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Vulnerability of coastal areas to sea-level rise: some global results

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SUMMARY

Assessment of the vulnerability of the various resources of the world's coastal zones to an acceleration of sea-level rise (ASLR) and related climate change effects requires detailed global information on the distribution, density and state of the resources and on the impacting hazardous events. For many resources, such as ecosystems for instance, data on a global scale are not readily available. Another complication is that in order to assess the consequences of hazardous events the response of coastal systems and their response time scales need to be known at a sufficient level of accuracy, which is not generally the case. Within the limits of these constraints this study considers the following three resources of the coastal zone and accompanying impacts:

- population at risk (i.e. the number of people subject to regular flooding) on a global scale;
- wetlands at loss (i.e. the ecologically valuable coastal wetland area under a serious threat of loss) on a global scale;
- rice production at change (i.e. the potential changes in coastal rice yields due to less favourable conditions) in South, Southeast and East Asia.

The present findings on global vulnerability are as follows:

<u>Globally, a rise in sea level of one metre could double the number of people vulnerable to coastal storm surges</u>

- Presently, between 100 million and 200 million people are estimated to live below the annual storm surge level. About 20% of this population experiences flooding annually.
- An additional one metre of SLR above the current mean sea level would increase the number of people subject to annual flooding by about 50%, when coastal defence systems would be maintained at their present efficiency levels. If a population growth scenario would be adopted the number of people subject to annual flooding would double by the year 2020.
- When coastal defense systems are allowed to respond naturally to the increased stress as a results of the ASLR (no maintenance of present efficiency levels), the number of people subject to annual flooding would rise dramatically.
- Because of differences in the regime of storm surge events, the increase of flood risk to ASLR is larger than average for small islands, the Southern Mediterranean coast, the African Atlantic coast and the Indian coast.
- Increases in severe storm frequency and intensity would further increase the number of people subject to annual flooding.

<u>Globally, the projected impact of a 1 m sea level rise on coastal wetlands is alarming</u>

- Worldwide over 900,000 km^2 of coastal area can be classified as "areas of international importance", indicating that their character is in accordance with the criteria set by the RAMSAR Wetlands Convention. One-third of this coastal area consists of coastal wetlands (saltmarshes, intertidal areas and mangrove forests) which are of great ecological and economic value.
- Coastal wetlands are presently being lost worldwide at an increasingly rapid rate. The increase in loss rates is closely connected with human activities such as enhanced subsidence and shoreline protection, blocking sediment sources for wetlands, and development activities, e.g., land reclamation and aquaculture development.
- An acceleration of sea level rise would increase the rate of net coastal wetland loss. In combination with human activities a 1 m sea level rise over the next century would threaten half of the world's coastal wetlands of international importance. In some areas, coastal

wetlands could be virtually eliminated, because their ability to migrate inland would be limited over such short timescales.

- Losses of coastal wetlands of international importance are expected to be larger than on average for the coasts of the United States, the coasts of the Mediterranean Sea, the African Atlantic coast, the coasts of East Asia, and the Australian and Papua New Guinean coast.

<u>A considerable part of the world's rice production is located in regions vulnerable to ASLR</u>

- Approximately 85% of the world's rice production takes place in South, Southeast and East Asia. About 10% of this production is located in areas which are estimated to be vulnerable to ASLR, thereby endangering the food source for more than 200 million people.
- Less favourable hydraulic conditions may cause lower rice production yields if no adaptive measures will be taken. Especially in the large deltas of Vietnam, Bangladesh and Myanmar (Burma) serious production reductions may be expected.

1. INTRODUCTION

Stimulated by the efforts of the Coastal Zone Management Subgroup (CZMS) of the Response Strategies Working Group (WGIII) of the Intergovernmental Panel on Climatic Change (IPCC) a growing number of countries, presently more than twenty five all over the world, are assessing the vulnerability of their coastal zones to ASLR. As each coastal country individually undertakes such studies, that information will assist in providing a global picture of the potential problems of ASLR on coastal resources and of the level of effort required in response. One of the aims of the CZMS is to provide a world-wide estimate of socio-economic and ecological implications of ASLR, based on the information made available through the case studies. Waiting for a sufficient number of country case studies to be completed would take too long in view of the UNCED conference. The primary objective of the study (Pennekamp et al., 1992) is, for this reason, to generate preliminary vulnerability results on a global scale. A secondary objective is to provide a reference for country case studies.

It must be emphasized that the incompleteness of the global data and many of the assumptions about physical processes, physical and socio-economic boundary conditions limit the accuracy of the country-by-country results presented in the study report (Pennekamp et al., 1992). It is therefore necessary to only rely on more aggregated results. When aggregated the reliability of the results is expected to increase, since inaccuracies in both input data and impact responses will tend to average out.

It is noted that this paper only presents a concise description of the comprehensive study which was carried out. The interested reader is referred to the study report this paper is based on (Pennekamp et al., 1992). The nature of this paper does not allow for systematic referencing, but a selection of references which were used is given in the section References.

2. METHODOLOGY

In order to define and assess the vulnerability of a coastal zone to ASLR uniform procedures are needed so that global, regional and national studies on impacts of ASLR can be compared and integrated. The Common Methodology ("The Seven Steps to the Assessment of the Vulnerability of Coastal Areas to Sea Level Rise - A Common Methodology" (CM)), developed by the CZMS in 1991, suggests a number of these procedures. Crucial to these procedures are the concepts of 'values at risk', 'values at loss' and 'values at change', which help to determine impacts in measurable and objective terms. These and other concepts of the CM are used in the present study.

values at risk, at loss and at change

In the present context, the concept of risk is defined as the consequence of natural hazardous events times the probability of occurrence of these events, **without** taking the system response into account. The concepts of loss and of change are defined as the consequences of natural hazardous events times the probability of occurrence of these events, **with** taking the system response into account. The natural hazardous events vary from global events as eustatic sea-level rise, to regional events as subsidence, changing rainfall or increase in storm surges. The socio-economic or physical response and the intrinsic time response scale of the relevant "system" (people, agriculture, ecosystems) determine the type of hazardous event which is relevant.

The concept of risk is considered to be appropriate in the context of assessing the consequences of ASLR and related climatic changes to the coastal zone population and nearby economic values. The short-term consequence of flooding events to population varies obviously from minor effects such as flooding of people's goods to the possibility of loss of life. It is considered not realistic to predict any changes these events have on the behaviour of the population in the longer term. It is, for instance, likely to assume that frequent flooding leads to migration, but this is certainly not true for countries such as Bangladesh, where migration is no realistic alternative, or for some barrier islands in the US where a reliable warning system allows for temporary evacuation. For this reason, the concept of 'risk' rather than the concept of 'loss' or 'change' is applied here to indicate the impact on the populations of the coastal zone.

The concepts of change and of loss are considered essential in the context of agricultural production and of ecosystems, respectively. In these cases it is not so much the short-term flooding events that determine the consequences on these resources, but rather the persistence of the average longer term hydraulic changes, of which the eustatic forcing and in some cases including the regional forcing of ASLR are the most important. The probability of occurrence of ASLR is assumed to be 100%, only the rates of change are subject to discussion (see e.g. Titus and Naranayan, 1992, these proceedings).

As indicated, the determination of 'values at loss' or 'at change' requires accounting for the system response in assessing the consequences of the hazardous event or combination of events. This, in turn, requires the introduction of the time rates of change of the events. In the current context (focusing on coastal wetlands and rice production) we only have considered the rate of change of eustatic plus local sea-level rise to be of importance. Also, we have adopted only one scenario value, viz. 1 m per 100 year. In a more sophisticated approach one could consider to evaluate results in a probabilistic manner by using scenario values for ASLR and related frequencies of exceedance and present the outcome in probabilistic terms.

delineation of the coastal zone area

For the determination of the impacts on the coastal zone resources which are the topic of the present study (population, ecosystems and rice production) it is necessary to delineate the coastal zone areas in which the risks, losses or changes would occur. With respect to ecosystems and rice production the delineation is based on the information given by the consulted databases themselves. For the population at risk the information was generated for this study, which created particular difficulties since a detailed zonation had to be determined in terms of areas and accompanying flooding frequencies, including those due to storm surges.

boundary conditions and scenarios

In line with the requirements of the CM a comparison of the different impacts is made for different scenarios of the external boundary conditions. These boundary conditions and their scenarios are:

- the rate of ASLR, for which the CM suggests to consider a rise of 0.3 m and 1.0 m by the year 2100 versus the present situation. In the present study only the 1.0 m scenario is considered versus the present situation;
- the socio-economic development, for which the suggestion of the CM is adopted to consider no development versus a predicted development over 30 years;
- the response strategy, for which the suggestion of the CM is adopted to consider only the minimum vs the maximum option is considered, i.e. no measures vs full measures.

It is noted that the CM purposely selects different time scales for the various scenario variables. Firstly, for ASLR 100 years is assumed so as to assure that the gradual, but often irreversible impacts of this large scale (in time and in space) phenomenon with a large inertia are clearly indicated. Secondly, for development 30 years is assumed, since it is virtually impossible to make a reliable prognosis over 100 years. Finally, for measures 0 year is assumed since a good first-order estimate of the adaptation costs may be obtained by assuming an instantaneous rise of mean sea-level for the design of protection measures, thus preventing the complications of specifying measures in time and of economic evaluation (financial depreciation methods) of these measures.

Only in the assessment of values at change and at loss the timescale is relevant, since for the prediction of the system's response the timescale is required. It must be noted that lack of data and lack of knowledge of the system response do limit the accuracy of the estimate of resources at change and at loss.

3. POPULATION AT RISK

specification of methodology

As mentioned above, the concept of risk is considered to be most appropriate for the assessment of the vulnerability of population in the coastal zone, since it indicates the consequences of the impact **without** taking the response into account. It is considered not realistic to make a general prediction of people's responses to increased flooding.

In line with the CM, population at risk is defined as the product of the population density in a certain risk zone and the probability of a hazardous flooding event in this risk zone, which products are to be summed over the risk zones. The resulting number is to be interpreted as the expected number of people subject to flooding events per unit time. This 'risk value' is able to reflect both changes in the population in the risk zone and the changes in flooding frequency due to ASLR.

An attempt was made to make as precise an estimate as possible of the population at risk so that effects of changes in the boundary conditions could be made explicit. Therefore, account has been taken of a detailed zonation in terms of areas and accompanying flooding frequencies, including those due to storm surges. For instance, first-order storm surge calculations were performed for the world's coastlines, producing flood levels for the 1 in 1, 1 in 10, 1 in 100 and 1 in 1000 years storms which were increased with ASLR, subsidence, and pressure effects. Figure 1 presents a global distribution of the thus derived hydraulic regimes per country. The determination of the areas subject to these flooding events requires both the availability of detailed area information and of the physical process of flooding. Obviously, these items could only be considered to a limited degree. Some of the consequences brought about by the approach are discussed further on.

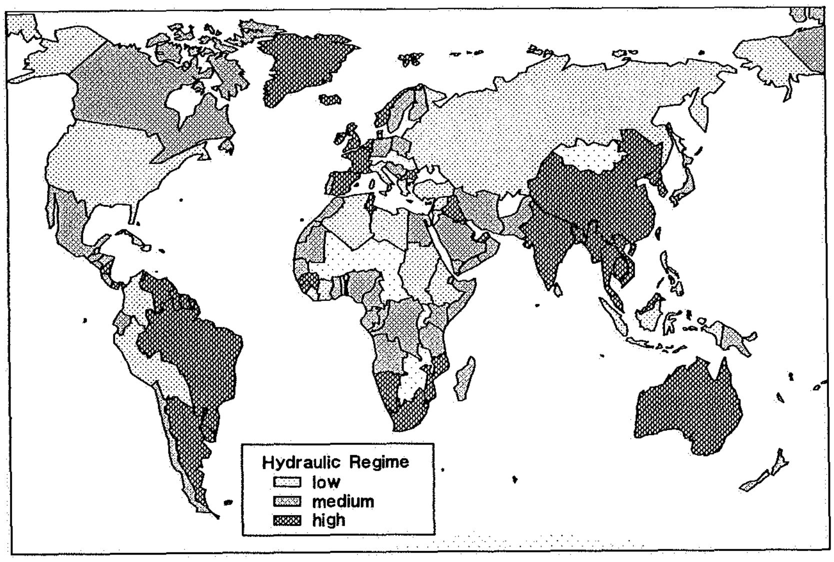

Figure 1 Global distribution of the hydraulic impact levels as derived from present storm surge levels

As mentioned before, for the population at risk a systematic variation of the boundary conditions is considered. In effect, the present study makes a comparison of the vulnerability for the following situations (future state refers to a development scenario of 30 years; ASLR refers to 1 m per 100 years; 'measures' refers to full protection):

- the present state of the countries without ASLR;
- the present state of the countries with ASLR without measures;
- the future state of the countries with ASLR without measures;
- the present state of the countries with ASLR with measures;
- the future state of the countries with ASLR with measures.

In summary, the following steps were undertaken to determine the population at risk for the various scenarios:
(1) Assessment of the maximum height contour of the coastal zone prone to flooding, taking into account present and future hydraulic conditions;
(2) Calculation of surface area captured between the coastline and the maximum height contour (maximum potential impact zone);

(3) Calculation of surface area of risk zones with accompanying flooding frequencies, accounting for the inundation process;
(4) Assessment of present state of protection to flooding in the low-lying countries;
(5) Calculation of population densities for the present and the future state;
(6) Calculation of population at risk for the different scenarios considered.

Each of these steps is discussed in detail in the study report. A simplified illustration of some aspects related to the above steps is given in Figure 2. As stressed above, the detailed country-by-country results have only limited accuracy and validity. Therefore aggregated results are presented, but first we will discuss some of the assumptions and associated effects.

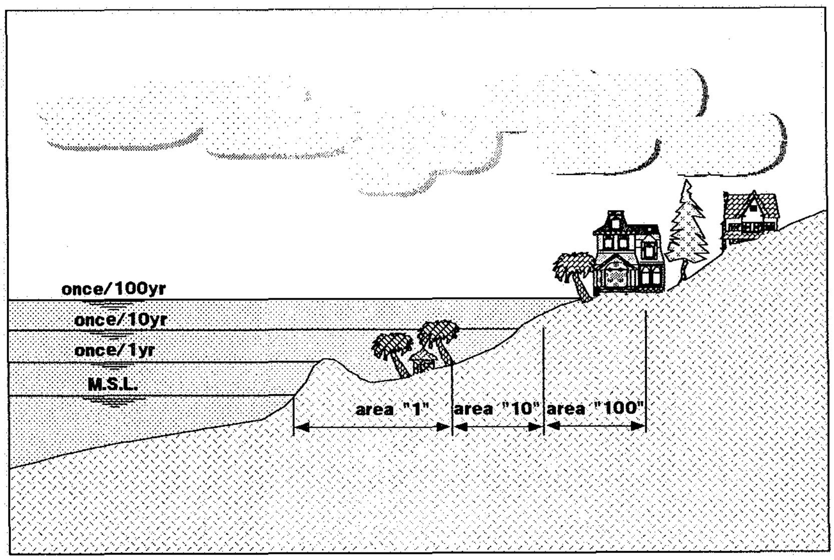

Figure 2 Simplified illustration of the hydraulic impact areas pertaining to the different levels of exceedance. Note that area "10" for example represents the surface area between the once per 1 year and the once per 10 year extreme surge level

some assumptions and their effects

- Limitations of data sources: The global data sources which were used allowed only for a limited spatial resolution of a number of variables, e.g. population distribution, height contours, surface areas between height contours. This introduces inaccuracies and requires assumptions, which all lead to inaccurate results on the scale of countries itself. Verification has shown, however, that averaged results on the scales of regions are accurate.

- No physical system response: In the assessment of population at risk any physical changes of the coastal environment in the course of time are ignored. Although this in many cases seems to be a realistic assumption because of the human restrictions of sediment availability (river regulation, river damming, coastal protection), it is not generally true (cf. Bangladesh's Ganges delta). The effects on the population risk numbers are, however, estimated to be of second order.

- Globalization of hydraulic conditions and regional effects: It was necessary to make assumptions about the additional effects which may increase the storm surge levels (e.g. subsidence, tides, barometric pressure). These estimates again will limit the accuracy of the results on the scale of countries, but less so on the scale of regions.

- Estimate of present protection status: Since there is no global information on the present protection status of the world's coastlines, it was assumed that the estimate could be based on present gnp per capita. By variation of the estimate the accuracy bands of the results were derived (Figure 3 illustrates the thus derived global protection status).

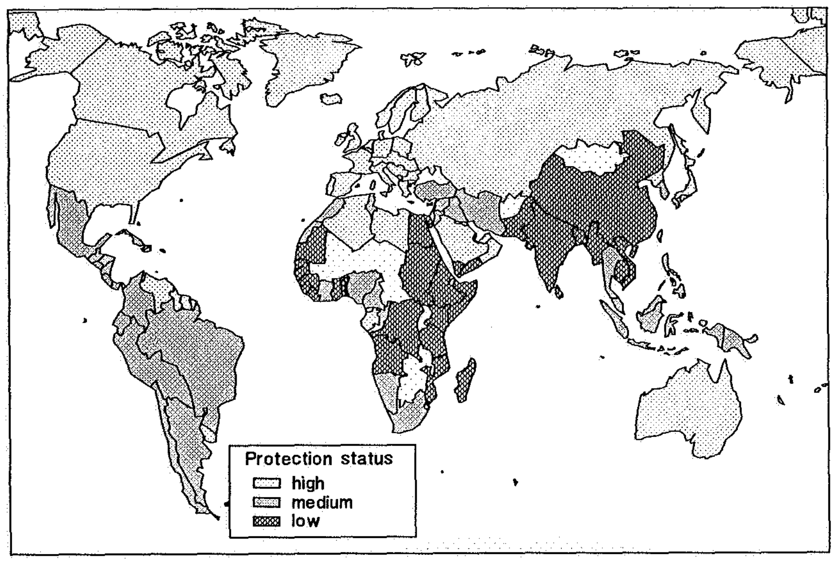

Figure 3 Global distribution of present protection status as derived from the GNP per country

aggregated results population at risk

(i) A considerable amount of the coastal population (the estimate ranges from one hundred million to two hundred millions of people) lives below the height contour which corresponds to the one per year storm surge level. (Note: there exist various estimates of the 'coastal population', such as "two-thirds of the world-population lives in the coastal zone" or "by the year 2000 six billion people live within 60 km from the coast". Here, however, it was attempted to keep to the very strict definition of people below the mentioned height contour.)

(ii) In case of an additional 1 m SLR on current MSL and ignoring any physical or human responses to this effect, the number of people experiencing flooding or inundation will increase by about 50%. Under the adoption of a 30-year population growth-rate, this figure will double.

(iii) Because of differences in the regime of extreme water level events (especially due to differences in decimating height levels (see Figure 4) the increase of flood risk in low-lying coastal regions due to ASLR is larger than average for small islands, the Southern Mediterranean coast, the African Atlantic coast and the Indian coast.

(iv) Another manifestation of climate change, i.e. storm frequency and intensity, may significantly increase these figures in those regions of the world where the storm frequency and intensity increases.

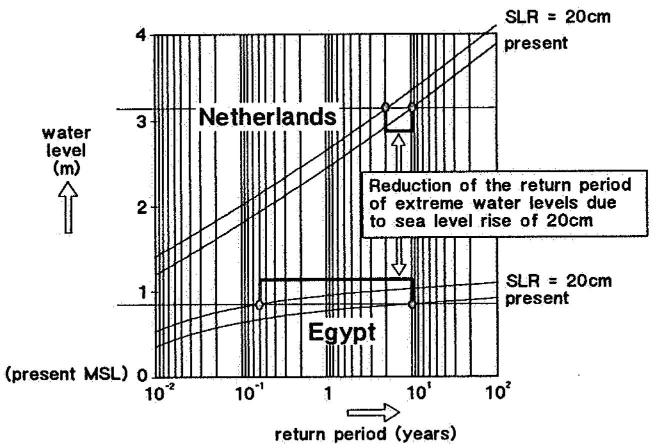

Figure 4 The impact of sea-level rise on return periods of extreme water levels. Sea-level rise will decrease the return period of extreme water levels. Note, moreover, that in countries with low decimating heights such as Egypt the return period of extreme water levels will decrease more rapidly than in countries such as the Netherlands

4. COASTAL ECOSYSTEMS AT LOSS

specification of methodology

As mentioned above, the concept of loss is considered to be most appropriate for the assessment of the vulnerability of ecosystems in the coastal zone, since it indicates the consequences of the impact **with** taking the response into account. It does not make any sense to indicate any increases in flooding, without quantifying its impacts on the coastal ecosystem. Furthermore, since it is difficult to quantify changes, e.g. with respect to biodiversity, only (the chance of) habitat area losses are estimated. The response mechanisms taken into account are only limited (mainly horizontal shifts of habitats). Thus, it is more appropriate to interpret the terminology 'at loss' as 'potentially at loss', since actual future losses may be counteracted by other feedback mechanisms of the physical and biological system.

In line with the CM, 'ecosystems at loss' are defined as the area of special ecological value which is expected to be lost over the indicated time horizon for a variation of the boundary conditions. In effect, the present study makes a comparison of the vulnerability for the following situations:

- the expected loss of coastal wetlands due to ASLR, without measures and without socio-economic development;
- the expected loss of coastal wetlands due to ASLR, with measures and without socio-economic development;
- the expected loss of coastal wetlands due to ASLR, without measures and with socio-economic development;
- the expected loss of coastal wetlands due to ASLR, with measures and with socio-economic development.

In summary, the following steps were undertaken to determine the coastal wetlands at loss for the various scenarios:

(1) Inventory of special ecological coastal areas (coastal wetlands);
(2) Global typology of coasts, based on morphogenesis;
(3) Overlay of inventory and typology, classification of response types;
(4) Analysis of historic and current trends of wetland loss;
(5) Specification of responses according to:
   - physical conditions (subsidence, tidal range, etc)
   - human development factors (population density, river regulation etc);
(6) Estimate of coastal wetland areas at loss.

Each of these steps is discussed in detail in the study report. So as to give an impression of the historic and present rates of wetland loss Figure 5 illustrates the documented evidence of wetland loss (see the reference list for sources). As stressed above, the detailed country-by-country results have only limited accuracy and validity. For this reason aggregated results are presented, but first we will discuss some of the assumptions and associated effects.

some assumptions and their effects

- Limitations of data sources: There exists a large variety of literature and databases describing coastal wetlands. Yet, some countries with extensive coastal wetland areas (e.g. Canada) could not be included because of lack of data. Furthermore, the inventoried data sources present the information non-uniform, and some data sources present contradictory information. These limitations indicate that only conclusions on a regional basis are relevant.

- Coastal wetland response: The causes of coastal wetland decline rates under the present conditions are a complicated mix of human-induced and natural causes. In order to estimate these decline rates on a regional scale including the additional effect of ASLR, assumptions had to be made, e.g. mangrove forests on low islands will disappear by definition contrary to those on high islands, and, countries will follow a preservation scenario for the coastal wetlands in those regions where wetlands are declining fastly.

aggregated results for coastal wetlands at loss

(i) Worldwide over 900,000 km^2 of coastal area can be classified as "areas of international importance", indicating that their character is in accordance with the criteria set by the RAMSAR Wetlands Convention.

(ii) One-third of the world's wetlands consists of coastal wetlands: salt marshes (15%), intertidal areas (10%) and mangrove forests (8%). While coastal wetlands are recognized to be of high ecological and economic value, they seem to be particularly vulnerable to ASLR.

(iii) Coastal wetlands are presently being lost at an increasingly rapid rate worldwide (see Figure 5). The increase in loss rates is closely connected with human activities such as enhanced subsidence and shoreline protection, blocking sediment sources for wetlands, and development activities, e.g., land reclamation and aquaculture development.

(iv) An acceleration of sea level rise would increase the rate of net coastal wetland loss. In combination with human activities a 1 m sea level rise over the next century would threaten half of the world's coastal wetlands of international importance. In some areas, coastal wetlands could be virtually eliminated, because their ability to migrate inland would be limited over such short timescales. If increasing human development is taken into account (the development scenario) this expected loss will increase in the order of 5 to 10%.

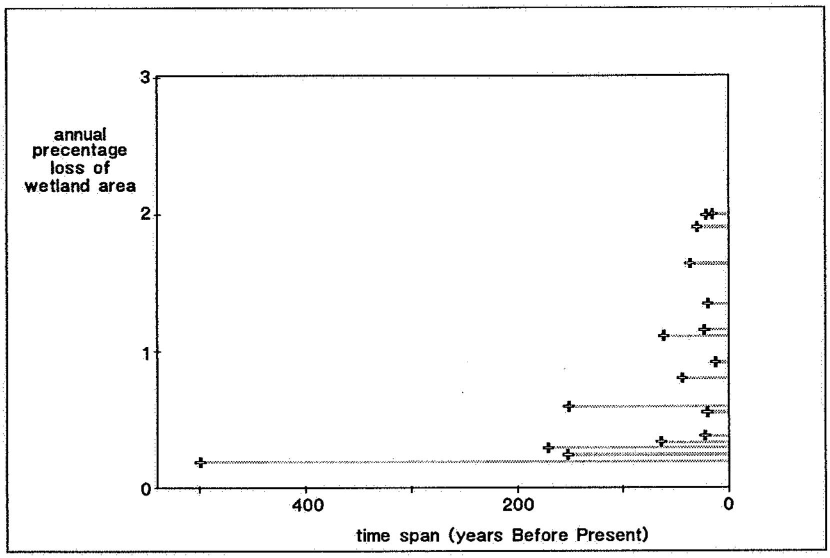

Figure 5 Coastal wetland loss: In the last 100 years the worldwide loss of coastal wetlands has accelerated precipitously (16 data points from 9 independent references on wetland losses in 11 countries)

(v) Losses of coastal wetlands of international importance are expected to be larger than on average for the coasts of the United States, the coasts of the Mediterranean Sea, the African Atlantic coast, the coasts of East Asia, and the Australian and Papua New Guinean coast.

5. RICE PRODUCTION AT CHANGE

specification of methodology

The concept of change is considered to be most appropriate for the assessment of the vulnerability of agriculture in the coastal zone. With 'production at change' the consequences of increased flooding and other climatic change factors on the agricultural area prone to flooding are considered in terms of changes in the crop yields. It is thereby assumed that it is not so much the actual loss of agricultural area that is dominant, but rather the production changes due to less favourable hydraulic and climatic conditions.

In line with the CM, rice production at change is defined as the production quantity which is expected to be lost over the indicated time horizon for the various scenario conditions. However, in the present study a more limited indication is given, i.e. the total production in the area impacted by more frequent flooding with an indication of the order-of-magnitude changes that may occur in this production. These order-of-magnitude changes are based on a simple, hypothetical model which assumes yield changes because of a shift of each crop type towards the next wetter type, due to the 'worsening' hydraulic conditions. Because of the limited accuracy of this approach it is not realistic to specify these order-of-magnitude changes for the various scenarios. Instead a 'future' situation is defined without distinction of any detail in the scenario variables.

In summary, the following steps were undertaken to determine the rice production at loss for the various scenarios:

(1) Inventory of mapping of rice production in Asia;
(2) Estimate of the production in areas prone to flooding;
(3) Hypothetical response exercise.

Each of these steps is discussed in detail in the study report. As stressed above, the detailed country-by-country results have only limited accuracy and validity. For this reason aggregated results are presented, but we will first discuss some of the assumptions and associated effects.

some assumptions and their effects

- Limitations of data sources: The current production figures which are based on literature have a limited accuracy both because of the limited spatial resolution and because of the relatively old production figures (late seventies).

- Crop production response: The determination of the response of rice crops to changing conditions requires rather sophisticated approaches, e.g. those used in the context of the analysis of climate change impact on crops in uniform regions which combine computer models with actual observations. The present approach must, therefore, be considered as a hypothetical approach which is found to produce figures of the same order of magnitude as found for some individual regions with the more sophisticated climate change approaches.

aggregated results for rice production at change

(i) Approximately 85% of the world's rice production takes place in South and Southeast Asia, and of this production about 10% is located in areas which are estimated to be vulnerable to ASLR such that the hydraulic conditions in these areas become less favourable for rice production.The amount of rice currently cultivated in this area feeds more than 200 million people.

(ii) Less favourable hydraulic conditions may cause lower rice production yields if no adaptive measures are taken. Especially in the large deltas of Vietnam, Bangladesh and Myanmar (Burma) serious production reductions may be expected.

(iii) A simple, hypothetical model indicates that up to 40% of the rice production in the areas vulnerable to ASLR may be affected. This could threaten the main food source of 80 million people.

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