have developed on the sheltered estuarine margins, along the creeks, and around the lagoons between 1.5 m below sea level and 2 m above sea level (Figure 3). They represent 70% of the total intertidal area of the Portuguese coast.

Approximately 70-95% of the nation's salt marshes have been reclaimed (Moreira, 1986). The land is defended from tidal submergence by dikes or embankments. The remaining marsh is characterized by a flat surface and is pocked by tidal pans and by a dense network of creeks. The microcliff of the vegetated salt marsh almost always shows a tendency to retreat, being undercut by the currents and collapsing afterwards. The resulting silty sediments are accumulating on the tidal platforms where they are stabilized by the low salt-marsh vegetation. The platform is sandy and muddy, with layers of broken shells, and cut by the creeks that are more deeply excavated into the mud than into the sand.

The tidal platforms developed in the Ria Formosa (Faro) lagoonal system are sheltered by the barrier islands (Figure 3). They are essentially sandy, with layers of clay and silt (Granja, 1984), and form islands that are colonized by a Mediterranean type of salt marsh. The creeks are not very deep, and their margins evolve mostly by the sliding of the sandy layers that overlay the silt. Here, as well as in Aveiro and in the Sado, the salt marsh is being covered by the sand coming from the transgressive dunes (on the spits and barrier islands) and from the beach ridges, blown by the wind, or carried by overwash events.

The cliffs differ in height, profile, and lithological composition (Figure 3). The highest cliffs (more than 50 m) are cut into hard rock, granite, and metamorphic rock on the northern coast, compact calcareous formations and schists on the southwestern coast, and interbanded limestone-mudstone-sandstone in the central coast, north of Serra de Sintra. They are connected to abrasive rocky platforms that have a lot of stacks, especially when cut into granite. The processes of retreat, consisting of large rotational landslides, are evident on the limestone and the mudstone cliffs.

Low cliffs, around 10 m, also can be found cut into granite in the north, and into calcareous formations such as at Cabo Raso on the central portion of the coast. Low cliffs, 15-20 m high, cut into the Miocene and the Pliocene sandstones are very frequent on the central and the southwest coast, and the Algarve coast between Sagres and Quarteira. They are connected to narrow limestone platforms with abundant stacks and patches of sandy accumulations that form several pocket beaches. These cliffs retreat by collapsing after being undercut at the base. Cliff retreat rates of 2 m/year due to human effects and a sea level rise were measured by Dias (1988).

COASTAL LAND USE

The coastal fringe in Portugal is largely natural. Intertidal areas and adjacent land within the public maritime domain are administered by the Navy and by the municipalities. No construction is allowed there, and even the public infrastructure for sanitary facilities, safety, and leisure is regulated and needs special authorization. These laws, the tidal range, and the annual storm waves of 5 m to 7 m discourage permanent human occupation of the very low coastal fringe. There is a strong contrast between the modest human occupation of the low coastal fringe and the very high population density of the coastal municipalities (Figure 4).

Among the coastal natural systems, the dunes and the estuarine and lagoonal wetlands are the most disturbed systems due to the permanent human occupation. The dunes are inhabited along most of the coast, except in the natural protected areas that occupy 25% of the total coastal area. Major tourist settlements occupy 29% of the secondary dunes, and some are even found on the primary dune (foredune), as occurs on the northern sandy coast and on the eastern Algarve coast, including the Ria Formosa barrier islands (Figure 5).

The traditional fishing settlements, located on the beach and in the foredunes, are now quite scarce (4% of the dune area) because they have been transformed into tourist villages or modern fishing ports. The most important traditional fishing settlements that are permanently occupied are found on the barrier islands of the Algarve and are dispersed on the central coast.

Other artificial structures, such as harbors and military airports, have been built on the dune fringe (Figure 5). In general, the foredune is occupied by natural vegetation that is regenerated or planted to minimize the migration of the sand inland. Forty-two percent of the total coastal dune area is planted with pines (primarily maritime pine), acacia, and eucalyptus. The coastal dune areas have high concentrations of tourism, but the highest concentration of population (Figure 4) is along the estuarine margins and the coastal fringe from Cascais to Lisbon (the Costa do Sol, the first tourist area of Portugal) (Cavaco, 1983).

The coastal fringe of Alentejo, from Troia (Setubal) to Sagres, shows very low population densities, and some places are deserted. The sector near Sines is an exception, due to the industrial complex and harbor of Sines, and also to the increasing tourist demand on this coast.

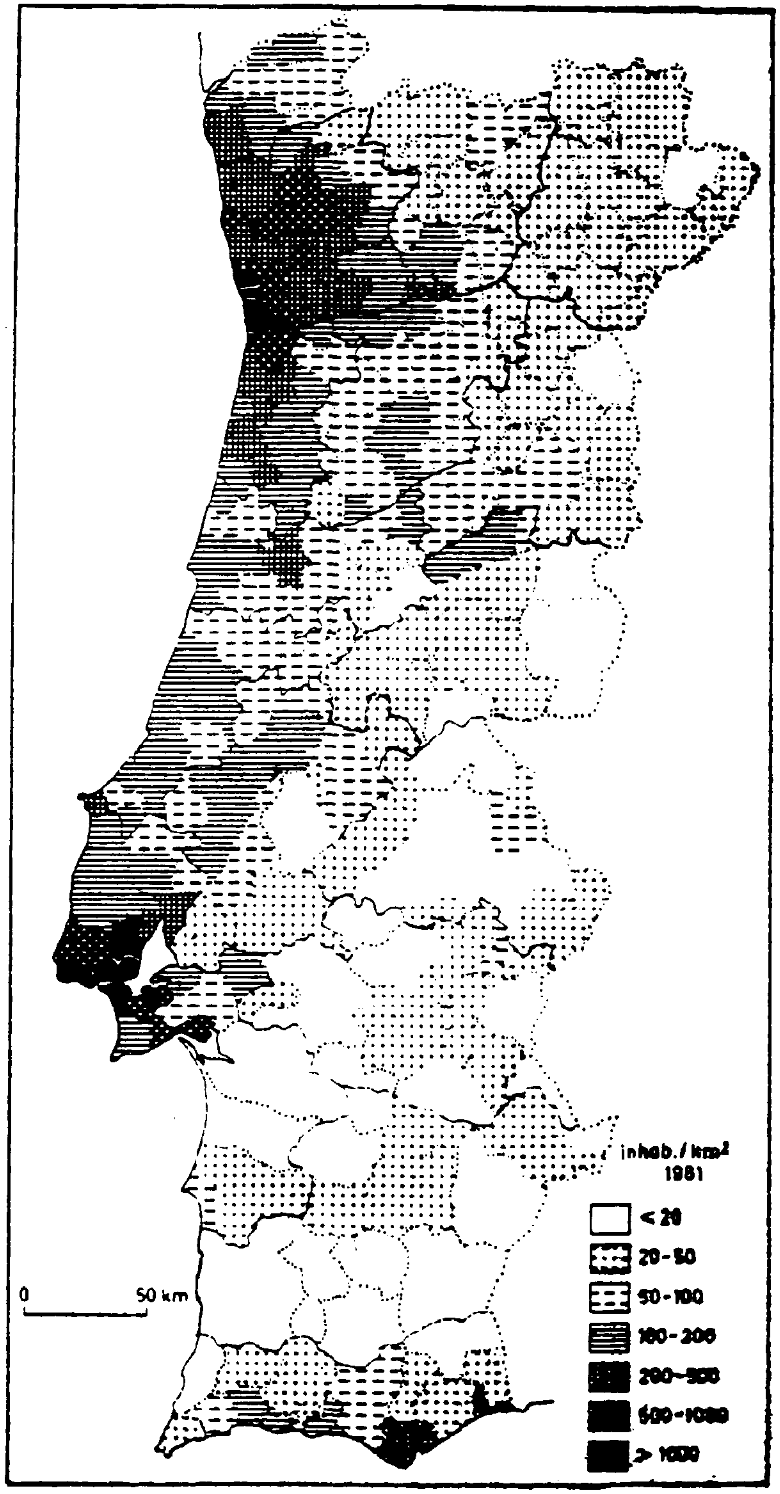

Figure 4. Distribution of the population density in Portugal (1981) by municipality (Concelho) (E.P.R.U., 1988).

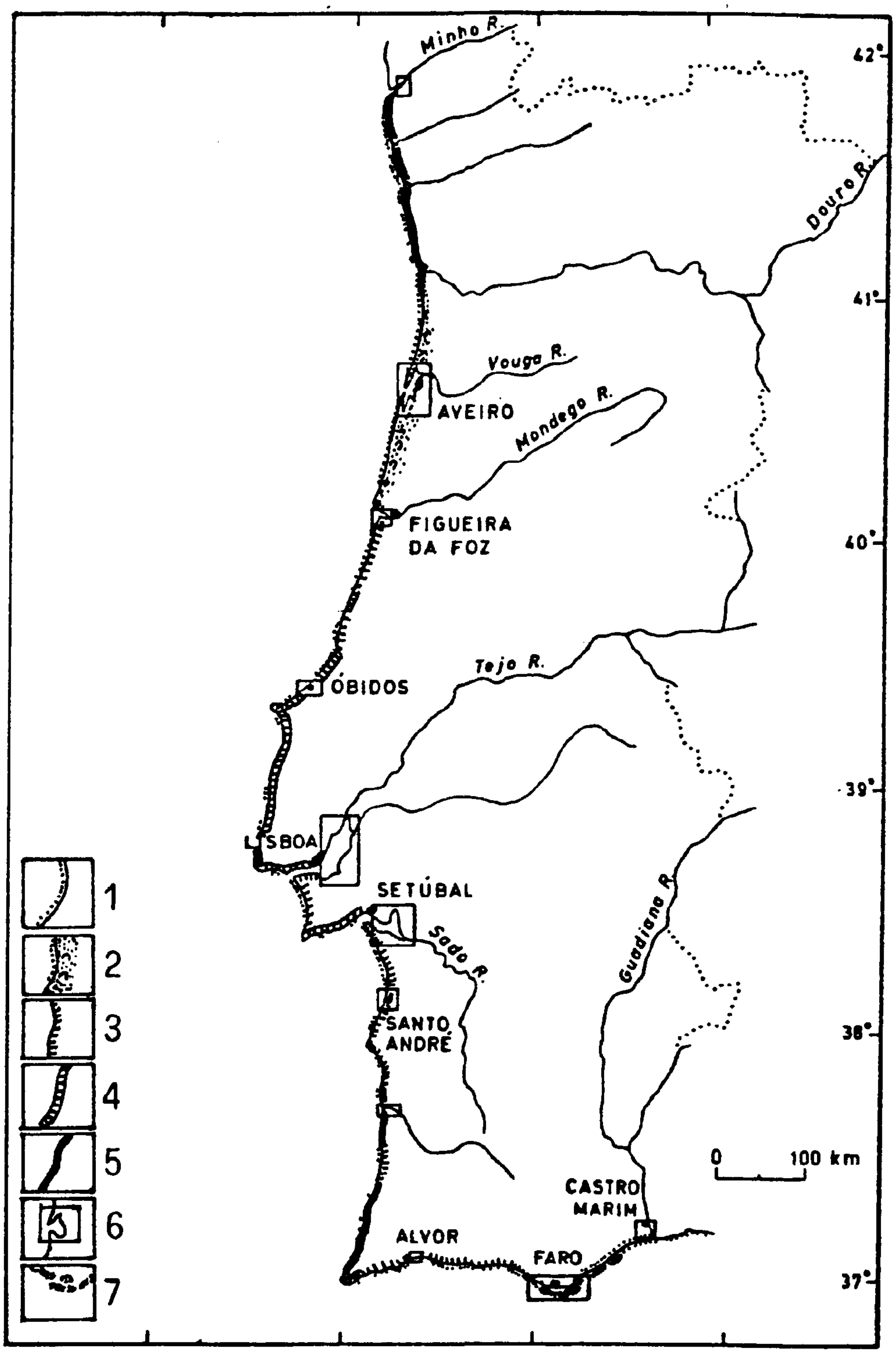

Figure 5. Principal types of land use on the coastal zone: (1) planted forest (pinelands); (2) natural coastal shrubland; (3) urban and tourist occupation; (4) cultivated areas; (5) natural reserves and protected areas; (6) harbors; and (7) airports.

North and West Europe

The coastal wetlands, which have developed on the intertidal platforms of the estuaries and lagoons (Figure 3), have been hurt by human activities more than any other part of the coastal zone. The salt marsh, as a natural system, occupies only around 10% of its original area, where it is protected as Natural Reserves or Parks due to its ecological value. More than 90% of the total area of the salt marshes are reclaimed; of this, 40% is totally or partly transformed into salt works and fish ponds. Agricultural fields (especially rice fields) represent 34% of the land use in association with pastures or grazing fields (2%). Harbors (commercial, fisheries, and leisure) occupy 12%; urban and industrial areas (8%) and airports (1%) form the remainder of the land use.

The salt works are on the high tidal mudflat, after building dikes that are more or less 0.5 m to 1 m above the spring high tide water level. Very often the dikes need to be repaired, and some of them are permanently reinforced by rock embankments or by wooden bulkheads that try to avoid or to minimize the erosive effects of the storms or the fluvial floods.

In most of the rice fields, the drainage water is discharged through gates into the estuarine deep channels during the low tides. In a very few cases is this drainage water pumped from the rice field drains to be discharged into the estuary, because the rice fields occupy the surface of the upper mudflat (1-3 m above sea level).

Salinization of the rice field soils occurs in summer owing to the dryness of the climate (Daveau et al., 1977). This situation happens frequently on the southern estuaries during the dry years, when the evapotranspiration is very high and there is insufficient freshwater to inundate the rice fields and to reduce the salinity of the water table.

The urban and industrial areas, as well as the harbors, represent the highest investment on the reclaimed areas. The most important towns and harbors of Portugal are located on the estuarine or on the lagoonal margins, and their artificial structures, such as harbor platforms, roads, and railways, are 2-4 m above sea level. It is the same with the airports that were built on the upper mudflat, as the airport of Faro, whose runways have cracked as the underlying muds settled.

THE IMPACTS OF POTENTIAL SEA LEVEL RISE

Some of the impacts the Portuguese coast could suffer from sea level rise will affect all of the coast, independent of its morphology. The erosion and submergence (partial or total) of the former intertidal area will increase, and the extent of other impacts will depend upon the coastal morphology, the rate of the sea level rise, the topography, and the resistance of the lithologic materials against the erosion. Therefore, the impacts in this paper are presented relative to the coastal morphology, classified as estuaries and coastal lagoons, beaches, and cliffs.

In the estuaries and coastal lagoons, the consequences of a 2-m rise in sea level (Figure 6c) will be the great enlargement of the estuarine area, penetrating into the fluvial system; the increase of the salinity into the estuaries and aquifers; the salinization of the soil water table in the fluvial plains and in the reclaimed lowlands; the submergence of part of the salines, the fish ponds, and the rice fields; the submergence of the total tidal platform ("slikke") and the low salt marsh; the retreat and disappearance of the salt marsh area; a great risk of erosion and flooding of the harbors and the low coastal urban areas; the submergence of the Faro airport; and the increasing risk of flooding and backup in the urban waste drains.

On the beaches, the main impacts will be the narrowing of the beach by about 50% and the retreat of the foredune; the disappearance of the pocket beaches; and new pocket beach formation close to the eroding sandstone cliffs. The Ria Formosa barrier islands will lose more than 50% of their area. New inlets will form, and washover will increase.

On the cliffs, the impacts of sea level rise will be the submergence of the abrasion platforms and the increasing retreat of the sandstone cliffs, of the limestone cliffs, and even of the hard-rock cliffs (especially in the active tectonic areas).

From the listed impacts, the more important will be those affecting the estuaries (low coastal wetlands and estuarine waters) and the lagoons, because they are both the most vulnerable and the most populated.

In the case of a sea level rise of 1 m (Figure 6B), the greatest economic impact will be the investment associated with coastal tourism. The most important tourist beaches of the country will disappear. On the coast of the Algarve, this problem will be in addition to the retreat of the cliffs, whose tops are very often highly developed.

For a sea level rise of 0.5 m (Figure 6A), the increased salinity of the estuarine waters, aquifers, and soils will be economically more important than the submergence of the lower tidal flats, or the erosive effects on the salt marsh not offset by accumulation of peat and sediment. Salinization will affect the freshwater supplies for domestic and industrial uses and the water table of the agricultural soils, especially in the rice fields. Sea level rise will also be costly for rice agriculture because of the need to pump drainage water from the rice fields before discharging it into the creeks.

Because of the reclamation of the salt marshes, this ecosystem will not migrate on the inland boundaries because they are formed of dikes or very steep dune slopes. In some places, the dikes are less than 50 cm higher than the spring high tide water level. Here, the erosive effects will be considerable because they already are a real problem to the owners of the rice fields.

RESPONSES TO SEA LEVEL RISE

The responsibility for managing the coastal zone rests with several entities of the central, regional, and local administrative authorities. The most important decisionmakers are the Navy (central administration) and the municipalities (local administration). The Department of the Environment must be consulted, as well as the other agencies that are related to the spatial organization of this zone.

Among the several organizations and services that take care of the coastal zone's protection and management are those that should be involved with the main problems concerning the impacts of sea level rise on the coastal lowlands. To some of these agencies, the impacts of sea level rise constitute surprising news, first because they had never considered it, and second because they thought that it was not so urgent a problem. To other agencies, the impacts are a real problem and they have been applying the classic engineering solutions to protect the coastline. We briefly summarize what officials in various agencies think about sea level rise.

National Navy

As the coastal fringe is a public domain, the national navy is responsible for managing the coastal margin that occupies the space between the high spring tides and a line located 50 m inland.

The Hydrographic Institute is the Navy surveying department with an interest in coastal dynamics. It produces the cartography of the sea bottom and does the research for controlling and monitoring all the conditions related to navigability. The phenomenon of sea level rise is, actually, one of the research programs partly supported by the Institute. Although the results demonstrate that sea level is rising between 1.27 mm and 1.54 mm per year (Taborda and Dias, 1989), the consequent impacts have not been viewed as a problem. Naval officials generally believe that protection structures should be built.

Municipalities

The response of the municipalities where tourism is the main economic source is to keep the beach as large as possible. They will rely on technology (coastal engineering structures, nourishment). Some municipal officials suggest that swimming pools be built at seaside as an insurance in case beaches are lost.

State Secretary of the Environment

The impacts on the natural systems will be controlled by several organizations connected to the environment: the General Directorate of the Environment (DGA); the General Directorate of the Quality of the Environment (DGQA); the General Directorate of Natural Resources (DGRN); the General Directorate of Hydraulic Resources (DGRH); and the General Directorate of Parks and Natural Reserves (DGPRN). These organizations, which report to the State Secretary of the Environment, are responsible for all aspects of environmental protection at this time. There is no Ministry of the Environment currently, and thus there is no cabinet-level representation for the environment in Portugal.

To some of these entities, the sea level rise issue was surprising, as was the evidence that it could have such severe impacts on the natural coastal systems, as well as on the economic systems. DGQA is developing some research

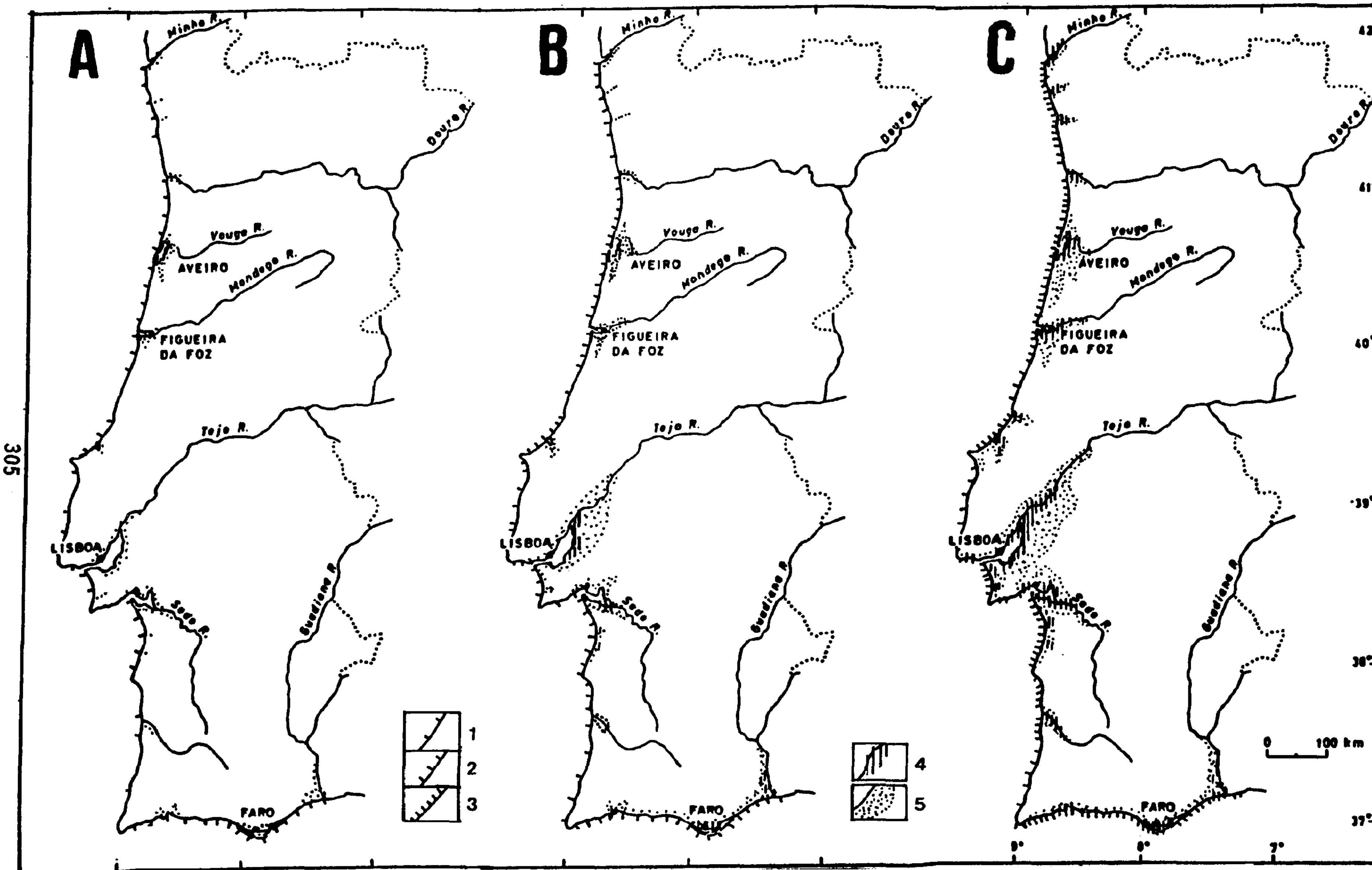

Figure 6. Location and relative importance of the impacts of potential sea level rises of (A) 0.5 m; (B) 1 m; (C) 2 m. 1, 2, and 3 - increasing erosion; 4 - submergence; 5 - salinization.

projects about climate change due to the greenhouse effect and the consequent warming of the atmosphere.

The discussion of the impacts of sea level rise on the coastal hydraulic systems will continue in the near future, although these agencies have a very small capacity of direct intervention. Clearly, they must advise the private owners and other official entities about the risks of certain investments.

Some impacts that have been controlled are those affecting the natural parks and reserves (DGPRN), especially on the coastal wetlands (Natural Reserves of Pancas-Tejo estuary, estuary of Sado, Ria Formosa, and Castro Marin-Guadiana), because the salt marshes will retreat and disappear as a result of the erosion and the submergence. A solution that must be considered is to allow marshes to migrate inland, replacing the existing estuarine brackish marshes, which are not very extensive because of the reclamation of the low fluvial plain and the channelization of the river courses.

General Directorate of Harbors

The potential impacts on harbors, and on other structures, of coastal engineering to protect beaches, such as avoiding the infilling of the estuarine navigation channels, monitoring the growing of the bars, and dredging, will be controlled by the General Directorate of Harbors (DGP). This agency controls the national and regional management of the harbors and other coastal protection structures, according to the regional and local civil administration (Commissions of Regional Coordination and Municipalities).

This office is not very concerned about sea level rise because the consequences will unfold slowly. They need to rebuild the coastal structures anyway, from time to time, so sea level rise can be incorporated gradually. The reinforcement of structures whose effective lifetime will be decreased and the building of new structures are the solutions most commonly suggested.

National Survey for Civil Protection

The National Survey for Civil Protection is part of the Ministry of Defense and protects the people against natural hazards. It is concerned with the impacts of a sea level rise of 1 m and 2 m because of the increased flooding risks in the urban drainage systems and the risk to buildings affected by the storm waves. They told us that they have no immediate answer to the problem, but they will consider it.

General Directorate of Agricultural Resources

The General Directorate of Agricultural Resources is responsible for the study of soils and the coordination of agricultural productivity. It is very concerned about the problem of salinization of the reclaimed estuarine soils and the alluvial soils. The subject is being studied, and several solutions and their economic feasibility are being considered, especially because of the potential for decreased rice productivity. At the same time, the cost of rice production will increase because of the cost of energy to pump the water from the drainage channels of the rice fields. One of the possible solutions may be to substitute other crops (oats, barley, or sugarbeets) for rice or to use the land for purposes other than agriculture.

General Directorate of Tourism

The Directorate of Tourism is one of the organizations connected to coastal management and planning. It is very concerned with the impacts of sea level rise on the coast, mostly on the beaches. Together with other agencies, it will try to find options that can provide practical solutions, such as jetties or artificial nourishment of the beach. A proposed solution to decrease the tourist pressure on the coastal fringe will be accepted with very great difficulty.

The impacts of the possible sea level rise will be controlled by several of these organizations as well as by the owners of the land. Very seldom will such impacts be responded to by only one agency.

CONCLUSION

One of the few conclusions we are able to draw is that the solutions will appear gradually as sea level rises. Neither structural solutions nor land use changes are yet part of the planning process in Portugal. This is hardly surprising given the recent nature of the issue. Nevertheless, because sea level rise could have important impacts, the time to start planning is now.

BIBLIOGRAPHY

Cavaco, C. 1983. A Costa do Estoril. Esboco Geografico. Ciencia e Tecnica 6, Lisboa, Ed. Progresso Social e Demografia:261.

Carvalho, J.R.R., and J.P. Barcelo. 1966. Agitacao maritima na Costa Oeste de Portugal Metropolitano. Lisboa, Laboratorio Nacional de Engenharia Civil, Mem. 290:63.

Daveau, S., et al. 1977. Repartition et rythme des precipitations au Portugal. Lisboa, Centro de Estudos Geograficos, Mem. 3:184.

Dias, J.M.A. 1988. Aspectos geologicos do Litoral Algario. Geonovas, 10:113-128.

E.P.R.U. 1988. Portugal em Mapas e Numeros. Lisboa, Centro de Estudos Geograficos, Rel. 28.

Feio, M. 1980. O Porto de Sines: prejuizos e reparacoes. Finisterra 15(29):74-84.

Ferreira, D.B. 1981. Carte Geomorphologique du Portugal. Lisboa, Centro de Estudos Geograficos, Mem. 6.

North and West Europe

Granja, H.M. 1984. Etude geomorphologique, sedimentologique et geochimique de la Ria Formosa (Portugal). These de 3, troisiemme cycle, Univ. Bordeaux 1:254.

Instituto Hidrografico. 1978, 1988. Tabela de Mares, 1979 and 1989 - I, Portugal, Lisboa.

Instituto Nacional de Meteorologia e Geofisica. 1974-1978. Anuario Climatologico de Portugal, Lisboa, 1974, 1975, 1976, 1977, and 1978.

Moreira, M.E.S.A. 1986. Man made disturbances of Portuguese salt-marshes. Thalassas 4(1):43-47.

Moreira, M.E.S.A. 1989. Geomorphology and sedimentation rates of the tidal mud flats of the Sado estuary. IGU-CCE Annual Regional Symposium Guide Book, Lisboa, 130 p.

Psuty, N.P. 1986. Impact of impending sea-level rise scenarios: the New Jersey barrier island responses. Bull. New Jersey Academy of Science 31(2):29-36.

Ribeiro, O., H. Lautensach, and S. Daveau. 1987. Geografia de Portugal I. A Posicao Geografica e o Territorio. Lisboa: Sada Costa, 334 p.

Servico Meteorologico Nacional. 1970. O Clima de Portugal. Fasciculo XII - Normais climatologicas do Continente, Acores e Madeira, correspondentes a 1931-1960, Lisboa.

Taborda, R., and J.M.A. Dias. 1989. Tide-gauge data in deducing sea level rise and crustal movements rate: the Portuguese case. IGU-CCE Annual Regional Symposium Guide Book, Lisboa. 130 p.

Titus, J.G. 1986. Greenhouse effect, sea level rise, and coastal zone management. Coastal Zone Management Journal 14(3):147-171.

CENTRAL AND SOUTH AMERICA

POTENTIAL IMPACTS OF SEA LEVEL RISE ON THE COAST OF BRAZIL

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EXECUTIVE SUMMARY

The impact of sea level rise on Brazil would be similar to the impacts on other nations: Wetlands and lowlands would be inundated, beaches would erode, coastal areas would flood more frequently, and saltwater would encroach inland. But the question remains: How severe will the effects be, how much will they cost, and what should we do?

Because Brazilians have only recently begun to ask these questions and almost no research has been done to answer them, we can not yet provide quantitative estimates of the impacts. Thus, it has not yet been possible to demonstrate the significance of the issue to public officials, which will be necessary before we can confidently recommend policy responses.

What we can offer is the perspective of scientists who are beginning preliminary assessments which we hope will eventually assist policy makers in the decision process.

We are persuaded by the point of view that the primary responsibility of researchers is to gradually develop an understanding of the implications of sea level rise in one's own country and develop recommendations based on that research, not on the results of analysis in other countries. Because serious analysis has not been undertaken, we would rather simply tell the IPCC that this is so than speculate on the implications of response strategies. We are pleased that our point of view is reflected in the conference report's section on South America.

Simply put, our strategic response to sea level rise at this time is to understand the problem so that in a couple of years we will have useful information for policy makers. This will require us to develop a comprehensive understanding of the coast of Brazil, then estimate inundation, erosion, flooding, and other effects, then evaluate the costs of alternative responses, and only then, recommend policies. Accordingly, the bulk of this paper is on the first step -- understanding the coast.

INTRODUCTION

Brazil is divided into five major geographic regions, according to geological, climatic, and economic characteristics (Figure 1). Four of these regions border the Atlantic Ocean (North, Northeast, Southeast, and South) and the coastline has an approximate length of 7,400 km, without considering the contour of bays and islands. Extending from latitude 4° north to 34° south, with climates ranging from tropical to subtropical, within each region the coastline may be further divided into different segments according to the geomorphological features or processes.

In Brazil, erosion problems have not been generally considered as caused by sea level rise, although a few reports (e.g., Muehe, 1989; Tomazelli and Villwock, 1989) have addressed this issue very recently. Frequently, the idea that sea level is dropping still persists. In fact, the relative sea level curves established for several sectors of the Southeast and South regions for the last 7,000 years (Delibrias and Laborel, 1971; Suguio et al., 1985), indicate that during two or three occasions, sea level has been up to 5 m higher than at present.

Despite the continuous drop in relative sea level during the last 2,300 years, evidence of coastal erosion begin to be noticed at different parts of the coastline. Lack of sediment supply, increase of storm intensity, local tectonic movements, and human interference may all contribute to this erosion. The absence of long-term tidal data and also the scarcity of topographic and cartographic material makes it difficult to follow coastal changes for a longer time span into the past. Most of the studies about coastline changes have been limited to typically unstable areas such as tidal inlets and river mouth bars, and therefore cannot be considered as evidence of erosion due to a marine transgression. Nevertheless, there is an increasing feeling, among some researchers, that a rise in sea level may also be responsible for some of the detected erosion.

In a shorter time scale, though, there might be a trend for a sea level rise. Pirazolli (1986) presented relative sea level curves for six locations in Brazil during the period 1950-1970. There was a rise at rates varying between 5 cm/century to 35 cm/century, except for one location near the mouth of the Amazon River, which showed a trend for decreasing sea level. This subject is further discussed in the section about tidal information. Although the time span of observation was too short to derive a definite conclusion, it is strong enough

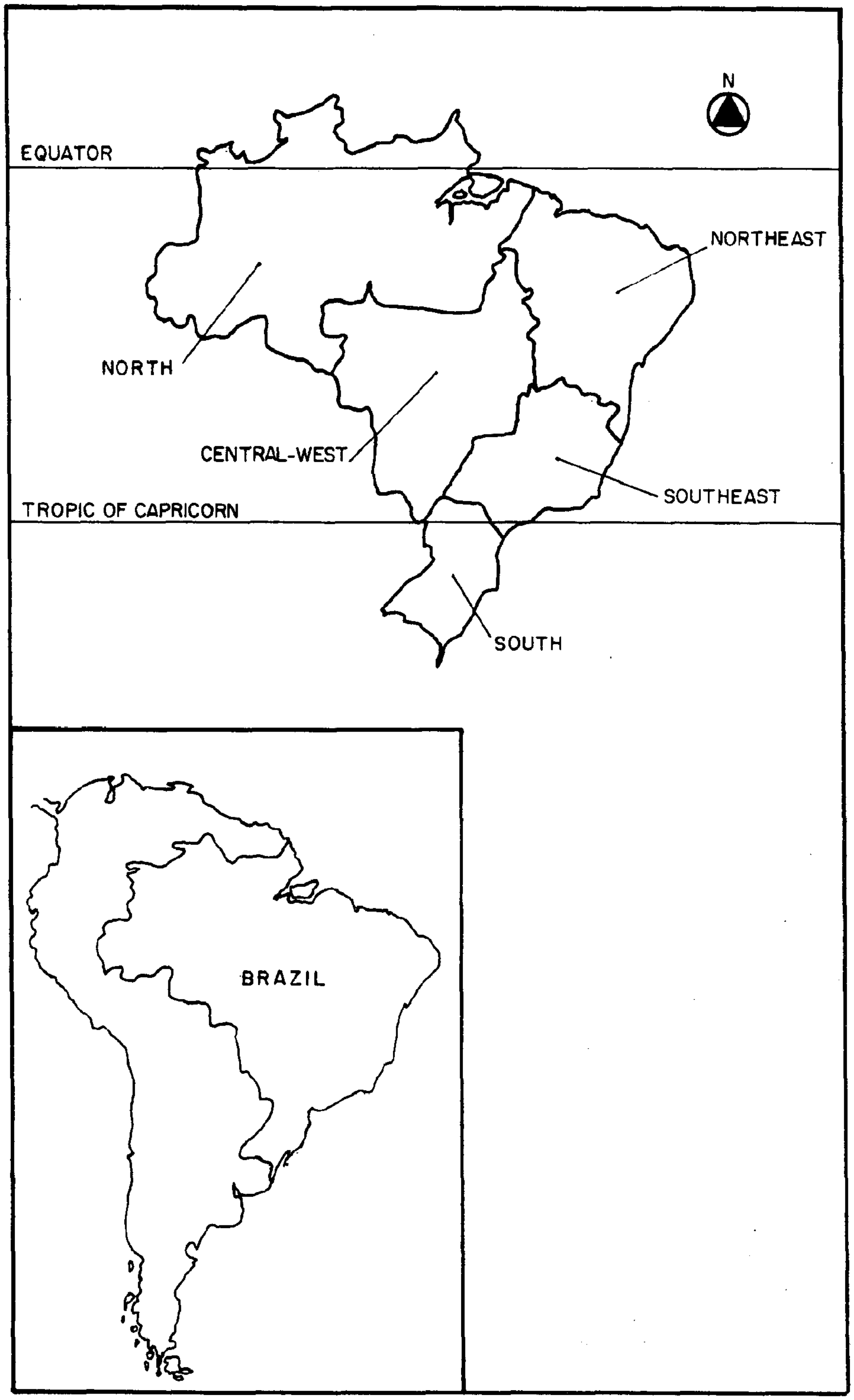


Figure 1. Geographic regions of Brazil.

to justify the beginning of comprehensive studies about the subject in Brazil, as well as special care in obtaining tidal data.

IMPACTS ON THE COASTLINE

The coast of Brazil was divided into five sectors, and for each of them the geomorphologic characteristics and the population distribution were presented. It is reasonable to assume that places with higher numbers of inhabitants per kilometer of coastline would be more susceptible to the impacts from a one-meter rise in sea level. Therefore, it can be derived from maps that the major impacts would be limited to the neighborhood of about fifteen coastal cities where the density is higher than 5,000 inhabitants per kilometer of coastline.

As a guide for evaluating these impacts, five areas are suggested for study in each of the sectors owing to their geomorphologic and socioeconomic characteristics. From North to South, these areas are Salinopolis (PA), near the mouth of the Amazon; Fortaleza (CE); Recife (PE); Rio de Janeiro (RJ); and Rio Grande (RS).

We briefly summarize concerns for four coastal regions: the North, the Northeast, the Southeast, and the South.

<u>The North</u>

The most important impact here would be the rising water levels in tidal rivers. Flooding of river valleys will confined to a fairly narrow area due the presence of high ground somewhat inland. Low-lying alluvial areas such as in the Marajo Island at the river mouth, however, might be inundated. Because the low-lying areas in northern Brazil are now sparsely populated, major consequences for the economy can be avoided as long as future development in the regions occurs takes sea level rise into account.

<u>The Northeast</u>

In this region, low-lying deltaic areas such as the Sao Francisco Delta will suffer an expansion of the mangroves into and used today for temporary housing and agriculture. A more serious problem will face coastal cities like Recife, Aracaju, and part of Maceio, where low-lying areas are flooded when heavy rains coincide with spring tides (Nou et al., 1983); with-50-cm rise in sea level the same effect would occur even during neap tides. Drainage problems and flooding will probably also confront the low-lying areas of the coastal plains of the Todos of Santos Bay in Bahia. These problems could be particularly severe in the heavily populated city of Recife, where urbanization has expanded throughout the floodplain the Capibaribe and Beberibe Rivers, exacerbating flooding and drainage problems (Figure 2).

<u>The Southeast</u>

The diverse types of coasts in this region (barrier beaches, pocket beaches, rocky shores, coastal lagoons, bays, estuaries) will respond in different ways

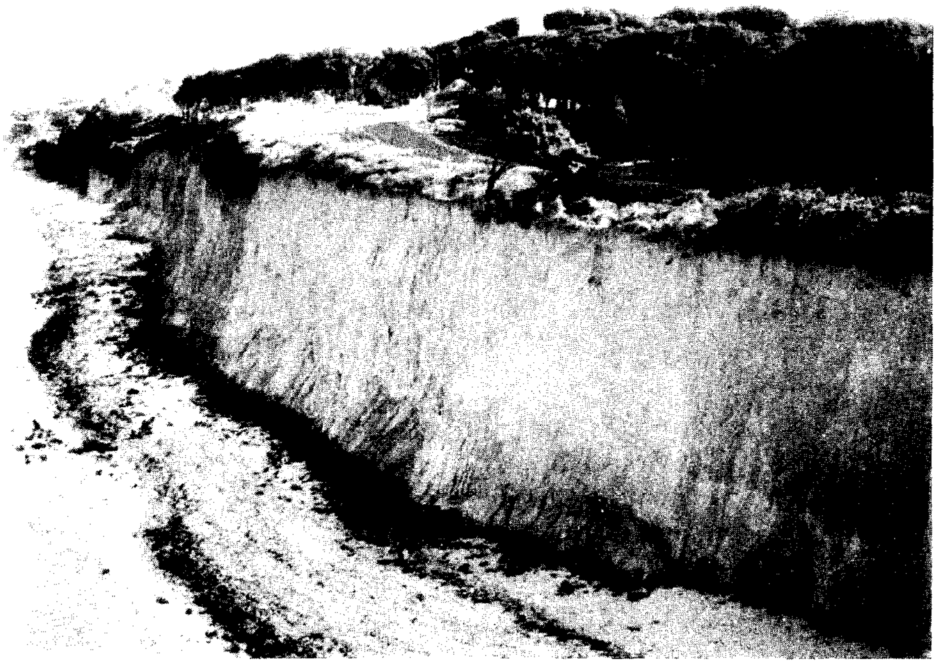


Figure 2. Retreating bluffs on the coast of Paraiba (northeast region); note a tree at the edge of the bluff (center).

to a sea level rise. Some areas are already eroding -- even though human interference is negligible -- suggesting that these areas are already exhibiting some of the signs of rising sea level.

For example, during the last fifteen years, the mouth of Paraiba do Sul River has seen extensive beach erosion with a resulting loss of valuable property (Argento, 1989). On the southern part of the delta, grayish black sandstone has been exposed, indicating that shores are retreating. Similar processes have been identified by Muehe (1984, 1989) at the barrier beaches between Cape Frio and Guanabara Bay, and the back side of the barrier that faces Araruama Lagoon appears to be eroding.

Another area in the State of Rio de Janeiro that may suffer from a rise in sea level is the fluvial-marine plain along the estuary of Sao Joao River located about 200 km south of Paraiba do Sul River. Currently, rice is extensively cultivated along the valley, using river water for irrigation. Besides the potential of flooding, sea level rise could threaten the water supply as saltwater advances farther upstream, a process that has already been observed.

Finally, the flat areas around Guanabara Bay appear to be vulnerable. These areas currently flood during heavy rains, especially along rivers and drainage canals. The combined effects of a rise in sea level and siltation of those canals will aggravate the flooding. Moreover, because the relative sea level was 5 m higher during the Holocene than today (Amador, 1974), the terrain in this area is very flat and hence extensive areas are vulnerable to flooding from storm surges. Similar problems seem likely to afflict other coastal plains and river valleys in the region (Figure 3).

The South

Little data have been collected on current shoreline changes. However, in Santa Catarina peat has emerged near the scarps of coastal barriers, indicating that shores are retreating. Similarly, peat is present on the foreshore and along the base of the foredunes along the beaches of Rio Grande do Sul. Erosion along the margin of Patos Lagoon also appears to be another indication of relative sea level rise. All of these trends would be exacerbated if sea level rise accelerated.

OCCUPATION OF THE COASTLINE

A study of the impacts of sea level rise must consider not only the geomorphological features of the coast, but also the economic impact it would have on the population. Due to the fact that no detailed assessment of the entire coastal zone of Brazil has ever been conducted, and also because it is always assumed that the population is not evenly distributed along the coast, the authors chose to characterize the human occupation of the coastline (measured in terms of inhabitants/km of coastline). This parameter is used to identify areas where potential impacts would be stronger for the following reason: an

Figure 3. Barrier island of Ipanema-Leblon, city of Rio de Janiero. Erosive processes have been observed on Leblon Beach (top) and waves reach the longshore avenue during storms.

area with a higher degree of occupation would most likely have more diversified activities (e.g., housing, water supply needs, waste disposal, harbors and marinas, tourism, agriculture), that would ultimately be affected by sea level rise. The cost for facing the adverse impact would probably be divided among all local residents in the form of increased taxes, reduced revenues or reallocated funds, even though the population might not be at risk of flooding (which is the first thought of impact).

Micro-regions, established by the Instituto Brasileiro de Geografia e Estatistica (IBGE), as a group of counties with homogeneous geographical characteristics, were chosen as the basic unit of the coastline. Then, for each micro-region located on the coast, only those counties that have a coastline were considered in this study, measuring the length of its coast and its population (based on 1980 census). The towns would be located at most 30 km from the coast.

First, a comparison was made between the population living in those coastal counties and the population of the state (figures are presented in Table 1). For the country as a whole, about 20.4% of the population might be potentially affected by the consequences of sea level rise (not necessarily flooding). In the north region, both states, Amapa (AP) and Para (PA), show a high concentration of population near the coast, respectively 82.9% and 50.7%, even though their total population is not significant compared to other states. This is because they are both located in the Amazon region, and their capitals are are located on the margins of the Amazon delta. In the northeast region, Pernambuco (PE) has the highest percentage (38.5%) which is explained by the dry weather in the interior and by its historical development since the 1600s as an important area of sugarcane plantations. In the southeast region, Rio de Janeiro (RJ) shows a percentage of 68.6%, which is a high figure. The reason is because the capital, the City of Rio de Janeiro, and its metropolitan region are located around two bays and represent the second largest urban center in the country. Finally, in the south region, Rio Grande do Sul (RS) is the state with the highest percentage of population (28.7%) in the coastal zone, mostly concentrated around Patos Lagoon, which has an area of 10,000 km^2 and whose coastline will be affected by sea level rise.

A second study was conducted in order to quantify the population density per unit length of coastline. Four classes were identified: those where the density was less than 1,000 hab/km, which characterizes remote areas; those where the density was between 1,000 and 5,000 hab/km, characteristic of most urbanized areas, where the economical activities should be more important; those with a density between 5,000 and 10,000 hab/km, typical of medium size cities, usually around state capitals; and, finally, above 10,000 hab/km, typical of large cities.

It was observed that 47.4% of the coastline has very low occupation (a weighted average value of 522 hab/km). These localities include preservation areas, small towns without appropriate surveying, or areas where data about coastline evolution would not be available at all. Consequently, it is difficult to make an assessment of impacts of sea level variations. On the other hand, it also suggests that a planned occupation -- which should take into account

Table 1. Population Living in the Coastal Zone (1980 Census)

Region	State	Population: In the state	Population: On the Coast	Percentage (%)
1	AP	175,257	145,313	82.9
	PA	3,403,391	1,726,131	50.7
2	MA	3,996,404	1,024,148	25.6
	PI	2,139,021	127,798	6.0
	CE	5,288,253	1,869,026	35.3
	RN	1,898,172	634,906	33.4
	PB	2,770,176	400,831	14.5
	PE	6,141,993	2,367,686	38.5
	AL	1,982,591	644,720	32.5
	SE	1,140,121	435,985	38.2
	BA	9,454,346	2,622,432	27.7
3	ES	2,023,340	845,546	41.8
	RJ	11,291,520	7,748,200	68.6
	SP	25,040,712	826,490	3.3
4	PR	7,629,392	101,804	1.3
	SC	3,627,933	877,168	24.2
	RS	7,773,837	2,234,681	28.7
	Brazil	119,001,427	24,232,034	20.4

NOTE: Region -- 1 = North; 2 = Northeast; 3 = Southeast; 4 = South.

data about sea level trends in neighboring areas -- would be the "best response"to avoid future problems.

In other areas, which amount to fifteen cities and 12.7% of the coastline, the population has already been established. Usual coastal engineering works for shore protection would be feasible there and detailed studies (for past evolution and future observations) are economically justifiable.

TIDAL INFORMATION

Tide data in Brazil has usually been obtained by the port authorities and by the Navy for navigation purposes. For various reasons -- like cost of maintenance and repair of equipment -- the time series has many gaps; this prevents a study of long-term variations.

As a rough guide of the tidal variation along the coast of Brazil, Table 2 presents figures obtained from the 1989 Tide Table published by the Diretoria de Hidrografia e Navegacao (DHN) for different ports along the coast. It is interesting to observe the decrease in tidal range, from 5.0 m near the Equator to 0.5 in Rio Grande, at the southern part of the country.

Studies conducted by Pirazolli (1986), including six locations in Brazil during the period 1950 through 1970, indicated a trend for sea level rise in four stations (Recife (PE), 27 cm/century; Salvador (BA), 16 cm/century; Canavieiras (BA), 31 cm/century; and Imbituba (SC), 5.5 cm/century; in Fortaleza (CE), the sea level has oscillated by an amount of 6.6 cm in fifteen years, showing a trend for rise at the end of the period of observation; in Belem (PA), there was an oscillation of 2.2 cm in twenty years, with a trend for decreasing in the last seven years of observation. This data justified the need for further investigation. Currently, groups of researchers at the Universidade Federal do Rio de Janeiro (UFRJ) and at the Instituto Oceanografico da Universidade de Sao Paulo (IOUSP) are studying long-term sea level variations at various points along the coast. The work, which should be completed by the end of 1990, includes: retrieval of tide data from graphs to digital format; correction for changes in datum; verification of errors and gaps; and determination of daily, monthly, and yearly mean sea level curves.

Brazil already participates in the GLOSS program of the Intergovernmental Oceanographic Commission (UNESCO), and the DHN of the Brazilian Navy is responsible for the installation of ten permanent tide gauges in the country, including three stations at oceanic islands. The IOUSP and the Brazilian Port Authority holding company (PORTOBRAS) also participate in this effort being responsible for two stations. Combining the data already available for the past twenty years with the data to be obtained during the next twenty years will enable us to have a clear picture of relative sea level changes at the beginning of next century.

Table 2. Tidal Range Along the Coast of Brazil

Region[a]	State	Location	Type[b]	Spring tide HW[c]	Spring tide LW[d]	Spring tide ΔH[e]
1	AP	Barra Norte	E	4.16	0.37	3.79
	PA	Salinopolis	M	5.08	0.36	4.72
2a	MA	Itaqui	B	6.28	0.44	5.84
	PI	Luis Correia	M	3.27	0.20	3.07
	CE	Mucuripe	O	2.93	0.17	2.76
	RN	Areia Branca	O	3.50	0.24	3.26
2b	RN	Natal	E	2.12	0.11	2.01
	PB	Cabedelo	E	2.36	0.08	2.28
	PE	Recife	M	2.33	0.10	2.23
	AL	Maceio	E	2.34	-0.01	2.35
	SE	Aracaju	E	2.04	0.06	1.98
	BA	Salvador	B	2.52	0.18	2.34
	BA	Ilheus	O	2.20	0.19	2.01
3	ES	Barra do Riacho	O	1.60	0.08	1.52
	ES	Tubarao	O	1.50	0.04	1.46
	RJ	Cabo Frio	O	1.26	0.09	1.17
	RJ	Rio de Janeiro	B	1.29	0.12	1.17
	SP	Sao Sebastiao	O	1.19	0.03	1.16
	SP	Santos	E	1.50	0.04	1.46
4	PR	Paranagua	M	1.64	0.07	1.57
	SC	Itajai	E	1.13	0.12	1.01
	SC	Imbituba	O	0.72	0.01	0.71
	RS	Rio Grande	M	0.43	0.05	0.38

[a] Region: 1 = north; *2a* = northeast, from Maranhao to Cape Calcanhar; *2b* = northeast, from Cape Calcanhar to Bahia; 3 = southeast; 4 = south
[b] Type of location of the tidal stations: O = open coast; B = inside bay; E = in estuaries; M = at the mouth of the estuary or bay
[c] HW = mean values of high water spring tide (elevation in meters relative to local datum).
[d] LW = mean values of low water spring tide (elevation in meters relative to local datum).
[e] ΔH = HW - LW.
Source: Values from 1989 Tide Table.

INSTITUTIONS INVOLVED IN ENVIRONMENTAL MANAGEMENT

The Constitution of 1988 and the state Constitutions that followed brought the environmental issues into a legal framework by declaring in one of its chapters that "all have the right to an environment that is in ecological balance." It also includes the coastal zone among the areas classified as "national heritage."

Brazil's National Coastal Zone Management Plan (PNGC) was established in May 1988. The Comissao Interministerial para os Recursos do Mar -- the government agency for sea resources -- is responsible, through its Secretary for Coastal Zone Management, for establishing general goals and common policies, and for giving technical and financial support to state and municipal agencies. However, each State is responsible for developing its own Coastal Management Plan. Each plan is supposed to include "macro-zoning" of the coast, the monitoring program, and a geographical information system. Because the program is new, macro-zoning is progressing in only six states, including Rio de Janeiro.

The various consequences of sea level rise -- erosion, flooding, and saltwater intrusion -- are intrinsic to any management plan. However, officials are not yet convinced that there is a problem. Many researchers still believe that sea level is falling around the coast of Brazil; and information on current sea level and even shoreline trends is unavailable for most of the coast.

Regarding the climate changes issue, the Brazilian government took an important step in October 1989 by enacting a law that creates the Comissao Interministerial sobre Alteracoes Climaticas -- an interministerial committee for climate changes, which includes the Secretaries of eight federal ministries, the Secretary of the Comissao Interministerial para os Recursos do Mar, and the directors of seven institutions related to research on meteorology, space science, environment, and agro-sciences.

Finally, studies are currently being developed in Congress in order to establish a national management plan for water resources. Dams for irrigation, water supply, and hydroelectric power plants can alter the balance of estuaries downstream; The significance of these impacts may be much greater than currently anticipated if sea level rise accelerates; and transition to a drier climate could further amplify the interactions between water resources and coastal management. Thus, these two programs need to work together to ensure that solutions to one type of problem (e.g., increased water supply needs to counteract increasing droughts) do not create other problems downstream (e.g., increased saltwater intrusion and loss of sediment in deltas).

The results of the new programs will not be known for many years. Whether they are going to work depends mostly on the amount of funds and effort that will be invested in environmental education.

MANAGEMENT PROGRAMS

The National Coastal Zone Management Plan was established in Brazil according to the Federal Law No. 7661 on May 16, 1988. It is made up of the National Policy for the Environment and the National Policy for Sea Resources. The Comissao Interministerial para os Recursos do Mar -- the government agency for sea resources -- is responsible, through its Secretary for Coastal Zone Management, for establishing general goals and common policies, and for giving technical and financial support to state and municipal agencies. However, each state is responsible for developing its own Coastal Management Plan. Each plan should include the macro-zoning of the coast (which is summarized in twelve thematic maps), the monitoring program, and the Geographical System of Information. A detailed explanation of PNGC can be found in Frischeisen et al. (1989) and Azevedo et al. (1989).

The PNGC is still in its infancy: the macro-zoning program is in progress in only six states (Rio Grande do Sul and Santa Catarina in the south region, Sao Paulo and Rio de Janeiro in the southeast region, and Bahia and Rio Grande do Norte in the northeast region) and it is expected to be completed by 1992. The concerns about a possible sea level rise are intrinsic to any management plan. However, in practice, it becomes very difficult to consider relative sea level variations either because tidal data are not available, or because there is no reference line that can be used to control erosion along unpopulated stretches of the coast.

Regarding climate changes, the Brazilian government took an important step by passing Federal Law No. 98352 on October 31, 1989. This law created the Comissao Interministerial sobre Alteracoes Climaticas -- an interministerial committee for climate changes. The committee includes the Secretaries of eight federal ministries, the Secretary of the Comissao Interministerial para os Recursos do Mar, and the directors of seven institutions related to research on meteorology, space science, environment, and agro-sciences.

Finally, studies are currently being developed in Congress in order to establish a national management plan for water resources. The Brazilian Association for Water Resources (ABRH), an association of engineers and other professionals who deal with hydraulic engineering and water resources, contributes to this plan by forwarding several proposals to the Congress committee. Multiple uses of water resources (irrigation, water supply, hydroelectric power plants, construction of dams) cause changes in river discharge, which alter the environment of estuaries downstream. The significance of these impacts may be much greater than currently anticipated if the climate becomes drier and sea level rise accelerates. Thus, it is desirable that the management plans for water resources and for the coastal zone work together to ensure that solutions to one type of problem (e.g., increased needs for water supply) does not create other problems downstream (e.g., increased saltwater intrusion and loss of sediment in deltas).

Perhaps the most difficult part is to establish stations and routines for collecting data, which is usually a very expensive task. Taking into account all regional differences in socioeconomic needs and priorities, as well as those differences in impacts due to global weather and oceanographic changes, the establishment of those national committees gives a promising perspective.

The results of all these plans will be felt in the future, though. Whether they are going to work depends mostly on the amount of funds and effort that will be invested in environmental education.

ENVIRONMENTAL LEGISLATION FOR THE COASTAL ZONE

The most important step in environmental legislation, with consequences yet to be perceived, was given by the Brazilian Constitution of 1988 and the State Constitutions which followed. Environmental issues were brought into a legal framework by the declaration in one of its chapters that "all have the right to an environment which is in ecological balance." It also includes the coastal zone among the areas classified as "national heritage."

Since 1934, the "Code of Water Resources" has been the basic law which regulates the uses of water resources, the occupation of the margins of rivers and lakes, and the occupation of the coastal area. It establishes that a strip of land 33 m wide, inland from a specific high-water line, belongs to the Union. Together with a resolution of the Brazilian Navy, public access to the shore is granted.

The National Policy for the Environment (1981) established the creation of a National Committee for the Environment (CONAMA) including representatives from federal ministries and civil organizations. CONAMA has since then approved several resolutions for protection of sensitive areas and for establishment of ecological stations. The following areas are included among those of permanent protection (Resolution 004, 1985): barrier islands, spits, and barrier beaches up to 300 m inland from the highest water line; mangroves; vegetation for fixing dunes; wetlands and other areas used by migrating birds; and land up to 100 m around lakes, lagoons, and reservoirs. As a matter of fact, since 1965, the "Forest Code" had considered mangroves and vegetation on dunes as being of permanent protection

The legal framework which grants a balanced use of the environment is essentially established. In addition to the federal laws listed above, each state has its own regulations and policies. In a scenario of sea level rise and climate changes, some of these legislations may need to be reviewed in face of scientific studies. However, the most urgent problem for the country seems to be how to enforce these laws, in such a vast area, with very limited resources. Furthermore, without the social and educational development of a large percentage of the population, it is extremely hard to achieve the goal of living in an ecologically balanced environment.

CONCLUSION

We have only begun to assess the implications of sea level rise and the greenhouse effect. Upon further investigation, we may find that we have been overlooking impacts that are more important than those described here; and some of the impacts that now seem serious may prove to be manageable. Any conclusions thus must be viewed as tentative and illustrative hypotheses necessary to guide future research.

In our view, the expected global rise in sea level implies that municipal, state, and federal authorities should take a preventive approach when selecting sites for urban expansion and location of industries. Due to the high cost of protecting developed areas from such a rise, this "preventive approach" includes the following steps:

1. Enforce coastal management programs, as the one currently in progress, and establish urbanization plans according to those programs;

2. Install long-term tidal gauges in order to furnish, twenty years from now, reliable data for inferring sea level trends;

3. Establish a methodology for observing (and quantifying) the evolution of shoreline, mangrove areas, and other coastal features;

4. Maintain a systematic data bank for oceanographic and meteorologic information according to international standards;

5. Incorporate the results of scientific assessments into coastal development plans, for example, by requiring construction to be set back from the shore;

6. Adopt flexible criteria for designing harbors and coastal structures, which take into account all the information available for the site and, at least, a "lower expectation" of sea level rise; and

7. Formulate educational programs about environmental (particularly coastal) protection and global climatic effects, addressed to different levels of the population.

The costs involved in these cautious measures could bring significant benefits in the future and could avoid greater socioeconomic impacts.

BIBLIOGRAPHY

Amador, E.S. 1974. Praias fosseis do reconcavo da baia de Guanabara. An. Acad. Brasil. Cienc. 46(2): 253-262.

Angulo, R.J. 1989. Variacoes na configuracao da linha de costa no Parana nas ultimas quatro decadas. II Cong. da Assoc. Bras. de Estudos do Quaternario. Rio de Janeiro, July 10-16, 1989. (in press).

Argento, M. 1989. The Paraiba do Sul retrogradation and the Atafona environmental impact. In: Neves, C. and Magoon. O.T. (ed.) Coastline of Brazil. American Society of Civil Engineers, New York. p. 267-277.

Azevedo, L.H., D.M.W. See, and D.R. Tenenbaum. 1989. Coastal zone planning. In: Neves, C. and Magoon, O.T. (ed.) Coastline of Brazil. American Society of Civil Engineers, New York. p. 70-83.

Bandeira Jr., A.N.; S. Petri, and K. Suguio. 1975. Projecto Rio Doce: Petroleo Brasileiro S.A., Internal Report, 203 p.

Cruz, O., P.da N. Coutinho, G.M. Duarte, A.M.B. Gomes, and D. Muehe. 1985. Brazil. In: Bird E.C.F. and M.L. Schwartz (ed.), The World's Coastline. Van Nostrand Reinhold Co., New York. p. 85-91.

Delibrias, C., and J. Laborel. 1971. R ecent variations of the sea level along the Brazilian coast. Quaternaria, XIV: 45-49.

Dias, G.T.M. 1981. O complexo deltaico do Rio Paraiba do Sul. IV simposio Quaternario no Brasil. Publ. Especial. 2:35-74. Rio de Janeiro.

Dias, G.T.M., and M.A. Gorini. 1979. Morfologia e dinâmica da evolucao do delta atual do rio Paraiba do Sul. Anais da V Semana de Geologia, UFRJ. Rio de Janeiro.

Dias, G.T.M., and C.G. Silva. 1984. G eologia de depositos arenosos costeiros emersos -- exemplos ao longo do litoral fluminense. In: Lacerda, L.D. de, Araujo, D.S.D. de, Cerqueira, R. and Turcq, B. (ed.) Restingas: Origem, Estrutura, Processos. CEUFF, Niteroi. p. 47-60.

Dominguez, J.M.L. 1989. Ontogeny of a strandplain: Evolving concepts on the evolution of the Doce river beach-ridge plain (East coast of Brazil). International Symposium on Global Changes in South America during the Quaternary: Past -- Present -- Future. Sao Paulo, May 8-12. Special Publication 1:235-240.

Dominguez, J.M.L., L. Maratin, A.C.S.P. Bittencourt, Y. de A. Ferreira, and J.-M. Flexor. 1982. Sobre a validade da utilizacao do termo delta para designar planicies costeiras associadas as desembocaduras dos grandes rio brasileiros. 32 Congr. Bras. Geol., 2 (Breves Comunicacoes): 92, Salvador.

Franzinelli, E. 1982. Contribuicao a geologia da costa do Estado do Para (entre a baia de Curaca e Maiau). In: K. Suguio, M.R.M. de Meis, and M.G. Tessler (ed.) Atas IV Simposio do Quaternario no Brasil. Rio de Janeiro, July, 27-31. p. 305-322.

Central and South America

Frischeisen, E.R., M.S.F. Argento, R. Herz, and R.P. Carneiro. 1989. The Coastal Management Program in Brazil. In: Neves, C. and Magoon, O.T. (ed.) Coastline of Brazil. American Society of Civil Engineers, New York. p. 1-9.

Marques, R.C.C. 1987. Geomorfologia e evolucao da regiao costeira do complexo estuarino lagunar Mundau-Manguaba. M.Sc. thesis, Departamento de Geografia, Universidade Federal do Rio de Janeiro. Rio de Janeiro. 152 p.

Martin. L., and K. Suguio. 1989. Excursion route along the Brazilian coast between Santo (State of Sao Paulo) and Campos (North of State of Rio de Janeiro). International Symposium on Global Changes in South America during the Quaternary. Sao Paulo, May 8-12, 1989. 136 p.

Martins, L.R., and J.A. Villwock. 1987. Eastern South America Quaternary coastal and marine geology: A synthesis. In: Quaternary coastal geology of West Africa and South America. INQUA-ASEQUA Symposium, Dakar, April 1986. p. 28-96.

Muehe, D. 1984. Evidencias de recuo dos cordoes litoraneos em direcao ao continente no litoral do Rio de Janeiro. In: Lacerda, L.D. de, Araugo, D.S.D. de, Cerqueira, R. and Turcq, B. (ed.) Restingas: Origem, Estrutura, Processos. CEUFF, Niteroi. p. 75-80.

Muehe, D., and C.H.T. Correa. 1989. The coastline between Rio de Janeiro and Cabo Frio. In: Neves, C. and Magoon, O.T. (ed.) Coastline of Brazil. American Society of Civil Engineers, New York. p. 110-123.

Nou, E.A.V., L.M. de M. Bezerra, and M. Dantas. 1983. Geomorfologia. In: Projeto Radam Brasil. Levantamento de Recursos Naturais V. 30, Folhas SC 24/25, Aracaju/Recife. Ministerio das Minas e Energia. Rio de Janeiro.

Nunes, T. de A.N., V.L. de S. Ramos, and A.M.S. Dillinger. 1981. Geomorfologia. In: Projeto Radam Brasil. Levantamento de Recursos Naturais V. 24, Folha SD 24, Salvador. Ministerio das Minas e Energia. Rio de Janeiro.

Pirazolli, P.A. 1986. Secular trends of relative sea level (RSL) changes indicated by tide-gauge records. Journal of Coastal Research, SI, 1:1-26.

Prates, M., L.C.S. Gatto, and M.I.P. Costa. 1981. Geomorfologia. In: Projeto Radam Brasil. Levantamento de Recursos Naturais V. 23, Folhas SB 24/25, Jaguaribe/Natal. Ministerio das Minas e Energia. Rio de Janeiro.

Prost, M.T., M. Lintier, and B. Barthes. 1988. Evolution cotiere en Guyane Francaise: La Zone de Sinnamary. 35 Congr. Bras. Geol. and 7 Congr. Latinoamericano Geol. Abstracts. Belem, Brazil, Nov 6-13, 1988, p. 407.

Silveira, J.D. da 1964. Morfologia do litoral. In: Azevedo, A. de. ed. Brasil a terra e o homem. Sao Paulo, Cia. Editora Nacional. p. 253-305.

Suguio, K. and L. Martin. 1976. Brazilian coastline Quaternary formations - The State of Sao Paulo and Bahia littoral zone evolutive schemes. An. Acad. Bras. Cienc., 48 (Suplemento): 325-334.

Suguio, K., and L. Martin. 1981. Progress in research on Quaternary sea level changes and coastal evolution in Brazil. Proc. Symp. on Holocene Sea Level Fluctuations, Magnitude and Causes, 1981, Dept. Geology, USC: 166-181.

Suguio, K., L. Martin, A.C.S.P. Bittencourt, J.M.L. Dominques, J.-M. Flexor, and A.E.G.de Azevedo. 1985. Flutuacoes do nivel relativo do mar durante o Quaternario Superior ao longo do litoral brasileiro e suas implicacoes na sedimentaca costeira. Rev. Bras. Geoc., 15 (4): 273-286.

Tomazelli, L.J., and A. Villwock. 1989. Brasil: evidencias de uma provavel tendencia contemporanea de elevacao do nivel relativo do mar. II Cong. da Assoc. Bras. de Estudos do Quaternario. Rio de Janeiro, July 10-16, 1989 (in press).

APPENDIX: GEOMORPHOLOGICAL DESCRIPTION OF THE COAST

General classifications of the main features of the Brazilian coastline have been presented by Silveira (1964) and by Cruz et al. (1984). Martins and Villwock (1987) presented a modified version based on the other two classifications. In the present paper, a similar pattern is followed with a few modifications.

The Barreiras group, which is mentioned in this classification scheme, represents tertiary sedimentary accumulations of varied composition and extends from the North up to the Southeast Region. Its flat-topped, table-like surface was deeply incised by the drainage system during the Pleistocene climate fluctuations. At the coast these deposits occur in the form of active or dead bluffs, several tens of meters high, carved by the action of waves. Lateritic concretions, found inside the deposits in the zone of the groundwater table fluctuation, are frequently preserved at the inner shelf, indicating the amplitude of coastal recession.

The North Region

The North Region extends from Cape Orange in Amapa (AP), at the border between Brazil and French Guyana, up to the south of the State of Para (PA) (Figure A-1). The 1,080-km-long coastline is strongly influenced by the sediment discharge of the Amazon, which is responsible for the enormous enlargement of the continental shelf. In front of and northward from the river mouth, the 10- and 50-m isobaths occur, respectively, at distances of about 100 and 150 km from the coast. The influence of the Amazon sediments could be followed, during the recent AMASED expedition, up to about 200 km offshore, where a sharp boundary between turbid and clear ocean water marked the distal influence of the river. Southward from the river mouth, the distances of the 10- and 50-m isobaths reduce to respectively 10 to 80 km. Both the north and south segments, the coast is characterized by a fringe of muddy sediments, deposited in front of a Barreiras-like hinterland and covered by mangroves. The south segment presents an irregular coastline, while the northern segment presents a smoother shoreline. These differences are obviously due to the large amounts of sediments from the Amazon River transported to the north.

Due to a tidal range of more than 3 m (reaching 10 m at some locations), erosive processes are strong. The low gradients of the rivers allow a wide penetration of tides. Problems have not been reported so far, but large destruction of mangroves at the ocean front occurs at the north sector (Dias, personal communication). Naturally, without long-term observation it is not possible to know if this is a general trend or only a cyclic phenomenon, as related by Prost et al. (1988) for the mangrove coast of French Guyana. For the south sector Franzinelli (1982) described the presence of active bluffs at Atalaia beach in Salinopolis, where the sediments of the Barreiras group lie on top of the calcareous sediments of the Pirabas Formation (Figure A-2). Dead bluffs, 7 m high, are also found at distances of about 100 m from the shoreline, in places where the Barreiras group has been eroded by a higher sea level.

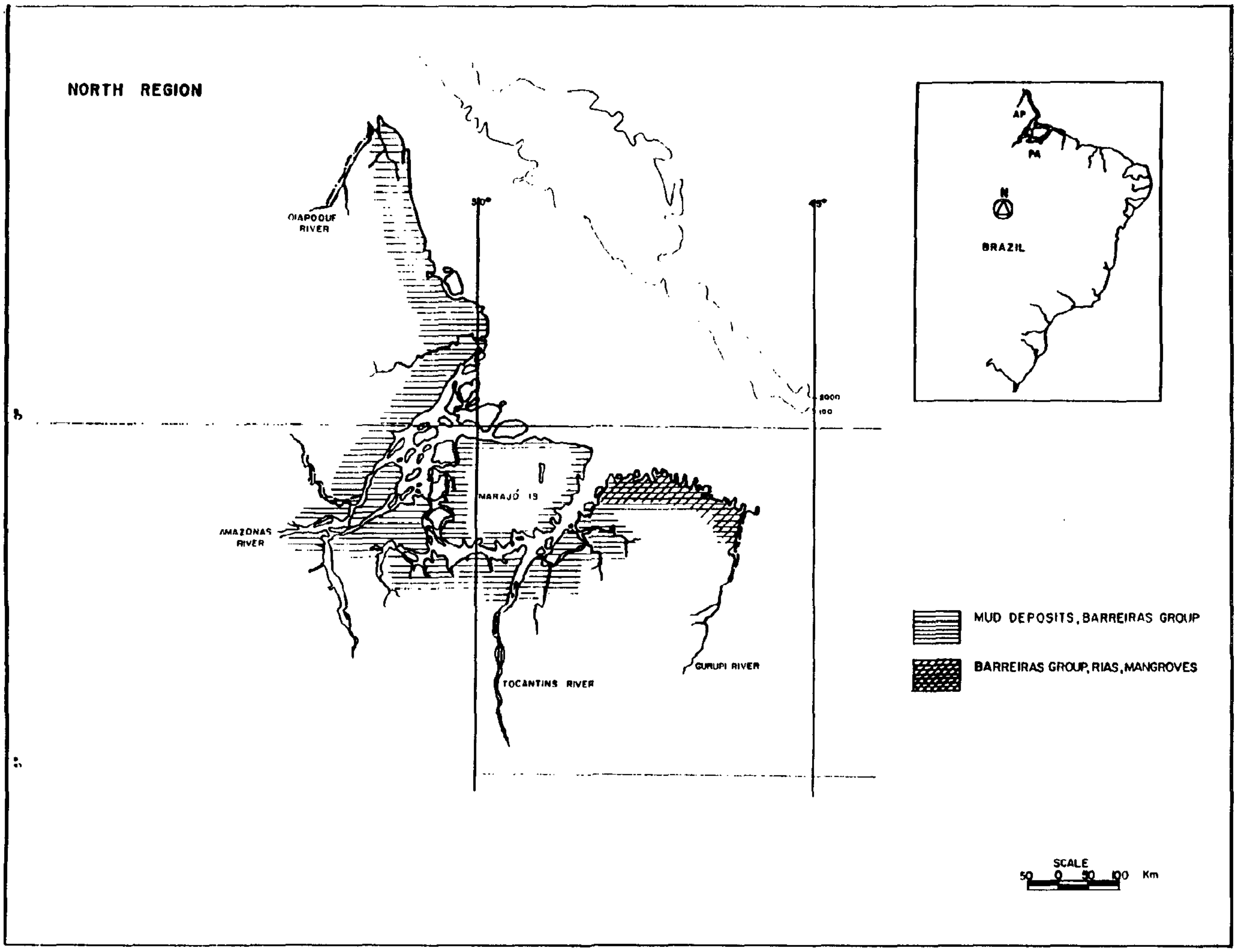


Figure A-1. Classification of main physiographic features of the Brazilian coastline: North Region.

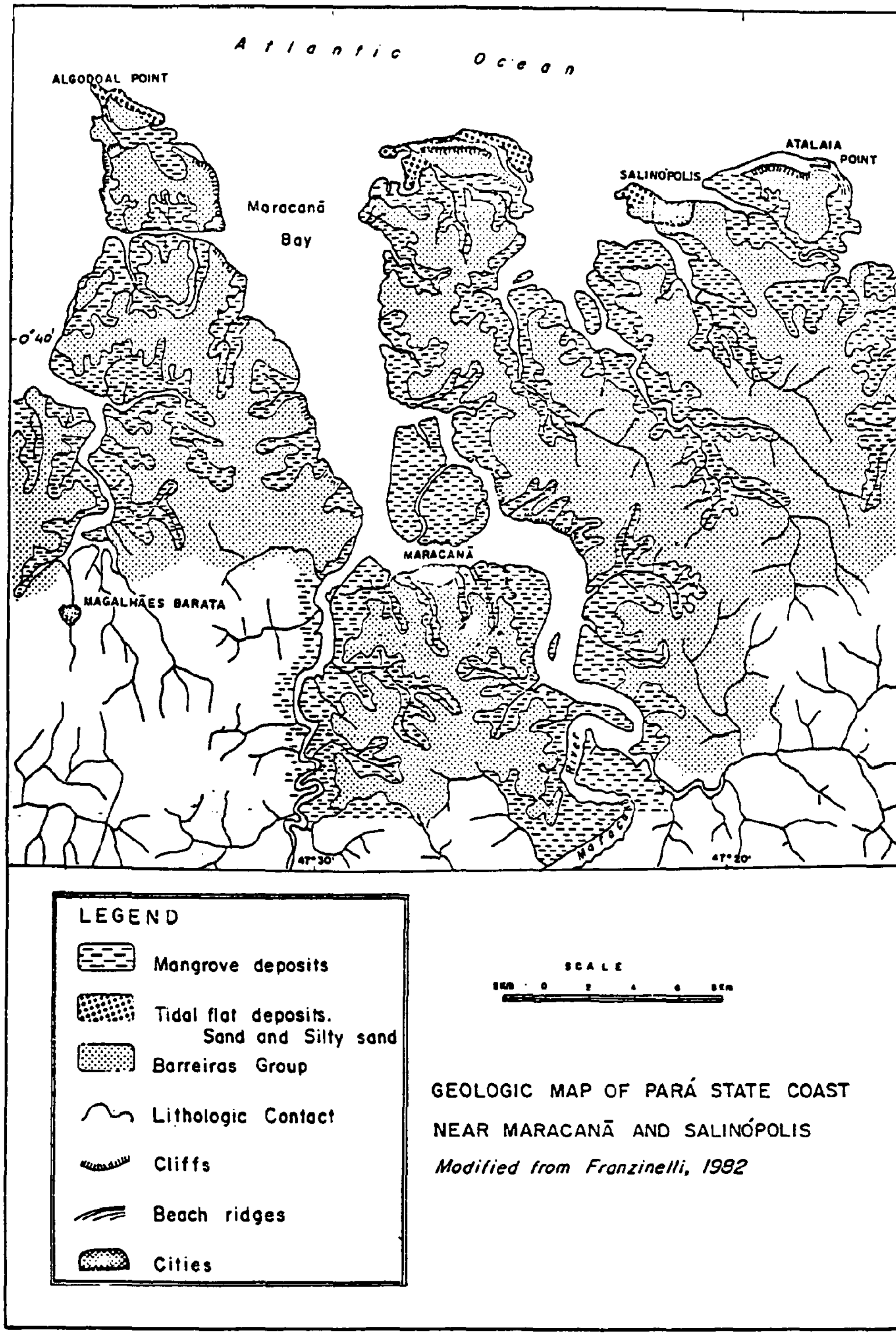


Figure A-2. Geologic map of part of the ria coast of Para, between Maracana and Salinopolis. (Frazinelli, 1982; Martins and Villwock, 1987).

For the whole region, a sea level rise will significantly increase the penetration of the tidal wave into the rivers. Flooding along the river valleys will be laterally confined by the higher areas of the Tertiary and Pleistocene sedimentary deposits. Depending on the sediment budget, low-lying alluvial areas such as in the Marajo Island at the river mouth, will be inundated.

The Northeast Region

The Northeast Region consists of nine states: Maranhao (MA), Piaui (PI), Ceara (CE), Rio Grande do Norte (RN), Paraiba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE), and Bahia (BA) (Figures A-3 and A-4).

With a length of about 2,480 km, the coast can be divided into two distinct sections. The first has a coastline 1,540 km long, roughly aligned in the east-west direction; the climate is dry and consequently extensive dune fields extend from the State of Maranhao up to Cape Calcanhar. The other section, southward from Cape Calcanhar up to the State of Bahia in the vicinity of Abrolhos plateau, has a coastline 1,940 km long, is aligned in the general north-south direction, and is subject to a humid climate.

The shelf width is narrow when compared to that of the North Region. The width of the inner shelf, roughly based on the 50-m isobath, decreases from up to 70 km, in the northern sector of the region, to only 25 km in the south, with a new enlargement to more than 100 km at the Abrolhos plateau in the southern extremity of the State of Bahia.

Deposits of the Barreiras group are typical for the whole region, as are the alignments of beach rocks ("recifes") in front of the shoreline (Silveira, 1964). The recifes frequently provide an important protection against the action of waves.

Coastal plains are generally narrow, depending on the distance of the retreat of the front scarp of the Barreiras group, but increase their extension by penetration along the lower courses of the river valleys (Nunes et al., 1981; Prates et al., 1981; Nou et al., 1983). In some places bluffs are still under the action of waves. In others, the coastal plain enlarges in front of major rivers and at the deltas of the Parnaiba River (at the border between Maranhao and Piaui), Sao Francisco River, at the border of the States of Alagoas and Sergipe, and in front of the Pardo and Jequitinhonha Rivers in the southern State of Bahia.

A large number of estuaries are found inside or in the proximity of the Todos os Santos Bay in Bahia.

As in the North Region, very few studies are available about recent coastal evolution. Marques (1987), in her study about the barrier beach in front of the Mundau-Manguaba estuarine lagoonal complex in Alagoas, showed a continuous lateral progradation of the barrier northeast from the tidal inlet during the

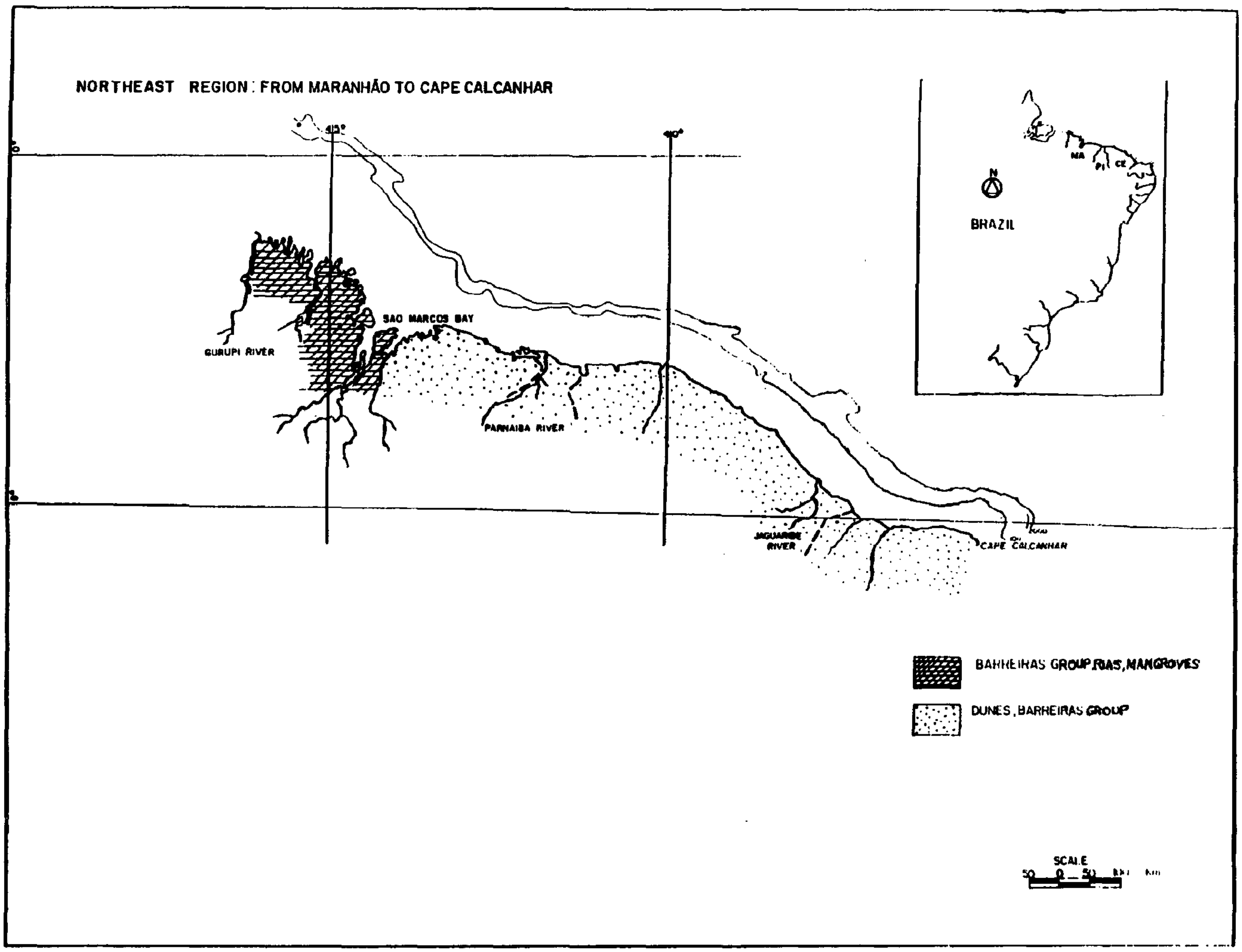


Figure A-3. Classification of main physiographic features of the Brazilian coastline: Northeast Region from Maranhao to Cape Calcanhar.

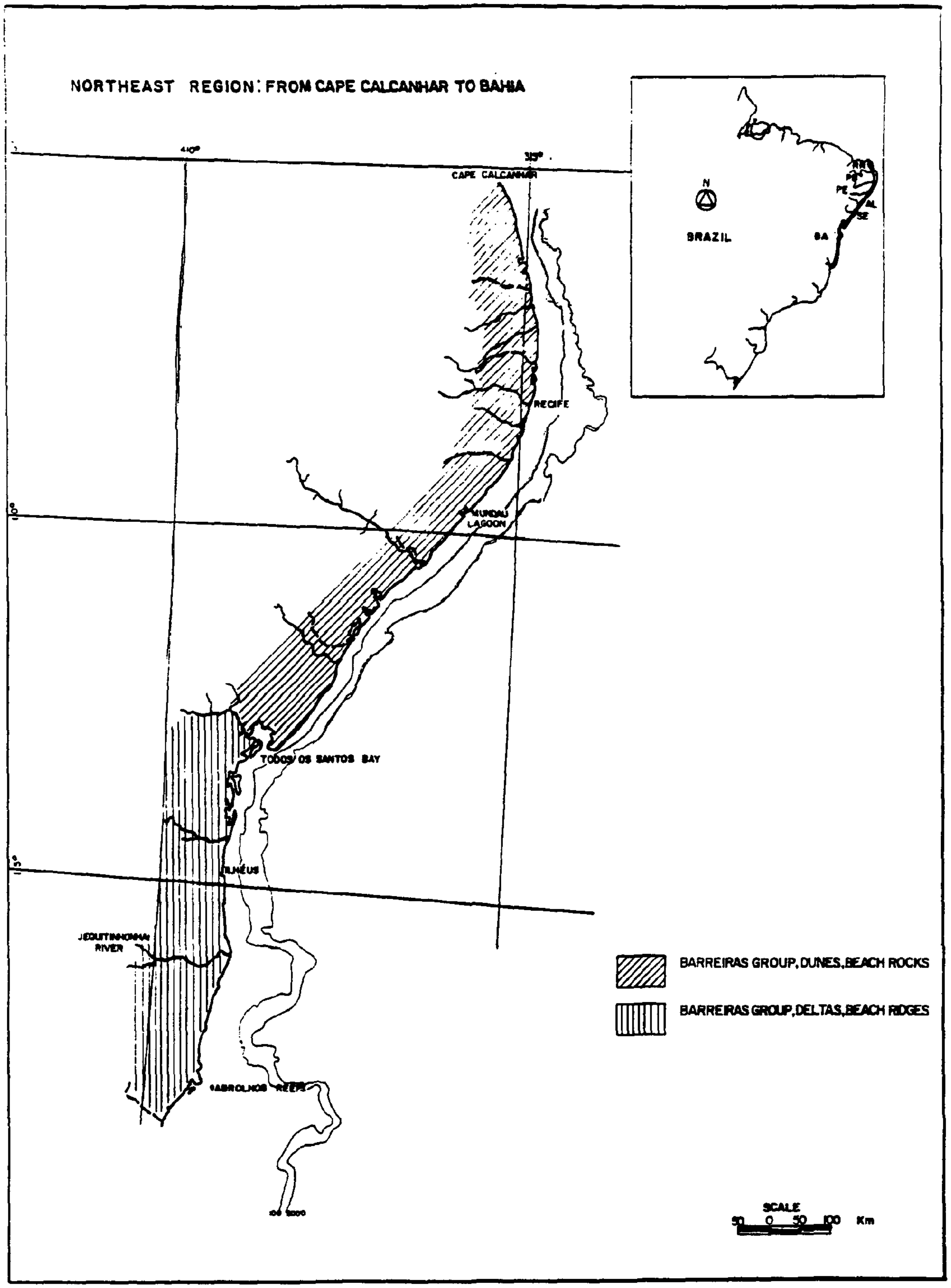


Figure A-4. Classification of main physiographic features of the Brazilian coastline: Northeast Region from Cape Calcanhar to Bahia.

period 1956 to 1984 and a net erosion, during the same period, at the southwest segment. But these changes may reflect only a local instability of a naturally unstable coastal segment and not a consequence of a sea level rise (Figure A-5).

Flooding in most of the coastal area due to sea level rise will be limited in extension by the scarps of the Barreiras group. Low-lying areas of the deltas, like the Sao Francisco Delta, may show changes in mangroves (both in area and in species of trees) and a possible limitation of the areas used for temporary cultures. A more serious problem will arise in coastal cities like Recife, Aracaju, and Maceio, where the expansion of urbanization into low-lying areas actually provokes inundations when heavy rains coincide with spring tides (Nou et al., 1983); with a 50-100 centimeter rise in sea level the same effect would occur even during neap tides. Drainage problems and inundations will probably also affect the low-lying areas of the coastal plains in the confluence of the Todos os Santos Bay in Bahia. These problems will become critical in the heavily populated city of Recife, where urbanization has expanded over the valley floor of the rivers Capibaribe and Beberibe, and where drainage problems and floodings very often occur.

Just north of the mouth of these rivers, a long and severe history of erosion has been recorded in the nearby historical town of Olinda. The causes of erosion are not completely clear yet. The area suffered subsidence in geological time. However, several engineering works -- groins, detached breakwaters, dredging -- that have been built might have accelerated the eroding process. A rise in sea level will strongly affect this area, and further problems will arise due to an intensification of erosion.

The Southeast Region

The 1,530-km-long coastline of the Southeast Region consists of the States of Espirito Santo (ES), Rio de Janeiro (RJ), and Sao Paulo (SP) (Figure A-6). Like the other regions examined, the table-like Barreiras group is still present, governing the width of the coastal plains up to the northern part of the State of Rio de Janeiro. An increase in the width of the coastal plains is due to the Rio Doce Delta in Espirito Santo State and the Paraiba do Sul Delta in the northern part of Rio de Janeiro State (Figure A-7). The adequacy of the term "delta" for both of these depositional features has been questioned by Dominguez et al. (1982), based on the argument that the progradation in front of the river mouth is a result of longshore drift of sediments derived from the inner shelf and not of fluvial sediment accumulation, as assumed by Bandeira et al. (1975) for the Doce River Delta and by Dias et al. (1979) and Dias (1981) for the Paraiba Delta. More recently, Dominguez (1989) changed his interpretation about the Doce river delta or strandplain, attributing a more significant role to the river as a sediment supplier than in his earlier model.

Southward from the Paraiba Delta, at Cape Frio, the coastline changes from northeast-southwest to an east-west direction. This stretch ends at Marambaia Island and is formed by barrier beaches, the only interruption being the rocky coast near the mouth of Guanabara Bay. The barriers may occur as either single

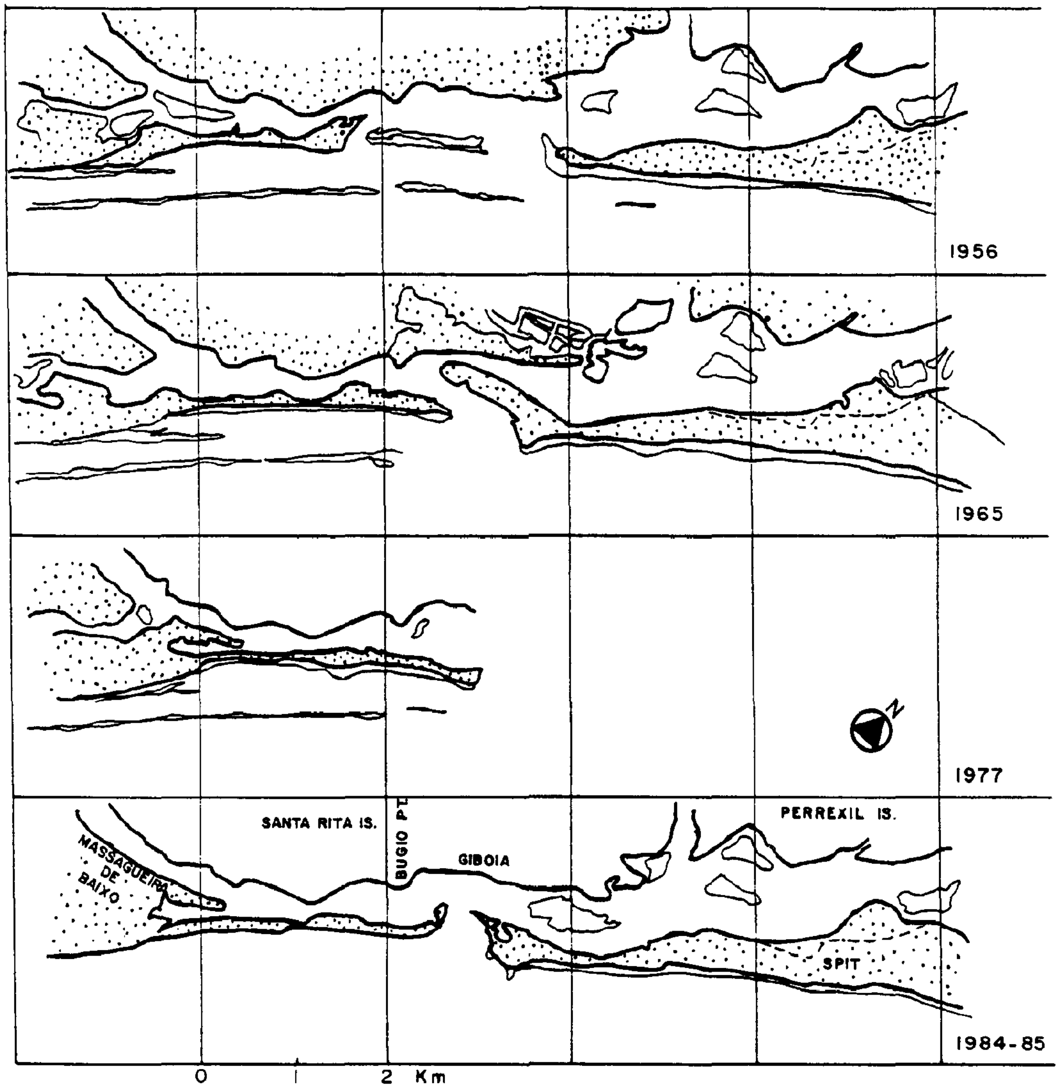


Figure A-5. Shoreline modifications of the barrier beach in front of the Mundau-Manguaba lagoonal-estuarine complex in Maceio, Alagoas (Marques, 1987).

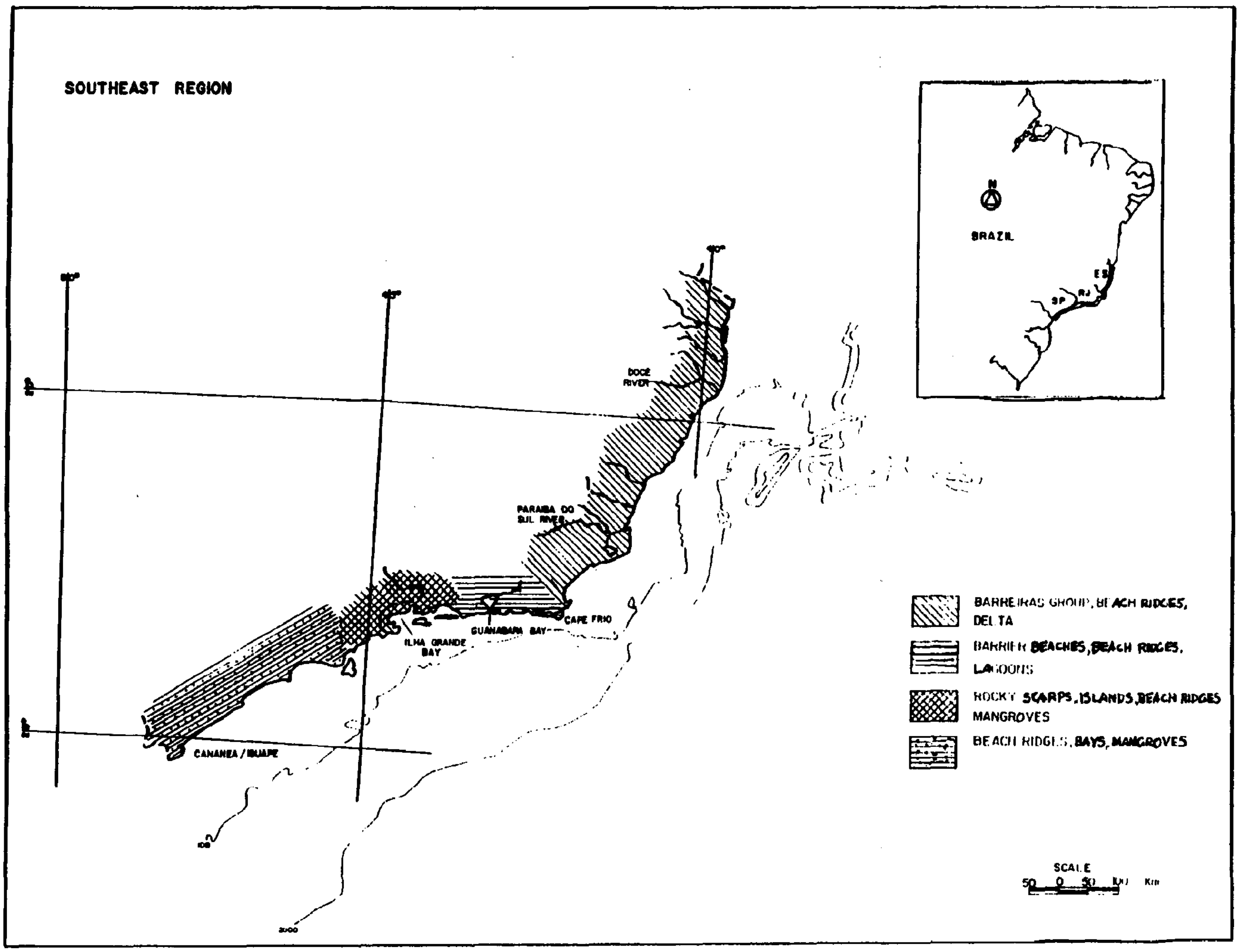
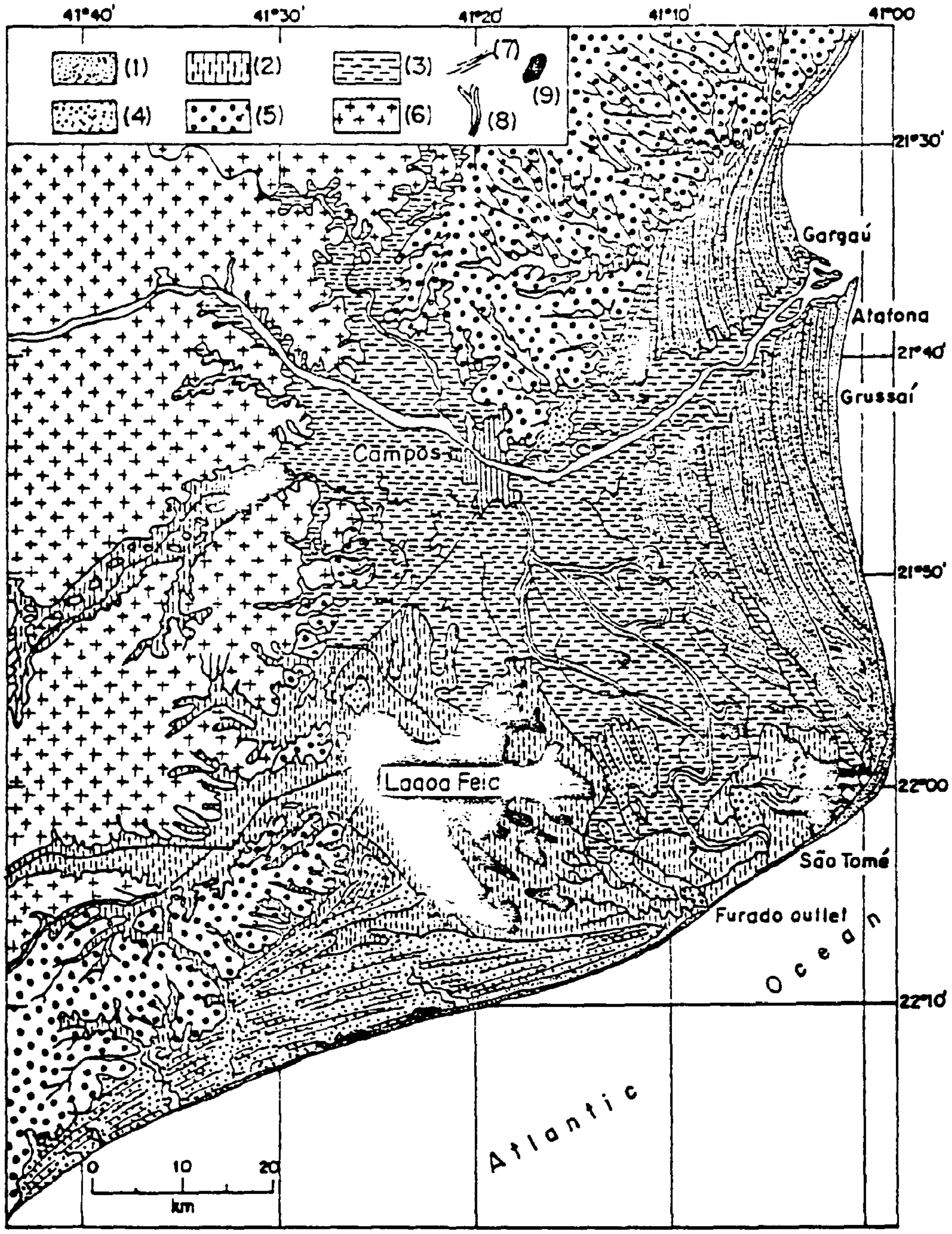


Figure A-6. Classification of main physiographic features of the Brazilian coastline: Southeast Region.



(1) Holocene marine terraces, (2) Lagoonal deposits, (3) Fluvial deposits (Intralagoonal delta), (4) Pleistocene marine terraces, (5) Barreiras Formation (Tertiary), (6) Crystalline basement (Précambrian), (7) Beach-ridges alignments, (8) Fluvial paleochannels, (9) Lakes.

Figure A-7. Geologic map of the Paraiba do Sul Delta or coastal plain. (Martin and Suguio, 1989).

or double alignment, with a sequence of coastal lagoons at their backside. Araruama is the largest of these lagoons, with its mouth near the town of Cabo Frio. The barrier beaches follow the west direction up to the bay of Sepetiba near the border with the State of Sao Paulo. From this point on, and along the whole State of Sao Paulo, the coastline returns to its northeast-southwest direction, with submergence characteristics in its northern part and emergence characteristics in the south. The transition between the drowned, indented coast, with its steep crystalline promontories, and few, narrow coastal plains, like Ubatuba and Caraguatatuba, and the emergence southern sector, with large plains up to 40 km wide (for instance, the southernmost Cananeia-Iguape plain) is very gradual. The region of Sao Sebastiao forms approximately the limit between these zones. The width of the inner shelf also follows the trend with the isobath of 50 m situated at a distance of 8 km from the coastline in front of Santos estuary and at 50 km in front of Iguape (Suguio and Martin, 1976). These authors explained that such phenomenon are due to a continental flexure where the inflexion axis strikes asymmetrically to the coastline.

The geomorphology of this region presents many diversified features (barrier beaches, pocket beaches, rocky shores, coastal lagoons, bays, estuaries) that will respond in different ways to a sea level rise. Some locations already present signs of erosion, even though human interference has been minimal.

The mouth of Paraiba do Sul River has shown strong instability in the past fifteen years, with extensive erosion of the adjacent beaches and loss of valued property (Argento, 1989). On the southern part of the delta, the coastal plain shows a sequence of ridges; at the beach face, formations of grayish black sandstone -- humic material cemented with ferruginous oxides -- have been exposed, indicating a process of erosion or retrogradation. This same process becomes also evident by the truncated configuration of coastal lagoons on the back side of transgressive barriers (Dias and Silva, 1984). Similar processes have been identified by Muehe (1984, 1989) at the barrier beaches between Cape Frio and Guanabara Bay, besides evidence of erosion along the back side of the barrier that faces Araruama Lagoon.

Another point in the State of Rio de Janeiro that may suffer from a rise in sea level is the fluvial-marine plain along the estuary of Sao Joao River, located about 200 km south of Paraiba do Sul River. At present, there is an extensive culture of rice along the valley, which uses the water from the river for irrigation purposes. Besides potential risks of flooding, the rise of sea level will cause a stronger saline intrusion, which has already been observed.

The flat areas around Guanabara Bay have flooded very often during heavy rains, especially along rivers and drainage canals. The combined effects of a rise in sea level and siltation of those canals will enhance the problem of flooding. On the other hand, because the relative sea level was 5 m higher during the Holocene than at present, not only were beach sediments deposited far from the present coastline (Amador, 1974) but the terrain also became very flat and appropriate for marine flooding of extensive areas. Similar problems should affect all low-lying areas of coastal plains and river valleys.

The South Region

This region is formed by the States of Parana (PR), Santa Catarina (SC), and Rio Grande do Sul (PS) (Figure A-8). The coastline is 1,310 km long. Along its northern portion, the coastal plains are narrow and less significant, having pocket beaches separated by rocky headlands. Paranagua Bay is the most important feature of this segment. Toward the south, the coastal plains gradually become wider, and important estuaries appear, like Guaratuba Bay (PR), the Itajai River (SC), and Laguna (SC), although along the coast of Santa Catarina, pocket beaches are very frequent.

Reaching the State of Rio Grande do Sul, though, the coastal plain widens considerably, reaching 120 km for an extension of almost 520 km, being the largest coastal plain in the country. This is where Patos Lagoon is located, which has an area of 10,000 sq. km and an average depth of 4 m, and is connected to the ocean through a single inlet at Rio Grande. The mild slope of the coastal plain extends offshore: the 50-m deep contour is about 30 km away from the beach, twice as far as in Santa Catarina.

Processes of erosion and accumulation have been reported by Angulo (1989) for the littoral of Parana, but observations of coastline changes were restricted to typically unstable areas like mouths of estuaries (a similar comment has been made already for Maceio, in the Northeast region). In Santa Catarina, the emergence of peat at the backshore near the scarp of the barrier indicates a trend of retrogradation. Tomazelli and Villwock (1989) present well-defined information about the presence of peat on the foreshore and along the base of foredunes along the beaches in Rio Grande do Sul. Erosion along the margin of Patos Lagoon is also interpreted by these authors as an indication of relative sea level rise. Due to the dominant onshore direction of local winds, a dune field tends to be built with sand removed from the beach. The erosive effects already observed might be intensified if this dune field is removed.

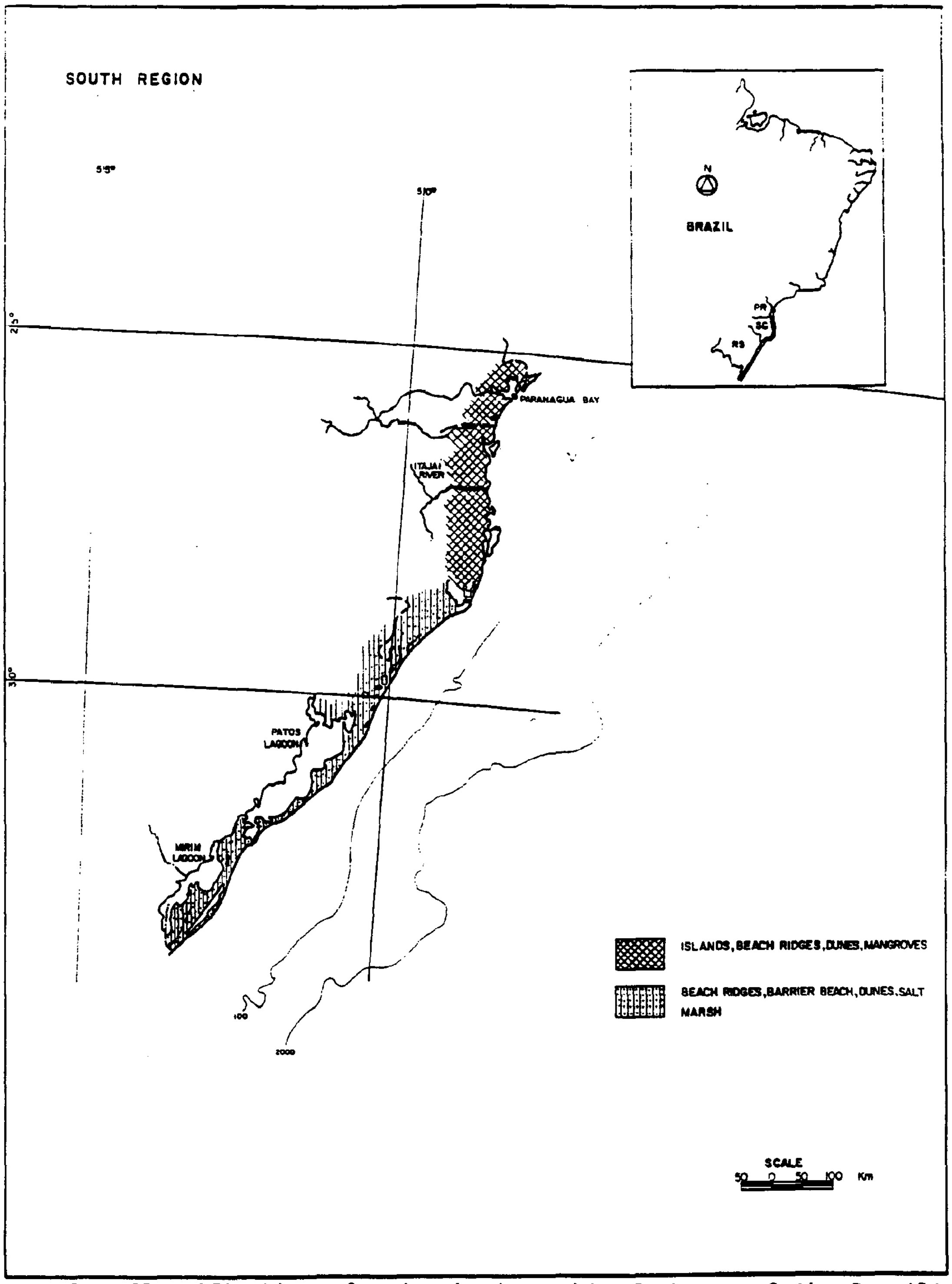


Figure A-8. Classification of main physiographic features of the Brazilian coastline: South Region.

POTENTIAL IMPACTS OF SEA LEVEL RISE ON THE GUIANA COAST: GUYANA, SURINAM, AND FRENCH GUIANA

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ABSTRACT

The northeastern coastal zone of the South American continent, known as the Guiana coast, stretches between the estuaries of the Amazon and the Orinoco Rivers and forms the coastline of Guyana, Surinam, French Guiana, and parts of Brazil and Venezuela. The coastal strip is of varying width and is below sea level at high tide in most places. As a result, extensive areas are covered with swamps, mangrove forests, and tidal and mud flats.

Early colonizers managed to establish plantations by draining the land. Because agricultural development has taken place in this zone, today over 90% of the population of Guyana, Surinam, and French Guiana live on the Guiana Coast. Therefore, most of the urban centers and communication lines are concentrated on the coastal zone in the three countries.

A rise in sea level would have serious economic and environmental consequences for the Guiana coast. The coastal stretch that is naturally protected by cheniers and shell beaches is likely to recede with the rising sea level. Much of Guyana and Surinam will be inundated, even if the sea level rises by as little as 30 cm.

Mechanisms are in place in both Guyana and Surinam to construct and maintain sea defense structures and to take emergency measures in case of breaches. But long-term plans to counter the consequences of sea level rise are nonexistent in the three countries. The governments concerned have not taken the possible threat of sea level rise seriously, and the coastal communities are mostly unaware of the possible danger.

INTRODUCTION

Along the northeastern coast of South America between the mouths of the Amazon and the Orinoco Rivers lies a 1,600-km-long, low coast dominated by swamps, mangrove forests, tidal flats, mud banks, and flat coastal plains. This

Guiana coast forms the coastline for Guyana, Surinam, French Guiana, and parts of Venezuela and Brazil.

More than 90% of the population of the Guianas live on the coastal plain. As a result, most of the urban centers, including the capitals, communication networks, and industries are concentrated there.

A rapid rise in sea level would inundate low-lying areas, erode the coastline, increase salinity of the lower courses of the rivers, disrupt coastal wetlands, and raise the water table. Although the heavy sedimentation that takes place on the Guiana coast may offset some of the erosion and wetland loss from a rapid sea level rise, it would do little to mitigate the other problems.

About 50% of the coast of Guyana is protected by sea defense structures, and provisions exist to take emergency measures in case of major breeches or failure of the sea defense system. However, the entire coast of Surinam and French Guiana, and the western portion of the Guyana coast, remain in their natural state.

PHYSICAL CHARACTERISTICS

The Coastal Plain

The coastal plain forms a distinct geomorphological region in the Guianas. It occupies only a small percentage of land in each country but is considered an important economic zone. It can be subdivided into two geomorphological regions: the young and the old coastal plains (Figure 1). The former does not rise more than 2.5 m above mean sea level and in places lies 1.5 m below high tide; the old coastal plain has an average elevation of 3 m rising to 8 m near its southern border. Both are underlain by clays of different periods.

CLIMATIC CHARACTERISTICS

The Guiana coast has a humid tropical climate with its characteristic high rainfall and high temperatures. Two distinct wet periods can be recognized in the rainfall pattern: the first lasts from mid-May to July, and the second from November to January, with the former having the most rainfall.

Marine Environment

The waves, in accordance with the wind direction, are northeasterly, and they meet the shoreline at an oblique angle. The coast may be considered as a low-moderate energy coast. Unlike the Caribbean islands, the Guiana coast is not subjected to hurricanes and storm waves. Wave energy is considerably reduced off the coast of Guiana because of the presence of fine sediments, which remain in suspension in the near coastal area. The tide is semi-diurnal and its effects are felt far inland along major rivers.

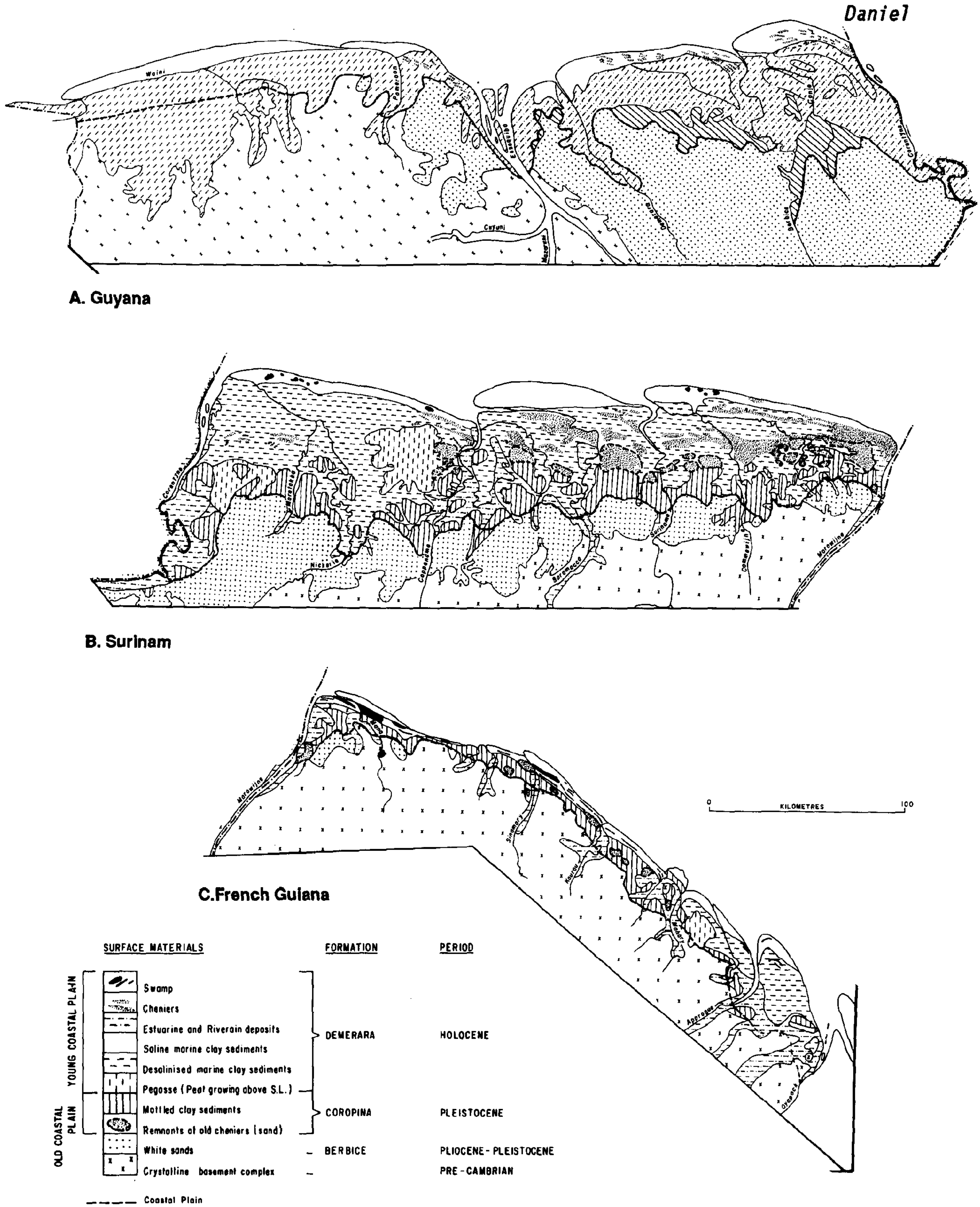

Figure 1. Geomorphology of the Guiana coast.

Sediment Transportation and Deposition

It is estimated that 100 million tons of sediment are transported westward every year by the ocean currents. A large proportion is kept in suspension by the changing tidal conditions, waves, and currents.

When the concentration of sediment in the water exceeds a critical level, it flocculates to form a coherent mass of viscous mud known as sling mud, and settles to form mudflats on the shoreline and mudshoals in the offshore region (NEDECO, 1972).

The mudshoals influence the development of the coastline of the Guianas. The coast that lies directly opposite the mudshoal is protected from wave action because the viscous nature of the mud damps out the waves. This coast may be designated as an accretionary coast. A coast that lies directly opposite a trough (between two mudshoals) is subject to wave erosion and may be designated as an erosional coast (Augustinus, 1978). It has been shown that the mud shoals migrate westward at an average rate of 125 m/month and the recurrence interval of a mudshoal is approximately 30 years (NEDECO, 1972). Thus, at any one point, the coast is subjected to either accretion or erosion.

Accretionary Coasts

An accretionary coast begins as a tidal flat at the landward end of a shoal and can extend as far as 0.8 km. As soon as the tidal flat begins to emerge above the high-water level, mangrove establishes itself and stabilizes the flat. The mud that emerges above the high-water level is subjected to physical, chemical, and biological ripening, leading to soil formation favoring other vegetation types in addition to mangrove.

Sand accretionary coasts are rare, and where they do occur, they are not as extensive as the clay accretionary coasts. Cheniers are extensively developed on the Guiana coast. Stretches of beaches entirely composed of shell fragments occur in several places along the northwestern coast of Guyana.

Erosional Coasts

Erosional coasts lie opposite a trough (between two mudshoals). When the eastern end of a mudshoal is eroded, the coast directly opposite it increasingly comes under wave action. Erosion on the shoreline begins at the edge of the mud flat. As the mud flat is gradually eroded, waves are able to come closer to the coast. The removal of mud exposes the root system of the mangrove to wave action, which eventually destroys the vegetation. Since the seedlings of the mangrove are not adapted to development under continuous inundation they are not replenished. Once mangrove is destroyed, erosion of the coast proceeds unhindered.

Vegetation and Fauna

Mangrove vegetation fringes the shoreline of the Guiana coast. Either a herbaceous swamp or a swamp forest occurs behind the mangrove. The largest swamp is located between the Pomoroon and Orinoco Rivers.

The wetlands on the Guiana coast have an exotic variety of animals, birds, insects, and marine life. The northwest coast is one of the breeding grounds for the scarlet ibis and many other birds. In the nearshore region, several shrimp species and two species of crabs are common. The northwestern coast is the annual nesting grounds for at least four types of giant sea turtles considered to be endangered species: greens, hawksbills, Ridleys, and leatherbacks. In the numerous canals and drainage ditches, freshwater fish abound.

Groundwater Resources

The geologic formation of the Guiana Shield favors the occurrence of groundwater on the coastal plain. More than 90% of the potable water on the Guyana coast is obtained from two aquifers that occur at two levels. The groundwater recharge area is the exposed portion of the white sand that underlies the rolling hills south of the coastal plain.

AGRICULTURAL AND ECONOMIC DEVELOPMENT

Agriculture

The predominant economic activity on the Guiana coast is agriculture, followed by fishing. The coastal belt has favorable soil and climate for lowland crops, such as sugarcane and rice. Among the three countries, Guyana has the most cultivated land (Figure 2). In both Guyana and Surinam, almost all agricultural activities are confined to the coastal belt. Apart from market gardening near large cities, agriculture is insignificant in French Guiana.

Agriculture is the major source of employment, economic growth, and foreign exchange in the Guyanese economy (Table 1). Most of the irrigation and land development programs are geared to two major crops, sugarcane and rice. Since fertile agricultural land is located very close to the coast, large sums of funds are allocated for drainage, irrigation, and sea defense works.

The land use pattern on the coastal belt of Surinam is similar to that of Guyana, but in Surinam agriculture contributes only 9.1% of the Gross Domestic Product (GDP).

In French Guiana, the main occupation on the coast is fishing, which constitutes 59.3% of all exports. Very few food crops are produced in French Guiana. Being an overseas territory of France, most of its food is imported.

POPULATION DISTRIBUTION

Over 90% of the population of the three countries live on the Guiana coast (Table 2). The capitals are also located on the coast, as are major towns and urban centers.

The main communication lines of the three countries are along the coast. Since most of the rivers on the Guiana Shield flow in a south to north direction,

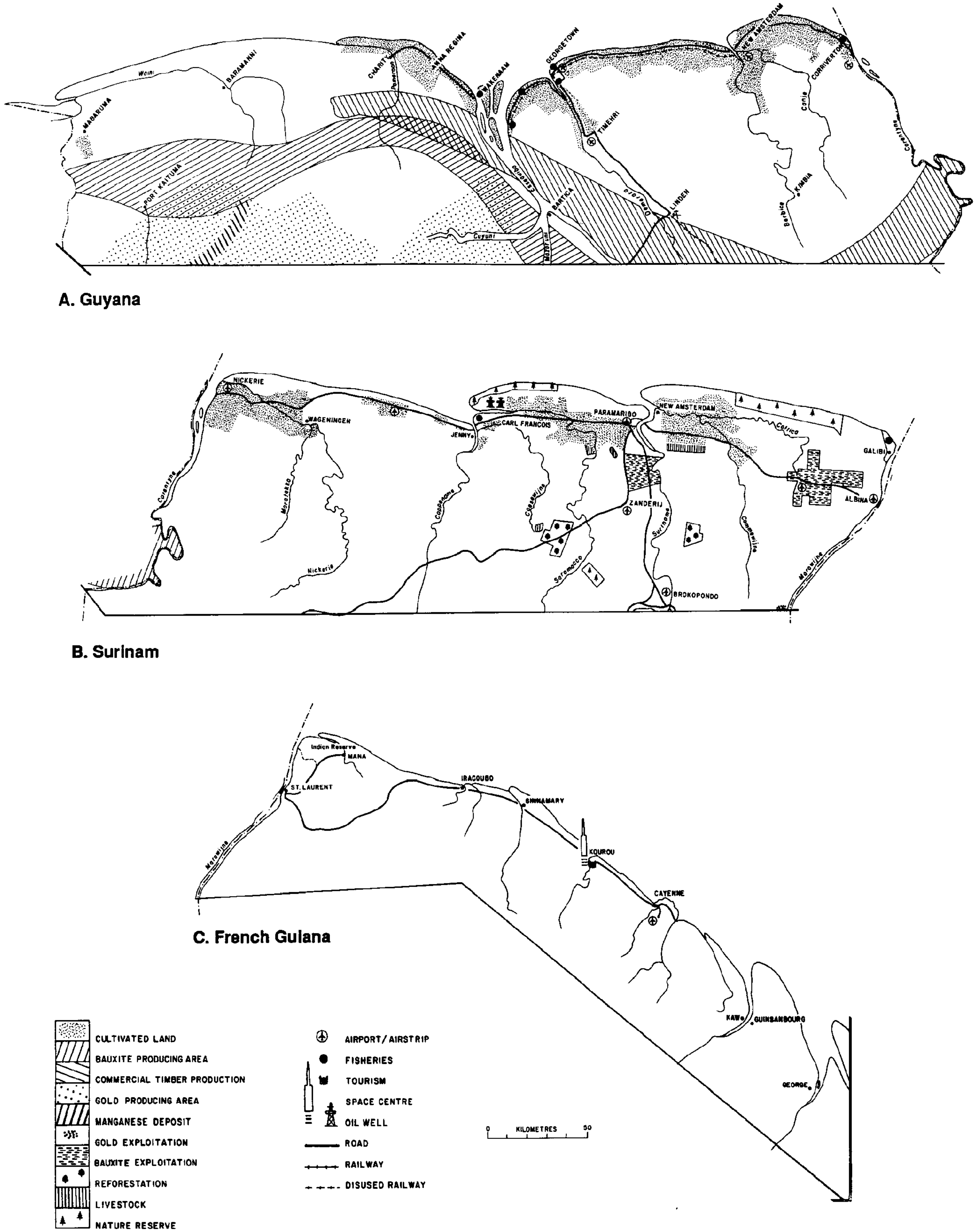

Figure 2. Land use of the Guiana coast.

Table 1. Agricultural Development

Component	Guyana	Surinam	French Guiana
Total population	756,000	354,860	85,700
Area (km^2)	214,969	163,265	90,000
Agriculture contribution to GDP(%)	29.0	9.1	N.A.
Total cultivated land (ha)	242,817	36,000	3,000
Irrigated land (ha)	161,818	20,000	N.A.
Sugarcane (metric tons)	3,520,000	150,000	5,000
Rice (metric tons)	300,000	270,000	7,790
Fish catches	27,600	3,600	1,400

N.A. = Not available.

ferry service and other forms of river transportation are provided at major river crossings.

With the exception of the bauxite processing industry in Linden (Guyana) and Brokopondo (Surinam), all the major industries and factories are located on the coastal belt, particularly in the capitals and port cities.

EFFECTS OF SEA LEVEL RISE

Methodology

To estimate erosion from 50-, 100-, and 200-cm sea level rise scenarios, we used the Bruun Rule:

$$S = \frac{al}{h}$$

where S = approximation of shoreline movement, a = rise in sea level, h = maximum depth of exchange of material between the nearshore and the offshore, and l = length of the profile of exchange.

On the Guiana coast, the sea bottom profile in the nearshore zone is shaped by the wave action to a depth of 2 meters (NEDECO, 1972). The orbital motion of waves is reduced to an almost horizontal to-and-fro movement. Wave velocity

Table 2. Population of Cities/Towns Located on the Guiana Coast

City/Town	Population	Distance from the coast (km)
Georgetown[a]	56,095	0
New Amsterdam	19,287	8
Rose Hall	3,167	0
Corriverton	18,617	0
Paramaribo (1987)	68,617	7.5
Nickerie	8,000	11
Cayenne (1988)	19,688	0
St. Laurent	3,486	27

[a]Unless otherwise noted all values are for 1981.

exceeds 0.70 m/sec, a critical velocity that is required to initiate erosion on the sea bottom (Augustinus, 1978). Therefore for convenience, the maximum depth of exchange of material between the nearshore and offshore (h) is taken as 2 meters.

The average distance between the 2-meter bathymetry and the shoreline is about 300 meters, but it varies according to the position of the mudshoals. To determine the length of the profile of exchange (l), distances between the 2-meter bathymetry and the shoreline were measured at intervals of 20 kilometers along the coastline on the map (scale 1:1,000,000).

RESULTS

Scenarios

Projected coastline positions for a 50-, 100- and 200-cm rise in sea level are shown in Figure 3(A-C). The future coastline shown here is highly generalized because of the small scale (1:1,000,000) of the map. Based on the EPA study of sea level rise (Titus, 1985), two scenarios, the mid-range high and mid-range low -- henceforth simply referred to as high and low, respectively -- were selected. Measurements taken from the map were compiled under the two scenarios to show the future rate of coastal erosion. They were also compared with both short-term and long-term historical rates of erosion (Table 3). The latest available maps were published in 1980. Therefore, 1980 was considered the baseline.

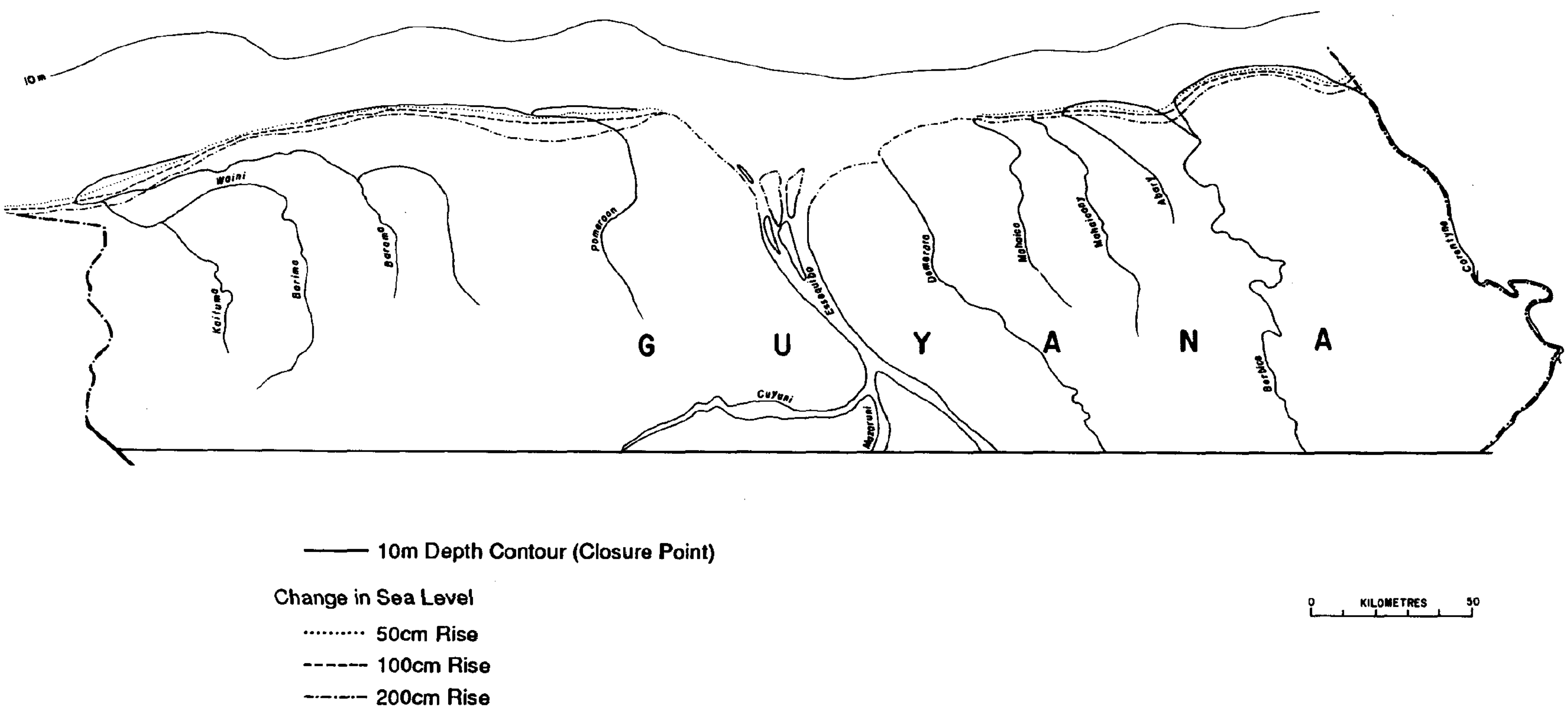

Figure 3A. Scenarios of sea level rise for Guyana.

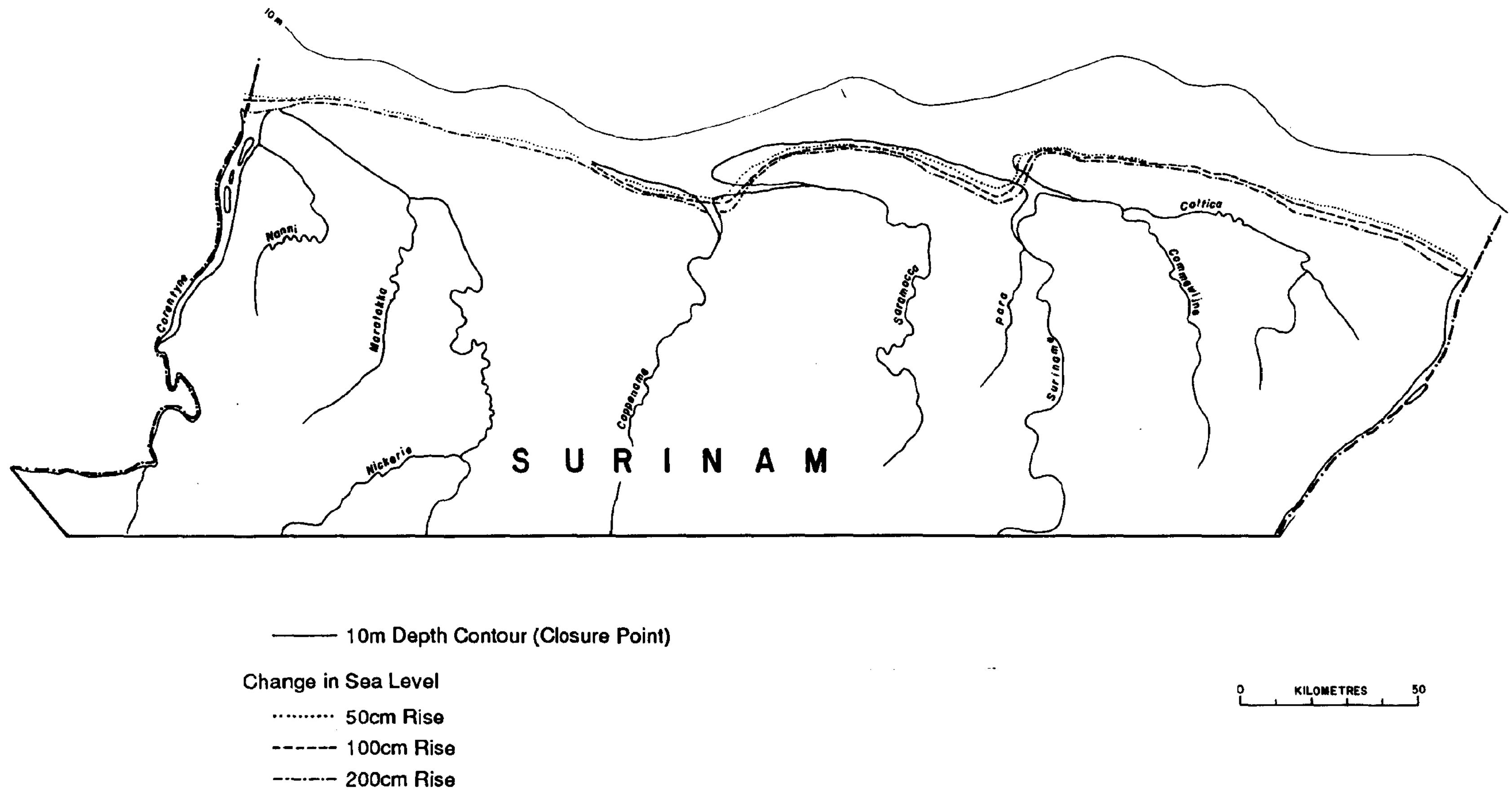

Figure 3B. Scenarios of sea level rise for Surinam.

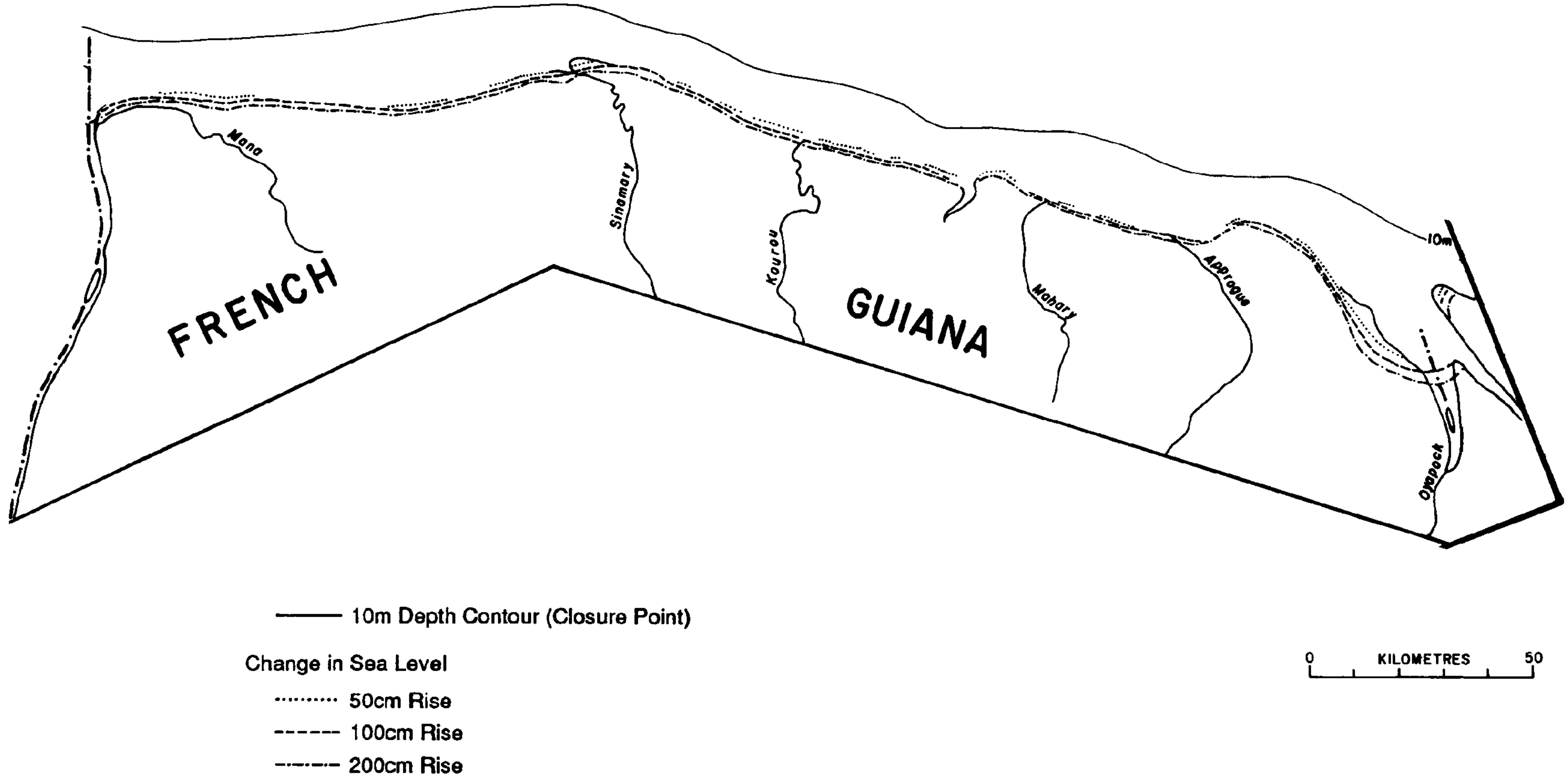

Figure 3C. Scenarios of sea level rise for French Guiana.

Table 3. Projected Recession on the Guiana Coast (Meters of shoreline retreat relative to its current position)

Coasts	50 cm Total shoreline retreat (m)	100 cm Total shoreline retreat (m)	200 cm Total shoreline retreat (m)	Historical records: Mid-term historical record (m/y) 1942-49	Historical records: Long-term historical record (shill) 1942-66	Historical records: Historical record (shill) 1830-1980
Wainini-Pomoroon	1200	2400	4800			
Pomoroon-Essequibo Estuary	2500	5200	10300	12	10-15	
Essequibo Estuary*	---------------sea defense-------------------			5		
Essequibo-Demerara*	---------------sea defense-------------------			5		
Demerara-Mahaica*	---------------sea defense-------------------			10-20		
Mahaica-Berbice	1100	2200	4300	28	15-25	6.2
Berbice-Corentyne	900	1800	3600	27	8-15	
Corentyne-Coppename	350	700	1400	20		
Coppename-Surinam	1200	2300	4600	4	15	
Surinam-Maroni	900	1800	3600			
Maroni-Sinnemary	500	1100	2200			
Sinnemary-Cayenne	400	900	1750			
Cayenne-Oyapock	600	1200	2400			

* We assume no erosion in areas that already have sea defenses.

Since the erosional environment on the coast varies significantly, each coastal segment between the major rivers is treated separately. A 50-cm scenario forecast would affect almost the entire coast. Further rise in sea level would only exacerbate the situation. Therefore, the scenario for a 50-cm rise in sea level is considered in detail.

50-cm Scenario

For a 50-cm rise in sea level, it is estimated that the wetland loss would be highest along the northwestern coast of Guyana. Several factors lead to this conclusion. The tidal range is very low in this area, which implies that existing wetlands are at low elevations. The area is also very flat and has many water courses. Above all, the area is subject to subsidence. Despite the high rate of peat growth and sedimentation, until recently the relative rate of sea level has been rising in the area (Brinkman and Pons, 1968).

Being sparsely populated with little or no development or infrastructure, the effects of sea level rise would be minimal compared to the densely populated coasts. The wetlands would simply migrate landward, as the coastland is very low and occupies a large area.

Saltwater intrusion would also disrupt the swamps since they lie at the same elevation as the mangrove. A rise in the water table would convert most of the low-lying swamps to brackish, open-water environments.

The estuaries generally have maintained a fairly stable shoreline on the Guiana coast (NEDECO, 1972). The estuarine areas receive much more sediment than the coasts. Erosion is balanced by sedimentation on the larger islands in the estuary (Daniel, 1984). However, the estuarine coasts facing the northeastern direction would be affected by the increased wave velocity when sea level rises to 50 cm.

Wetland loss would be greater along the coast where sea defenses exist. With the erosion of the mangrove and the tidal flats, large waves would be able to approach the seawall more frequently, thereby increasing the pressure on the seawall and increasing the incidents of overtopping. Laboratory studies have indicated that if the sea level rises by as little as 30 cm, overtopping would increase threefold (NEDECO, 1972). Saltwater intrusion in the rivers and creeks is also likely to increase with rising sea level.

Western Surinam, particularly the area adjacent to the mouth of the Corentyne River, has development similar to the eastern coast of Guyana. Rice cultivation is extensive and, with improvement of drainage and irrigation, is expanding. Several acres of swamps have been drained and converted to rice cultivation.

Most of the urban and agricultural development in Surinam is located on a chain of cheniers that occurs farther inland. The vast swamp that exists between the cheniers and the coast is undisturbed. Furthermore, several hectares of land on the coast are preserved as nature reserves. Therefore higher sea levels would simply cause the wetland to migrate inland.

In French Guiana, a 50-cm rise in sea level implies a very low erosion rate. This area experienced a slight uplift in the past (Brinkman and Pons, 1968). A few islands that lie in the offshore area are underlain by resistant crystalline basement rocks. Since the extent of the lowland is limited by the rapidly rising land southward, wetland loss would be proportionately higher on this coast than elsewhere. Initial sea level rise is likely to affect only the mangrove-fringed coast. Other problems associated with sea level rise, such as higher water table and increased salinity in the surface and groundwater, can also be expected, although economic loss is not likely to be significant.

A slightly higher erosion rate is forecast for the coast east of Cayenne, an area also subject to subsidence (Brinkman and Pons, 1968). If the subsidence continues, erosion is likely to be greater. Because of sparse settlements in the region, very little economic development has taken place.

100-cm Scenario

A 100-cm rise in sea level for a high scenario would occur by the year 2062 according to the EPA estimates, and a low scenario as interpolated from the EPA estimate would occur by the year 2080. On the northwestern coast of Guyana, further encroachment of swamps by mangrove vegetation can be expected.

Total land loss would be great (over 5,000 m). Along the eastern part of the Guyana coast and parts of Surinam coast, land loss would be considerable (over 2,000 m) and much farmland would be affected.

The area most affected would invariably be the coast that is protected, unless foreshore erosion is prevented. Mangrove in the foreshore area in front of the sea defense structures will be completely wiped out by the rising sea level. Georgetown, a city that is well fortified against sea erosion, is likely to come under increasing pressure as the sea level rises.

200-cm Scenario

A 200-cm rise in sea level for a high scenario would occur by the year 2095 and for a low scenario in 220 years' time, as interpolated from the EPA estimates. The effects of a sea level rise of this magnitude are difficult to determine at this time. On a few unprotected coasts, strips of land up to a kilometer wide would be permanently inundated, forcing the mangrove to migrate landward, and swamp vegetation would be drastically changed. The lower courses of several rivers that flow parallel to the coast would be altered as the land separating the river channels from the coast is eroded away. Urban development and roadways previously located on the unprotected sections of the coast would have been relocated on the old coastal plain.

Major cities and towns protected against sea erosion would have embarked on a beach fill program, and perhaps a few kilometers of breakwater would have been built, but the costs of such programs would be prohibitively high. Increasing problems in sewage disposal, stormwater disposal, rising water table, and saltwater intrusion in the cities would be enormous. The effects of sea level rise described previously would be exacerbated. Some coastal settlements have already experienced some of these effects, although not necessarily due to rising sea level.

Sedimentation along the coast may partially offset the effects of wetland loss, but sedimentation occurs unevenly along the coast and is influenced by a cyclic pattern, resulting in net decrease of land area. The scenarios forecast in this study do not take into consideration the possible effects of sedimentation. Calmer sea conditions have caused heavy sedimentation on the Guiana coast in the past. Furthermore, at the mouth of the Amazon River, suspended solids increase as much as fivefold during the wet period compared with the dry period (Gibbs, 1967). Thus, an increase in discharge in the Amazon system through increased rainfall or increased deforestation and runoff could supply more sediments.

PAST TRENDS IN RECESSION

Contradictory views have been expressed on the severity of erosion on the Guiana coast. NEDECO (1972) concluded that there had been a net erosion on the Guiana coast. On the other hand, the Hydraulics Research Station (HRS) at Wallingford refuted this claim. In a recent study, Augustinus and Mees (1984) claimed that the coast of Guiana has been receding.

Based on the positions of cheniers, NEDECO (1972) calculated that the coast of Guyana was receding at the rate of 20 m/year and the Surinam coast was receding at the rate of 12 m/year between 1947/48 and 1957, and 8.5 m/year between the years 1957 and 1966. Augustinus and Mees (1982) also observed that on the Surinam coast, erosion has diminished and accretion has taken place. On the whole, recession has averaged 10-30 m/year on the Guiana coast. NEDECO (1972) observed that with the rise of sea level in the past century, the 10-30 m/year historical rate of erosion has accelerated in recent years. Various rates of erosion calculated by NEDECO are given in Table 3.

Historical records also show that the shore has advanced along some coasts. For example, at Pt. Isere (French Guiana) and Totness (Surinam), rapid accretion has taken place.

Seawalls do not always prevent erosion. Although the coast may appear visibly stabilized after the construction of a seawall, erosion can continue in the foreshore area. NEDECO demonstrated that the foreshore area is oversteepened where sea defense structures exist. Augustinus and Mees (1984) attributed the receding shoreline in Guyana to the lack of mangrove development.

Seawalls without adequate toe slope protection are particularly prone to oversteepening of the foreshore and the eventual collapse of the seawall itself. This happened in Clonbrook near the Mahaica River mouth, where a 152-meter section of seawall sank more than 0.6 meters after the foundation collapsed into the sea (Starbroek News, 1989a).

RESPONSES

Guyana

In Guyana, settlement has meant a constant battle against the sea. The settlers built artificial dams and sluice gates between the naturally occurring cheniers to form a defense against erosion.

Because of the complexity of the coastal processes and their effect on the low-lying areas for the past four decades, successive governments in Guyana have sought the help of international consultants to study the coast. Two such consultants, NEDECO and HRS, made in-depth studies of the coastal problems. The former also studied Surinam's coastal problems. The two consultants perceived the coastal problems differently and suggested conflicting strategies (Daniel, 1988).

NEDECO's model for the Guiana coast predicted a 30-year cycle of erosion and accretion with a net land loss of 10-30 meters annually. They observed that strengthening the seawall at the present site would not help, because the accelerated erosion in the foreshore region would eventually undermine the seawall. They recommended a seawall of a different design for the priority areas, such as Georgetown and its environs. The priority areas were determined on the basis of a cost-benefit analysis. In the low-priority areas, such as rural areas, a new seawall several meters inland from the present sea defense system was suggested. This simply means abandoning several acres of valuable agricultural land fronting the coast.

Based on economic, statistical, and historical data, HRS suggested that Guyana should be prepared to respond to emergencies rather than build a strong sea defense system and supported the present policy of strengthening the sea defense as and when necessary.

Comparing the two reports, it is clear that NEDECO'S suggestions are valid in light of the accelerated sea level rise. HRS's report is based on more conservative estimates and does not take into consideration the possibility of future sea level rise.

The seawall has to be considerably strengthened and raised to counter the effect of rising sea level. Other defensive measures would include increasing the toe slope on the seaward side and systematic beach filling. On some vulnerable coasts these measures have already been taken. The present height and width of seawalls is determined according to the cost factor. Overtopping, even at present levels, is not desirable, but because of the high costs, they are so designed. Raising the seawall by as little as 30 cm would increase the cost so exorbitantly that a country like Guyana could ill afford it.

A plan proposed by NEDECO (1972) to build a breakwater to the city's coastline may have to be implemented. A beach fill scheme would also lessen the problem.

Disposal of sewage in densely populated urban centers would pose severe problems when the water table rises along with the rising sea level. At present, a majority of houses are equipped with septic tanks. A rise in the water table would render most of them useless, unless drainage is drastically improved.

In the eastern part of Guyana, where most of the agricultural land is located, a well-integrated plan will have to be implemented to counter the effects of sea level rise. Sections of seawall will have to be rehabilitated and drainage facilities improved.

At present, Guyana is equipped to take emergency measures in the event of breaches in the sea defense system. The Hydraulics Division of the Ministry of Agriculture is responsible for the maintenance of the sea defense system. It can obtain resources from the government and the private sector without legislative approval to incur expenses under "force account" to repair seawalls and contain flow whenever necessary.

Routine surveillance and maintenance work is carried out by the regional councils, but they do not carry out major repairs. Increasing problems associated with shortages of manpower, materials, machinery, and funds have prompted the government to reconsider centralization of sea defense.

Although the government is prepared to take emergency measures for sea defense, a rapid sea level rise in the future and its potential impact are not envisaged by the engineers. The problem of coastal erosion is perceived simply as a cycle of erosion and accretion associated with the movement of mudshoals in the nearshore region.

The Ministry of Housing, which regulates land use and implements housing policies, does not restrict the construction of buildings near the seawall. In Georgetown, some houses are less than 15 meters from the seawall. Major government and private housing developments are located close to the seawall in Enterprise, Nuitenzuil, Success, Lusignan, and along many parts of the coast. The Ministry does not perceive the possible sea level rise to be an immediate threat and has no policies to curb the construction of buildings close to the seawall.

Similarly, the Guyana Water Authority (GUYWA), which controls the distribution of potable water in Guyana, does not have a policy to deal with the impact of future sea level rise on water resources. Even records of water quality, transmissivity, recharge rates, and discharge rates of each well site are not kept. Such data are obtained only when major surveys are carried out. The last major survey was carried out by Worts in 1958.

Mining of sand from the cheniers is prohibited by law, a measure that would prevent accelerated erosion. Similarly, several species of animals and birds that take sanctuary in the coastal swamps and forests are included among the endangered species specified in the Guyana Wild Life Preservation Act. The recently formed Guyana Agency for Health Education and Food Policy is required to review all development projects and submit environmental impact reports. Its function is similar to that of the U.S. Environmental Protection Agency. Despite all of these developments, there is no coherent policy to take countermeasures against the possible rise of sea level in the future.

Coastal dwellers who live in areas that are repeatedly affected by erosion and flooding are fully aware of the implications of a failure in the sea defense system, but are unable to perceive the larger problem of sea level rise because of lack of information. Recently, the possible threat of sea level rise and its possible consequences were mentioned at two regional conferences held in Guyana. The Commonwealth Secretariat also has completed a study on Guyana's coast and has warned the government of the possible consequences of sea level rise. These recent developments have helped the government to perceive more clearly the problem of sea level rise.

Surinam

Surinam's land development on the coast has followed a pattern similar to that of Guyana. Most of its agricultural land is restricted to the coastal plain. But unlike Guyana, it is not close to the coastline. Therefore, extensive flood control and sea defense were unnecessary. In addition, Surinam's coast is fairly stable, and coastal erosion is not as acute as on the coast of Guyana.

The western Surinam coast, east of the Corentyne River where a large area is under rice cultivation, is considered a stable area. The small farmers who hold less then 4 hectares of land are mostly located along the rivers in Comowijne and Surinam. Therefore, farmers in Surinam do not encounter erosion and flooding as frequently as their Guyanese counterparts. They are not used to perceiving the sea as a threat. However, an increase in sea level may cause the rivers to overflow and damage low-lying rice farms.

Because large areas along the coast have been preserved as nature reserves and Paramaribo is located several kilometers from the coast, the Surinamese do not seriously consider the effects of sea level rise. Nevertheless, the administration in Surinam commissioned NEDECO (1968) to study erosion along the coast. NEDECO later conducted a more elaborate survey of the entire Guiana coast (1972).

Surinam follows a vigorous environmental policy. Several organizations in Surinam have carried out joint surveys with their Dutch counterparts on various aspects of the environment. The Soil Survey Department of the Ministry of Natural Resources has carried out research in collaboration with the Soil Survey Laboratory of Wageningen, the Netherlands, on soil and erosion along the coast. The Dutch navy has conducted hydrographic surveys off the coast of Surinam and a Dutch engineering firm has been dredging the rivers frequently. The International Maritime Organization (IMO) has also been conducting studies in Surinam waters, as well as in Guyana and French Guiana. The Department of Lands and Surveys and Aerial Photography has compiled maps of the coastal area based on aerial photographs taken at regular intervals, and the Ministry of Agriculture and Fisheries and the Department of Surveys of Waterways and Water Courses have also carried out several hydrologic studies.

Since the coastal problem in Surinam is not as acute as in Guyana, there is hardly any awareness among the coastal dwellers about the possible danger of sea level rise. Because Surinam collaborates closely with several Dutch organizations, it would not be difficult for the government to take countermeasures against the impacts of sea level rise when the need arises.

French Guiana

Economically, French Guiana would be least affected by a future rise in sea level. But physically it could suffer extensive losses of wetland areas.

The coastal area is included in the Cayenne arrondissement (district) according to administrative divisions. It is subdivided into 14 communes, the smallest French division. Each commune is no more than a village with basic facilities, such as running water. Most decisions are made in Cayenne, if not in Paris. Being an Overseas Department of France, French Guiana is totally dependent on the metropole. Modern ideas on the environment, greenhouse effect, future rise in sea level, etc., hardly trickle down to Cayenne. It still remains in its colonial lassitude. The only modern development has been the construction of a space center at Korou.

Few studies of the environment have been carried out in French Guiana. Studies conducted along the Guiana coast by international consulting firms have included the offshore region of French Guiana. The French navy also has conducted regular hydrographic surveys off the coast of French Guiana. Any long-term plan of action to counter the effects of sea level rise would have to originate from France. Unless urban centers along the coast are seriously threatened, responses from the administration in French Guiana are unlikely.

CONCLUSION

A rise in sea level, predicted as a result of global warming processes, would severely affect the low-lying areas of the Guiana coast. They would be affected by wetland losses, coastal erosion, a rise in the water table, and saltwater intrusion into surface water and groundwater resources.

These impacts would vary along the entire length of the coast. Most parts of Guyana would be affected because its coast lies below high water level. The northwestern coast would be the most affected because of subsidence. The area east of the Essequibo River, where most of the cultivation takes place, is protected against wave erosion by some form of sea defense, ranging from concrete seawalls to the naturally occurring cheniers. Wetland loss in the foreshore area of this coast would be considerable, and the pressure on manmade sea defense structures would increase even under a low scenario forecast for a 50-cm rise in sea level.

Most of Surinam's coast is fringed by mangrove, and parts of it are formal nature reserves. Furthermore, erosion is not as severe as on the coast of Guyana. Under a low scenario forecast for a 50-cm rise, wetlands would migrate inland. Wetland losses in French Guiana would be higher because low-lying areas are limited. But economic losses would be minimal because its coast remains largely undeveloped.

In general, the responses to the accelerated sea level rise in the region are poor. Although Guyana's coastal dwellers have been battling the sea since the colonial period, such problems as erosion and flooding are perceived as local phenomena. Few government organizations or local inhabitants consider the future rise of sea level to be a serious threat. Recently, however, concern about the consequences of future sea level rise has been shown at higher government levels. Nevertheless, no efforts have been made to restrict developments along the coastal highway.

In Surinam and French Guiana, the possible effects of sea level rise are not seriously considered because most economic development, with few exceptions, has largely taken place away from the coastline. Coastal dwellers in both these countries do not endure as many problems as their Guyanese counterparts, and are therefore less vulnerable.

BIBLIOGRAPHY

Augustinus, P.G.E.F. 1978. The changing shoreline of Surinam (South America). Ph.D. Thesis Publication No. 95, Foundation for Scientific Research in Surinam and The Netherlands Antilles, The Netherlands: University of Utrecht, 232p.

Augustinus, P.G.E.F. 1982. Coastal changes in Surinam since 1948. Proceedings Furoris Congress on Future of Roads and Rivers in Surinam and Neighbouring Region. University of Surinam. The Netherlands: The Delft University of Technology, pp. 329-338.

Augustinus, R.G.F.G., and R.P.R. Mees. 1984. Coastal erosion and coastal accretion between the estuaries of the Corentyne and the Essequibo Rivers: A contribution to the coastal defense in the Republic of Guyana. The Netherlands: State University of Utrecht, Laboratory for Physical Geography.

Brinkman, R., and L.J. Pons. 1968. A pedo-geomorphological classification and map of the Holocene sediments in the coastal plain of the three Guianas. Paper No. 4. Wageningen, The Netherlands: The Soil Survey Institute.

Daniel, J.R.K. 1984. Geomorphology of Guyana. Occasional paper. Dept. of Geography, University of Guyana. Release Books, 72p.

Daniel, J.R.K. 1988. Sea defense strategies and their impact on a coast subject to a cyclic pattern of erosion and accretion. Ocean and Shoreline Management 2:159-175.

Gibbs, R.J. 1967. The geochemistry of the Amazon River System: Part I. The factors that control the salinity and the composition and concentration of the suspended solids. Bull. Geol. Soc. Am. 78:1203-1232.

NEDECO. 1968. Surinam transportation study. Report on hydraulic investigation. The Hague, The Netherlands: Netherlands Engineering Development Consultants, 293 p.

NEDECO. 1972. Report on sea defence studies. The Hague, The Netherlands: Netherlands Engineering Development Consultants,

Starbroek News. 1989a. News item, May 3, 1989. Guyana Publications Ltd.

Titus, J.G. 1985. Sea level rise and the Maryland coast. In: Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. J.G. Titus et al., eds. Washington, DC: U.S. Environmental Protection Agency, p. 1-32.

IMPACTS OF SEA LEVEL RISE ON THE ARGENTINE COAST

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ABSTRACT

The Argentine coast exhibits a variety of environmental settings, including estuarine and deltaic areas, marshes, sandy and pebbly shores, and cliff exposures. Different wave and tide regimes operate along the coast.

Although erosion typifies much of the nation's 5,000-kilometer coastline, these problems are particularly severe in the Province of Buenos Aires with 40% of the country's total population and one third of its coastline. The main urban developments, harbors, industrial complexes, and tourist resorts are located in this province. Floods are very dramatic on the Rio de la Plata shores, which have the highest population density. Here the water level rose 4.75 m in 1940 and 3.85 m in 1958. In the latter case, more than a half million inhabitants were affected in different ways. The Coriolis effect has been regarded as a major cause for the storm surges on the Argentine side of the Rio de la Plata.

South of the Rio de la Plata, the oceanic shorelines show dissipative characteristics with a significant littoral drift (between 400,000 and 1 million m^3/year). There is high erosion in many areas; for example, the Mar Chiquita beach has been retreating more than 5 m/year during the last three decades. Beach-sand mining for construction also contributes to erosion. Unplanned urban

development can also account for property loss and damage. At Mar del Plata, the main tourist resort in Argentina, groins, jetties, and seawalls have been constructed since the beginning of the century without the utilization of basic geomorphological information, thereby partially solving local problems but increasing erosion along downdrift areas.

Fifteen tide-gauge stations, a few of them with extensive records, are distributed along the Argentine coast. The 64-year record of Puerto Quequen, located 120 km southwest of Mar del Plata, shows a rise in sea level of 16.09 cm/100 years. This locality seems to be the most reliable, in terms of both historic data and tectonic stability.

Coastal plain flooding is also critical in areas such as the Rio Salado Basin, where topographic gradients are extremely low and the phreatic surface is very shallow. In addition, salt intrusion of coastal aquifers can be predicted as a combined result of sea level rise and coastal retreat. Overpumping has already created this type of problem in the city of Mar del Plata.

Urban development on the sandy coastline of the northern Buenos Aires Province has caused the elimination of extensive sand dunes, which are the only available storage bodies for groundwater. Beach erosion in this area is partly due to the restriction in sediment supply from the sand dunes.

The accelerated rate in sea level rise predicted for the next century will exacerbate the described processes. Although several impacts can be predicted for the Patagonian coast, they are far less dramatic than those in the northern coast because of the much lower population density and urban/industrial development.

In the absence of a general legal/organizational framework, institutional responses to coastal problems are limited to specifically oriented government offices, mostly at the provincial level (e.g., hydraulic departments, water resources agencies). Some municipal counties backed by community organizations are involved in dealing with the development and management of coastal resources, although they usually lack expertise. It is expected that future efforts, based upon scientific evidence, will result in the adoption of legal and administrative procedures for proper use and protection of the coastal zone.

INTRODUCTION

In recent years, increasing atmospheric concentrations of CO_2 and other greenhouse gases is producing a global warming, which could expand ocean water and melt polar ice sheets. Predictions of future sea level rise suggest a 1-m rise within the next 60 to 150 years (Hoffman, 1984). Estimates of future sea level rise vary according to the relative contribution of different factors involved (thermal expansion, retreat of alpine glaciers, melting of the Greenland and Antarctic ice-sheets). Gornitz et al. (1982) established that "eustatic" sea level is presently rising at a rate that exceeds 1 mm/year.

Lanfredi et al. (1988) have estimated that sea level is currently rising 1.6-mm/year in Puerto Quequen, which probably has the only reliable tide-gauge station in Argentina. This station has a 64-year record and is located in a tectonically stable area, which allows for a true eustatic component to be considered.

Even without considering the present or predicted rates in sea level rise, the Argentine coastal areas are undergoing several impacts (shore erosion, salt intrusion, pollution, etc.) as a response to both natural and predominantly human-induced processes. If the rate of sea level rise were to accelerate as predicted, it would be necessary to adopt policies and management regulations to adequately deal with it. Government and community structures would play an important role in this regard.

CHARACTERIZATION

Natural Features

According to the Koeppen climatic system, the Argentine coast is temperate from the Parana Delta down to 40 km SW of the Rio Negro, arid from there to Rio Gallegos, and "cold humid" to the south of that location.

The coastline of Argentina is about 5,700 km long (Figure 1), not including the Malvinas and Antartica. (Note: While Argentina claims both of these sectors, the United Kingdom currently administers the Malvinas (Falkland Islands) and Argentine ownership of the Antarctica sector is not universally recognized.) A very wide continental shelf extends offshore, reaching in some places, over 800 km in width. Main coastal landforms (Figure 1) are deltas, estuaries, marshes, cliffs and wave-cut terraces, sandy and pebbly shores, and ice-fringed coastlines (Antarctic area). Sandy coastlines are typical along the strip extending from Cabo San Antonio to Mar Chiquita Lagoon, in northeastern Argentina, where a 150-km-long barrier develops. In this area, the shoreline shows dissipative characteristics with a significant littoral drift (between 400,000 and 1 million m^3/year). Figure 2 illustrates a number of coastal features.

Pebbles are a typical component of the Patagonian shores. They originate in the reworking of mainly Quaternary pebbly substrates from continental terraces, pediments, and fluvial deposits. Wave and tidal action at different sea level positions resulted in several raised shorelines of Pleistocene and Holocene age, which are a typical feature on the coastal plain. These high sea level stands are also well represented in the Mampas coastal plains. In all cases, fossil molluscs are present in the sediments; these constitute the best tools for correlation and dating (Feruglio, 1950; Rutter et al., 1989).

It is known that sea level was higher than today at least three times during the Quaternary: (1) during the Holocene (maximum sea level about 6,000 years ago), (2) during the last interglacial (120,000 years ago), and (3) during a previous interglacial. On the Argentine shelf, the Wisconsin shoreline was dated in about 18,000 years ago, at depths beyond 100 m (Fray and Ewing, 1963)

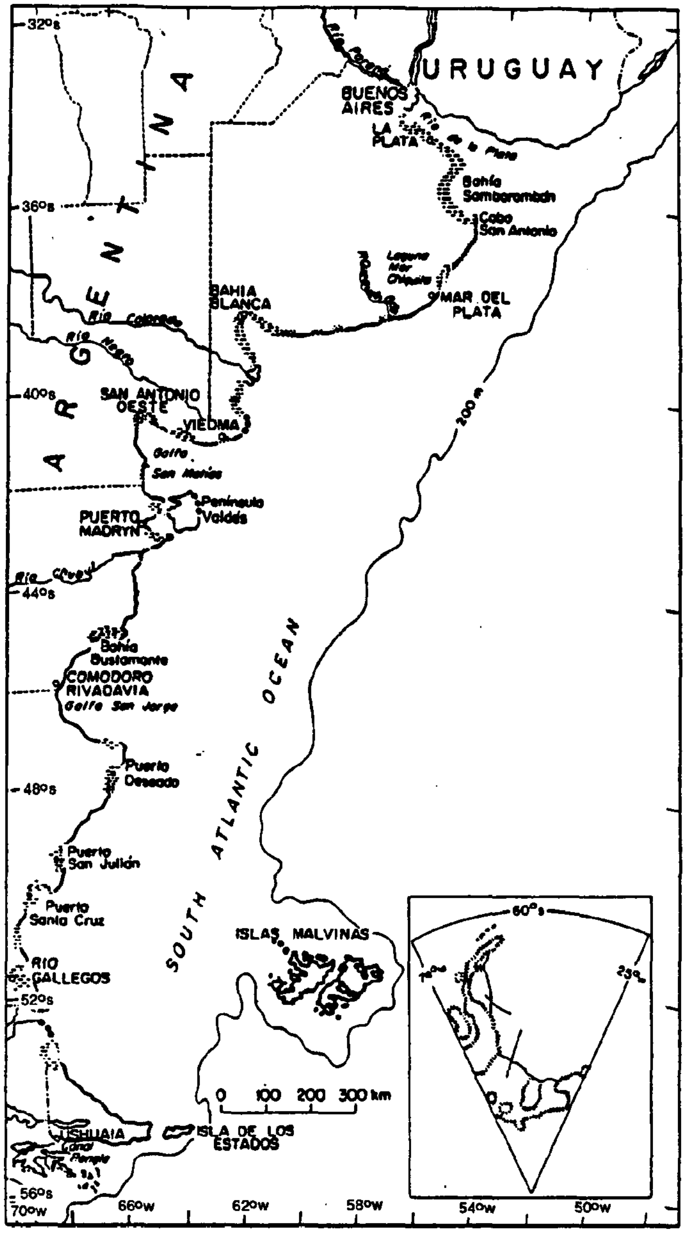


Figure 1. Distribution of predominant geomorphic features along the Argentine coast (Schnack, 1985).

Brackish and saltwater marshes are present along the coast, the former mainly in the northeastern sector of Buenos Aires Province (Samborombon, Mar Chiquita) and also in Bahia Blanca and further southward (Figure 1). The latter are predominant in Patagonia, where macrotidal environments prevail. The Patagonian coast is predominantly rocky, and cliffy, whereas the Buenos Aires (Pampas) coastline alternates between extensive low-lying and cliffy areas.

Cliffs in the Province of Buenos Aires are generally composed of semi-consolidated, deposits of the Plio-Pleistocene age, reaching their maximum altitude (25 m) in the vicinities of Mar del Plata. Only in this city, an old, lower Paleozoic quartzite outcrops at the sea. The Patagonian coast exhibits mainly Tertiary sediments, both of marine and continental origin. Lastly, Quaternary, glacially derived sediments outcrop in eastern Tierra del Fuego, and Cretaceous marine rocks are the main feature on the Beagle Channel area.

Although there are several embayments along the whole Argentine coast, Mar Chiquita Lagoon inlet is the only one that has the proper attributes of such a feature. At a typical microtidal setting, the Mar Chiquita inlet (less than 100 m wide and less than 3 m deep in the channel axis) shows both seasonal (or storm-driven) and historic shifting. As can be seen in Figure 3 (for location see Figures 1 and 4), the inlet has a historic trend of northward shifting coincidental with the regional net littoral drift. However, engineering works have modified the natural adjustment of the inlet. In the tide-dominated Patagonian coast, a few embayments exhibit some features that are common attributes of tidal inlets. At San Antonio Bay, in northern Patagonia (Figure 1), a well-developed flood-ebb delta is active, but no freshwater inflow exists in the area.

Wetlands are distributed all along the Argentine coast. The most typical and extensive are those in Bahia Samborombon, where muddy, tidal flats develop along 100 km of coastline, at the Salado Basin depression (Figures 1 and 4). Also, tidal flats and marshes are present from Bahia Blanca southward. Wetlands along the Patagonian coast are not so extensive. They are more restricted to low-lying areas at the several embayments. In all cases, marshes are temperate and show the presence of typical vegetation (<u>Spartina</u>, <u>Salicornia</u>). The general topography at low-lying areas would allow marsh and vegetation to shift inland if a rapid sea level rise occurred. In some cases, e.g., restricted marshes in Patagonia, where a rocky slope borders a narrow coastal plain, migration would be limited to a few hundred meters, thus causing marshes to disappear.

The most prominent estuarine environment is the Rio de la Plata, a water body shared by Argentina and Uruguay. As a continuation of the Parana River Delta, the Rio de la Plata has a submerged deltaic front composed of silt-clay, but sand banks also occur. The main body is freshwater, but the outer part is brackish. Although no river discharge occurs at present, Bahia Blanca, a brackish-water environment with mesotidal action, hosts one of the most important harbors. Here, muddy environments and suspended materials, as well as drifting sandwaves and channels, are driven by tidal currents.

A

B

C

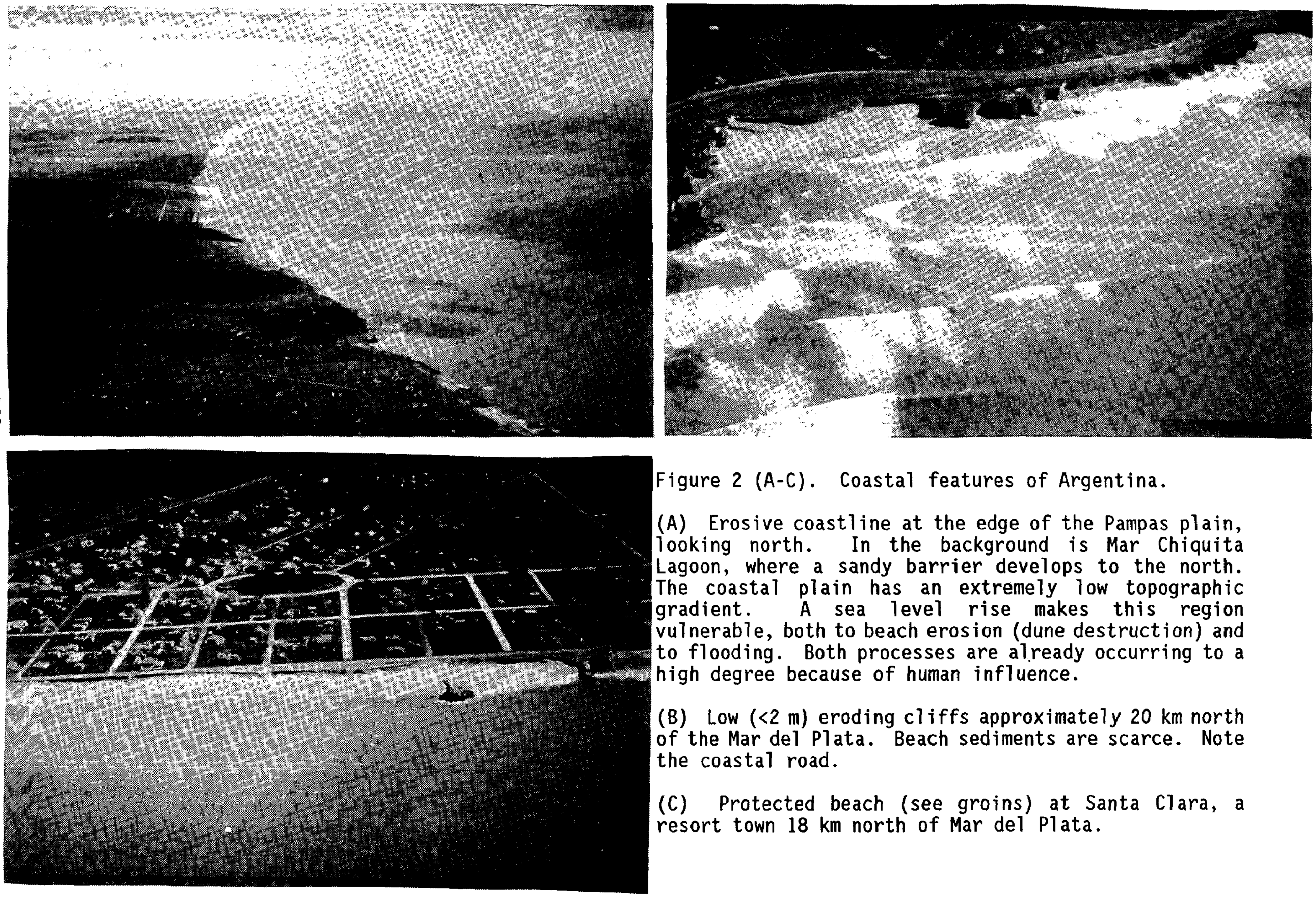


Figure 2 (A-C). Coastal features of Argentina.

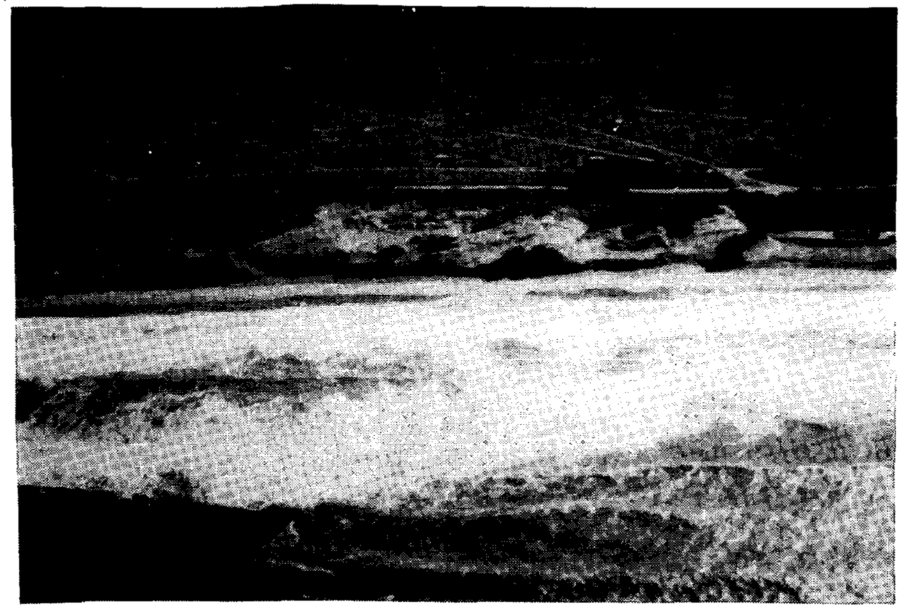
(A) Erosive coastline at the edge of the Pampas plain, looking north. In the background is Mar Chiquita Lagoon, where a sandy barrier develops to the north. The coastal plain has an extremely low topographic gradient. A sea level rise makes this region vulnerable, both to beach erosion (dune destruction) and to flooding. Both processes are already occurring to a high degree because of human influence.

(B) Low (<2 m) eroding cliffs approximately 20 km north of the Mar del Plata. Beach sediments are scarce. Note the coastal road.

(C) Protected beach (see groins) at Santa Clara, a resort town 18 km north of Mar del Plata.

D

E



F

Figure 2 (D-F).

(D) Stone defense to rebuild beaches at Mar del Plata (constructed in the early 1980s). By the 1970s, beaches in this area were lost. Many other beaches are protected by groin systems.

(E) 15 km south of Mar del Plata center, eroding beaches in an area where sand mining for construction is doen. Note the improverished dune "relicts" resting on an approximately 10 m high cliff which now is being reactivated by dune disappearance.

(F) Part of a tidal salt marsh in Coleta Mabespina (Patagonia). Many similar environments of varying area (usually small in Patagonia and lareger in Buenos Aires Province) are distributed along the Argentine coast. Some may not migrate landward as sea level rises because of topographic (hills) or human barriers, hence, a significant wetland loss may result.

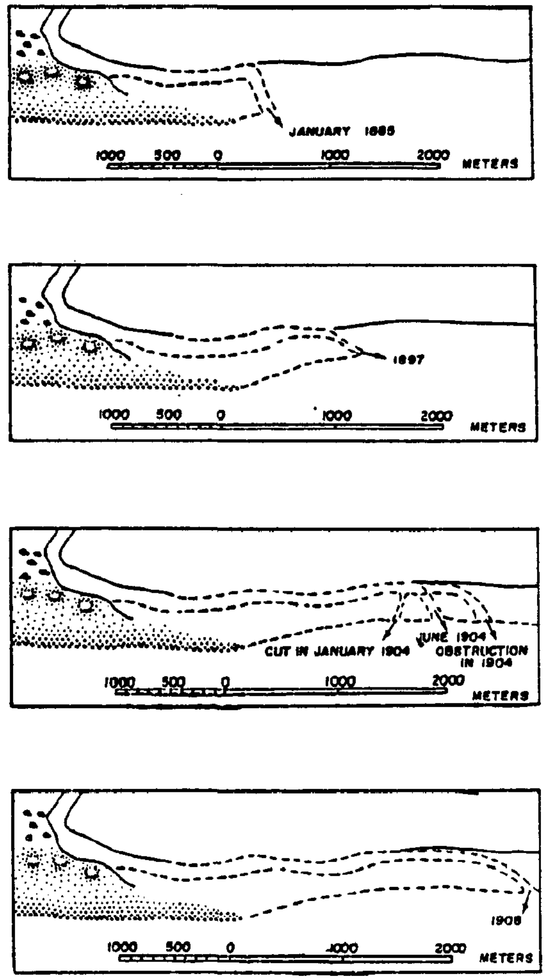


Figure 3. Historic migration of Mar Chiquita Lagoon inlet.

Several other estuaries are represented in the coast of Patagonia by the river outlets under macrotidal conditions, but few detailed studies have been done in relation to water chemistry and dynamics. Bottom sediments are variable, with gravels, sands, and muds in different proportions according to the source and dynamics. In this macrotidal setting, most of the fine sediments are transported in suspension. Because of the large tidal amplitudes, some of these estuaries have extensive uncovered areas during the ebb tide. One such areas is the Rio Gallegos outlet, where tidal ranges reach 12 m (Figure 1).

Cultural and Economic Features

According to Brandani and Schnack (1987), human activities along the coastal zone of Argentina include urban development and recreation; industry and commerce; port activities; fishing, military and naval bases; research; and conservation of natural resources. In certain areas, beach sand is mined for building purposes. Other activities include: mining of coastal gravels and shells (from Quaternary deposits), offshore oil exploration and extraction, and algae exploitation. The general features of the major Argentine harbors are shown in Table 1.

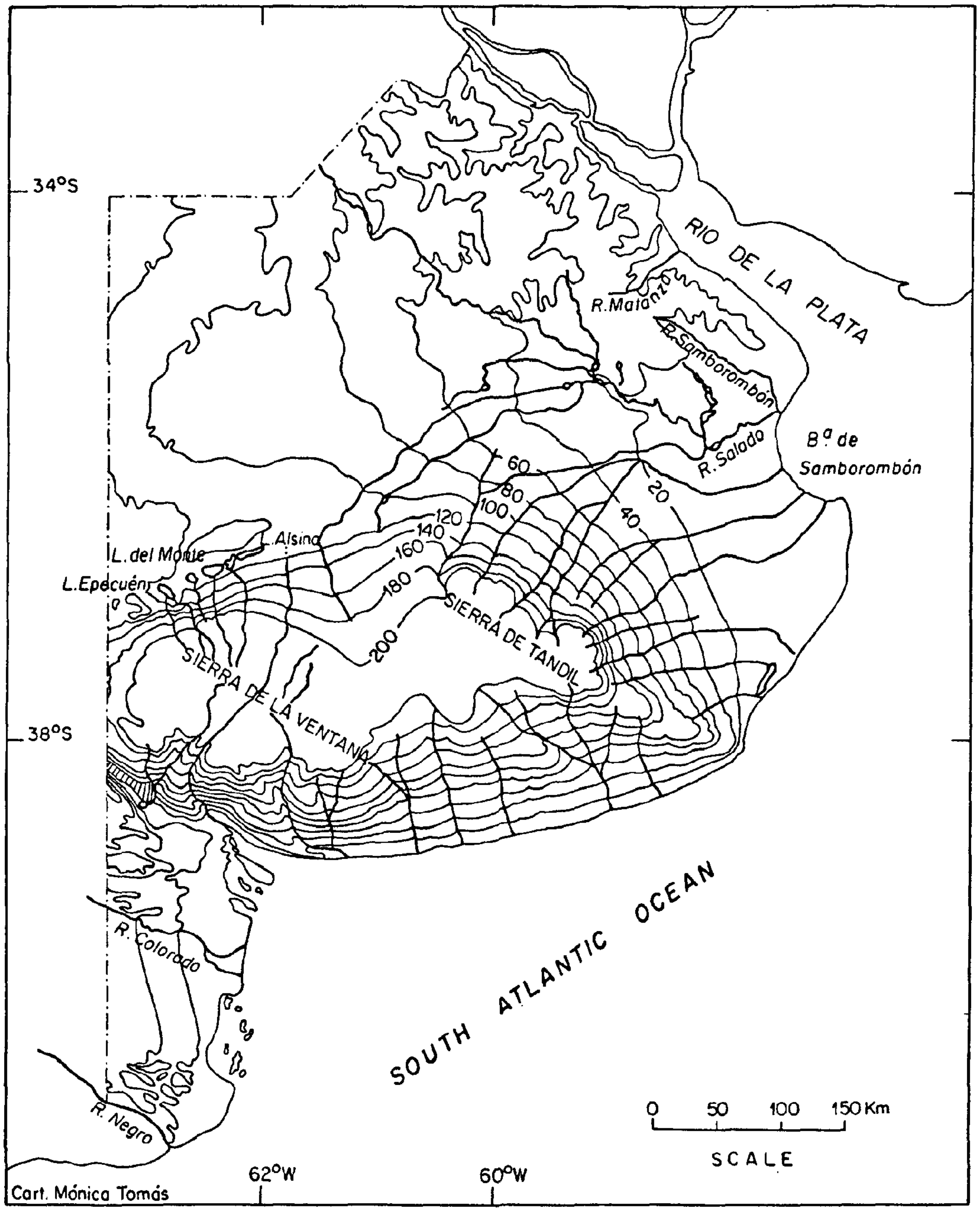


Figure 4. General topography of the Province of Buenos Aires. Note the extremely gentle slope in the Salado Basin depression and in the Rio Colorado-Rio Negro region.

Table 1. General Characteristics of the Main Harbors in Argentina

PORT	LOCATION	PURPOSE	FACILITIES	ANCILLARY FACILITIES	ECONOMIC ACTIVITIES
Buenos Aires	ϕ = 34° 34' S Ω = 58° 23' W	General cargo, bulk and container bulk terminal	Wharves, berths, cranes, warehouses, sheds, grain elevators	Dockyards, shipyards	Chemical, textile, metallurgical, and food industries
Mar del Plata	ϕ = 38° 03' S Ω = 57° 33' W	Fishing port and bulk terminal	Wharves, berths, cranes, warehouses, sheds, grain elevators	Dockyards	Fishing industries, packing houses, agricultural and cattle-raising activities
Quequen and Necochea	ϕ = 38° 35' S Ω = 58° 42' W	Grain in bulk terminal and fishing port	Wharves, berths, grain elevators, warehouses	Workshops and small dockyards	Fishing and food industries (meat and flour), agricultural and cattle-raising activities
Bahia Blanca	ϕ = 38° 47' S Ω = 62° 16' W	General cargo, grain in bulk terminal, and fishing port	Wharves, berths, cranes, grain elevators, warehouses, sheds	Workshops and small dockyards	Agricultural and cattle-raising activities petrochemical industries
Puerto Madryn	ϕ = 42° 46' S Ω = 65° 02' W	General cargo	Wharves, berths, cranes, warehouses	Small dockyard	Aluminum factory, fishing industries, and sheep-raising activities
Zone of Comodoro Rivadavia	ϕ = 45° 52' S Ω = 67° 29' W	Oil terminal and fishing port	Wharves, berths, cranes	Workshops	Oil fields, sheep-raising activities, and fishing
Puerto Deseado	ϕ = 47° 45' S Ω = 65° 55' W	Fishing port	Wharves, berths, cranes, warehouses	Workshops	Sheep-raising activities, and food industries
Ushuaia	ϕ = 54° 49' S Ω = 68° 13' W	Fishing port and general cargo	Wharves, berths	Small dockyard	Fishing activities

Demography

In Argentina, over 41% of the population inhabits the coastal zone. Population densities vary along the coast. A general gradient develops from north to south, with the greatest population numbers and densities in the nation's capitol, Buenos Aires city, and associated urban centers. The lowest population concentrations and variety of activities are found in Patagonia, south of the Colorado and Negro Rivers, where a few small urban centers support most of the regional population and activities.

Most of the largest urban centers and 25% of its urban centers with more than 5,000 inhabitants are coastal. However, the fact that the federal capital (Buenos Aires city), with only 17 km of coastline along the Rio de la Plata, contains 10% of the country's total population must be considered. Buenos Aires, together with its suburbs (Greater Buenos Aires) is estimated to have ten million inhabitants (30% of the national population).

The continuing historical pattern of population migration to the city (averaging a yearly growth rate of 47% between 1869 and 1980, against 13% for the national population growth) has been caused by mutually reinforcing factors: the Port of Buenos Aires handling 90% of the total waterborne transit and commerce of the country; the siting around the city of many of the nation's industrial and productive activities; and the concentration of a strongly centralized federal government.

The Province of Buenos Aires, with more than 1,500 km of coastline and nearly 12 million people (40% of the national population) is by far the most important coastal province (state) of Argentina. The average density is 35.3 people/km^2 and over 90% of the population lives in urban centers, the largest of which are all coastal (Figure 5): La Plata with 460,000 people, followed by Mar del Plata with 410,000 people, and Bahia Blanca with over 220,000 inhabitants. Rural areas are dominant along most of the coastline. It is here -- not the cities -- where the topography is vulnerable to major inundation from sea level rise, as can be observed in the Salado Basin depression with extremely low topographic gradients (Figure 4).

The Patagonian region varies in population distribution according to the specific province. In Rio Negro Province, only 12.5% of the population live in coastal centers. This is due to the strong economic influence of the Rio Negro Basin and the city of San Carlos de Bariloche, at the foot of the Andes. Farther south, in Chubut, more than 80% of the 263,000 inhabitants live in coastal urban centers. Santa Cruz Province, the third largest in Argentina, has only 114,900 people and its density is correspondingly very low: only 0.5 people/km^2. The National Territory of Tierra del Fuego has only 40,549 inhabitants with 38,515 people living in just two coastal cities: Rio Grande (21,969) in the north, and the capital of Ushuaia in the south (16,546).

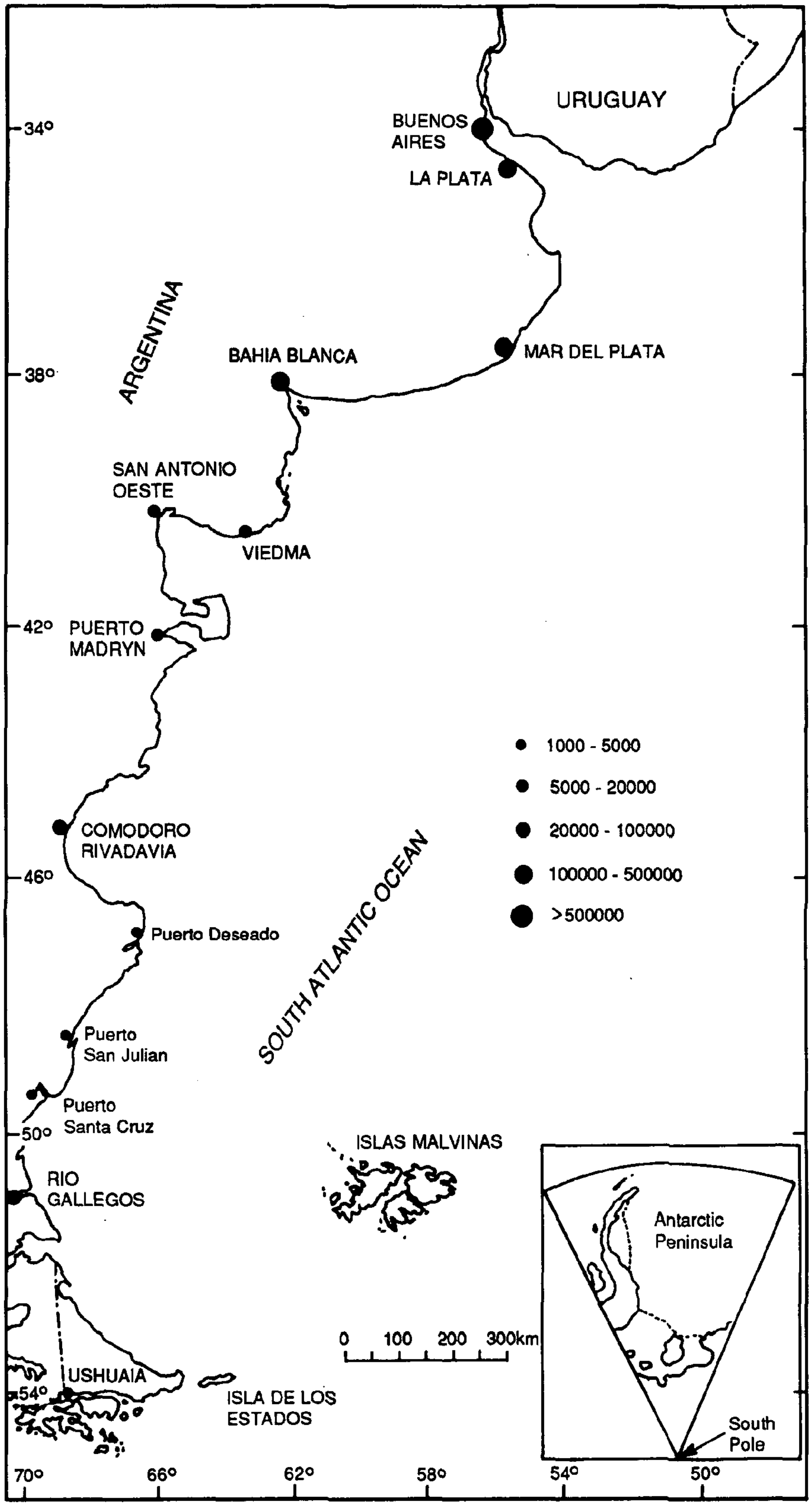


Figure 5. Population of urban centers on the Argentine coast.

Land Use

Low-lying coastal lands are mainly rural and are found mostly in the Province of Buenos Aires (Salado Basin in the north, and the southern tip of the state, from Bahia Blanca to Bahia Anegada). The Salado Basin coastal plain, facing Samborombon Bay, is largely devoted to agriculture (mainly cattle). Because this is a flood-exposed area, activities are somewhat restricted.

The area immediately above the highest tide levels in Bahia Blanca is partly occupied by housing developments related to the various industries established nearby; much of this area is subsiding. South of Bahia Blanca, the coastal area is mainly devoted to agriculture. In the northern, sandy belt of Buenos Aires Province (Figure 1), and extending southward to Mar del Plata and Miramar, tourism is the main land use.

At the Salado Basin, the recurrence of historic floods led the Public Works authorities to construct drainage canals toward Samborombon Bay at the beginning of the 20th century. However, results have not been optimal, as floods have occurred ever since.

As a general case, the Patagonian coastal lands are mainly devoted to sheep raising; a very localized algae farming also takes place.

Fisheries

Most Argentine fisheries are export-oriented. In 1981, the country contributed 1.69% of the world exports (Espoz, 1985). Fisheries are mainly found in shelf waters. Fish catches are by far predominant, but molluscs and crustaceans are also important resources. Oyster and scallop beds are present in shallow waters in northern Patagonia. Crustaceans (e.g., prawn, king crab) represent typical catches in Patagonia and Tierra del Fuego.

Commercial sea-farming is not commonplace along the Argentine coast. Only a few oyster and mussel farming projects are being carried out in San Antonio Oeste, and crustaceans projects in Mar del Plata and Puerto Madryn. In all cases, they are only at the experimental stage.

The main fishing activities are centered in the ports of Mar del Plata, with most of the fishing fleet and processing installations, and more than 70% of the total yearly catch. Other important harbors are: Ingeniero White (Bahia Blanca), San Antonio Este, San Antonio Oeste, Puerto Madryn (Figure 4). Additional small harbors are distributed along the Patagonian coast.

IMPACTS OF SEA LEVEL RISE

Considering the variety of environments and the socioeconomic importance of certain regions of Argentina, a rapid sea level rise, as predicted for high and low scenarios (Hoffman, 1984), would result in major damage to coastal areas in low-lying, flood-exposed plains and in open marine beaches and cliffs.

Beach Erosion

Erosion is an ongoing process, even at the present rate of sea level rise which has been estimated for the region as 1.6 mm/y (Lanfredi et al., 1988). The coastline between Cabo San Antonio and Mar del Plata is undergoing severe erosion, partly due to natural causes (e.g., lack of fluvial sediment input, sea level rise) and mainly because beach-sand mining and dune urbanization take place without any planning or environmental assessment. Engineering structures have been installed to protect the shore, but in many cases they operate locally and cause downdrift erosion by trapping the transported sediments. At Mar del Plata (Figure 6) several groins and jetties have been installed throughout this century. Also, Mar del Plata harbor certainly influences erosion in the downdrift direction (northward in the whole region) by breakwaters at its entrance.

Since erosion is a typical problem of the sandy shoreline and of the cliff exposures of Buenos Aires Province, sea level rise should only exacerbate the existing problems. At Mar Chiquita beach (Figures 4 and 7), a shore retreat of more than 5 m/y has been determined (Schnack, 1985), causing land losses and property destruction. This is the highest rate in shoreline retreat established for the whole coast of Argentina. Many other localities north of Mar Chiquita also show increasing erosion as a consequence of human intervention.

In a well-known paper, Bruun (1962) describes a method for determining shoreline retreat produced by sea level rise. He assumes that after a sea level rise the beach profile will simultaneously undergo an upward and a landward shift, though retaining its original shape. Thus, the final beach profile displacement can be considered as the result of two rigid translations: a vertical one and a horizontal one, the latter being the shoreline retreat.

For the given scenario (Hoffman, 1984), considering a 0.50-, 1.00-, and 2.00-m sea level rise to take place in a period of 50 years, a beach profile at Punta Medanos (Figure 4) would undergo a retreat of 1.93, 3.86, and 7.73 m/yr, respectively. These estimates show the dramatic impacts of predicted, rapid sea level rise. Furthermore, human-induced erosion represents a major factor that must be considered at least as effective as sea level rise itself.

Hydrological Impacts

Although hydrological problems along most of the Argentine coast may be foreseen as a direct consequence of sea level rise, the Buenos Aires Province shows most clearly the effects of anthropogenic activities due to its high population density, despite the fact that this population is concentrated at very specific points. These activities are responsible for the shifting or breakdown of the natural equilibrium. This is particularly true when dealing with groundwater resources, for processes operate at different intensities and time scales. Moreover, as groundwater motion is slow, thus hindering direct observation, the consequences arising from management decisions may not be noticed for several years, and so the results could be irreversible when detected.

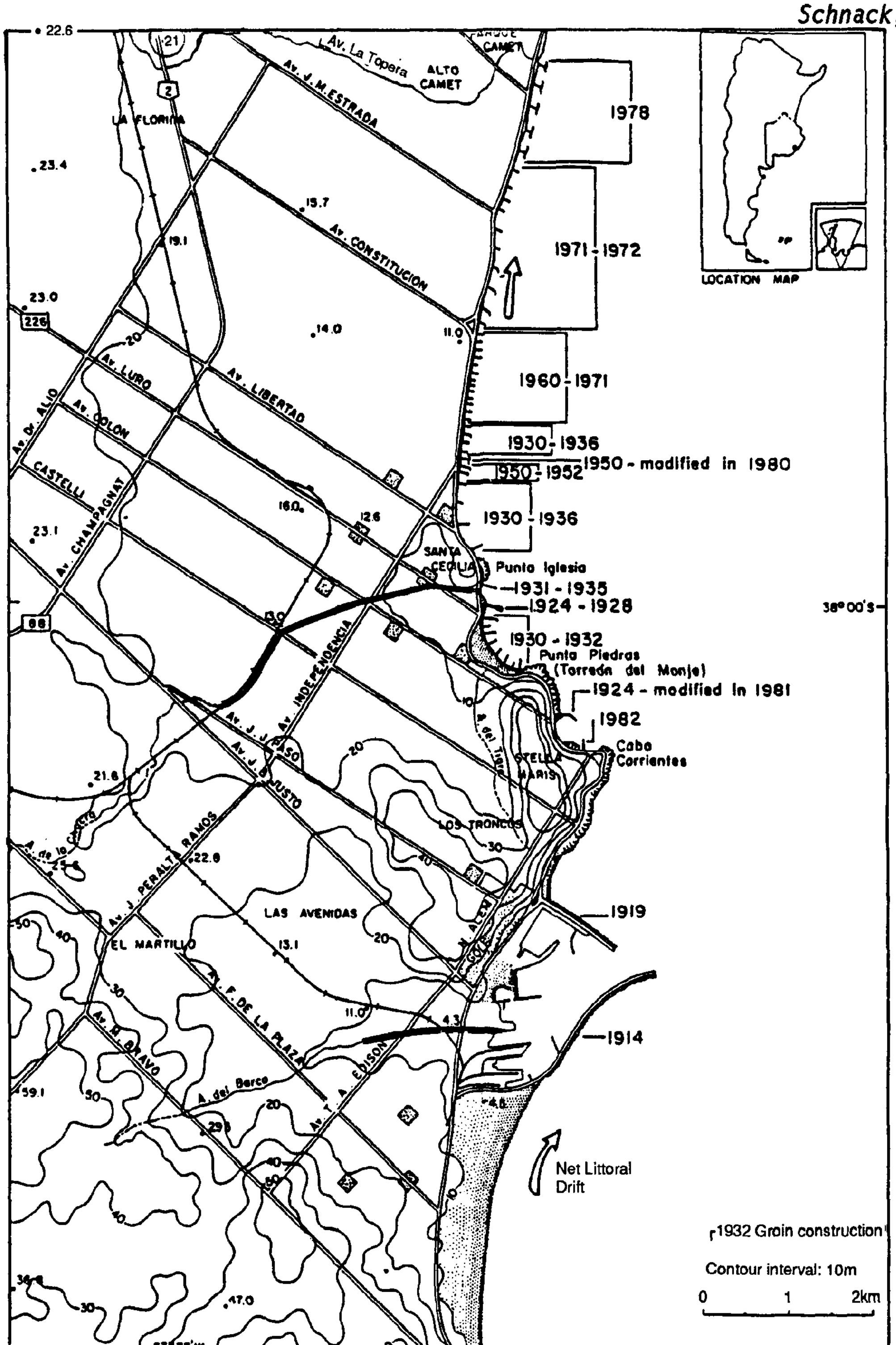


Figure 6. Engineering structures at Mar del Plata. Except for the harbor, all the structures have been installed to protect the shore from erosion.

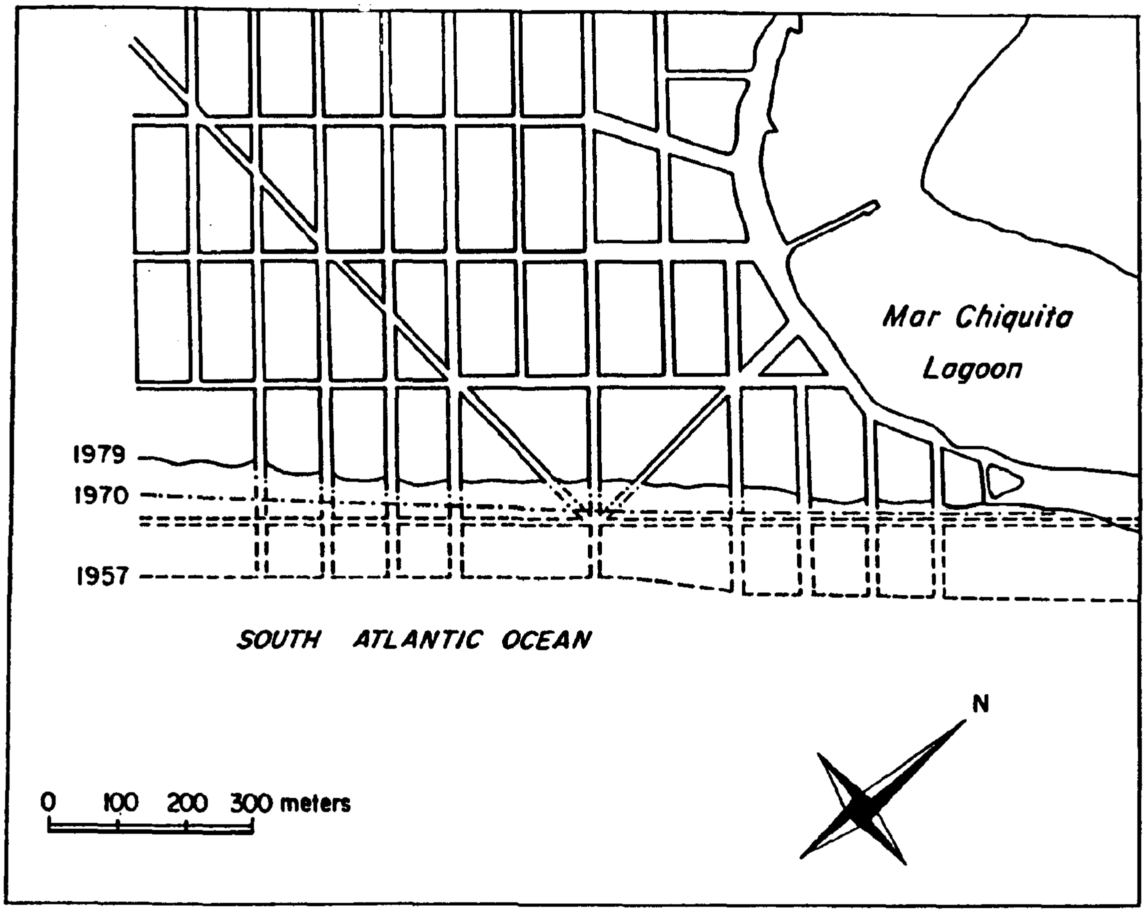


Figure 7. Shore retreat at Mar Chiquita beach. Note the land losses, including property.

Besides the highly disturbed deltaic area, on which little, if any, background information is available, three main coastal environments can be considered in the province: cliffed, sandy, and marshy shores. As a result of sea level rise, saltwater encroachment can take place, the impacts being mainly dependent on the physical coastal setting, climatic variation, and human factors.

A common feature of the three environments is the lack of sufficient available data, with the exception of some urban areas. This poses serious restrictions on the reliability of numerical solutions, for they depend upon both the quality and quantity of the input data.

In Mar del Plata, located at the easternmost extreme of the Tandilia Sierra, the aquifer consists of partially reworked Plio-Pleistocene loess-like sediments, with an average depth of 100 m. It had undergone over-pumping until the 1960s. As a result, seawater intrusion was detected, and nearly all the pumping wells located within the city and close to the coast were abandoned. The exploitation zone had to be shifted to the north. This action led to a restoration of groundwater tables which had flooded buildings, and has acted as a hydraulic barrier preventing a landward migration of the freshwater/saltwater interface. Today the situation in the well field can be considered at equilibrium. Hence, in Mar del Plata the landward migration of the saltwater front due to sea level rise would be negligible when compared with the human-induced migration.

A different situation can be observed toward the north of Mar Chiquita (a small town located about 30 km north of Mar del Plata). A sand dune barrier, which extends for more than 150 km and becomes progressively wider northward, overlies marine-estuarine sediments of Holocene and Pleistocene age (Fasano et al., 1982; Parker, 1980). At the low-lying coastal plain of Samborombon Bay, sand dunes are replaced by shelly beach ridges (Sala et al., 1977). Both sand dunes and shelly ridges are the only available freshwater storage bodies. These storage bodies can be idealized as if they were an elongated island surrounded by seawater on the east and brackish-to-salty continental waters on the west. Because of this, the sandy barrier could be largely influenced by a eustatic sea level rise. According to the erosion rate measurements, e.g., 5 m/y at Mar Chiquita (Schnack, 1985) (Figure 6), the horizontal component exceeds in orders of magnitude the rise in sea level (1.6 mm/y) in the vulnerable sandy coastline. The landward migration of the interface would be largely controlled by the beach retreat. Changes in altitude of the base level play a minor role. In fact, as stated by Urish and Ozbilgin (1989), the groundwater/free seawater interface is a highly dynamic boundary. On sandy sloping beaches, tidal fluctuations and wave run-up cause an effective mean sea level generally higher than free-water mean sea level.

Kana et al. (1984) summarizes the different opinions about the effect of sea level rise on the position of the freshwater/saltwater interface in a water table aquifer. Some state that the whole system would shift upward and landward proportionally to sea level rise and shoreline retreat, respectively. Others consider that freshwater rise would not follow sea level rise at the same rate, but would be some fraction of it as a consequence of decreasing recharge and increasing discharge.

Under nondeveloped conditions, the lens-shaped groundwater reservoir can be regarded as being in dynamic equilibrium by direct recharge from precipitation and discharge to the sea. It seems reasonable that a sea level rise of the magnitude considered here is sufficiently slow to allow groundwater to reach a new equilibrium position.

Floods are very dramatic on the Rio de la Plata shores, with the highest population density. Here the water level rose 4.75 m over datum in 1940 and 3.85 m in 1958. In the latter case, more than a half million inhabitants were affected by property losses and other damages.

Central and South America

The marshy areas of Buenos Aires Province extend mainly south of Bahia Blanca and also border Samborombon Bay. In these environments, erosion does not seem to be a dominant process. Due to the extremely gentle topographic gradient, minor positive variation in sea level causes the flooding of extensive areas with consequent land loss (Figure 3). This would allow an inland movement of seawater, resulting in its intrusion into the groundwater system. Additional effects, such as longer-lasting floods are linked to higher water tables, which inhibit the infiltration process during precipitation. From the point of view of groundwater as a resource, these effects would not pose a severe risk because brackish-to-salt water dominates.

Other Impacts

A rapid sea level rise would result in several disturbances of various degrees of importance, depending on the urban development, industries, general resources, and installations.

Impact on harbors (Table 1), in any of the predicted scenarios, would be high in Buenos Aires and Bahia Blanca because of the flat, low-lying terrain of the surrounding areas where very important economic activities take place. At Mar del Plata, Quequen, Puerto Madryn, and Comodoro Rivadavia the impact would be only moderate and the affected areas would be those next to the shoreline. Landscape damage and pollution effects can be predicted. At Puerto Deseado and Ushuaia the impact would be low, mainly restricted to the port facilities and their adjacent areas.

Wetlands would also be affected, either by migration and recolonization or by disappearance when migration is restricted by highlands or hard substrates. As we consider a rapid sea level rise, it is likely that inland migration of wetlands would keep pace in vertical growth relative to the rate of sea level rise. Under these conditions, a rough estimate suggests an average loss of 50% of the wetlands area.

The inland transportation of pollutants would also be a direct effect of a rising sea level. This would be particularly important in heavily populated, industrial, and harbor areas (Buenos Aires, Mar del Plata, Bahia Blanca), as well as in Patagonia, where oil spills may be transported inland (Comodoro Rivadavia). Although they are not yet in existence, sea-farming establishments may also be affected to some extent.

RESPONSES

Institutional Background

Government and legal instruments for coastal planning and protection are dispersed and no specific framework for coasts is available. A document on national priorities for marine and coastal research (SECYT, 1983) identified the lack of properly trained personnel and of coordination between research and management activities as significant issues.

At present, coastal issues show several problems related to organizational levels: lack of coordination and overlapping among public agencies; confusing and contradictory laws and regulations, and insufficient resources for adequate coastal zone management.

The conflicts between pollution, recreation, and coastal protection, for instance, are significant in the larger summer resorts of Buenos Aires Province, such as Mar del Plata. Coastal erosion has led to the construction of a variety of costly defenses in order to prevent the disappearance of beach resources and to reverse the destructive tendencies caused by sand-trapping devices (mainly groins). These defenses produce the desired effect in one place, i.e., accumulation of sand, but at the expense of other beaches, which end up being heavily eroded, as is the case between Mar Chiquita and Miramar (Figures 4 and 6). These conflicting activities in Buenos Aires Province have an institutional background. Construction of coastal defenses is the responsibility of a Directorate of the Provincial Ministry of Public Works, and a separate Directorate of the same Ministry grants permits for sand extraction from beaches and dunes, an erosion-triggering activity. No integrated planning procedures exist among the Directorates within the Ministry. Moreover, while tourist use and exploitation of the shore are the domain of municipal governments, port activities (a major source of pollution and erosion in Buenos Aires and Mar del Plata, among others) are under federal government jurisdiction.

Table 2 presents a summary of governmental units related to functional or sectorial aspects of marine and coastal zone management. The hierarchical level for each government unit (whether national or provincial) is shown in Roman numerals (I is the highest and corresponds to the chief executive's office, whether the nation's president or the governors). When some sector is also represented within the government structures of coastal provinces, its hierarchical level is indicated. Only names of the federal institutions are listed under the "nation" heading. Provinces are, from north to south: BA , Buenos Aires; RN, Rio Negro; Ch, Chubut; SC, Santa Cruz, and TF, Tierra del Fuego.

Table 2 lists only those sectors currently related to coastal zones for which some governmental unit exists. For farming, ranching, education, and forestry, no special orientation to coasts is found within governmental structures. For the last sector, this is understandable since the Argentine shoreline is essentially a treeless corridor (Brandani and Schnack, 1987). However, farming practices affect estuaries and coastal wetlands through the concentration of runoff products, agrochemicals, and sediments.

Defense and production are concentrated in units of relatively high hierarchical level within the federal government. Development and wildlife management have a higher priority in the provinces than at the national level. Development is mostly industrial in nature, and ecological management emphasizes the exploitation of specific renewable resources for production or consumption, rather than the conservation of integrated environmental systems.

Table 2. Argentine Governmental Organizations With Primary Policy Authority for Marine and Coastal Resources

Sector	Name	Hierarchical level	Provinces				
			BA	RN	Ch	SC	TF
Defense operations	Armada	II	ne	ne	ne	ne	ne
Foreign policy	Ministerio de Relaciones Exteriores	II	ne	ne	ne	ne	ne
Customs	Direccion de Aduanas	IV	ne	ne	ne	ne	ne
Port administration	Administracion General de Puertos	IV	ne	ne	ne	ne	ne
Port activities	Capitania General de Puertos	V	ne	ne	ne	ne	ne
Port maintenance	Direccion de Construcciones Portuarias y Vias Navegables	V	ne	ne	ne	IV	ne
Navigation[b]	Prefectura Naval	IV	ne	ne	ne	ne	ne
Fisheries control	Direccion de Pesca	III	III	III	IV	IV	IV
Coastal tourism[d]	Subsecretaria de Turismo	IV	III	III	IV	III	III
Research (civilian)[c]	Consejo Investigaciones Cientificas y Tecnicas	IV	II[a]	II[a]	ne[e]	IV	ne[e]
	Universidades Nacionales[ad]	IV	IV[e]	IV[e]	IV[e]	ne	ne
	Instituto de Investigaciones Pesqueras	IV	ne	ne	ne	ne	ne
	Direccion del Antartico	IV	ne	ne	ne	ne	ne
Research (military)[c]	Direccion de Investigacion y Desarrollo	III	ne	ne	ne	ne	ne
	Servicio Hidrografia Naval	III	ne	ne	ne	ne	ne
Shore protection		ne	III	III	IV	III	ne
Wildlife management	Direccion de Fauna Silvestre	VI	IV	III	III	III	IV
Parks--conservation		ne	IV	III	IV	IV	IV
Zoning--Pollution control[a]	Direccion de Ordenamiento Ambiental	V	III	III	IV	IV	IV
Waterworks	Obras Sanitarias de la Nacion	IV	IV[af]	ne	ne	ne	ne
Oil and gas development[ab]	Secretaria de Energia	III	ne	ne	ne	ne	ne
	Yacimientos Petroliferos Fiscales	IV	ne	ne	ne	ne	ne
	Gas del Estado	IV	ne	ne	ne	ne	ne
Mining	Secretaria de Mineria	III	III	III	IV	IV	IV
Industrial development	Secretaria de Desarrollo Regional	IV	IV	IV	III	III	III

[a]More than one governmental unit deals with sector.
[b]In addition to several governmental units, national companies participate in sector.
[c]Separate units are dedicated to sector with different objectives.
[d]University research is actually carried out by Departments or Institutes, with lower hierarchy than indicated.
[e]Located in coastal provinces where they research according to regional needs.
[f]Some coastal cities may have a company providing primary services.
ne = Non existing.
Source: Brandani and Schnack (1987).

There is no specific legal framework for coastal issues at either the national or provincial level in Argentina. Some legislation related to other aspects (e.g., control of pollution by naval vessels, fisheries, etc.) considers a few coastal aspects. Also, a number of provincial decrees (e.g., to prevent sand mining on beaches) and municipal resolutions provide some approaches to solving coastal problems from a legal point of view.

Expected Responses to a Sea Level Rise

If we consider the preceding paragraphs, it is clear that sea level rise is not an issue at the institutional or the general public levels. Only a small part of the scientific population regards this as an important problem. In addition, there is insufficient evidence, from an observational basis, to really evaluate if a true sea level rise is occurring throughout the entire coastline. Most of the erosion and environmental disturbances are due to human intervention on coastal areas. Moreover, it must be considered that other hazards, such as inland flooding, earthquakes, landslides, and other phenomena, seem to have more dramatic effects and general concern among the public and institutions because they tend to affect the economy more noticeably.

However, if an integrated, environmental policy is established, the coastal issue may become progressively more important. Coastal protection would be seriously considered and sea level rise properly regarded as an important factor.

Based upon scientific evidence, future efforts should result in the adoption of legal and administrative procedures for proper use and protection of the coastal zone.

BIBLIOGRAPHY

Brandani, A.A. and E.J. Schnack. 1987. The Coastal Zone of Argentina: Environmental, Governmental and Institutional Features. Journal of Shoreline Management 3:191-214.

Bruun, P. 1962. Sea Level Rise as a Cause of Shore erosion. Journal of Waterways and Harbors Div. 88:117-130.

Caviglia, F.J. 1988. Intrusion salina en el Rio de la Plata. I.T.B.A., Buenos Aires, 38 p.

Espoz Espoz, M. 1985. Introduccion a la Pesca Argentina. Fundacion Atlantica, Mar del Plata, 336 p.

Fasano, J.L., Hernandez, M.A., Isla, F.I. and E.J. Schnack. 1982. Aspectos evolutivos y ambientales de la laguna Mar Chiquita, Provincia de Buenos Aires, Argentina. Oceanologica Acta No. Esp., 285-292.

Feruglio, F. 1950. Descripcion geologica de la Patagonia. Y.P.F.

Fray, C. and M. Ewing. 1963. Pleistocene sedimentation and fauna of the Argentine Shelf. In: Wisconsin Sea Level as Indicated in Argentine Continental Shelf Sediments. Proceedings of the Academy of Natural Sciences of Philadelphia. 115:113-126.

Hoffman, J.S. 1984. Estimates of future sea level rise. In: Greenhouse Effect and Sea Level Rise. M. Barth & J. Titus, eds. Van Nostrand Reinhold Co., New York. 79-103.

Kana, T.W., Michel, J., Hayes, M.O. and J.R. Jensen. 1984. The physical impact of sea level rise in the area of Charleston, South Carolina. In: Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold Co., New York, 105-150.

Lanfredi, N.W., D'Onofrio, E.E. and C.A. Mazio. 1988. Variations of the mean sea level in the southwest Atlantic Ocean. Continental Shelf Research. 8(11):1211-1220.

Parker, G. 1980 Estratigrafia y evolucion morfologica durante el Holoceno en Punta Medanos (Planicie costera y plataforma interior). Provincia de Buenos Aires. Simp. sobre Problemas Geologicos del Litoral Atlantico Bonaerense, Com. de Inv. Cient. de la Provincia de Buenos Aires. Resumenes (La Plata). 205-224.

Rutter, N., Schnack, E., del Rio, J., Fasano, J., Isla, F. and U. Radtke. 1989. Correlation and dating of quaternary littoral zones along the Patagonian Coast, Argentina. Quaternary Science Reviews 8:213-234.

Sala, J.M., Gonzalez, N. and M. Hernandez. 1977. Efectos de la barrera hidraulica natural en las aguas subterraneas del litoral de Bahia Samborombon. Obra del Centenario del Museo de La Plata. t. IV, Geologia. La Plata, 153-166.

Schnack, E.J. 1985. Argentina. In: The World's Coastlines. E. Bird and M. Schwartz, eds. Van Nostrand Reinhold Co., New York, 69-78.

SECYT (Secretaria de Ciencia y Tecnica). 1983. Programa de investigacion y desarrollo en Pecursos Marinos Costerns y lagunares de la Provincia de Buenos Aires. Buenos Aires. 30 p.

Urish, D.W. and M.M. Ozbilgin. 1989. The coastal groundwater boundary. Groundwater 27(3):310-315.

REGIONAL IMPLICATIONS OF RELATIVE SEA LEVEL RISE AND GLOBAL CLIMATE CHANGE ALONG THE MARINE BOUNDARIES OF VENEZUELA

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ABSTRACT

Sea level data on the marine boundaries of Venezuela have been analyzed using several tidal-gauge stations with continuous records ranging from 21 to 36 years. The rates of change in sea level have been highly variable. All of the time series examined, except two, show a tendency toward increase in sea level, with values ranging from 3.26 mm/year in Maracaibo Lake (an area of remarkable petroleum and groundwater extraction during the last 50 years) to 0.91 mm/year at Amuay. The easternmost tidal-gauge stations, located on Carupano and Puerto Hierro, exhibit a lowering trend, which can be explained in terms of tectonically induced uplift of this regional land mass due to its proximity to the boundary between the Caribbean and the South American tectonic plates.

In an attempt to determine the Venezuelan coastal zone's vulnerability, this paper indicates the lowland areas likely to be affected by this phenomenon and discuss the resulting environmental, social, economical, and geopolitical implications of these changes. Among other factors associated with global climate change, the frequent occurrence of tropical storms and hurricanes in the Caribbean Basin, and the changes in their track and destructive potential, emerge as some of the most negative effects influencing the Venezuelan coastal zone in the near future.

INTRODUCTION

Global warming could disrupt environmental conditions and political institutions throughout the world. In the recent past, the threat of a greenhouse warming has been studied by the United Nations Environment Programme (UNEP) through its Regional Seas Action Plans, in conjunction with the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission of UNESCO.

A 1988 UNEP study of the Wider Caribbean Region (including the Caribbean Sea, the Gulf of Mexico, and the Florida-Bahamas area of the Atlantic Ocean) emphasized the marine and coastal environment and addressed the implications of climate changes in that region. That research served as a starting point to initiate local scientific concern about anthropogenically induced global climate changes in Venezuela.

This paper characterizes the Venezuelan coastal zone and summarizes its main geodynamic and geomorphological features, its typical ecosystems, and its socioeconomic importance. It presents some evidence of local variations in climate conditions along the marine boundaries of Venezuela, examines the local signal of relative mean sea level variability from tidal-gauge records, and discusses the resultant environmental, social, geopolitical, legal, and economic implications of the regional pattern of alterations in climate conditions. Finally, it presents, for the consideration of Venezuelan authorities, a set of recommendations of domestic importance toward implementing an effective national response policy.

NATURAL CHARACTERISTICS OF THE VENEZUELAN COASTAL ZONE

Venezuela's coastline constitutes approximately 52% of the southern coastal boundary of the Caribbean Sea and an appreciable portion of shoreline on the Atlantic Ocean. Many types of coastal environmental stages are exposed along the approximately 4,000 kilometers of the Venezuelan shoreline: sandy marshland, beaches, cliffs, deltaic plans, coastal lagoons, barrier islands, estuaries, and bays. These environments are distributed on both Venezuela's Caribbean Sea boundary (2,720 kilometers) and its Atlantic Ocean border (1,300 kilometers). In addition, its 200 nautical miles of Exclusive Economic Zone (EEZ), with an area of 630,000 square kilometers, comprises around 300 islands, islets, and keys.

While sandy shorelines and beaches appear frequently along the Caribbean Sea border, sandy marshlands are confined to the Peninsula of the Paraguana at the western section. The presence of cliffed coastal portions is clearly evident. Deltaic zones are few, with the Orinoco Delta, on the Atlantic margin, emerging as the most extensive one, occupying 88,000 square kilometers in its drainage basin and 22,500 square kilometers in its receiving basin. The Unare Delta, in the central section of the Caribbean boundary, with a drainage basin of 22,300 square kilometers and only 28 square kilometers of area in its receiving basin, consists of two big coastal lagoons (Unare and Piritu) separated from the sea by very low-lying sandy barriers and partly protected by a mangrove forest of limited extent.

Any general attempt to summarize a broad geodynamic characterization of the Venezuelan coastal area should consider the following features:

- It lies on a very tectonically active zone. Located along the country's easternmost coastal section is a significant proportion of present-day global seismicity (see Figure 1).

- The local surface wind field presents a remarkable persistency in its mean directional distribution, reflecting the regional predominance of easterly winds and implying favorable conditions for coastal upwelling throughout the whole year. However, with regard to the wind field's strength, a notable westward intensification is evident, and consequently, the local rate of evaporation on the western Venezuelan coastline is enhanced.

- The seasonal fluctuation of the Intertropical Convergence Zone is usually thought to be the most important factor controlling the local rainfall pattern.

- The local tidal regime presents a microtidal mean range and gradual westward increase of the form number, implying the occurrence of mixed, mainly semidiurnal, tides at the easternmost section; mixed, mainly diurnal tides at the central part; and diurnal tides at the westernmost portion.

- Tropical cyclone activity has not been significant in the past. Specifically, up to 1972, only three tropical storms occurring over the southern coastal boundary of the Caribbean Sea had reached the category of "hurricane" during the entire century.

- The coastline along the marine boundaries of Venezuela shows clear signs of geomorphological changes. Table 1 shows the area of the Venezuelan shoreline where coastline changes have been well documented (see, for example, Bird, 1985).

VAST RESOURCES OF THE VENEZUELAN COASTAL ZONE

The socioeconomic and ecological importance of the Venezuelan coastal area is well established.

Oil Resources

About 50% of the total population of Venezuela, estimated to be 20 million people for 1990, resides in the coastal zone. Additionally, the oil industry, which is the primary resource for national income, bases its operations on structures located mainly on the coastal margin. In particular, these structures

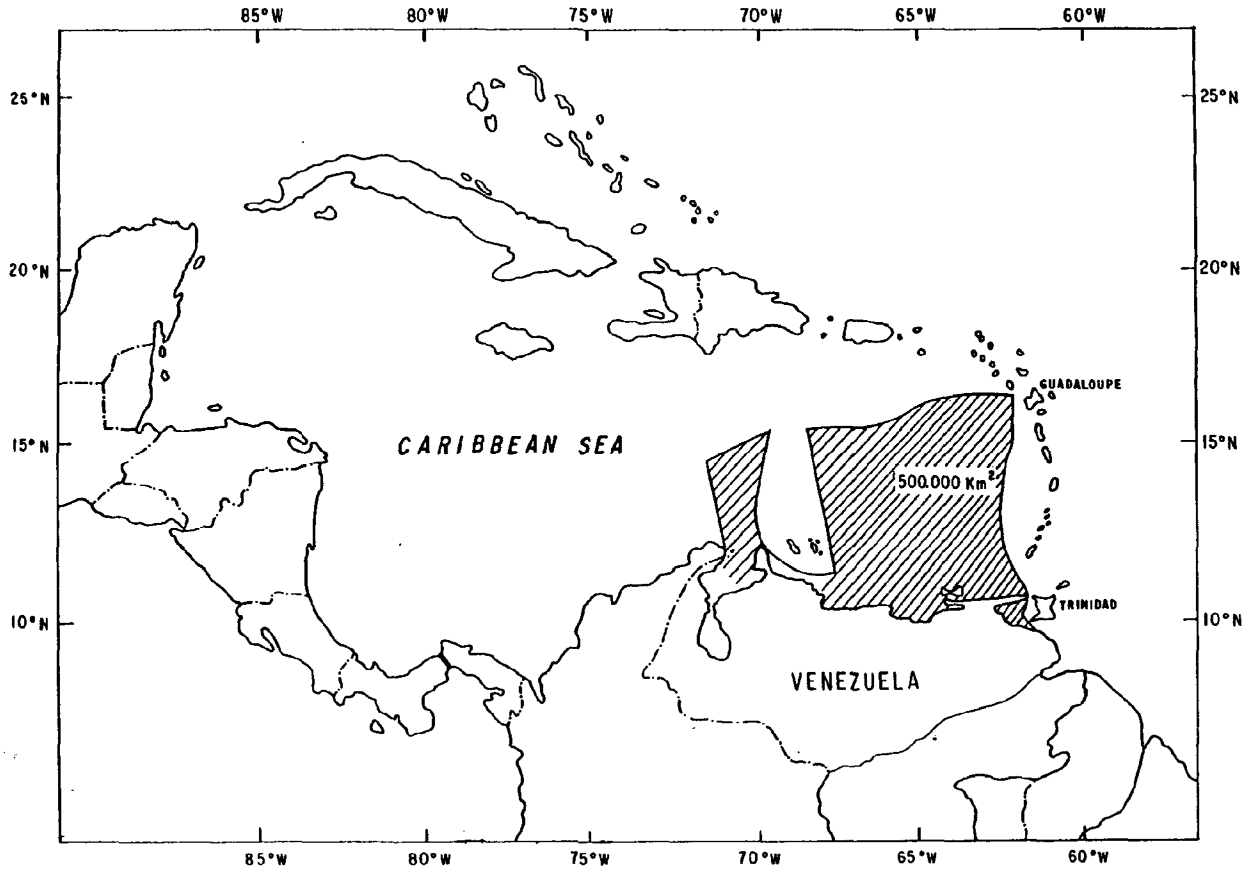


Figure 1. Venezuelan marine territory in the Caribbean Sea.

are located on the westernmost portion. They include the estuarine system formed by the Lake of Maracaibo, the connecting waterways of El Tablazo Bay, and the Maracaibo Straits. Expansion of the national oil industry implies, in addition, the establishment of macro-facilities on the easternmost section of the Venezuelan coastal margin (Araya and Paria Peninsulas) during the next five years.

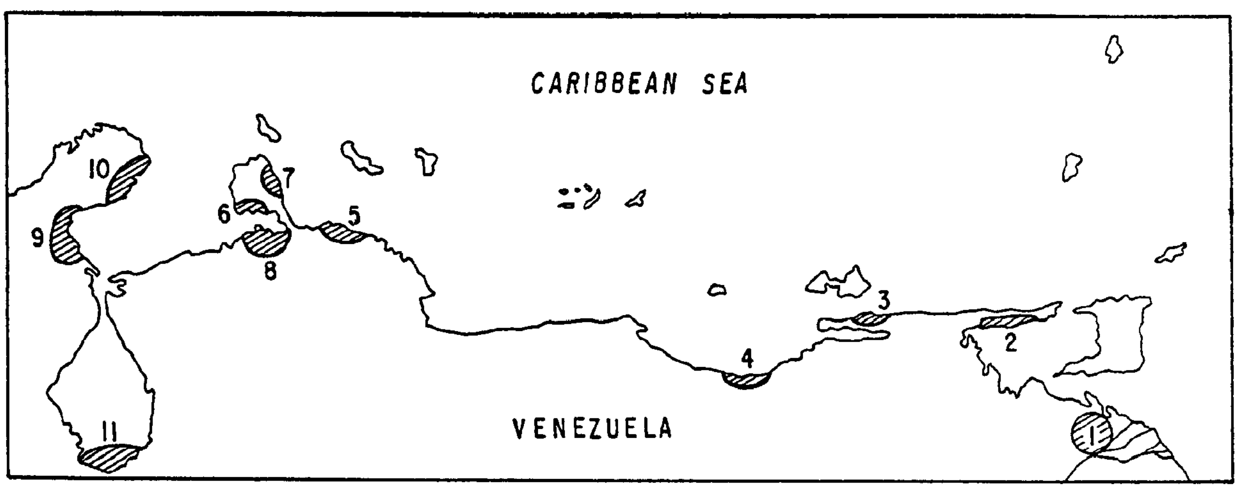
Fishery Resources

The entire coastal zone of Venezuela possesses valuable fishery resources that have the potential of continuous production if they are efficiently used. The wind-induced coastal upwelling observed in the area is the key physical mechanism responsible for the high biological production characterizing local fishery activities.

The northeastern section of the country has been an important fishing area for a wide variety of pelagic and demersal species. Specifically, the Gulf of Cariaco, the western coast of the Araya Peninsula, and the southern and

Table 1. Venezuelan Coastline Changes

1.	Orinoco Delta	Progradational long-term trend
2.	Gulf of Paria	Encroaching of swampy shores at the north
3.	Western shore of the Araya Peninsula	Sea gaining
4.	Coastal boundary of the Unare Bay	Erosion
5.	Tucacas	Beach erosion
6.	Eastern shore of the Medanus Isthmus	Extensive beach erosion
7.	Falcon Province on the Paraguana Peninsula	Active cliffing
8.	Mitare Delta	Progradation
9.	Southern side of the Guajira Peninsula	Active cliffing
10.	Western coast of the Gulf of Venezuela	General recession os sandy coastline
11.	Swampy southern shore of the landlocked embayment of Lake Maracaibo	Progradation



northeastern coasts of the Island of Margarita are zones of above-average sardine fishing (Sardinella anchovia). The northwestern coastal portion, including the Maracaibo estuarine system and the Gulf of Venezuela, has been the source of the large increase in the total Venezuelan production of shrimp. Additionally, the central and eastern areas of the Venezuelan coast present a set of marine physical conditions favorable to surface catches of Atlantic skipjack and yellowfin tuna. This has been extremely beneficial to the local economy during the last five years.

Marine Ecosystems

Some of the most productive and biologically complex marine ecosystems in the world, such as coral reefs, seagrass beds, and mangrove forests, are present along the Venezuelan coastal zone (see Figure 2).

Coral reefs, consisting of the consolidated skeletons of corals, accumulate rapidly in geological time and constitute the basis of many coastal fisheries. They provide food, shelter, and nursery areas for commercially valuable fishes and crustacean species. In addition, the reef forms breakwaters, which protect harbors and bays, and limit coastal erosion.

Mangrove forests, a coastal feature of tropical regions, develop in low-lying coastal areas where freshwater is supplied by rivers or terrestrial runoff. The forests provide, through their prop roots, a surface to which marine organisms can become attached. This, in turn, reduces tidal and wave energy.

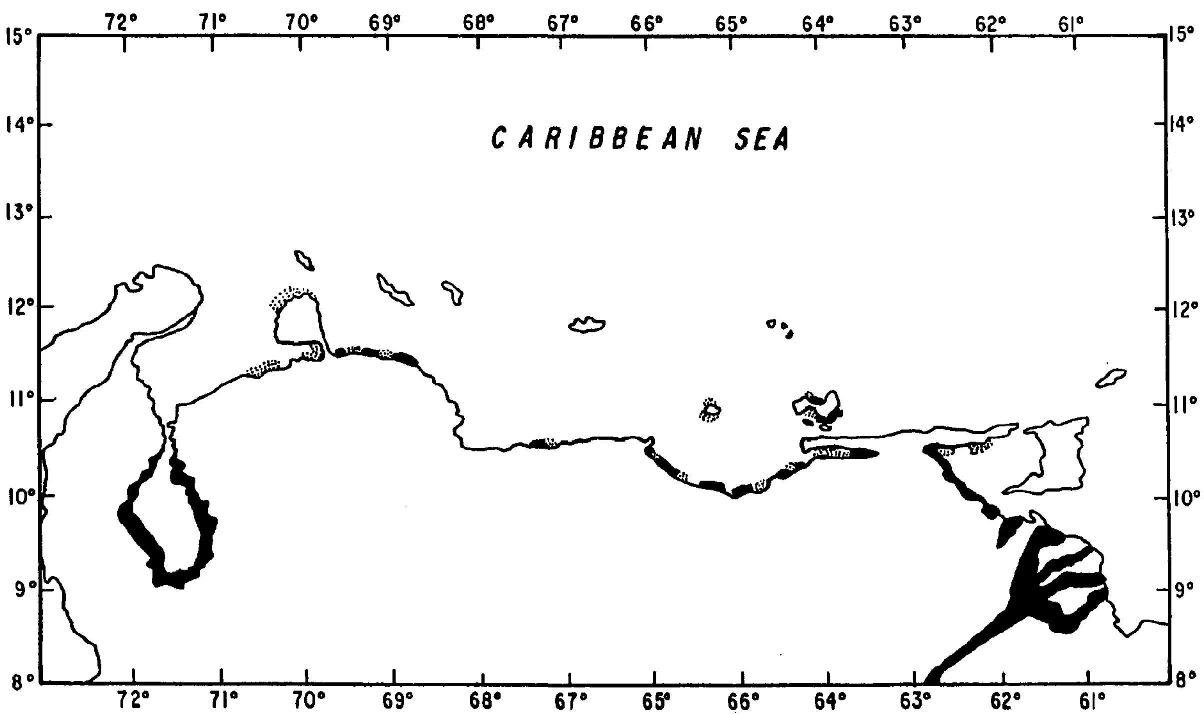


Figure 2. Spatial distribution of mangrove forests (■) and seagrass beds (▒) along Venezuelan marine boundaries.

Seagrass beds, which cover the bottoms of coastal bays, provide sediment retention and stabilization processes that are very important for adjacent coral reefs. The beds prevent the abrasion and burial of the reefs during conditions involving high wave energy. Additionally, seagrasses serve as nurseries for the juvenile populations of commercially important species, including fishes and invertebrates (lobsters, conches, bivalves, etc.).

EVIDENCE OF CLIMATE CHANGE ALONG THE COASTAL AREA OF VENEZUELA

Evidence of long-term climate variations along the coastal margin of Venezuela in recent decades has been reported by Aparicio (1988). The main qualitative findings of that study, based on data records no older than 35 years, are summarized in Table 2.

The pattern of variability in relative mean sea level along the Venezuelan marine boundary, extracted from tidal-gauge stations, shows strong local tectonic signals at the easternmost zone (see Table 3). In fact, signals given by sensors located on Puerto Hierro and Carupano reflect a clearly tectonically induced uplift of this local land mass, which can be explained in terms of the proximity of this zone to the boundary between the Caribbean and the South American tectonic plates. The global signals of sea level rise seem to be present along the central part of the Venezuelan coastal margin, such as is evidenced by examination of the records at Cumana and La Guaira. Another strong local signal can be seen by examining sea level data from the Maracaibo tidal-gauge station. A clearly anthropogenically induced local subsidence characterizes that signal, due to petroleum/groundwater extraction activities in the area during the last 50 years.

IMPACTS OF GLOBAL CLIMATE CHANGE

The most obvious negative effect is submersion due to mean sea level rise and loss of low-lying lands. The areas that seem to be particularly vulnerable

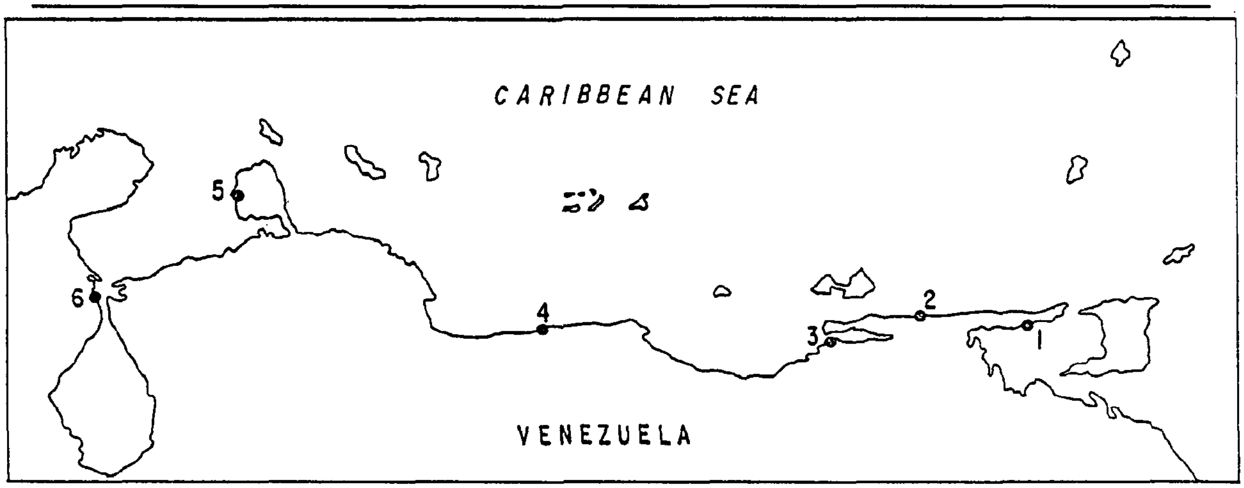
Table 2. Long-Term Temporal Variability of Climatological and Surface Oceanographical Conditions Along the Marine Margin of Venezuela[a]

Parameters	Long-term linear trend
Air Temperature	Increase
Evaporation	Increase
Precipitation	No significant change
Zonal Wind Stress	Decrease
Sea Surface Salinity	Increase

[a]Based on data collected on land site coastal weather stations.

Table 3. Relative mean Sea Level Variability Along the Venezuelan Coast Long-Term Linear Trend

Station Code	Location	Lat.	Long.	Record length	Linear trend (mm/year)	Standard deviation (mm/year)
1	Puerto Hierro	10°37'N	62°05'W	1955-1963	-4.36	3.26
2	Carupano	10°40'N	63°15'W	1967-1987	-2.12	1.07
3	Cumana	10°28'N	64°12'W	1953-1976	1.92	0.59
4	La Guaira	10°28'N	66°56'W	1953-1989	2.24	0.41
5	Amuay	11°45'N	70°13'W	1953-1985	0.91	0.61
6	Maracaibo	10°41'N	71°35'W	1964-1989	3.26	0.61



are the most external portion of the Orinoco Delta, the easternmost area of the Peninsula of Paria, and the region enclosing the small Unare Delta and the Unare and Piritu lagoons, which constitutes, perhaps, the Venezuelan coastal area that may have received the most negative influences from human activities in recent years. Specifically, this region is experiencing (1) erosion, mainly induced by deforestation and industrial and urban development, and (2) salinization of the Piritu Lagoon, which is due, in part, to restriction of the freshwater supply (gradual damming of the Unare River) and to uncontrolled use of chemicals in certain agricultural processes.

Saline intrusion in local groundwater resources is another negative effect produced by sea level rise that will affect the Venezuelan coastal area -- specifically, those coastal aquifers located in the Peninsula of Paraguana region, which, in turn, have been under indiscriminate exploitation during the last 25 years. Surely, a sea level rise will worsen the actual water quality of these aquifers, with negative consequences to local agricultural resources (Alvarado, personal communication, 1989).

Coastal erosion of beaches will have a tremendous impact on national efforts to develop the tourism industry. The most vulnerable areas seem to be Tucacas, on the Falcon Province; beaches on the Mochima National Park, which is located in the country's eastern coastal region; and Margarita Island, which has very high economic activity along its margin.

A particular case to be considered concerns the geopolitical implications for Venezuela derived from the reduction in area affecting Aves Island, which is the only outcrop of the Aves Ridge above sea level into the Venezuelan Basin of the Caribbean Sea. This island constitutes a large portion (about 135,000 square kilometers) of Venezuelan marine territory (see Figure 3). A comparison of geological surveys of Aves Island, which is only 3.7 meters above sea level at its highest point, reveals that the island has been progressively reduced in size during the last 30 years. Probably the factors responsible for this reduction are mainly local erosional processes and the subsidence rate of the Aves Ridge (Schubert and Laredo, 1984). Sea level rise in the Caribbean Sea, which has been actually estimated to average approximately 4 mm/year (Maul and Hanson, 1988), could exacerbate the present-day erosional instability of Aves Island with unpredictable consequences for Venezuela from a legal point of view.

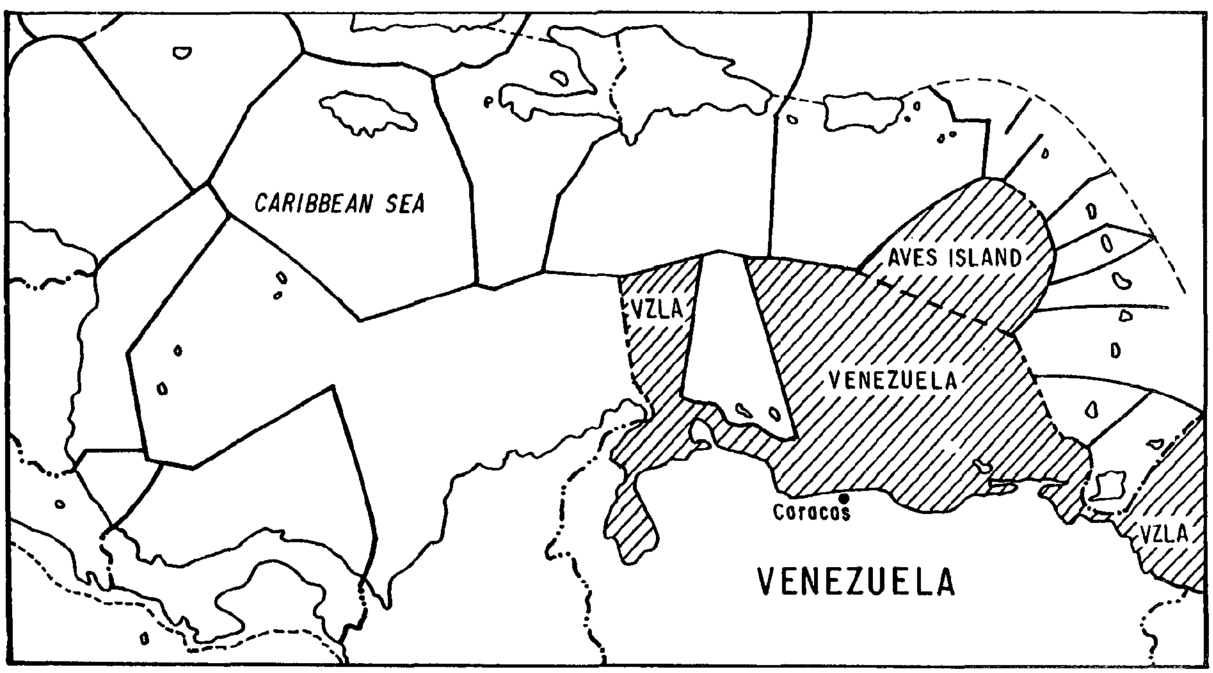


Figure 3. Aves Island generates approximately 135,000 Km^2 of marine territory for Venezuela.

Central and South America

Displacement of traditional fishing sites, even on a relatively small spatial scale, could emerge as a consequence of the alteration of the thermohaline structure of the coastal marine surface layer along the Venezuelan shoreline. This could harm local artisanal fisheries, with a negative effect on domestic economies, especially those located along the eastern section of the country.

Sea surface temperature (SST) in the Atlantic Ocean/Caribbean Basin is supposed to increase in response to global warming of the lower atmosphere. As a result, this part of the world would present, in the near future, better thermal conditions for the genesis of hurricanes and tropical storms. A recent work (Emanuel, 1987) reports that an increase in SST of 1.5°C would enhance the potential maximum hurricane wind by about 8%. It also has been reported that more frequent intensification of tropical systems to tropical storms could be expected (Shapiro, 1988). As has been mentioned previously, the Venezuelan marine margin has been out of the standard track of hurricanes during this century. However, two recent facts related to cyclonic activity in the Caribbean region deserve special consideration: (1) the strongest recorded hurricane of this century, Hurricane Gilbert, beat the Caribbean Sea in 1988, and (2) a hurricane (Hurricane Joan) hit the Venezuelan coastal territory for the first time during this century in 1989 (see Figure 4). Changes induced by global climate variations in the location of the geographical area favorable to the genesis of hurricanes and tropical storms on the tropical Atlantic Ocean are, then, of crucial importance for Venezuela.

RESPONSE POLICY

Despite the efforts of the local scientific community, the need to adopt strategies to manage the impact of global climate changes on the Venezuelan coastal geography has not yet been clearly understood by national authorities. This seems to be a logical consequence of the considerable uncertainty characterizing technical reports regarding the magnitude of future alterations of global lower atmospheric and surface marine conditions typifying regional climate.

Actually, Venezuelan scientists involved in this problem face the task of motivating official decision-making agencies. In this sense, the international pressure placed on the Venezuelan government, which has been recently invited to subscribe to global agreements related to the matter (The Montreal Protocol, The Hague Declaration), has been considerably beneficial.

Arrangements are being made to form a local technical committee that would have as its primary task the preparation of a government response to the implications of global climate changes on Venezuela's geography. In this sense, local official agencies dealing with environmental policy, and Venezuelan scientists related to the earth sciences, are being encouraged to initiate a work platform on the basis of collective action and shared efforts.

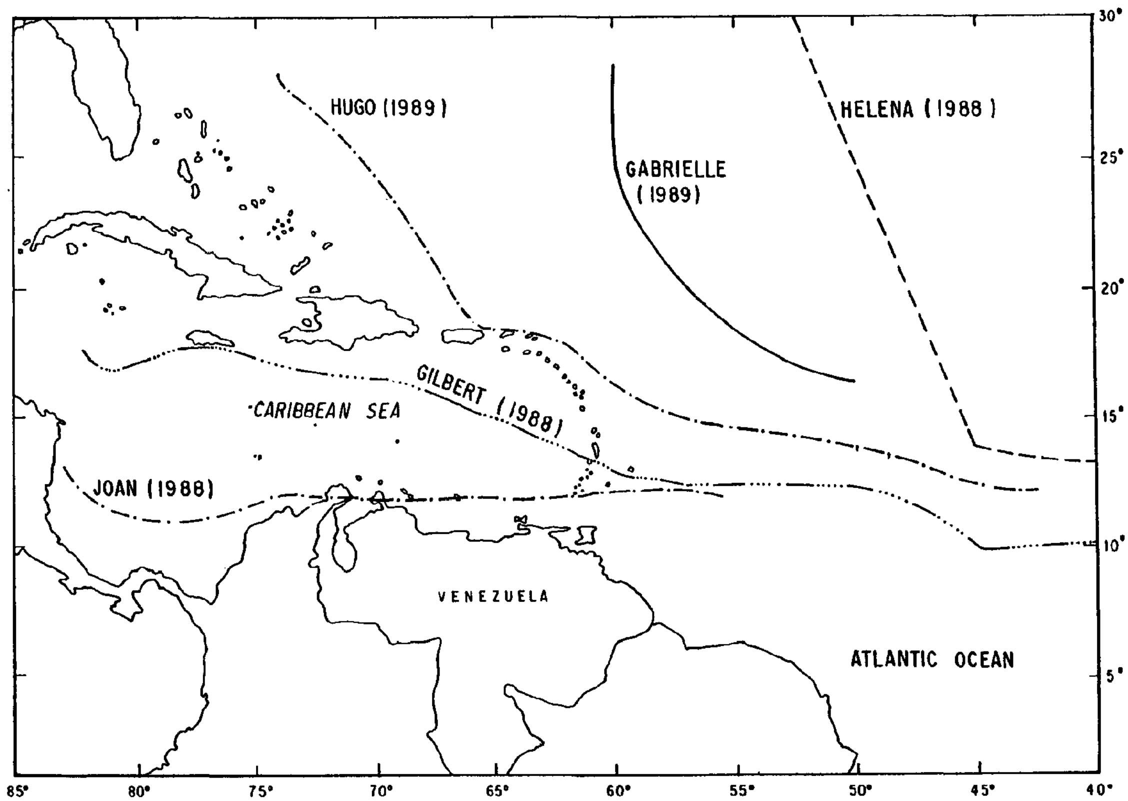


Figure 4. Track of the most destructive hurricanes affecting the greater Caribbean Sea region during 1988 and 1989.

This committee will be sponsored by the Ministerio del Ambiente y de los Recursos Naturales Renovable (MARNR), which is the national agency responsible for environmental policy in Venezuela. The following specific objectives are to be addressed by that committee in the immediate future:

- Coordinate national activities related to research and monitoring of meteorological and oceanographic surface conditions among all regional institutions charged with the responsibility of studying climate variability and its local impact.

- Expand the actual tidal-gauge network operating on the Venezuelan coastal boundary, taking advantage of our participation in the Global Observer System (GLOSS).

- Evaluate the feasibility of establishing onshore and offshore structures on critical coastal areas facing high risks due to sea level increases.

- Coordinate a long-term policy for reducing and reversing the ongoing deforestation of Venezuelan territory.

- Establish public education plans to promote better understanding of the topic of climate change and to assess its potential impacts on society.

- Motivate regional scientific centers related to environmental research to establish studies that will address and identify the degree of vulnerability of particular geographical areas to specific climatological anomalies.

- Stimulate research on alternate, nonconventional energy sources as part of a long-term policy devoted to reducing the use of fossil fuels, combined with more efficient use of energy, over the next few decades.

- Organize the Venezuelan contributions to global research programs about climatic changes and their implications, such as the World Ocean Circulation Experiment, Tropical Ocean Global Atmosphere Programs and the International Geosphere/Biosphere Program.

CONCLUSION

In view of the clear evidence that climatological anomalies on the coastal area of Venezuela have the potential to induce serious social, economical, and ecological implications, the Venezuelan government should consider this topic to be a matter of urgency. The need to compile inventories of natural coastal resources and existing environmental information must receive first priority, so that a worst-case climatological scenario can be developed for the country. This could provide an impact analysis that would facilitate the early implementation of an effective national policy.

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Without the cooperation of the following members of the Venezuelan scientific community, it would not have been possible to produce this report.

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BIBLIOGRAPHY

Aparicio, R. 1988. Some meteorological and oceanographic conditions along the southern coastal boundary of the Caribbean Sea (1951-1986). In: UNEP(OCA)/CAR WG.1 Report Implications of Climate Changes in the Wider Caribbean Region (in press).

Bird, E.C. 1985. Coastline Changes. A Global Review. New York: John Wiley & Sons.

Emanuel, K.A. 1987. The dependence of hurricane intensity on climate. Nature 326(2):483-85.

Maul, G.A., and K. Hanson. 1988. Sea level variability in the intraamerican sea with concentration on Key West as a regional example. In: UNEP(OCA)/CAR WG.1 Report Implications of Climate Changes in the Wider Caribbean Region (in press).

Schubert, C., and M. Laredo. 1984. Geology of Aves Island (Venezuela) and subsidence of Aves Ridge, Caribbean Sea. Marine Geology 59:305-18.

Shapiro, L.J. 1988. Impact of climate change on hurricanes. In: UNEP(OCA)/CAR WG.1 Report Implications of Climate Changes in the Wider Caribbean Region (in press).

IMPACTS OF AND RESPONSES TO SEA LEVEL RISE IN CHILE

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INTRODUCTION

The latitudinal extent of Chile's Pacific coastline offers a wide variety of geomorphological and oceanographic situations. The coast extends from 18° to 56° south, roughly equivalent to the latitudinal difference between Mexico's border with Guatemala and the Alaskan/Canadian border. If the indentation of the coast is taken into consideration, as well as the perimeter of numerous islands situated in the fiords region, the length of Chile's coastline is greater than 25,000 km. Figure 1 shows the variation of Chile's coast.

CHARACTERIZATION

Natural Features

Coastal Climatology

The Chilean coast is under the influence of tropical, subtropical, and temperate climates of western continental margins. The ocean has an important moderating influence upon the temperatures. As Fuenzalida (1971) points out, the temperatures between 20° S and 30° S are 2.8°C colder than the latitudes would suggest; between 50° S and 60° S they are 4.6°C warmer. Therefore, despite having a difference of almost 37 degrees of latitude, the difference of the mean temperature is only 12.8°C. By contrast, there is a marked difference in the total amount of precipitation. In Arica at 18°28' S, the total amount is 1.1 mm; on the other hand, in San Pedro at 47°43' S, the total annual amount is 4,076.1 mm (Figure 2).

Tides and Waves

Tides in Chile are generally mixed-semidiurnal; that is, two high waters and two low waters during a tidal day, with a diurnal difference.

A

B

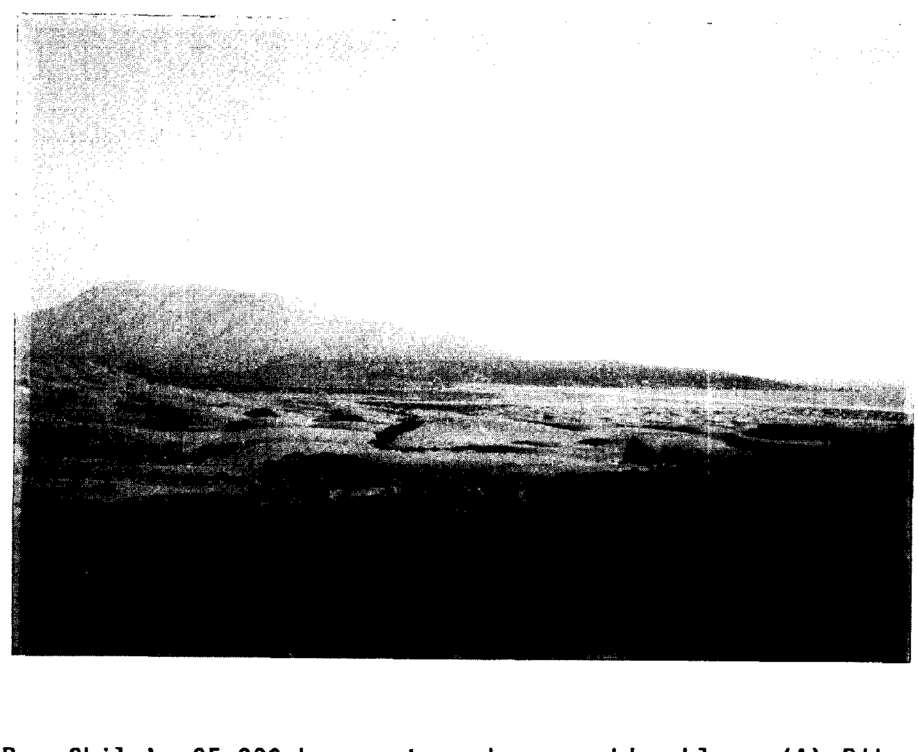

Figure 1A-B. Chile's 25,000-km coast varies considerably. (A) Ritoque (32° 48'S) -- artificial foredune; and (B) Longotoma (32° 22'S) -- sandy coastline.

C

D

Figure 1C-D. (C) Papudo (32° 30'S) -- storm surge effect. Beach is now replenished with dune sediments. (D) Punta Con Con (32° 55'S) -- Rocky coast, high terraces, with old stabilized dunes. By human interference, these dunes have been reactivated.

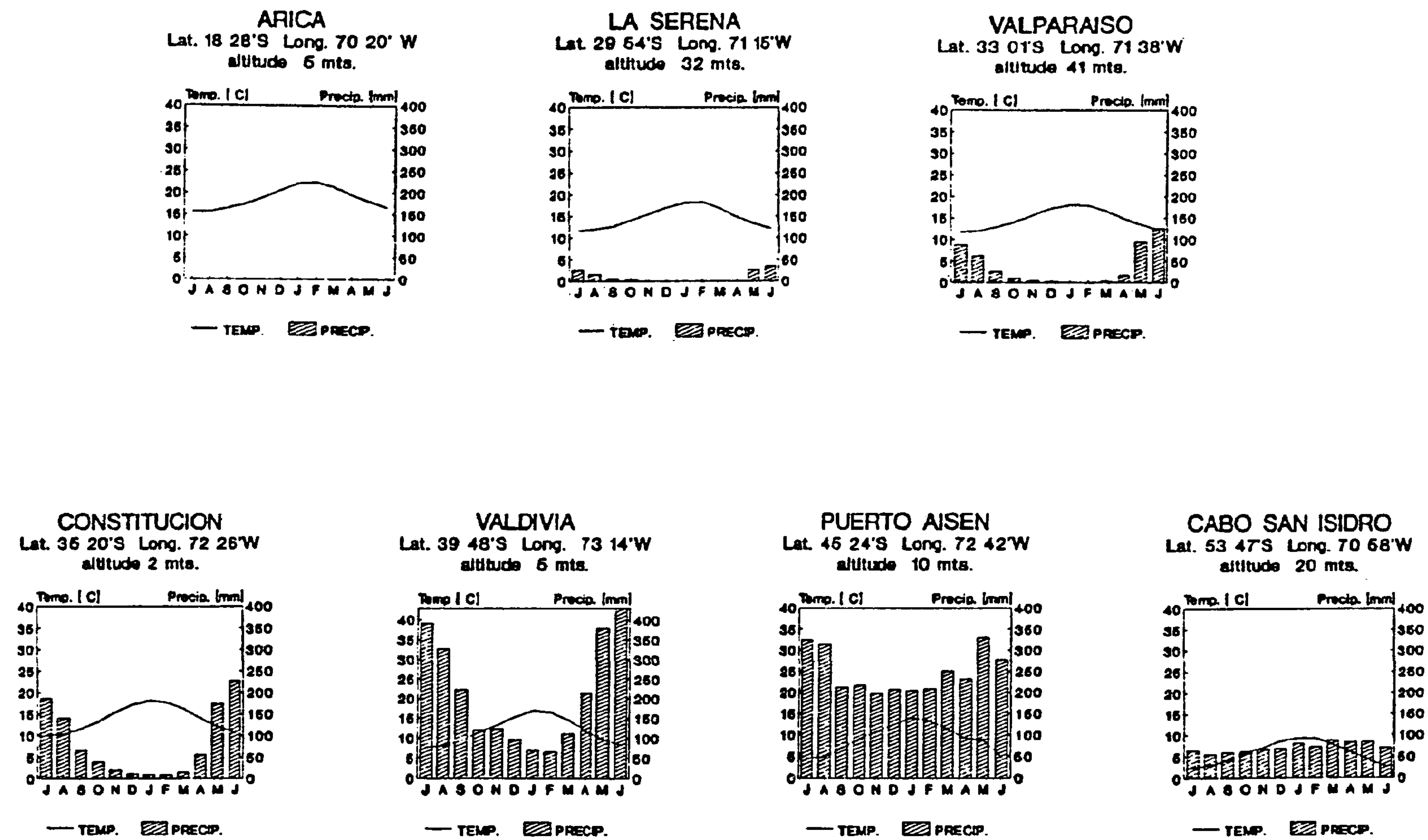

Figure 2. Chilean coastal climatic types. Note the great pluviometric contrast and thermic homogeneity.

The tidal ranges vary. Between 18° and 41° S latitude, the maximum amplitude is between 1.5 and 1.9 m, respectively. Within the fiords region to the south, especially between the Gulfs of Ancud and Corcovado, tides are 5 to 8 m because of a resonance effect. South of this sector, down to Punta Arenas at 52° S, the amplitudes vary between 1.8 and 2.5 m. There is a great contrast between the west and east entrances of the Straight of Magellan. At Punta Dungeness, the easternmost point, the amplitude reaches 10 m, while at the western entrance of the straight the amplitude is only about 2 meters. At the Tierra del Fuego islands to Cape Horn, the range is between 1.5 and 3 meters.

The information about waves on the coast, especially that collected with instruments, is scarce. Data exist primarily for the central area of the country, where there seems to be good correlation between wind patterns and wave patterns (see Appendix 1: Waves of Chile).

Surges

Storm surges occur occasionally on the Chilean coast; these are caused by large and intense atmospheric perturbances in the South Pacific, known as "Bravezas" in Chile. According to Paskoff (1970), they progress along the coastline from south to north in the form of great waves, many meters above the usual height reached by the storm waves, and linger 24 to 48 hours[1] (see Appendix 1).

Tsunamis

Since 1652, over 30 tsunamis have been recorded on the Chilean coast (I.H.A., 1982). With an expected 1-m rise, surges will increase their penetration inland. Generated by earthquakes and submarine movement, these have devastating effects. As an example, on 13 August 1868, the tsunami that affected the Port of Arica dragged the North American ship Wateree for more than 2 miles from its anchoring ground and finally deposited it 400 m inland over the coastal dunes.

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[1]This author's description of the morphologic effects and the wave levels reached during an event that occurred in 1968, which affected a coastal sector of approximately 2,500 km between Arica and Talcahuano, coincides with one presented by Araya-Vergara (1979). In 1968, a number of roads located more than 5 m above sea level were destroyed by waves, as were hotels, houses, and restaurants, which had foundations 5-7 m above sea level. In general, all points near the coastline situated at the holocene level "La Vega" (1-2 m) were affected by the "Bravezas," and various points situated above the Pleistocene level "Cachagua" (5-7 m) were also affected (for example, the airstrip of the naval aviation base at Quintero). The foredunes of various beaches of central Chile were eroded. The effects produced by these spasmodic phenomena, not very frequent, are long lasting and much more notorious than the effects of continuous wave action related to the usual storms occurring over several years.

Central and South America

Coastal Geomorphology

The Chilean coast between 18° S and 41° S is dominated by marine processes, acting under hyperarid, semiarid, Mediterranean, and oceanic temperate climates, with rocky coasts and pocket beaches dominating. To the south of this sector, oceanic temperate climate dominates, with domination by marine processes along the open coast to the west and fluvial domination in the inland fiords (Figure 3) (Appendix 2 provides more detail).

Neotectonics

A particular characteristic of the Chilean coastline is its great vertical mobility, the result of its location in a plate convergence zone. Because of this, strong movements of uplifting and sinking occur with magnitudes that surpass those expected from a sea level rise induced by the greenhouse effect. For more than a century, the data of various authors have shown that the magnitude of the vertical movements can frequently exceed 150 cm (Meneses Toro, 1897; Vidal Gormaz, 1901; Saint Amand, 1963; Pflaker and Savage, 1970; Fuenzalida and Harambour, 1984; Gonzalez, 1985).

It cannot be clearly distinguished whether the tendency is toward downfall or uplifting, because in some latitudes the coast has moved in both directions. However, there seems to be a slight predominance of uplifting north of 39° S and sinking south of this latitude.

The most recent movements have been determined by I.G.M. (1985), who found a mean uplift of 33 cm in the coastal sector of San Antonio-Algarrobo (33°20'-33°30' S) due to the earthquake of March 3, 1985. Barrientos et al. (1981), using the tide gauge of Puerto Montt (41° S), indicated an uplifting of the region of about 4.7 cm/year between 1964 and 1973, diminishing to 2.4 cm/year between 1980 and 1985; this same site sank 200 cm during the May 1960 earthquake.

Cities and Population

The population of Chile is approximately 12.5 million, 80% of which is urban and mainly concentrated in Santiago. The urban coastal population represents 21% of the total population, and a large part of it resides in urban areas of more than 100,000 inhabitants. The regions of Valparaiso and Bio-Bio together contain 55.35% of the total urban coastal population of the country.

The main coastal cities are located on coastal stepped plains separated by dead coastal cliffs. At first, the cities were located over the low (between 5 and 20 m) and narrow marine terraces but later they grew toward the higher terraces (Figure 4).

The main tourist centers are the sandy coasts of Coquimbo Bay (29° S) and the central coast (33°30' S). The bathing resorts extend over coastal dunes, including the foredune. Protection structures for wave action are infrequent, except in places where adequate structures for ports have been built, e.g.,

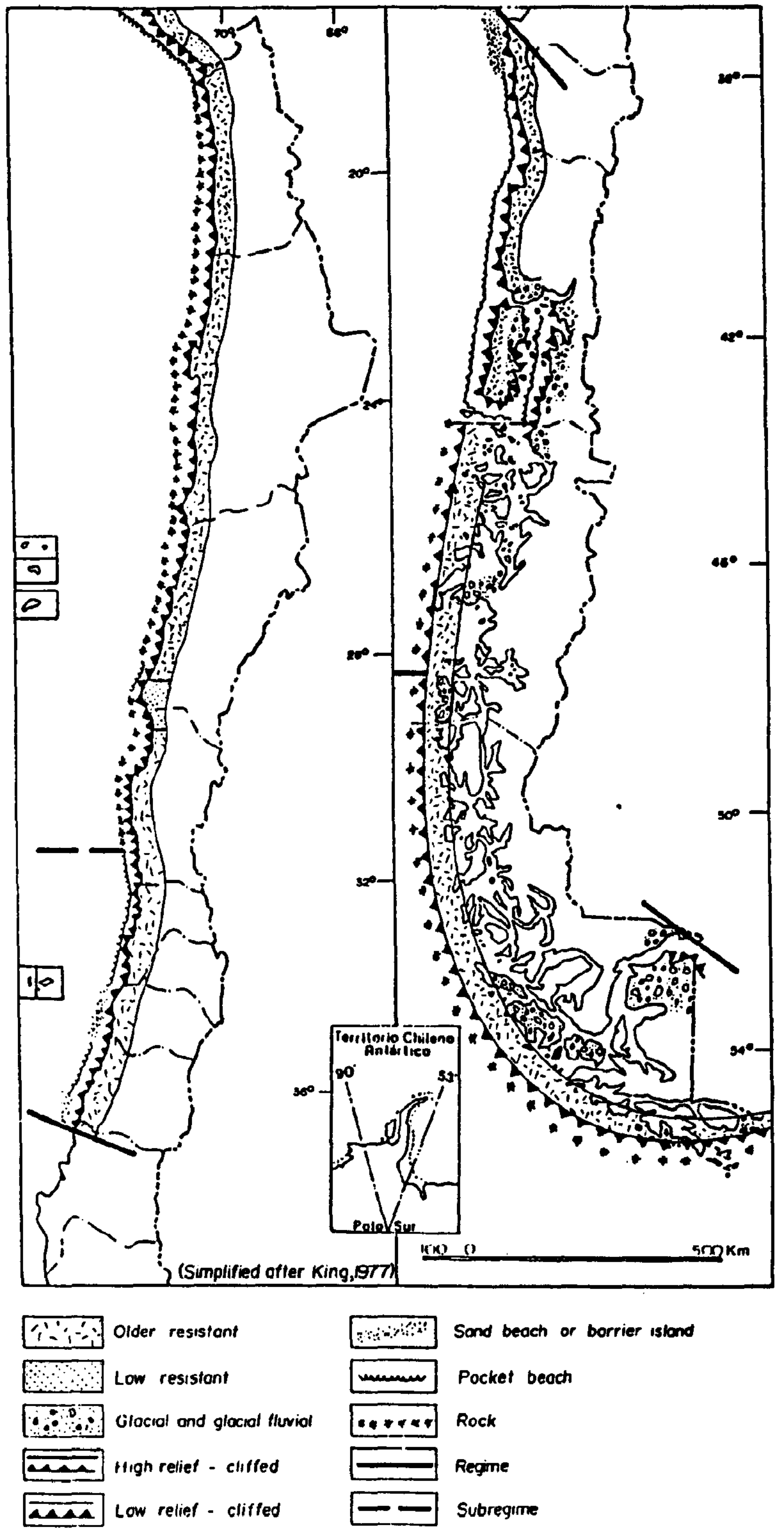

Figure 3. Coastal landform types.

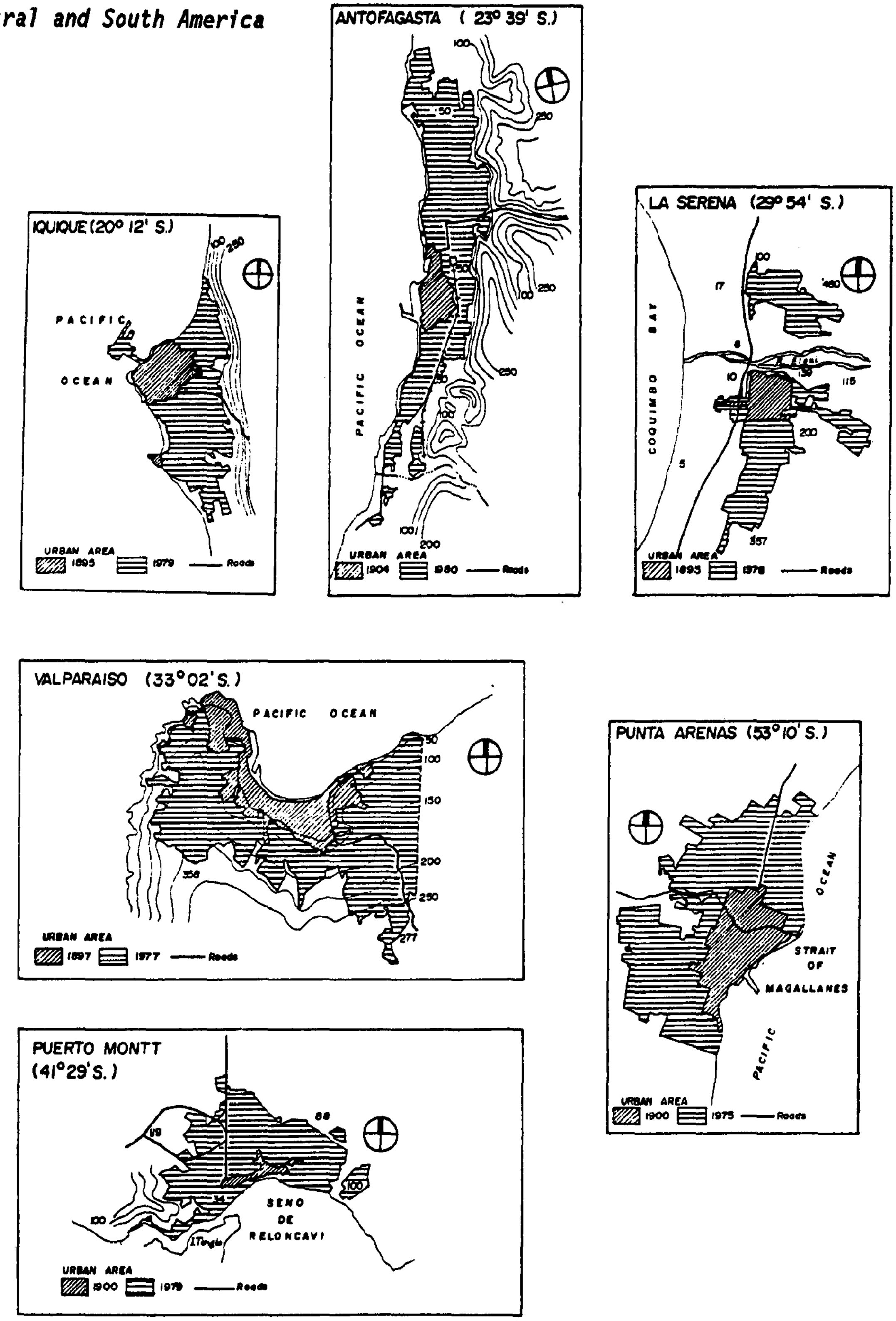

Figure 4. Some Chilean cities located over marine terraces.

docks, marinas. With a sea level rise of about 1-2 m, these bathing resorts will be only somewhat affected.

Economic Aspects

The National Accounts give an idea of the relative importance of some economic activities held in the coastal zone. The Gross Domestic Product was $18.5 billion (U.S. dollars). Tourism (primarily coastal, but incorporating activity from all over the country) accounted for 0.94% of this total, and fishing accounted for 0.88%.

IMPACTS OF SEA LEVEL RISE

The existing coastal national maps of Chile do not permit a quantitative evaluation of the area affected by a sea level rise of 20 and 200 cm, given that maps have contour intervals of 25 m or greater.

The Rocky Coastline

Considering the steepness of the rocky coast along its 30,000 km, a sea level rise of 20 cm will not have any noticeable effect. A 50- to 100-cm sea level rise would probably affect scarce coastal tourist installations, but only during storms.

A rise of 200 cm would produce effects on harbor structures, requiring their redevelopment, as happened in the tectonic sinking of 1960. A sea level rise of 100 to 200 cm would accelerate the recess of cliffs in soft rocks (sandstone) of the central zone of Chile affecting populated centers, essentially tourist centers.

South of 41° S, the attacking of the cliffs created in soft glacial outwash, will affect a great number of populated centers of the eastern coast of Chiloe. Coastal protection works would be necessary in this sector. We estimate that over 60 km of seawall will be necessary to shelter the threatened areas.

The Sandy Coastline

Although they constitute only 2.1% of the total coast, sandy shorelines support important economic activities (tourist and industrial as well as residential). All the pocket beaches are located in front of cliffy landscapes, so they cannot migrate inland in the eventual case of a sea level rise.

A sea level rise of 50 cm or more will substantially diminish the area of pocket beaches. A rise of 2 meters would eliminate them completely.

The sandy shorelines associated with dune fields have an important sediment supply from the rivers and enough space to shift inland. In this case, a sea level rise of 50 cm or more will affect the foredune, making it retreat inland. Important industrial facilities would be affected, particularly those at Quintero

Bay (32°46' S), San Antonio (33°33' S), Constitucion (35°18' S), and Talcahuano (36°42' S). Approximately two-thirds of all the coastal bathing resorts would be partially inundated.

RESPONSES

Institutions and Agencies Associated With the Coastal Zone

The national administrative organizations related to the coastal zone are within three independent ministries:

1. Ministry of National Defense, Marine Subsecretary, which consists of

   a. General Office of the Marine Territory and Merchant Marine. This organization has the control and monetary responsibility for the entire coast, territorial sea, and exclusive economic zone of the Republic. Its inland jurisdiction extends 80 m inland, starting at the limit of the spring high tide line. The essential mechanism for control of the coastal area lies with the members of this office, who permit the particular use in any form of beaches, beach lots, the sea floor, portions of water, and rocks within and/or out of the bays. The agency also has responsibility for issuing permits for extraction of sediments and landfill for coastal engineering.

   b. Navy Hydrographical Institute. This agency is in charge of all studies and preparation of documents for navigational aid, such as tide tables, marine navigational charts, and navigational tracks. It is also in charge of meteorological forecasting and doing basic research in oceanic and coastal physical oceanography. It is a member of the International Tsumani Alarm System of the Pacific.

2. Ministry of Public Works, Harbor Works Office. This agency is in charge of the design, calculation, and studies of harbor works, and conducts research in coastal oceanography.

3. Ministry of Economy, National Fishery Service. Administers the fishery sector, promotes and coordinates investigation in this domain. This office is in charge of the methods and installations of aquaculture, fishing quotas, and extraction of live products from the littoral zone.

The previously named institutions, together with other institutions from a group of Chilean universities, form the CONA or "Comite Oceanografico Nacional" (National Oceanographic Committee).

The CONA has prepared a National Oceanographic Plan for the period 1987-97, which is based on a four-year survey of national institutions concerned with oceanic scientific technological work. Five research programs are proposed to investigate the structure and interrelationships of ecosystems within Chilean seas.

Agency Perceptions About Greenhouse-Induced Sea Level Rise

Conversations held with members of some of the relevant agencies suggest that a sea level rise of 20-50 cm is not perceived as a problem. Because there is a lack of awareness concerning a greenhouse effect-induced sea level rise, no one is planning a response to it. Local planners are more concerned about solving current problems; nevertheless, they indicate that when it becomes necessary to protect small fishery facilities or installations in contact with the beach, they will support solutions based on seawall tetrapods.

Also, due to the effects of strong winter storms, some tourist beaches have been nourished with sand. The filling is done with sediments extracted from inland deposits. In some cases, the foredune has been elevated using mechanical and vegetational methods. This is done because of dune management and not as a response to a marine erosion.

Frequently, local planners have been forced to respond to tectonic sea level rising, but this is not predictable and for this reason they do not consider a slow sea level rise of 20 to 50 cm over many years to be an emergency.

Chilean government agencies will be able, from a technological point of view, to apply protective actions in critical areas when the problem is adequately evaluated.

APPENDIX 1: WAVES OF CHILE

The reports that give the most adequate synthetic view are those of Araya-Vergara (1971, 1979); both are on central Chile. The information provided by Davies (1980) based on the works of Holcombe (1958) and Meisburger (1962) gives a very useful integrated view.

Holcombe (1958) concluded that in the Southern Hemisphere, the mean latitude of the zone of maximum value of gale force winds oscillates only between 54° S and 56° S during the winter-summer period. Because of this persistence of high-frequency gale-force winds and the length of the fetch, the southern storm belt is the most evident and important wave-generating area in the world and produces a high proportion of the world's ocean swell (Davies, 1980).

The path followed by the swell generated at latitude 55° S in front of the Chilean coast produces wave trains with a west and southwest component from 41° S toward the north. This pattern of waves makes the coast of Patagonia the most attacked by storm waves during the year.

With the data compiled by Meisburger (1962), Davies presents various synthesis charts in which it is possible to appreciate that for the Chilean coasts the frequency of occurrence, in at least half the year, of waves of 2 m or higher is as follows:

South Latitude	%
38° - 56°	> 40
38° - 30°	30 - 40
30° - 25°	20 - 30
25° - 18°	10 - 20

The greatest height reached by waves occurring with a frequency of 3% or greater in at least half the year is as follows:

South Latitude	Height (m)
56° - 45°	> 6.0
45° - 40°	6.0 - 5.0
40° - 22°	5.0 - 3.7
22° - 18°	3.7 - 2.2

In a more detailed scale, Araya-Vergara (1971) shows the wave characteristics in Chile, according to the works of D.O.P.-Tudor Eng. Co. (1965), as well as the unedited reports of the Laboratoire Central d'Hydraulique de France, for Constitucion (35°18' S) and San Antonio (33°35' S). The results of his analysis indicate that the origin of the most frequent waves is from the southwest, which coincides with the prevailing winds.

In Arica in December 1975 and July 1977, with a total of over 3,396 waves recorded, the mean period during the summer had a value of 12 seconds and a significant height of 1.15 m; during winter the mean period was 9 seconds and the significant height was 1.3 m.

In Iquique there are only data for the month of June 1987. Using 1,336 waves, the mean period was 11.02 seconds with a significance height of 1.08 m.

The wave data are scarce and discontinuous. They refer only to a sector of the coast dominated by the southern west coast swell environment.

There are no automatic wave records situated along the coast dominated by the southern storm wave environment, especially south of 41° S.

Important differences between the coast facing directly the open Pacific and those of the interior waters of the fiord coast probably exist.

APPENDIX 2: GEOMORPHOLOGY OF CHILE

Distribution of Cliffed Coasts

According to Araya-Vergara (1982), the length of the cliffed and rocky coastline is 33,711 km; 700 km of the northern region of Chile correspond to the mega-cliff described by Paskoff (1978), along which can be distinguished four sections. The first section, between 18°28' S and 20°13' S, is an active cliff with unevenness between 400 and 1,000 m; a second section between 20°13' S and 21°24' S is a dead cliff behind a terrace 2 to 3 km wide; a third section between 21°24' S and 23°28' S, with unevenness between 500 and 1,200 m, is also a dead cliff with a terrace in front, composed of marine Miocene deposits, sculpted by the sea; the fourth section, which reaches 25°22' S, presents active and dead sectors, with mean heights of 500 m, but in some places it can reach an altitude of 2,000 m. This is a major feature of the north coast of Chile. In general, in this sector hard rocks appear on the surface, giving a stable appearance.

South of 25° to 33°44'S there are predominantly cliffs and bluffs in essentially igneous formations. Another section also with predominance of cliffs but in tertiary soft sedimentary rocks as well, is developed to 36°30'S. From this sector to 43°30'S are hard cliffs sculpted in micha-schists alternating with soft tertiary sandstone. It is also possible to distinguish an internal sector between 41° S and 43° S with soft cliffs sculpted essentially in glacial outwash, but in sheltered environments. From 43° S to 56° S, hard rock cliffs and bluffs dominate with some morainic intercalations.

Distribution of Low Unconsolidated Coasts

The lower coasts, including the deltas, constitute 2.1% of the total; according to Araya-Vergara (1982) they add up to 580 km. They are discontinuous and concentrated in groups related with the existence of fluvial sedimentary sources and with a minor association, to soft sedimentary rocks at the shoreline. The main groups of beaches which can be distinguished are the following:

29° S - 30° S...........Coquimbo - La Serena
32° S - 33° S...........Longotoma - Concon
33° S - 37° S...........Chile Central
38° S - 43° S...........Arauco - Chiloe

In general they are in dynamic equilibrium, with not much evidence of retreat or advance in the long range. However, Andrade (1985) has found evidence of recession in the Chiloe coast, in the internal sector. It may be explained by a relative sea level rise due to recent subsidence movements and applications of the Bruun rule.

Most of the constructed coasts correspond to beach ridges, composed of sand. In the interior coast of Chile spits and hooks are very frequent, formed by sand and gravel that the sea extracts from the cliffs sculpted in glacial outwash. At Tierra del Fuego it is common to find beaches supplied by morainic deposits.

A great number of beaches along Chile correspond to pocket beaches, which are located over rocky platforms between resistant rocky promontories. Although data are scarce, our observations from fieldwork in central Chile indicate that they have a general thickness less than 4 m at the backshore.

A frequent phenomenon in central Chile is the development of coastal dunes, associated with beaches which are generally located north of the river inlets. This ensures a good sedimentary supply because of the longshore drift generated by waves mainly from the southwest, which coincides with the prevailing winds and which also transports the sand inland.

The principal coastal dunes are located between 29° S and 42° S. They cover approximately 131,000 hectares, according to the inventory made by IREN-CORFO (1966). Most of the modern active dunes are located between 33° S and 38° S according to Castro (1985).

Castro (1985) provided a synthesis of the different morphologic elements found in the coastal dunes, distinguishing:

a) The foredune.

Located in contact with the backshore forming a parallel band to the beach, its width is variable between 50 to 200 m; the average height is 5 m. There is a close association between the morphologic aspect of the dune and the vegetation found on it. Thus in central Chile, the foredune is composed of a group of hummocky dunes, elongated in the direction of the wind, with a pointed tail to leeward. They are separated by deflation corridors. There are obstacle dunes produced by the capture of sand by vegetation . The most frequent species is Ambrosia chamissonis, which possesses a radicular system which develops to great depth; it is an accidentally introduced species from California (Kohler, 1970), which apparently is substituting for the native species Carpobrotus chilensis, which helps form lower dune hummocks.

The Chilean foredune does not have the aspect of a continuous wall as in North America or the northwest coast of Europe, colonized by Ammophila arenaria, but has aspects of a nebkha field. In some places where dune control has been applied with Ammophila arenaria, the foredune gives a massive appearance as in the case of Chanco (35° S).

b) Interdune depression.

A depression separates the foredune from the moving sand ridges of the interior. It has a variable width; its major axis is parallel to the beach, frequently comprising an active deflation area and sand transportation area. But on occasions, it may be occupied by a coastal lagoon or a marsh. In this sector the water table is very close to the surface, so it has vegetation adapted to these conditions such as Scirpus nodosus. The depression may also develop by the deflation of old coastal ridges.

c) Moving sand ridges.

These occupy the greatest area within the dune field. They have a variety of forms, in which we can distinguish some individuals, such as barkhans. The coalescence of barkhans leads to transverse dunes which are organized as waves moving to the interior many hundreds of meters, invading agricultural lands and villages. They do not have vegetation cover.

d) Stabilized dunes.

Frequently in contact with active dune fields are various generations of dunes stabilized by natural vegetation. A variety of this group are the longitudinal dunes, which appear within this axis in the same direction as the prevailing wind. They present associations of Puya chilensis and Cereus sp.

Other morphological types are the undulated dunes. Their vegetational layer is composed by low gramineous and bushes such as Baccharis concava.

Both of the described stabilized dune forms are dated as Holocene (Paskoff, 1970; Caviedes, 1972). Holocene dune reactivation can be verified in many places starting as blowouts, evolving on occasion as parabolic dunes. The origin of the reactivation is normally because of human interference.

A third variety of stabilized dunes corresponds to hills which are smoothly undulating and which have not lost totally their original form due to natural and anthropic causes. Paskoff (1970) assigns them a Pleistocene age. They may be covered by mesomorphic scrub bush more or less dense.

A sea level rise of 1 m could affect rapidly the foredune, but the Holocene dunes would not be affected immediately.

Distribution of Aquatic Features

Wetlands

Although there has been no inventory of wetlands in the country, or estimates as to the dimension or nationwide distribution of wetlands, a few reports give us a general idea of their morphology and their floristic composition.

Geomorphologically, Andrade (1985) described some tidal marshes on the Gulf of Ancud showing morphological patterns similar to those of the temperate zone of the Northern Hemisphere. In this study area they show evidence of erosion by the sea due to a tectonically induced sea level rise caused by crustal subsidence.

In relation to their requirements of low wave energy and great tidal range, they tend to develop better between 40° and 43° S in protected positions in estuaries or behind sand barriers. In the botanic studies done by Ramirez et al. (1988), Schwaar (1978), and Reiche (1934), some of the halophytes described are Triglochin maritimun, Cotula coronopifolia, Eleocharis melanostachys, Selliera radicans, Spartina densiflora, and Salicornia sp. In general, the tidal marshes develop adjacent to a cliffed landscape in the Gulf of Ancud. A rapid sea level rise would probably endanger the permanency of these intertidal ecosystems, since in many cases they do not have space to migrate upslope because they are bounded by bluff coasts.

APPENDIX 3: AVAILABLE CARTOGRAPHIC AND AERIAL PHOTOGRAPHIC DATA

The actually available cartographic documents are produced and distributed by two agencies of the Ministry of Defense: the Instituto Geografico Militar (IGM) and the Instituto Hidrografico de la Armada (IHA). The first agency produces topographic charts, and the second agency produces navigational charts.

The IGM charts exist in various scales and projections, and cover the country partially according to the scale:

Scale	Coastal Sector	Contour Interval
1:500,000	18° S - 56° S	Form Curve
1:250,000	18° S - 27° S	250 m
	53° S	250 m
	55° S	250 m
1:100,000	18° S - 27° S	50 & 100 m
1:50,000	18° S - 47° S	25 & 50 m
1:25,000	30° S	25 & 50 m
	31° S	25 & 50 m
	37° S	25 & 50 m
	40° S	25 & 50 m

The IHA navigational charts include only bathymetric data in meters. They, as well as the IGM charts, cover the country partially. Due to its specific purpose, there is a greater scale variety; therefore we will only indicate the number of charts for each scale.

Scale	No. of Charts	Scale	No. of Charts
1 : 3,000,000	2	1 : 45,000	2
1 : 2,000,000	2	1 : 40,000	35
1 : 1,000,000	2	1 : 35,000	5
1 : 500,000	10	1 : 32,000	4
1 : 260,000	1	1 : 30,000	40
1 : 250,000	2	1 : 25,000	19
1 : 200,000	16	1 : 24,000	1
1 : 165,000	1	1 : 20,000	72
1 : 150,000	8	1 : 16,000	2
1 : 130,000	1	1 : 15,000	53
1 : 125,000	1	1 : 12,500	1
1 : 100,000	13	1 : 12,000	5
1 : 80,000	2	1 : 10,000	94
1 : 75,000	1	1 : 8,000	20
1 : 70,000	3	1 : 7,500	1
1 : 65,000	1	1 : 6,000	5
1 : 60,000	5	1 : 5,000	20
1 : 50,000	20	1 : 4,000	3
		1 : 2,000	2

There are various vertical aerial photo missions. The Photogrametric Service of the Air Force (SAF) is officially in charge of producing this type of document. However, many other missions produced by other agencies in the past are available.

Year	Approx. Scale	Latitude	Agency
1942-45	1 : 30,000	?	USAF
1955	1 : 70,000	17°30'- 37°10'S	HYCON
1961	1 : 20,000	37°- 38°20'S	HYCON
1961	1 : 50,000	37°- 43°30'	OEA
1974-75	1 : 55,000	32°15 - 34° 43°30 - 51°	SUSAF
1978-80	1 : 30,000	33° - 41°S	SAF
1978-80	1 : 60,000	18° - 56°S	SAF

On occasion, other charts and aerial photographs, which were produced for specific uses, can be obtained through public and private organizations. These documents are not standard issues; therefore, there are no general indices for them.

BIBLIOGRAPHY

Andrade, B. 1985. Estudio morfosedimentologico de marismas del Golfo de Ancud, Chile. Revista de Geografia Norte Grande 12:27-33.

Araya-Vergara, J.F. 1971. Determinacion preliminar del las caractersticas del oleaje en Chile central. Not Mens. Museo Nac. Hist. Nat. Santiago, Chile 15(174):8-11.

Araya-Vergara, J.F. 1972. Bases geomorfologicas para una division de las costas de Chile. Informaciones Geograficas 22:5-36.

Araya-Vergara, J.F. 1976. Reconocimiento de tipos e individuos geomorfologicos regionales de la costa de Chile. Informaciones Geograficas 26:9-30.

Araya-Vergara, J.F. 1979. Las incidencias cataclismaticas de la bravezas en la evolucion de la costa de Chile. Informaciones Geograficas 26:19-42.

Araya-Vergara, J.F. 1982. Analisis de la localizacion de los procesos y formas predominantes de la linea litoral de Chile: Observacion Preliminar. Informaciones Geograficas 29:35-55.

Barrientos, S., S.N. Ward, and E. Lorca. 1981. El terremoto de 1960 en el sur de Chile y sus deformaciones cuasi-permanentes. Comunicaciones 39:158.

Canon, J.R., and E. Morales. 1985. Geografia del Mar Chileno. Colecion Geografia de Chile. Santiago, Chile: I.G.M. Vol. IX., 244 p.

Castro, C. 1985. Resena del estado actual de conocimiento de las dunas litorales en Chile. Rev. de Geografia de Chile Terra Australis 28:12-32.

Castro, C. 1988. The Artificial Construction of foredunes and the interference of dune-beach interaction. Journal of Coastal Research (Special Issue No. 3).

Caviedes, C. 1972. Geomorfologia del cuaternario del Valle del Aconcagua. Chile Central. Cuad. Geogr. Friburg No. 11.

Davies, J.L. 1964. A morphogenic approach to world shorelines. Zeit. fur Geomorph. 8:127-142.

Davies, J.L. 1980. Geographical variation in coastal development. Geomorphology Texts No. 4. London: Longman. 212 p.

D.N.H.A. 1961. El maremoto del 22 de Mayo de 1960 en las costas de Chile. Publicacion No. 3012. Valparaiso, Chile: Departmento de Navegacion e Hidrografia de la Armada. 129 p.

Fuenzalida, R., and S. Harambour. 1984. Evidencias de subsidencia y solevatamiento en la peninsula de Brunswick, Magallanes. Comunicaciones No. 34. Sanitago, Chile: Universidad De Chile, p. 117-120.

Fuenzalida-Ponce, H. 1971. Climatlogia de Chile. Santiago, Chile: Universidad de Chile, Departmento de Geofisica y Geodesia. Publicacion Interna de la Seccion Meteorologia. 73 p.

Gonzalez, O.M. 1985. Mapa neotectonico preliminar de America del Sur. Ceresis. Santiago, Chile: I.G.M.

Holcombe. 1958. Similarities and contrasts between the Arctic and the Antarctic marine climates. In Polar Atmosphere Symposium. Part I. Metheorology. London:

I.G.M. 1985. El terremoto del 3 de Marzo de 1985 y los desplazamientos de la corteza terrestre. Rev. Geog. de Chile Terra Australis 28:7-12.

Inman, D.L., and C.E. Nordstrom. 1971. On the tectonic and morphogenic classification of coasts. Journal of Geology 79:1-21.

I.H.A. 1982. Instituto Hidrografico de la Armada. Maremotos en la costa de Chile. Publicacion 3016. Valparaiso, Chile: I.H.A. 48 p.

IREN-CORFO. 1966. Inventario de dunas en Chile (29° 48' - 41° 50' Lat. sur). Publicacion No. 4. Instituto de Investogaciones de Recursos Naturales CORFO. 20 p. July.

King, C.A. 1977. Classification and morphometry of the coast between 20° S and 42° S. Rev. Geog. Valparaiso 8:27-57.

Kohler, A. 1970. Geobotanische untersuchungen ankustendunen Chileswischen 27 and 42 Grad. Sud. Breite. Bot. Jahrb 30:50-200.

Kohler, A. 1967. Die entwicklung der vegetation auf kustendunen mitelchiles. Umschau in Wissenschaft und Technik. 20/67:666-667.

Meisburger, E.P. 1962. Frequency of occurrence of the ocean surface waves in various height categories for coastal areas. U.S. Army Engineer Research and Development Laboratories. Report 1719-RR.

Meneses, T.J.N. 1897. Jeografia de Chile. Santiago, Chile: Imprents El Comercio. 159 p.

Orson, et al. 1985. Response of tidal salt marshes of U.S. Atlantic and Gulf coast to rising sea level. Journal of Coastal Research 1(1):19-37.

Paskoff, R. 1970. Le Chili semi-aride. In: Recherches Geomorphologiques. Bordeau, France: Biscaye Freres. 420 p.

Paskoff, R. 1978. Sur l'evolution geomorphologique du grand escarpement cotier du Desert Chilien. Geogr. Phys. Quat. 32(4):351-360.

Pflaker, G., and J.C. Savage. 1970. Mechanism of the Chilean earthquakes of May 21 and 22, 1960. Geol. Soc. Amer. Bull. 81:1001-1030.

Central and South America

Ramirez, C. et al. 1988. Estudio vegetacional de una marisma del centro-sur de Chile. Medio Ambiente 9(2):21-30.

Reiche, C. 1934. Geografia botanica de Chile. Santiago, Chile: Imprenta Universitaria.

Saint-Amand, P. 1963. The Great Earthquakes of May 1960 in Chile. Washington, DC: Smithsonian Institution. pp. 337-363.

Schwaar, J. 1978. Halophyten-gesellschaften in Sudchile. Verhandlungen der Gesellschaft fur Okologie Kiel 1:409-411.

Tudor Eng. Co. 1965. Report for a Waterfront Facility. Constitucion, Chile. San Francisco, CA: Tudor Eng. Co. 276 p.

Vidal Gormaz, F. 1901. Hundimientos i solevantamientos verificados en las costas Chilenas. Revista Chilena Hist. Nat. (Valparaiso) 5(10):213-224.

LIVING STRATEGIES AND RELOCATION IN LATIN AMERICA

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ABSTRACT

Accelerated sea level rise will produce multiple and irreversible transformations locally, regionally, and nationally in Latin America. Such changes will not only involve geographic and economic aspects of the countries, but also will produce irreparable losses to their historical and sociocultural inheritance, particularly in the affected communities.

This paper focuses on how to study the implications of relocation, not the implications themselves, with particular emphasis on "strategies for living" with the relocation of affected communities, which is at present a well-known concept in the Latin American social sciences field. This criterion makes it possible to account for all the dimensions of social effects -- i.e., demographic, socioeconomic, or cultural. It is defined as "the way in which the community is organized and uses its environment." The family group is the primary unit of analysis; the local community is also considered.

Because most inhabitants near the shore are subjected to marginal economies bordering on poverty, such "strategies for living" may be little more than strategies for survival.

INTRODUCTION

In Latin America, sea level rise will have multiple and irreversible social, economic, and cultural effects locally, regionally, and nationally. These effects will be so extensive that even the interior provinces will be affected, because national transport, services, trade, and production centers are located on the coast. Direct damages to these centers will affect national activities and will bring about new physical, social, economic, and cultural configurations, significantly restructuring communities and the future historical process.

The resettlement process is a <u>social</u> process that frequently is overlooked in favor of the costs of flood damages, coastal defense, and other <u>physical</u> effects of flooding. Frequently, poor families settle in coastal areas near cities because urban centers supply services, consumer goods, and transitory and informal work sources. Consequently, we must design a relocation policy that takes into account not only the losses of goods and dwellings, but also the disruptions in the formal and informal links of the local community at all levels.

We have developed a "living strategies" concept for the population in general and "survival strategies" for the most impoverished sectors. These strategies account for all the demographic, socioeconomic, and cultural dimensions that must be considered when relocating communities. According to Cernea (1989), in general, previous efforts to relocate communities have often failed because people focused on physical logistics and underestimated the social, cultural, political, and labor-market effects.

This paper lays out an analytic structure by which one could analyze the social effects of relocation strategies. We warn the reader at the outset, however, that the paper does not specifically address the effects themselves.

THE RESETTLEMENT PROBLEM

Involuntary displacements of population due to sea level rise would cause economic and cultural shocks to many communities and destroy production goods, valuable natural resources, and the local environment. Such displacements would also create problems in areas that receive the transplanted population, because if vacant land were scarce, the available natural resources would be severely taxed (Cernea, 1989). Partridge (1983) wrote "the relocation process destroys a pre-existent form of life." It transforms "every form of life, in all its different aspects, such as institutional and social ones, economic systems, guidelines to the community organization, power structures, everyday activities, or the cultural tradition."

Because having one's hometown destroyed can give people a feeling of helplessness, relocation strategies should focus on returning to the people some control over their own lives, similar to the control they previously had. (It cannot be exactly like the original control, because the preexisting socioeconomic organization will not exist after the resettlement.) In addition, officials in Latin America must take three important factors into account: (1) the characteristics of the people to be relocated: in general these people belong to the lowest socioeconomic stratum, which is why the relocation problem is inseparably linked to the survival of these sectors; (2) the sociocultural identity crisis, which makes people question the efficiency and validity of their traditional strategies and survival schemes and increases their uncertainty to such an extent that it immobilizes their capacity to respond; and (3) the impact produced on social relations networks, on the existing leadership structure, and on the behavioral guidelines.

METHODOLOGICAL APPROACH

Analyses of resettlement strategies should follow three guidelines: Do not collect socioeconomic and cultural data without taking into account the model of possible relocation policy. On the contrary, put the data in the order of the model from the precise moment of their recollection, description, and analysis. Otherwise, the data will not be read in their proper context. The model must consider the specific characteristics of the flooded area (which are seldom included), and its type of links with the affected population. Finally, the scheme must carry out an analysis in a more complex field than that of the usual socioeconomic descriptions. Actually, sudden relocation basically affects the population living strategies that include a number of relationships -- e.g., economic cooperation, neighboring links -- the modification of which gives rise to the main social and economic cost that we are trying to reduce.

Defining this theoretical scheme is necessary for creating living strategies that are equivalent to the present ones, so as to satisfy the needs of the transplanted population. This "equivalent reposition" not only refers to the replacement of affected dwellings and goods but also to the possibility of obtaining work and earnings.

UNIVERSE OF ANALYSIS

According to the previous scheme, we define as "universe under study" the population whose link to the area represents a significant component to its living strategies. That is, not only are the residents in the area included, but also the nonresidents who maintain ties (of labor, patrimony, etc.) with that area, developing in this way some aspect of their overall living strategy. Then, the main question is, Which are the modalities of that link between the population and the affected area? These relations occur at different dimensions (demographic, social, cultural, and economic) and result from the particular historic development of the area, from its cultural reality, from its regional economic institutions, and from its physical features (COMIP, 1984). It is also necessary to analyze the compulsory vs. uncompulsory character of that link. Among all the possible modalities, the most essential is that of the compulsory link on an economic basis. This category includes the economic activities that require the concurrence of some of the features of the area, such as obtaining the area's raw materials (ichthyic fauna, soil materials, etc.) and food (fishing), using its water for transport, using the area's coastal features or its proximity to urban centers and ports for supplies and services, and using its resorts for recreational activities and its land for production or dwelling. The uncompulsory link, which can be easily reproduced in another area, will include agricultural activities that are not inherent to the area, industrial and commercial activities that do not require the area's raw materials, community services (health, education, dwelling, etc.), and the familiar or community links (cultural, religious, political, ethnic, etc.).

LIVING AND/OR SURVIVAL STRATEGIES

In developing relocation strategies, we are not dealing with good or bad players who follow strategies either to win or to lose. Rather, we are concerned with human beings who are doing their best to survive (Bartolome, 1983). Also, the unit of analysis is not the individual, but rather the family, since people organize themselves in families so as to face the problem of living.

Central and South America

First of all, the survival strategies concept is used to study the implications between the population factors (fertility, and familiar structures and types) and a community's economic structure (productive patterns, labor markets, etc.). Later on, the concept is enlarged to include politics and organizing behavior, provided the basic needs are satisfied not only in the area of economics but also the areas of the society and politics. First, of the strategies the poor social groups or sectors were analyzed. Then, with the prompt diffusion of the concept, the middle and even the most privileged layers of society were investigated. This approach allowed for the literature to include generic definitions as well as more restricted and specific formulations.

As an example of the first type, it is worth mentioning the definition that describes the survival strategies "as the attitudes or arrangements that take place in the family to face the problem of existence or living, which in many cases does not surpass the survival level" (Rodriguez, 1981). Consequently, any type of family belonging to any social group or stratum can be the subject of a strategy. Because of this definition, the living strategies notion has been adopted.

In contrast, among other authors who use restricted formulations are Duque-Pastrana (1973), who introduced this concept to the social sciences. They have sustained that in order to ensure the family income, the survival strategies must delineate the economic roles of every member of the family, even extended family members. From this point of view, the subjects are exclusively families belonging to the impoverished sector of society, and the strategies are only of an economic sort. Aside from their discrepancies, the different approaches have overlapped on the following items:

- the unit of analysis is the family instead of the individual;
- the survival or living strategies vary according to social strata; and
- the strategies are subjected to the prevailing "economic structure."

In this work we will define the "living strategies" concept as the modality in which the unit organizes itself and makes use of its resources to reproduce and/or optimize its material and nonmaterial conditions of existence; "survival strategies" has a corollary definition, applied to the poorest social strata. This definition is chosen because the problem of relocation involves all the social sectors of the area to be flooded and these people are affected not only economically but also socially, demographically, and culturally.

Groups who develop the living strategies consist of individuals who are linked to one another by bonds that admit a common past and that jointly project toward the future. The living strategy they use assigns the participatory roles to each member of the group. The strongest group is the family, the fundamental unit of analysis. We define this group as people whose association is based on sharing a residence; being linked by blood or marriage; interacting daily, regularly, and permanently; and tending jointly to the reproduction and/or optimization of their material and nonmaterial conditions of existence.

THE ENDOGENOUS COMPONENTS OF THE STRATEGIES

Because of the complexity of the problem of relocating, it is not easy to delimit precisely the components of the living strategies, at least at the level of those categories and variables that constitute them. Nevertheless, advances provided by the specialized literature define a basic group of aspects or dimensions of them that can be arranged according to different fields in which they appear.

For example, in the socioeconomic field, the relevant elements are connected with activities that involve obtaining goods and services to fulfill the unit's basic needs. They include ways of being part of the productive structure, such as in the employment arena; how the work is organized within the unit; ways and sources for consuming goods and services; the network of interchanging goods and services; and the network of mutual aid or extrafamiliar cooperation.

In the cultural field, special relevance is acquired by the values and the rules put into practice in the acquisition and preservation of goods and services (e.g., attitudes toward the role of women). These habits, attitudes, and behavior are passed on through social inheritance (Bartolome, 1983). In fact, they become such a part of the culture that they can obstruct the possibility of improvement of the survival condition (Arguello, 1981).

The demographic field includes the considerations of the structure of the units and their characterization in terms of sex, age, fertility, construction ways of unions, mortality, migrations (especially those of a labor sort), the familiar living cycle stages (initial, expansion, and fission), duration of said stages, etc. These aspects are important to plan resettlement policies that may take into account the family requirements in the long run.

Many variables have ambiguous implications according to the context in which they appear. For example, in the demographic factors case, the fact that a farming couple has many children could be considered as a survival strategy, based on the reasoning that the more children they have, the more manpower they can count on, and consequently the better resources they can have to fulfill their needs. However, the large number of offspring can be a burden and, as a result, a conditioning could occur that could influence negatively, because they are in the family cycle's first stages and they have scarce productive resources.

CONTEXTUAL FACTORS

Table 1 lists a number of contextual factors that must be taken into account for an exhaustive understanding of the strategies.

Local Level

The local level or the immediate social environment is where we find the articulation of relationship or neighboring links that form the basis of sociocultural identities and informal economic relations. In many cases, these links contribute more to the support of the family than the monetary or formal income. To know these links is very important because, apart from having an

Table 1. Factors That Should Be Considered in Evaluating Relocation

Contextual factors	Endogenous characteristics
- Access to the land	- Demographic
- Social organization	- Migratory
- Work market	- Occupational
- Productive organization	- Educational
- Goods market	- Sociocultural
- Goods and services offered	- Consumption
- Public policies	
- Development projects	

Source: COMIP - Precensus Tasks (1985).

effect on the strategies, they determine the behavior of population in social processes, such as resettlement.

Regional/Subregional Level

This leads to a careful consideration of the surrounding regions or subregions and of the area's interactions with them, even beyond the frontiers among countries, surpassing the reductions to both the ecological and the political administrative aspects. It is at this level where we will detect, on the one hand, the structure of production and employment and, on the other hand, the mechanisms to obtain goods and services through the so-called "needs fulfillment circuits." The analysis of these circuits allows us to know the type of needs to be fulfilled, to what extent they are fulfilled (especially the basic needs), the area (space) where the goods and services are acquired, and the way of approaching them.

National Level

The national level determines the historic and cultural context of development. It is also at the national level where it would appear to be convenient to evaluate the public policies that could affect the living strategies and, above all, the scope and covering of the actions arising from such policies in the regional field of the affected area, provided that process will affect said field.

PROOF OF CONSISTENCY

A specific census was carried out according to this conceptual scheme for the relocation policy of an Argentine-Paraguayan multipurpose hydroenergetic project in the Parana River, Corpus Christi. Contrary to the conventional census, it accounted for strategies, sociocultural components, and the formal and informal links that exist in the affected area, apart from the demographic and economic components.

The same proof also verified the methodology's consistency and the relevance of the constitutive variables. The typology elaborated on these variables and on the previous knowledge about the population. These variables appeared to be effectively discriminating, despite the fact that some "mixed" productive insertion strategies were detected together with the cyclic character of some of them, which revealed the necessity of incorporating the historic prospect to achieve their adequate characterization. The important fact here is that an exploratory proof has been carried out. This census does not rule out the necessity of using other types of instruments and careful studies to become more knowledgeable as regards cultural rules and values and the circuits that lead us to fulfill the needs of people being relocated.

CONCLUSIONS

Resettlement is not simply physical evacuation, but a complex social process. The following criteria are essential to a successful resettlement:

1. To fix as an aim of the policy that the whole of the affected population could reconstruct its living strategies, generally improving its conditions of existence. This reconstitution would consist of:

   - keeping or substituting its resources and their optimization modalities;

   - keeping its social articulations and the cultural components of its lifestyle;

   - introducing in its strategies changes positively valued by the people in terms of their life projects; and

   - obtaining the recognition of the involved actors that the subject of this process is the population at an individual level as well as under the different associative forms. Involved actors include agency, the affected people, and the authorities.

2. To define as policy subjects all those who might be linked to the affected area and whose link might constitute a significant component of their living strategy (residents or nonresidents).

3. To define the living strategies as an affected object, because the disruption between the units and the particular field where they develop basically affects them. Consequently, they also appear to be the replacement object -- that is to say, what the relocation policy must restore to the population. This strategy's reconstruction will not imply a mechanical transposition, but rather a functional replacement equal to the economic and social conditions that are necessary to carry out the strategies. This implies that other aspects, positively valued by the people, could be generated functioning as alternatives of those that cannot be reconstructed.

4. It is not likely that the replacement can be carried out at comparable levels, especially for those sectors whose conditions of existence are definitely inferior to the socially accepted minimum standards of existence. As a result, we will aim to generally improve those conditions.

5. To encourage the people's participation in relocation decisions, both direct and channeled through the different associative forms (either formal or informal). The policy's formulation and its application will grow out of that participation, positive modalities valued by the affected people, and from specific modalities for each social sector.

6. To set the relocation units on two levels: one based on family, and the other based on customs for the preservation of links and networks among units.

7. To contemplate the reconstruction of the community's structure, and the integration of the relocated people among each other and with the receiving population.

8. To aim at establishing the new settlements in places as near as possible to the former location, so as to maintain most of the preexisting links and to count on circuits to obtain resources and to fulfill needs already proved and recognized.

9. To include all the aspects -- social, economic, judicio-legal, technical, etc. -- to guarantee the integral management of such resettlement.

BIBLIOGRAPHY

Arguello, O. 1981. Estrategias de supervivencia: un concepto en busca de su contenido. Economia y Demografia XV. Buenos Aires.

Bartolome, L.J. Estrategias adaptativas de los pobres urbanos: El elemento entropico de la relocalizacion compulsiva. Entidad Binacional Yacyreta y Depto. de Antropologia Social, Universidad Nacional de Misiones, Argentina.

Bartolome, L.J. 1983. Aspectos sociales de la relocalizacion de la poblacion afectada por la construccion de grandes presas. UN-OEA. Buenos Aires.

Borsotti, C.A. La organizacion social de la reproduccion de los agentes sociales, las unidades familiares y sus estrategias. Demografia Economica. Mexico.

Cernea, M. 1989. Relocalizaciones involuntarias en proyectos de Desarrollo. Banco Mundial, Report No. 805, Washington.

COMIP. 1984. Tareas precensales, primera etapa. Buenos Aires-Asuncion.

COMIP. 1985. Tareas prcensales, segunda etapa. Buenos Aires-Asuncion.

COMIP. 1986. Formulacion preliminar de al Politica de Relocalizacion. Buenos Aires-Asuncion.

Duque-Pastrana, E. 1973. Las estrategias de supervivencia economica de las unidades familiares del sector popular urbano: una investigacion exploratoria. PROELCE. Chile.

Jelin, E. 1983. Familia, unidad domestica y division del trabajo (que sabemos, hacia donde vamos). CEDES. Buenos Aires.

Massei, C. 1983. Methodologia general para el analisis socio-economico del emprendimiento en la zona de Corpus. Efectos sociales de las grandes presas de America Latina, Seminar. UN-OEA. Buenos Aires.

Massei, C., and G. Borches. 1983. Evaluacion y planificacion regional de una obra publica de propositos multiples de gran envergadura. Buenos Aires.

Massei, C., and G. Borches. 1984. Concepto de estrategias de vida y su inclusion en la elaboracion de politicas de relocalizacion, Seminar. UN-OEA. Posadas, Argentina.

Partridge, W. 1983. Relocalizaciones en las distintas etapas de desarrollo de los emprendimientos hidroelectricos. UN-OEA. Buenos Aires.

Rodriguez, D. 1981. Discusion en torno al concepto de estrategias de supervivencial. Relatorio del taller sobre estrategias de supervivencia. Demografia y Economica, Nro. 46. Mexico.

Torrado, S. 1981. Sobre los conceptos de estrategias familiares de vida and proceso de reproduccion de al fuerza de trabajo: Notas teoricas-metodologicas." Demografia y Economica, Nro. 46. Mexico.

Torrado, S. 1983. La familia como unidad de analisis en censos y encuestas de hogares. CEUR. Argentina.

NORTH AMERICA

RESPONDING TO GLOBAL WARMING ALONG THE U.S. COAST

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INTRODUCTION

The process of responding to accelerated sea level rise in the United States is well under way, at least for a phenomenon that is not expected for several decades. Over the last seven years, almost all of the coastal states have held at least one major conference on the subject, and a few of them have altered coastal development policies to accommodate a future rise. Public officials are generally familiar with the issue, as are representatives of the press, nongovernmental organizations, and coastal investors. The federal government has conducted assessments of possible nationwide responses, and of implications for specific types of decisions, such as the design of coastal drainage systems, maintenance of recreational beaches, and protection of coastal wetlands.

This paper examines possible responses to sea level rise in the United States. Because the most important question is what should we actually do in response to rising sea level, we focus primarily on the planning and engineering strategies that will determine how activities on the coast eventually change. Nevertheless, because the process by which society comes to understand the need for action is also important, we conclude with a brief summary of the evolution of U.S. sea level rise studies in the 1980s.

FUTURE RESPONSES: SHORELINE RETREAT AND FLOODING

The most important responses to sea level rise in the United States can be broadly classified as responses to shoreline retreat, increased flooding, and saltwater intrusion. In each case, the fundamental question is whether to retreat or to hold back the sea.

Shoreline retreat has received by far the greatest attention; nevertheless, because flooding involves the same strategic questions, we combine the discussion. Because there is a general consensus in the United States to "let nature take its course" in national parks and other undeveloped areas, we examine only developed areas. We divide our discussion of this impact into two parts: barrier islands and the open coast, and sheltered areas. We conclude the section by discussing when action is likely to be necessary.

Barrier Islands and the Open Coast

Oceanfront communities could respond to sea level rise by protecting developed areas with dikes, pumping sand onto beaches and other low areas, or retreating from the shore. Along mainland beaches, the last option generally implies no coastal protection; in barrier islands, however, it would also be possible to engineer a landward retreat of the entire island, creating new land on the bayside to offset that lost to oceanside erosion. The four options are illustrated in Figure 1.

To obtain a rough understanding of the relative costs of these options, we examined Long Beach Island -- a long, narrow barrier island developed with single-family homes and one- and two-story businesses (see Figure 2). Table 1

Table 1. Cost of Sea Level Rise for Four Alternative Options for Long Beach Island, New Jersey (millions of U.S. dollars)

Sea level rise (cm)	Levee with beach		Raise island	Island retreat	No protection
			Total Cost		
30	52		105	41	55
60	434		285	109	462
90	509		522	178	843
120	584		786	247	1548
150	659		1048	308	1740
180	734		1310	371	1932
210	809		1574	431	total loss
240	884		1835	492	total loss
			Incremental Cost		
	Levee	Sand			
30	0	52	105	41	55
60	330	52	180	68	407
90	0	75	237	69	381
120	0	75	264	69	705
150	0	103	262	61	190
180	0	103	262	61	total loss
210	0	110	262	61	total loss
240	0	110	258	61	total loss

Source: Weggel et al. (1989) (dike cost); Yohe (1989) (no protection).

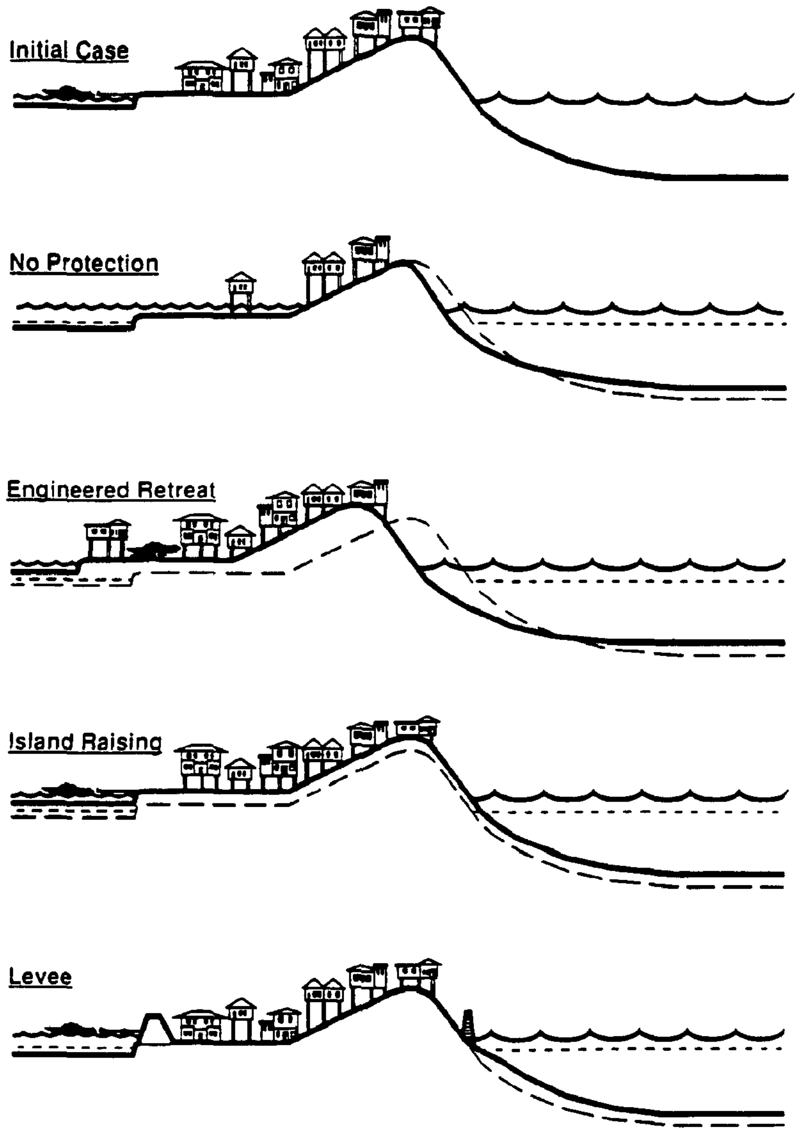

Figure 1. Responses to sea level rise for developed barrier islands.

illustrates the costs of the four options for a rise in sea level between 30 and 240 cm. For a rise greater than 50 cm, any of the protection options would be less expensive than allowing the sea to reclaim the valuable resort property. Although surrounding the entire island with a dike would be less expensive than raising the island, it would be culturally unacceptable because it would interfere with access to the beach, and people would lose their views of the bay.

Engineering a retreat would also be much less expensive than raising the island in place, because the latter option would require more (and higher

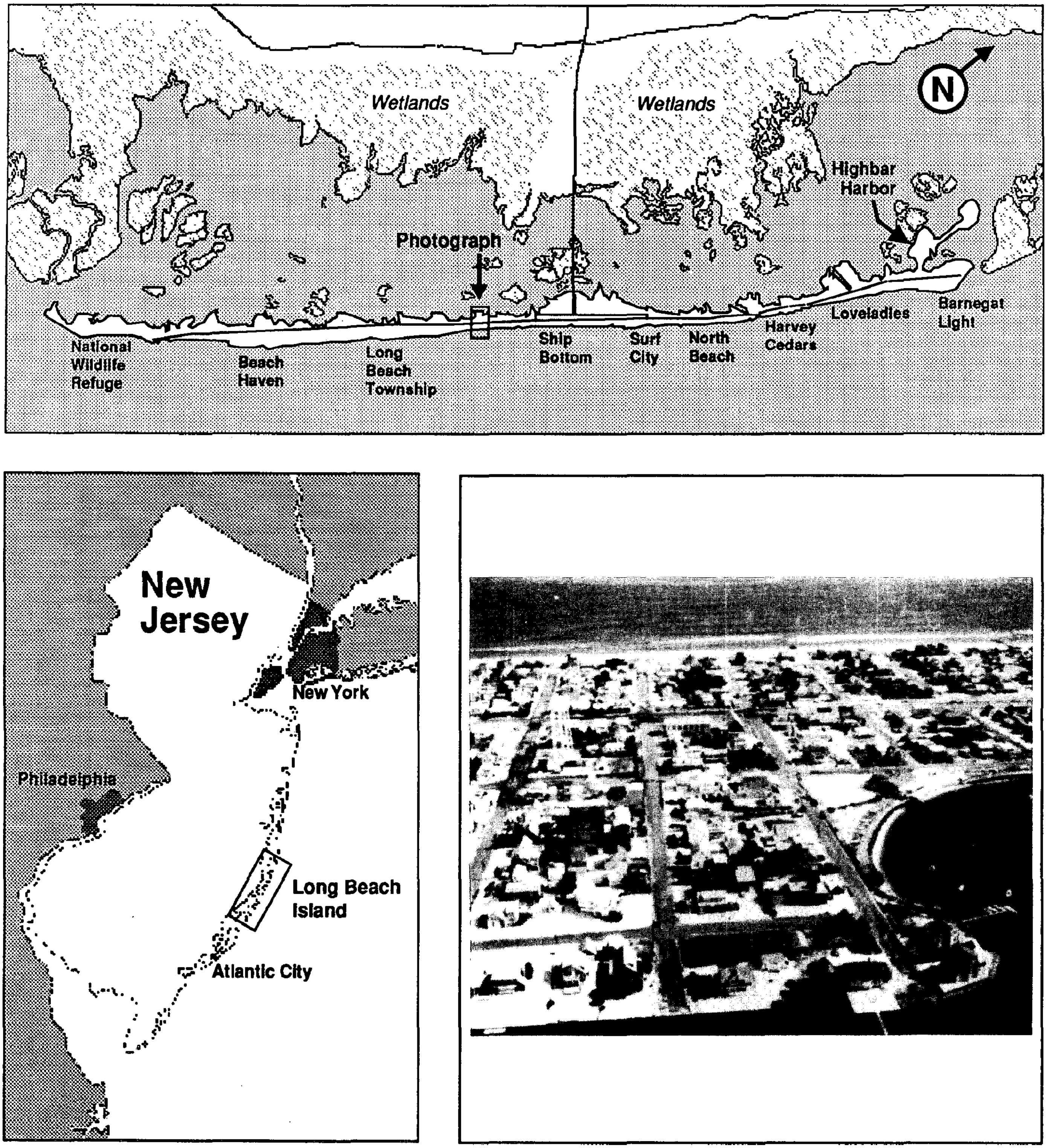

Figure 2. Long Beach Island, New Jersey.

quality) sand. However, this option would be vigorously opposed by the oceanfront owners who would have to move their houses to the bay side, as well as by bayfront owners who might lose their access to the water. Moreover, filling new bayside land would disrupt back-bay ecosystems unless the estuary were also allowed to migrate landward onto the mainland (which we discuss below). As Table 2 shows, island raising would cost less than $600 per house per year (U.S. dollars) until after sea level had risen more than 60 cm; this would be less than the rent for one week. Thus, we suspect that the more expensive but less disruptive approach of pumping sand onto beaches and the low bay sides of barrier islands would be the most commonplace, at least in the beginning.

Table 3 compares the ability of the four options to satisfy various desirable criteria. (Most of the rationale for this table is found in Titus, 1990.) An important lesson from the Long Beach Island study is that the least expensive solutions are not always the most likely; dikes are culturally unacceptable, and an engineered retreat is administratively difficult. Nevertheless, the noneconomic criteria should not always outweigh economics.

Leatherman (1989) estimated the quantity of sand necessary to hold back the sea for every coastal state but Alaska, and estimated the cost assuming that sand does not become more expensive. Titus et al. (1990) adjusted those cost estimates on the assumption that as least-cost supplies are exhausted, it will

Table 2. Evolution Over Time of the Relative Costs of Retreat Island Raising (Long Beach Island, New Jersey)

Sea level above 1986 (cm)	Year*	Years before sea will rise 15 cm	Cost (millions)		Cost (U.S. $/yr/house)	
			Retreat	Raise island	Retreat	Raise island
15	2013	18	20	57	77	219
30	2031	14	34	85	168	420
45	2045	12	34	95	196	548
60	2057	11	34	110	214	692
75	2068	10	34	127	235	879
90	2078	9	34	132	261	1015
105	2087	9	34	132	261	1015
120	2096	8	34	132	294	1142
150	2112	7	30	132	296	1305
180	2126	6.5	30	132	319	1406
210	2139	6	30	132	346	1523

* Assuming global sea level rises one meter by the year 2100.
NOTE: All costs assume that until the particular year, the community has responded to sea level rise by raising the island in place.
Source: Titus (1990)

Table 3. Ability of Alternative Responses to Satisfy Desirable Criteria, Long Beach Island, New Jersey (assuming 1 m rise by 2100)

Policy:	Dikes Islands	Raise Retreat	Engineered	Abandonment Forced	Abandonment Unplanned
Criteria					
Social Cost					
Cumulative ($millions)	584	786	247	1548	1548
Present Value ($millions, 3%)	115	130	46	170	170
Environmentally Acceptable	No	Usually	Usually	Yes	Yes
Culturally Acceptable	No	Yes	Yes	No	Maybe
Legal	Yes	Yes	Maybe	Maybe	Yes
Constitutional	Yes	Yes	Yes	Maybe	Yes
Institutionally Feasible	Yes	Yes	Maybe	Maybe	Yes
Performs Under Uncertainty	Poor	Good	Good	Good	Good
Immmune to Backsliding	Yes	Mostly	Somewhat	No	Mostly

Source: Titus (1990).

be necessary to go farther out to sea for suitable sand. Table 4 illustrates the resulting estimates of dredging costs for current trends and rises in sea level of 50, 100, and 200 cm. Titus et al. also estimated the cost of elevating buildings and utilities as sea level rises.

These calculations are only rough estimates. Leatherman probably underestimated total sand requirements by assuming that beaches would be designed only for a one-year storm; designing them for a 100-year storm would increase the cost by 50-100 percent. Moreover, Titus et al. ignored the cost of elevating multifamily buildings, and sea level rise would be factored into routine reconstruction of water and sewer lines at no incremental cost. On the other hand, our calculations assume that all developed areas will be protected. Although this is a reasonable assumption for Long Beach Island and similar areas, it would be less expensive to abandon more lightly developed islands. Moreover,

Table 4. Nationwide Impact of Sea Level Rise on the United States

Trend	50 cm	100 cm	200 cm
<u>If No Shores Are Protected</u>			
Dryland lost (sq mi)	3,315-7,311	5,123-10,330	8,191-15,394
Wetlands lost (%)	17-43	26-66	29-76
<u>If Developed Areas Are Protected</u>			
Dryland lost (sq mi)	2,200-6,100	4,100-9,200	6,400-13,500
Wetlands lost (%)	20-45	29-69	33-80
Cost of coastal defense (billions of 1988 dollars):	32-43	73-111	169-309
Open coast:			
Sand	15-20	27-41	58-100
Elevate structures	9-13	21-57	75-115
Sheltered shores	5-13	11-33	30-101
<u>If All Shores Are Protected</u>			
Wetlands lost (%)	38-61	50-82	66-90

Source: Titus et al. (1989).

a number of states have already required construction to be set back from theshore a few hundred meters, suggesting that no protection would be required for the first 50 cm of sea level rise.

Sheltered Waters

Americans' affinity for beaches and concern for the environment have created a strong constituency against holding back the sea with dikes and seawalls, counterbalancing the natural tendency of all landowners to protect their property. Along the open coast, both interests can be accommodated, because beach nourishment protects property by maintaining the natural shoreline. Along sheltered waters, however, the prospects for avoiding a conflict are not as great. As Figure 3 shows, protecting property with dikes and bulkheads would prevent wetlands from migrating inland and could eventually result in their complete loss in some places.

In a recent EPA report to Congress on the implications of global warming, Park et al. (1989) examined the potential loss of wetlands and dryland for a sample of 46 sites comprising 10 percent of the U.S. coastal zone, for three alternative responses: no protection, protecting areas that are densely developed today with dikes and bulkheads, and protecting all shores. For each site, Weggel et al. (1989) estimated the cost of protecting developed areas from

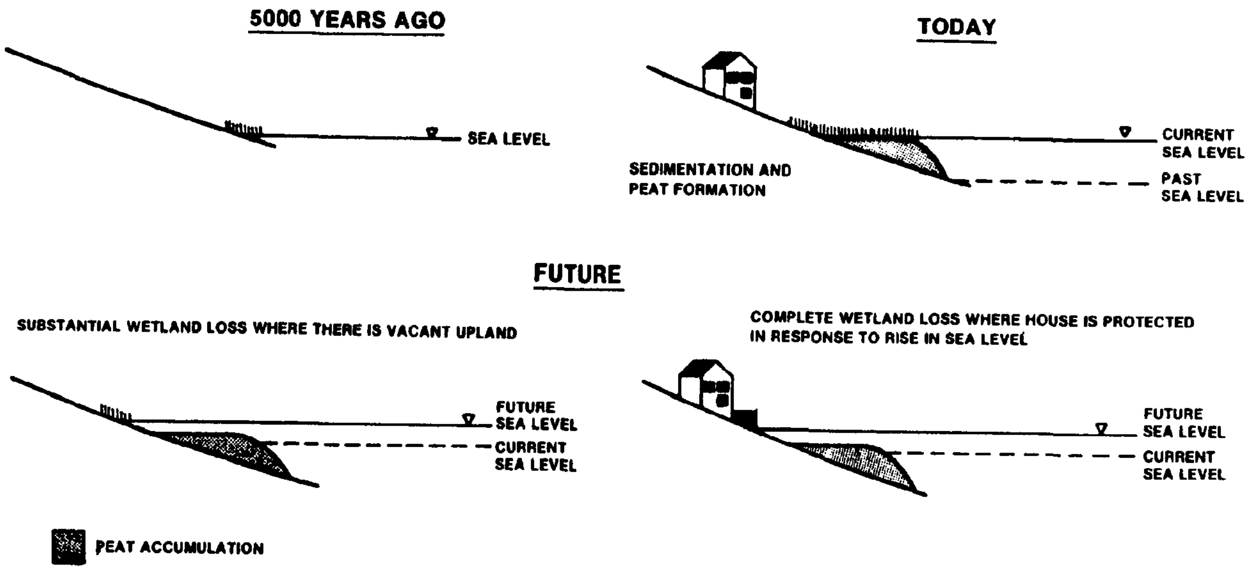

Figure 3. Evolution of a marsh as sea level rises (Titus, 1986).

a 2-meter rise. Titus et al. (1990) used cost functions suggested by Weggel et al. and estimates of inundated land from Park et al. to interpolate the cost estimates, and developed confidence intervals for the estimates of lost land.

Table 4 illustrates the nationwide results (the source studies provide regional detail). For a one-meter rise, the cost of protecting the most densely developed 1,000 square miles of coastal lowlands would work out to $3,000 per acre per year, which would generally warrant protection. However, such protection would increase the loss of wetlands by 300-500 square miles, and would reduce the area of shallow water for submerged vegetation by another 500-700 square miles. Moreover, many vacant areas are being rapidly developed. If all areas must be protected, the additional loss of wetlands would be 1,800-2,700 square miles, and another 3,000-7,000 square miles of shallow waters would be lost.

The political process will have to decide whether to abandon coastal lowlands to protect the environment. To help the necessary discussions get under way we are circulating a draft that investigates seven options for enabling coastal wetlands to migrate landward (Titus, 1989). The first two apply only to undeveloped areas: prohibiting development and purchasing coastal lowlands. The next three involve doing nothing today and purchasing land and structures when inundation is imminent; forcing people to move out when inundation is imminent; or hoping that protection will prove to be uneconomic. The final two options, which we call "presumed mobility," allow people to use their property as they choose, but on the condition that they eventually will abandon it if and when sea level rise threatens it with inundation; presumed mobility could be implemented, whether by prohibiting construction of bulkheads and levees or by converting property ownership to long-term or conditional leases that expire when sea level rises a particular amount.

Table 5 summarizes our assessment of each option to satisfy various desirable criteria, including low social cost, low cost to taxpayers, performance under uncertainty, equity, constitutionality, political feasibility, and the risk of backsliding. Unlike the table for barrier islands, we omit environmental criteria because each of these options is each designed to achieve roughly the same level of environmental protection.

Our overall assessment is that presumed mobility would be the best general approach. A general prohibition of development would probably violate the takings clause of the Bill of Rights; buying 20,000 square kilometers of land would be expensive, and in any event, these options apply only to areas that have not yet been developed. Doing nothing today seems unlikely to protect wetlands because (1) purchasing property in the future would be even more expensive if it is developed; (2) forcing people to move out of their homes would be politically impossible if they are willing to tax themselves to pay for the necessary protection; and (3) economics alone is unlikely to motivate people to abandon developed areas.

One of the most overlooked but important criteria is performance under uncertainty. No one knows how much sea level will rise in the future; only rough estimates are available. Thus, policies likely to succeed for a rise anywhere between 0 and 3 meters should be preferred over those that might be superior for a particular scenario but might fail if other scenarios unfold. For this criterion, the approach of presumed mobility is clearly superior: ecosystems will be protected no matter how much sea level rises; real estate markets will be able to efficiently incorporate new information on sea level trends; and if the sea does not rise significantly, the policy costs nothing. By contrast, buying coastal lowlands or prohibiting development requires policy makers to draw a (disputable) line on a map above which the policy does not apply. If sea level rises more than assumed, ecosystems eventually will be lost; if it rises less, society will have unnecessarily forfeited the use of valuable coastal land.

When Will a Response Be Necessary?

A recent study by the National Research Council (Dean et al., 1987) concluded that because dikes can be erected in a relatively short period of time, no action is necessary today. This argument also applies for beach nourishment on the open coast. However, our analysis of wetland-protection options suggests

Table 5. Alternative Strategies for Protecting Natural Shorelines: Areas That Have Not Yet Been Developed

Policy	Cost to public	Social Cost (vs. no sea level rise) Present value	Social Cost (vs. no sea level rise) Cumulative	Economic Efficiency	Performance under uncertainty: Sea Level	Performance under uncertainty: Economics	Constitutional	Equitable	Political feasibility	Risk of backsliding	New institutional requirements	Likelihood of success
1. Prohibit Development	None	Speculative premium +<1% of base value	Land	Poor	No	Yes	No	No	None	Possible	Regulatory	Almost certain at first, unlikely in long run
2. Buy coastal land	Speculative premium	Speculative premium + <1% of base value	Land	Poor	No	Yes	Yes	Yes	None	Possible	Park Service aquisition	Almost certain at first, unlikely in long run
Defer Action												
3. Order people out later	None	<1% of land and structures	Land and structures	Fair	Yes	Perhaps	Maybe	Doubtful	Low	Very likely	Police	Unlikely
4. Buy out later	land and structures	<1% of land and structures	Land and structures	Fair	Yes	No	Yes	Yes	Low	Very likely	Park Service Aquisition	Unlikely
5. Rely on elements/ economics	None	<1% of land and structures	Land and structures	Fair (if it works)	Yes	Useless	Yes	Yes	Good	Low	Hazard Mitigation	Unlikely
Presumed mobility												
6. No bulkheads	None	<1% of land value	Land + residual value of structures	Optimal	Yes	Yes	Probably	Usually	Good	Likely	Regulatory	Very likely
7. Leases	<1% of land & residual value	<1% of land value	Land + residual value of	Optimal	Yes	Yes	Yes	Yes	Fair	Very unlikely	Change in titles of	Almost certain

that these measures are likely to be effective only if they are implemented several decades in advance: people would need several decades to depreciate structures and to become accustomed to the idea that property must be abandoned to the sea to protect the environment.

A number of planning mechanisms are in place along the ocean coast to foster a retreat. North Carolina and a number of other states require houses to be set a few hundred meters back from the beach and prohibit hard engineering structures along the beach. South Carolina prohibits reconstruction of storm-damaged property if such property is too close to the shore.

Along wetland shores, however, only Maine has implemented planning measures to allow ecosystems to migrate inland. That state has explicitly incorporated presumed mobility into its development regulations, which state that structures are presumed to be movable; in the case of apartments that are clearly not movable, the regulations state that if the buildings would block the landward migration of wetlands and dunes resulting from a one-meter rise in sea level, the developer must supply the state with a demolition plan. Although other states require construction to be set back somewhat from the wetlands, the setbacks are small compared with the inland migration of wetlands that would accompany a one-meter rise in sea level.

FUTURE RESPONSES: MISSISSIPPI DELTA

Louisiana is currently losing over 100 square kilometers of land per year because human activities are thwarting the processes that once enabled the Mississippi Delta to expand into the Gulf of Mexico. For thousands of years, the annual river flooding would deposit enough sediment to enable the delta to more than keep pace with sea level rise and its own tendency to subside. In the last century, however, the federal government has built dikes along the river and has sealed off "distributaries" to prevent flooding and to maintain a sufficiently rapid riverflow to prevent sedimentation in the shipping lanes. As a result, sediment and nutrients from the river no longer reach most of the wetlands, and they are being rapidly submerged. Moreover, with flows in distributaries cut off, saltwater is penetrating inland, converting cypress swamps to open water lakes and otherwise disrupting wetlands. If sea level rise accelerates, the already rapid disintegration of coastal Louisiana would follow suit.

As with other coastal areas, both dikes and abandonment are possible. However, there is a general consensus that these options should be avoided if possible, because in either event, most of the delta's wetlands would be lost, and those wetlands support 50 percent of the nation's shellfish and 25 percent of its fish catch. Thus, federal and state officials are focusing primarily on options to restore natural processes that would enable at least a large fraction of the delta to survive even an accelerated rise in sea level. The U.S. Congress has authorized a number of projects to divert freshwater and sediment to wetlands by effectively cutting holes in the dikes. Under current policies, however, such projects will likely divert only a small fraction of the river water to avoid siltation of shipping lanes.

In the long run, protecting Louisiana's wetlands would require people to allow the vast majority of the river's discharge to reach the wetlands. This would be possible if navigation were separated from the streamflow of the river. One way to do this would be to construct a series of canals with locks between New Orleans and the Gulf of Mexico, and to completely restore the natural flow of water to the delta below the canal. Unfortunately, requiring ships to pass through locks would hurt the economic viability of the Port of New Orleans. Another option would be to build a new deep-water port 10-20 miles to the east.

Perhaps the far-reaching response, one that has been advocated by the state's Secretary for Environmental Protection, would be to allow the river to change course and flow down the Atchafalaya River. Without a $1 billion river control structure, the river would already have done so. Although from a purely environmental perspective this option is most appealing, it would further accelerate the loss of wetlands in the eastern part of the state and would enable saltwater to back up to New Orleans, requiring the city to find a new water supply.

It is somewhat ironic that human activities designed to prevent flooding may leave the entire area permanently below sea level in the long run. There may be a lesson for Bangladesh and other nations who are considering flood-protection dikes to protect land from surges in river levels: build dikes around a few cities, but make sure the river is still able to flood enough areas for the flow of water to slow sufficiently to deposit sediment onto farmland and wetlands, rather than washing sediment out to sea where it will benefit no one.

FUTURE RESPONSE: SALTWATER INTRUSION

Responses to saltwater intrusion, like shoreline retreat and flooding, can involve either holding back the sea or adapting to a landward encroachment.

Preventing Salinity Increases

Figures 4 and 5 illustrate why sea level rise increases the salinity of estuaries and aquifers, respectively. In the former case, a rise in sea level increases the cross-sectional area of the estuary, slowing the average flow of water to the sea, the major process that keeps the estuary from having the same salinity as the ocean. Assuming that the tides continue to carry the same amount of water and that mixing stays constant, salinity will increase because the force of freshwater is reduced while the saltwater force is increased. Moreover, if the bay becomes wider, the tidal exchange of water will increase, further increasing the freshwater force. (Because it is difficult to graphically represent the previous explanation, Figure 4 expresses it in a different fashion by comparing the amount of freshwater entering the estuary with the amount of seawater from the tides.)

Salinity increases can be prevented either by impeding the ability of saltwater to migrate upstream or by increasing the amount of freshwater entering the estuary. During the drought of 1988, the New Orleans District of the Corps of Engineers designed a barrier across the bottom of the Mississippi River that blocked saltwater on the bottom while allowing the ships and freshwater to pass on the top. In many cases where human withdrawals of freshwater have increased estuarine salinity enough to have adverse environmental consequences, water resource agencies have constructed projects to divert freshwater into estuaries. Elsewhere in Louisiana, the Corps has designed projects to divert water from the Mississippi River to wetlands that are suffering adverse effects of saltwater intrusion; and Everglades National Park has long had a similar arrangement with the Corps of Engineers and the South FLorida Water Management District.

The Delaware River Basin Commission (DRBC) releases water from its system of reservoirs whenever salinity reaches undesirable levels, to protect Philadelphia's freshwater intake and aquifers in New Jersey that are recharged by the (usually) fresh part of the river. Hull and Tortoriello (1979) estimated that a 13-cm rise in sea level would require an increase in reservoir capacity of 57 million cubic meters (46,000 acre-feet), while Hull and Titus (1986) suggested that a 30-cm rise would require about 140 million cubic meters, about one-fourth the capacity that would be provided by the proposed Tocks Island reservoir. Hull and Titus also noted that the DRBC has identified reservoir sites sufficient to offset salinity increases from sea level rise and economic

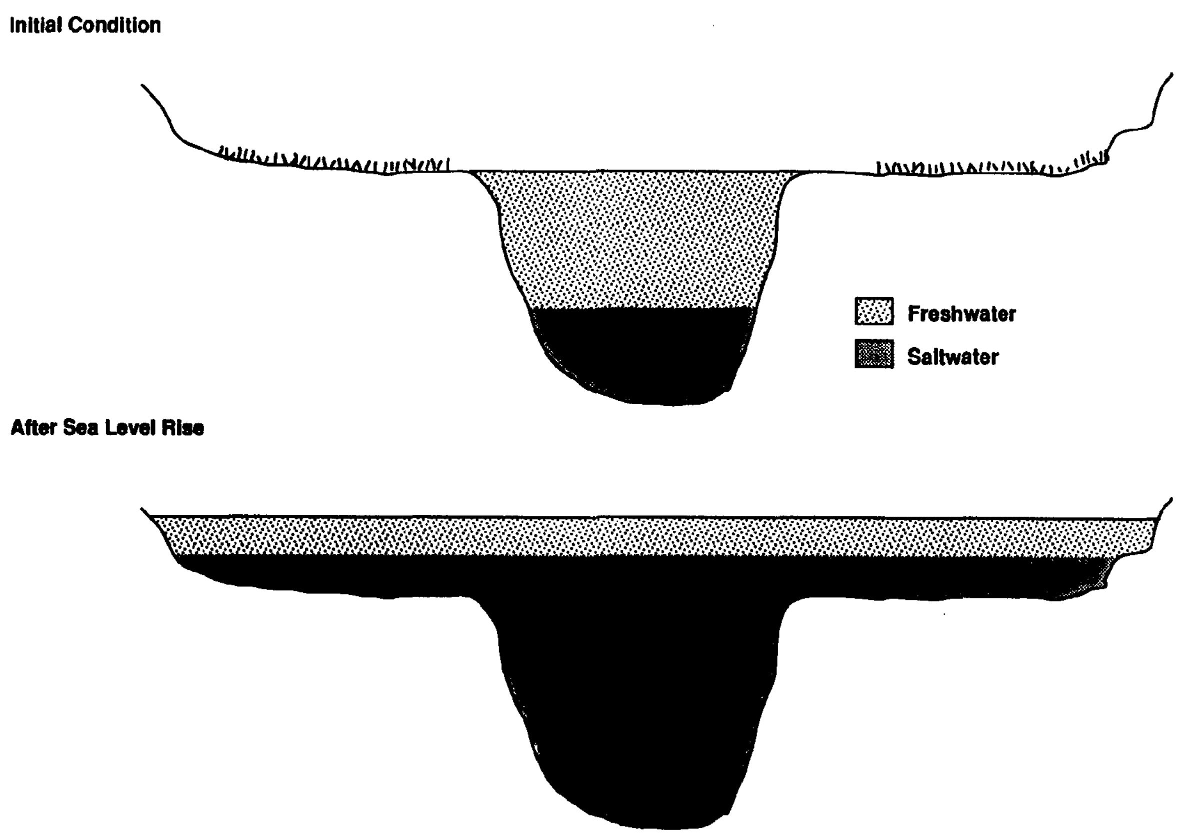

Figure 4. Increasing bay salinity due to sea level rise.

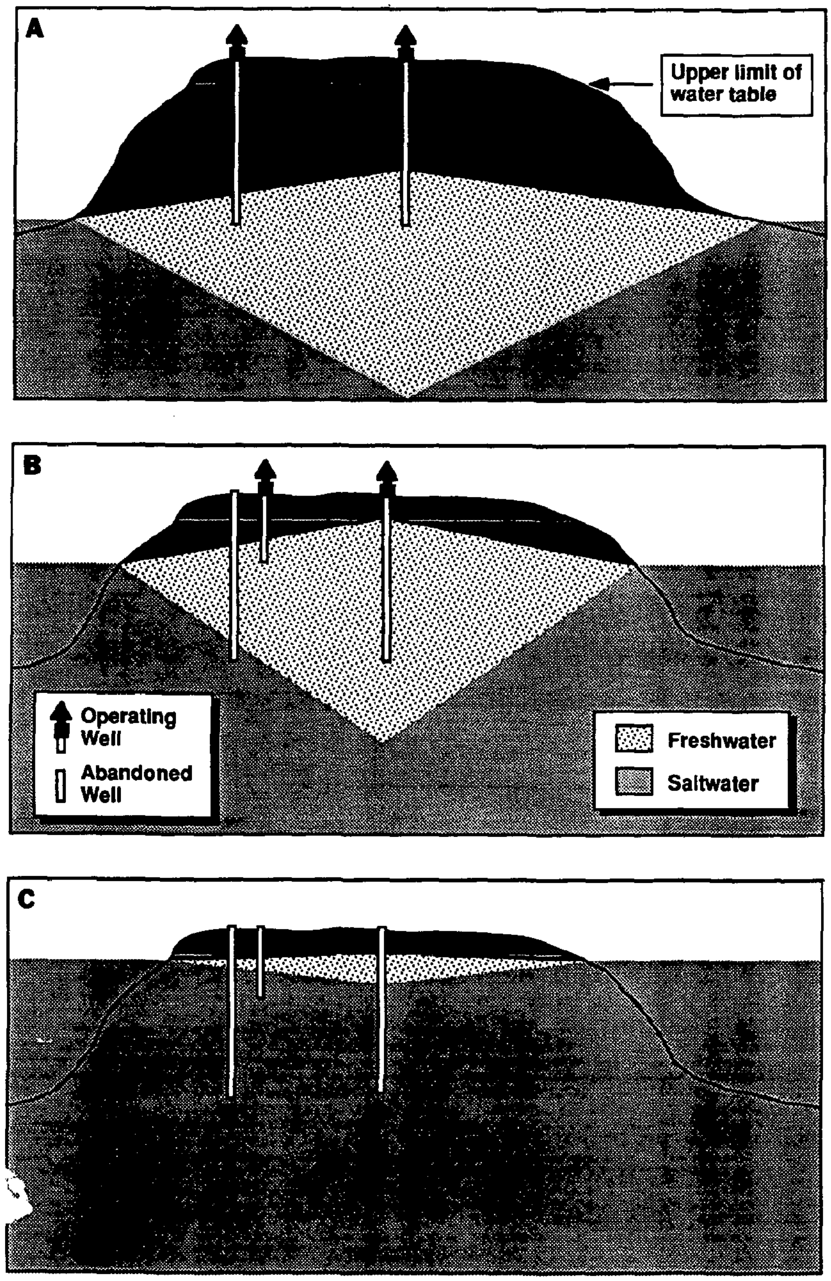

Figure 5. Impacts of sea level rise on groundwater tables. According to the Ghyben-Herzberg relation, the freshwater/saltwater interface is 40 cm below sea level for every cm by which the top of the water table lies above sea level. When water tables are well below the surface, a rise in sea level simply raises the water table and the fresh/salt interface by an equal amount (A-B). Where water tables are near the surface, however, drainage and evapotranspiration may prevent the water table from rising. In such a case (C), the freshwater table cour narrow greatly with a rise in sea level: for every 1-cm rise in sea level, the fresh/salt interface would rise 41 cm.

growth well into the 21st century. Williams (1989) conducted a similar analysis of the impacts of and responses to sea level rise in the Sacramento Delta in California.

Although dams can be useful, one must understand their limitations. Most important, there is a finite amount of water flowing in the typical river; dams can increase the freshwater flow during the dry season because they reduce the flow during the wet season. Because droughts are generally the only time when high salinity is a concern, the impact on salinity during the wet season is generally not a problem. Dams also reduce flooding, which (as we discussed above) can be viewed as a benefit by people who might otherwise lose property (or drown) in a flood; but this is a liability to the extent that flood prevention keeps sediment from reaching wetlands and enabling them to keep pace with sea level. A final problem is that if climate change makes droughts more severe in the future, it may be difficult to find sufficient reservoir capacity to offset the resulting reductions in riverflow, let alone increase riverflow enough to offset sea level rise. Salinity increases in aquifers can also be prevented by either increasing the force of freshwater or by decreasing the force of saltwater. The most notable application of the former approach is in southern Florida, where water managers maintain a series of freshwater canals whose primary purpose is to recharge the Biscayne Aquifer with freshwater. Various types of barriers have also been identified for blocking saltwater intruding into the estuary (Sorensen et al., 1984).

Decreasing depletive uses of water can help to offset salinity increases. For example, during droughts the Delaware River Basin Commission has the power to curtail diversions of water to New York City. Reducing water consumption within the basin is a critical component of water management strategies in this and many other regions.

Adapting to Salinity Increases

If measures are not undertaken to prevent increase of salinity, people will have to adapt to it. Some cities could respond by moving their intakes upstream. Note that this appears to be the only response to increased salinity that would work with sea level rise but (at least in many cases) not with decreased riverflow. In the case of sea level rise, moving the uptake upstream the same distance as salinity advanced would leave the public (and if ecosystems were able to migrate upstream and inland, the environment) in roughly the same condition as before the sea level rose. By contrast, if less freshwater is flowing into an estuary, there may no longer be enough freshwater to supply the previous level of consumption.

Another response is to shift to alternative supplies. For example, if flows in the Mississippi River decline, or if wetland loss motivates policy makers to allow the river to change course, New Orleans would have to abandon the river as a supply of freshwater. Many argue that the river is polluted enough to view such a situation as a "blessing in disguise," and have suggested that the groundwater under Lake Ponchartraine would be a suitable source (Louisiana Wetland Protection Panel, 1987). Nevertheless, alternative supplies are finite and may become increasingly scarce as the economy grows, especially in areas where the greenhouse effect fails to increase precipitation enough to offset the increased evaporation that warmer temperatures invariably imply.

Water conservation is likely to play an increasingly important role in efforts to adapt to reduced availability of freshwater. Many jurisdictions already place restrictions on depletive uses, such as watering lawns and washing cars. Officials in New Jersey are planning to ration the water that farmers withdraw from the Potomac-Raritan-Magothy Aquifer, which is recharged by the Delaware River. Nevertheless, regulations of water use are difficult to enforce and generally apply only to a limited number of visible activities.

In our view, the best long-term response would be to treat water like any other scarce commodity: sell water at a market-clearing price, rather than at a price based on cost. There is an emerging trend in this direction among large water users in the western United States, but the principle is likely to face severe cultural and institutional barriers. First, Americans generally believe that water should be as free as the air we breathe. Second, public utilities generally are not allowed to make a profit. Nevertheless, with increasing government deficits and a gradual acceptance of the scarcity of water, the public would probably learn to accept water markets.

The Need for Near-Term Action

As with dikes built to prevent inundation, there is no need to build dams or canals to counteract future saltwater intrusion. Nevertheless, setting aside sufficient land for future dam sites is similar to allowing wetlands to migrate landward: it will be less expensive to prevent people from developing the land today than to buy people out later. Accordingly, to the extent that regions will rely on dams in the future, it would be best to identify those sites today and implement policies that will keep options open for future reservoir construction.

The matter of reserving land for dams or wetlands illustrates a principle that may apply to other commodities: even when a particular action will not be necessary for a few decades, it is best to establish the "rules of the game" in advance so that people can gradually take whatever measures are necessary based on how they perceive the probability and eventuality of the particular situation that is anticipated. If we want to use water efficiently, its price will eventually have to rise. Political realities prevent a substantial rise today, but if the government put everyone on notice that it would charge a fair-market price beginning in the year 2030, the public would probably accept such a policy. It is easier to agree on what is fair when no one is immediately threatened, and honorable people do not object to fulfilling the conditions of treaties, contracts, and other arrangements made by a previous generation.

EVOLUTION OF THE U.S. RESPONSE: 1982-1989

For most practical purposes, the United States began to seriously examine potential responses to accelerated sea level rise in the summer of 1982. Two officials of the U.S. Environmental Protection Agency (EPA), John Hoffman and the head of his office, Joseph Cannon, were troubled by an apparent failure in information transfer. For several years, climatologists had warned that a global warming due to the greenhouse effect was likely (NAS, 1979, 1982). Yet federal, state, and local officials responsible for coastal decision making either were generally unaware of this prospect or viewed it as mere speculation.

No one had estimated the likely rise in sea level for specific years, and even if they had, the EPA officials were not sufficiently familiar with coastal activities to know whether consideration of a possible rise would warrant changes in current decision making. But Hoffman had a hunch that sea level rise would justify changes in at least some decisions, and convinced Cannon to initiate a small program to begin the process by which the United States prepared to live with a rising sea on a warmer planet.

In retrospect, it may seem strange that EPA, a regulatory agency responsible for controlling pollution, first addressed the greenhouse effect issue by initiating a program to adapt to a global warming, rather than a program to reduce emissions of greenhouse gases into the atmosphere. Even then, a number of environmental groups were initially suspicious that the Agency was effectively "throwing in the towel." But in the context of what could actually be accomplished at the time, the strategic decision Cannon made was perfectly rational. The nation had just elected a new president who had promised to relax environmental regulations; nonregulatory approaches to protecting the environment seemed to have more promise. The planned sea level rise project would encourage state and local officials to anticipate sea level rise, with the hope of averting situations that would otherwise eventually necessitate regulations. Moreover, there was no public consensus to reduce global warming; a project aimed at increasing awareness would help create the political conditions necessary for policy makers to consider reducing emissions of CO_2 and other greenhouse gases.

The first major activity of the Sea Level Rise Project was an interdisciplinary study in which Hoffman et al. (1983) estimated the range of future sea level rise; Leatherman (1984) and Kana et al. (1984) used those scenarios to estimate the physical effects on Galveston, Texas, and Charleston, South Carolina; Sorensen et al. (1984) provided rough cost estimates for engineering responses to sea level rise; and Gibbs (1984) and Titus (1984) performed economic analyses using the information provided by the other researchers. The results were presented at a conference in Washington in 1983 and were published the following year (Barth and Titus 1984).

The initial effort was only partly successful. On the positive side, Hoffman's study estimating sea level rise prompted the National Academy of Sciences to prepare their own estimate (Revelle 1983), so that by the end of the first year, there were two available studies, both of which suggested that a substantial rise in the next century was likely. We were also successful in making officials and coastal scientists aware of the potential for a significant rise: (1) our reports were written for the layman -- no matter how technical the subject matter of a study, they always included an overview chapter that explained the contents; (2) we sent out form letters to most of the people in the country working on coastal issues, telling them how to obtain our reports, and about one-third of them responded by requesting at least one document; and (3) we gave about 50 speeches and briefings every year on the subject to government offices and public meetings.

However, we failed to obtain our most important objectives. By 1984, we had identified only a handful of issues where we could make a case that sea level rise required changes in current practices. Moreover, while we continued to study the issue, we were generally unable to convince federal and state agencies with a stake in sea level rise to undertake efforts themselves to address the issue. There were four notable exceptions: (1) the National Academy of Sciences formed panels to (a) estimate the future contributions of glaciers to sea level rise (Meier et al., 1985) and (b) assess the engineering implications of a possible rise (Dean et al., 1987); (2) Orrin Pilkey, the most prominent environmental activist on coastal matters, began to incorporate global warming into his many speeches to civic groups on the need for coastal development to be more sensitive to environmental processes; (3) the Army Corps of Engineers agreed to cofund with EPA a $25,000 study on the implications of sea level rise for coastal protection works (Kyper and Sorensen, 1985); and finally (4) the legislature of Terrebonne Parish, a local government in Louisiana, passed a resolution calling on Congress to improve estimates of future sea level rise and initiated a $100,000 study on response strategies for their community, which was already facing substantial erosion due to subsidence (see Edmonson, Volume 1).

It was clear that we were doing something wrong, so in mid-1984 we changed the focus of our studies. From then on, we decided to fund studies only after we had internally developed a specific hypothesis demonstrating that a consideration of sea level rise would alter decisions people make today. In the ensuing two years, we commenced studies to investigate the following hypotheses: (1) sea level rise would destroy a large fraction of our coastal wetlands unless planning solutions were soon implemented to require development to be abandoned to allow wetlands to migrate inland (Titus et al., 1984); (2) because groins help to control erosion due to alongshore transport but not the offshore erosion from sea level rise, a consideration of the issue would prompt the State of Maryland to drop its plans to build more groins at Ocean City, Maryland, and instead employ beach nourishment; (3) because it is much easier to put slightly larger pipes in a coastal drainage system during construction than subsequently to add new pipes, it would be rational to design new coastal drainage systems with an allowance for sea level rise; (4) sea level rise would accelerate the already alarming rate of land loss in Louisiana, and hence, imply that action is much more urgent than currently assumed; and (5) increased salinity in the Delaware Estuary might eventually necessitate additional reservoirs to protect Philadelphia's water supplies, and although they need not be built today, the risk of this eventually happening warrants land use planning to ensure that all the suitable sites are not developed.

Because we had conducted "back of the envelope" assessments that demonstrated the need to consider sea level rise before funding them, all of the studies turned out to demonstrate that even a 50-50 chance of accelerated sea level rise would warrant changes in current decision making. Although sea level rise was probably not the only reason, within a month of the Ocean City study's (Titus et al., 1985) release, the State of Maryland announced that it would shift its erosion-control strategy from groins to beach nourishment (Associated Press, 1985). (The wetland study (Titus, 1988) was not released until much later, but even while it was still in draft, the State of Maine responded by issuing regulations requiring that structures be removed if necessary to enable wetlands and dune ecosystems to migrate landward.)

Although the other studies (Titus et al., 1987; Louisiana Wetland Protection Panel, 1987; Wilcoxen, 1986) did not precipitate specific actions, they provided additional examples to buttress our claim that people should begin preparing for sea level rise, even though it is uncertain. We continued to give about 30 speeches a year on the subject to various communities and professional organizations, trying where possible to talk to enough people beforehand to develop a hypothetical example relevant to their own activities where planning for sea level rise today would be warranted. The fact that we could cite studies demonstrating the rationality of planning today increased the credibility of our assertion that the particular audience should consider it as well; and the fact that Maryland and later Maine had made a decision based on sea level rise helped convince people that policy makers are capable of planning for the long-term future.

Although many scientists, reporters, low-level officials, and members of the public continued to request our reports, in the beginning of 1986 we knew that we had failed to achieve our primary goal of motivating people to prepare for sea level rise. We had the sense that we were fulfilling a need to have someone thinking and telling people about the long-term implications of current activities, but that for most people, our activities were little more than a curiosity; practical people could safely ignore the issue of sea level rise.

But then the British Antarctic Survey discovered an emerging hole in the ozone over the South Pole. This seemingly unrelated event attracted the attention of several U.S. Senators, who held hearings on the subject and decided to include the related issue of global warming. Suddenly, widespread public attention was focused on the greenhouse effect and its impact on sea level. The unusually hot year of 1988 further increased public awareness. For the first five years of our project, we were able to motivate only a few agencies to undertake any substantive efforts; in the last two years, the momentum of the issue has motivated dozens of initiatives, as Klarin and Hershman (Volume 1) discusses.

We would like to think that our initial efforts laid the groundwork for the emerging response to sea level rise, even though at the time our efforts seemed futile. By this line of reasoning, our initial reports explaining the issue convinced low-level officials, low-level environmental spokesmen, and coastal scientists that sea level rise is important, but failed to convince high-level officials, heads of nongovernmental organizations, or prominent scientists that the time was ripe for addressing the issue. When the ozone hole and hot year of 1988 convinced leaders that global warming is a serious issue, their lower-level counterparts were already informed and ready to recommend action.

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We will never know whether our efforts made much of a difference in the final analysis. Nevertheless, on the assumption that they did, we briefly offer a few lessons that may be useful for nations beginning to prepare for future sea level rise. First, it is important to designate an individual to work full time on the issue. A key to the success of the EPA project is that Hoffman was able to find someone who was sufficiently interested in the issue to stay with it for the better part of a decade. It takes time to develop expertise when a new issue emerges: much of the relevant information is unpublished, and disciplines ranging from law and economics to biology and engineering must be synthesized.

Second, because responding to sea level rise is likely to be decentralized, public information is sufficiently important to warrant 10-20 percent of the total budget and 25 percent of the project manager's time. Thousands of one-hour conversations with reporters and professionals working on related issues will be necessary, as well as many shorter conversations with curious citizens. Anyone who views their time as too valuable to completely satisfy all inquiries is doomed to failure. College students and low-level assistants who have the initiative to question the project manager about the implications of future sea level rise often surface later as influential researchers or directors of organizations. Although the typical conversation on the subject may accomplish little, the totality of thousands of conversations over the course of several years produces a critical mass by which people begin to talk to each other about the issue and spend their own time investigating its implications.

If the need to satisfy all inquiries is recognized, the project manager will find that he or she can save time by preparing summary reports that explain the issue to someone with no background in the issue. Managers of government projects often commission numerous studies, and in their own minds, develop a broad vision of the issue. But while they make the studies available, they rarely prepare reports summarizing their perspective. This is unfortunate both because preparing such reports disciplines one to examine the weaknesses in their opinions, and because their overviews of the issue would correspond more closely to what the public needs to know than would the reports prepared by specialists in particular disciplines.

Finally, studies should begin with a socially relevant hypothesis before being funded. In our case, the hypothesis was that a particular change in current activities was warranted even if one allows for the possibility that sea level might not rise. In some cases, it is worth examining an issue just to make sure that no action is yet necessary. However, any project manager unable to present a cost-benefit argument in favor of action today in at least a few cases should be criticized for, at best, a lack of imagination and for, at worst, directing resources to the wrong issues and thereby forfeiting any savings that might be realized from preparing for sea level rise in other ares. Such criticism may not always be fair, but the fear of receiving it will be a powerful incentive to ensure that "no stones go unturned."

CONCLUSION

No one would accuse the United States of overreacting to the prospect of a rise in sea level from the greenhouse effect; the process has been slow, but steady. After seven years, we have reached the point where the relevant disciplines and the relevant government agencies are considering the issue and looking for opportunities to respond. Everyone realizes that it is difficult to convince politicians to make short-term sacrifices for the long-term good, but we have a public that is concerned about environmental quality in general and the greenhouse effect in particular.

We understand that many of the assumptions American researchers take for granted would not apply in other nations. Nevertheless, we believe that two recommendations are universally appropriate for any foreign colleague who decides to dedicate a number of years helping a nation prepare for rising seas. Focus your efforts on identifying actions that need to be taken today and make sure that no one ever considers you an expert on the issue. What you learn will be important only if its knowledge becomes commonplace.

BIBLIOGRAPHY

Armentano, T.V., R.A. Park, and C.L. Cloonan. 1988. Impacts on coastal wetlands throughout the United States. In: Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Titus, J.G., ed. Washington, DC: U.S. Environmental Protection Agency.

Associated Press. 1985. Doubled erosion seen for Ocean City. Washington Post, November 14th. (Maryland Section).

Barth, M.C., and J.G. Titus, eds. 1984. Greenhouse effect and sea level rise: A challenge for this generation. New York: Van Nostrand Reinhold.

Broadus, J.M., J.D. Milliman, S.F. Edwards, D.G. Aubrey, and F. Gable. 1986. Rising sea level and damming of rivers: Possible effects in Egypt and Bangladesh. In: Effects of Changes in Stratospheric Ozone and Global Climate. Titus, J.G., ed. Washington, DC: U.S. Environmental Protection Agency and United Nations Environment Program.

Dean, R.G., et al. 1987. Responding to changes in sea level. Washington, DC: National Academy Press.

Everts, C.H. 1985. Effect of sea level rise and net sand volume change on shoreline position at Ocean City, Maryland. In: Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, DC: U.S. Environmental Protection Agency.

Gibbs, M. 1984. Economic analysis of sea level rise: Methods and results. In: Greenhouse effect and sea level rise: A challenge for this generation. Barth, M.C., and J.G. Titus, eds. New York: Van Nostrand Reinhold.

North America

Hoffman, J.S., D. Keyes, and J. G. Titus. 1983. Projecting future sea level rise. Washington, DC: Government Printing Office.

Hull, C.H.J., and J.G. Titus, eds. 1986. Greenhouse effect, sea level rise, and salinity in the Delaware Estuary. Washington, DC: U.S. Environmental Protection Agency and Delaware River Basin Commission.

Kana, T.W., J Michel, M.O. Hayes, and J.R. Jensen. 1984. The physical impact of sea level rise in the area of Charleston, South Carolina. In: Greenhouse effect and sea level rise: A challenge for this generation. Barth, M.C., and J.G. Titus, eds. New York: Van Nostrand Reinhold.

Kana, T.W., et al. 1986. Potential impacts of sea level rise on wetlands around Charleston, South Carolina. Washington, DC: U.S. Environmental Protection Agency.

Kana, T.W., W.C. Eiser, B.J. Baca, and M.L. Williams. 1988. New Jersey case study. In: Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Titus, J.G., ed. Washington, DC: U.S. Environmental Protection Agency.

Kyper, T., and R. Sorensen. 1985. Potential impacts of selected sea level rise scenarios on the beach and coastal works at Sea Bright, New Jersey. In: Coastal Zone '85. Magoon, O.T., et al., eds. New York: American Society of Civil Engineers.

Leatherman, S.P. 1984. Coastal geomorphic responses to sea level rise: Galveston Bay, Texas. In: Greenhouse effect and sea level rise: A challenge for this generation. Barth, M.C., and J.G. Titus, eds. New York: Van Nostrand Reinhold.

Louisiana Wetland Protection Panel. 1987. Saving Louisiana's wetlands: The need for a long-term plan of action. Washington, DC: U.S. Environmental Protection Agency.

Meier, M.F., et al. 1985. Glaciers, Ice Sheets, and Sea Level. Washington, DC: National Academy Press.

National Academy of Sciences. 1979. CO_2 and Climate: A Scientific Assessment. Washington, DC: National Academy Press.

National Academy of Sciences. 1982. CO_2 and Climate: A Second Assessment. Washington, DC: National Academy Press.

Park, R.A., M.S. Treehan, P.W. Mausel, and R.C. Howe. 1989. The effects of sea level rise on U.S. coastal wetlands. In: The Potential Effects of Global Climate Change on the United States. Volume B: Sea Level Rise. Smith, J. and D. Tirpak, eds. Washington, DC: U.S. Environmental Protection Agency.

Revelle, R. 1983. Probable future changes in sea level resulting from increased atmospheric carbon dioxide. In: Changing Climate. Washington, DC: National Academy Press.

Sorensen, R.M., R.N. Weisman, and G.P. Lennon. 1984. Control of erosion, inundation, and salinity intrusion. In: Greenhouse effect and sea level rise: A challenge for this generation. Barth, M.C., and J.G. Titus, eds. New York: Van Nostrand Reinhold.

Titus, J.G. 1984. Planning for sea level rise before and after a coastal disaster. In: Greenhouse effect and sea level rise: A challenge for this generation. Barth, M.C., and J.G. Titus, eds. New York: Van Nostrand Reinhold.

Titus, J.G, S.P. leatherman, C. Everts, D. Kriebel, and R.G. Dean. 1985. Potential impacts of sea level rise on the beach at Ocean City, Maryland. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G. 1986. Greenhouse effect, sea level rise, and coastal zone managment. Coastal Management 14:3.

Titus, J.G., ed. 1988. Greenhouse effect, sea level rise, and coastal wetlands. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G. 1989. Greenhouse effect, sea level rise, and wetland policy: will Americans have to abandon an area the size of Massachusetts? Submitted to Environmental Management (draft).

Titus, J.G. 1990. Greenhouse effect, sea level rise, and barrier islands. Coastal Management 18:1.

Titus, J.G., T. Henderson, and J.M. Teal. 1984. Sea level rise and wetlands loss in the United States. National Wetlands Newsletter 6:4.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Webb, and J.O. Waddell. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. Journal of Water Resources Planning and Management 113:2.

Titus, J.G., R.A. Park, S. Leatherman, R. Weggel, M.S. Greene, M. Treehan, S. Brown, and C. Gaunt. 1989. Greenhouse effect and sea level rise: Loss of land and the cost of holding back the sea. Submitted to Natural Resources Journal (draft).

Wilcoxen, P.J. 1986. Coastal erosion and sea level rise: Implications for Ocean Beach and San Francisco's Westside Transport Project. Coastal Zone Management Journal 14:3.

Williams, P. 1989. The impacts of climate change on the salinity of San Francisco Bay. In: The Potential Effects of Global Climate Change on the United States. Volume A: Water Resources. Smith, J. and D. Tirpak, eds. Washington, DC: U.S. Environmental Protection Agency.

SEA LEVEL RISE: CANADIAN CONCERNS AND STRATEGIES

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INTRODUCTION: THE CANADIAN CONTEXT

Canada is a coastal nation bordering on three oceans and possessing over 244,000 kilometers of coastline -- the longest of any nation in the world. A number of major cities and highways border on the ocean. There are also hundreds of fishing villages, over one thousand small-craft harbors, and numerous fishing plants. Many native communities are also located close to the shore, near the marine natural resources upon which they traditionally depend for food. Various industries, such as pulp and paper mills, coastal shipping, container ports, and oil refineries, are also located at the shore for obvious marine transportation advantages.

A rise in mean sea level is expected to have major impacts upon Canada's coastal resources and infrastructure. Fortunately for Canada, a large proportion of the coastline rises fairly steeply out of the sea, in the form of rocky shores and fjords, and is thus not at risk of flooding and erosion. Much of Canada is also remote. As a consequence of Canada's particular geography and relatively low population densities, the potential impacts in Canada of rising sea level, while expected to be of substantial significance and requiring specific policies and strategies for adaptation, are not expected to be catastrophic or even severe. This is very much in contrast to countries that possess much more exposed coastal lowlands or that simply do not have the physical space to consider alternatives for human resettlement, even if they wanted to do so.

In much of Canada, coastal impacts arising from higher ocean temperatures, changes to river runoff, and related changes to the oceanography, circulation patterns, ice cover, and hydrological cycle may be more important than those resulting from sea level rise. For example, Pacific cod are already at the southern limit of their distribution and may move north if water temperatures increase substantially. Canadians are generally more concerned with noncoastal impacts, such as potential shifts in agricultural and forestry patterns, hydroelectric power generation and lower water levels in the Great Lakes. (These impacts are addressed by the "RUMS" subgroup of IPLC work group 3.)

In Canada, the assessment of sea level rise and the development of adaptive options is still in its infancy. In the context of climate change, four recent studies have been carried out: three relate to the impacts of sea level arise on specific coastal cities (Charlottetown, Prince Edward Island; St. John, New Brunswick; and Vancouver, British Columbia), and the fourth provides an overview of impacts in Atlantic Canada. Generally, these studies have been based on the hypothetical scenario of a one-meter rise, which is then superimposed upon the 20- and 100-year flood levels. This information is then superimposed on maps of coastal resources to estimate the resources at risk. The Vancouver study also looked at scenarios of 2- and 3-meter rises in sea level (Figure 1). It can be concluded from these studies that the economic impacts of sea level rise can be estimated reasonably well. However, the ability to predict the impacts on natural ecosystems generally, and on marine ecosystems in particular, has not yet advanced very far, which reflects the complexities of those systems and the level of scientific ignorance.

POTENTIAL IMPACTS AND POSSIBLE ADAPTIVE OPTIONS

To review some of the specific impacts that might occur in Canada and some of the potential adaptive options, it is useful to adopt a general hypothesis of a one-meter rise in sea level (as opposed to looking at a 5-meter rise) over the next 50 years. Based on present trends and predictions, a change of this magnitude is a useful starting point for examining the need for coastal zone management decisions over the next 10-25 years.

We caution that Canadian studies have not yet considered the vertical movement of the Earth's crust. Data for the east coast show considerable spatial variability. For example, in the Gaspe Peninsula, land is rising as much as 40 centimeters per century; while in southern Newfoundland (400 kilometers to the east), land is subsiding about 50 centimeters per century; and at the northern tip of Newfoundland (a further 400 kilometers north), it is rising at 100 centimeters per century (Figure 2). Thus a rise in global sea level would not necessarily imply a relative rise in sea level at all locations; it might simply decrease the current rate at which sea level is falling. Similar spatial variability has been observed on the west coast, where both tectonic processes and glacio-isostatic rebound contribute to sea level change. The removal of groundwater and the extraction of offshore and nearshore hydrocarbon resources may also cause subsidence and compaction. The key points are that all of the contributing processes have to be integrated to arrive at the overall net change of mean sea level, and that these changes will vary from place to place.

Following are some of the key impacts expected in Canada and the adaptive options to deal with them.

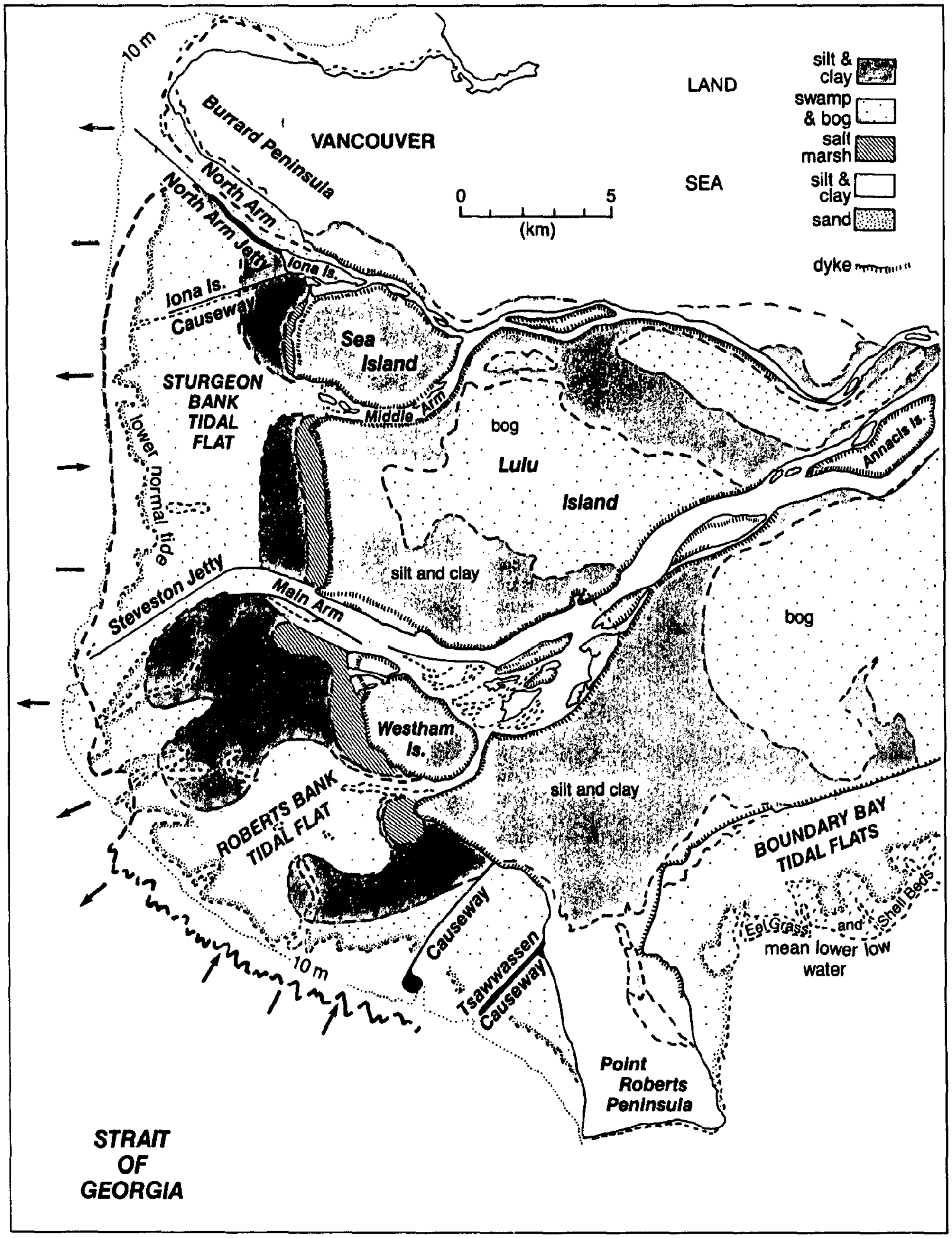

Figure 1. Geologic map of the low-lying Fraser River Delta region of heavily populated Greater Vancouver, B.C. Map shows the location of dykes to prevent flooding of deltaic islands. Broken line marks seaward limit of the delta foreshore. Arrows indicate direction of present advance or retreat of the delta front, solid bars denote no change (R.E. Thomson, personal communication).

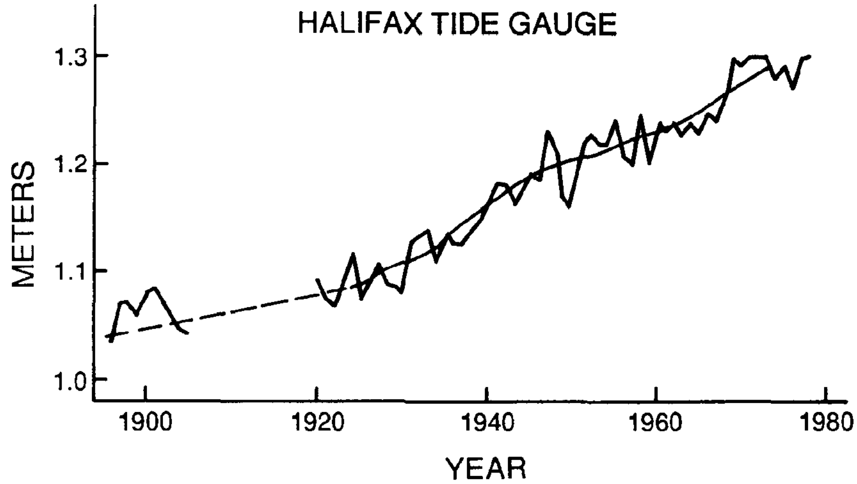

Figure 2. Sea level at Halifax, Nova Scotia is already rising at the rate of 0.3 meters per century. This is thought to be post-glacial adjustment, the greenhouse effect could greatly accelerate the trend.

Coastal Infrastructure

With a rise in sea level, coastal infrastructure related to human settlement and industrial development on all coasts will be subjected to some level of increased flooding. In some cases, this risk will be new; in others, existing flood risks will be exacerbated by increased water levels. Coastal infrastructure so affected may be grouped into three general categories, namely:

- existing permanent structures that would suffer loss or damage solely attributable to a rise in sea level. Replacement or preventive strategies, including resettlement, would require major new expenditures. However, depending on the magnitude of the potential loss or damage, investment in adaptive options may be unavoidable. The loss of valuable waterfront land would also fall into this category, but it might be offset by reclamation/landfill projects.

- existing nonpermanent structures with finite life expectancies, which would normally need to be replaced within the next 50-75 years anyway. With careful planning, the incremental cost of taking sea level rise into account when structures are replaced may be negligible in these cases.

- new or planned infrastructures. The opportunity exists now to design such structures to avoid or minimize the impact of sea level rise, also at minimal cost.

In short, advance planning taking sea level rise into account before construction is the most intelligent and cost-effective approach to the development of new coastal infrastructure. Based on the studies to date, the cost of replacing or modifying coastal infrastructures in Canada in response to sea level rise could be in the range of U.S. $3-4 billion or more. A large fraction of this cost could be avoided by incorporating sea level rise into routine maintenance and reconstruction costs.

Homes, Buildings, and Roads

In most coastal cities, a number of waterfront properties and structures will be subject to flooding from a one-meter rise in sea level. Higher levels will increase the risks posed by surface waves, tides, ice jams, storm surges, river runoff, and sea ice. Accurate risk assessment will require detailed data compilation and flood zone mapping at the local level.

The mitigative options range from permanent floodproofing of individual structures frequently subjected to flooding to temporary protective measures for areas subject to infrequent flooding. Where there are extensive lowlands and the value of the affected infrastructure justifies it, a system of protective dikes may be created. In the residential area of Richmond, British Columbia, south of Vancouver, which constitutes high-price real estate located on a delta, a diking system already exists. However, it would need to be topped off to allow for higher sea levels, storm surges, and waves. Further new diking would be needed if flooding threatens other farmlands within the river valley. In the case of much less valuable property, such as the Village of Tuktoyaktuk (comprising Inuit homes, oil company exploration shorebases, and an airport) located on the shores of the Beaufort Sea and Arctic Ocean, it may be more cost-effective to actually move the location of the town, or at least the flood-prone sections, to higher ground. Fortunately for Canada, few situations will actually require large-scale human resettlement.

Finally, new development on the waterfronts of Canada's major cities (for residential, commercial, industrial, transportation, and recreational purposes) continues to draw considerable business investment, simply because the waterfront is one of the most desirable places to be. Property zoning, construction codes and standards, and coastal zone planning processes need to take into account the explicit possibilities of sea level rise.

Municipal Sewers and Water Supplies

A rise in sea level will affect the operation of sewer outfalls. In addition, there will be flooding of existing storm and sanitary sewers located near the water, which will result in either corrosion of the sewer pipes or a backing up of the sewer systems resulting from inhibited outflows from the higher sea levels at the outfall to the sea. Such flooding will in turn cause property damage and create a health risk, including possible contamination of the drinking water system. In light of the overriding public health considerations, a modification of the affected sewage and water supply systems is inevitable. In many communities, new sewers and sewage treatment systems are being planned at a cost of billions of dollars. To protect those investments, it is essential to design now for higher sea levels in the future.

North America

Ports, Small-Craft Harbors, Breakwaters, and Fish Processing Plants

By their very nature, such facilities need to be located near the water's edge. In Atlantic Canada alone, there are over 1,000 small-craft harbors, over 100 federal government wharves, 13 ferry terminals, 21 marine service centers, and over 500 fish-processing plants.

The routine maintenance and replacement of wharves probably could be planned to take into account higher sea level. Wharves will definitely need to be raised. Old Federal wharves, for example, are only 1 meter above normal high tides, but newer wharves are meters higher. Fish plants would have to be moved further inland or somehow modified to keep the work areas dry. For small-craft harbors, a rising sea would (at least slightly) reduce maintenance dredging requirements.

On the other hand, changes in currents, circulation, wave and ice patterns, river deposition, and the resulting changes in shoreline erosion patterns could more than offset such savings. Site-specific assessments and engineering studies would be needed. Not only might breakwaters have to be raised to afford better storm protection from higher seas, but their location and configuration might need to be changed to adapt to new wave refraction patterns and changes in the way rivers deposit sediment.

Roads, Bridges and Causeways

Canada has an extensive network of roads, small bridges, and causeways throughout its coastal region. Many of these structures would be vulnerable to a one-meter sea level rise. The corrective measures would include relocating or raising roads, reinforcing and raising causeways, and raising bridges -- all at a cost significantly greater than normal maintenance costs. Some major new causeways are at the planning stage -- e.g, the causeway to Prince Edward Island -- but proper planning can allow for higher sea level and changing ice regimes.

Erosion

Coastal erosion is a problem in many parts of Canada, especially on the east coast (Figure 3). In some cases, shores are retreating as much as 5 meters each year. Sea level rise is generally expected to aggravate the problem. However, the actual response of vulnerable shorelines will also depend on changes to wind and wave patterns, currents, the geology and geomorphology, the ice regime, local land subsidence, and sediment supply limitations. Our ability to predict the timing and magnitude of changes to erosion patterns will require further research on a site-specific basis. Realistically, however, the implementation of shoreline protection measures will only be economically feasible for those areas where the value of the shoreline investment is sufficiently high, such as residential and recreational developments, harbors, power plants, and other infrastructure.

Figure 3. Accelerated erosion can be expected in places where an increase in mean sea level would allow wave-induced erosion to attack vulnerable cliffs instead of dissipating on the beach, as in this area at the head of the Bay of Fundy.

Tidal Power

One of the more interesting coastal development concepts in Canada is that of tidal power in the Bay of Fundy, where the tidal range is as much as 10-12 meters in some locations. From numerical models, it has been calculated that an increase of 1 meter in sea level at the ocean entrance (Georges Bank) would increase the tidal range at the head of the bay by about 1.7% -- that is, by 20 centimeters. Therefore, the height of the tidal power barrage would need to be raised by about 1.2 meters. Fortunately, the increase in tidal range also results in greater power output, so that if development proceeds, the increased cost of engineering and construction will be roughly balanced by the increased revenues from power generation.

Estuaries

The question of impacts in our estuaries has not generally been resolved and requires further research and site-specific studies. In general, one would expect a rise in sea level to extend partway upstream, which would raise water levels and salinities. However, water levels will also be directly controlled by the extent of river outflows and ice cover. Outflows will vary from one part of the country to another and require accurate predictions of temperature and precipitation.

In the St. Lawrence River, a related concern is the expected lowering of water levels in the Lower Great Lakes by 30-80 centimeters, which would decrease the outflow of the St. Lawrence River by 20%. This, in turn, would not likely decrease water levels in the river. The net result of these complexities, including crustal movements, is considerable uncertainty in the expected rise or fall of sea level in our estuaries, and it is too soon to design adaptive strategies. Much more basic and site-specific hydraulic research needs to be conducted before we even know what conditions we need to adapt to. (Note: The drop in lake levels is independent of sea level rise, and is generally, expected to result from increased evaporation at higher temperatures).

Agricultural Lowlands

A small percentage of Canada's agricultural production takes place near the ocean shoreline, primarily in the Fraser River delta and in low-lying lands on the east coast. Many of these areas are already diked, and they also have "aboiteaux," which are essentially tidal gates that allow water to drain from these lands during low tide. The solution to combat sea level rise will be to gradually increase the height and extent of these structures. Moreover, new dikes and weirs may need to be built along the shores of the Fraser and St. Lawrence Rivers as rises in sea level extend farther upstream.

Marshes, Wetlands, and Wildlife Habitat

The key areas that may be affected are easy to identify and are located mainly in the major estuaries and deltas (the Fraser, St. Lawrence, MacKenzie Rivers) and low-lying lands along the southern shores of Hudson Bay and on the east coast. However, the impacts are not so easy to predict.

No doubt, a sea level rise will inundate parts of these habitats. But where topographic gradients permit, and if sea level changes slowly enough, these productive systems will hopefully reestablish themselves farther up the shoreline, and various biological species and their food supplies will recolonize or adapt to their new surroundings. It is also possible that such habitat may not be reestablished. For large remote areas, such as Hudson Bay, it is very likely that no adaptive options are practical, except to allow nature to run its course. For less remote areas, critical habitat might be replaced by manmade development of new habitat at nearby locations, but at considerable effort and cost.

For some fish and other species of economic importance, new habitat is already being created as part of a Fish Habitat Management Policy, which strives to achieve no net loss of natural habitat. On the west coast of Canada, significant amounts of new habitat for salmon have been created by planting eel grass in several major salmon estuaries. Further habitat development is a practical means of mitigating losses of salmon and trout habitat from sea level rise in estuaries and rivers.

Economic approaches also exist to replace lost production of certain economically valuable fish species that spawn or grow in estuaries and the nearshore. Salmon are being produced on a large scale through artificial enhancement, in which eggs from wild fish are recovered during the spawning season and grown in temperature-controlled hatcheries to an appropriate size before being released to the sea. This approach does not resolve the habitat problem per se, but it does contribute to sustainable development and economics.

Another solution to the economic problem is commercial aquaculture. In Canada, a considerable aquaculture industry has developed over the past decade, mainly for salmon, oysters, and mussels. The industry's value has grown from $13 million in 1982 to $100 million in 1988, mainly on the Pacific coast, and further major expansion, especially to the east coast, is projected. Clearly, there is an economic opportunity here that can also assist in mitigating the effects of rising sea level.

Finally, it must be noted that the key climate issue facing fisheries in Canada is not sea level rise, but the changes in water temperatures, circulation patterns, wind-induced upwelling, and other factors that will determine the future distribution, recruitment, and production of fish. This has major implications for national and international resource management strategies and agreements, fishing industrial strategies, and regional economics. (See Everett, Volume 1, for additional discussion of response strategies to protect fisheries).

FUTURE ACTION

From a coastal zone management point of view, a considerable degree of skepticism exists in Canada regarding the risk of sea level rise over the next few decades and beyond. It must be recognized that while research and understanding of climate change takes place at national and international levels, a large part of the decision making to mitigate local and regional effects takes place at the local or regional level of government. At what stage of research and assessment will there be sufficient knowledge and understanding to encourage or persuade natural resource managers and local officials to actually allow for higher sea levels in planning for habitat management and protection; for the owners of real estate and infrastructure in the coastal zone to actually spend money to floodproof existing buildings or to invest in diking and other protective measures, or to make the increased investment in planned coastal works needed to avoid future flooding, or even to ensure that rising sea level is taken into account in existing coastal planning and decision making processes? Whatever that point of credibility may be, it is clear that we are still far from reaching that point.

Where, then, do we go from here? I believe that the following actions are needed:

- Continue research on global climate change to reduce current uncertainties in the prediction of sea level rise resulting from global warming.

- Encourage further research and monitoring related to sea level change, which must include the contribution of vertical movements of the Earth's crust and groundwater depletion to relative sea level change as well as global warming effects.

- Develop regional models for climate change, and carry out multidisciplinary site-specific studies that integrate all the factors that influence net changes to water levels in estuarine and coastal areas, including interactions among precipitation and runoff, tides, ice cover, crustal movements, erosion, sedimentation, storm surges, and waves.

- Improve the scientific understanding of marine coastal ecosystems in order to conduct ecological impact assessments related to rising sea level.

- Develop detailed inventories and mapping of coastal infrastructure and natural resources in areas potentially affected by changes in sea level, in order to facilitate improved impact assessments.

- Continue research into coastal geomorphology and sedimentology in order to understand coastal erosion processes, to predict the impacts of higher sea levels, and to develop adaptive strategies.

- Encourage multidisciplinary impacts research related to sea level.

- Encourage the innovation and development of adaptive options.

- Facilitate the public dissemination of information and research results relating to sea level rise.

- Encourage those involved with coastal zone management, building standards/codes, property zoning, and sustainable development planning to take into account the future possibilities for rising sea levels. Development of flood-prone lands must be discouraged, by legal prohibition if necessary.

BIBLIOGRAPHY

Anon. 1989. The full range of responses to anticipated climatic change. United Nations Environment Program and Beijer Institute, April.

Forbes, L.B., R.B. Taylor, and J. Shaw. 1989. Shorelines and rising sea levels in eastern Canada," EPISODES, Vol. 12, No. 1, p. 23-28.

Lane, P. et al. 1988. Preliminary study of the possible impacts of a one-meter rise in sea level at Charlottetown, Prince Edward Island. Climate Change Digest, Report No. CCD 88-02, Environment Canada, Ottawa, Canada.

Martec Limited. 1987. Effects of a one-meter rise in mean sea level at Saint John, New Brunswick and the lower reaches of the Saint John River. Climate

Change Digest, Report No. CCD 87-04, Environment Canada, Ottawa, Canada.

Sanderson, M. 1987. Implications of climatic change for navigation and power generation in the Great Lakes. Climate Change Digest, Report No. CCD 87-03, Environment Canada, Ottawa, Canada.

Scott, D.B., and D.A. Greenberg. 1983. Relative sea level rise and tidal development in the Fundy Tidal System. Canadian Journal of Earth Sciences, 20(10):1554-1564.

Smith, J.V. 1989. Possible impacts of mean sea level rise scenarios on downtown Vancouver. Unpublished manuscript prepared for Atmospheric Environment Service, University of Waterloo, Ontario, Canada.

Stokoe, P. 1988. Socioeconomic assessment of the physical and ecological impacts of climate change on the marine environment of the Atlantic region of Canada - Phase 1. Climate Change Digest, Report No. CCD 88-07, Environment Canada, Ottawa, Canada.

THE LOWLANDS OF THE MEXICAN GULF COAST

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ABSTRACT

Mexico's Gulf of Mexico coast is largely lowland subject to a large range of marine influences. Of six large lowland areas that are subject to relative widespread flooding, four are within deltaic systems.

The coastal zone has been undergoing considerable change as a result of port development related to the extraction of oil and to the concentration of oil refineries and petrochemical plants. This area has also undergone a great expansion of commercial agriculture, cattle ranching, and high-cost tourist development.

There are, at present, many conflicts between the development interests and the local economies based on the coastal resources. The intensity of exploitation is currently causing serious deterioration of the environment, which is produced by a combination of the cultural processes superimposed on the natural changes. The losses of marshlands, mangroves, and other aspects of the coastal aquatic system are problems that need to be addressed. Although attempts have been made to control some of the changes by constructing coastal protection devices, these "solutions" have been neither well-planned nor successful. An awareness of the dynamics of the coastal system and the changes driven by a rising sea level must be introduced into the decisionmaking process.

INTRODUCTION

Approximately two million Mexicans live within five meters above sea level. Although a one-meter rise would inundate only a fraction of the nation's coastal zone, it would threaten some of the most valuable land, including tourist resorts, port facilities, and the wetlands that support an important fishing industry.

The intent of this paper is to summarize the present state of knowledge concerning the physiographic information, the wetland areas, and the socioeconomic aspects of the Mexican Gulf Coast and to identify some of the impacts to the system as a result of a future sea level rise.

IMPACTS OF SEA LEVEL RISE

Physical Effects

Sea level rise particularly threatens the barrier islands along the Gulf of Mexico; as sea level rises, they will gradually narrow and some will shift inland. The islands in front of the southern portion of the Laguna Madre will certainly shift landward, and additional inlets are likely to form, further segmenting these islands. On the other hand, the barrier in front of the Tamiahua Lagoon will narrow at first, although it will eventually break up as well.

The high, dune-lined barrier islands near Veracruz, Alvarado, and Coatzacoalcos have sufficient size and mass to resist erosion, at least in the early years. There will be some loss of sediment and there will be a slight shift of the beach into the dune zone, but the effects will be limited. Along the Tabasco-Campeche barrier system, the effects will vary: In western Tabasco, the barriers in front of most of the smaller lagoons will be removed by overwash and breaching, creating a very indented shoreline. The area from Tupilco, Tabasco, to Champoton, Campeche, is very low but very wide. Along this segment, the coast will erode at a very rapid rate as sea level reaches to higher levels and removes sediment from the low-lying beach ridges. The oil port of Dos Bocas will be increasingly exposed to storm effects and breaching of the jetties and shore protection structures.

The very narrow barrier along the Yucatan Peninsula will diminish greatly in size and probably break up. The salt-evaporation ponds at Progresso will be threatened as they are initially overtopped by inundation with higher sea level and then erosion as they become exposed to wave attack. The barrier island at Cancun will become every narrower and more liable to storm damage as sea level rises, thus threatening all existing and future infrastructure.

Mexico's wetlands would also be vulnerable to a rise in sea level, especially given the impacts of economic development. Their inundation would normally be balanced by an upward growth as organic and inorganic matter accumulates to a new level. The problem of sea level rise is compounded in

Mexico because nearly all of the major rivers leading to the vast wetland areas are dammed and the sediment supply has been attenuated for decades. The product of the sea level rise and a decreasing sediment supply will lead to a loss of wetland area and a loss of primary productivity of the wetlands, the estuaries, and the adjacent nearshore areas. This could lead to serious deterioration of the local fisheries industries, independent of problems of pollution and overfishing.

The wetlands of Laguna Madre and the Tamiahua Lagoon have already shown the effects of a limited sediment supply. Their bordering wetlands are very narrow. The Alvarado Lagoon and the Papaloapan lowlands will show a considerable change both as a result of the higher water level and the severe loss of sediment supply coming into the estuary.

The Grijalva lowlands will be the most seriously affected because it is the largest wetland area in Mexico and because of local subsidence and sediment starvation associated with the Malpaso Dam. Wetlands are already migrating onto the slightly higher coastal beach ridges and sand dune topography, while the bodies of open water are increasing and the shoreline is migration inland. The new population centers there and the petroleum industry will be affected as the water table rises and it becomes more difficult to drain the surface water off the land and lead the sewage away.

Socioeconomic Implications

Port activity could be affected by the sea level rise, especially in areas where the infrastructure is essentially at beach level, such as at Campeche, Ciudad del Carmen, Frontera, Dos Bocas, and parts of Coatzacoalcos and Veracruz. In Carmen, Frontera, and Dos Bocas, there is no higher ground to accommodate a landward retreat. The landscape is only a few meters above sea level and any increase will expose these sites to greater storm damage.

Much of the lowland is used for some type of economic activity. Oil exploration is certainly a common use throughout much of the coastal plain, and it is especially prevalent in the Tabasco lowlands. In addition, cattle pasture, coconut plantations, cacao, maize, sugarcane, lumbering, and fishing are important economic pursuits. With the exception of fishing, all of the other economic activities will be adversely affected by a higher sea level because of the changing salinities and water table. Whereas the entire area will not be affected uniformly, the net effect will be a loss of surface area where each of these economic activities can be practiced. The petroleum industry will be able to conduct its exploration phase despite sea level rise. However, some of the stationary infrastructure may be negatively affected as shoreline erosion or higher water levels begin to encroach upon these structures.

Responses

One can reasonably expect that revenue-producing activities such as tourist beaches, ports, and petroleum activities will be protected with traditional coastal engineering measures. The casualties in this process will almost certainly be the environment and people pursuing traditional activities who lack the necessary resources to hold back the sea.

The coastal environment in Mexico is currently being exploited in manners likely to have an adverse impact in the long run. If we are unable to adequately address current environmental problems, how can we prepare for consequences of a rise in sea level that is still decades away?

Nevertheless, Mexico does have institutions that are capable of planning for the future, provided that the actions do not substantially undermine economic growth. In this regard, it seems wise to direct future coastal development to areas that are at least three meters above sea level; not only would this prevent future environmental impacts, but it would leave these areas less vulnerable to flooding even in the short term. Similarly, along the ocean coasts, tourist facilities should be set back from the shore; this would make them less vulnerable to hurricanes and would enable the beach to survive accelerated sea level rise.

But perhaps the most important first step in planning for sea level rise would be increased awareness on the part of the public in general and governmental officials in particular. Information transfer is a slow process. This is an area where researchers and universities can play an important role, rather than being outside observers and critics of governmental processes. The scientists and economists in Mexico need to begin discussing the implications of global climate change, so that we can better inform the policy makers of possible responses.

We note in particular that the Sea Grant College programs of California and Texas are interested in collaboration with Mexican scientists. We strongly urge these organizations to collaborate with the relevant Mexican Universities on the issue of sea level rise, with the goal of a bilateral conference on sea level rise similar to the Miami conference but focused on the common coastal problems facing states on either side of the U.S./Mexican border.

THE COASTAL ENVIRONMENT OF MEXICO

Coastal Geomorphology

The Mexican coast on the Gulf of Mexico has a length of approximately 2,500 km. The coastal plain has a width varying from 30 to 150 km. The coastal relief generally is even and low, being traversed by more than 25 important rivers and incorporating 23 coastal lagoons of very different sizes. The coastal inlets are very important owing to the different transitions between the barrier islands, river mouths, and deltas, linking floodplains, lagoons, marshes, swamps, and mangroves.

The rocky coasts appear in short sections and are of low altitude; some are composed of compact volcanic rocks forming isolated promontories on the general coastal outline. On the Caribbean margin, the coast is rectilinear and rocky with short sections of indented configuration. Escarpments are low and formed in calcareous rocks incorporating a narrow abrasion and accumulation platform, isolated from the open sea by a coral barrier.

The predominant types of coast are sandy beaches (1,629 km), followed by the swampy coast and marshes (389 km), very important around the estuaries and lagoons; the rocky coast has a length of 382 km.

Climate

The regional climatic characteristics of the Mexican Gulf Coast are the dominant pluviometric system and the yearly temperature distribution (Garcia, 1989). Garcia divides these elements into three broad zones that from north to south are as follows:

- The Tamaulipas northern coast, which is hot and arid, characterized by temperatures higher than 18°C during all the year, with a yearly rainfall of less than 800 km. Seasonally, it has an extreme climate, with a yearly thermal range of more than 14°C. During the winter it receives cold wind masses and during summer torrential rains associated with cyclones or tropical storms.

- The central part of the littoral is subhumid toward the north and humid at the south, with an average yearly temperature that varies from 22°C to 26°C and a yearly rainfall between 1,000 and 1,500 mm, increasing to the south. During the winter the coast receives north winds, that is, cold wind masses, and during autumn, the easterly tropical waves are common. The rest of the year the trade winds are dominant.

- The southeast section comprises the complete Yucatan Peninsula. It has a circulation system similar to the above, with the exception of the temporary stationary high pressure cell over the south-central section of the gulf. The high pressure cell is responsible for a series of climatic zones that vary from a dry semiarid condition at the northwest end of the peninsula to a subhumid climate toward the south and southwest interior.

The gulf is a favorable area for tropical cyclones and their accompanying floods and storm tides (Jauregui, 1967). Almost 35% of the cyclones originating in the Caribbean Sea touch or cross the Mexican coasts. Winters contribute storm waves caused by the north winds, in addition to the frontal rains and orographic rainfall created when the humid air masses collide with the slope of the Sierra Madre.

Waves and Currents

Three types of wave regimes are found at the Gulf of Mexico and the Caribbean coast (Lankford, 1977):

- waves and storm surge associated with the tropical cyclones;

- waves and storm surge associated with the movement of polar wind masses known in Mexico as north winds (Nortes); and

- waves and wind surge that is generated within the limited fetch of the gulf basin.

The dominant winds show a preference for directions from the northeast, east, and southeast quadrants. The wind waves typically have short periods of between 5 and 7 seconds, and the average heights are of 2.3, 2.3, and 1.4 m from the northwest, north, and northeast, respectively (Lankford, 1977). In general terms they can be considered as intermediate to low energy waves, except for the north wind and hurricane situations, where waves of more than 4.5 m have been observed.

The hurricanes occur in the summer, causing intense storms. The cyclonic paths show a preference in their course for the Yucatan Peninsula and its platform, crossing it, and more frequently approaching the northwest coast than the southwest coast.

The Nortes develop between October and February. Each year between 15 and 20 Norte events occur, each one with a duration of 1 to 5 days. It is frequent that they exceed 100 km/hr, creating storm tides that inundate lowlands, erode the shores, and transfer sediment in numerous directions. There is a movement of sands in the dune fields, with an orientation from north to south, prograding the coastal lagoons to the lee.

Cultural and Economic Features

Demography

The coastal zone of the Gulf of Mexico is shared by six states of the Federation: Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo, with a total of 57 municipalities which together in 1980 had a population of 2.8 million, representing the 4.1% of the total population of the country (Table 1).

Even though the Gulf of Mexico coastal zone has a long tradition of human settlement, at present it does not have a dense population. In recent decades there is a slight tendency toward an increasing population, especially in the urban areas. In the year 2000, it is estimated that the coastal zone will record a population of 4.5 million inhabitants, that is, 4.7% of the total population of the country.

Distribution of Human Settlements

Of the 2.8 million coastal inhabitants in 1980, 70% lived at an altitude between 1 m and 5 m, mainly along the coast or at river borders very near their mouths. About 60% of the coastal population reside in cities (Table 2); 44.9% live in cities with more than 100,000 inhabitants.

Table 1. Total Population of Mexico and the Gulf of Mexico Coastal States and of the Coastal Zone, 1960-2000

Area	1960	1970	1980	1990	2000
Country	34,923,129	48,377,363	66,846,833	78,140,006	1,802,174
Coastal States	5,080,858	7,138,668	10,090,396	1,244,617	14,950,947
% Total Country	14.55	14.76	15.09	15.93	16.29
Coastal Zone	1,236,269	1,864,189	2,792,613	3,526,055	4,303,529
% Total Country	3.54	3.85	4.18	4.51	4.69
% Total Coastal States	24.33	26.11	27.68	28.33	28.78

Source: Censos Generales de Poblacion (1960, 1970, 1980).

Table 2. Distribution of the Coastal Zone Population by Size of the Settlement, 1980 (Size of the settlement by number of inhabitants)

	1-999	1,000-14,999	15,000-19,999	20,000-99,999	more than 100,000	Total
No. of villages	5,129	194	3	8	6	5,341
(%)	96.0	3.6	0.06	0.02	0.1	100.0
Total Population	572,937	540,510	54,391	345,597	1,236,337	2,749,772
(%)	20.8	19.7	2.0	12.6	44.9	100.0

Source: General Population Census (1980).

Cities

In general, all the states that constitute the gulf coastal zone have important cities (Table 3). There are other smaller cities that during the last decades have obtained great importance, registering a high rate of demographic growth, such as Ciudad del Carmen in Campeche and Cancun in Quintana Roo.

Most of the cities with more than 15,000 inhabitants perform harbor functions; included here are the largest with the exception of Matamoros.

Port Facilities

The region has 56 ports, of which 17 are sea ports and the rest are fluvial ports. Major ports are located in the States of Tamaulipas, Veracruz, Tabasco,

Table 3. Population of the Cities With More Than 15,000 Inhabitants, 1960-2000

City	1950	1960	1970	1980	1990	2000
Campeche	31272	43874	69506	128434	147551	179263
Carmen	11603	21164	34656	72489	84016	103631
Cancun[a]				33273(5)		
Chetumal	7247	12855	23685	56709	64928	80850
Cozumel	2332	2915	5858	19044	20807	26115
Tampico	94345	124894	185059	267957	313314	371414
Matamoros	45846	92327	137749	188745	234697	282108
Veracruz	101221	153705	230220	305456	415456	511678
Coatzacoalcos	19501	37300	69753	186129	211255	264489
Minatitlan	22455	34350	68397	145268	168239	208388
Tuxpan	16096	23262	33901	56037	64940	77986
Alvarado	8840	12548	15792	22633	26109	30571
Panuco	6615	8818	14277	26652	30483	37040
Gtz. Zamora	4480	6518	9099	15037	17347	20772
Progreso	13339	17060	21352	30183	34190	39672

Source: General Population Census (1950, 1960, 1970, 1980).
[a]It was not possible to make a projection of the Cancun population, because it is of recent creation and has no population register for the period 1950-1970.

and on the coast of the Yucatan Peninsula. The gulf coastal zone is important because of the petroleum industry, both in production as well as in processing. From the coastal zone of Tamaulipas, Veracruz, Tabasco, and Campeche is extracted most of the Mexican oil. In 1985 the zone had 370 fields (S.P.P. 1986, p. 88-110). The processing industry is represented by petrochemical refineries. The most important petrochemical complex is Coatzacoalcos-Pajaritos-Minatitlan-Cosoleacaque-Cangrejera; it is primarily located along the lower Coatzacoalcos River. The complex has 33 petrochemical plants: 12 in Cosoleacaque, 11 in Minatitlan, 13 in Pajaritos, and 21 in Cangrejera. It also has a refinery in Minatitlan, with a capacity of 258 thousand barrels per day.

In 1985, this complex, together with the one at Ciudad Madero, also located in the gulf coastal zone, had the highest production in the country. The production obtained was 968 million barrels of crude oil and 1,186,667 million cubic feet of natural gas (S.P.P. 1986, p.47), representing 98.1% and 90.2%, respectively, of the total production in the country. With regard to petrochemicals, in 1984 the production of refined oil was 200 million barrels and petrochemicals amounted to 8.5 million metric tons; that is 41% and 74% of the yield in the country.

Equally important is the oil-line and gas-line net in the State of Tabasco that starts at the Sonda de Campeche with a terminal at the port of Dos Bocas.

Also, Campeche has the majority of maritime production platforms in the Gulf of Mexico, with a total of 48 (Ecodevelopment, 1988).

Recently the first nuclear electric plant at Laguna Verde started to function. It is located on the Veracruz coast 70 km northeast of Veracruz. The plant has two units, each one with a capacity of 654,000 kilowatts.

Even though the gulf coastal zone and the Mexican Caribbean have had an uneven touristic development, it is important to point out the touristic installations exist in some points of this region. Located in the Caribbean, Cancun is the principal touristic node. In only one decade it has risen to become the most important tourist site in the country. Its development has been totally planned. It was principally created to satisfy an international demand. In 1988 it was able to offer lodging in 9,520 rooms.

Veracruz and Cozumel are also considered to be important touristic centers. In 1988 they were able to offer 4,400 and 2,320 rooms respectively. Veracruz covers principally the demand for national tourism, while Cozumel is important for international tourism.

The ports and installations mentioned having the greatest exposure to effects caused by the sea level increase are Tampico, Alvarado, Coatzacoalcos, Dos Bocas, Frontera, and Ciudad del Carmen. Each has an altitude that varies between 0 and 3 meters.

LAND USE

At the coastal zone, the combination of different elements of the hydrologic cycle creates two great natural systems: (1) the coastal lands system and (2) the coastal waters system (Toledo, 1984); both are highly productive.

Use of the Land of the Coastal System

The use of the land (Table 4) of the first mentioned systems, the coastal lands, can also be divided in two: (1) one of natural origin and (2) the other introduced by man.

In the Tamaulipas coastal strip, dry shrub vegetation is dominant. Forest cover is located in well-defined areas, presenting some variants depending of the rainfall requirements. A small portion at the northwest and north of the Yucatan Peninsula completely lacks vegetation.

Among the land uses introduced by man, one is extensive cattle raising that takes great advantage of the natural pasture characteristic of the zones. New pastures that have technically modified some ecosystems as the forest have also been introduced. The use of the land for natural and induced pasture covers the largest surface area (25%) of the coastal zone. Most of the cattle production in the zone is destined for the internal market, principally in the central part of the country.

Table 4. Use of the Land in the Coastal Zone of the Gulf of Mexico

Use of the Land	Surface in km²		Percentage	
	Partial	Total	Partial	Total
Pasture ground		12167		25.0
Bush	6257			12.9
Tamaulipas Bush	375		0.8	
Mesquite	1278		2.6	
Rosettophyle Bush	1809		3.8	
Cacicuale Bush	2795		5.7	
Forest		10011		22.5
Low Perennifoil	979		2.0	
High Subperennifoil	7335		15.0	
Medium Subperennifoil	1118		2.3	
Low Subperennifoil	1558		3.2	
Savanna		4365		8.9
Mangrove		4504		9.2
Tular and popal		5685		11.6
Agriculture		4542		9.3
Temporal	3472		7.1	
Irrigation	1070		2.2	
Without irrigation	316			0.6
Total	48826			100.0

Of less importance is the use of the agricultural land in its two forms, natural and irrigated. For the latter, the most important zone is located at the north of the coastal region (Tamaulipas) near the U.S. border, principally dedicated to the cultivation of cereals. In non-irrigated agriculture, the commercial monocultivation plantings (sugarcane and bananas) are located principally in Veracruz and Tabasco.

Use of the Coastal Waters System

The water system is one of the most important systems in the coastal zone for its fragility as well as for its ecologic conditions, and because it is highly productive. It can be divided into two subsystems, both intimately tied through physiographic and ecologic processes in a way that -- on one hand -- there is the vegetation typical of the system (mangrove, Tular, and Popal) and -- on the other hand -- there are the waters.

The mangrove is principally limited at the border of the coastal lagoons and in the mouths of the rivers. The most important associations are located in the Tabasco and Campeche littorals. The red mangrove is characteristic of this community, reaching heights up to 25 meters; it is used for marine construction and in the manufacture of charcoal (Ecodevelopment Center, 1988).

The Popal, or marsh, consists of an association of hydrophytes, including Thalia, Cyperus, Colathea, and Heliconia. Very often, it is found together with tulares. The greatest extension of this type of vegetation is located at the south of Veracruz and in Tabasco. Commonly it is burned during the dry season to take advantage of the land for cultivation.

Economic Importance of the Coastal Zone

The Gulf of Mexico coastal zone has played an important part in the development of the country. At the beginning of the 20th century, it was distinguished for plantation agriculture (sugarcane, banana, and sisal, among others). Later, it acquired importance for commercial cattle raising, principally for the internal markets. During the last decades, the oil industry has become the most relevant economic activity. It is important to point out that the coastal states (Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo) contribute 14.7% of the gross internal product of the country, and the coastal zone contributes 3.9%.

At present, plantation agriculture is still the most important in the coastal zone (INEGI, 1985). The region contributes 47.3% of the sugar production in the country. Of importance is the irrigation agriculture, especially in the coastal plain of the State of Tamaulipas that produced 41.5% of the national sorghum that year.

Cattle raising has been acquiring great importance, principally the breeding of bovine cattle. The region had 26.4% of the national production of this type of cattle in 1983. But, undoubtedly, the oil industry has distinguished this region for its crude production as well as for petrochemicals (see industrial installations).

FISHING

The Gulf of Mexico and the Caribbean coastal zone with its 2805 km of coastline, its 771,500 km^2 of exclusive economic zone, and a broad continental shelf, represent a significant fishing zone, even though not the most important in the country. Outstanding within the region are the Campeche sound and some tropical fisheries.

North America

Fishing in the region, even though limited principally to the littoral zone, including the coastal lagoon systems, is also carried out in the shelf. The State of Campeche has excelled in this type of fishing. As a whole, the zone had a 1983 production of 275,493 tons (INEGI, 1985).

When studying the fisheries of the region, great differences are noted between the Gulf of Mexico and the Caribbean. The first presents a sustained production, carried out principally on the continental platform. In 1983, it registered a value of production of 3,842,141 million pesos. The most important species captured are shrimp, oyster, clam, crab, sea fish, mullet, and snook. In the Caribbean zone, even though the fishing activity is not so important, some fisheries have developed that have economic importance (snail and lobster). The value of the fishing production of the zone represented in 1983 a value of 7576.5 million pesos. Among the fisheries of the region, the most important are the following:

Shrimp

Shrimp represent a great economic value, and a considerable part of the production is exported. Shrimp from the Gulf of Mexico have a benthic habitat; they are distributed from the littoral lagoons up to 200 meters depth on the continental platform (Ecodevelopment, 1988). According to the catch figures for 1985, the Gulf of Mexico littoral contributed 25,149 tons, which represented 33.8% of the national production (Secretaria de Pesca, 1977). In 1984, 100 shrimp cooperatives were registered, with bigger vessels destined to catch shrimp in the open sea. Seventy-nine cooperatives shrimped in the estuaries and lagoons. The former reported 76.9% of the shrimp production and the latter 23.1% (op.cit.). Most of the estuary shrimp are obtained at Laguna Madre and Tamiahua Lagoon (97.2%).

Oysters

The oyster resource commercially exploited in the Gulf of Mexico's littoral is principally the sand bank oyster or American oyster (<u>Crassostrea virginica</u>) and, of less importance, the mangle oyster (<u>Crassostrea rhizophora</u>).

The oyster fisheries that have developed in the Gulf of Mexico's littoral are the most important in the country; 96% of the national production originates from them. The principal oyster fisheries are located in the following coastal lagoons: Laguna Madre, Laguna de Pueblo Viejo, Tamiahua, Lagunas Carmen and Machona, and Laguna de Terminos.

In the Gulf of Mexico, 52 cooperative societies exploit the oyster, but only 11 of them register 80% of the total production. Together, the 52 cooperatives employ approximately 15,000 fishermen.

GOVERNMENTAL RESPONSES TO COASTAL ENVIRONMENTAL PROBLEMS

Social Context

The developing countries present numerous problems, which in some instances become more serious because of the inadequate handling of the resources they have. A clear example of this situation are the Mexican shores of the Gulf of Mexico and the Caribbean.

Recently, the region has registered a remarkable economic growth. Going from an almost isolated rural region, commercial cattle raising, tropical plantations, the petroleum activity, and tourism have dramatically altered the landscape.

One can question whether these changes have been for the better. The development of the region has often proceeded as if the only objective is to maximize current revenues without regard for the future. The economic growth of the region has had high social and environmental costs. Toledo (1984), for example, argues that petroleum exploitation is responsible for a substantial degradation of the environment. Similarly, the extensive growth of cattle raising and agriculture has been at the expense of the natural vegetation.

Even though the area has registered an accelerated economic growth, much of the population receives no benefit; many people are economically marginal, performing economic activities in the traditional way, in large part because the people inhabiting the coastal regions are not trained to compete within the new labor markets. Yet the introduction of the new economical activities has greatly altered their standard of living.

Another aspect that characterizes the urban development of the region is the spontaneous settlements, principally inhabited by people left behind by economic development. Nolasco (1979) estimates that for the year 1990, Coatzacoalcos and Minatitlan will have a "marginal" population of 182,488 and 123,931 inhabitants, respectively, representing 86% and 73% of the total population. This enormous population is not only marginal socially and economically within the urban space, but it is spatially relegated to those places with the most adverse physical conditions for urbanization, potentially the most exposed to the negative effects of sea level rise.

Environmental Regulation

Given the threat to coastal environments, Mexico has taken some measures -- but because they were started too late, they have a corrective more than a preventive character.

One of the first actions was the Federal Law to Prevent and Control Environmental Pollution, issued in 1971. For the first time, the Mexican Legislature considered the importance of controlling the environmental deterioration and created offices to enforce environmental laws.

However, it was not until 1980 that important steps were taken to protect the environment. In 1981, the Public Works Law was issued, which required those planning the construction of buildings to consider the environmental impact.

In 1982, the Federal Protection of the Environment Law entered into effect and with it important advances were obtained, even though the scope was confined to controlling air and water pollution. In 1988, the General Law of Ecologic Balance and Environmental Protection brought remarkable changes in how Mexican institutions conceptualized problem. Under this law, regulations have been developed that focus on the entire ecology, considering conservation, restoration, and improvement of the environment, as well as on the protection of natural areas, flora, and fauna (wild and aquatic). Also, the new law refers to the reasonable utilization of the natural elements, encouraging estimates of the economic benefits of protecting ecosystems and preventing air, water, and soil pollution.

This law defines "environmental impact" to include environmental modification caused by human or natural action. Thus it would appear to require consideration of sea level rise due both to natural factors and to the greenhouse effect. Currently, implementation has centered only on the impacts of human activities. Even under this more restrictive interpretation, however, considering sea level rise appears to be required, since the environmental implications of new projects will be different if sea level rises. The Secretaria de Desarrollo Urbano y Ecologia (SEDUE)-Urban Development Ecology Department is currently in charge of evaluating the environmental pollution.

At this point, one might ask who makes the decisions in the management of the Mexican littoral zone. In accordance with Merino and Sorensen (1988), a great number of jurisdictions and powers on the littoral are identified, but unfortunately there is no integrating program for the coast.

Table 5 shows the many agencies involved in coastal zone management; the vast majority of these offices are managed by the federal government. This condition is one of the main difficulties confronted within a coastal zone in carrying out integrated planning. Although the Committees in Charge of the Planning and Development of the States (Coplades) theoretically carry out a coordinated effort, a lack of administrative coordination is observed in practice. The same condition is also observed among the federal agencies.

According to Merino (1988), there are five types of impediments to an integrated management of the coast: (1) lack of proper identification of the problem; (2) scant coordination among government agencies; (3) lack of economic means; (4) lack of continuity and governmental inefficiency; and (5) improper knowledge of resources and ecosystems. These problems apply to sea level rise as well as to other coastal problems.

We would add two other impediments to that list. First, like most of the other countries represented in this report, there is a lack of environmental education and public awareness in Mexico of the implications of the many threats to the ecology. Moreover, one must consider the environment within the context

Table 5. Government Agencies With Powers or Mandates Over the Coastal Zone

Government Level	Government Agency	Abbreviation	English Name	Attributes and Functions
Federal	Secretaría de Programación y Presupuesto	SPP	Budget and Programming Ministry	Approval of plans and budgets of other ministeries
Federal	Secretaría de Desarrollo Urbano y Ecologia	SEDUE	Urban Development and Ecology Ministry	Control of urban centers, environmental regulations, creation and management of park and reserves, control over the ZFMT.
Federal	Secretaría de Energia Minus e Industria Paraestatal	SEMIP	Energy, Mines and State Industries Ministry	Control over oil and mineral extraction.
Federal	Secretaria de Pesca	SEPES	Fishing Industry	Fisheries regulation and promotion.
Federal	Secretaria de Marina	SM	Marine Ministry	Coastal and oceanic surveillance. Contingency facing management.
Federal	Secretaría de Turismo	SECTUR	Tourism Ministry	Tourism promotion and development plans in touristic areas.
Federal	Secretaría de Comunicación y Transporte	SCT	Communications Transport Ministry	Construction and operation of ports and navigation services.
Federal	Secretaría de Gobernación	SG	Ministry of the Interior	Control over islands and their underwater platforms.
Federal	Secretaría de Relaciones	SRE	Ministry of Foreign Affairs	Permits and concessions on foreign activities on the coastal and Exclusive Economic Zones.
Federal	Secretaría de Agricultura y Recursos Hidráulicos	SARH	Agriculture and Hydraulic Resources Ministry	Control over fresh waters, dumps, and river discharge.
State Federal	Comités de Plancación del los Estados	COPLADE	State Development Planning Committees (one for each State)	Development planning for the state, coordination between federal and state governments.
State	Gobiernos de los Estados	---	State Governments	General planning and definition of the state priorities.
Municipal	Gobierno Municipal	----	Municipal Governments	Local actions and powers.

Table taken from Merino (1987).

of other priorities. Mexico has serious economic problems, and the attention of policy makers is focused on activities that generate foreign exchange such as oil production. Although this is a reasonable response to the financial crisis, one must not lose sight of the fact that people's well-being does not depend on economic activities alone.

CONCLUSION

The gulf coastal plain is a very important part of the cultural, natural, and economic base of the Mexican nation. It is already being affected by the encroachment of the sea into the coastal plain. Some of the features can absorb the changes and retain most of their characteristics, albeit after a landward migration. However, many other features are suffering the many impacts of human interference with natural processes, with pollution, and a deteriorating natural system. The impacts of a rising sea level are yet another negative element that has to be absorbed along with the others. The combination of sediment deficits, subsidence, and coastal pollution is magnifying the effects of sea level rise.

The causes of the problem are not simple, nor will the solution be simple. It will be difficult to command the attention of policy makers faced with more pressing economic and social problems. Nevertheless, some preparation of sea level rise and other consequences of global warming are clearly warranted. The general history of environmental protection suggests that a problem must be studies for years, sometimes decades, before governments can implement solutions. Accordingly, the highest-priority response in Mexico should be for coastal environmental scientists and engineers to begin exploring the possible consequences. A major conference in Mexico on the topic is clearly warranted.

BIBLIOGRAPHY

Contreras, F y L.M. Zabalegui. 1988. Aprovechamiento del litoral mexicano, Centro de Econdesarrollo y Secretaria de Pesca, Mexico.

Garcia, E. 1988. Modificaciones al sistema de clasificacion climatica de Koppen. Offset Larios, Mexico.

Garcia, E. 1989. Mapa de climas, Clave IV-4-10, Atlas Nacional de Mexico, Instituto de Geografia, UNAM, Mexico.

Instituto Nacional de Estadistica Geografia e Informatica. 1985. Anuario de Estadisticas Estatales, Mexico.

Jaurequi, E. 1967. Las ondas del este y los ciclones tropicales en Mexico, Revista de Ingenieria Hidraulica, Vol. XXI, Num 3, Mexico.

Lankford, R. 1977. Coastal Lagoons: Their origin and classification. In: Estuarine Processes. Wiley, M., ed. New York: Academic Press, pp. 182-215.

Merino, M. 1987. The coastal zone of Mexico. Coastal Management 15:27-42.

Merino, M. and J. Soremsen. 1988. La zona costera mexicana: recursos, problemas e instituciones, En Ecologia y Conservacion del Delta de los rios Usumacinta y Grijalva, Memorias, INIREB, 91-110, Mexico.

Nolasco, M. 1979. Ciudades Perdidas de Coatzacoalcos, Minatitlan y Cosoleacaque, Centro de Ecodesarrollo, Mexico.

Psuty, N.P. 1967. The Geomorphology of Beach Ridges in Tabasco, Mexico. Coastal Studies Series. Baton Rouge, LA: Louisiana State University Press.

Secretaria de Pesca. 1987. Pesquerias Mexicanas: Estrategias para su Administracion, Mexico.

Secretaria de Programacion y Presupuesto. 1981. Atlas Nacional del Medio Fisico, Mexico.

Secretaria de Programacion y Presupuesto. 1982. X Censo General de Poblacion y Vivienda del Estado de Campeche, Mexico.

Secretaria de Programacion y Presupuesto. 1982. X Censo General de Poblacion y Vivienda del Estado de Quintana Roo, Mexico.

Secretaria de Programacion y Presupuesto. 1983. X Censo General de Poblacion y Vivienda del Estado de Tabasco, Mexico.

Secretaria de Programacion y Presupuesto. 1983. X Censo General de Poblacion y Vivienda del Estado de Tamaulipas, Mexico.

Secretaria de Programacion y Presupuesto. 1983. X Censo General de Poblacion y Vivienda del Estado de Veracruz, Mexico.

Secretaria de Programacion y Presupuesto. 1983. X Censo General de Poblacion y Vivienda del Estado de Yucatan, Mexico.

Secretaria de Programacion y Presupuesto. 1986. La Industria Petrolera en Mexico, Mexico.

Toledo, Alejandro. 1984. Como destruir el paraiso, El desastre ecologico del Sureste, Centro de Ecodesarrollo, Mexico.

West, R.C., N.P. Psuty, and B.G. Thom. 1969. The Tabasco Lowlands of Southeastern Mexico. Coastal Studies Series. Baton Rouge, LA: Louisiana State Univeristy Press.

Zavala, J. 1988. Regionalizacion natural de la zona petrolera de Tabasco, Casos de Estudio, INEREB, Mexico.

RAISING MIAMI -- A TEST OF POLITICAL WILL

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ABSTRACT

Miami and the remainder of metropolitan Dade County are built on extraordinarily porous water-bearing rock and sand, which lies 1.6 meters below the surface, extends down to a depth of 45 meters, and extends out under the ocean. Shallow dikes with supplemental pumping will not keep out a rising sea, which simply would float the freshwater table up from below. Even though fill can be strip-mined on publicly held local lands and transported to the area by barge, if the sea level rose one meter, more than $600 million of public investment would be required in Dade County to raise streets and improve canals, drainage, and pumping, a sum equal to a 1% rise in the local capital budget for the next 100 years. Landowners might incur additional costs to raise buildings. Even if the investment were made, the county might be more vulnerable to hurricane damage.

The cost estimates given here assume the streets will be raised as they are reconstructed, roughly at 35-year intervals. If the county does not raise streets in advance of sea level rise, costs incurred as a result of sea level rise might be an order of magnitude higher. Increasing construction costs today to raise streets above the levels of adjoining lots, however, for the sake of future sea level rise will require a good deal of public education and foresight from policymakers.

INTRODUCTION

This paper uses a case study of Miami to illustrate the likely impacts of sea level rise on a major city. Specifically, we examine the impacts that global climate change, coupled with sea level rise, could have on Dade County's water control and drainage systems, building foundations, roads, bridges, airports, sewage transport and treatment systems, and water supply.

Although it varies in actual practice, the nominal replacement cycle for most infrastructure is 30 to 50 years; some water supply investments have 100-

year lives. Because communities are essentially locked into capital stock for a relatively long time, much of the present infrastructure could be vulnerable to rapid climate change. Sea level rise, temperature change, and changes in precipitation patterns, for example, all could alter the balance between water supply and demand before much of a community's capital stock is due to be replaced. The nature and pattern of precipitation could affect drainage requirements, as well as highway design and maintenance. In addition, household relocation in response to climate change could radically alter the population growth projections on which capacity decisions about water, highway, and wastewater treatment systems are based.

The uncertain, yet potentially imminent, impact of global climate change already has increased the riskiness of infrastructure investment. Applying design standards and extrapolating from historical data still might not provide reasonable assurance that water and power supply, dam strength and capacity, bridge underclearances, or storm sewerage capacity will be adequate given the long lives of these facilities.

The National Flood Insurance Program's maps identifying the 100-year floodplain and 500-year floodway will no longer be reliable as a basis for local building and zoning ordinances designed to minimize flood losses.

Especially in coastal areas, the possibility of accelerated change in global climate may soon require careful decisions regarding how and when to adapt the infrastructure. Emphasizing life-cycle costing and upgrading during reconstruction, in anticipation of future changes, could yield large, long-term cost savings.

Corporate investment analysts have developed methods, including decision theory, portfolio analysis, and chance-constrained programming, to guide decisionmaking under uncertainty. Infrastructure analysts at all levels of government might be wise to adapt these methods to their work.

Growing uncertainty about future temperature, precipitation, and sea levels might dictate a reassessment of existing standards and safety factors for ventilation, drainage, flood protection, facility siting, expansion capability, and resistance to corrosion, among others. Prompt identification of inevitable changes could allow communities time to adjust design standards based on geographic location -- for example, on roadbed depth and home insulation levels -- and thus realize significant savings.

THE METHODOLOGY AND ASSUMPTIONS

We assumed that a gradual sea level rise would be managed through strategies such as raising the land in low-lying areas, upgrading levees and dikes with pumped outflows, retreating selectively from some areas, and increasing the freshwater head, roughly in proportion to sea level rise, to prevent saltwater intrusion into the aquifer. The case study does not examine how climate change might affect beach erosion or discuss related actions that might protect the developed barrier islands of Miami Beach and Key Biscayne, which largely lie within 1 meter of sea level.

Preliminary analyses and estimates by local engineers and planners, undertaken at our request, formed the primary basis for the case study. Further information was drawn from Rhoads et al. (1987) and from the Comprehensive Development Master Plan for Dade County (Metropolitan Dade County Planning Department, 1979, 1988).

Our analyses assumed a 1-meter rise in sea level. The temperature and precipitation impacts of global climate change were estimated by applying the percentage changes, by season, indicated by two climate change models (Jenne, 1988), to historical climate data from 1950 to 1980. The models examine the weather changes that might result from an effective doubling in carbon dioxide levels. Both the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL) models suggest Greater Miami's (essentially Dade County's) average temperature could rise from 26°C to 29°C (75°F to 80°F). Both models suggest the precipitation level might remain reasonably constant.

DADE COUNTY'S WATER SUPPLY INFRASTRUCTURE

Greater Miami exists within an unusually complex environmental setting. An intricate water management system already has evolved to protect the area against flooding, to provide freshwater, to irrigate nearby agricultural lands, and to limit saltwater intrusion, which could harm the Everglades National Park and contaminate much of the potable water supply. The effects on the infrastructure of an effective doubling in carbon dioxide will be shaped by the hydrology and existing water management system.

Miami is a hydrologic masterwork, a densely populated area bounded by water from below and on all sides. When the city was first developed, the entire southern tip of Florida was a mangrove swamp called the Everglades or River of Grass. The Everglades often was awash in freshwater. The initial settlement was built on local high points of the Atlantic Coastal Ridge, 10 to 23 feet above sea level, and immediately adjacent to Biscayne Bay and the Atlantic Ocean.

Today, most of Greater Miami is on lower ground. It was made habitable through drainage and reclamation (Metropolitan Dade County Planning Department, 1979). Water drainage from the Kissimmee River Basin and Lake Okeechobee begins northwest of Miami and runs through canals to Miami and other coastal cities. To the northwest are three water conservation areas used in the South Florida water management system. South and west of the inhabited area is the Everglades National Park, a unique ecology. On the east, Miami is bounded by the Biscayne Bay and the Atlantic Ocean.

Just a few feet below Miami's surface lies the Biscayne Aquifer, the major freshwater supply for the area. Maps in the Dade County Comprehensive Plan show that the height of the water table varies by about 3 feet between seasons, but exceeds sea level in most of the aquifer. The water table is very close to the surface except along the high points of the Atlantic Ridge. In the wet season, water flows less than 5 feet below 34% of Miami streets (measured by Dan Brenner, Assistant Highway Engineer, City of Miami Department of Public Works, 1986).

The Biscayne Aquifer is wedge-shaped. It is 100 to 200 feet deep along and below Biscayne Bay and averages 100 feet in depth in the developed area. West of the city, it falls off rapidly and ends near the Dade County line. Because of the aquifer's shape, much of the water can be tapped only by wells dug in or just west of Miami.

The seaward edge of the aquifer is saltwater. In many cases, the cone of depression for the wells comes close to the salt line in the dry season. Since the 1940s, Miami has used freshwater pressure to prevent further saltwater intrusion into the aquifer. Currently, control structures and canals are used to create a 2- to 3-foot head differential (Metropolitan Dade County Planning Department, 1979). As a result, there is saltwater intrusion from 0.25 to 2 miles inland in the developed areas and about 5 miles in the Everglades National Park where the aquifer is shallower.

The Biscayne Aquifer is one of the most permeable in the world, an extraordinarily transmissive layering of sand, solution-riddled limestone, and sandy limestone roughly 100 times more permeable than packed sand (Metropolitan Dade County Planning Department, 1979). Wellfields are recharged simply by channeling water across the aquifer and letting it percolate down (South Florida Water Management District, 1987). The height above sea level and groundwater discharge areas of the aquifer change constantly in response to such relatively minor factors as rainfall and tides (Metropolitan Dade County Planning Department, 1979).

Because of Miami's high temperatures, reduced evaporation loss makes the Biscayne Aquifer a much better place than shallow surface lakes to store water for use in the dry season (Metropolitan Dade County Planning Department, 1979). Furthermore, overuse of surface storage would destroy the unique Everglades ecology, which requires cyclic drying.

In the remainder of this paper, we present the case study results. Specifically, we discuss Dade County's possible responses to sea level rise; how the various parts of the infrastructure could expect to fare and what improvements might have to be made; and what the costs of climate change/sea level rise are likely to be.

HOW WILL DADE COUNTY RESPOND TO SEA LEVEL RISE?

Because of the Porous Aquifer, Diking Alone Will Not Control Sea Level Rise

In most coastal communities, the major challenge of a 1-meter rise in sea level would be to control surface inundation. The solution in both New Orleans and the Netherlands has been to dike the water at the surface and pump out the modest seepage into ditches behind the dikes.

To apply this approach in Miami would require building a dike that holds water back for the entire depth of the Biscayne Aquifer. Essentially, a water-impermeable barrier would be needed along the length of Broward and Dade Counties to a depth of 100 to 150 feet. Otherwise, the pressure of the seawater would cause it to rush into the aquifer below the surface and push the freshwater in the aquifer up more than 3 feet, raising it very close to the surface. If the freshwater were pumped out, it gradually would be replaced by saltwater and the freshwater storage capacity of the aquifer would be lost.

Raising Land and Increasing the Freshwater Head Might Be Primary Responses

A very preliminary analysis suggests two primary responses to sea level rise. First, raise the land in low areas rather than trying to dike. Second, increase the freshwater head roughly in proportion to sea level rise, thus maintaining the freshwater storage capacity of the aquifer. The latter method will not raise the water table notably more than sea level rise alone.

Thus, if sea level rose 3.3 feet, Miami might raise its freshwater head by 2 to 3 feet to control the infiltration of subsurface seawater into the aquifer, as well as raise or build surface levees and add pumping capacity in developed low-lying sections. Even this approach might not work because the necessary water may not be available, especially during droughts. According to the Dade County master planning staff, Miami could face a water supply deficit in the 21st century. The most practical solution to the shortage would be to purify sewage effluent for use in cooling towers and for lawn watering, or to desalinate water at three times the cost.

For the purposes of this report, consistent with Rhoads (1987), we have assumed that selective retreat, levees with pumped outflows in selected low-lying areas, and elevation of some facilities and structures, as well as an increase in the freshwater head to protect the aquifer, would be the most cost-effective combination solution on the mainland. For a discussion of the appropriate intervention for Miami Beach and other developed barrier islands, primarily beach nourishment, consult Leatherman (1989).

Sea Level Rise May Necessitate Increased Coastal Defense

In coastal communities such as Miami, sea level rise could stimulate extensive upgrading of coastal defense structures such as dikes, saltwater guard locks, and pumping systems to prevent inundation, erosion, storm surges, and reduce saltwater intrusion into aquifers and rivers. Currently, these structures are such a minor category of infrastructure that they are not inventoried or included in needs assessments.

A 1-meter rise in sea level would not inundate much of the developed Miami mainland, although it would increase considerably the risk of flooding, especially during hurricanes. One area at risk of inundation is the large, low-lying area south of Miami, a low-density residential area built on land reclaimed by adding fill. Levees and water control structures used for flood protection in these areas should prevent inundation if they are upgraded. Structures in these areas generally sit on piles and fill already raised 1 to 1.5 meters above the land surface to reduce flood risks.

Dade County's water management system includes about 1,000 kilometers of canals, 400 kilometers of levees, and 30 control structures (Metropolitan Dade County Planning Department, 1979). It seems unlikely that the canals would require rebuilding, but they might have to be dredged more frequently. The levees (dikes) probably would be raised in selected areas, which can only be identified through detailed studies. Robert Hamrick at the South Florida Water Management District estimates it could cost approximately $7,000 per linear kilometer to raise the levees 60 centimeters with mounds of crushed limestone, which is extensively quarried in local open pits. The fill is scooped from a copious supply that lies virtually at the surface on public lands, and then is loaded on flat-bottomed barges and sprayed onto the tops of the levees. Interpolating from the analysis in Weggel (1989), we estimate that $60 million could be spent on canal and levee improvements if sea level rose 1 meter over the next 100 years. Hamrick also suspects that the 30 control structures in Dade County would be redesigned and replaced at an estimated cost of $1.6 million each, a total of $48 million in 1988 dollars.

The current water management system relies mainly on gravity drainage. With sea level rise, much pumping capacity might have to be added to prevent subsurface saltwater intrusion. Both the capital and operating costs could be large.

HOW WILL THE PRESENT INFRASTRUCTURE FARE?

Building Foundations Are Adequate

A preliminary examination of the structural stability of footings and pilings suggests that buildings are not likely to suffer structural instability from a 1-meter rise in the water table. When a building is on coral rock or limestone, concrete footings with reinforcing steel frequently provide structural support. A monolithic slab with flared ends to a depth of 45 to 60 centimeters is a typical foundation for a residence, since most residential structures and commercial buildings are too close to the water table to have basements. Larger residences might have both seatings and footings. Tall buildings, including residential condos, are most likely to rest on piles, although other techniques, including spread footings and compacting, are used to provide structural support.

Flooding raises little possibility of structural instability due to settling or foundation cracking, for example, because the foundations are overdesigned by a factor of 1.5 to 2.0, according to engineers at Florida Atlantic University. Currently, regulations and permitting procedures, including Dade County Flood Criteria and criteria of the National Flood Insurance Program, require most new construction to be on raised lots to prevent flood damage.

One-Third of the Streets Might Need To Be Raised

A typical city street consists of a 4-centimeter layer of asphalt constructed over a 20-centimeter lime rock base. Beneath the base is a subgrade, with its top 15 centimeters compacted to a minimum of 95% of its maximum density. If the sea level and water table rose roughly 1 meter, given the annual fluctuations in the water table and its proximity to the surface, the subgrade and base of many city streets would be subject to a certain amount of saturation. Complete structural failure would occur if a heavy load were to pass over the surface. To prevent collapse, vulnerable streets would have to be raised by 1 meter.

Dan Brenner of the City of Miami Department of Public Works estimates that approximately 34% of street and highway mileage -- 400 kilometers -- is 1.5 meters or less above the water table. Raising streets by 1 meter during reconstruction, according to the Department of Public Works, would cost between $450 and $55 per linear meter (remember that fill is cheap) with minimally improved transitions to adjacent properties. Reconstructing the 400 kilometers to adjust for a 1-meter rise in sea level could add roughly $237 million to the $1.4 billion reconstruction cost of these projects. If a 2.5% rate were used to compute further costs, expected costs would be minimized by raising a Miami street even though the subbase clearly would not be affected by sea level rise in the next 10 years, but as long as there were a 38% or greater chance that sea level rise would be substantial enough to affect the subbase after 10 years. (This cost estimate for raising streets omits substantial private costs for better drainage, raising of some yards (especially at newer buildings where the structure itself already is raised), raising lots at reconstruction, and positive sewage pumping from the houses to the mains in some areas.)

If sea level rise required streets and buildings to be raised, the connectors from buildings to the sewer interceptors also would have to be rebuilt. Pump stations also might have to be raised and modified to maintain the same driving force (differential in inside versus outside pressure), and overflow structures might need to be improved.

In the City of Miami, the costs of adapting elevated houses and other building connections to existing sewer lines would be the responsibility of private property owners. The remainder of the costs would be public. The Miami Department of Public Works estimates that the costs to raise and modify pump stations, modify overflow structures and miscellaneous appurtenances, and raise manholes alone could be $8 million.

The aesthetic and drainage impacts of raising streets could be dramatic. Except for recently constructed houses (which often are raised to meet flood ordinances), people's houses, yards, and garages would be 1 meter below the streets (and canals), a situation strongly reminiscent of the Dutch countryside. Some yards and houses surely might be raised when they are reconstructed, and yards might be raised or flanked by covered exfiltration trenches. Fortunately, there are no basements.

North America

Many Causeways and Bridges Could Be Raised at Reconstruction

The causeways running from Miami across Biscayne Bay to Miami Beach are between 1.5 and 3 meters above sea level and might be at risk of structural weakening and failure. They also would be vulnerable if higher sea level increased hurricane storm surges. These potential impacts could be avoided if reconstruction over the next 100 years used design features to mitigate the effects of sea level rise. On the other hand, if modifications were not made during reconstruction, the cost of retrofitting the bridges could be substantially higher.

Except for steel drawbridges, most bridges in Miami are constructed of concrete and steel, with a life expectancy of 50 years. Only those near the coast have epoxy-coated reinforcing bars, a practice introduced in 1970 to fight corrosion. Without remedial action, the effects of sea level rise might include the following:

- Pavement failure in low-elevation bridge approaches.
- Erosion beneath low-lying bridge abutments and consequent differential settlement, stresses, and strains.
- Potential lifting of corrugated steel and box culverts.
- A drop in the elevation of fenders on the piers over navigable waters. (Fenders protect against damage from vessels bumping into the substructure.)
- Reduced underclearances on navigable waterways.
- Reduced accessibility inhibiting proper inspection and maintenance.
- Added wave "slapping action."
- Increased likelihood of flood backwaters, particularly for bridges that have underclearances of 3 to 6 feet over non-navigable waters.

Regardless of improvements over the next 100 years, bridges with piers and piles in both Biscayne Bay and in rivers could experience deeper scouring, although the waterflow velocity under non-storm conditions would decrease because of the increased water depth. Scouring also could increase if storms became more frequent or severe.

Airports Might Need Better Drainage

Miami International Airport is a major international hub. Located in northwest Miami, its airfields and aprons cover 20 square kilometers. Unlike the majority of major commercial airports, most of the surface area is asphalt pavement. The aprons are concrete. The asphalt varies in thickness from 5 to 40 centimeters depending on the base. An extensive drainage system allows storm runoff to empty into ditches by the airfield, then into the Blue Lagoon and the Tamiami Canal. The groundwater elevation ranges from 60-90 centimeters to 1 meter, runways 2.7 to 3.0 meters, and taxiways and aprons 24 to 27 meters. A 1-meter rise in groundwater would not flood the pavement or base, but would affect drainage retention capacity and exfiltration during a storm. If several large pumping stations were constructed to draw down the airport water table at the onset of a storm, acceptable operating conditions could be maintained. Drainage interconnections and related improvements such as pump stations, dikes, and culverts might cost $30 million (Tripp, 1989).

The likely impact of sea level rise on one of Miami's wastewater treatment facilities, located on Virginia Key, also was assessed. Since Virginia Key has no freshwater beneath the surface, intrusion is not an issue. The treatment plants are approximately 3 meters above sea level. Berms and dikes reach elevations of approximately 4 meters, while sterile fill material from the sludge plants has accumulated to elevations around 30 feet. A severe hurricane producing higher storm surges still could wash out portions of the island. If the activated sludge treatment plants were still in operation as sea level rise accelerated, the berms and dikes on the island might have to be raised to prevent processed sludge from being washed into Biscayne Bay. Another possible effect of a hurricane is that dirt beneath the plant could be washed out, causing the piping to collapse.

Storm Sewers and Drainage Trenches Might Require Major Upgrading

Miami relies primarily on localized drainage and canal systems, involving exfiltration that carries surface storm water to subsurface groundwater. Highly permeable soils make this a cost-effective form of stormwater drainage, except in low-lying areas where there are fine soils that do not drain well. Where natural drainage systems are not effective, or tidewaters and easterly winds increase the water head pressure at discharge outlets to the bay, a positive drainage pipe system is used.

Standards for storm sewers vary at the federal, state, and local levels. Interstate highway storm sewers are designed for 10-year storms. On arterial streets in areas of high population density, 3-year storms serve as the design standard. On local streets, Miami's system is designed for a rainfall rate of 3.75 centimeters per hour. Ponding occurs three or four times per year on local streets with this type of storm drainage (City of Miami Department of Public Works, 1986).

In 1988, Miami started a 12-year, $267 million program to reduce flooding and ponding. This program includes constructing 225 kilometers of exfiltration trenches at a cost of $105 million, as well as positive drainage construction at a cost of $55 million. These systems are designed to provide protection against flooding from 25-year storms (City of Miami Department of Public Works, 1986).

Even with these planned improvements, if sea level rises 1 meter, flooding and ponding problems could be worse than they are today, especially because the water table will be closer to the surface. The costs of adequate future flood protection almost certainly would be several hundred million dollars.

Water Supply Might Be Reduced Unless Hurricanes Increase and Demand for Electricity Could Increase

Miami's water supply could be reduced by water used to prevent saltwater infiltration. Some wellfields almost certainly would have to be relocated farther inland. Potentially more important than the actual water expenditure, sea level rise would raise the aquifer closer to the surface, putting it within easy reach of the roots of more plants. Using evapotranspiration and soil moisture models, Rhoads (1987) estimates that soil moisture deficiency probabilities could double, assuming no change in rainfall.

The warmer temperatures also could raise water demand, most notably for commercial cooling towers. Indeed, Linder et al. (1987) project that increased air-conditioning needs in south Florida could raise peak electricity demand by 20%.

Although the solution to these problems will require detailed study, one alternative is to increase capacity to produce desalinated water -- e.g., by boiling and cooling, reverse osmosis filtration, or some new technology -- or to use purified effluent as a backup supply for drought periods. Full cost pricing of this water would encourage greater conservation and thus reduce demand. Another complexity requiring study is the need to maintain some water in the water conservation areas, since the water containments are designed to function with a vegetative lining.

The largest uncertainty about water supply is the impact that climate change will have on hurricanes. Hurricanes historically have contributed substantially to aquifer recharge (Metropolitan Dade County Planning Department, 1979). Rising temperatures could increase hurricane frequency and intensity -- a mixed blessing that would ensure an adequate water supply but inflict billions of dollars in wind and flood damage.

POTENTIAL COSTS OF CLIMATE CHANGE TO MIAMI

Table 1 shows that the total costs to make the improvements and repairs discussed in the previous section of this paper could easily exceed $600 million. The costs could be much higher if changes in sea level or global climate came through abrupt "sawtooth" shifts, making it difficult to adapt infrastructure primarily during normal repair and replacement.

The infrastructure costs suggested here are large but not unmanageable. We estimate that the costs could be accommodated by increasing annual capital spending by 1 to 2% for the next 100 years.

Table 1. Probable Infrastructure Needs and Investment in Miami in Response to a Doubling of CO_2 (millions of 1987 U.S. dollars)

Infrastructure Needs	Costs
Raising canals/levees	$60
Canal control structures	$50
Pumping	not estimated
Raising streets*	$250 extra reconstruction cost
Raising yards	not estimated
Pumped sewer connections	not estimated
Raising lots at reconstruction	not estimated
Drainage	$200-300
Airport	$30 not estimated; retrofit costs more than raising at reconstruction
Sewer pipe corrosion	minimal
Water supply	not estimated
Total	$600+

*Assumes streets will be raised as they are reconstructed, roughly at 35-year intervals. If the county does not raise streets in advance of sea level rise, the cost may be an order of magnitude higher.

THE POLITICS OF ANTICIPATING SEA LEVEL RISE

Cost-effective adaptation to global climate change will require complex, careful decisions about how and when to adapt the infrastructure. Life-cycle costing and expensive upgrading in anticipation of future changes will be essential. To accomplish this will require strong leadership. It will also require careful examination of the available options for controlling the sea. Hard political decisions will need to be made concerning how well Dade County can afford to protect its coastal exposures and how the costs will be split among affected property owners, local governments, the Metropolitan Dade County government, the State of Florida, and the Federal Government.

The economic cost of climate change is not the only expense Miami faces. However, local officials also will incur substantial political costs as they attempt to meet the impending infrastructure crisis. Suppose Miami chooses the most cost-effective course and acts in anticipation of a rising sea. Bridges and roads could be raised as they come due for reconstruction. Water, sewer, and drainage facilities could be modified to counteract the effects of an anticipated rise in sea level. City officials might have to educate the bond market. Raising bridges or streets, for example, could be viewed as overbuilding. It could be an uphill battle to convince bond underwriters that the city actually was pursuing a strategy that protects investors.

North America

Even if no extra costs were involved, raising streets could prove quite controversial. Few people will like looking up at the street from their living room windows. Worse, no one will feel comfortable the first time runoff from a hurricane pours down the edge of the streets into drainage ditches in their yards. Imagine the hue and cry when some of those ditches overflow.

The political price of such pre-emptive action could be high. Taxpayers would be asked to pay extra taxes to help underwrite infrastructure improvements because sea level might rise at some uncertain future date. Given voters' general aversion to tax increase of any kind, candidates or elected officials pursuing such a strategy could face problems at the polls. There would undoubtedly be considerable political debate over spending money in anticipation of an uncertain event versus using that money to address known current problems.

Opposition to anticipatory action might not be the only political reaction. Lobbying and political organizing could focus on location issues, that is, what parts of the city will be considered priority areas and thus will be the first to be protected.

Inaction also is politically risky. Imagine voter reaction if nothing is done in advance of sea level rise until the transportation system is affected. Road collapses make headlines, especially if people are killed as a result. Emergency repairs to roads and bridges, even if undertaken before any damage occurs, can cause massive traffic delays. That kind of spending can break budgets, as outside contractors are needed to do work that normally would be done locally. Emergency raising and rebuilding of the lowest 5% of the streets, one seventh of those that might need to be raised before the rise in sea level reaches one meter, could cost $240 million at normal construction prices, about half the total amount the city spends currently on capital construction. Bridges and bridge approaches would have to be reconstructed simultaneously, adding further costs. Raising streets during normal reconstruction would be far less disruptive. Again, unduly massive hurricane damage really could generate controversy.

Miami officials seem unlikely to take any major anticipatory action on global climate change until some precipitating event, possibly a direct hit by a major hurricane. Other possible incentives might be revision of engineering design standards to require consideration of possible sea level rise, or the availability of federal matching funds for planning responses to global climate change or for risk-reduction activities.

Regardless of the approach Miami officials choose, much public education, campaigning, and political acumen will be required. The city faces a long, hard row to high ground.

BIBLIOGRAPHY

City of Miami Department of Public Works. 1986. Storm Drainage Master Plan, Executive Summary, Miami, FL: City of Miami Department of Public Works, September.

Jenne, R. 1988. GISS and GFDL Climate Projections. Denver, CO: National Center for Atmospheric Research.

Leatherman, S. 1989. Cost of Defending U.S. Open Coast from Rising Sea Level. College Park, MD: University of Maryland.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. 1987. Potential Impacts of Global Climate Change on Electric Utilities. Fairfax, VA: ICF Incorporated. 824-CON-AEP-86. December.

Metropolitan Dade County Planning Department. 1988. Comprehensive Development Master Plan for Dade County, Florida. Miami, FL: Metropolitan Dade County Planning Department. April.

Metropolitan Dade County Planning Department. 1979. Comprehensive Master Plan for Dade County, Florida. Miami, FL: Metropolitan Dade County Planning Department. July.

Rhoads, P.B., C.C. Shih, and R.L. Hamrick. 1987. Water Resource Planning Concerns and Changing Climate: A South Florida Perspective. In Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues, conducted by the Science and Public Policy Program, University of Oklahoma. Washington, DC: U.S. Environmental Protection Agency, pp. 348-363.

South Florida Water Management District. 1987. Water Resources Data and Related Technical Information to Assist Local Government Planning in Dade County. West Palm Beach, FL: South Florida Water Management District.

Tripp, R. 1989. Personnal communication to the Urban Institute from Howard, Needles, Tammen and Bergendoff, 1989.

Weggel, J.R., S. Brown, J.C. Escajadillo, P. Breen, and E.L. Doheny. 1989. The Cost of Defending Developed Shorelines along Sheltered Waters of the United States from a Two-Meter Rise in Mean Sea Level. In: The Potential Effects of Global Climate Change on the United States. J. Smith and D. Tirpak, eds. Washington, DC: U.S. Environmental Protection Agency.

ACCOMMODATING SEA LEVEL RISE IN DEVELOPING WATER RESOURCE PROJECTS

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ABSTRACT

Apparent sea level rise along the Gulf of Mexico coast varies from about 3 to 35 millimeters per year. In developing civil works projects, this factor must be accommodated. Much of the central coastal area consists of marshlands that are about 25 to 50 cm above see level. Small rises in sea level therefore can, inundate large areas. Changes in sea level can also cause saltwater to intrude into brackish estuaries, killing the marsh grasses and converting marshlands into open water. These marshes are valuable for the production of fish and fur bearers, for recreation, and for their social attributes. Several projects and studies under way are aimed at reducing the rate of loss occurring at present--estimated to be about 100 square kilometers per year. Sea level rise is one of several variables being considered in developing plans to save this coastal area.

INTRODUCTION

Sea level rise is one of the many factors that influence the planning and development of federal water resource projects in coastal areas of the United States. It affects both sides of the scale used by planners attempting to balance development with environmental preservation.

Federal participation in a water resource development project results from congressional action based on impartial studies by the U.S. Army Corps of Engineers. The process begins when a local government seeks congressional assistance in solving a specific water-related problem. The U.S. Congress responds by asking the Corps of Engineers to determine the economic, environmental, and social feasibility of a project to solve the problem and the appropriate level of federal participation.

The U.S. Army Corps of Engineers is the largest engineering organization in the United States. The U.S. Congress has given the Corps the mandate to provide engineering services in times of both war and of peace. The Civil Works elements of the Corps of Engineers are concerned with the development of water resource projects. Military officers fill the top leadership position in the Corps; the staff consists of primarily civilian professionals. In the New Orleans District in Louisiana, for example, 7 military officers and over 1,300 civilians work with the Corps of Engineers. The Corps works closely with many other federal agencies, including the Environmental Protection Agency, the Fish and Wildlife Service, the National Marine Fisheries Service, and the Soil Conservation Service. It also works with many state and local agencies. The costs of Corps projects are generally shared with a local or state government.

Corps regulations (Engineering Circular 1105-2-186) concerning future sea level rise require that a sensitivity analysis be done to determine if whether and how potential projects would be affected. That determination is based on an extrapolation of historic local sea level rise as the minimum level and curve III (i.e., 1.5-meter rise by 2700) of the National Research Council report (1987) as the high level (see Figure 1 in Titus paper on effects of sea level rise). Since it may be 25-35 years before we can determine which sea level rise scenerio is appropriate, projects sensitive to sea level rise should be designed to allow for future modification should it become necessary.

EFFECTS OF SEA LEVEL CHANGE

The impact of changing sea level on the development of water resource projects depends on the project. We examine several examples.

Navigation Channel Projects

For channel projects, rising sea level would increase available depth, assuming no change in sedimentation which would have a small but positive effect on shipping. On the other hand, onshore facilities built at or near historice sea level could be damanged. In developing projects of this type, planners must provide for sea level rise in the design of onshore facilities and should recognize that future channel maintenance costs may be less than current ones.

Navigation Locks

This paper defines navigation locks as structures designed to raise vessels from waterways that are tidal to water surfaces at higher (nontidal) elevations (see Figure 1). Because the height of the gates and walls of these structures is a function of the higher elevations, sea level rise should have little impact on their design. Again, as sea level rises, the required lift will decrease, resulting in slightly lowered operating costs.

Saltwater Guard Locks

These locks designed to prevent saltwater intrusion into freshwater basins that are at or near sea level. During high tides, the oceanside water levels exceed those on the inside (Figure 2). For this type of structure, any increase

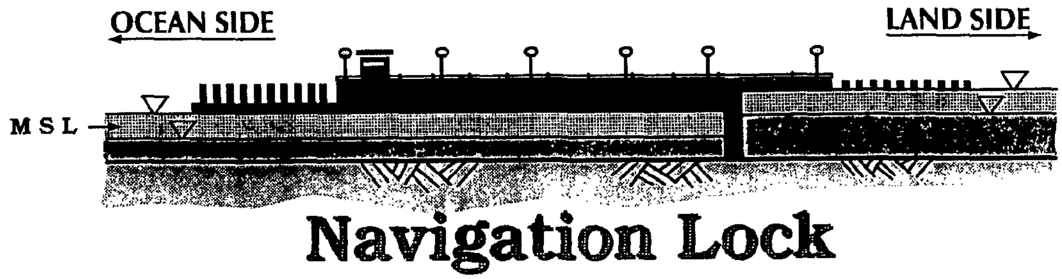

Figure 1. Diagram of navigation lock.

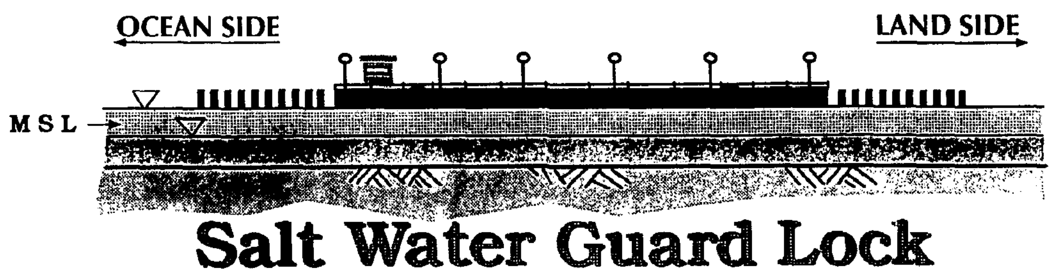

Figure 2. Diagram of a saltwater guard lock.

in sea level will require a like increase in the height of the walls and gates. This can be accomplished by either building the structure initially to accommodate future sea level rises or constructing the lock so that it can be added to in the future.

Food Control Channels and Levees

As sea level rises, the effective carrying capacity of a channel dike (leveed) decreases. The only way to make up for such a decrease is to add to the heights of the dikes. To accommodate future increases in sea level, it is usually prudent to acquire the necessary real estate when the original dike is built, and to do any necessary relocation of utilities to conform with future conditions. The dike itself can be raised in the future as conditions change.

Hurricane Protection Dike

This special type of levee is one of the public works structures most sensitive to changes in sea level. Typically, a hurricane protection dike is built to encircle a major populated area. That area is often at or below sea level. These dikes are usually built to protect against the most severe meteorological events possible for the area (the Standard Project Flood). As shown in Figure 3, the populated area is, in effect, a bowl, and any overtopping of the dikes would cause water to pond and flood the city. It is imperative that these dikes be upgraded as sea level rises. As with other types of dikes, it is prudent to acquire sufficient rights-of-way and perform all utility relocations to conform to future changes.

LAND LOSS IN LOUISIANA

Projects designed to protect barrier islands or coastal marshes are particularly vulnerable to changes in sea level. To illustrate the problem of developing this particular type of project to accommodate future sea level changes, an area along the central Gulf of Mexico will be used.

Located in the State of Louisiana, the coastal area consists mostly of low-lying marshlands less than 1 or 2 meters above sea level. As a result, small changes in sea level inundate large areas of the coastal marsh. This area contains 40% of the coastal marshes of the United States and is suffering 80% of the national coastal marsh loss. These marshes were formed over geologic time as the Mississippi River migrated across the coastal area following natural geologic processes. Today, those lands are under attack from a number of sources. No single cause can be pointed to as the culprit. Coastal and deltaic processes are too complex to permit easy answers. Each force - natural and human-induced - acts upon the other, synergistically intensifying and accelerating each effect.

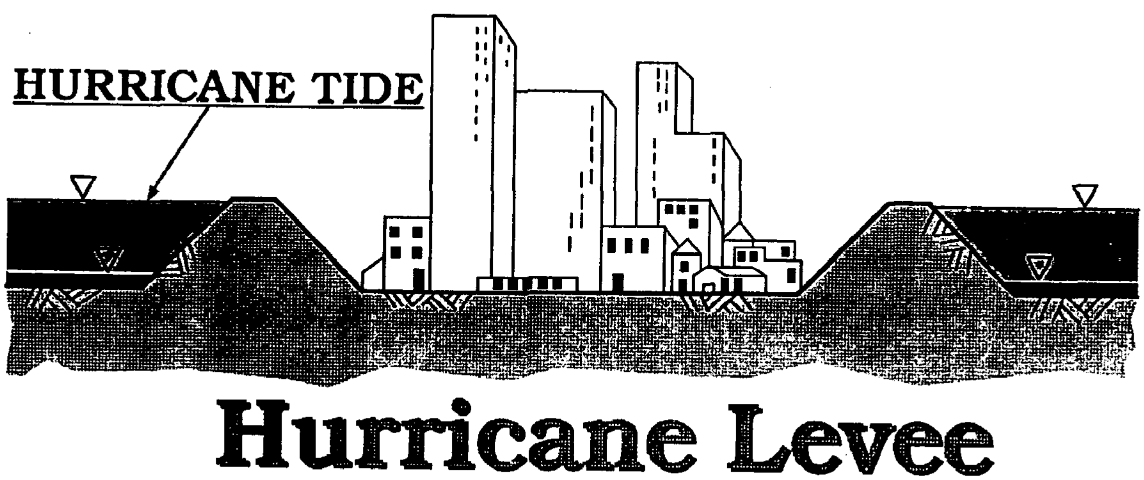

Figure 3. A hurricane protection dike used to surround a populated area and protect it from the most severe meteorological events.

Causes of Land Loss

Nature is responsible for a share of the marsh loss. The long-term forces of sea level rise, subsidence, compaction, saltwater intrusion, and erosion have caused significant changes in the relative land and water surface elevations.

Compaction and subsidence together are estimated to average 0.6 meters per century, but the rate ranges from about 4 meters at the mouth of the active delta of the Mississippi River to 1 meter at Grand Isle to less than 1/2 meter in the western portion of the state. Historical data indicated that sea level rise is an additional 0.15 meters per century. Accordingly, changes in eustatic sea level forecast by many investigators (Boesch, 1983; Hoffman, 1983; Nummendal 1983: Templet, 1985) are currently being exceeded by relative sea level rise along the Louisiana coast.

Both sea level rise and subsidence accelerate saltwater intrusion and erosion, changing the marsh habitat. Erosion eats away at Louisiana's 70,000 kilometers of tidal shoreline and at the barrier islands. The erosion causes the shore and barrier beaches to retreat from 3 to 12 meters each year.

The gradual erosive effect of daily natural forces on the barrier islands is dramatically accelerated by hurricanes and storm tides. Big storms cause massive damage by cutting through islands and widening and deepening passes, such as that which occurred on one of the Chandeleur Islands that was widened during Hurricane Juan.

Though natural forces play an important role in coastal land loss, the activities of people are also a major cause. Flood control is indispensable in the floodplain of the Mississippi River and its tributaries. This flood protection and the economic development in Louisiana's coastal wetlands have caused much of the marsh loss.

Flood control dikes on the rives have changed the annual hydrologic regime. In a natural hydrologic cycle, the swollen Mississippi and Atchafalaya Rivers would overflow their banks every spring, flooding the marshes with nutrient-and sediment-rich water. The sediments and nutrients would build and sustain the natural diversity of the marsh. Since dikes were built for flood control and protection of national and international navigation, the only water that flows into the marshes is rainfall. Each year, 183 million tons of sediment are carried down the river. This material is not building new marsh as it did prior to the levee construction; rather, it is dropping off the edge of the Continental Shelf into the deep waters of the Gulf of Mexico.

In this fragile coastal environment, activities in the interest of economic development interact with and intensify the natural processes. Leveeing, channelization, oil exploration, and agricultural, urban, and industrial expansion have accelerated the rate of marsh loss. The marshes are laced with 13,300 kilometers of navigation, drainage, and petroleum access canals that segment the marsh.

With no annual flood of fresh water to hold back intruding saltwater, the marshes and cypress swamps that are not tolerant to salt are being destroyed and replaced with open-water ponds. These open-water areas increase the interface between water and marsh, causing more erosion. Across the Louisiana coast, one hundred square kilometers of marshlands are lost each year.

Effects of Land Loss

What will this loss of a half million hectares of Louisiana's coastal marsh mean to the economy of the nation, to the development of the state, and to the people who live, work, and play in the coastal marshes?

About $300 million in marsh real estate value will be lost by 2040. Moreover, as marshes are lost, the Gulf of Mexico's estuarine-dependent fishery will decline. By the year 2040, commercial and recreational fish and wildlife harvests will be down to about 70 percent of the present harvest. The impact on the nation's economy will be an annual loss of $114 million. Sport fishermen and hunters will lose 4 million activity-days of recreation by 2040 as compared with today. The annual economic impact of this to the nation will be $19 million.

Loss of the coastal marshes threatens most of the national, state, and local development investment in the coast. This includes about 250 kilometers in portions of major waterways built by federal and state governments. The banks of these waterways will be lost to erosion. The cost of the increased maintenance dredging that will be required in these waterways could exceed $50 million a year.

Hurricane protection dikes will have to be enlarged and shielded from erosion. About 90 kilometers of federal hurricane protection projects, including the "Lake Pontchartrain and Vicinity," the New Orleans to Venice," and the "Larose to Golden Meadow" projects, will have to be protected to maintain the current level of protection. The estimated coasts could exceed $38 million.

Roads, pipelines, and utilities will require relocation. Nearly 160 kilometers of federal and state highways, about 44 kilometers of railroad tracks, 2,500 kilometers of oil and gas pipelines, and 620 kilometers of utilities and telephone lines will have to be relocated. These relocations would cost billions of dollars.

Property will be lost or will have to be protected at great expense. About 1,800 business, residences, camps, schools, electric power substations, water control structures, pumping stations for gas, oil, and water, and storage tanks will have to be protected or relocated.

Ongoing Projects

Land loss is a significant national problem, and the U.S. Army Corps of Engineers has several projects and studies that specifically address this problem. Protecting people along the Mississippi River from flooding requires a system of river dikes which confine the water that historically flooded the marshes adjacent to the river and prevent the annual nourishment of those marshes essential for their maintenance.

The Corps of Engineers and the State of Louisiana plan to restore a portion of the marsh flooding cycle in a way compatible with flood protection. Three freshwater diversion projects are scheduled for implementation in the Louisiana coastal areas. Those projects will introduce fresh water from the Mississippi River into the adjacent marshes and estuaries. Fresh water diverted through these structures will restore and enhance wetland vegetative growth by establishing desirable salinities. These salinities and much-needed nutrients carried by fresh water will increase the productivity of the marshes' fish and wildlife.

Another tool to help offset coastal land loss is the use of dredged material to build new or restore sinking marshes. Over 1,200 hectares have been created through the Corps of Engineers' maintenance dredging program. Creation of another 7,500 hectares through the future enlargement of the Mississippi River is planned.

Diverting sediment to create new lands has also helped to mitigate some of the ongoing losses. In addition to those already constructed, the Corps of Engineers is studying the cost-effectiveness of a system of uncontrolled sediment diversions within the active delta of the Mississippi River.

The Corps of Engineers' regulatory program has been a major influence on human activity in the coastal zone. Each year the Corps' New Orleans District issues between 1,500 and 2,000 permits, and processes between 2,000 and 2,500 permit applications. Permitted work is inspected to ensure that it conforms to Corps criteria, which include measures designed to prevent as much damage to marshes and other wetlands as possible. For example, the permit applicants are required in some cases to construct a wooden road over the marshes, rather than dredging an access canal.

Louisiana Coastal Area Studies

Several ongoing studies are attempting to develop long-term solutions to the coastal loss problems. The costs of these studies are being shared by the federal government and the State of Louisiana. In these studies, specific areas will be targeted for preservation or enhancement. Obviously, every acre of the coastal marshes cannot be saved, but many acres can.

Many factors will be used to determine which area exhibit the highest likelihood of success. Topography will play a major role -- shallow water areas not subject to high wave energy would be a prime location. Other factors would include cost, proximity to populated areas, availability of a sediment supply, and environmental considerations. The Corps/state study is using a variation on the usual federal benefit-to-cost evaluation methodology. In this study, alternatives will be compared based on cost-effectiveness. A full array of both structural and nonstructural solutions will be analyzed.

North America

Sea level rise will complicate this already complex situation. Since many of the solutions being considered do not involve hard structures, but rather include such approaches as freshwater diversion, sediment diversion, dredge spoil placement, and regulatory control, it is likely that sea level rise can be accommodated.

BIBLIOGRAPHY

Boesch, D.F., Levin, D., Nummendal, D., and Bowles, K. 1983. Subsidence in Coastal Louisiana: Causes, Rates, and Effects on Wetlands. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Hoffman, J., D. Keyes, and J. Titus. 1983. Projecting Sea Level Rise to the Year 2100. Washington, DC: U.S. Environmental Protection Agency.

Nummendal, D. 1983. Future sea level rise along the Louisiana coast. Shore and Beach, April.

Templet, P. 1985. Land loss in Louisiana: A White Paper. Zachary, LA: Templet Resources.

U.S. Army, Corps of Engineers. 1988. Guidance on the Incorporation of Sea Level Rise Possibilities in Feasibility Studies. Engineering Circular 1105-2-186 Draft V 1.31, 20, Washington, DC: U.S. Corps of Engineers

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