Impact of Sea Level Rise on Society

Edited by Herman G. Wind

Report of a project-planning session / Delft
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IMPACT OF SEA LEVEL RISE ON SOCIETY

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Foreword

There is an internationally growing evidence that human activities will affect our planet not only on a regional but also on a global scale. Sea level rise as a consequence of a man induced climate change will create problems on an international scale indeed. The present report analyses the effects of sea level rise on society in a clear and unified way. The report presents first of all the generated comprehensive view of a possible sea level rise with its effects on environment, economy and social structures. It heightens in my view the international public awareness which is the key to the solution of the matter.

Sea level rise is also of special interest to the Netherlands and therefore to me, as one of the tasks of my ministry is to protect the country from flooding. In this sense the rising sea level is one of the elements which should be thoroughly taken into account. Considering the situation of this country, the sea level has been a preoccupation of ours for hundreds of years already. The past centuries have – admittedly by trial and error – taught us much. By the construction of dikes and dams we have been able to hold the rising sea in control.

These kinds of projects have made it possible for us to attain a high degree of security in the meantime. The Delta Project is an example that speaks for itself. In the Dike Management Act it will be worked out that this degree of security will be maintained.

Recent years have shown, however, that changes in climate can have a much greater influence on the level of the sea and on the security.

It is therefore a matter of vital importance to this country to know what to expect in the coming decades. The situation is such that the current rise in sea level already obliges us to deal with the consequences on our coasts. As a result of the rise in sea level several score million cubic metres of sand will shift from our dunes to the sea, a problem we have to handle in the control and maintenance of our coast. It is clearly a problem with a vital international scope.

Presently 70% of the world's sandy coastline has shown a net erosion over the past few decades. This connection makes it clear that we are dealing with a question of international proportions.

Already in the 1970's this led to an international approach on the basis of the World Climate Program. This program is of special importance and is composed of four main components, with particular emphasis on research into the influence of man on the climate, as well as studies in the effects of climate changes on society. From these studies it has become clear that we will have to contend seriously with the possibility of an accelerated rise in sea level in the coming years.

The experts base these expectations on the measured changes in the composition of the atmosphere. The last decades have seen an increase in the carbon dioxide content as well as that of other so-called trace gases. It is also expected that in the near future this increase will continue. These gases contribute to the so-called 'greenhouse effect'. Climate models in which the changes are introduced show evidence of important temperature rises.

The knowledge concerning climate and climatic developments is still clearly in its infancy. The climate system is an unusually complex matter in which the interaction among atmosphere, the oceans, the land surface and the polar ice caps makes the problem particularly difficult. Much international research still in its beginning phase, has been devoted to penetrating this system.

The Netherlands Ministry of Transport and Public Works is above all involved in the vast problem of world and regional climate changes and their consequences, from a meteorological, oceanographic, hydrologic and inland watercourses standpoint. One of the possible consequences is, as was said, the increase in sea level. The research into the rise in sea level will be continued within my ministry because of its great urgency. In view of the lengthy and extensive preparations needed for precautionary measures, anticipation of an accelerated rise in sea level is necessary now.

At present there is still clearly the question of increasing the general international awareness of these developments. This is why it is so fortunate that in this report the international scope is emphasized. The results of this study, as recorded in this document, also emphasize the importance for the Netherlands. Thus the Netherlands will be in a position to contribute in an international context.

As has been said, more anticipatory research into the greenhouse effect is still necessary. In the government's coalition agreement focus on the extent and seriousness of the CO_2 problem is being intensified. The rise in sea level is a matter of international importance. For all low lying countries in the world it is a potential danger.

Knowledge and know-how will therefore have to be mobilized and put into practice on a global scale.

Without doubt this is a problem of the very long term. Considering its magnitude and the possibilities for managing it in future developments, anticipation now is already more than worth while.

All this is necessary for the provision of a good product: a safe and livable environment for the future.

Mrs. N.Smit-Kroes
Minister of Transport and Public Works

Preface

It is estimated on the basis of observed changes since the beginning of this century, that global warming of 1.5°C to 4.5°C would lead to a sea level rise of 0.20-1.40 m (in the next century). This is one of the conclusions of the 1985 Villach Conference.

Such a rise in mean sea level will have various effects on society, for example in the fields of economics, public health, ecology, sociology and administration. In terms of our daily problems, these effects may appear to be irrelevant. But can the same be said for investments in agriculture, engineering structures, land use, etc., which have time scales of decades? How can these impacts be assessed and, if necessary, remedial actions formulated? Are these impacts outside our present day experience and should we therefore be careful with our 'remedies'?

These topics were covered during the ISOS Workshop (Impact of Sea Level Rise on Society), held in Delft in 1986. The contributions to the workshop ranged from the causes of sea level rise to the economic methods of evaluating impacts.

The workshop was initiated by the General Director of Delft Hydraulics Mr. J.E.Prins and was organized by a team consisting of Messrs. G.Baarse, H.Pot, P.Vellinga, F.R.Rijsberman, R.Thiemann, C.B.Vreugdenhil, H.G.Wind and Mrs. M.van Winden. The editor is indebted to Messrs. E.Allersma, B.Peerbolte, R.Reinalda and J.B.Wade for corrections to the manuscript.

Many of the impacts of sea level rise are discussed in the book. Chapter 2, which deals with impact assessment, has been presented in a form which makes it suitable, for a textbook for workshops etc.

This book provides an instrument for assessing and combating a 'rising' problem.

The Editor

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CHAPTER 1

Framework of analysis and recommendations

CEES B.VREUGDENHIL & HERMAN G.WIND

1 INTRODUCTION

1.1 *Impact of sea level rise on society*

There is a growing awareness today that human activities are beginning to affect our planet on a global scale. Sea level rise and other potential consequences of climate change create problems that can be solved only by international cooperation. Humanity would do well to increase its sense of stewardship for the planet it inhabits.

An increasing body of evidence suggests that in the coming decades a global warming due to the greenhouse effect will lead to a substantial rise in sea level. Estimates for the next century range from 0.5 to 2 metres. Because a large part of the world's population lives in low lying areas near the sea such a rise will have an important impact on society (UNEP-ICSU-WMO 1985).

Unlike most issues involving air pollution, an effective solution to the greenhouse effect will require action decades before the impacts occur, because of time lags in natural processes. Even if all emissions were stopped, temperatures would continue to rise for a few decades and sea level could rise for an even longer period of time.

Coastal infrastructure and coastal protection works take decades to implement and can last for centuries. Therefore, to ensure an effective and timely response, scientists, engineers and policy makers must join forces to consider the consequences for today's activities.

When, in 1985, the Delft Hydraulics Laboratory was granted the Commonwealth Award of Distinguished Service in Invention by the Bank of Delaware, on the recommendation of Sigma Xi, the Scientific Research Society, it was decided to take this opportunity to organize a workshop on the impact of sea level rise on society. The role of the institute cannot be to study the greenhouse effect in all its ramifications, but rather to concentrate on the water component in it: the impacts of sea level rise. The scope of the workshop is world wide.

The ISOS (Impact of Sea Level Rise on Society) Workshop was held in Delft, the Netherlands, from 27 to 29 August 1986. A number of experts in various fields involved (physics, engineering, environment, economics, social science, policy analysis) were invited to contribute to a framework of analysis showing the impact of sea level rise. The framework was drawn up by the organizers, based on written contributions by the participants. During the session, the frame work was intensively discussed and improved upon. To make things as clear as possible, three case studies were carried out, each showing different impacts of sea level rise.

The present report can be viewed as an attempt to analyse the effects of sea level rise on society in a unified way, so that it can be useful to those responsible for coastal lowlands, by showing possible alternative courses of action and the time that may be needed to implement them.

On the 29th of August 1986, the project planning session was followed by a meeting in which the framework of analysis and the recommendations were presented to the Dutch Minister of Transport and Public Works, Mrs. N. Smit-Kroes, and to officials of several countries and international organizations involved.

The participants of the workshop are listed in the first pages of the book. The first chapter deals with the framework of analysis and the recommendations of the workshop. Furthermore an outline of three test cases is given. In Chapter 2 the consecutive parts of the framework of analysis are described. The resulting framework has been applied on a general scale to the test case of the Netherlands. A review of the workshop contributions is given in Chapter 3. The full contributions, which served as a basis for the study, are reproduced in the Addendum.

1.2 *Aim and set-up of the workshop*

The ISOS Workshop has been set up to generate a comprehensive view of a possible or probable sea level rise, together with its effects on environment, coastal defence and other engineering matters, economy and social structures. The study has the character of a 'mental experiment' or 'brain game' in which certain, more or less likely events are analysed under a number of assumptions on physical, economic and social conditions. In several of the disciplines involved, forecasts for more than twenty years ahead are almost impossible. Therefore the forecast value of this study is very limited. Nevertheless, it serves to heighten public awareness of the great range of possible consequences and countermeasures that can be imagined.

Since it is not possible nor useful to set up a 'mental experiment' in a global sense, three case studies are elaborated, which are meant to be typical for various settings throughout the world. The case studies serve to test various policies and programmes of action, giving a first indication of, e.g. the time available to prepare certain actions.

The results of the workshop are meant to be a support to decision makers and to help them to appreciate what may happen and what are the alternative strategies available. A recommendation or choice of particular strategies is not made as this would misjudge the positions of both the decision makers and the participants of the project-planning session.

It has been made quite clear in previous studies that sea level rise is not an autonomous process but is part of changes in the coupled system of atmosphere and oceans. It is not our intention to repeat or expand the study of this coupled system; rather we will use known results to draw up possible scenarios for sea level rise.

The time scale of the atmospheric and oceanic changes may be quite large, particularly if (partial) melting of the polar ice caps is considered. We limit our study to a period of approximately 100 years, because of the difficulties of predicting the changes in society beyond this period. These difficulties become apparent by imagining a similar study having been attempted in 1886. We are, therefore, obliged to make explicit assumptions on physical, technological, economic, and social developments which together form context scenarios for our study.

The effects of sea level rise, either directly by loss of land and facilities, or indirectly by expenditures needed for coastal defence and other costs, will influence the economic and social conditions in a country. To study this, we would need to construct extensive socio-economic models. This is outside our present capability. We will restrict ourselves therefore to the direct effects of sea level rise and do not consider any possible actions, such as restrictions on fossil fuel consumption, and/or reforestation, that might reduce the sea level rise.

1.3 *Relevance and selection of case studies*

The impacts of sea level rise have automatically a direct relevance to coastal lowlands. The immediate impacts are related to:

- loss of land by inundation of river deltas (such as those of the Ganges and Brahmaputra, Yangtze, Mekong, Nile Rivers) or by erosion or flooding of coastal areas;
- increased storm damage to dikes, dams, coastal structures; changes in morphology and ecology;
- increased saltwater intrusion into rivers, and saline seepage.

Figures 1 and 2 show vulnerable areas in Europe and the world.

The length of the world's coastline is between 0.5 and one million kilometres. The land area influenced by a rise of sea level is in the order of five million square kilometres: about three per cent of the total land area, but one

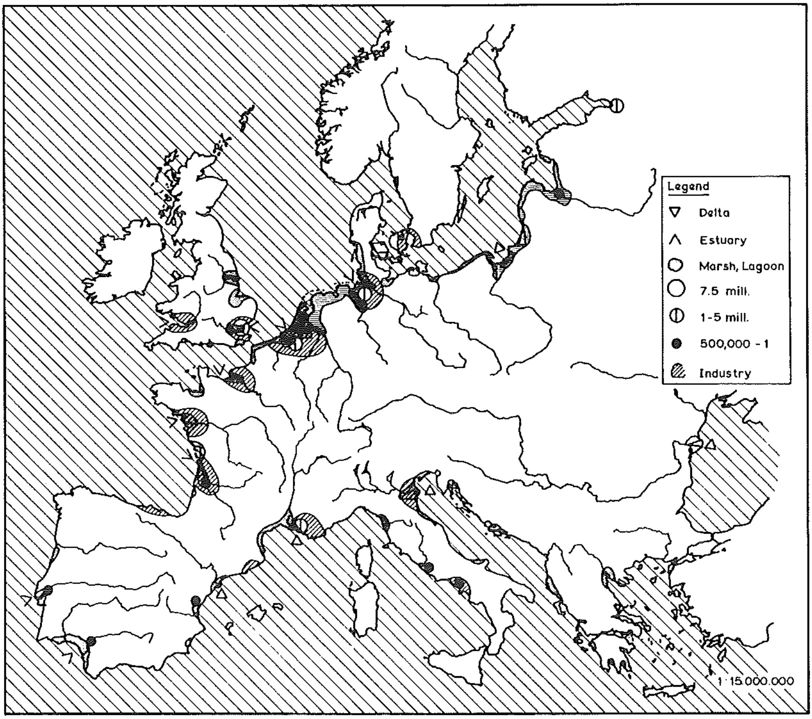

Figure 1. European areas vulnerable to a rising sea level.

third of the total area of cropland in the world. Large parts are densely populated, including many large cities, and totalling in the order of one billion people. Characteristic values of arable land are US $300,000/km^2 in Bangladesh and US $3 million/km^2 in the Netherlands.

In a session of limited scope, like ISOS, it is impossible to give a comprehensive review of the impacts of sea level rise in all these regions; this, in fact, is not the purpose of the session. Rather, the session is intended to provide some information on possible effects and to indicate the consequences of possible strategies open to decision makers. In order to achieve this, three case studies have been selected as mentioned in Section 1.2. These cases are typical for the various social, economical and environmental situations involved. Further sufficient data are available to perform the studies with an acceptable level of realism. From a consideration of the alternatives, the following three case studies have been selected:

1. The Netherlands, an example of a highly industrialized country with a well-organized coastal defence system and a long tradition of ‘battling the sea’.

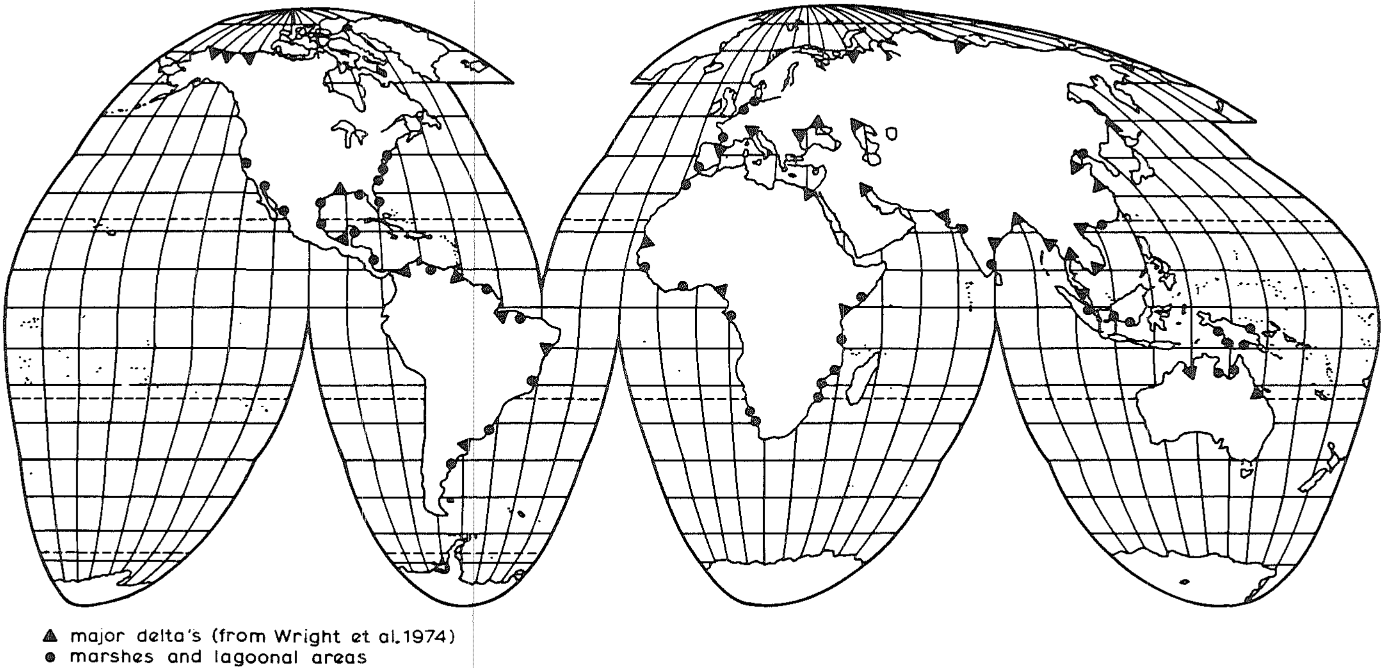

Figure 2. Areas in the world vulnerable to a rising sea level.

2. Bangladesh, a low-lying country with limited economic prospects but where a rise in sea level could potentially have considerable impact.

3. The Maldive Islands, a region of perhaps restricted worldwide interest but where tremendous social, cultural and environmental impacts are to be expected.

2 OVERVIEW OF ANALYSIS

Sea level rise has impacts, not only on engineering structures, but also on the entire socio-economic system of a country (e.g. Kellogg 1981). To include the total system, a framework for analysis has been set up as shown in Figure 3.

Due to restrictions in aim and scope (Section 1.2) some factors, such as economy and social structures, have been considered as external, i.e. not

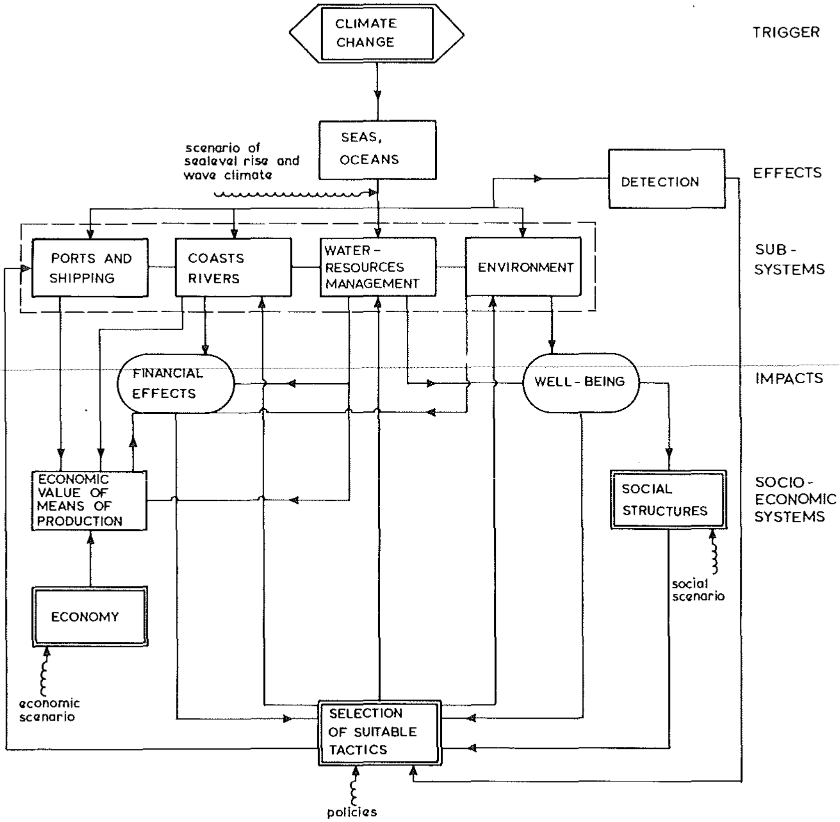

Figure 3. Flow scheme of impact of sea level rise on society.

influenced by the sea level rise. A short discussion of the various factors is given below. For ease of analysis and presentation, a simple computer simulation model has been developed which is described in more detail in Chapter 2.

This model may give an impression of precision. This, however, is not the intention and it has been used solely to simplify the investigation of the relative importance of certain assumptions and context scenarios. The case study, also reported in Chapter 2, clarifies this point.

2.1 *Physical processes*

The Villach conference (1985, see also Barth & Titus 1984) concluded that a sea level rise of 0.2-1.4 metre is likely to occur within the next century. The main mechanism is the thermal expansion of ocean water due to heating of the atmosphere. This process has been started in the surface ocean layers and will continue for tens of years even if all carbon dioxide emission would be stopped now. Significant increase of melting of polar ice caps is not expected within the next 100 years.

A sea level rise in the Netherlands of 0.2 metre/century, shown in Figure 4, is an extrapolation of current rates and is not a reason for serious concern. The probability of a 1 m rise is difficult to quantify, but relatively high; this would lead to large effects. More extreme rises have a lower probability but extremely high effects. Some possible scenarios for sea level rise are illustrated in Figure 4. It should be noted that rates of rise of 1 metre/century have occurred previously in geological history, at the end of ice ages.

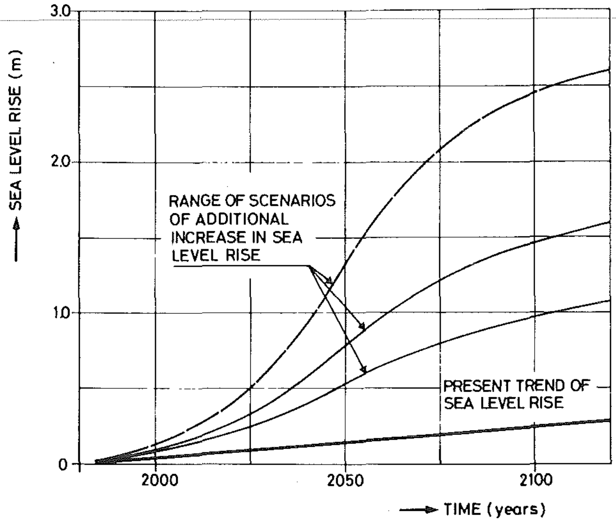

Figure 4. Scenarios of sea level rise.

There will be a corresponding change in climate, since atmospheric heating is the prime cause behind sea level rise. The state of the art of atmospheric science is, however, such that it is impossible to decide if a temperature increase of a few degrees will lead to essential changes in storm patterns.

A one metre rise of sea level will have only very small effects on tide propagation, storm surges and wave generation. Even for a five metre rise of the level of the North Sea, the changes of tidal ranges are relatively small (Delft Hydraulics 1980).

The impact on the safety in low coastal areas, however, is considerable. The chance of a catastrophic event along the coast of the Netherlands increases a hundred-fold by a sea level rise of 1.5 m. The recurrence period of the impacts such as the catastrophic 1953 storm surge would become three years instead of 300 years.

2.2 *Detection*

It is difficult to detect a change in trend of sea level rise because of the relatively great variability of mean sea level. Even if well-organized networks of gauges are available, it is estimated that definite conclusions cannot be drawn within the next 10 to 25 years. This introduces an important time lag between identifying the need and taking the necessary decisions and actions.

2.3 *Economic conditions*

In estimating the risk of a rising sea level in terms of possible economic damage, and in taking decisions on engineering works for coastal defence, the overall economic conditions of the region being considered play an important part. Broad assumptions are made here, since it is not the intention to include a comprehensive macro-economic model in the studies. At this stage it is assumed that the economic growth rate and the social rate of discount can be specified under different economic scenarios. It is appreciated that these parameters are influenced strongly by many other social, economic and political factors, but these are outside the scope of our study.

Considering different scenarios will enable us at least to achieve some basic ideas on the sensitivity of the results to varying economic conditions. This procedure, however, is insufficient for, and not intended to be, an economic base for strategy choice (planned retreat, coastal defence, etc.).

2.4 *Social conditions*

There is an interaction between social conditions and the impacts of sea level rise. On the one hand, particularly if coastal defence is impossible, there could be a large social impact in the form of the abandoning coastal areas and the migration of population. Whether or not this is considered acceptable depends on the values and norms of the society. On the other hand, the way in which a society responds to threats from a rising sea level depends very much on the social structure. It is very difficult to 'model' this in quantitative terms; rather, a contextual scenario should take these conditions into account, e.g. in the form of a delay between the moment that the need for action is discerned and the moment that the action is actually taken, in whatever form. For each of the case studies some possible assumptions have been made in this respect.

2.5 *Coasts, rivers and water management*

In the case studies the coastal defence system is represented very schematically. In each segment of the coast (only two or three segments per case) the type of coastal defence is indicated as solid (dikes, sea walls), flexible (dunes, deltas, mangroves, lagoons) or none. With solid coastal defences the relative level of the construction, together with water level data and wave statistics, determines a certain risk of failure, which enters into the economic considerations. The risk of failure increases with rising mean sea level, even though tides, waves and storm surges remain unaltered. It is a matter of policy to decide whether to defer action, to set up a planned retreat or to strengthen the coastal defence structures, and how quickly to respond, taking into account the time needed to take a decision (construction time, etc.). Policy can be influenced by economic considerations: the expected damage to the invested capital behind the defence structure, perhaps including possible loss of human lives in case of flooding. The direct cost of dike construction or, in the case of abandonment, of loss of agricultural area, industries and cities, will also influence the decisions made.

With rivers two main impacts have to be considered. One is flooding and the need for protection in the form of dikes or embankments. The considerations are the same as those applied to coastal defence. Additional costs may also be involved in the construction of irrigation channels, pumping stations etc. The second impact is the increased salt intrusion which will affect fresh water intakes for irrigation and domestic water supply. In addition there may be increased saline seepage and additional fresh water will be required for flushing. The cost of all these actions have to be taken into account, or, if no actions are taken, the loss of value of agricultural production and other economic activities.

Finally, many engineering structures on the coast or river banks (bridges, harbours, cooling-water intakes, intakes for drinking water supply, locks) will have to be adapted or rebuilt if they are to continue to operate.

2.6 *Environment*

Geological records indicate that the natural environment has a great capacity to adapt to changing conditions and, for example, rises in sea level of 1 metre/century have occurred without the extinction of any species or organisms. It can therefore be assumed that, in many cases areas of natural interest will be able to adapt to a rising sea level, in various ways. The rate of adaptation depends on the type of vegetation, for example, agricultural regions can adapt in 10 years, grassland can adjust in tens of years. Forests, however, due to the low turnover rate, may need hundreds of years.

In cases of protected coasts, the consequence of inland migration of wetlands being obstructed by dikes or sea walls may be that certain types of natural environment are reduced in size or completely disappear. The fate of wetlands depends on the possible rate of sedimentation. Rates of 1 cm/year, which are sufficient to cope with of 1 metre per century sea level rise, have been observed. In some instances the loss of such regions has to be faced. This may also lead to loss of fishing-grounds or fish breeding regions, and consequently to loss of fish production. In other cases, the fishing industry may be revitalized.

The inland environment behind dikes may be affected by changes in wetness or increases in salinity, particularly if drainage facilities are not adjusted. This can lead to changes in the type and volume of agricultural production. Since there are insufficient quantitative data about environmental relationships only mainly qualitative aspects have been included in our framework. The region of environmentally interesting natural regions is recorded and the effects on these regions have been assessed for each case study. Will they be shifted or will they adapt to the sea level rise? If not, how serious will be the consequences?

2.7 *Strategies and actions*

The way in which society responds to sea level rise and its impact is determined by a multitude of conditions. Many other problems compete with sea level rise for the attention of politicians and decision makers and experience shows that only a sudden event or even a disaster will trigger countermeasures, even if there is the prior awareness for the problem. An example is the great flood in the Netherlands in 1953 which brought an existing program for flood protection into action.

A major factor influencing the policies, strategies, and actions to be taken is the availability of finances for dike construction, adaptation of infrastructure, etc. Even if the financial means are there, society must be willing to make a great share available for this purpose. The question of responsibility may also be involved. Because CO_2 emission with its consequences of atmospheric heating and sea level rise is caused mainly by industrialized countries, this may lead those Third-World countries who are faced with the consequences of increasing flood hazards to call upon the international community to finance countermeasures.

Such factors imply that a certain lead time has to be taken into account from the decision to the realization of the action. An estimate of this 'delay' time has to be made for each case study, depending on the assumptions made for the particular social conditions.

Whatever the circumstances, the choice of decision makers is between 'positive defensive action, planned retreat or abandonment'. Each choice can be elaborated in various forms. A 'mental experiment', as conducted here, in principle creates the opportunity for a systematic comparison of alternative policies and programmes of action. Each can be considered for its financial, technical, social and environmental consequences and compared with a set of 'acceptable impacts'. In the process there is a possibility for the optimization of policies. However, the uncertainties involved make this approach less relevant. The results would suggest an exactness that is not justified. In the present framework, the programme of actions is therefore treated as an input scenario. Using a simulation procedure, the impacts of a certain programme of actions can be studied, which will give the decision maker an insight into possible courses of events and the alternative solutions to cope with them. A point of particular interest is the time available for taking action, in view of the uncertainty in various context scenarios, and the 'delay' inherent in the political, social and technological systems. In particular, planned retreat appears to require much more lead time than fortification of coastal defences, which in turn requires more lead time than abandonment.

3 CASE STUDIES

The framework of analysis, explained in Chapter 2, has been applied to testcases in the Netherlands, Bangladesh and the Maldives. The three test cases are discussed below.

3.1 *The Netherlands*

The Netherlands lie on the Northwestern European Plain on the North Sea and cover an area of about 37,000 km^2. Geologically the country is basically formed by the delta of three large rivers: the Rhine, Meuse and Scheldt. Its geographical situation gives the Netherlands a temperate maritime climate. Some of the delta areas have been moulded by the action of glaciers and the wind during the pleistocene glaciations. The result of these geomorphological processes can still be seen in the present landforms of the higher eastern and southern part of the country, which have an elevation of more than three metres above sea level. Most of the remainder, in the north and the west of the country (the lowlands), consists of reclaimed land, surrounded by dikes and drained artificially; a substantial area has an elevation below sea level. Roughly two thirds of the Netherlands is agricultural land, most of it grass land, used for feeding livestock. Nearly 20% of the total land surface is arable land and a minor part (3%) is used for horticulture, which represents, however, an extremely high economic value.

With a population of 14.5 million and an average density of approximately 400 inhabitants per square kilometre the Netherlands is one of the most densely populated countries in the world. Industry engages about 20% of the total workforce, trade and transport 26%, and agriculture only 6%. More than 40% are employed in service occupations, including civil service, local government and education. The gross national product (1986) amounts to US$ 160 billion; contributions of the different economic sectors are about proportional to the workforce they employ.

Its low-lying position along the border of the North Sea makes the Netherlands very susceptible to the influence of a rise of sea level. Currently its coast line is protected by a system of dikes and dunes against storm surges with a frequency of once every ten thousand years. This grade of safety has been created by the final completion of the Delta Plan in 1986, which includes an extensive scheme of dikes and barriers in the south west. A one metre rise of sea level will reduce this safety to the order of 10% of the present factor, that is, against storm surges with a frequency of once in thousand years. The maintenance of this system is of fundamental importance in view of the size of the low-lying area protected by the coastal defence system and the high number of people living there and the enormous economic value represented.

The rise of water level outside the dikes will increase saline seepage. This phenomenon is caused by the considerable head difference between the ditches behind the dikes and the sea, which produces an underground flow of salty water into the polder water system. Agricultural production and the quality of drinking water will be affected seriously unless countermeasures are taken. Salt intrusion through the river mouths will add to this problem.

A third consequence of sea level rise will be the reduced efficiency of harbour terminals and related infrastructural works in the Rotterdam area, the biggest sea port in the world.

For the case study the lowlands of the country have been divided into three segments, see Figure 5.

Segment A consists of the Provinces of Groningen, Friesland and the IJsselmeer Polders. This segment includes a mainly agricultural, sparsely populated area, protected by dikes and the dunes of the islands that separate

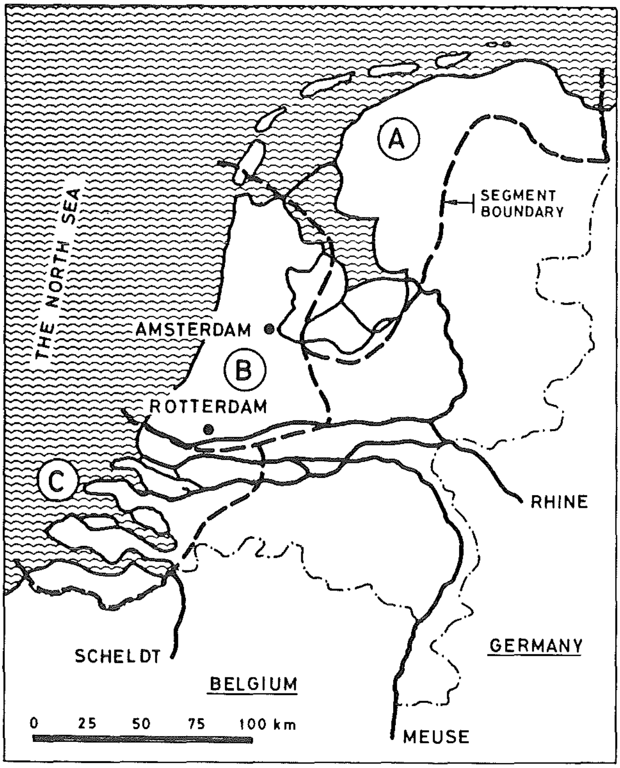

Figure 5. The Netherlands and segment boundaries.

the Wadden Sea from the North Sea. The Wadden Sea is a tidal wetland area with a high ecological value.

Segment B consists Central-Western Holland. This segment is a densely populated, urban, industrialized area. It also includes the main horticultural sectors, which are threatened by an increased salt load. Rotterdam harbour area is also part of this segment.

Segment C is the Delta area and is comparable with Segment A in terms of population density and land use. This area includes the actual river delta and has a relatively long coastline. Its situation along the southern part of the North Sea makes it particularly vulnerable to storm surges.

3.2 *Bangladesh*

Bangladesh lies on the Bay of Bengal in the delta area of the rivers Ganges, Brahmaputra and Meghna and forms the transition zone between the Indian subcontinent and South-East Asia. It covers an area of 140,000 km^2. By far the largest part of Bangladesh (around 80%) consists of alluvial lowlands, only bordered by hills in the east. A plain complex system of rivers, creeks and other watercourses is characteristic for the country. Four different physical landscape units can be considered within the lowlands. The smallest is the foothills to the north. Centrally located are the meander plains of the rivers, zones that continuously change due to erosion and accretion of the river banks. The tidal plains form a third unit which includes the area south of Khulna and another area bordering the Chittagong coast. The fourth unit is the active estuarine river mouth area; enormous amounts of river sediment add to the accretion of existing islands and the formation of new islands, which are eroded during storm surges.

The typical monsoon climate of Bangladesh, combined with deforestation in the uplands of the river basins, causes seasonal floods in at least 50% of the country.

With a total population of about 100 million people, of which 85% lives in the countryside, Bangladesh is the most densely populated agrarian country in the world. Its population increases by 2.6% per year.

Three quarters of the workforce is employed in agriculture, contributing to half of the country's domestic product. About 10% of the workforce is employed in the industrial sector contributing 11% to the gross domestic product. The gross domestic product amounts to US $14 billion.

Rice, sugarcane and jute (the latter for export) are the main agricultural products. The final crop yields depend very much on the time and amount of rainfall (and flooding). Some areas have been diked and are drained artificially. About 20% of the arable land is irrigated. Water and flood control are the main problems in agriculture and land reclamation projects have been started.

For the case study Bangladesh has been considered in three segments related to the extent by which they will be affected by sea level rise, see Figure 6.

Segment A is the area west of the main active delta. It includes an extensive zone of tidal plains south of Khulna (the Sunderbans), covered by mangrove forests, and a part which is also under influence of tidal flooding, though not daily, (around) the town of Khulna itself. This zone has been partially protected by dikes. Rise of sea level will cause a serious drainage problem here. The total population is about 12.5 million, inhabiting an area of 21,000 km^2. The mangrove forests have a natural and also an economic value for wood production and fisheries.

Segment B is the central river delta area. Morphologically it is a very dynamic zone, characterized by continuous erosion and accretion. As a result farmers often lose their land and are forced to settle down in other areas. Agricultural production is low in this area. The construction of dikes to fix the existing land/water configuration seems to be the only solution. This is,

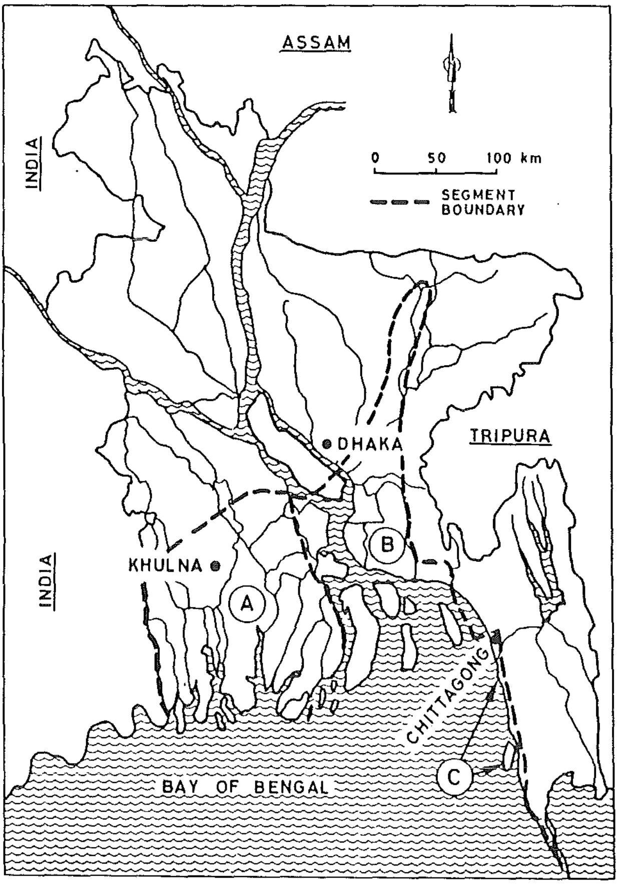

Figure 6. Bangladesh and segment boundaries.

however, costly and will increase the flow velocity in the water channels, possibly causing more erosion.

Segment C is formed by a narrow coastal zone near Chittagong, a town which will be affected seriously if there is a substantial rise of sea level. Chittagong with its 1.3 million inhabitants is the main harbor and industrial town of the country. Agricultural production, with two crops yearly, is relatively high. The land is protected from normal storm surges by a dike.

3.3 *Maldives*

The Republic of Maldives comprises a group of more than 1200 islands, strung out from north to south, about 670 km southwest of Sri Lanka, and stretching from just north of the equator up to about 8°N. Maldives rest on a submarine ridge, which may be volcanic in origin.

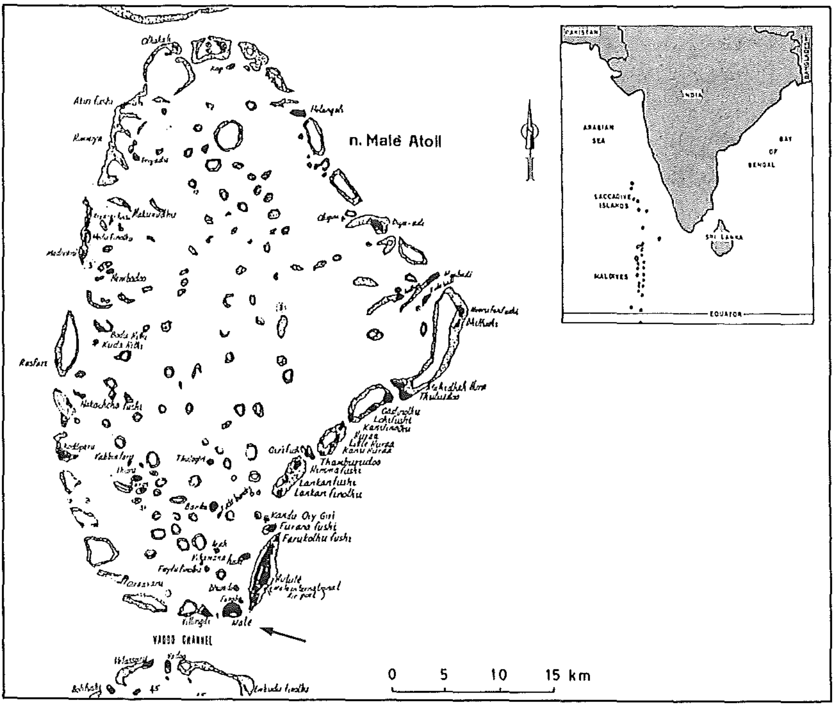

Figure 7. North Male Atoll with the Capital Island of Male (Maldives).

The islands are grouped into 19 atolls, covering a land area of 298 km^2. An atoll is a ring-shaped island of coral, which encircles a lagoon (the word atoll is itself, Maldivian). All of the islands are built entirely of coral, coral sand and other coral detritus, and none exceeds a land area of 13 km^2. The climate is characterized by two tropical monsoon seasons, with an average precipitation of 2100 mm per year. The total population of 182,000 people is dispersed over about 200 islands, nearly 50,000 living on the capital island of Male. One third of the labour force is engaged in fisheries, a quarter in manufacturing activities and the remainder in agriculture, tourism, services, transport and small-scale industries.

The gross domestic product amounts to US $77 million, about 15% of which is due to fisheries, 15% to tourism and 10% to agriculture, with millet and coconuts as main products. The main contribution is government activities, representing 20% of the gross domestic product.

The maximum elevation of the islands is not more than two or three metres above sea level. Thus, the main threat of a rising sea level to Maldives will be simply the loss of land area. Since natural growth rates of coral vary from a millimetre to several centimetres per year, one may expect that the physical elevation of the islands can keep pace with the sea level rise. However, where people have occupied entire islands, as in the case of Male, natural coral growth has been reduced drastically. Artificial measures have to be applied in order to protect this island and its inhabitants from a drowning disaster. Given the high porosity of coral and coral sand the construction of dikes may not be feasible to solve the problem since the continuous inflow of water underground will necessitate immense amounts of energy for land drainage.

Only one segment is considered, the capital isle of Male, which covers just 1.6 km^2, see Figure 7. This will give a typical picture of the impacts which can be expected on all the coral islands.

4 FINDINGS AND RECOMMENDATIONS OF THE WORKSHOP

4.1 *Findings*

1. Sea level has risen 0.1 to 0.15 metres in the last century. The magnitude of this rise is consistent with the changes that would result from increases of carbon dioxide and other greenhouse gases in the atmosphere, as predicted by atmospheric and ocean models. However, it is not yet possible to prove that sea level rise is accelerating nor whether the rise is due to the greenhouse effect or other factors.

2. The presently projected global warming may cause a substantial rise in the sea level. Current evidence indicates that a 0.3 metre rise could occur in the next 50 years, a 0.5 to 2.0 metre rise by 2100, and a 5 metre rise in the next 200 to 500 years.

3. Such a rise will inundate wetlands and lowlands; accelerate coastal erosion; increase the risk of flood disasters; create problems with respect to drainage and irrigation systems; and increase salt water intrusion into groundwater, rivers, bays and farmland. These effects could damage port facilities and coastal structures; destroy quality farmland; disrupt fisheries and bird habitats; diminish storm buffer protection; and result in the loss of recreational beaches.

4. Because the increase in the rate of sea level rise will be very gradual, it may be difficult to reach a consensus about the need for taking actions. Unfortunately, present data on sea level rise are limited.

5. Communities can respond to sea level rise by (a) defending the shore, (b) raising the land surface either naturally or artificially, (c) moving present activities and developments landward or (d) adapting to the increased flooding and inundation.

6. Many areas can be protected with dikes, seawalls, beachfill, landfill and other engineering solutions. However, economic and environmental impacts will often make such a protection strategy unacceptable. Consequently,

different strategies for protecting land will have to be developed, such as encouraging the ‘natural’ vertical accretion of land.

7. There is no limit to how high dikes can be built. High dikes, however, can create a false sense of security. The larger the rise in sea level, the greater the disaster that would result if a dike was to be breached.

8. A comprehensive view over a broad variety of aspects of society such as ecology, sociology, technology, engineering, and economics will be required. Measures to prevent or reduce undesired effects of sea level rise should not be treated in isolation. Society requires multi-functional solutions to its present day multi-aspect problems. Given the large differences in regional conditions, analysis should be site-specific.

9. A rising sea level is not unprecedented. Many areas of the world have experienced substantial local rises. This constitutes a valuable body of experience that could be useful when responding to future sea level rise.

10. A comprehensive view requires knowledge of the various systems and their interrelationships. A model can be used to simulate the various processes in a structured way and a sufficiently elaborated consistency model can be used to simulate, evaluate, and compare various strategies. Such a model will increase the awareness of the scientists and policy makers involved. Present models are not yet sufficiently well developed to simulate ecological, economic, and engineering factors satisfactorily.

11. Sea level rise and the implementation of response strategies will have serious effects at 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 needed for reconstruction. Migration of people and enterprises will disrupt the existing economic structure. Interregional and interpersonal redistribution of income through increased tax revenue transfers will be unavoidable. The necessary redirection of national economic efforts may well meet overall capacity constraints, particularly in less developed countries.

12. Where retreat from threatened areas is unavoidable, the migration of people may cause serious social losses. War and civil disruptions will increase the vulnerability of the infrastructure protecting the population against a higher sea level.

13. Beach resorts provide important revenues to coastal areas throughout the world. However, even a 0.3 metre rise projected for the next 40 years could erode beaches 25 to 50 metres, which in many cases would be the entire beach. The planning of coastal resorts should consider whether it would be more cost effective to set buildings back further or to undertake substantial beach nourishment.

14. Although sea level rise would have important impacts throughout the world, this workshop has examined three countries in detail:

The Netherlands. A substantial rise in sea level would eventually require changes in coastal protection strategies. It seems unlikely that new dikes should be built now. However, the success of current projects will depend in part on how well future sea level rise is taken into account.

Bangladesh. A two metre rise would eventually inundate 10 to 20% of this country, and also threaten other parts with flooding. Efforts to protect the country with dikes would require a massive economic effort. However, the substantial amount of sediment washing down the Ganges could potentially enable a large part of the land to keep pace with sea level rise. Current river management activities will threaten the ability of the land to keep up, unless they are designed to take sea level rise into account.

The Maldives. These islands are generally less than two metres above sea level. Therefore, the entire nation could be inundated. Fortunately, the undeveloped coral reefs could keep up with sea level rise to a great extent. However, developed coral reefs would not keep up. Because the coral is permeable, dikes would not prevent the islands from being flooded. Therefore, it may be necessary to raise the level of the entire islands.

4.2 *Recommendations*

Research

Governments and the world scientific community should develop a coordinated international research program on the impact and policy implications of sea level rise. This would entail:

a) the accuracy of estimates of future rises in sea level should be improved;

b) the ecological, economic, and social costs and benefits of (additional) coastal defence systems, planned resettlement, and other strategies should be investigated;

c) methods and models for integrating the diverse interdisciplinary information about the impact and policy implications of sea level rise should be developed to support policy formulation; and

d) the experience of areas that have undergone local rises in sea level in the past should be investigated.

Monitoring

A coordinated international program of monitoring of sea level rise, related processes, and their impact should be initiated. Such a program should examine:

a) sea level, tides, waves, surges, and related climatic parameters;

b) hydrology and geomorphology including run off, salinity, sediment transport, and changes in sea bottoms and shorelines;

c) ecology, especially the responses of individual species and entire ecosystems to sea level rise;

d) social aspects, especially the perception of danger related to a higher sea level and reactions of the population toward the threats involved; and

e) demographic and economic activities in areas possibly affected by sea level rise.

Awareness

It is important to increase the awareness of the implications of sea level rise for present and future development and planning activities. It will be necessary to:

a) bring together scientists, engineers and policy makers in international workshops;

b) brief Ministers of national governments on the potential impact of sea level rise; and

c) incorporate sea level rise and other effects of climate change into the curricula of secondary schools and universities.

ACKNOWLEDGEMENT

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CHAPTER 2

Policy analysis

GERRIT BAARSE & FRANK R.RIJSBERMAN

1 INTRODUCTION

This chapter deals with the development of an operational approach for the assessment of impacts of sea level rise on society. Based on a review of the most important impacts of sea level rise on various human activities and interests, an approach is outlined for describing these impacts in a consistent and coherent framework for analysis. Because the impacts should be described in a quantitative way as much as possible, the core of the approach is formed by what is referred to as the computational framework. This computational framework should allow for an assessment of the effects of sea level rise, and, more importantly, an assessment and subsequent evaluation of alternative management strategies that can be developed to alleviate the negative effects of sea level rise.

The computational framework described was partly worked out as a mathematical model and implemented on a microcomputer. This simplified model version was tested in three case studies, involving the Netherlands, Bangladesh, and the Maldive archipelago, in order to test and illustrate the feasibility of the approach.

The main objective of this work is to provide a structured framework for a policy analysis of the problem of sea level rise. A policy analysis simultaneously considers the technological, socio-economic, ecological, and institutional aspects of the problem, its possible consequences and its potential solutions in a consistent approach. Such a policy analysis is considered as a requirement for a useful discussion of the sea level rise problem in a broad context, and for the exploration and evaluation of options which society has to adopt to cope with sea level rise.

Section 2 of this chapter outlines and explains some major elements of the policy analysis approach and indicates the kind of problems for which a policy analysis is suitable. For this purpose, a brief description is provided of some sample studies that were recently carried out. In Section 3 the phenomenon of sea level rise is identified as a policy problem for which a policy analysis based on a modelling approach seems appropriate. An overview of the major functions to be performed, and requirements to be met by this modelling approach are presented in Section 4. The modelling approach, which is referred to as the ISOS (Impacts of Sea Level Rise On Society) model, is developed theoretically in Section 5. An operational model version which has been developed from this concept for use in the ISOS workshop is described in Section 6. It should be noted that this model version has severe restrictions, since it only contains some of the main features of the theoretical model in a highly simplified form. As such, the present model version can only illustrate the possible applications and merits of the approach, and provide a basis for further discussion and model development. Conclusions and recommendations in this respect are contained in Section 7.

2 WHY POLICY ANALYSIS?

2.1 *Introduction*

Policy analysis is defined as a systematic process with which to identify, analyze and evaluate alternative options for solving a policy problem. As such, policy analysis is an aid to planning and decision-making. Policy problems have existed since the beginning of human civilization. However, in our world of growing demands and complexity, the need for better structured approaches and more sophisticated methods and tools to deal with such problems has become more and more apparent. The exploitation and utilization of the world's resources to meet the ever increasing needs of a rapidly expanding population has truly affected the face of the earth. In many places, the occupation of space, the exploitation of water and land resources, and the productivity of natural systems have been pushed to the limit. A great variety of social, economic and administrative systems have come into effect with which to guide and control the production, consumption and distribution processes that 'make the world go round'. The strain on the overall system has become manifest in a great many social, economical, environmental, technical and political problems. Examples are:

- worldwide malnutrition and conditions of poor health;
- low per capita incomes;
- pollution of air, water and soil;
- disruption of ecological systems (deforestation, overfishing, land erosion, declining soil fertility);
- poor housing, public facilities and transportation systems;
- international conflicts regarding the use of water resources, ocean resources (fisheries), air pollution, waste dumping in international rivers, coastal waters and oceans.

These types of problems have a number of common characteristics, the most important being:

- a high degree of complexity, given the many social, economical, technical and administrative aspects involved;
- a great deal of uncertainty, both from the point of view of future developments, and limited knowledge about relationships and characteristics that determine the functioning of systems;
- many possible measures required to alleviate (parts of) the problem;
- a complicated decision-making structure.

In recent years, existing policy problems have highly stimulated the development of multi-disciplinary approaches to improve the quality of decision-making. An important factor in this process has undoubtedly been the increased awareness of the public, not only with respect to the nature and consequences of the actual problems, but also regarding the effectiveness (and non-effectiveness) of decison-making. Another important aspect has been the very rapid development in computational facilities, which has enabled creation of sophisticated computational techniques and the collection, processing and utilization of massive amounts of data.

2.2 *General approach*

2.2.1 *Outline and definitions*

In relation to policy analysis, the following key words apply: policy problem, scenarios, measures, strategies or policies, alternative options, evaluation, analysis, systematic process.

A policy problem is an existing or anticipated discrepancy between the actual and desired situation with respect to the status or functioning of a socio-economic and/or natural resource system. Note that several problems can (and in most instances will) occur simultaneously. Moreover, where problems do not exist in the present situation, if no actions are taken, they may arise in future, due to autonomous developments in e.g. population growth, changes to the physical environment or socio-economic developments. Observed or anticipated problems provide the triggers for the execution of a policy analysis in order to improve the situation.

Scenarios are defined as different sets of assumptions with respect to uncertain future developments or situations that affect the functioning of the system considered but are not determined by, or controlled within this system. Examples are meteorologic and hydrologic conditions, population growth, economic and technological developments.

A measure is a single, specific action that aims at solving, preventing or alleviating (parts of) a problem. An integrated set of measures is defined as a strategy or policy. Note that in most cases, various measures and strategies can be conceived of. Different strategies or policies that apply to the same policy problem are referred to as alternative options or alternatives.

An evaluation of alternative options is required to support planning and decision-making. The evaluation takes place on the basis of an analysis of alternative options and their impacts. A systematic process implies the execution of a well-conceived and logically structured sequence of steps from problem formulation to decision-making.

It should be emphasized that policy analysis is merely an aid to decision-makers for selecting a preferred policy from a number of, usually complex, alternatives under uncertain conditions. Policy analysis will certainly not replace the judgement of decision-makers, but it may improve the quality of decisions by ensuring a solid basis of quantitative information, provided by an organized and understandable analysis (Koudstaal & Pennekamp 1983).

Most policy problems the world is facing today deal with the planning for proper management of the socio-economic system in relation to its utilization of natural resources. The overall objective of such planning is to enhance the general well-being of people. Clearly, in this kind of planning, both the socio-economic structure of society and the natural resource system play a major role. Consequently, systems that are subjected to a policy analysis approach usually contain the following three main categories of elements.

1. Production activities like agriculture (food and non-food crops), fisheries (including aquaculture), livestock, forestry, mining, industry and tourism.

2. Natural resource system components and related natural phenomena, e.g. fresh and saline surface water bodies, groundwater, land, soils, minerals (both quantity and quality where relevant), and related problems like flooding, subsidence, pollution, etc.

3. Man-created facilities and institutions, e.g. capital and material inputs, facilities related to public water supply, energy generation and distribution, sewerage and water treatment, marketing systems, credit support, health care; water-related works and infrastructure; transport and storage related infrastructure; works related to land reclamation and coastal protection.

In order to produce goods and services, the production activities consume resources drawn from the natural resource system, and generate waste materials and other non-product outputs that may adversely affect the natural resource system. The man-created facilities and institutions include all physical and non-physical inputs of human origin required for the direct socio-economic needs, i.e. the production activities and control of production processes, the management of natural resources and the control of natural resource related problems. Measures to improve the situation would either change the available facilities (e.g. add infrastructure), or change the operation, management or control related to human facilities and activities.

The status or performance of the socio-economic and natural resource system is judged by expressing it in a number of socio-economic and environmental indicators or criteria, like: income per head and income distribution, gross national (or regional) product, balance of payment, public health, housing and education; state of aquatic and terrestrial ecosystems; quality of soils, water bodies and atmosphere; diversity and numbers of species. By comparing these indicators to a pre-specified set of requirements the extent of existing or future problems can be established, and the effects of potential strategies assessed.

A formalized approach to the above type of planning problem contains the following three elements:

- a conceptual framework;
- a computational framework;
- an information system.

These elements are described below.

2.2.2 *Conceptual framework*

The conceptual framework defines the procedure to be followed in the policy analysis. As such it outlines the analysis objectives, definitions and boundary conditions, the steps of analysis and the contents of each step, and the analytical approach and tools to be used in their execution. The conceptual framework distinguishes two phases (Koudstaal & Pennekamp 1983):

1. Setting Up The Analysis (SUTA);
2. Carrying Out The Analysis (COTA).

SUTA is a first round of analysis to prepare a detailed outline for the actual analysis (COTA). As such, it includes a first appraisal of system performance and related problems, leading to a specification of:

- problem statement and analysis objectives;
- system boundaries (areal boundaries, aspects to be considered, e.g. which production activities, natural resource system components and specific problems to take into account);
- time horizon and target years for planning;
- base year for price and cost levels;
- operational objectives and indicators (criteria);
- overview of approach and tools to be used;
- workplan for actual analysis.

The various steps in SUTA require a continuous interaction with decision-makers and other interest groups, see Figure 1.

The actual analysis (COTA) consists:

1. Estimation of present and future levels of relevant production activities;
2. Analysis of production activities (input-output relationships, price and cost structures, production values and potential production losses);
3. Analysis of natural resource system components and related problems;
4. Formulation and analysis of strategies;
5. Evaluation of strategies;
6. Presentation of results.

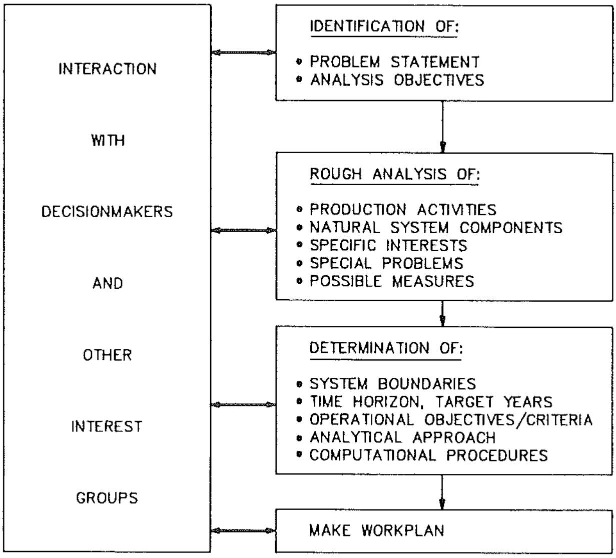

Figure 1. Steps in Setting Up The Analysis (SUTA).

The first three steps comprise the COTA preparation phase, involving model development and data collection, while the last three steps form what is referred to as the integration phase, involving the actual use of models and data and the interpretation of analysis results. The latter then feeds into the decision-making process, see Figure 2.

At least two important factors usually complicate the analysis of policy problems and their potential solutions. First, there is the element of time, that enters into the analysis in two different ways; (1) as a change in the demographic, environmental, technological, or institutional situation due to autonomous developments, e.g. affecting demand levels and system boundary conditions (to be expressed in scenarios); and (2) as a seasonal variation, introducing a stochastic element in both supply and demand patterns, and in the occurrence of certain natural phenomena, e.g. flooding. Second, there is the element of space, which complicates the matching of demands and supplies, and the prediction of the occurrence and effects of natural hazards, given the spatial variation of natural phenomena, resource locations and human facilities. The analysis of the performance of such a complex system under varying conditions determines the requirements for the computational framework.

2.2.3 *Computational framework*

The computational framework is defined as the whole of the mathematical models, analytical techniques and computational procedures that yields the quantitative information as it is required in the analysis underlying the

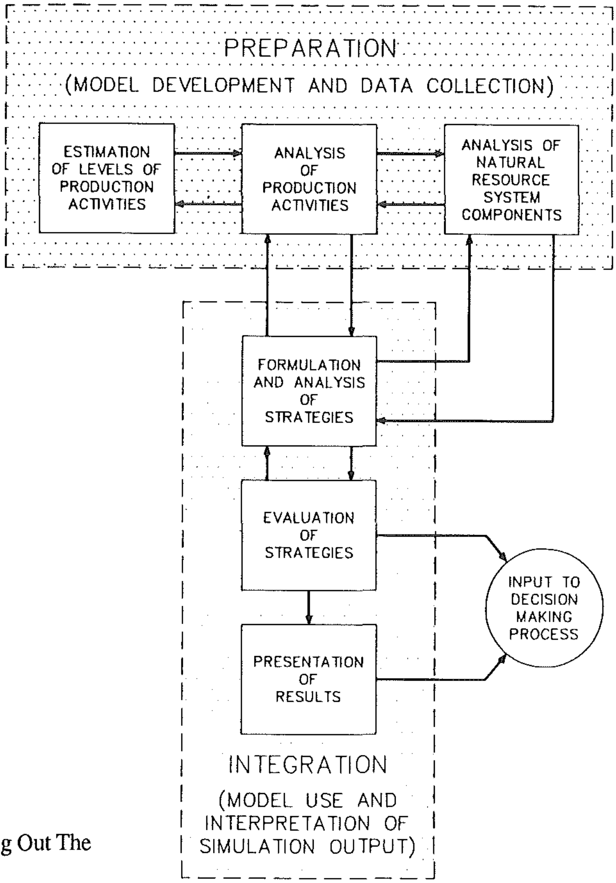

Figure 2. Steps in Carrying Out The Analysis (COTA).

evaluation and decision-making procedure. The term 'framework' indicates the fact that, in most instances, the various models and procedures do not stand by themselves, but form a structure in which the output of one model or computation may be the input for another.

2.2.4 *Information system*

The information system provides the required information that either feeds into the computational framework, or is used in the analysis and evaluation procedure directly. The information system may contain three major components: reference materials, the database for the computational framework and database related software. Reference materials include such things as books, photographs, maps, and records of field measurements or, in short, the non-computerized part of the information. The database is the computerized information, structured in a way to facilitate efficient use in the computational framework. Database related software includes the programs that support data management, such as, data organization, accessing, editing, plotting and printing of data, data generation and statistical analyses.

2.3 *Example problems and studies*

Policy analysis is undertaken to support planning and decision-making in connection with complex systems involving multiple, and usually conflicting, objectives. Consequently, the need for policy analysis may arise on various levels, and with respect to various types of policy problems. Examples of these policy levels are:

- project level: planning and decision-making regarding large infrastructural works, e.g. land reclamation projects, coastal protection schemes, barriers and closure works;
- sector level: water resources systems, energy supply systems, transportation systems;
- regional level: management and development of specific areas, e.g. coastal zone management, urban and rural development programs;
- national level: national programs regarding e.g food supply, housing programs, education, public health (diseases, safety from flood hazards).

During the last decade, the experience with policy analysis for these types of problems has gradually developed. A number of examples recently carried out in the Netherlands are briefly described below.

Policy analysis for flood protection Eastern Scheldt estuary

The policy analysis of the Eastern Scheldt aimed at selecting one of three major strategies to protect the estuary from floods (Goeller et al. 1977). The first option was to raise the existing dikes along the estuary, totalling a length of well over 100 kilometres. The second was to build a closure dam in the mouth of the estuary. The third was to build a storm surge barrier which would be closed by gates during storm surges, but would remain open under normal operation, thus preserving the unique tidal estuarine environment of the Eastern Scheldt. Many complicated effects were involved with the three alternatives. The policy analysis provided the basic information and many useful insights to support the decision-making. The Government finally decided to build the storm surge barrier, involving an investment of about Hfl. 6 billion, i.e. an equivalent of US $3 billion.

Policy analysis for coastal protection of the island Texel

The sandy North Sea coast of the Dutch Wadden Island Texel has been eroding during the last decades. In addition to safety from flooding, a number of other human interests, associated with the dune area, such as nature preservation, recreation (tourism), and groundwater extraction for the island's drinking water supply had to be taken into account. A policy analysis was carried out to evaluate the possibilities of coastal protection, taking into account all the relevant effects of such measures, both technically and in terms of the human interests at stake (Baarse & Rijsberman 1986). The analysis provided the information that enabled decision-makers to reach a consensus. Soon after completion of the analysis, it was decided to maintain the larger part of the island's coastline at its present position, involving an investment of at least 100 million Dutch guilders.

Policy analysis for water management of the Netherlands

The Policy Analysis of the Water Management of the Netherlands (PAWN) aimed at supporting the managment tasks of the Dutch Public Works Department with respect to the planning and operation of the national water resources system. Specifically, the study was intended to develop a methodology for assessing the multiple consequences of national water management policies, and to apply this methodology in generating and evaluating alternative policies (Goeller et al. 1983). The analysis included all important water users, like agriculture, horticulture, industry, drinking water supply, navigation, etc. Moreover it dealt with surface water and groundwater, water quantity and water quality. A great number of mathematical tools were developed in order to describe the behaviour of natural system components and to assess the impacts of alternative water management options on users and related interests. The information produced by the study led to the creation of a Policy Note, accepted in Parliament, and providing the outline for national water resources planning and decision-making in the next decade.

Management analysis for the North Sea

The Management Analysis of the North Sea (MANS) is a major policy analysis that has only recently started. It is primarily being carried out by the Dutch Public Works Department, supported by the other ministries involved with the North Sea. The study aims at providing a framework for analysis that will facilitate the evaluation of different policies with respect to the utilization of the North Sea. Such policies might include all possible uses of the sea, such as: navigation, fisheries, oil and gas mining, sand and gravel mining, waste disposal, recreation, etc. Specific attention will be paid to the functioning and stability of the natural system in the long term, in relation to the inputs of many types of residuals that enter the North Sea in various complicated ways. In addition to the state and characteristics of the natural system, the costs and benefits related to alternative uses wil be taken into account explicitly. It is anticipated that the study will provide a considerable amount of relevant information to support national and international planning and decision-making.

Given the nature and potential of policy analysis, and the results that were recently obtained in a number of different complicated fields of planning and decision-making, it is suggested that a similar approach would prove very useful in relation to the phenomenon of sea level rise. The following sections elaborate on this.

3 SEA LEVEL RISE AS A POLICY PROBLEM

3.1 *The nature of the problem*

A basic description of the nature of policy analysis and related policy problems was provided in the previous chapter. Considering some of the major characteristics and implications of sea level rise, many parallels can be easily identified. Some of the most relevant features of sea level rise that come to mind are:

- the overall importance of the problem (global nature);
- the many different interests and trade-offs to be taken into account;
- the variety of possible measures/strategies;
- the dynamics of the processes involved (natural and socio-economic);
- the complex decision-making structures;
- large uncertainties related to existing knowledge and future developments.

The overall importance of the problem immediately follows from the fact that an accelerated sea level rise will directly or indirectly affect almost all countries in the world. The major impact will be on the coastal zones, which are in general characterized by low-lying, flat, fertile and densely populated areas. Important effects are also anticipated on shallow coastal waters and estuaries which are usually extremely productive areas, performing a key role in the world's food supply. As a result, the extent and consequences of possible impacts may be of immense proportions.

As sea level rise may change the spatial dimensions and physical appearance of man's living environment, it bears upon all human interests associated with the functions and values of this environment, e.g. housing, food production, industrial production, infrastructural and other man-made facilities, ecological performance, etc. The minimization of harmful effects may bring about a variety of trade-offs, which will usually involve investment patterns on the one hand, and all kinds of socio-economic and environmental effects on the other (loss of facilities and captital goods, food production capacity, safety, disruption of natural systems, etc.). One of the implications is that the problem and its effects need to be studied by a multidisciplinary team, including, amongst others, physical scientists, economists, ecologists, civil engineers and sociologists.

In general a large variety of possible measures/strategies can be conceived of. In terms of coastal defence options, many possibilities emerge when taking into account the specifications of e.g. type of structure, location, materials used, dimensions, phasing in time, etc. The same is true when considering options related to a change of land use, or remedial measures to reduce some of the adverse effects with respect to for example water management, salinization, port structures and operations. Clearly, numerous combinations of such meaures might be prepared.

The complexity of the analysis is further emphasized by the dynamics of the processes involved. This holds for the response of natural systems and processes, like the ecological system or morphological processes, but also for the response of people in general (households) and specific interest groups such as owners of threatened land and facilities (farmers, industries), people that are to be resettled, nature conservancy groups, etc.

The decision-making structures will typically be complex. The problem of sea level rise will touch upon all governmental levels and all different departments, and is likely to activate many interest groups. It also involves international aspects (mostly from the viewpoint of developing common approaches and sharing information). An important complication emerges from the fact that decision-makers in general tend to have a relatively short term view, which is clearly inadequate for the kind of problems and solutions to be considered here.

The problem of sea level rise is surrounded by uncertainty. One reason is the lack of knowledge about many of the complex processes related to the causes and effects of sea level rise. Another has to do with the uncertainty in future developments. The nature of the problem requires the introduction of a relatively long time horizon. This, in turn introduces large uncertainties about future developments, not only with respect to the phenomenon of sea level rise itself, but also regarding other natural conditions, demographic developments, socio-economic developments (activity levels, income situation), land use, etc.

Obviously, the problem of sea level rise requires a well structured approach that fits the above characteristics and needs. It is felt that the concept of policy analysis will meet these requirements.

3.2 *Key elements of the approach*

According to the definition provided in the previous chapter, a policy analysis of the problem of sea level rise would basically aim at providing an overview of the relevant effects of alternative strategies in support of decision-making. The key elements are:

- relevant effects;
- alternative strategies;
- decision-making.

In order to explore the implications and possibilities of a policy analysis appproach to the problem of sea level rise, each of these elements are described below in some detail.

3.2.1 *Relevant effects*

Sea level rise will have different impacts on different types of areas. It is therefore useful to distinguish the following different zones:

- seas and oceans;
- estuaries, lagoons, delta areas and tidal wetlands;
- shoreline;
- lower rivers;
- land areas.

Seas and oceans. Seas and oceans are arbitrarily defined as the offshore area beyond the 3 metres depth contour. In fact, this artificial boundary only serves to separate the various kinds of nearshore shallow water bodies. The expected effects on seas and oceans proper are limited. Offshore drilling platforms and related structures may be adversely affected by increasing water levels, but no substantial effects are anticipated within the normal lifespan of such structures, given the present estimates of maximum sea level rise which generally are within a few metres up to the year 2100 (Hoffman et al. 1983, Thomas 1986, Titus 1987). A possible effect may occur on tidal ranges and wave climates. Because of the variation in local conditions, no general statement can be made in this respect. Off hand this does not appear to be a very important effect. Navigation will generally be affected in a positive sense, if at all. A negative effect might occur if siltation of shipping routes increases, because of changes in sedimentation and erosion patterns. Again this will very much depend on local conditions, however.

Estuaries, lagoons, delta areas and tidal wetlands. All of these areas belong to shallow coastal waters, usually characterized by an intensive tidal influence, a high turbidity and productivity, and a high degree of human activity (fisheries, navigation, recreation, waste dumping). Also from an environmental and ecological point of view, the most valuable areas are often found in the nearshore shallow waters (coral reefs, mangroves, tidal wetlands).

The main potential effect of sea level rise in the shallow coastal waters is the increase of water depth. If an increase of water depth is actually realized, the consequences may be dramatic. Intertidal zones may be lost and mangroves may disappear. The physical and morphological boundary conditions of shallow waters may change considerably, affecting the functioning of ecological systems. In turn, this may cause the loss of environmental values, such as bird life, fish spawning and nursery grounds, fish and shellfish production.

The increase of water depth cannot be taken for a fact, however. Depending on local sedimentation and erosion patterns, and on factors determining vegetation growth, it is conceivable that bottom levels will be able to keep up with rising water levels. This has been proved in the Mississippi Delta which has been exposed to a relative sea level rise of 1 cm/year caused by subsidence (Day 1987). If no dikes are present, the loss of intertidal areas may be compensated by inland expansion, although the odds are that losses exceed gains (Titus et al. 1984). Also, the compensation of intertidal area will be at the expense of former land areas.

So in general, the effects on shallow coastal waters are strongly determined by local circumstances, and a good understanding of the physical and biological processes is required to make any predictions in this respect. But if the accretion of bottom levels cannot keep up with rising waters and inland expansion of intertidal area is not possible (because of dikes or a steeply rising coast) major effects are to be expected.

Shoreline. The shoreline is the shallow zone between water and land and is primarily considered in its function of protecting the land from the sea. A number of different types of shoreline can be distinguished.

Unprotected coasts will be confronted with a gradual loss of land, the rate of which is determined by the rate of sea level rise and the landward slope. Risks of flooding for landward areas will increase.

Natural sandy coasts will be subject to (increased) erosion. As the equilibrium beach profile will follow rising water levels, the shoreline will ultimately retreat in inverse proportion to the submerged slope (Bruun 1962). As a result dune areas will be lost and safety from flooding will be reduced, unless costly measures are taken to maintain a body of sand of sufficient dimensions at a fixed position, e.g. by artificial sandfills.

Hard coasts which serve as a man-made protection against flooding will face a more severe wave attack as the energy reduction on the shallow nearshore decreases with rising water levels. Increased erosion may undermine hard structures like dikes, dams, groynes and sea walls, leading to high maintenance costs. Probabilities of dike failures by overtopping will rapidly increase with a rising sea level (Goemans 1987). Several structures and infrastructural facilities located on the shoreline may have to be adjusted at considerable cost, e.g. breakwaters, quays, terminal areas, industrial complexes, docks, sluices, etc.

Natural hard coasts of sufficient elevation, like the Norwegian fjords, will not be affected in any way.

Lower rivers. Backwater effects will cause the lower river water levels to rise with rising sea level. This could have immediate effects on certain river-related infrastructural facilities like bridges (reduced clearance), locks and sluices, port structures, quays, embankments and river training works. The safety from flooding will be reduced. The increased water depth in the lower river may enhance salinity intrusion, although the river bottom will gradually follow the river water level, depending on river sediment flows (Hull & Titus 1986). The increased salinization may affect the quality of intake water for drinking water, industrial use and irrigation. A rise of the river bed level may affect the capacity of intake structures.

Land areas. Basically, two major types of direct effects may occur. First, there can be an actual loss of land in cases where the natural, unprotected shoreline retreats, and where land has been used as a site for coastal or lower river protection systems. Second, the risk of flooding will increase. In both cases, the (potential) effects are related to all production functions and human facilities that are present in the affected or threatened zone, e.g. agriculture, industry, housing, infrastructure, etc.

In additon, a number of indirect effects may emerge. Sea level rise increases the head difference between the sea and the fresh water bodies in low-lying coastal plains (below sea level). Saline seepage will be the result which may affect both the secondary and tertiary surface water system and groundwater aquifers. This almost certainly would be harmful to the natural environment and to water users drawing upon affected surface and groundwater bodies (agriculture, drinking water, industry). Higher water levels in lower rivers and coastal waters may affect the drainage capacity of adjacent land areas, which again may cause damage to production activities (e.g. agriculture) and facilities such as roads and buildings (Kuo n.d.).

These effects, brought about by different processes in different zones, can be translated into a number of main categories, for example:

- economic effects (property and production losses, cost of remedial measures);
- public health (safety, diseases, availability of food supplies);
- environmental/ecological (loss of nature areas, disruption of ecological systems);
- social (unemployment, resettlement, loss of public utilities);
- administrative (legal problems, competence and jurisdiction, administrative boundaries).

The analysis of impacts should focus on providing information according to the above categories in order to actually facilitate the planning and decision-making process.

3.2.2 *Alternative strategies*

In principle, three main strategies can be distinguished:

1. Reduce/prevent sea level rise;
2. Prevent land losses by coastal defence and reduce impacts of sea level rise by remedial measures;

3. (Selective) retreat (in relation to land use planning options).

Within each of these main strategies several individual measures can be identified. Actual strategies can of course contain elements of all three.

Achieving a reduction of sea level rise would involve measures to reduce the production of CO_2 and other greenhouse gases. In order to predict the effects of these kind of measures, a thorough understanding would be required of the processes involved and their dynamics, time scales and irreversibility. The measures would have to be applied on a global level in order to be (potentially) effective.

In the approach outlined here no explicit attention is given to the analysis of the causes of sea level rise and the potential measures to reduce it. Sea level rise results from a number of physical processes that are related to increasing global temperatures. However, the actual causes and the relative contribution of different processes are still not really understood, and estimates of expected future sea level rise vary widely (Hoffman et al. 1983, Thomas 1986, Titus 1987). Hence there is at present no strong basis for including the phenomenon of sea level rise proper in a policy analysis. Strong indications exist however, that severe problems may occur in the next centuries. Therefore, for the purpose of the analysis, it is assumed that a substantial sea level rise in fact will occur. The potential benefits of sea level rise reduction measures could be evaluated from the difference in negative effects that would result in simulations with different sea level rise scenarios.

A strategy based on preventing or eliminating the loss of land and other negative impacts of sea level rise could include, for example:

- the protection of existing land by building or improving coastal defences; for this there are numerous options involving types of protection (dikes, dunes), dimensions (height, width, slopes), constructional aspects (materials), position and location of protection, and the phasing in time of implementing flood protection measures;
- infrastructural measures related to water resources management, drainage facilities, reduction of salinity intrusion;
- infrastructural measures related to navigation and ports (e.g. breakwaters, quays, terminal areas, transportation systems, etc.).

A strategy based on (selective) retreat and adjusted land use planning could contain measures related to:

- zoning and land use planning (relocation of human activities in time and space);
- resettlement programs;
- compensatory measures (subsidies, reimbursement);
- rebuilding of human facilities and infrastructure;
- cultivation of 'unused' areas (mountain land, deserts, forests).

3.2.3 *Decision-making*

The analysis should facilitate the decision-making process, i.e. the information produced should be useful to decision-makers. At least three implications follow from this. First, the information should be easily understood and interpreted. Second, the information should be complete, or at least should take into account all important aspects that are relevant for the desision-making process. Third, the results of the analysis should be acceptable to the decison-makers.

To meet the first requirement, the information collected and computed should be expressed in logical and meaningful units and be presented in a way that can be comprehended by decision-makers. Well-structured tables or graphs, provided with adequate explanation, will serve this purpose. It is important that only a limited amount of information is provided at any one time.

To satisfy the second requirement no information that may be relevant in the decision-making process should be omitted, even if the assessment of certain effects is only qualitative. As uncertainty usually plays a major role, the risks of being wrong should be taken into account explicitly in presenting the effects of alternative options. In addition, the information presented should take into account the most relevant trade-offs between e.g. costs, environmental effects, safety, housing conditions, food supply and income situation.

The acceptability of the results can be greatly enhanced by being very explicit about the way the impacts were assessed, i.e. a clear insight should be provided into e.g. the system assumptions and scenarios used, data sources and data processing procedures, mathematical models and computational techniques, calibration and verification procedures.

4 FUNCTIONS AND REQUIREMENTS OF A MODELLING APPROACH

A policy analysis aims at providing information to support decision-making. Such information pertains to the effects or impacts of alternative strategies or policies. Evaluation and decision-making are based on a comparison of such effects and for ease and clarity, the effects of alternative strategies should be expressed quantitatively, to the extent possible.

A comparison of actual numbers really provides the decision-maker with a clear insight into the relative effects on important impact categories, of one strategy next to another. It allows the decision-maker to consider different combinations of measures and strategies to suit his set of value judgements; it also allows him to make very explicit trade-offs against different types of impacts. For example, it may be useful to know that both Strategies A and B are better than Strategy C from the viewpoint of nature preservation. It is far more useful to know that strategy A affects x hectares of a nature preservation area that is classified as 'most valuable', while strategy B affects y hectares of an area classified as 'valuable'. This kind of information would, under certain conditions, be suitable for helping to decide between A or B. An even more straightforward situation could be created if the value of a hectare of different nature preservation areas could be expressed quantitatively. The preference for one strategy versus another with respect to the impact category 'nature' could then be determined simply on the basis of cost computations.

Conceptually, it is only a small step further to a situation in which all relevant effects are expressed quantitatively. The fact that one strategy compared to another might be this much better with respect to impact one, and that much worse with respect to impact two, now introduces the possibility to make actual trade-offs.

The above illustrates the usefulness of being able to quantify different types of effects. However, it should be realized that the quantification of effects may have severe limitations. In certain situations, these limitations are such that an actual quantification would be no longer useful in the evaluation process. This may be the case if the quantitative assessment is either uncertain, unreliable or even unrealistic. Another potential problem in this respect is that the desire to quantify effects may limit the scope of the analysis beyond reality, e.g. in case effects that cannot be quantified are simply omitted. But even if such effects are brought to the attention in a qualitative way, there is still the risk of overemphasis of the 'hard' facts.

The conclusion is that a quantification of impacts is inevitable to actually support the decision-making process in complex problem fields. Yet, one should not so much follow a simple quantitative approach, but rather an approach that aims at providing a complete and unbiased overview of all possible consequences of alternative strategies. A sound policy analysis should therefore take into account the following rules:

1. Boundary conditions, starting points and systems assumptions should be stated explicitly;
2. A complete overview of relevant effects, whether quantified or not should be provided;
3. An adequate insight in the consequences of major uncertainties should be provided by applying sensitivity analysis and/or using scenarios.

A computational framework will be very suitable for generating the quantitative information required about the problem of sea level rise, provided that the above rules are taken into account. The main functions of such a computational framework, referred to in the following chapters as 'the ISOS model', are:

- to integrate and confront with each other, the results of detailed studies on the specific effects of sea level rise in order to detect inconsistencies and/or the need for additional information;

– to investigate the effects of specific individual measures taken to prevent sea level rise, reduce damage resulting from sea level rise, or alleviate the negative effects of sea level rise in order to 'design' these measures in such a way as to generate maximum beneficial effect at minimum cost;

– to analyse the effects of uncertainty in the various components of the analysis, with respect to the causes and effects of sea level rise itself, and to the effects of measures, mainly through the analysis of a set of thoughtfully constructed scenarios;

– to evaluate a set of alternative strategies to deal with sea level rise, for a given study area and time horizon, in order to generate information that can be used by decision-makers for selecting the most appropriate strategy for implementation.

In view of the nature of the problem and related phenomena, and the objectives listed above, the ISOS model should meet a number of different requirements. The most important requirements are outlined below.

– The model should provide an overview of all relevant impacts of sea level rise (economic, public health, environmental/ecological, social, and administrative or institutional) in all relevant zones (seas and oceans, estuaries/wetlands, shoreline, lower rivers, and land) over the adopted time horizon. In other words, the model should have a multidisciplinary set-up, and should take into account spatial and temporal effects.

– The model will serve as a tool for improving communication between disciplines. This means that differences in the nature of the impact assessment for the various sectors, for example, a quantitative versus a more qualititative approach, and differences in accuracy, will have to be dealt with appropriately.

– The model should facilitate interaction between decision-makers. To do this the model should be used interactively in a conversational mode, easy to use by non-experts and the results should be produced in comprehensive overviews, e.g. in summary tables and graphs.

– The model should be able to produce results which reflect the costs and effects of possible measures or strategies and to take into account relevant scenarios, e.g. those related to the extent of sea level rise, economic developments.

– The model should be able to deal with trade-offs in time, that is investments made beforehand to anticipate in time on future problems, given time delays.

Obviously, it will not be possible to quantify all relevant impacts such as the effects on public health or on the environment. On the other hand, the rationale of a policy analysis is that it is helpful to decision-makers in that it provides as much quantified and properly organized information as is reasonably possible. This affects the design of the ISOS model in a major way. It implies that the model will be based on a mix of quantitative and qualitative information, and that the final results or outputs of the model will have to be in the form of tables or graphs that summarize a set of effects rather a single number or ranking.

It is clear that the relationships between the processes, phenomena and effects involved are, in most instances, of a quite complex nature. If a more or less detailed description of these relationships, if at all available, would be included in the model while at the same time meeting the above requirements, the model would probably grow beyond proportion and become unmanageable. Therefore, the ISOS model described here should be considered as a simplified 'overview' model in which each equation or parameter reflects the result of a more sophisticated model, a more detailed analysis, expert knowledge or good judgement. As such, the 'ideal' ISOS model would ideally contain all the available knowledge about all relevant aspects in a highly condensed and simplified form. It could then be used and understood by the people actively involved in (the preparation of) decision-making.

The structure and use of a model that will meet the requirements outlined above are dicussed in the following sections.

5 THE ISOS MODEL-THEORY

A model for the quantitative evaluation of the impacts of sea level rise on society is outlined in this section. This model is referred to as the ISOS model and should be considered as an ideal, state-of-the art, version in the sense that it could be produced if there were no limits to the availability of time or money. In the opinion of the authors, however, such a model is technically feasible, i.e. the required data and knowledge exist at least for certain geographic locations. This model is envisaged as the successor to the simplified, illustrative model version described in the section hereafter.

The basic structure and components of the 'ideal' ISOS model, and the implementation and use are discussed below.

5.1 *Model structure and components*

The main components of the 'ideal' ISOS model are:
- sea level rise;
- impact area;
- impact mechanisms;
- measures;
- effects.

These components, and their main interactions are shown in the simplified

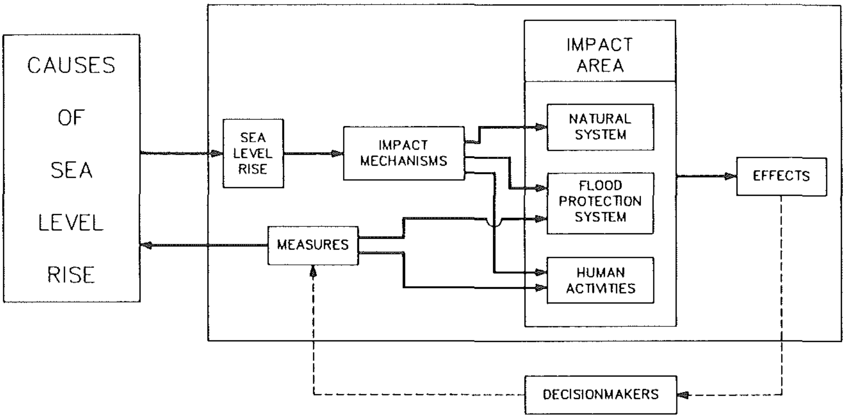

Figure 3. Main components in the ISOS model.

diagram of Figure 3. As was explained in Section 3.2.2, the causes of sea level rise are not included in the model, i.e. they are outside – or exogenous to – the model. Consequently, the extent of the sea level rise has to be included as a scenario variable. Through various so-called impact mechanisms sea level rise affects the impact area, consisting of a number of different zones (like estuaries, shoreline, land etc.), basically containing the impact categories: natural system, flood protection system and human activities. The effects of sea level rise, as perceived by the decision-makers, give rise to measures which, in turn, influence either the causes of sea level rise, the protection against floods, or the human activities.

The above-mentioned model components are described in more detail below. Before embarking on this task, however, it is important to point out that this ideal model is not envisaged as an all-inclusive 'super' model. Even in its final form the model would largely consist of a number of repro-functions which represent the main impact mechanisms, based on more in-depth research, and possibly more sophisticated modelling, of that particular aspect. This is closely related to the functions of the model as a tool for policy analysis, as outlined in Section 4.

5.1.1 *Sea level rise*

Sea level rise, the cause of the impacts under consideration, is included in the model as a scenario variable, i.e. a number of the most likely possible developments of the mean sea level over time are assumed in, for instance, high, low and in-between scenarios. The assumed developments are based on other studies. The modelling of the causes of sea level rise directly should not be attempted because of the complexity involved and the fact that the mechanisms are insufficiently known. The amount of sea level rise to be considered in the model at any time during the simulation should be based on at least two components: an isostatic rise, which is a linear trend due to geophysical causes, and a rise caused by other effects such as thermal expansion of ocean water and melting of polar ice masses. The latter component would be expressed in the model in a functional relationship over time, the characteristics of which would be based on more specific research. The value of this function at a specified time horizon, e.g. after 100 years, is then the scenario variable to be used in the model.

The sea level rise is the main independent variable in the model. Most other effects are a direct function of the increase in sea level. For the Netherlands it can be assumed that even relatively large changes in mean sea level would not affect tidal motion or wind wave action significantly. Consequently, a model for the Netherlands would only account for the change in mean sea level. This may be different in other areas, however, in these cases the changes in tidal motion and wave pattern should be included in the model.

5.1.2 *Impact area*

The impact area, broken down into a number of impact categories, constitutes a major part of the model. The most important effects are related to the following impact categories.

a) The natural system, relevant in all zones, but particularly in the estuaries, lagoons, delta areas and tidal wetlands. The major characteristics should be brought into the model through careful and detailed studies that provide an inventory and description of the existing ecosystems, their vulnerability and their relative value in terms of quality, rarity, etc.

b) The protection against flooding, mainly along the shoreline but also along the lower rivers, in terms of present topography and landforms, natural barriers and infrastructural facilities, their dimensions, physical characteristics, structural stability and frequency of overtopping.

c) The human activities and facilities, also present in all zones, but mainly on land, in terms of invested capital, number of people involved, nature and quantity of goods and services produced, location and land occupation, sensitivity to flooding, ease of relocation, etc.

These categories represent the main elements of the system that is impacted by sea level rise.

5.1.3 *Impact mechanisms*

The actual heart of the model, and also the most complicated part, is the set of mechanisms through which sea level rise impacts the various system components. These impact mechanisms are described in some detail for each of the zones that are taken into account, see Section 3.

For the sea and oceans, only few, if any, impacts can be imagined that lend themselves to a systematic description. For this reason this zone is not included in the remainder of the model discussion.

The zone consisting of estuaries, lagoons, delta areas and tidal wetlands, is in a constant state of change as a result of very complex physical, chemical and biological processes involving e.g. waves, tidal motion and currents, transport and influxes of sediments and various substances, and production of organic material, etc. The balances of sediment and organic material in this zone should be described in detail on the basis of hydrodynamic, morphological, and biological modelling in order to determine the resulting effects of sea level rise on the physical and biological characteristics of the system.

Models already exist for the physical and some of the biological processes, and the necessary data appear to be available for some areas such as the Netherlands, and presumably can be obtained for other areas. These kinds of models are quite sophisticated however, and require considerable work for each particular area and sea level rise scenario. The results of detailed studies, in terms of functional relationships between sea level rise and e.g. changes in water depth, bottom level, intertidal area, etc., form the impact mechanism of sea level rise on this zone.

The ultimate effects of these physical changes on the natural system are much harder to determine. It is expected that environmental/ecological effects, which are of crucial importance particularly in this zone, will be hard or impossible to quantify. In such cases the analysis emphasizes the characteristics of the affected area, its sensitivity to change, and the amount of change expected. It can be determined, for instance, whether a certain area consists of ecosystems that are considered to be of national (park) importance – as determined by environmental specialists' expert judgement – whether this ecosystem is vulnerable to change, and whether the expected changes in the physical system are likely to result in major changes in the ecosystem.

A more easily determined effect of changes in the physical system may be that on the depth of navigation channels to ports and harbours as a result of possible changes in the sediment budget. Changes in depth and steepness would, in theory at least, change the flux of sediment along the coast which could affect the amount of dredging required to maintain water depth in the navigation channels.

The shoreline zone can be more readily analysed quantitatively. Similar hydrodynamic and morphological models to those used in the nearshore area would yield the changes in the physical system. The effects of these changes are determined by the characteristics of the shoreline and its coastal protection system (if present). The question whether the coast is 'hard' or 'soft' plays a major role in this respect.

For a sandy or muddy coast the impact mechanisms to be considered relate to the area of land that would be flooded as a result of sea level rise, the increase in erosion, and the increased flood risk for the land behind the dune areas. For a hard coast – typified by a sea dike – the analysis concentrates on the structural safety of the dike and the increased risk of overtopping. These relationships can all be quantified in specific studies, however, and can be used as an input for the ISOS model.

A separate analysis would be required for the effects on ports and harbours located in the shoreline zone. Although such effects would very much depend on local circumstances, it is expected that they could be quantified given sufficient time and financial resources.

An analysis similar to that for the shoreline zone would have to be conducted to determine the impact mechanisms for lower rivers. The parameters in this analysis would take into account the effects on structures such as bridges and sluices, and the safety against flooding provided by river dikes.

A final zone, which is likely to create both really interesting and really complicated problems for the analysis, is the land area. The main impact mechanism at stake here is, of course, flooding which can have a number of significantly different impacts on the various human activities that occupy the land. In addition, there are other impact mechanisms such as increased salt intrusion, decreased drainage, and other effects in connection to water resources management. The two main impacts related to flooding are: (1) land lost permanently, as in the case of a soft, unprotected coastline, or a defended coast that is given up; and (2) land with an increased flood frequency. Such variables can be readily quantified. Problems in the analysis arise, however, because of the complexity of the effects of flooding, ranging from loss of human life, damage to structures and transportation systems, crop damage, damage to the natural environment, and disruption of economic activities (even in areas far removed from, but depending on, the areas flooded).

The above kinds of impacts enter into a complicated web of interrelated, socio-economic factors, particularly in a highly developed, and densely populated country like the Netherlands. A proper impact analysis should also include the distribution of effects across income groups in the population (e.g. as a result of differences in the capacity to recover from flooding effects through available capital) and the distribution of effects across regions (e.g. if one region benefits from the flooding of another by taking over some of its economic activities).

In principle, the analysis of the land-related impacts can be carried out at various levels of detail and aggregation, depending on, among other things, the availability of time and financial resources. It is fairly obvious, however, that due to the importance of spatial effects some form of a two-dimensional horizontal model will inevitably have to be used, for instance one based on a grid system, to describe the impacts of sea level rise on the various land activities. An impression of what such a grid system may look like is presented in Figure 4. Data base systems such as Geographic Information Systems – now available at reasonable prices for microcomputer applications

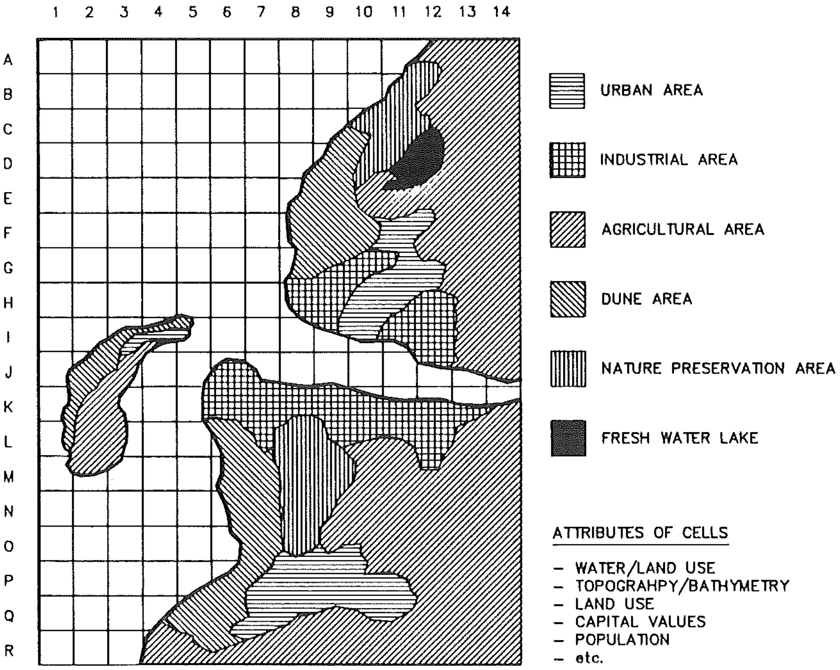

Figure 4. Example of a grid system as a basis to organize geographical model input and output data.

– would be valuable tools for setting up and organizing the flow of input and output data for the model.

5.1.4 *Measures*

Theoretically the measures considered in the model could include ways of affecting the causes of sea level rise. In view of the difficulties in quantifying these causes (the reason why sea level rise itself is a scenario variable), such measures are not taken into account, however.

In the zone of estuaries, lagoons, deltas or tidal wetlands sea level rise will become manifest by gradual flooding of dryland areas. Apart from local interfering in this process such as embankment construction, practically no large scale measures are possible to counteract this landward shifting of the tidal area. However, it might be quite desirable to maintain tidal areas from the environmental/ecological point, in which case such a migration process should be allowed for. Another possible measure to be considered in the coastal zone in specific cases where it turns out to be relevant is the dredging of navigation channels.

One major class of potential measures is that related to flood protection and coastal defence. This includes a long list of options ranging from beach nourishment, through groynes and other minor structures to full-fledged sea dikes requiring major national investments. Which is most appropriate for a particular stretch of coast depends on the local conditions, local expertise, and available building materials. The best technical solution to achieve a desired safety standard at a given sea level, together with an estimate of its cost and frequency of overtopping, would be determined in a separate analysis and be an input to the model.

Another major class of potential measures is that related to changes in locations of activities and land use. This includes anything from a general retreat, abandoning large threatened areas to the sea, to a subtle and complicated re-arranging of activities so as to move highly flood-sensitive activities to less flood prone areas. It might be sensible, for instance, to move residential areas and highly capital intensive industries further inland, while locating 'wilderness' areas, national parks, and extensive agriculture further seaward. What complicates most of these possible measures is the long time lag involved, the resistance of social groups and institutional organizations against change, and the political complications if the land use changes proposed involve different administrative jurisdictions across provinces or even countries.

5.1.5 *Effects*

Once a model has been developed, it would be possible to show the effects of sea level rise if no action were taken other than the continuation of the policies in effect at present (the base case), the effects of individual measures, and the effects of complete policies or strategies. In each case the effects should be expressed in monetary terms as much as possible. These effects could include:

- direct capital loss as a result of flooding through damage to buildings, infrastructure, and for instance, agricultural crops;
- direct and indirect economic losses as a result of disruption of economic activities;
- imputed values of loss of recreational opportunities as a result of damages to natural areas and beaches;
- costs of measures to prevent or reduce damages from sea level rise, or to alleviate damage.

Similarly there will be major effects for which it is not possible to indicate monetary values, but for which there may be at least quantitative estimates, such as:

- loss of life;
- nature areas lost or affected;
- reduction in safety standards against flooding;
- impacts on employment levels.

Effects that cannot be expressed in monetary terms but which can be quantified, would be calculated in the model and shown along with the monetary effects in the summary tables and graphs that form the model output.

There will still remain, however, effects which cannot be quantified; these include, for example:

- value of loss of life,
- importance of changes to ecosystems,
- administrative and institutional costs.

5.2 *Model implementation and use*

The objective of the policy analysis approach described here is to provide information for decision-making. The analysis is – to use an expression from business management – part of a Decision Support System. Several types of problems, and associated Decision Support Systems, can be identified. The most straightforward are the structured problems, defined as problems that can be solved based on quantitative data. In policy analysis type problems one usually deals with unstructured problems. Unstructured problems are defined as those problems that require intuition and judgement for their solution, in addition to data.

There are many examples of policy analyses which attempt to ignore the unstructured character of the problem field, and used a purely mathematical (e.g. optimization) approach. Such approaches usually require many simplifying schematizations and assumptions, and often lack appropriate possibilities to reflect the decision-maker's judgement. Consequently, for many practical problems, this type of approach has not been very successful.

The approach advocated here is to explicitly account for the unstructured character of the problem. This means that the decision-maker has to be an actor in the Decision Support System. The policy analyst does not attempt to identify the optimal solution, but provides information for the decision-maker in an interactive setting. This allows for the use of qualitative information such as the experience, intuition and judgement of the decision-maker. The approach is far from sophisticated mathematical modelling which attempts to isolate the maximum possible amount of information in mathematical relationships in order to identify optimal decisions without further human intervention.

Modelling for Decision Support Systems is characterized by (Horsey 1986):

- incorporation of the decision-maker in the analysis;
- adaptability and flexibility in response to changes in decision or data structures;
- focus on ease of use in interactive mode for those less familiar with the computer;

– information management emphasizing the creative use of formats, contexts and media for use of information in the analysis.

Three stages can be distinguished when providing information for decision-making (Rijsberman 1987):

1. Data base management, characterized by conclusions and decisions inferred directly from the raw data, based largely on empirical experience rather than modelling;
2. System component modelling, in which data base management is combined with quantitative analysis of relationships in parts of the system, but where decisions still have to be largely based on experience and judgement,
3. Integrated decision support systems which combine the data base management and the component models in a coherent integrated framework which incorporates the decision-maker and in which all available information is pooled and analyzed interactively for maximum support to the decision-maker.

A most suitable technique that is now available is the use of spreadsheets. Spreadsheets were developed for decision support system applications in business and finance, and have been extremely successful. As a result, spreadsheets are among the most popular business software packages on the market for micro computers. Because of spreadsheets many individuals without programming or computer experience, particularly managers, are able to do their own modelling.

Scientists and policy analysts have generally not appreciated the full potential of spreadsheets. There are many books on spreadsheet applications, but only very recently have engineering and similar applications begun to appear.

Spreadsheets also have excellent capabilities for the decision support type models because they are:

– flexible and easy to use in developing models, compared with programming languages such as BASIC or FORTRAN;

– user-friendly, i.e. models are easily developed for specific use by non-computerexperts;

– very useful for developing data management systems and user interfaces for presentation of results in graphic and summary report form;

– more simply debugged than e.g. FORTRAN, even though large and ill-designed spreadsheets can easily become cumbersome;

– all intermediate calculations are available for checking errors.

An example of the advantage of the use of spreadsheets in a decision support is the following. During the summer of 1985 a model was developed by Rijsberman and Grigg for the operation of a water supply system. This model was based on an earlier version of the same concepts (Grigg & Bryson 1975), applied from Forrester type dynamic modelling. The earlier model in BASIC was unsuccessful – even though it produced proper numbers – because it was very inaccessible and did not have a good user interface. As a result of the inaccessibility of the model, the intended use, namely, interactive modelling with decision-makers, was never realized. However, this same model in a spreadsheet application was shown to be a better tool for interaction with non-experts, as was verified in a meeting with the managers of the Fort Collins Water Supply Department – whose data were used to set up the model.

In addition to being a very useful technique for the development of interactive, decision support oriented models, spreadsheets are also used to link other, more complicated models. Spreadsheets can provide front and back ends for some models that are not very user-friendly, that is, they can be used to:

- prepare input files for other models that require large tables of numbers in a specific format;
- process output data from other models into more accessible and informative tables and summaries;
- produce graphs based on the output from other models.

6 THE ISOS MODEL-APPLICATION

This section describes the illustrative model that was developed for the ISOS workshop held at Delft Hydraulics in August 1986. The model contrasts with that outlined in the previous section which could be developed given sufficient time and financial resources. The main purpose of this illustrative model was to demonstrate the type of model that could be developed, and to initiate the discussion among the experts of various disciplines involved in the workshop.

Section 6.1 below describes the set-up of the illustrative model in some detail. Section 6.2 deals with some aspects of its use, and Section 6.3 briefly describes its application for the Netherlands.

6.1 *Set-up of the model*

6.1.1 *General*

The model enables the user to assess a number of impacts of sea level rise on society, within the framework of a selected scenario consisting of the following elements: rate of sea level rise, economic (capital) growth rate, population growth rate and social discount rate. The model is also capable of showing the effects of certain measures that can be taken to counteract the negative effects of sea level rise.

The model simulates the situation in a specific country or geographic

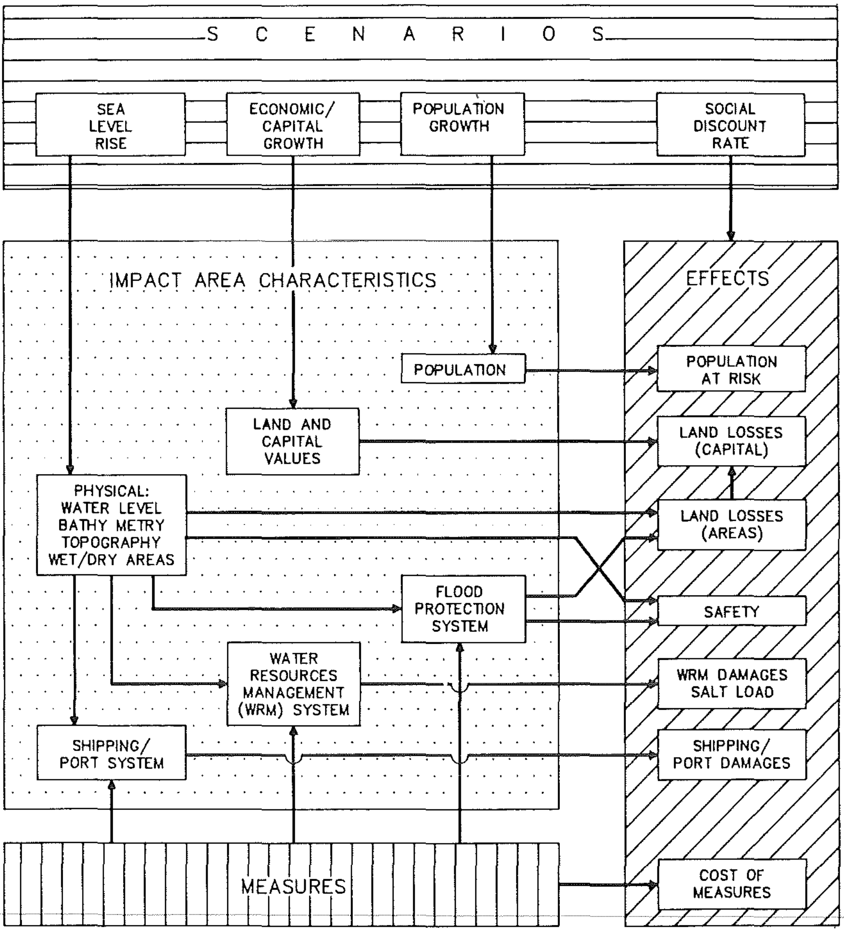

Figure 5. Simplified ISOS system diagram.

region. Each country or region to be analyzed may be subdivided into three different segments. Input data can be specified for each of these segments separately to reflect major differences in the characteristics of the area under study. The model simulates a period of 100 years in discrete timesteps of 5 years.

The main components and relationships contained in the illustrative model are shown in the diagram in Figure 5. In this diagram, the following major blocks have been distinguished:

- scenarios;
- impact area characteristics;
- measures;
- effects.

The arrows going in and out the impact area block reflect the various impact mechanisms as they were considered in the model. Each of the major blocks and the most important impact mechanisms are considered below.

6.1.2 *Scenarios*

The model requires a scenario specification which includes the following elements:

- sea level rise;
- economic/capital growth;
- population growth;
- social discount rate.

Sea level rise. Sea level rise is computed as an increase from the initial year of the simulation (in this case 1985). It has two components: an isostatic rise, which is the present linear trend due to geophysical causes, and an additional rise caused by thermal expansion and melting of the polar ice masses. The latter term is expressed by a hyperbolic tangent function, for which the maximum rise expected at the end of the time horizon (in this case 2085) is specified as a scenario variable.

Economic/capital growth. Economic growth projections pertain to the monetary values to be associated with different types of land. Initially specified land values are adjusted over time using an economic (capital) growth rate which is specified as a scenario variable.

Population growth. Population projections are obtained simply by specifying a net population growth rate.

Social discount rate. The social discount rate reflects society's time preference for financial benefits or expenditures. It is of specific interest if financial trade-offs are to be made involving a long time horizon and considerable time laps between capital outlays and returns on investments, as is clearly the case here. Again, the social discount rate is a scenario variable in the model.

6.1.3 *Impact area characteristics*

The spatial representation in the model is not by means of a grid, which is one of the model's major limitations, but by a division of the coastline into a maximum of three segments (based on differences in either/or: natural system, flood protection system, and type and extent of human activities). This division in segments allows for a differentiation between, e.g. a segment of coastline with a sea dike, as opposed to a dune coast, or a segment of coast with a highly urbanized/industrialized hinterland, as opposed to more rural/ agricultural areas.

The surface areas of land at risk used for urban/industrial, agricultural, and environmental purposes are specified in each segment, as well as the surface area of the intertidal zone; no other spatial data are included. This means that it is not possible to differentiate between location of activities close to, or far from, the coastline. As a result, measures related to land use, planning and relocation of activities cannot be taken into account. Another important limitation is that changes in land use other than those caused by sea level rise, e.g. through urbanization cannot be included.

The impact area characteristics considered include:

- population;
- land and capital values;
- physical characteristics of the area;
- flood protection system;
- water resources management (WRM) system;
- shipping and port system.

The population, reflected in the number of people for each segment, is computed for each timestep using the population growth rate.

Land and capital values are expressed in monetary values to be associated with different types of land use. These monetary values are updated in each timestep using a capital growth rate.

The physical characteristics pertain to:

- the sea water level as affected by sea level rise;
- the 'wet' and 'dry' areas in each segment on either side of the coastline; the dry area broken down into different types of land use;
- the bathymetry and topography of the various segments, expressed in an average inclination for both the wet and the dry land.

The details of the flood protection system are described by the presence and height of the existing protection system, its safety against flooding at the start of the simulation period, and the length of the coastline.

The WRM and shipping/port systems are essentially represented by a set of damage and investment functions, driven by sea level rise. These are discussed in the following paragraphs. The WRM system includes the salt intrusion conditions, as described by the present salt load, the initial average head difference, and a coefficient that enters into the functional relationship for the computation of the salt load.

Impact mechanisms. The most important impact mechanisms considered in the model relate to:

- land losses (both area and capital);
- safety against flooding;
- salt load;
- damages related to WRM and the shipping/port system.

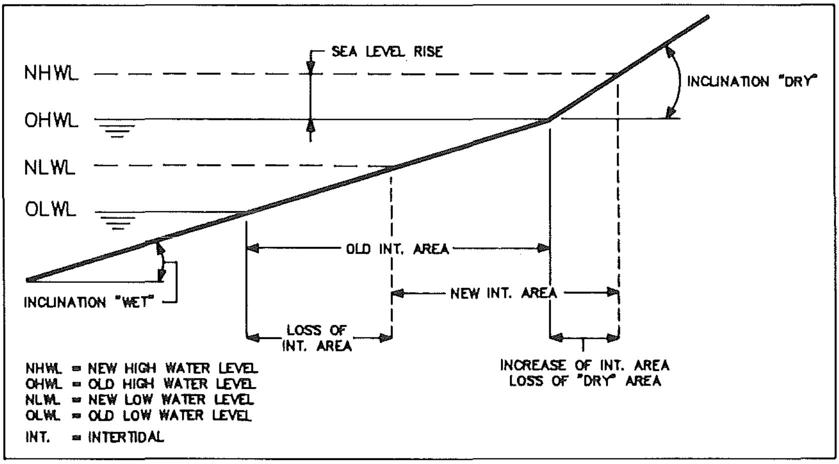

Figure 6. Principle of land losses calculation.

Land losses. Two main categories of land are distinguished in the model, 'dry' land and 'wet' land. The dry land is divided into three land types: urban/industrial, agricultural and environmental. The wet (intertidal) area is considered as a single category. If there is a specific flood protection system, all areas on the seaside of this system are assumed to be intertidal. For each of the three segments considered, an average inclination for the wet and the dry part of the land is specified and used to calculate changes in land area with rising sea level. The boundary of the intertidal area is assumed to move inland proportionally with sea level rise and the 'dry' inclination if there is no flood protection system. The dry land areas of urban/industry, agriculture and environment are then reduced accordingly. On the wet side, the intertidal area is reduced proportionally with sea level rise and the 'wet' inclination. If there is a flood protection system, there will only be a reduction in intertidal area. The above principle is illustrated in Figure 6.

For each of the four land types (three dry and one wet) monetary values per unit area are specified as inputs for each segment. Capital losses associated with land losses are calculated by multiplying the areas lost with these monetary values, taking into account the capital value growth rate and the social discount rate in order to reflect the time element involved.

Safety against flooding. The model has a greatly simplified approach to express the changes in safety against flooding in terms of the frequency of overtopping of the flood protection system. The frequency of overtopping depends on the present frequency (which is assumed to be known) and the sea level rise minus any increases in the height of the flood protection system. The relationship between frequency of overtopping and sea level is assumed to be

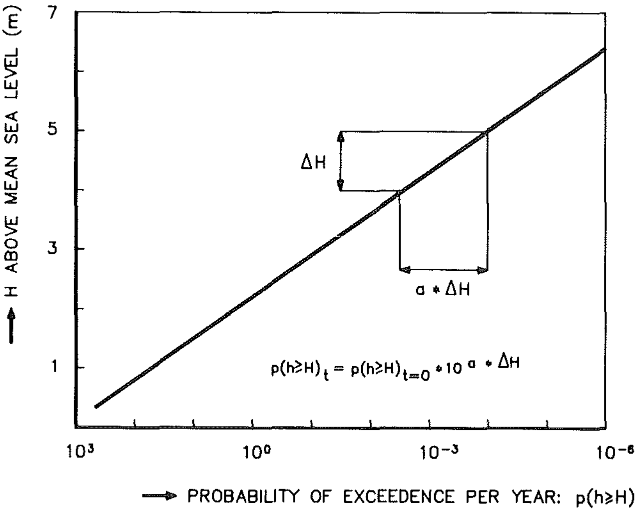

Figure 7. Principle of safety circulation.

log-linear, and is expressed by a single coefficient which indicates the inclination of the log-linear curve. This principle is illustrated in Figure 7.

No attempt is made to calculate damages caused by flooding, because this would require an assessment of the extent, intensity and duration of particular floods, as well as an estimate of disruption of economic activities and damage to infrastructure. An indication of the effect of flooding is obtained by calculating the population and capital at risk.

Salt load. The inland salt load due to seepage is assumed to increase with the relative increment in head difference between sea level and inland waters. This functional relationship is assumed to be almost linear. The salt load caused by salinity intrusion in rivers depends on the increase in water depth according to an exponential relationship. In the model an exponential function is used to reflect both phenomena. The salt load is expressed in tons (Cl-) per year and is computed per timestep for each segment separately. The increase of the salt load relative to the initial value is reduced by WRM measures in the same proportion as the monetary WRM damages described below.

Damage related to WRM and the shipping/port system. The damage to the WRM and the shipping/port system is computed for each timestep and reflect the damage incurred over a five year period. The variable computed is the actual damage, taking into account the effects of investments made to reduce or avoid damages. The damage computation is built around the following assumptions (for illustration see Figure 8):

– The potential damage (without investments) can be expressed as an

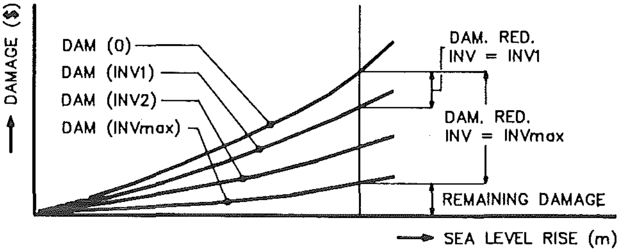

Figure 8. Principle of damage calculation.

exponential function of sea level rise (the curve DAM(0) in Figure 8);

– There is a maximum (useful) investment, which is also expressed as an exponential function of sea level rise, beyond which no additional damage reduction can be obtained (the curve DAM(INVmax) in Figure 8);

– The maximum investment establishes a maximum damage reduction that is a fraction of total damage; this maximum reduction is a function of sea level rise;

– The effect, in a given timestep, of investments made in the previous timestep is a function of the ratio of the sum of the actual investments and the maximum investment.

Using these assumptions, the damage can be calculated for every timestep as a function of sea level rise and investments made prior to the timestep under consideration. The specific characteristics of the nature of the damage functions for both the WRM and the shipping/port system are reflected in a number of input parameters which determine the value and shape of the functional relationships.

6.1.4 *Measures*

The maximum length of the simulation period in the model is 100 years, with timesteps of five years each. New measures can be introduced in the model for each timestep, and for each segment of the coast. The measures included in the model are related to:

- the flood protection system;
- the WRM system;
- the shipping/port system.

The main class of measures in the present model relates to the protection of the coast, since land use planning measures cannot be investigated in the simple spatial representation used. For each timestep and segment of the coast it can be decided whether or not to build a flood protection system, or to increase the height of existing systems. The costs per unit length of building a flood protection system, or raising its height, are specified as model inputs.

Two other classes of measures included in the model relate to decisions on investments in measures to reduce the WRM and/or shipping/port damages.

These are expressed by the investment functions described in the previous paragraph.

Subsequent investments are assumed to have a decreasing effectiveness, which is expressed as the fraction of maximum damage reduction that can be obtained. The rationale behind this approach is the following. Investments to reduce damages in both sectors are not continuous but reflect concrete projects with varying costs and effectiveness. It is assumed that a separate analysis has identified a series of potential projects with their costs and effectiveness. These projects, then, can be ranked with respect to their net effects. It is assumed that the most effective projects would be carried out first, so that a series of projects to be implemented would show a decreasing effectiveness. This set of projects is represented by the investment functions.

In relation to the various measures that can be considered, the model takes into account a set of time lags to allow for the period required to implement a certain measure before it becomes effective. In this respect, it is assumed that it will take 20 years before a newly built flood protection system comes into effect, and likewise, 10 years to effectuate an increase in dike height. Water resources and shipping/port measures are assumed to take effect 5 years after the investment decision is made. All cost outlays associated with the measures are assumed to occur at the time of the decision.

6.1.5 *Effects.* The effects that are computed and displayed by the model include:

- population at risk;
- land loss by type of land, in terms of area and capital;
- safety against flooding for each of the segments;
- total salt load in tons per year;
- damage to WRM and the shipping/port system;
- cost of measures.

The effects of sea level rise and the strategies implemented are shown in the model in two output tables and three types of graphs(Tables A1, A2; Figures A1-A3). Table A1 provides a summary report of the above outputs in timesteps of 25 years, and comprises a mixture of (undiscounted) monetary and non-monetary effects. The computation of all monetary effects is based on constant prices.

Table A2 provides an overview of net present values for the monetary effects.

More informative, perhaps, are the graphs of monetary values, land areas lost, and return periods of flooding, that complement the model output.

An overview of input and output data, variable names, and physical units related to the present model is shown in Appendix A.

6.2 *Use of the model*

The model in its present version allows the user to assess a number of impacts of sea level rise on society, within the framework of a selected scenario and a set of possible measures. Measures relate to building or adjusting flood protection systems, or to improving the WRM and/or the shipping/port system. Flood protection measures are reflected in the model by specifying a height for a flood protection system to be built or raised at discrete timesteps. Measures related to the WRM or shipping/port system are specified in terms of investments by timestep.

The model can handle a maximum simulation period of 100 years, to be simulated in discrete timesteps of 5 years. Measures of all kinds can be specified for each segment and any desired timestep. They will not be effective, however, until the specific delay time for each measure has expired. A simulation can be carried out as a single run over 20 time steps, specifying all measures in advance, or step by step which enables measures to be specified during the simulation, taking into account the results of intermediate simulation.

The model is programmed in a LOTUS 1-2-3 Spreadsheet. The major components of this spreadsheet are:

- an input data block (general and segment specific input data);
- a block of scenario variables;
- an input table of measures;
- a matrix of model computations;
- two tables of model results;
- three (optional) graphs.

The model is user-friendly, in the sense that the various activities related to specifying inputs, running the model and displaying the outputs, are menu-based. In addition the model contains a brief internal documentation. Consequently the model can be readily used by non-experts.

The model in its present version has two basic different possible uses:

- an exploration analysis to obtain some insight in the nature of the problem, the effect of certain mechanisms, and potential trade-offs involved,
- a tentative analysis of actual strategies.

Possible steps involved in the first kind of analysis are:

- compilation of model inputs for a typical area of interest;
- preparation of a run with a 'best' set of input data and scenario variables (considered to be a base case for further exploration);
- analysis of results of the base case and identification of potentially promising measures on the basis of a number of trial runs;
- investigation of the sensitivity of the model results to scenario variables like the extent of sea level rise, the social discount rate or the economic growth rate, and input variables related to capital values, safety computation, damage and investment functions, etc.;

– exploration of the step by step simulation possibility versus the pre-specification of measures for the entire simulation period.

Strategy analysis deals with the actual identification, analysis and interpretation of strategies. The objective could be simply formulated as: 'to find the 'best' strategy to deal with the effects of sea level rise, under various scenario conditions'. An obvious question then is: 'how to determine if one strategy is better than another?' In this respect, the model offers a number of concrete results that may be helpful. First, a report is produced of costs and monetary losses. Second, the safety of the flood protection system is determined. Together with the number of people and the estimated capital values at risk, this provides a means of judging the acceptability of the situation. Finally, some environmental effects are shown in terms of area losses (wet and dry environmental area) and the increase of the salt load.

Using this information the following approach can be taken. Consider the sum of monetary losses and try to minimize the sum of these losses, while maintaining a minimum acceptable safety level, and keeping the environmental effects as limited as possible. In this respect, monetary quantities should be interpreted critically, especially in relation to the effect of the social discount rate. In this appproach, the time delay between decision-making and measures coming into effect forms an additional complicating factor.

The research strategy expressing this approach can be implemented in the following stages:

1. Prepare a base case for different sets of scenario variables;
2. Study the results of each base case, with specific attention to the nature and extent of the adverse effects;
3. Identify possible measures and try to combine these into a limited number of two or three strategies;
4. Investigate the effects of each strategy and make adjustments to strategies based on observed effects. Repeat this procedure until a more or less satisfactory result is obtained;
5. Compare the results obtained under different scenarios and try to formulate conclusions/observations;
6. Make a number of sensitivity runs with different scenario or input variables to increase the understanding of the effects of certain developments and assumptions.

It should be realized that the present model can only give tentative support to the above kind of analysis. Rather than trying to arrive at an actual judgement about potential strategies, at this stage the following objectives should be pursued:

– to gain insight into the process of identifying and evaluating strategies;

– to develop a basic understanding of the main phenomena and principles which determine the effects of strategies and of the critical aspects in the evaluation procedure;

– to arrive at some generalized conclusions about the specific nature of the problems and the possible solutions for a typical area;

– to obtain a general indication about the value of the kind of tool used, assuming that effort is to be devoted to its further development;

– to judge the value of the tool as it is now, in terms of what are the most important components or relationships missing and how could these be implemented in an improved version.

6.3 *An example application for the Netherlands*

At the Delft workshop of August 1986, the illustrative model was tentatively applied in three case studies, involving the Netherlands, Bangladesh and the Maldive archipelago. An example application for the Netherlands is briefly described in this section.

An overview of the case study area is provided in Figure 9, showing the Netherlands' coastal zone schematized into three segments A, B and C. All inputs and outputs for the example computation are presented in Appendix A. Table A1 provides an overview of the basic data used in the example. These

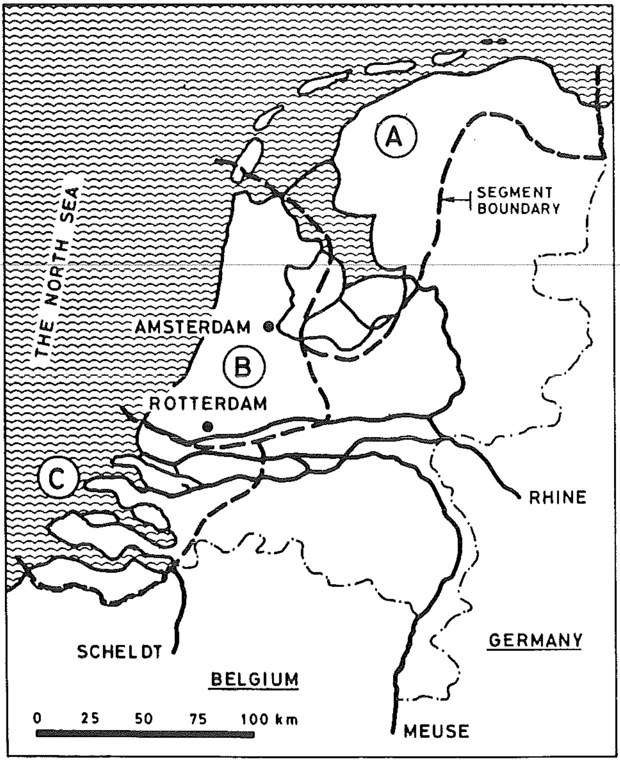

Figure 9. Area and segments involved in the Netherlands' case-study.

data are shown in two parts, i.e. a constant part that is valid for the entire area, and three blocks of data that pertain to the segments A, B and C, respectively.

The run-specific data for a reference situation, or base case, are shown in Table A2. These data comprise the four scenario variables used (maximium additional sea level rise in 100 years HMAX, population growth rate PG, economic/capital growth EG, and the social discount rate DR. The second part of the run-specific data is the table of potential measures: building or raising of dikes, water resources management measures and shipping/port measures, to be specified in time for each of three segments. As can be observed from Table A2, no measures were specified for the base case.

The results of the base case calcultation are shown in the summary report as shown in Table A3. Three types of graphs are shown in Figures A1 to A3, respectively.

Table A3 shows a summary of some important impacts for discrete time intervals of 25 years. From this table it can be observed that total sea level rise under the selected scenario amounts to 1.11 m after 100 years, increasing the flood risk for each of the three segments with a factor of about 46. The population at risk increases to 10 million because of autonomous population growth.

The second block of the summary report provides a financial report. Because the entire study area is protected by dikes, no land losses occur, other than losses of intertidal area, expressed in a loss of both capital and area (the latter in the third part of the table). Capital losses associated with land losses behind the dikes are zero. The financial losses associated with intertidal area are quite modest, because of the limited economic activity in these areas. For the financial losses associated with WRM and shipping/ports, numbers start to appear after 1985 showing a progressive increase with sea level rise. The WRM damages include a part that is due to the increasing salt load. As no measures were implemented in the base case, the cost of measures is zero. Financial cost and damages are totalled in the row 'total monetary'. All numbers in this block reflect the total impact in the preceding 25 year interval.

In the third block, an overview is provided of some aggregated environmental effects. This block contains the total (dry) land area loss, loss of (dry) environmental area (both zero), the loss of intertidal area and the salt load. The latter increases with sea level rise according to some weakly progressive, exponential function. All variables appear as state variables, i.e. they reflect the current state of the system at 25 year intervals.

All money values appearing in the summary report have not been discounted. Total discounted money values over the entire simulation period appear in the last part of the table, showing the net present values of land capital losses, WRM and shipping/port damages, and cost of measures, both separately and as a total. Note that the financial damage related to the intertidal area loss is quite small compared to shipping/port, and especially WRM damages. The environmental effects, as indicated by the total area loss in the third block of the table, may be enormous however. The base case shows a total monetary value (or loss) of \$3634.5 million. Note that this number is undiscounted, as the social discount rate applied in the base case is zero.

To illustrate the use of the model, the following cases were considered next to the base case. Indicated in the overview below are the changes in the input data compared to the base case.

Case 1: HMAX (non-isostatic part of sea level rise) equals 2 m.
Case 2: HMAX = 3 m.
Case 3: social discount rate is 2%.
Case 4: social discount rate is 5%.
Case 5: WRM measures: \$200 million investments in 1990 for each of three segments (A, B and C).
Case 6: WRM measures like in case 5; social discount rate is 2%.
Case 7: WRM measures: \$50 million investments in 2000, 2010, 2020 and 2030, respectively, for each of the segments A, B and C; social discount rate is 2%.
Case 8: WRM measures: \$30 million investments in 2000, 2010, 2020 and 2030, respectively, for segments A, B and C; social discount rate is 2%.
Case 9: Like case 8. In addition: raising of dikes in segments A and C with 0.5 m in the year 2050; raising of dikes in segment B with 0.5 m in the years 2015 and 2045, respectively.

The various cases are summarized in Table 1.

Case 1 (Table A4). The summary report for case 1 is presented in Table A4. Total sea level rise under this scenario amounts to 2.02 m in the year 2085. The probability of dike failure has increased to 0.108 in 2085 for all three segments, an increase by a factor of 1000 from the situation in 1985. The loss of intertidal area has increased by about 50% compared with the base case, the salt load by about 30%. Total monetary losses have almost doubled.

Case 2 (Table A5). The summary report for case 2 is presented in Table A5. Total sea level rise now is 2.93 m in 2085. The dikes will have surely failed before 2085. The loss of intertidal area has reached a maximum before the year 2060 (all intertidal area has disappeared). The salt load has increased by about 70% compared to the base case. Total monetary losses have tripled.

Cases 3 and 4 (Tables A6 and A7). The results of cases 3 and 4 are presented in Tables A6 and A7, respectively. If a social discount rate (SDR) of 2% is

Table 1. Overview of the runs with the ISOS-model.

Part.	SLR	SDR	WRM						Raising dikes		
	H_{max}		A		B		C		A	B	C
Case	(m)	(%)	Amt*	yr	Amt	yr	Amt	yr	Δ(m)yr	Δ(m)yr	Δ(m)yr
Base case	1	0									
Case											
1	2	0									
2	3	0									
3	1	2									
4	1	5									
5	1	0	200	1990	200	1990	200	1990			
6	1	2	200	1990	200	1990	200	1990			
7	1	2	50	2000	50	2000	50	2000			
			50	2010	50	2010	50	2010			
			50	2020	50	2020	50	2020			
			50	2030	50	2030	50	2030			
8	1	2	30	2000	30	2000	30	2000			
			30	2010	30	2010	30	2010			
			30	2020	30	2020	30	2020			
			30	2030	30	2030	30	2030			
9	1	2	30	2000	30	2000	30	2000	0.5 2050	0.5 2015	0.5 2050
			30	2010	30	2010	30	2010		0.5 2045	
			30	2020	30	2020	30	2020			
			30	2030	30	2030	30	2030			

*Amount in million US $.

applied, the net present value (base year is 1985) of the total monetary losses is reduced to $923 million, or roughly 25% of the undiscounted total losses in the basecase (Table A3). If a social discount rate of 5% is applied, the net present value of total losses will be reduced to $199 million (Table A7), only some 5% of the undiscounted value. These two examples illustrate the strong influence of the social discount rate.

Case 5 (Table A8). The effect of WRM measures is illustrated in Table A8. If the social discount rate is zero, an investment in WRM measures of $200 million for each segment, to be applied the soonest possible after 1985, would be optimal. According to Table A8, this would reduce total monetary losses to $2834 million, saving some $800 million in comparison with the base case. The cost of the measures ($600 million) are now included in the report of monetary losses.

Case 6 (Table A9). If in the situation of case 5 the social discount rate is set to 2%, the total monetary losses are $1078 million. Compared with case 3 (having the same social discount rate but no measures), we now lose $155 million (compare Tables A6 and A9). This is merely the result of the introduction of the social discount rate, which makes the cost of the measures, to be laid out in 1990, count a lot more than the benefits that slowly build up during a long stretch of time after that.

Case 7 (Table A10). Case 7 shows the effects of an attempt to more optimally allocate the investments in WRM measures in time. Using the same total investment of $200 million for each segment, equal parts of $50 million are now implemented in 2000, 2010, 2020 and 2030, respectively. Table A10 shows a total monetary loss of $902 million, which saves $20 million in comparison with case 3 (Table A6). Hence, this investment scheme would be cost effective under the social discount rate applied.

Case 8 (Table A11). The social discount rate not only influences the optimal phasing of investments, but also the optimal level of investments proper. This is demonstrated by the results of case 8 (see Table A11). If the investment scheme of $50 million units in case 7 is replaced by an investment scheme of $30 million units, all other things being equal, the total monetary losses go further down to $843 million, saving another $60 million compared to case 7 (Table A10). So, while in the undiscounted situation the investment scheme of case 5 would be optimal ($200 in 1990 for each segment), the investment scheme of case 8 would be optimal if a social discount rate of 2% is applied ($30 million in 2000, 2010, 2020 and 2030 for each segment).

Case 9 (Table A12). In addition to the investment scheme of case 8, it was attempted to maintain a minimum safety level in each of the segments by raising the dikes, under the assumption that the minimum raise is 0.5 m. The flood protection requirements adopted were: no probability of flooding higher than 1 in 1000 years for segments A and C, and no probability higher than 1 in 5000 years for segment B. It turns out that this condition can be met by a one time raising of the dikes in segments A and C by 0.5 m, no later than the year 2050. For segment B, the dikes should be raised two times, i.e. no later than 2015 for the first time and no later than 2045 for the second time. Table A12 shows the results for this case. It can be verified that the above flood protection requirements were met. Compared to case 8, the total monetary losses have increased with about $500 million, which is totally due to the cost of raising the dikes. More detailed information regarding case 9 is provided in Figures A4 through A6. Figure A4 shows a graph of total monetary losses. Figures A5 and A6 show the safety against flooding (return periods) for segments A and B, respectively.

7 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been drawn from this chapter:

1. It is essential to generate systematic overviews of the effects of sea level rise, under different scenarios and strategies, as an aid for decision-making.

2. In addition a basis should be created for communicating factual information over a wide variety of disciplines in order to effectively mobilize the knowledge and ingenuity available in the world for coping with the problem of sea level rise.

3. In view of the characteristics of the problem, a policy analysis approach would be appropriate to meet the above requirements.

4. Policy analysis would offer a feasible approach because, at least for certain regions in the world, enough knowledge and information is available to quantify many of the relevant effects.

5. Comprehensive, and yet realistic, overviews of effects can only be provided by a simplified 'overview' model based on a collection of reprofunctions, each of which may reflect the results of detailed studies and/or more sophisticated models.

6. It is thought that a well-conceived model based on the principles outlined in this report would serve as a vehicle for communication across disciplines and provide a powerful and flexible instrument with which to prepare for the decision-making which will be necessary in response to this very serious problem.

7. The results obtained with the illustrative model version, developed for the ISOS workshop in Delft in August 1986, give rise to moderate optimism in this respect. Care should be taken, however, in the interpretation of results from the model, because, inevitably, not all relevant effects could be quantified then.

To develop the methodology and tools required for a more realistic evaluation of the effects of sea level rise and the potential strategies to deal with this problem further, it is of great importance to carry out more detailed, and in-depth, research for several case study areas. In this respect, the following recommendations should be considered carefully:

a) Specific, detailed aspect studies should be carried out to collect more information, and to define impact mechanisms further, particularly those related to morphological and environmental effects in the intertidal area, changes in probability of flooding, flooding mechanisms, and the consequences of flooding.

b) A more comprehensive and realistic modelling approach should be developed and implemented based on the principles as outlined in Section 6.

c) An international platform should be established to bring together existing knowledge, to initiate the required aspect studies and to develop further and implement the 'ideal' ISOS model.

d) An institutional arrangement should be set up for funding, maintaining, and making available the results of international cooperation in the field of sea level rise.

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APPENDIX A: INPUT DATA AND RESULTS FOR EXAMPLE APPLICATION FOR THE NETHERLANDS

Table A1. Overview of basic data in example application for the Netherlands.

INPUT:

"description"	"name"	"value"	"units"
CONSTANT:			
Name of Case Study		Netherlands	
current trend of sea level rise	CSLR	0.2	m/100yrs
Coeff safety formula	COEFF	1.5	
Costs of raising coastal defense	CRD	5	10^6$/m/k
Initial costs of coastal defense	ICD	0.5	10^6$/km
WRM exponent investment function	a	1.3	
WRM exponent damage function	b	1.2	
WRM exponent investment efficiency	c	0.7	
WRM exponent maximum effect	d	0.3	
shipp/port exponent investment function	e	1	
shipp/port exponent damage function	f	1.1	
shipp/port exponent investment efficiency	g	0.9	
shipp/port exponent maximum effect	h	0.1	
SEGMENT A:			
population 1985	POPA	1.3	10^6
surface area industry/urban 1985	AUA	310	km2
surface area agriculture 1985	AAA	5600	km2
surface area environment 1985	AEA	670	km2
surface area intertidal 1985	AIA	2100	km2
length of coastline	LCA	150	km
height of coastal defense 1985	HDA	8	m
avg capital value industry/urban 1985	VUA	400	10^6$/km2
avg capital value agriculture 1985	VAA	3.2	10^6$/km2
avg capital value environment 1985	VEA	0.8	10^6$/km2
avg capital value intertidal 1985	VIA	0.01	10^6$/km2
safety 1985	SA	0.0001	
incline wet	IWA	0.0001	tng
incline dry	IDA	0.0001	tng
WRM investment function constant	WIVA	320	10^6$
WRM damage function constant	WDMA	85	10^6$
salt load 1985	SLA	20000	ton/year
average head difference	HDA	2	m
seepage coefficient	SCA	1.1	
shipp/port investment function constant	SIVA	120	10^6$
shipp/port damage function constant	SDMA	25	10^6$
SEGMENT B:			
population 1985	POPB	6.05	10^6
surface area industry/urban 1985	AUB	910	km2
surface area agriculture 1985	AAB	4000	km2
surface area environment 1985	AEB	510	km2
surface area intertidal 1985	AIB	10	km2
length of coastline	LCB	125	km
height of coastal defense 1985	HDB	10	m
avg capital value industry/urban 1985	VUB	750	10^6$/km2
avg capital value agriculture 1985	VAB	6.8	10^6$/km2
avg capital value environment 1985	VEB	1.5	10^6$/km2
avg capital value intertidal 1985	VIB	0	10^6$/km2
safety 1985	SB	0.0001	
incline wet	IWB	0.02	tng
incline dry	IDB	0.01	tng
WRM investment function constant	WIVB	800	10^6$
WRM damage function constant	WDMB	145	10^6$
salt load 1985	SLB	150000	ton/year
average head difference	HB	3	m
seepage coefficient	SB	1.1	
shipp/port investment function constant	SIVB	220	10^6$
shipp/port damage function constant	SDMB	65	10^6$

Table A1 (cont.).

SEGMENT C:			
population 1985	POPC	0.85	10^6
surface area industry/urban 1985	AUC	250	km2
surface area agriculture 1985	AAC	2100	km2
surface area environment 1985	AEC	220	km2
surface area intertidal 1985	AIC	800	km2
length of coastline	LCC	160	km
height of coastal defense 1985	HDC	12	m
avg capital value industry/urban 1985	VUC	500	10^6$/km2
avg capital value agriculture 1985	VAC	4	10^6$/km2
avg capital value environment 1985	VEC	1	10^6$/km2
avg capital value intertidal 1985	VIC	0.01	10^6$/km2
safety 1985	SC	0.0001	
incline wet	IWC	0.0004	tng
incline dry	IDC	0.0004	tng
WRM investment function constant	WIVC	185	10^6$
WRM damage function constant	WDMC	37	10^6$
salt load 1985	SLC	45000	ton/year
average head difference	HC	1.8	m
seepage coefficient	SC	1.1	
shipp/port investment function constant	SIVC	65	10^6$
shipp/port damage function constant	SDMC	20	10^6$

Table A2. Run-specific data for base case.

```
 ************************************************************************
         *********    CASE: Netherlands, Run: 0        *********
SCENARIO:
maximum additional sea level rise            HMAX            1 m
population growth                            PG            0.2 %/yr
economic/capital growth                      EG              3 %/yr
social discount rate                         DR              0 per 5 yrs


MEASURES:
                               1985     1990     1995     2000     2005
BUILD DEFENSE A, HDA= (m)
BUILD DEFENSE B, HDB= (m)
BUILD DEFENSE C, HDC= (m)
DELTA HDA (m)
DELTA HDB (m)
DELTA HDC (m)
WRM MEASURES A (10^6 $)
WRM MEASURES B (10^6 $)
WRM MEASURES C (10^6 $)
SHIPP/PORT MEAS A (10^6 $)
SHIPP/PORT MEAS B (10^6 $)
SHIPP/PORT MEAS C (10^6 $)
*************************************************************************


*************************************************************************
    2010     2015     2020     2025     2030     2035     2040     2045









*************************************************************************



*************************************************************************
    2050     2055     2060     2065     2070     2075     2080     2085









*************************************************************************
```

Table A3. Summary of results for base case.

```
------------------------------------------------------------------------

SUMMARY REPORT:                   1985      2010      2035      2060      2085
------------------------------------------------------------------------
SEALEVEL RISE (m)                 0.01      0.11      0.37      0.81      1.11

SAFETY A                       0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY B                       0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY C                       0.00010   0.00015   0.00036   0.00164   0.00465
POPULATION (10^6)                  8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)          0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)         0.0       3.3      17.3      60.7      82.7
WRM DAMAGES (10^6$)                0.0      54.3     254.5     770.7    1353.9
SHIPP/PORT DAMAGES (10^6$)         0.0      28.9     119.7     331.6     557.0
SUMM COST MEASURES (10^6$)         0.0       0.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)             0.0      86.4     391.5    1163.0    1993.6

TOTAL LAND LOSS (km^2)            0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)          0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)            0.00    194.47    678.60   1520.81   2094.30
SALT LOAD (ton/year)            215000    227268    254593    302793    336043
------------------------------------------------------------------------

PRESENT VALUES OF:
------------------------------------------------------------------------
ON LAND CAPITAL LOSS                        0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS              163.9 10^6 $
WRM DAMAGES                              2433.4 10^6 $
SHIPPING/PORT DAMAGES                    1037.2 10^6 $
SUMMED COST OF MEASURES                     0.0 10^6 $
TOTAL MONETARY VALUES                    3634.5 10^6 $
------------------------------------------------------------------------
```

Table A4. Summary of results for Case 1.

```
------------------------------------------------------------------------

SUMMARY REPORT:                   1985      2010      2035      2060      2085
------------------------------------------------------------------------
SEALEVEL RISE (m)                 0.03      0.18      0.64      1.47      2.02

SAFETY A                       0.00010   0.00019   0.00091   0.01612   0.10834
SAFETY B                       0.00010   0.00019   0.00091   0.01612   0.10834
SAFETY C                       0.00010   0.00019   0.00091   0.01612   0.10834
POPULATION (10^6)                  8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)          0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)         0.0       5.0      31.3     108.1      31.8
WRM DAMAGES (10^6$)                0.0      92.4     474.7    1554.5    2781.3
SHIPP/PORT DAMAGES (10^6$)         0.0      47.0     211.8     630.8    1077.5
SUMM COST MEASURES (10^6$)         0.0       0.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)             0.0     144.4     717.9    2293.4    3890.6

TOTAL LAND LOSS (km^2)            0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)          0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)            0.00    293.62   1166.58   2687.28   2908.92
SALT LOAD (ton/year)            215000    234229    283839    376231    438610
------------------------------------------------------------------------

PRESENT VALUES OF:
------------------------------------------------------------------------
ON LAND CAPITAL LOSS                        0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS              176.2 10^6 $
WRM DAMAGES                              4903.0 10^6 $
SHIPPING/PORT DAMAGES                    1967.2 10^6 $
SUMMED COST OF MEASURES                     0.0 10^6 $
TOTAL MONETARY VALUES                    7046.3 10^6 $
------------------------------------------------------------------------
```

Table A5. Summary of results for Case 2.

```
-----------------------------------------------------------------------------
SUMMARY REPORT:                    1985      2010      2035      2060      2085
-----------------------------------------------------------------------------
SEALEVEL RISE (m)                  0.04      0.24      0.91      2.13      2.93

SAFETY A                        0.00010   0.00023   0.00229   0.15791   2.52465
SAFETY B                        0.00010   0.00023   0.00229   0.15791   2.52465
SAFETY C                        0.00010   0.00023   0.00229   0.15791   2.52465
POPULATION (10^6)                   8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)           0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)          0.0       6.7      45.4      78.4       0.0
WRM DAMAGES (10^6$)                 0.0     133.4     714.1    2413.4    4348.2
SHIPP/PORT DAMAGES (10^6$)          0.0      65.9     307.9     943.9    1623.0
SUMM COST MEASURES (10^6$)          0.0       0.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)              0.0     206.0    1067.3    3435.7    5971.2

TOTAL LAND LOSS (km^2)             0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)           0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)             0.00    392.78   1654.55   2910.00   2910.00
SALT LOAD (ton/year)             215000    241211    313375    451045    543480
-----------------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------------
ON LAND CAPITAL LOSS                          0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS                130.5 10^6 $
WRM DAMAGES                                7609.0 10^6 $
SHIPPING/PORT DAMAGES                      2940.6 10^6 $
SUMMED COST OF MEASURES                       0.0 10^6 $
TOTAL MONETARY VALUES                     10680.1 10^6 $
-----------------------------------------------------------------------------
```

Table A6. Summary of results for Case 3.

```
-----------------------------------------------------------------------------
SUMMARY REPORT:                    1985      2010      2035      2060      2085
-----------------------------------------------------------------------------
SEALEVEL RISE (m)                  0.01      0.11      0.37      0.81      1.11

SAFETY A                        0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY B                        0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY C                        0.00010   0.00015   0.00036   0.00164   0.00465
POPULATION (10^6)                   8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)           0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)          0.0       3.3      17.3      60.7      82.7
WRM DAMAGES (10^6$)                 0.0      54.3     254.5     770.7    1353.9
SHIPP/PORT DAMAGES (10^6$)          0.0      28.9     119.7     331.6     557.0
SUMM COST MEASURES (10^6$)          0.0       0.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)              0.0      86.4     391.5    1163.0    1993.6

TOTAL LAND LOSS (km^2)             0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)           0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)             0.00    194.47    678.60   1520.81   2094.30
SALT LOAD (ton/year)             215000    227268    254593    302793    336043
-----------------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------------
ON LAND CAPITAL LOSS                          0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS                 42.2 10^6 $
WRM DAMAGES                                 612.7 10^6 $
SHIPPING/PORT DAMAGES                       268.2 10^6 $
SUMMED COST OF MEASURES                       0.0 10^6 $
TOTAL MONETARY VALUES                       923.2 10^6 $
-----------------------------------------------------------------------------
```

Table A7. Summary of results for Case 4.

```
-----------------------------------------------------------------------
SUMMARY REPORT:                     1985      2010      2035      2060      2085
-----------------------------------------------------------------------
SEALEVEL RISE (m)                   0.01      0.11      0.37      0.81      1.11

SAFETY A                         0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY B                         0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY C                         0.00010   0.00015   0.00036   0.00164   0.00465
POPULATION (10^6)                    8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)            0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)           0.0       3.3      17.3      60.7      82.7
WRM DAMAGES (10^6$)                  0.0      54.3     254.5     770.7    1353.9
SHIPP/PORT DAMAGES (10^6$)           0.0      28.9     119.7     331.6     557.0
SUMM COST MEASURES (10^6$)           0.0       0.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)               0.0      86.4     391.5    1163.0    1993.6

TOTAL LAND LOSS (km^2)              0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)            0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)              0.00    194.47    678.60   1520.81   2094.30
SALT LOAD (ton/year)              215000    227268    254593    302793    336043
-----------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------
ON LAND CAPITAL LOSS                          0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS                  9.0 10^6 $
WRM DAMAGES                                 130.4 10^6 $
SHIPPING/PORT DAMAGES                        60.2 10^6 $
SUMMED COST OF MEASURES                       0.0 10^6 $
TOTAL MONETARY VALUES                       199.6 10^6 $
-----------------------------------------------------------------------
```

Table A8. Summary of results for Case 5.

```
-----------------------------------------------------------------------
SUMMARY REPORT:                     1985      2010      2035      2060      2085
-----------------------------------------------------------------------
SEALEVEL RISE (m)                   0.01      0.11      0.37      0.81      1.11

SAFETY A                         0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY B                         0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY C                         0.00010   0.00015   0.00036   0.00164   0.00465
POPULATION (10^6)                    8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)            0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)           0.0       3.3      17.3      60.7      82.7
WRM DAMAGES (10^6$)                  0.0      11.3      20.3     270.1     731.5
SHIPP/PORT DAMAGES (10^6$)           0.0      28.9     119.7     331.6     557.0
SUMM COST MEASURES (10^6$)           0.0     600.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)               0.0     643.4     157.3     662.4    1371.2

TOTAL LAND LOSS (km^2)              0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)            0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)              0.00    194.47    678.60   1520.81   2094.30
SALT LOAD (ton/year)              215000    215394    218560    238801    272822
-----------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------
ON LAND CAPITAL LOSS                          0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS                163.9 10^6 $
WRM DAMAGES                                1033.2 10^6 $
SHIPPING/PORT DAMAGES                      1037.2 10^6 $
SUMMED COST OF MEASURES                     600.0 10^6 $
TOTAL MONETARY VALUES                      2834.4 10^6 $
-----------------------------------------------------------------------
```

Table A9. Summary of results for Case 6.

```
-----------------------------------------------------------------------

SUMMARY REPORT                   1985      2010      2035      2060      2085
-----------------------------------------------------------------------
SEALEVEL RISE (m)                0.01      0.11      0.37      0.81      1.11

SAFETY A                      0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY B                      0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY C                      0.00010   0.00015   0.00036   0.00164   0.00465
POPULATION (10^6)                 8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)         0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)        0.0       3.3      17.3      60.7      82.7
WRM DAMAGES (10^6$)               0.0      11.3      20.3     270.1     731.5
SHIPP/PORT DAMAGES (10^6$)        0.0      28.9     119.7     331.6     557.0
SUMM COST MEASURES (10^6$)        0.0     600.0       0.0       0.0       0.0
TOTAL MONETARY (10^6$)            0.0     643.4     157.3     662.4    1371.2

TOTAL LAND LOSS (km^2)           0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)         0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)           0.00    194.47    678.60   1520.81   2094.30
SALT LOAD (ton/year)           215000    215394    218560    238801    272822
-----------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------
ON LAND CAPITAL LOSS                        0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS               42.2 10^6 $
WRM DAMAGES                               222.3 10^6 $
SHIPPING/PORT DAMAGES                     268.2 10^6 $
SUMMED COST OF MEASURES                   545.5 10^6 $
TOTAL MONETARY VALUES                    1078.2 10^6 $
-----------------------------------------------------------------------
```

Table A10. Summary of results for Case 7.

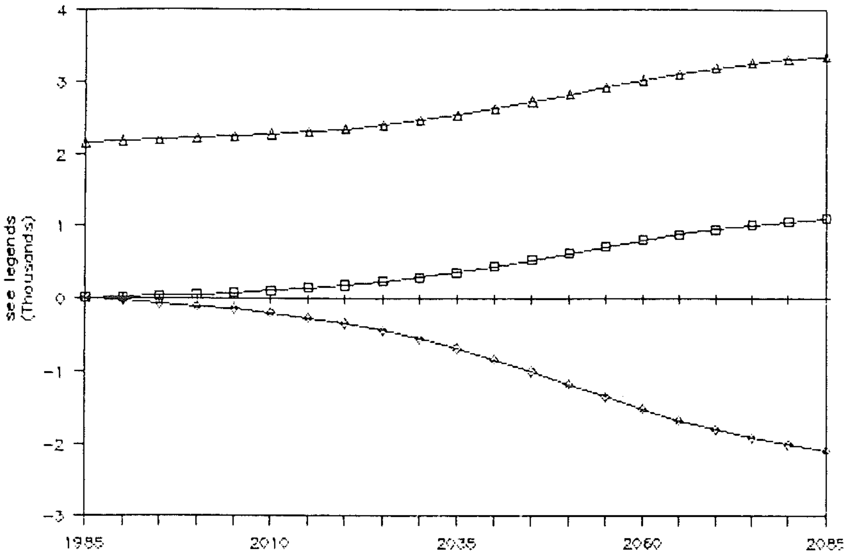
```
-----------------------------------------------------------------------

SUMMARY REPORT                   1985      2010      2035      2060      2085
-----------------------------------------------------------------------
SEALEVEL RISE (m)                0.01      0.11      0.37      0.81      1.11

SAFETY A                      0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY B                      0.00010   0.00015   0.00036   0.00164   0.00465
SAFETY C                      0.00010   0.00015   0.00036   0.00164   0.00465
POPULATION (10^6)                 8.2       8.6       9.1       9.5      10.0

LAND CAPITAL LOSS (10^6$)         0.0       0.0       0.0       0.0       0.0
INTERTID. CAP LOSS (10^6$)        0.0       3.3      17.3      60.7      82.7
WRM DAMAGES (10^6$)               0.0      35.0      35.4     270.1     731.5
SHIPP/PORT DAMAGES (10^6$)        0.0      28.9     119.7     331.6     557.0
SUMM COST MEASURES (10^6$)        0.0     300.0     300.0       0.0       0.0
TOTAL MONETARY (10^6$)            0.0     367.2     472.4     662.4    1371.2

TOTAL LAND LOSS (km^2)           0.00      0.00      0.00      0.00      0.00
LANDLOSS ENVIRONM (km^2)         0.00      0.00      0.00      0.00      0.00
LOSS INTERTIDAL (km^2)           0.00    194.47    678.60   1520.81   2094.30
SALT LOAD (ton/year)           215000    215394    218560    238801    272822
-----------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------
ON LAND CAPITAL LOSS                        0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS               42.2 10^6 $
WRM DAMAGES                               245.8 10^6 $
SHIPPING/PORT DAMAGES                     268.2 10^6 $
SUMMED COST OF MEASURES                   346.4 10^6 $
TOTAL MONETARY VALUES                     902.7 10^6 $
-----------------------------------------------------------------------
```

Table A11. Summary of results for Case 8.

```
-----------------------------------------------------------------------
SUMMARY REPORT                          1985     2010     2035     2060     2085
-----------------------------------------------------------------------
SEALEVEL RISE (m)                       0.01     0.11     0.37     0.81     1.11

SAFETY A                             0.00010  0.00015  0.00036  0.00164  0.00465
SAFETY B                             0.00010  0.00015  0.00036  0.00164  0.00465
SAFETY C                             0.00010  0.00015  0.00036  0.00164  0.00465
POPULATION (10^6)                        8.2      8.6      9.1      9.5     10.0

LAND CAPITAL LOSS (10^6$)                0.0      0.0      0.0      0.0      0.0
INTERTID. CAP LOSS (10^6$)               0.0      3.3     17.3     60.7     82.7
WRM DAMAGES (10^6$)                      0.0     38.0     68.0    377.5    912.7
SHIPP/PORT DAMAGES (10^6$)               0.0     28.9    119.7    331.6    557.0
SUMM COST MEASURES (10^6$)               0.0    180.0    180.0      0.0      0.0
TOTAL MONETARY (10^6$)                   0.0    250.1    385.0    769.8   1552.4

TOTAL LAND LOSS (km^2)                  0.00     0.00     0.00     0.00     0.00
LANDLOSS ENVIRONM (km^2)                0.00     0.00     0.00     0.00     0.00
LOSS INTERTIDAL (km^2)                  0.00   194.47   678.60  1520.81  2094.30
SALT LOAD (ton/year)                  215000   215394   218560   258039   291828
-----------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------
ON LAND CAPITAL LOSS                          0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS                 42.2 10^6 $
WRM DAMAGES                                 325.0 10^6 $
SHIPPING/PORT DAMAGES                       268.2 10^6 $
SUMMED COST OF MEASURES                     207.9 10^6 $
TOTAL MONETARY VALUES                       843.3 10^6 $
-----------------------------------------------------------------------
```

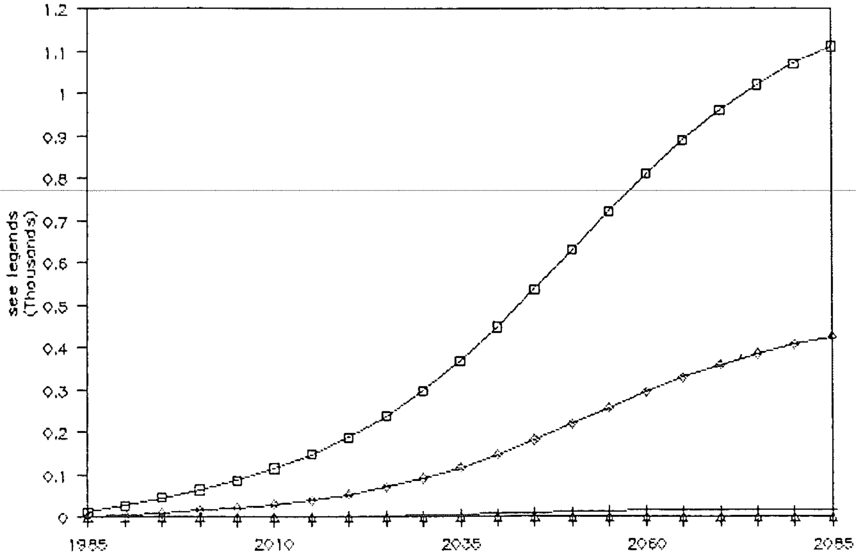
Table A12. Summary of results for Case 9.

```
-----------------------------------------------------------------------
SUMMARY REPORT                          1985     2010     2035     2060     2085
-----------------------------------------------------------------------
SEALEVEL RISE (m)                       0.01     0.11     0.37     0.81     1.11

SAFETY A                             0.00010  0.00015  0.00036  0.00029  0.00083
SAFETY B                             0.00010  0.00015  0.00006  0.00005  0.00015
SAFETY C                             0.00010  0.00015  0.00036  0.00029  0.00083
POPULATION (10^6)                        8.2      8.6      9.1      9.5     10.0

LAND CAPITAL LOSS (10^6$)                0.0      0.0      0.0      0.0      0.0
INTERTID. CAP LOSS (10^6$)               0.0      3.3     17.3     60.7     82.7
WRM DAMAGES (10^6$)                      0.0     38.0     68.0    377.5    912.7
SHIPP/PORT DAMAGES (10^6$)               0.0     28.9    119.7    331.6    557.0
SUMM COST MEASURES (10^6$)               0.0    180.0    492.5   1087.5      0.0
TOTAL MONETARY (10^6$)                   0.0    250.1    697.5   1857.3   1552.4

TOTAL LAND LOSS (km^2)                  0.00     0.00     0.00     0.00     0.00
LANDLOSS ENVIRONM (km^2)                0.00     0.00     0.00     0.00     0.00
LOSS INTERTIDAL (km^2)                  0.00   194.47   678.60  1520.81  2094.30
SALT LOAD (ton/year)                  215000   215394   218560   258039   291828
-----------------------------------------------------------------------

PRESENT VALUES OF:
-----------------------------------------------------------------------
ON LAND CAPITAL LOSS                          0.0 10^6 $
INTERTIDAL AREA CAPITAL LOSS                 42.2 10^6 $
WRM DAMAGES                                 325.0 10^6 $
SHIPPING/PORT DAMAGES                       268.2 10^6 $
SUMMED COST OF MEASURES                     708.3 10^6 $
TOTAL MONETARY VALUES                      1343.8 10^6 $
-----------------------------------------------------------------------
```



Legend:
□ Sea level rise (mm)
◇ Loss of intertidal area (km^2)
\+ Loss of 'dry' environmental area (km^2)
△ Salt load (100 tons/yr)

Figure A1. Land losses and salt load – base case.



Legend:
□ Sea level rise (mm)
\+ Land capital losses (million $)
◇ WRM and shipping/port losses (million $)
△ Cost of technical measures (million $)

Figure A2. Monetary losses – base case.

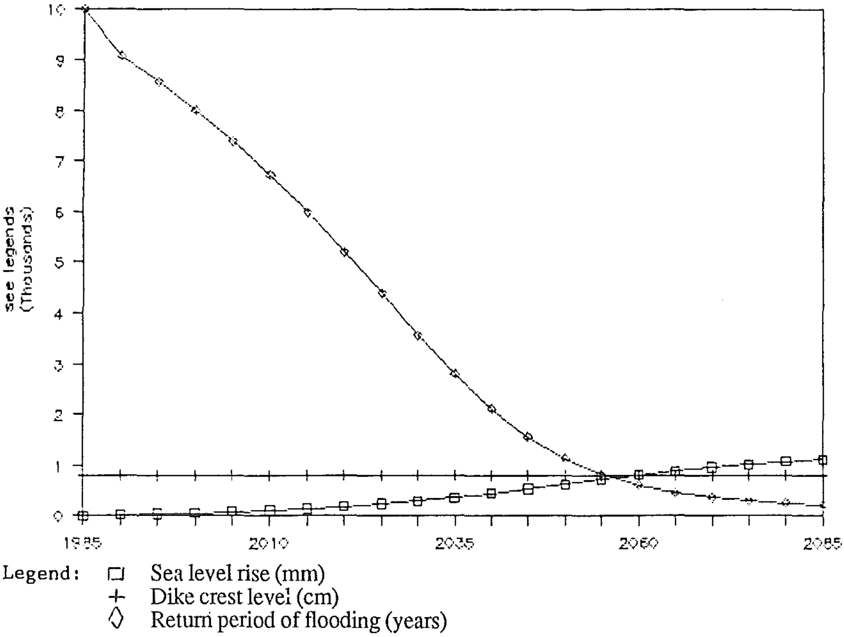


Figure A3. Return periods of flooding – base case (segments A, B and C).

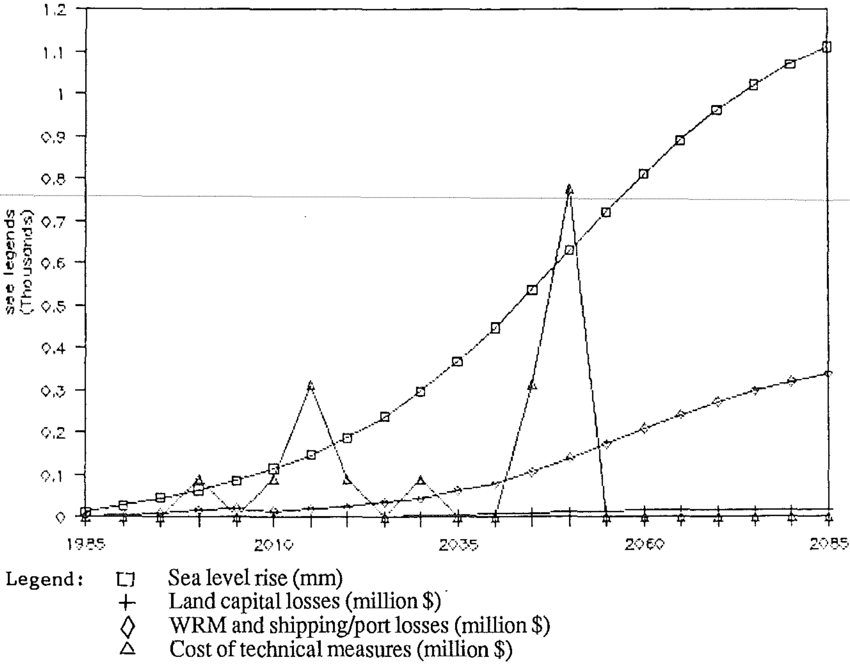


Figure A4. Monetary losses Case 9.

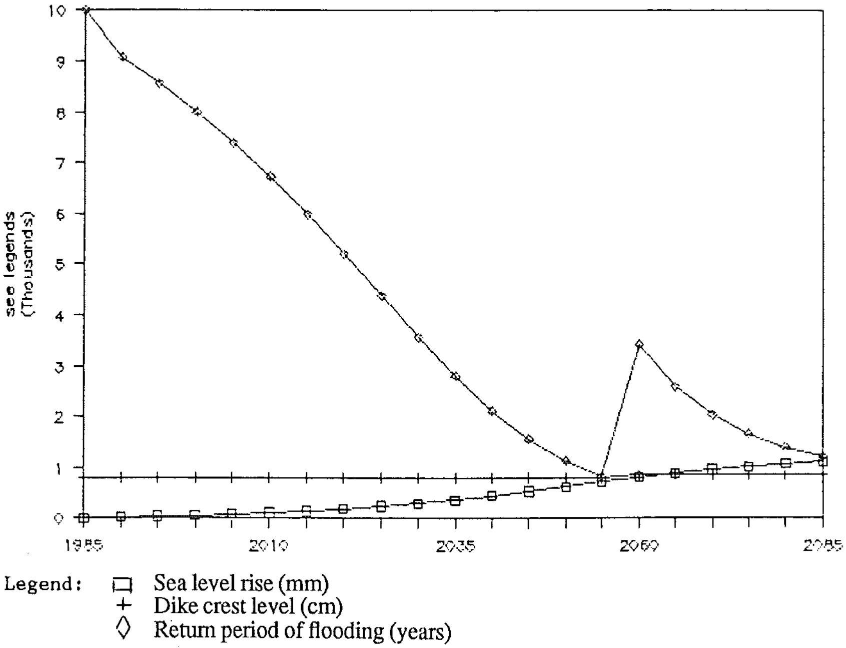


Figure A5. Return periods of flooding for Case 9 segment A.

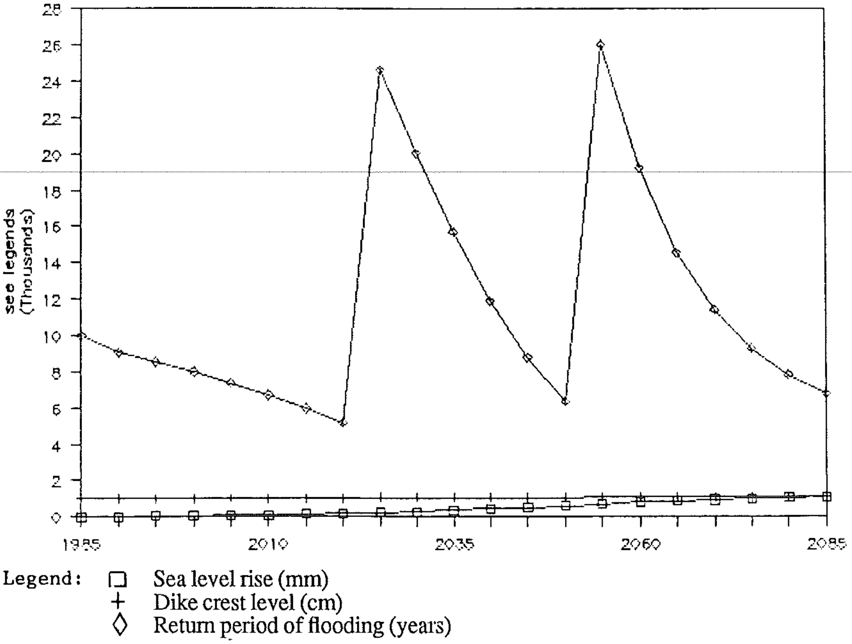


Figure A6. Return periods of flooding for Case 9 segment B.

CHAPTER 3

An outline of the contributions to the workshop

EGGE ALLERSMA & HERMAN G.WIND

In this chapter an outline is presented of the contributions of the participants of the ISOS Workshop. The full text is attached as an Addendum at the end of the book.

1 THE LOWER COUNTRIES AND A HIGHER ATLANTIC

H.A.Becker

A mental experiment

Conservative forecasts lead to a sea level rise of one metre in the next century, but the uncertainty is such that 'low probability – high impact' considerations lead to 2 m in the first century and another 3 m in the following hundred years. The process gradually lowers the coastal lands in respect to mean sea level. It reduces the safety in large areas and it inflicts considerable losses in the form of damage and counter-measures.

The effects of sea level rise are discussed in the form of a mental experiment based on a limited number of assumptions mainly for the case of the Netherlands as a country, but also in view of similar conditions in Europe and the rest of the World.

The main questions to be answered are:

- What are the expected societal developments?
- What will be the rise and what will be the induced developments?
- What will be the impacts on society, and how can positive impacts be enhanced and negative impacts be limited?

Development of Dutch society

The society, in the next 100 years, is expected to develop mainly in the application in the fields of 'physical' and 'social' technology, i.e.:

- more of the same;
- integration of markets leading to reduction of migration but involving

tensions during the integration process;

- a more value oriented attitude with more equality and emancipation;
- a growth of the national income related to the integration of markets and improvement of well-being.

In view of these assumptions, two extreme scenarios can be designed viz.:

- an upward spiral in societal development leading to a willingness to bear the costs of countermeasures, and
- a downward spiral in development, probably worsened by the sea level rise, and not allowing for the full absorption of the impacts.

Coastal protection

Protection against the attack of the sea has a place on the political agenda. It may have to become even more prominent and require more sophisticated technology. Critical accidents have proven to influence public opinion. The reaction may roughly take the form of one of the following three variants:

- Increased traditional efforts meeting the threat;
- a vanguard defence off the coast creating a double defence; or
- partial abandonment of land and retreat of the defence line.

Choice of the second variant seems the most promising in view of safety.

Strategies

The rising sea level will constitute a scientific and technological challenge, and an economic impact influencing the societal development. The response will depend on the propensity and the ability to invest resources (economical and social) on a national scale in an amelioration of the sea defence. Much depends on the more or less autonomous development of the country as a whole according to one of the two scenarios.

Conclusions

This brain game, with arbitrarily chosen assumptions, does not lead to a forecast. That is simply impossible with a time horizon of 100 years and within a short essay. Nevertheless, some tentative conclusions can be drawn:

- the impacts depend on the general ups and downs of society during the period;
- what would be a disaster in a poor country would be a minor inconvenience in a prosperous society;
- the development of physical and social technology may be deliberately influenced in the course of a century;
- an active attitude with respect to scenarios can lead to an imaginative approach to this complex problem.

2 THE CAUSES AND EFFECTS OF SEA LEVEL RISE

J.G.Titus

Causes

The worldwide average sea level depends mainly on the shape and size of the oceans, the amount of water in these oceans and the average density of the sea water. The expected global warming would accelerate the rate of sea level rise by expanding the ocean water, by melting glaciers and, eventually, by causing polar ice sheets to melt and slide down into the oceans.

Global average sea level has risen 0.1 to 0.15 m over the last century. Ocean and glacial studies suggest that the rise is consistent with model simulations based on a warming of 0.4°C over the past century. However, no cause and effect relationship has been conclusively demonstrated.

The predicted future global warming could cause the global average sea level to rise 0.1 to 0.2 m by 2025 and 0.2 to 2 m by 2100. Thermal expansion could cause a rise of 0.25 to 0.8 m by 2100, Greenland and alpine glaciers could each contribute 0.1 to 0.3 m. The contribution of Antartic deglaciation is likely to be between 0 and 1 m. However, the possibility cannot be ruled out that increased snowfall could increase the size of the Antartic ice sheet, or that meltwater and enhanced calving of the ice sheet could increase the contribution of Antarctica to as much as 2 metres.

Disintegration of the West Antarctic ice sheet might raise sea level an additional 6 metres over the next few centuries. Glaciologists generally believe that such a disintegration would take at least three centuries, and probably as long as 500 years. However, a global warming might result in sufficient thinning of the Ross and Filcher-Ronne ice shelves in the next century to make the process irreversible.

Local trends in subsidence and emergence must be added or substracted to estimate the sea level rise at a particular location.

Effects

A substantial rise in sea level would permanently inundate wetlands and low lands, accelerate coastal erosion, exacerbate coastal flooding and increase the salinity in estuaries and aquifers. The human response may vary between complete abandonment of the land and adequate protection; depending on the physical and socio-economic conditions.

Bangladesh and Egypt appear to be among the nations most vulnerable to the rise of sea level. Up to 20% of their usable, and densely populated, land could be flooded with a 2 m rise in sea level. A large fraction of the world's coastal wetlands may be lost, threatening fishing breeding grounds. A rise of 1 to 2 m by 2100 could destroy 50-80% of the coastal wetlands in the United States. No estimate of the worldwide impact is available but the U.S. figure may be representative.

Coastal erosion could threaten recreational beaches throughout the world. Case studies have concluded that an 0.3 m sea level rise would result in beaches eroding 20-60 m or more. Only major beach preservation works can avoid unacceptable narrowing of the beaches and damage to property.

Sea level rise will increase the frequency of high floods, thus causing more damage and requiring more flood protection and more flood insurance. Increased salinity from sea level rise would convert swamps into open water and threaten water supplies.

Future sea level rise may already be an appropriate factor to consider in designing coastal drainage and flood protection structures. It may put restrictions on the development of coastal areas.

Other impacts of global warming might offset or exacerbate the impacts of sea level rise. Increased draughts might amplify the salinity impacts. Increased hurricanes and rainfall in coastal areas could amplify flooding. Higher temperatures might enable mangrove swamps to advance further from the equator and cause a more rapid vertical accretion in large areas.

3 SEA LEVEL RISE ON THE AWAKENING EARTH

H.Tennekes

Some fragments of a vision

1. Mother Nature may act in unexpected ways when she is confronted with the impact of technological progress.
2. The self-organizing potential and the regenerative power of the planet system (Gaia) are poorly understood and may lead to unexpected reactions.
3. The world may need a global meta-strategy (Genesis) to cope with a great variety of 'lean years'.
4. Predictability of phenomena is greatly limited by chaos and non-linearity but in many cases coherent structures appear to arise from apparent chaos.
5. The possibility of the emergence of a global consciousness on Earth cannot be dismissed.
6. Humanity is part of the global body, but is it the triumph of evolution or some malignant growth?
7. Are natural disasters so much worse than man made ones?

A review from science

A continuing sea level rise may increase the interest in earth sciences on a global scale with, probably, a special international organization.

Meteorologically, nature is not necessarily our enemy. In this case it is mankind itself and it could be the same agressor that would create forests and reduce CO_2 production to redress the situation. It may not yet be too late.

Although of limited value due to the finite predictability horizon, models of non-linear systems may only serve to scare us when contemplating the consequences of our own stupidity.

4 THE DATA ACQUISITION OF AND TRENDS OBSERVED IN GLOBAL MEAN SEA LEVEL

P.L.Woodworth

Mechanisms

There is still considerable difficulty in accounting for the magnitude of the estimates of global sea level rise over the last century. Air temperatures are known to have increased; probably associated with a number of forcings, such as CO_2 concentration and volcanic activity. The evidence for a corresponding rise in sea temperatures is controversial and cannot explain the whole sea level rise.

Glacier melting, reduction in size of solar ice caps, fluctuations in Antarctic precipitation, variation in the earth's rotation rate and polar motion are other related natural phenomena. Construction of reservoirs, irrigation works and other human activities may also influence the amount of water in the oceans.

As our knowledge of the total mechanism is hardly able to explain the observed 2 mm/year rise of sea level, predictions of future changes of sea level are extremely uncertain. More monitoring of the various parameters and more realistic modelling of the climate and the ocean-atmosphere system are urgently required.

Data management

The Permanent Service for Mean Sea Level of the Institute of Oceanographic Science collects and distributes data from stations all over the world. At present, most information pertains to North America, Europe and Japan. Many records are of limited value due to uncertainty about the datum, local tectonics, etc.

Global estimates of sea level change can be improved by three means viz.:

- better geographical distribution of the tide gauges;
- independent measurements of vertical land movements, and
- removal from the records of 'noise' caused by oceanographic and meteorologic phenomena.

Detection of trends

Recent estimates of a 'global average' value for the rate of sea level rise vary between 1 and 3 mm/year. The most recent trend for the period of 1881-1980 is 1.43 ±0.14 mm/year with little or no change during the first half of the period and a rate of 2.27 ±0.23 mm/year between 1930 and 1980. This leads to the conclusion that the present rate is uncertain to within at least a factor of 2.

Prediction of future trends is even more difficult. An increase of ocean temperature is believed to lag one or two decades behind the air temperature while melting of glaciers is a relatively instantaneous process. Therefore, a first indication must be expected from the air temperature and glaciers, but not from the sea level.

The detection of a statistically significant acceleration in the records over the next 50 years appears extremely difficult.

Case studies

For the three ISOS case studies, the data about the southern North Sea are relatively abundant, for the data about Bangladesh no detailed datum information is available and very little is known about the Maldives.

Mean sea level in Holland and Bangladesh are considerably influenced by local conditions such as subsidence, wind, air pressure, river discharges, tides, etc. This is even more true for extreme high waters. These factors have to be studied and taken into account in an estimate of the local change of mean sea level as related to a global rise of mean sea level. This will require modelling of the local phenomena, using parameters based on observations in the present situation.

Although islands in the open ocean, such as the Maldives, are unlikely to suffer from large storm surges, observations may lead to more knowledge about mean sea level variations as well as the occurrence of extreme levels.

5 ESTIMATING THE IMPACT OF INUNDATION

R.S.Chen

Many effects of a climatic change are still unclear, even qualitatively. The accelerated rise of global sea level is only one aspect, the impact of which is relatively easy to assess. The present value of property represents a first order estimate of the effect of inundation of an area.

Coastal USA

Topographic maps and data from censuses lead to a fairly good estimate of land area, people and property involved in inundations in coastal United States of America. In total, a sea level rise of 4.6 m would roughly effect an area of about 100,000 km^2 with 10 million inhabitants and US$ 100 billion of estimated market value. The most vulnerable states are Florida and Louisiana but inundation may also threaten considerable percentages of the land of Delaware, Maryland, the District of Columbia, New Yersey and The Carolinas. The area is small but the socio-economic impact is large in New York.

Dynamics

A more dynamic approach to the problem should take into account the existing experience with similar phenomena. Coastal erosion is occurring world-wide and takes about US$ 300 million annually in the USA alone. Storm damage is also a well-known phenomenon. Land subsidence can have natural causes (Venice) but mining activities lead to even more rapid sinking of large areas (Texas, Japan, Bangkok). The Great Salt Lake and the Great Lakes are examples of a rising water level.

Studies of these analyses might shed light on the possible effects of an accelerated sea level rise on environmental, economic, psychological, cultural and other factors.

6 CONSEQUENCES OF SEA LEVEL RISE: IMPLICATIONS FROM THE MISSISSIPPI DELTA

J.W.Day Jr

The Mississippi Delta

With its apparent sea level rise of about one metre per century for a very long time, the Mississippi Delta can serve as a good example of the effects to be expected from an accelerated sea level rise over larger areas in the future.

The present delta of the Mississippi River has been formed during the past 5000 to 7000 years by a large supply of sediments despite of continuing subsidence. About 20,000 km^2 of its total area of 50,000 km^2 are wetlands; the rest consists of shallow aquatic systems and low ridges.

Over the past several decades the process has reversed in an accelerating land loss which is now 100 km^2/year. The cause is a vertical aggradation deficit due to:

- reduction of the sediment input from the river and the sea;
- intrusion of salt water; and
- deterioration of the wetland vegetation.

Flood control and water management led to bundling which prevents the intrusion of sediments and nutrient river water. Reclamation and salt intrusion reduce biomass production in wetlands. In this way human intervention leads to a reduction of vertical accretion, to changes of wetlands into water and, eventually, to submergence.

The complex organisation of the management of the area, with conflicting interests and property rights, leads to an erratic, sometimes adverse, response to the problem.

Implications for other regions

Lessons to be learned from experience with the Mississippi Delta are:

1. With sufficient sediment input, coastal regions can withstand a consider-

able sea level rise; provided that the system remains open for sediment distribution;

2. Critical problems are submergence and salt intrusion;
3. Causes of insufficient vertical accretion are reduced sediment input and reduced biomass production (salinity and reclamation);
4. There is a time lag of several decades between the sea level rise and the effects becoming exponentially apparent;
5. Low land is more vulnerable, especially in large flat areas with a small tidal range and few floods;
6. Sea level rise must be adequately monitored;
7. The first effects of accelerated sea level rise will become visible in areas with small tides such as the Gulf of Mexico, the Mediterranean and the Black Sea;
8. In view of the time lag and the exponential effect, measures should be taken at an early time although it will be difficult to prove the need;
9. Measures must be carefully considered to avoid mistakes;
10. Flood protection must be combined with the spreading of sediments;
11. Landownerships, legislation and agriculture are major complicating aspects of the management;
12. The use of natural forces (wind, water, sediments, vegetation) in ecological engineering is recommended;
13. Coordination of longterm planning is required.

The first step to be taken against the rising sea level is monitoring of the changes of the levels of the water and the land in a number of locations on earth. A powerful tool appears spatial modelling of the development of a coastal area.

7 ECOLOGICAL EFFECTS OF A RAPID RELATIVE INCREASE OF SEA LEVEL

W.J.Wolff

Species and environment

Generally, the environment determines which species of plants or animals can occur in a particular place. A rise of sea level will change the aquatic environment of all coastal plants and animals. For some terrestrial species also the hydrological conditions may change. As sea level rise will not be an isolated process, its effects combine with direct consequences of increased CO_2 levels and climatic change.

Geological processes

Sea level changes as predicted have been normal geological processes during recent successive glaciation periods. As the rate of evolution of species is small compared with the time scale of these changes of sea level, all present species have survived such events.

Coastal species of plants and animals live in ecosystems which occur in zones parallel to the coast. Geological record and historical data show that these zones react to a sea level rise with a landward shift. The same may be expected in the future.

Effects of sea level rise

In view of these considerations, it seems unlikely that many species will become extinct due to a new sea level rise. The majority of the plants and animals will gradually shift landward, with more or less time lag depending on their nature. Morphological processes will play a role in this general migration.

Human intervention may lead to a different result because the zones cannot pass a defended coast. Then some ecosystems may disappear. Within the protected area, changes depend on the indirect changes of the environment.

The ecological changes will influence human use of the environment. Fisheries resources will change. Certain species may decrease especially along shores with human intervention. Agriculture will be forced landward along unprotected coasts. Salt marshes along protected coasts may reduce in area. Forestry will react with a relatively large time lag. It may be expected that some nature reserves will change considerably or even be lost.

8 SOME POLICY-ORIENTED OBSERVATIONS CONCERNING SEA LEVEL RISE

T.Goemans

Context and impacts

Sea level rise is only one of the consequences of the increasing atmospheric CO_2 concentration. During its development, in the course of a hundred years, also the societal context will change considerably. Climate changes will differ regionally and there will be winners and losers. But the rise of sea level will only be a loss for all coastal areas.

The expected impacts will be:

- loss of land by inundation and erosion;
- increase of storm damage;
- change of the morphology and the ecology;
- intrusion of salt water, and
- rising of river water levels.

Strategies coping with these impacts can essentially take two extreme forms, viz.:

– accepting the retreat of the shoreline meaning loss of property and migration of people; or

– protection of the coast at the price of a coastal defence system.

For poor countries, the first may be the only strategy possible. Giving up the highly developed West European coastal areas seems unthinkable.

Strategies

The uncertainty about the rate of sea level rise leads to the use of various scenarios to determine impacts and costs of protection by alternative strategies. During several years, the Netherlands has spent about 0.1% of its GNP on coastal defence works. Can the world's coasts be defended for 0.1% of the GWP (US$ 10 billion) and will the world provide that amount for the purpose?

In this respect three observations may be useful:

– decision makers are more apt to react to discrete events than to slow developments;

– the burden of protection will be unequally distributed and it will not allways be imposed on the causers of the damage; and

– other related climatic changes may complicate the battle for monetary resources.

9 SEA LEVEL RISE, EVALUATION OF THE IMPACTS OF THREE SCENARIOS OF SEA LEVEL RISE ON FLOOD PROTECTION AND WATER MANAGEMENT OF THE NETHERLANDS

W. van der Kley

The Dutch Ministry of Transport and Public Works has evaluated three scenarios of sea level rise with respect to their impacts on flood protection and water management. The chosen future developments of sea level are:

1. Continuation of the present trend of 0.2 m per century;
2. An extra sea level rise of 1 m between 2000 and 2100 and the present trend after that time, and
3. A continuation of the rise after 2100 with 5 m in 300 years.

Only the consequences of the sea level rise are considered; possible climatological changes are disregarded.

Scenario 1 will lead to some local problems which can be solved by the present protection policy and management, at least during the coming two centuries. The present morphologic and ecologic developments will continue.

Scenario 2 will require considerable measures but it will not change the 'face of the Netherlands'. Measures can rely on existing and well-tried principles.

The expense is in the order of Hfl. 10 billion. The rapid rise will upset the morphologic system in the coastal zone, the estuaries and the Wadden Sea.

The drainage system will have to be adjusted. River stages and the river beds will rise in upstream direction. The intrusion of salt water will require careful consideration. Dunes will erode and sea defences have to be strengthened. Certain navigation facilities will require adaptations.

Scenario 3 will deviate from 2 after 2100. It will require very large integrated efforts and measures of broad scope. Decisions are not necessary in the coming decades. Abandonment of large parts of the country seems not necessary but the 'face of the Netherlands' will change drastically; especially in the coastal zone. The morphological systems of the delta, the coast and the Wadden Sea will be severely upset. There will be an urgent pressure to close the whole coast. Total expenditure will be at least Hfl. 40 billion in the 22nd and 23nd centuries.

The drainage system, also of the main rivers, will require a drastic adjustment. The Wadden Islands may migrate to the coast. Sea defence will require enormous efforts with the closing of more estuaries. Water supply will be threatened by salt intrusion.

Choice of strategy

The necessity of an anticipation for an uncertain future is clearly present. Monitoring of the process is very important because the information is required as a base for decisions. Some of these have to be made around 2030. Because the phenomenon is man-made, the possibility of influencing the process must not be excluded.

10 IMPACTS OF A RAPID RISE OF THE SEA LEVEL ON FLOOD PROTECTION AND WATER MANAGEMENT OF LOW-LYING COASTAL AREAS

A. Volker

A rapid rise of the mean sea level of 1 to 2 metres in 100 years will have a considerable impact on all environmental conditions in low deltaic areas, coastal marshes and embayments in coastal lowlands. They are often densely populated, (with large cities and harbours) and highly productive in the agricultural sector. The impacts on morphology and water quality will lead to countermeasures in the fields of flood protection and water management.

Morphology

A common situation is that of a growing delta. The land areas are built up by sediments from the river and the sea; to an elevation slightly above high tide in the coastal strip and to the level of the 1 to 5 years' flood along the rivers. So, the land level rises and the delta accretes into the sea. The whole process is strongly related to the local relative change of mean sea level.

A rapid increase of the global rise of mean sea level will upset the present dynamic equilibrium. The process will adapt to the new rate of rise which generally means a slowing down of the rate of accretion; even recession and drowning may be the result.

Flood protection

A rise in mean sea level will also influence the propagation of the tides and the generation of storm surges. Sea dikes will have to be heightened, often even more than the rise of mean sea level. In some cases a shortening of the coastline by enclosure of embayments may be feasible. The rise of sea level and the related backwater effects increase the water levels in the estuary and, with some time lag, in the lower part of a river. In these areas also the flood protection has to be adapted.

Water quality

A rise of mean sea level will cause the heavier saline sea water to intrude more upstream in estuaries. The salt renders the water unsuitable for many purposes; especially during periods of low discharge when the need for fresh water is high. The eco-system will also be affected.

The seepage of salt water from the sea and from estuaries into the coastal aquifers will increase considerably as a consequence of the increased head as well as the increased penetration in the estuaries. In much larger areas in (especially arid) coastal zones, the ground water will become brackish and will require countermeasures.

Water management

In many humid tropical areas without storm surges, rice is grown on land with little protection against floods by fresh river water. A rise of sea level of 1 m or more will upset these conditions and require measures to maintain the present levels of productivity.

In embanked areas with artificial drainage the lifting capacity of the devices has to be increased. In some cases, gravity drainage will have to be replaced by pump-lifting.

Although salt intrusion may adversely influence the availability of water for irrigation, and require intakes more upstream, the resulting increase in head may be beneficial.

Cities, harbours and other industrial areas will have to be protected from flooding by water from the sea or the river by embankments and from precipitation by pump-lift drainage.

The drainage of coastal storage reservoirs to the sea will be hampered by a substantial rise of sea level and their operation may require considerable adaptation.

Planning

The planning, world-wide, of all measures required to cope with the predicted rise of sea level will encounter two fundamental difficulties, viz.:

– the predictions of a possible sea level rise are most uncertain and may remain so for the coming two or three decades, and

– the detection of a change of the ratio of rise will require observations during at least 5 to 10 years.

This means that remedial measures will always lag considerably behind actual hydrographic developments. It has been proposed to examine the implications of these difficulties for the Rhine and Meuse Delta, the Mekong Delta and the Nile-Delta, for which adequate information is available.

11 SOME REMARKS ON ECONOMIC IMPACTS OF SEA LEVEL RISE AND THE EVALUATION OF COUNTER-STRATEGY SCENARIOS

R.H.Funck

The decision problem

Sea level rise is defined as its probability being Δh varying between 0 in 1986 and unity in 2086. Countermeasures must be planned and executed within such a time that the probability of a serious sea level rise to occur during that period will be sufficiently low to constitute an acceptable risk. The evaluation takes place from the point of view of the national economy taking into account regional differences. Basically two strategies are regarded viz.: saving of the land (involving technical protection measures) and resettlement, to be realised depending on the scenario considered.

The cost-benefit methodology is considered the most convenient approach in view of the purpose and the applicability of possible methods. A multi-criteria evaluation is kept in mind for the evaluation of social values to which prices cannot be attached.

Strategy alternatives

The spatial distribution of socio-economic values in an area generally leads to the identification of some discrete alternative scenarios instead of a spatially continuous evaluation.

An important element in the evaluation is the social rate of discount. Only with a rate below four to five percent, caring for the well-being (or even for the continuation of life) after a century will influence current decisions. National budget can also pose an important restraint. Others are the capacity of the construction industry and problems with the interregional redistribution of impacts in the socio-economic field.

Socio-economic framework

The main socio-economic effects of the sea level rise and its counter-strategies to be determined in the evaluation of strategies are:

- construction;
- change of (real) national income;
- migration;
- loss of land and production;
- environmental changes; and
- social disturbance.

Evaluation

Then, the evaluation of the stategies will involve a cost-benefit calculation for each of them as well as a weighing and comparison of the various societal factors. This should lead to the strategy with the most acceptable combination of economic and social effects.

This evaluation of strategies supplies structured information on their relative desirability to be taken into account in the political decision process. The fact that the future of the sea level rise is quite uncertain, requires the development of a more precise view. It seems possible that public pressure will raise the value of the societal factor so high that it precludes certain technically feasible alternatives.

12 SOME SOCIETAL CONSEQUENCES OF THE RISING SEA LEVEL

L.H.Klaassen

A theoretical framework is developed in which various types of costs related to raising dikes and increased safety are incorporated. Assumptions about the value of human life, underlying decisions to increase safety of sea defence structures, are pointed out.

The total damage (Z), defined as the cost of dike rising (K) and the damage to capital and human life (A) inflicted by a catastrophe with probability P(x) can be expressed as

$$Z = K_o + k\,l(x - x_o) + P(x)\,A$$

where

K_o = fixed costs of dike raising,
k = marginal costs of dike raising per unit of length,
l = length of the dike,
$P(x)$ = probability of a catastrophe with the dike at level x,

A = value (per catastrophe) of capital and human life and their future development.

If further the probability of a catastrophe is assumed to be

$$P(x) = e^{-\alpha(x-\bar{x})}$$

where $\bar{x}$ = reference water level with $P(x) = 1$

then the total damage Z reaches a minimum when

$$x - \bar{x} = -\frac{1}{\alpha} \ln \frac{kl}{\alpha A}$$

This equation relates the value of capital and human life to the height of the dike. Inversely, the establishment of the height of a dike (with a certain flooding chance) implies the valuation, in money terms, of human life.

Addendum

1 THE LOWER COUNTRIES AND A HIGHER ATLANTIC[1]

Henk A.Becker

In the next hundred years a rise of the sea level will force the Netherlands to strengthen its coastal protection. Conservative forecasts mention sea level rises up to 1 m in the next hundred years. If we look at forecasts falling into the category of 'low probability-high impact' we find a rise of 2 m in the first hundred years and a further rise by 3 m in the hundred years to follow. Higher dikes can protect the densely populated areas below sea level in the Netherlands to a limited extent only, however. If Dutch society gets caught in a downward cultural, economic and social spiral, improving the defence against the sea will become difficult. If military or civil wars occur it will be a considerable disadvantage that millions of inhabitants of the Lower Countries live below sea level. If on the other hand Dutch society shares in a development towards a more positive cultural, economic and social order, there is a chance that the investments for improving the system of dikes and dunes can be realized without too much difficulty and that a relatively safe type of protection against the sea can be built. A substantially higher sea level may provide opportunities for producing electricity by using water power in the Netherlands. This contribution provides a mental experiment, based on a limited number of assumptions.

1.1 TOWARDS A MENTAL EXPERIMENT

An exploration of the impact of sea level rise on society in the next hundred years requires some preliminary methodological considerations. Is there the scientific know-how available to handle questions related to developments in the natural environment and in society in the next hundred years?

The only approach suitable for this type of question is called a 'gedankliches Experiment'. It originates from history, and the historian and sociologist Max Weber has applied and improved this method (Weber 1968:287). A mental experiment starts with stating the assumptions that will be used. The assumptions provide the frame of reference for the 'brain game' of speculating about future events that constitute the main activity in the experiment. Mental experiments may be executed by applying discursive reasoning. Sometimes quantified models are used, for instance a computer simulation mainly based on estimations of the values of the variables involved. Running a quantified model of this type naturally remains a 'mental' experiment if most of the variables involved are not based on empirical evidence.

In this contribution the mental experiment will deal primarily with the Netherlands. The political boundaries of this country in the mid-eighties of the twentieth century will not be taken too seriously, however, because developments over a period of hundred years are involved. The Flemish part of Belgium or the western part of Germany will be taken into consideration also if necessary. The Netherlands will be looked at in its geographical setting, relating it to other countries in Western Europe and 'the West' in general. Countries in other parts of Europe and in northern Africa will be added into the process if and when necessary. In some instances an even larger area has to be considered.

A consideration of the societal consequences of sea level rise implies an analysis of a macro-system in an institutionalized setting. We are dealing with a nation with a long historical tradition, a specific language and a geographical area of its own. In a case like this we can select a number of approaches that still fall within the category of the mental

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[1] Parts of this contribution have also been published in *Social Scenarios of Sea Level Rise*, June 1987.

experiments but that provide opportunities for a relatively focused analysis. We can apply 'historical analogies' (Martino 1975:91). We can also use (speculative) contextual scenarios, strategies and impact assessments. In this way we can for instance profit from experiences with futures studies gained by Shell and other business enterprises (Beck 1983). The scenario approach has a terminology of its own. A short taxonomy is given in Appendix 1.1.

Keeping these methodological considerations in mind we can formulate the following cluster of questions that will be dealt with in this contribution:

a) what are the main developments to be expected in Dutch society in the next hundred years, taking the external relationships of this country into consideration?

b) what has to be expected with regard to sea level rise and other developments inducing the Netherlands to strengthen its coastal protection, and which coastal protection solutions are available?

c) what impacts will the sea level rise have on Dutch society, and what impacts will be generated by the projects to improve the protection against the sea? How can positive impacts be enhanced and negative impacts be curbed?

Changes in the natural environment, alternative solutions to the coastal threat, risk analyses and benefit-cost estimates are not dealt with in detail in the present contribution, but are treated in other contributions.

1.2 DUTCH SOCIETY IN THE NEXT HUNDRED YEARS

A general assumption is , that the development and application of technology will be the main factor differentiating Dutch society in 2086 from its predecessor in 1986. Technology, defined in a broad sense, can be seen as the prime mover for the next hundred years. By technology I mean know-how with regard to the gathering, storage, analysis and transmission of data and with regard to the management of and intervention in society. Essential to this general assumption is a decrease in the differences between 'physical' and 'social' technology. Advancements require favourable developments in both physical and social technology.

Starting from this general assumption I now formulate a number of interrelated assumptions on a less abstract level:

1. By 1986 technology had evolved sufficiently to make it possible to estimate the further development of technology in the next hundred years. In this period technology will be 'more of the same'.
2. Technology will influence countries in western Europe and (to a lesser extent) elsewhere primarily by stimulating an integration of markets.
3. Integration of markets will slow down migration from poor to rich countries.
4. Tension and conflict in Dutch society in the next hundred years will be strongly related to the integration of markets. If the integration of markets (internal and external) stagnates, huge numbers of migrants from economically depressed areas will enter the Netherlands, causing cultural, economic and social tension. If on the other hand an integration of markets progresses, economic differences can be diminished and mass migration can be avoided.
5. The cultural changes of the last decades will continue in the next hundred years. This applies especially to the value-orientation towards equality. Continuing emancipation will be regarded as a matter of course. The quest for equality will trigger demands for redistribution of income, power and privileges. Value-orientations towards the natural environment will develop along the lines of the last decades, unless a major effort is made to diffuse value-orientations of a different kind. The strength and weaknesses of social technology are documented in Rogers (1983).
6. The growth of the national income in the Netherlands will be related to the integration of markets.
7. The improvement of well-being will be related to the cultural changes and the growth of the national income and its distribution.

These assumptions are neither original nor empirically 'tested'. They provide a frame of reference for designing images of the future and images of processes leading to these futures. Each assumption may require more arguments.

The assumptions are related to the Netherlands and its external relationships. Within this context our attention will focus on the actors directly related to the defence against the sea. The government agencies, private corporations and pressure groups constitute the focal system for our analysis.

The next step is the design of two contextual scenarios describing more or less autonomous developments confronting the Netherlands, and within this country the coastal defence system.

The first contextual scenario will be called upward spiral. In this scenario a high growth of technology is a basic assumption and integration of markets is favourable. Migration towards the Netherlands remains within limits that do not raise major difficulties. Tensions and conflicts can be kept at a low level. The quest for emancipation, equality and environmental protection is strong but reasonable. Material prosperity is high, feelings of well-being are on a high level, and the political powers are willing to bear the costs of improving the coastal defence. In short it is an extremely favourable prospect.

The second contextual scenario is the downward spiral. In this scenario technological growth is generally slow, or one or more components lag behind. The integration of markets slows down and economic differences may trigger mass migration. Albeda (1986) has drawn attention to the fact that western Europe lives on a demographic volcano. Between 2015 and 2020 France, Germany and Italy together will have about 140 million inhabitants. The countries on the other side of the Mediterranean will host 350 to 380 million people. If the inhabitants of the developing countries become aware, that the difference in prosperity between their countries and the developed countries will remain the same or even increase, their patience will become exhausted. If developing countries are not rewarded for waiting quietly for better times, their ultimate reaction is predictable. The result will be mass migration towards the rich, underpopulated areas. In this contextual scenario the cultural change of the seventies and early eighties is extrapolated to the future in the upward spiral scenario. Tensions and conflicts will, however, make the demands for redistribution of incomes, emancipation and environmental protection more difficult to meet. The national income will be too low to 'buy off' social problems. Feelings of well-being will become scarce.

The two contextual scenarios do not represent linear developments. They will show ups and downs, loops and temporary breakdowns. To emphasize this they have both been called 'spiral'. Of these two contextual scenarios the 'downward spiral' is by far the most plausible. A doomsday scenario like the second one is not a forecast of an inevitable future, however. Intervention (timely, large scale) could change the course of events.

In Appendix 1.2 an overview is given of the two contextual scenarios. To this overview information on other questions is added. A blank column invites the reader to design his or her own contextual scenario, strategies and impacts.

1.3 RISES OF THE SEA LEVEL AND PATTERNS OF COASTAL PROTECTION

A major flooding dominates the area of coastal protection in the Netherlands in the last decades. In 1953 a storm swept up the North Sea, dikes broke, a considerable number of people were killed and thousands had to leave their homes. In the years to follow the Delta Works were built. One of the last major constructions was the Easterscheldt barrier. The financial aspects of the Easterscheldt barrier have generated quite a lot of unfavourable publicity in this country.

The Delta Works got political and public support as a result of the disaster in 1953. Similarly, some decades earlier, the Zuyder Sea could be separated from the North Sea by a dike only because a disaster had taken place. Would it be carrying historical analogies too far to suppose, that only a major disaster in the future will induce decision-making bodies in the Netherlands to allocate enough funds for the building of new dikes and similar protective constructions?

Protection from the North Sea is one issue out of many struggling for a place on the political agenda in this country. It will require sophisticated social technology to provide protection from the North Sea with a lasting position in the political arena.

With regard to the physical changes to be expected a number of expectations have been voiced:

a) as 'high probability-high impact' a sea level rise on the Dutch coast up to 1 m in the next hundred years,

b) 'low probability-high impact', 2 m sea level rise in the first hundred years, followed by another rise of 3 m in the following hundred years,

c) 'low probability-high impact', changes in the climate that will bring hurricanes to the Dutch coast that are familiar now only to tropical areas.

The political and construction side of the issue will be determined to a large extent by critical incidents. As an example of a critical incident major floodings have been mentioned already. These can be influencial if they happen in the Netherlands, in surrounding areas like the Belgian or German North Sea coast, or in other regions. As a rule only a disaster that occurs nearby has an impact on the political powers or the public in general.

Which solutions have been brought forward with regard to the defence of the Dutch coast against the rising of the North Sea? As stated in other contributions, three variants have been elaborated, on a speculative basis.

In the first place a conventional solution in which existing dikes are improved. The dunes will be repaired as soon as they lose sand and because the sand does not disappear, it can be brought back to the dunes again. In places where the dunes only provide a slim line of defence, it may be necessary to construct hidden 'thresholds' of concrete. These thresholds will protect the area behind the dunes in the case of an emergency, long enough to prevent flooding. Later on the sand can be restored to the dunes. One of the interesting aspects of this solution is the decision not to replace dunes by dikes. The ability of dunes to provide a flexible response to the sea has been underrated in the past.

A second variant is a vanguard dike alongside the line of dunes. This vanguard dike would create a lagoon ten to twenty km wide. Of course this variant could also include protective measures for the line of dunes, for instance hidden thresholds.

A third variant proposed a partial abandonment of the areas that now constitutes the Netherlands. Large parts of the provinces of Zeeland, North Holland, Friesland and Groningen would be left out of the new pattern of dikes and only the big cities like Amsterdam, The Hague and Rotterdam would fall within the next line of protection against the North Sea.

These solutions have been designed primarily against a rise of the sea level. Additional protection against a change in the pattern of storms related to a change in climate has not been included. If changes in this respect are taken into consideration, the second alternative seems the most promising solution. It provides a double line of defence and it does not involve the resettlement of a large number of people. The second alternative would change the coastal area in an ecological sense to quite an extent, however.

1.4 IMPACTS AND MAIN STRATEGIES

The sea level rise and the potential solutions in the field of dikes etc. are discussed below in relation to developments in Dutch society at large and to the strategies Dutch political actors might follow. Only a brief sketch can be given here. The pattern of assumptions described in Section 1.2 also provides a scheme for the discussion in this section.

The rising sea level constitutes a challenge of major importance to technological developments. It might trigger the R&D to stimulate a balanced growth of both physical and social technology. A development of both the major sides of technology is necessary because not only physical problems are involved. The willingness to invest resources on a national scale to improve sea defences requires systematic and reliable social technology. Are the social sciences prepared to cooperate? They have 'audited' a large number of old forecasts (Ascher 1978, Makridakis et al. 1984). They have also evaluated more than three thousand old innovations (Roger 1983). In short they have adopted the approaches that have been applied in other empirical sciences to make progress in forecasting (e.g. Schuurmans 1981) and intervention.

Next we take a look at the integration of markets. The rise of the sea level will force not only the Netherlands but also neighbouring countries and countries far away (Bangladesh for instance) to make major investments in an improvement of their sea defence. This drain on their national income would become less heavy if the national income increased as a result of an integration of markets. Advanced technology could improve telecommunications, especially 'work at a distance'. By bringing employment to developing countries they can increase their national income and the propensity to emigrate would become less severe.

This brings us to migration. Tinbergen has pointed out, for instance, that a redistribution of employment and income between nations is necessary to increase the chances for less tension and conflict. Albeda, as cited, draws attention to the 'population volcano'. Disasters like floods in other countries may increase the flow of immigrants to the Netherlands.

Tensions and conflicts have been touched upon indirectly already in this section. In periods of military or civil war a double line of protection against the sea as provided by the second alternative (vanguard dike) would be very important.

The issue of cultural values demands special attention. Danzin (1977) has pointed out that the challenges confronting western Europe are severe. According to him only a Second Renaissance would provide a basis for meeting these challenges. Of course a development like a 'renaissance' cannot be evoked by any of the social technologies available. In any case it is necessary to avoid policy measures that repress a revival of western Europe.

How is welfare related to the issues under consideration? As already mentioned, an integration of markets could result in a rise of national incomes that could meet the cost of investments needed to improve sea defences without too much difficulty. A cost-benefit analysis of such investments is given in another paper. At this point it is interesting to take into consideration that a higher sea level increases the prospect of producing electricity by using water power. Peak hour electricity for instance could be produced by using water behind high dikes. A major change in the tidal pattern on the Dutch coast is not to be expected, as another paper points out.

As a last point well-being is reconsidered. A higher sea level will force the Dutch population to improve its patterns of coping behaviour related to risk and uncertainty. On the other hand challenges that have been met adequately in the past may result in feelings of pride and satisfaction. As a rule feelings like these are limited to those who feel incorporated in society as a whole. Large numbers of citizens feel excluded. Social scientists have warned against developments that put people into the position of a 'structural loser'. Becoming unemployed once, for instance, does not hurt most people fatally. Becoming unemployed several times, combined with other personal disasters, may turn a person into a structural loser. Large numbers of structural losers may become a threat to society.

1.5 CONCLUSIONS

At the end of this mental experiment we have to remind ourselves that we have worked on a 'brain game', not a forecast. Our set of assumptions is based on arbitrary choices, even if they may seem plausible. Forecasting societal developments in the Lower Countries on a time horizon of one hundred years is simply impossible.

We have to realize also, that this short essay is not based on a large-scale scenario project. A full-fledged preparation of policy activities related to the problems involved would require a scenario project of many man-years. It would involve for instance differentiation of the analysis for periods of ten to twenty years.

Nevertheless a number of tentative conclusions can be drawn. In the first place it has become obvious, that the impact of sea level rise and a strengthening of sea defences on Dutch society is dependent on the ups and downs in that society during the next hundred years. What would be a major economic disaster to an impoverished country would be a minor inconvenience to a prosperous country.

The second conclusion is related to the degree of autonomy of the processes involved. If a period of one hundred years is discussed, systematic and large scale intervention might improve conditions for favourable developments. Social technology has its limits, however. Some kinds of intervention have been a success a number of times before (Rogers 1983). If intervention implies a repetition of already tested techniques the impacts can be predicted within certain limits (Becker et al. 1985, Becker & Porter 1986a, b). If intervention is related to more or less new problem areas, social experiments have to be carried out first.

The final conclusion concerns the reader. Scenarios require an active audience with an open mind. If the reader takes the contextual scenarios and the strategies as a learning environment and starts to design and execute his or her own mental experiment, the scenarios will have been worthwhile.

If imagination combined with a critical attitude are absent, scenarios only provoke disgust.

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APPENDIX 1.1: SHORT TAXONOMY ON SCENARIO PROJECTS

'Scenarios' and related instruments of futures studies are used in this and other contributions. This appendix provides a short taxonomy. As a starting point the components of a 'scenario project' are described. A scenario project consists of:

a) an analysis of the processes that have led to the problems to be studied in the project. This component also demands a 'problem analysis' (term for the overview of the past: baseline analysis),

b) an analysis of the processes that will influence the future of the 'focal system' more or less autonomously (term: contextual scenario),

c) an analysis of processes that will shape the future of the 'focal system' (term: analysis of the future of the focal system),

d) design of courses of action that actors in the focal system can take to eliminate or minimize the problem at hand (term: strategies),

e) an analysis of the impacts the strategies can have on the focal system and on its context, taking positive and negative consequences into consideration (term: impact assessment),

f) comparative analysis of the strategies considered, as a preparation of choices to be made (term: strategic planning),

g) design of courses of action that could decrease negative effects of the preferred strategy and that could promote the utilization of this strategy (term: implementation strategy).

This overview of the components of a scenario project requires some comments.

In the first place we have to keep in mind, that in a specific scenario project one or more components may be present in a rudimentary form only. If for instance a baseline analysis has been published recently, a new scenario project need to treat only the past of the problem involved in a restricted way.

In the second place it is necessary to describe a specific combination of components. Quite often in publications a combination is used of (1) a contextual scenario, (2) a description of the future of the focal system, (3) one strategy and (4) an analysis of its impacts. A combination like this as a rule is termed 'a scenario' (e.g. Appendix 1.2).

In the third place it should be pointed out that statements about the future (components b to g) can consist of (1) forecasts in a strict sense, (2) futures explorations and (3) futures speculations. A forecast in a strict sense (or 'prognosis') is a statement about future events presented in quantitative terms, related to a model, and based on an analysis of past events (historical information). A futures exploration provides information about the future based partly on empirical data and partly on discursive analyses. A futures speculation is based primarily on discursive reasoning (an 'utopia' for instance).

A fourth comment covers the terms 'risk' and 'uncertainty'; economists especially have elaborated two kinds of futures studies. The first one provides information about the future based on historical information and related to a model (term: risk). The second one gives information about the future without historical information about the future (term: uncertainty). A statement about the future based on risk can be compared with a prognosis. A statement based on uncertainty may be either a futures exploration or a futures speculation. Scenario-projects as a rule provide prognoses on a limited number of variables and for relatively short periods only (for instance about demographic developments). Most variables in scenario-projects show values stated under uncertainty.

Comment number four relates to the terminology to be found in publications on scenario projects. Some components sometimes are termed in ways differing from this short taxonomy. For instance a contextual scenario may be called (1) a scenario, (2) a context, etc. If there is terminological confusion a description of the characteristics of the category involved will provide the precision and unambiguity that is necessary. Some taxonomies provide each category with (1) one preferred term, and if necessary also with, (2) a list of synonyms and (3) a list of terms to be avoided.

The fifth comment deals with the boundaries of the focal system. In the analysis of social consequences of sea level rise the coastal defence system, including the related government agencies, private organizations and pressure groups may be taken as the focal system. The Netherlands becomes a context in this case. Often in the analysis the Netherlands will have to be studied in its relationship towards other countries in western Europe, North America, Africa etc. In a concentric approach like this wider focal systems are often considered than just the coastal defence system.

The sixth comment focuses on the 'autonomy' of the processes taking place in the future. Of course a lot of developments might be stopped or forced to change their course. The capacity of national governments, private firms, pressure groups, international organizations and other actors to intervene in a systematic and effective way is limited, however. Some interventions can be carried out on a routine basis. If a specific intervention has never before been a success, actors are advized to proceed carefully. It may require long series of social experimentations and full care social engineering to obtain the results desired. A lot of desired social reform is simply impossible, at least for the time being.

APPENDIX 1.2: MENTAL EXPERIMENTS ON 'IMPACTS OF SEA LEVEL RISE ON SOCIETY'

	Contextual Scenario 1 upward spiral	Contextual Scenario 2 downward spiral	Contextual Scenario 3
Assumptions regarding contextual relationships			
Technological growth	High	Low	
Integration of markets	High	Low	
Immigration	Low	High	
Tension and conflicts	Low	High	
Cultural change	High	High	
National income	High	Low	
Well-being	High	Low	
Sealevel rise			
Linear rise, no change in storm pattern	Negative impact	Negative impact	
Accelerating rise, hurricanes	Very negative	Disastrous	
Coastal defence strategies			
Conventional solutions	High risk	High risk	
Vanguard dikes	Best alternative	Too expensive	
Partial abandonment	High risk plus protest	High risk plus protest	
Critical incidents			
Major flooding of area	Disaster (Political stimulant)	Disaster	
Impacts and national strategy in general			
Technological growth	Stimulate balanced growth	Coping behaviour	
Integration of markets	Stimulate employment opportunities elsewhere	Coping	
Immigration	Prevented in general	Coping	
Tension and conflicts	Major prevention	Coping	
Cultural change	Apply social technology to make preferences more realistic	Coping	

Appendix 1.2 (cont.).

	Contextual Scenario 1 upward spiral	Contextual Scenario 2 downward spiral	Contextual Scenario 3
National income	Avoid gross inequalities, stimulate balanced growth	Coping	
Wellbeing	Beware of 'structural losers'		
Implementation strategy coastal defence			
Preparation	Start R&D now, choose robust solution, enter political agenda		
Execution	Flexible execution		
Implementation strategy coastal defence			
Preparation	Start R&D now, choose robust solution, enter political agenda		
Execution	Flexible execution pattern, including disaster relief planning		
Operation	p.m.		

2 THE CAUSES AND EFFECTS OF SEA LEVEL RISE
James G.Titus

2.1 INTRODUCTION

For the last several thousand years sea level has risen so slowly that for most practical purposes it has, in fact, remained constant. As a result, people and other maritime species have had the opportunity to extensively develop the shorelines of the world. Whether one is talking about a vacation spot in Rio de Janeiro, swamps in Bangladesh, farmland in the Nile Delta, marshes along the Chesapeake Bay, or the merchants of Venice, life along the coast is in a sensitive balance with the level of the sea.

This balance would be upset by the rise in sea level that could result from the global warming. Such a warming could raise sea level one metre or more in the next century by expanding ocean water, melting mountain glaciers, and perhaps eventually causing polar ice sheets to melt or slide into the oceans. Such a rise would inundate low-lying areas, drown coastal marshes and swamps, erode beaches, exacerbate flooding, and increase the salinity of rivers, bays, and aquifers throughout the world.

This contribution provides an overview of the causes and effects of sea level rise.

2.2 CAUSES OF SEA LEVEL RISE

2.2.1 *Past trends in sea level*

The worldwide average sea level depends primarily on (a) the shape and size of ocean basins, (b) the amount of water in the oceans, and (c) the average density of seawater. Subsidence, emergence, and other local factors can cause trends in 'relative sea level' at particular locations to differ from trends in 'global sea level'.

Hays & Pitman (1973) analyzed fossil records and concluded that over the last 100 million years, changes in mid-ocean ridge systems have caused sea level to rise and fall over 300 m. However, Clark et al. (1978) have pointed out that these changes have accounted for sea level changes of less than one mm per century. No published study has indicated that this determinant of sea level is likely to have a significant impact in the next century.

The impact of climate on sea level has been more pronounced. Geologists generally recognize that during ice ages the glaciation of substantial portions of the northern hemisphere has removed enough water from the oceans to lower sea level one hundred metres below present levels during the last (18,000 years ago) and previous ice ages (Don et al. 1962, Kennett 1982, Oldale 1985).

Although the glaciers that once covered much of the northern hemisphere have retreated, the world's remaining ice cover contains enough water to raise sea level over 75 m (Hollin & Barry 1979). Table 2.1 shows Hollin & Barry (1979) and Flint (1971) estimate that existing alpine glaciers contain enough water to raise sea level 30 or 60 cm, respectively. The Greenland and West Antarctic Ice Sheets each contain enough water to raise sea level about 7 m, while East Antarctica has enough ice to raise sea level over 60 m.

There is no evidence that either the Greenland or East Antarctic Ice Sheets have disintegrated in the last two million years. However, it is generally recognized that sea level was about seven metres higher than today during the last interglacial period, which was one to two degrees warmer (Moore 1982, Mercer 1968). Because the West Antarctic Ice Sheet is marine-based and thought to be vulnerable to climatic warming, attention has focused on this source for the higher sea level. Mercer (1968) found that lake sediments and other evidence suggested that summer temperatures in Antarctica have been 7° to 10°C higher than today at

Table 2.1. Snow and ice components (modified from Hollin & Barry 1979). Source: Meier et al. (1985).

	Area (10^6 km^2)	Ice volume (10^6 km^3)	Sea-level equivalent[1] (m)
Land ice			
East Antarctica[2]	9.86	25.92	64.8
West Antarctica[3]	2.34	3.40	8.5
Greenland	1.7	3.0	7.6
Small ice caps and mountain glaciers (Hollin & Barry 1979, Flint 1971)	0.54	0.12	0.3
Permafrost (excluding Antarctica)			0.6
Continuous	7.6	0.03-0.7	0.08-0.17
Discontinuous	17.3		
Sea ice			
Arctic[4]			
Late February	14.0	0.05	
Late August	7.0	0.02	
Antarctic[5]			
September	18.4	0.06	
February	3.6	0.01	
Land snow cover[6]			
N.Hemisphere			
Early February	46.3	0.002	
Late August	3.7		
S.Hemisphere			
Late July	0.85		
Early May	0.07		

1. 400,000 km^3 of ice is equivalent to 1 m global sea level.

2. Grounded ice sheet, excluding peripheral, floating ice shelves (which do not affect sea level). The shelves have a total area of 1.62 x 10^6 km^2 and a volume of 0.79 x 10^6 km^3 (Drewry & Heim 1983).

3. Including the Antarctic Peninsula.

4. Excluding the Sea of Okhotsk, the Baltic Sea, and the Gulf of St. Lawrence (Walsh & Johnson 1979). Maximum ice extents in these areas are 0.7 million, 0.4 million, and 0.2 million km^2, respectively.

5. Actual ice area excluding open water (Zwally et al. 1983). Ice extent ranges between 4 million and 20 million km^2.

6. Snow cover includes that on land ice but excludes snow-covered sea ice (Drewry & Heim 1983).

some point in the last two million years, probably during the last interglacial period 125,000 years ago, and that such temperatures could have caused a disintegration of the West Antarctic Ice Sheet.

Tidal gauges have been available to measure the change in sea level at particular locations over the last century. Studies combining these measurements to estimate global trends have concluded that sea level has risen 1.0 to 1.5 mm/yr during the last century (Barnett 1983, Gornitz et al. 1982, Fairbridge & Krebs 1962). Barnett (1983) found the rate of sea level rise for the last fifty years to be between 2.0 and 2.5 mm/yr, while in the previous fifty years there was little change; however, the acceleration rate of sea level rise was not statistically significant. Emery & Aubrey (1985) have filtered out estimated land surface movements in their analyses of tidal gauge records in northern Europe and western North America, and have found an acceleration in the sea level rise over the last century.[1] Braatz & Aubrey (n.d.) have found that the rate of relative sea level rise on the east coasts of North America accelerated after 1934.

Several researchers have attempted to explain the source of current trends in sea level. Barnett (1984) and Gornitz et al. estimate that thermal expansion of the upper layers of the oceans resulting from the observed global warming of 0.4°C in the last century could be responsible for a rise of 0.4 to 0.5 mm per year. Roemmich & Wunsch (1984) examined temperature and salinity measurements at Bermuda, found that the 4°C isotherm had migrated 100 m downward, and concluded that the resulting expansion of ocean water could be responsible for some or all of the observed rise in relative sea level. Roemmich (1985) showed that the warming trend 700 metres below the surface was statistically significant. However, Barnett (1983) found no significant trend based on an examination of the upper layers of the ocean. Nevertheless, Braatz & Aubrey (n.d.) note that long-term steric changes in the ocean are not confined to the upper layers of the oceans, which implies that the Barnett analysis does not necessarily contradict the Roemmich & Wunsch conclusion.

Meier (1984) estimates that retreat of alpine glaciers and small ice-caps could be responsible for a current contribution to sea level of between 0.2 and 0.72 mm per year. The National Academy of Sciences (NAS) Polar Research Board (Meier et al. 1985) concluded that existing information is insufficient to determine whether the impacts of Greenland and Antarctica are positive, negative, or zero. Although the estimated global warming of the last century appears at least partly responsible for the last century's rise in sea level, no study has demonstrated that global warming might be responsible for an accelerated rate of sea level rise.

2.2.2 *Impact of future global warming on sea level*

Concern about a substantial rise in sea level as a result of the projected global warming stemmed originally from Mercer (1968), who suggested that the Ross and Felchner-Ronne ice shelves might disintegrate, causing a deglaciation of the West Antarctic Ice Sheet and a resulting six to seven metre rise in sea level, possibly within 40 years.

Subsequent investigations have concluded that such a rapid rise is unlikely. Hughes (1983) estimated that such a disintegration would take at least two hundred years, and Bentley (1983), five hundred. Other researchers have estimated that this process could take considerably longer (Fastook 1985, Linge 1985).

Researchers have turned their attention to the magnitude of sea level rise that might occur in the next century. The best understood factors are the thermal expansion of ocean water and the melting of alpine glaciers. In Revelle (1983) the model of Cess & Goldenberg (1981) was used to estimate temperature increases at various depths and latitudes resulting from a 4.2°C warming by 2050-2060 (Figure 2.1). While noting that his assumed time constant of 33 years probably resulted in a conservatively low estimate, he estimated that temperature increases would result in an expansion of the upper ocean sufficient to raise sea level 30 cm.

Using a model of the oceans developed by Lacis et al. (1981), Hoffman et al. (1986) examined a variety of possible scenarios of future emissions of greenhouse gases and global warming. They estimated that a warming of between 1° and 2.6°C could result in a thermal expansion contribution to sea level of between 12 and 26 cm by 2050. They also estimated that

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[1] This result was reported in the North America study. The data also shows it to be true in the northern Europe study, but the result was not reported. David Aubrey, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts, pers. comm.

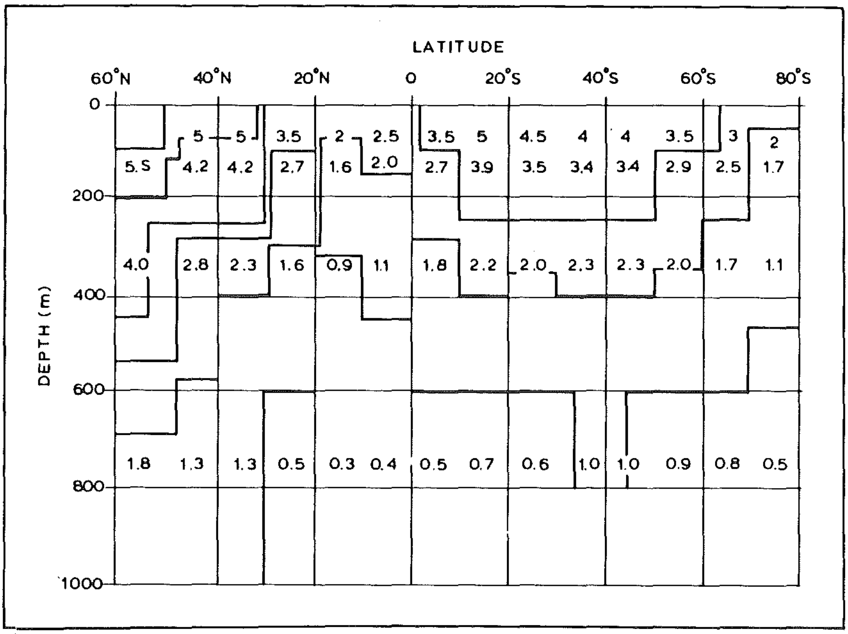

Figure 2.1. Computed near-equilibrium changes in ocean temperature for a doubling of atmospheric carbon dioxide and probable increase in other greenhouse gases, about 2080. The surface temperature increase is based on Flohn's (1982) prognosis.

a global warming of 2.3° to 7.0°C by 2100 would result in thermal expansion of 28-83 cm by that year.

Revelle (1983) suggested that, while he could not estimate the future contribution of alpine glaciers to sea level rise, a contribution of 12 cm through 2080 would be reasonable. Meier (1984) used glacier balance and volume change data for twenty-five glaciers where the available record exceeded fifty years to estimate the relationship between historic temperature increases and the resulting negative mass balances of the glaciers. He estimated that a 28 cm rise had resulted from a warming of 0.5°C, and concluded that a 1.5° to 4.5°C warming would result in a rise of 8-25 cm in the next century. Using these results, the NAS Polar Board concluded that the contribution of glaciers and small ice-caps through 2100 is likely to be 10 to 30 cm (Meier et al. 1985). They noted that the gradual depletion of remaining ice cover might reduce the contribution of sea level rise somewhat. However, the contribution might also be greater, given that the historic rise took place over a sixty-year period, while the forecast period is over one hundred years. Using Meier's estimated relationship between global warming and the alpine contribution, Hoffman et al. (1986) estimated alpine contributions through 2100 at 12-38 cm for a global warming of 2.3° to 7.0°C.

The first published estimate of the contribution of Greenland glacier meltwater to sea level was Revelle's (1983) estimate of 12 cm through the year 2080. Using estimates by Ambach (1980, 1982) that the equilibrium line (between snowfall accumulation and melting) rises one hundred metres for each 0.6°C in air temperatures, he concluded that the projected 6°C warming would be likely to raise the equilibrium line 1000 metres. He estimated that such a change in the equilibrium line would result in a 12 cm contribution to sea level rise for the next century.

The NAS Polar Board (Meier et al. 1985) noted that the large ablation area makes

Greenland a 'significant potential contributor of meltwater to the ocean if climatic warming causes an increase in the rate of ablation and an upward shift of the equilibrium line'. They found that a 1000 m rise in the equilibrium line would result in a contribution of 30 cm through 2100. However, because Ambach (1985) found the relationship between the equilibrium line and temperature to be 77 m/°C, the panel concluded that a 500 m shift in the equilibrium line would be more likely. Based on the assumption of a 6.5°C warming by 2050 and constant temperatures thereafter, the panel estimated that such a change would contribute about 10 cm to sea level through 2100, but also noted that 'for an extreme but highly unlikely case, with the equilibrium line raised 1000 m, the total rise would be 26 cm'. Although Bindschadler (1985) had treated the two cases as equally plausible, his analysis was conducted before the results of Ambach (1985) were known; he had since indicated agreement with the findings of Meier et al. (1985).[1]

Available estimates of the Greenland contribution assume that all meltwater flows into the oceans and that the ice dynamics of the glaciers do not change. The NAS Polar Board suggested that some of the water would refreeze, decreasing the contribution to sea level rise. Although a change in ice dynamics might imply additional deglaciation and increase the rate of sea level rise, the panel assumed that such changes were unlikely to occur in the next century.

The potential impact of a global warming on Antarctica in the next century is the least certain of all the factors by which a global warming might contribute to sea level rise. Meltwater from East Antarctica might make a significant contribution by the year 2100, but no one has estimated it.[2] The contribution of ice sliding into the oceans, known as 'deglaciation', has been the subject of several studies.

Bentley (1983) examined the processes by which a deglaciation of Antarctica might occur. First an accelerated melting of the undersides of the Ross and Filchner-Ronne ice shelves would occur due to warmer water circulating underneath them. The thinning of these ice shelves could cause them to become unpinned and their grounding lines to retreat. Revelle (1983) suggests that the ice shelves might disappear in 100 years, after which time the Antarctic ice streams would flow directly into the oceans, without the back pressure of the ice shelves. Bentley suggests that all the ice could be discharged over a period of 500 years, and possibly as rapidly as 200 years.

Although a West Antarctic deglaciation would occur over a period of centuries, it is possible that an irreversible deglaciation could commence before 2050. If the ice shelves thinned more than about one metre per year, Thomas et al. (1979) suggested that the ice would move into the sea at a sufficient speed that even a cooling back to the temperatures of today would not be sufficient to result in a reformation of the ice shelf.

To estimate the likely Antarctic contribution for the next century, Thomas (1985) developed four scenarios measuring the impact of a 3°C global warming by 2050:

– A shelf melting rate of 1 m/yr with seaward ice fronts remaining at present locations: implies a rise of 28 cm by the year 2100;

– a shelf melting rate of 1 m/yr with ice fronts calving back to a line linking the areas where the shelf is grounded, during the 2050's: implies a rise of 1.6 m by 2100;

– same as case 1 but with a melt rate of 3 m/yr: implies a rise of 1 m by 2100;

– same as case 2 but with a melt rate of 3 m/yr: implies a rise of 2.2 m by 2100.

Thomas concluded that the 28 cm rise implied by case 1 would be most likely. He also stated that even if enhanced calving did occur, it would be likely to occur after 2050, 'suggesting that probably associated sea level rise would be closer to the 1 m of case 3 than the 2.2 m of case 4'.

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[1] Robert Bindschadler, Goddard Space Flight Center, Greenbelt, Maryland, pers. comm.

[2] James Hansen, Goddard Institute for Space Studies, New York, pers. comm. to J.S.Hoffman.

The NAS Polar Board (Meier et al. 1985) evaluated the Thomas study and papers by Lingle (1985) and Fastook (1985). Although Lingle estimated that the contribution of West Antarctica through 2100 would be 3 to 5 cm, he did not evaluate the contribution from East Antarctica, while Fastook made no estimate for the year 2100. Thus, the panel concluded that 'imposing reasonable limits' on Thomas' model yields a range of 20 to 80 cm by 2100 for the Antarctic contribution. However, they also noted several factors that could reduce the amount of ice discharged into the sea: The removal of the warmest ice from the ice shelves, the retreat of grounding lines, and increased lateral shear stress. They also concluded that increased precipitation over Antarctica might increase the size of the polar ice sheets there. Thus, the panel concluded that Antarctica could cause a rise in sea level up to 1 m, or a drop of 10 cm, with a rise between 0 and 30 cm most likely.

Table 2.2 summarizes the various estimates of global sea level rise. Hoffman et al. (1983) estimated that the rise would be between 56 and 345 cm, with a probably rise between 144 and 217 cm. Revelle (1983) estimated that the rise was likely to be 70 cm, ignoring the impact of a global warming on Antarctica; Revelle also noted that the latter contribution was likely to be 1 to 2 m per century after 2050, but declines to add that to his estimate. The NAS Polar Board (Meier et al. 1985) projected that the contribution of glaciers would be sufficient to raise the sea level 20 to 160 cm, with a rise of 'several tenths of a metre' most likely. Thus, if one extrapolates the earlier NAS estimate of thermal expansion through the year 2100, the 1985 NAS report implies a rise between 50 and 200 cm. The estimates of Hoffman et al. (1986)

Table 2.2. Estimates of future sea level rise (cm). Sources: Hoffman et al. (1986), Meier et al. (1985), Hoffman et al. (1983), Revelle (1983), Thomas (1985).

	Thermal expansion	Alpine glaciers	Greenland	Antarctica	Total
Year 2100 by cause (2085 in the case of NAS 1983)					
NAS (1983)	30	12	12[1]	70	
EPA (1983)	28-115	[3]	[4]	56-345	
NAS (1985)[4]	–	10-30	10-30	–10–+100	50-200
Thomas (1985)	–	–	–	0-200	–
Hoffman et al. (1986)	28-83	12-37	6-27	12-220	57-368

Total rise in specific years[2]	2000	2025	2050	2075	2085	2100
NAS (1983)	–	–	–	70	–	–
EPA (1983)						
Low	4.8	13	23	38	–	56.0
Mid-range low	8.8	26	53	91	–	144.4
Mid-range high	13.2	39	79	137	–	216.6
High	17.1	55	117	212	–	345.0
Hoffman et al. (1986)						
Low	3.5	10	20	36	44	57
High	5.5	21	55	191	258	368

1. Revelle (1983) attributes 16 cm to other factors.
2. Only EPA reports made year-by-year projections for the next century.
3. Hoffmann et al. (1983) assumed that the glacial contribution would be one to two times the contribution of thermal expansion.
4. NAS (1985) estimate includes extrapolation of thermal expansion from Revelle (1983).

were similar to the estimates of Hoffman et al. (1983) for the year 2100, but for the year 2025, they lowered their estimate from 26-39 cm to 10-21 cm.

2.2.3 *Future trends in local sea level*

Although most attention has focused on projections of global sea level, impacts on particular areas would depend on local relative sea level. Tidal gauge measurements suggest that relative sea level has risen 10 to 20 cm per century more rapidly than the worldwide average along much of the US coast (Hicks et al. 1983). However, Louisiana is subsiding close to 1 m per century, while parts of Alaska are emerging 10 cm or more per century. Bruun argues that throughout most of the world, sea level has been rising. However, Bird (in Titus 1986) argues that sea level appears to be stable in Australia, which may imply that future rates of sea level rise will also be 10 to 15 cm per century less than the worldwide average.

Local subsidence and emergence are caused by a variety of factors. Rebound from the retreat of glaciers after the last ice age has resulted in the emergence of Alaska and parts of Scandinavia. The emergence in polar latitudes has resulted in subsidence in other areas. Groundwater pumping has caused rapid subsidence around Houston, Texas; Taipei, Taiwan; and Bangkok, Thailand, among other areas (Leatherman 1984; Kuo, in Titus 1986). River deltas and other newly created land subside as the unconsolidated materials compact.

Although subsidence and emergence trends may change in the future, particularly where anthropogenic causes are curtailed, no one has linked these causes to future climate change in the next century. However, the removal of ice from Greenland and Antarctica would deform the ocean floor. Clark & Lingle (1977) have calculated the impact of a uniform 1 m contribution from West Antarctica. They concluded that relative sea level at Hawaii would increase by an additional 25 cm, and that along much of the US Atlantic and Gulf Coasts there would be an additional 15 cm. On the other hand, sea level would drop at Cape Horn by nearly 10 cm, and the rise along the southern half of the Argentine and Chilean coasts would be less than 75 cm.

Other influences on local sea level that might change as a result of a global warming include currents, winds, and freshwater flow into estuaries. None of these impacts, however, has been estimated.

2.3 EFFECTS OF SEA LEVEL RISE

A rise in sea level of one or two metres would permanently inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, and increase the salinity of estuaries and aquifers. Substantial research has been done on the implications of sea level rise for coastal erosion and wetlands, while relatively little work has been done in the other areas.

2.3.1 *Submergence of coastal wetlands*

The most direct impact of a rise in sea level is the inundation of areas that had been just above the water level before the sea rose, also described by Park et al. in Titus (1986). Coastal wetlands are generally found at elevations below the highest tide of the year and above mean sea level. Thus, wetlands account for most of the land less than 1 m above sea level.

Because a common means of estimating past sea level rise has been the analysis of marsh peats, the impacts of sea level rise on wetlands are fairly well understood. For the rates of sea level rise of the last several thousand years, marshes have generally kept pace with sea level through sedimentation and peat formation (Emery & Uchupi 1972, Redfield 1967, 1972, Davis 1985). As sea level rose, new wetlands formed inland while the seaward boundary was maintained (Figure 2.2a, b). Because the wetland area has expanded, Titus et al. (1984)

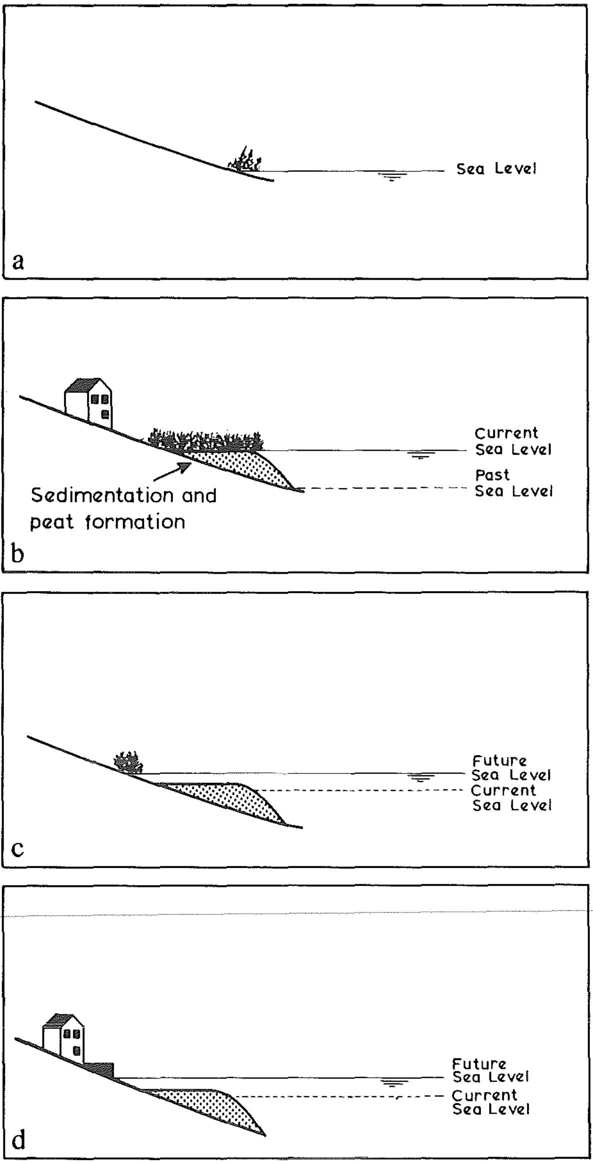

Figure 2.2. Evolution of marsh as sea level rises: a) 5000 years ago, b) today, c) future – substantial wetland loss where there is vacant upland, d) future – complete wetland loss where house is protected in response to rise in sea level.

hypothesized that one would expect a concave marsh profile, i.e. that there is more marsh area than the area found immediately above the marsh. Thus, if sea level rose more rapidly than the marsh's ability to keep pace, there would be a net loss of wetlands (Figure 2.2c). Moreover, a complete loss might occur if protection of developed areas prevented the inland formation of new wetlands (Figure 2.2d).

Kana et al. (1986) surveyed marsh transects in the areas of Charleston, South Carolina, and two sites near Long Beach Island, New Jersey, to evaluate the concavity of wetland profiles and the vulnerability of wetlands to a rise in sea level. Their data from the Charleston area showed all the marsh to be between 30 and 110 cm above current sea level, an elevation range of 80 cm. The area with a similar elevation range just above the marsh was only 20% as large. Thus, a rise in sea level exceeding vertical marsh accretion by 80 cm would result in an 80% loss of wetlands. In the New Jersey sites, the marsh was also found within an elevation range of 80 cm; a rise in sea level 80 cm in excess of marsh accretion would result in 67-90% losses.

The future ability of marshes to accrete vertically is uncertain. Based on field studies by Ward & Domeracki (1978), Hatton et al. (1983), Meyerson (1972), and Stearns & MacCreary (1957), Kana et al. (n.d.) concluded that current vertical accretion rates are approximately 4 to 6 mm/yr in the two case study areas, greater than the current rate of sea level rise but less than the rates of rise projected for the next century. If current accretion trends continue, then 87 and 160 cm rises by 2075 would imply 50 and 80% losses of wetlands in the Charleston area. Kana et al. (n.d.) also estimated 80% losses in the New Jersey sites for a 160 cm rise through 2075. However, because the high marsh dominates in that area, they concluded that the principal impact of an 87 cm rise by 2075 would be the conversion of high marsh to low marsh.

In both cases, the losses of marsh could be greater if inland areas are developed and protected with bulkheads or levees. Because there is a buffer zone between developed areas and the marsh in South Carolina protecting development from a 160 cm rise would increase the loss from 80-90%. Without the buffer, the loss would be close to 100%.

Louisiana, whose marshes and swamps account for 40% of the coastal wetlands in the United States (excluding Alaska), would be particularly vulnerable to an accelerated rise in sea level. The majority of the Louisiana wetlands are less than one metre above sea level, and are generally subsiding approximately one metre per century as its deltaic sediments compact (Boesch 1982). Until the last century, the wetlands kept pace with this rate of relative sea level rise, because of the sediment the Mississippi River conveyed to the wetlands.

Human activities, however, have largely disabled the natural processes by which coastal Louisiana might keep pace with sea level rise. Dams, navigation channels, canals, and flood protection levees have interrupted the flow of sediment, freshwater, and nutrients to the wetlands. As a result, over 100 km^2 of wetlands convert to open water every year (Gagliano et al. 1983). A substantial rise in sea level would further accelerate the process of wetland loss in Louisiana.

To develop an understanding of the potential nationwide impact of sea level rise on coastal wetlands in the United States, Park et al. (in Titus 1986) use topographic maps to characterize wetlands elevations at fifty-two sites comprising 4800 km^2 (1.2 million acres) of wetlands, over 17% of all US coastal wetlands (see also Armentano et al. n.d.). Using published vertical accretion rates, they estimate the impact of 1.4 and 2.1 m rises in sea level through the year 2100 for each of the sites. Park et al. (in Titus 1986) estimate that these scenarios imply losses of 40 and 76% of the existing coastal wetlands in their sample, which could be reduced to 22 and 58% if new wetlands are allowed to form inland. However, Titus (in press) found that if the Park et al. sample is weighted according to an inventory of wetlands in particular areas (Alexander et al. 1986), the resulting estimates of US wetland loss are somewhat higher, 47-82% of existing wetlands, with a potential for reducing those losses to 31 to 70%.

Throughout the world, people have dammed, leveed, and channelized major rivers, curtailing the amount of sediment that reaches river deltas. Even at today's rate of sea level rise, substantial amounts of land are converting to open water in Egypt and Mexico (Milliman & Meade 1983). Other deltas, such as the Ganges in Bangladesh and India, are currently expanding seaward. These areas would require increased sediment, however, to keep pace with an accelerated rise in sea level. Additional projects to divert the natural flow of river water would increase the vulnerability of these areas to a rise in sea level. Broadus et al. (in Titus 1986) examine this issue in detail for Egypt and Bangladesh.

Several options have been identified for reducing wetland loss due to sea level rise. Abandonment of developed areas inland of today's wetlands could permit new wetlands to form inland. In some cases, it might be possible to enhance the ability of wetlands to accrete vertically by spraying sediment on them or – in the case of Louisiana and other deltas – restoring the natural processes that would provide sediment to the wetlands. Finally, some local governments in Louisiana have proposed to artificially control water levels through the use of levees and pumping stations (Edmonson & Jones 1985).

The need for anticipating sea level rise would vary. Artificial means to accelerate wetland accretion need not be implemented until the rise takes place (although a lead time would be necessary to develop the required technologies). Similarly, levees and pumping stations could be delayed. On the other hand, a planned retreat would require several decades of lead time to permit the design of new mobile structures and the depreciation of the old immobile structures.

2.3.2 *Inundation*

Although coastal wetlands are found at the lowest elevations, inundation of lowland could also be important in some areas, particularly if sea level rises at least one metre. Unfortunately, the convention of ten-foot contours in the mapping of most coastal areas has prevented a general assessment of land loss. Although a few case studies have been conducted in the United States, very few studies have been undertaken to quantify the potential impacts on other countries, other than the paper by Broadus et al. (in Titus 1986).

Kana et al. (1984) used data from aerial photographs to assess elevations in the area around Charleston. They concluded that 160 and 230 cm rises would result in 30 and 46% losses of the area's dry land, respectively. Leatherman (1984) estimated that such rises would result in 9 and 12% losses of the land in the area of Galveston and Texas City, Texas, assuming that the elaborate network of sea walls and levees were maintained (many of the summary results from Leatherman 1984, Kana et al. 1984 and Gibbs 1984 appear in the appendix of Titus et al. 1984).

Schneider & Chen (1980) conducted the first nationwide assessment of the inundation from projected sea level rise. Unfortunately, the smallest rise in sea level they considered was a 4.5 m (15 ft) rise, in part because smaller contours are not generally available in topographic maps. Nevertheless, their findings suggest which coastal states would be most vulnerable: Louisiana (which would lose 28% of its land and 51% of its wealth), Florida (24 and 52%), Delaware (16 and 18%), Washington, DC (15 and 15%), Maryland (12 and 5%), and New Jersey (10 and 9%).

As with wetland loss, the responses to inundation fall broadly into the categories of retreat and holding back the sea. Levees are used extensively in the Netherlands and New Orleans to prevent the flooding of areas below sea level and could be similarly constructed around other major cities. In sparsely developed areas, however, the cost of a levee might be greater than the value of the property being protected. Moreover, even where levees prove to be cost-effective, the environmental implications of replacing natural shorelines with man-made structures would need to be considered.

2.3.3 *Coastal erosion*

Sea level rise can also result in the loss of land above sea level through erosion. Bruun (1962) showed that the erosion resulting from a rise in sea level would depend upon the average slope of the entire beach profile extending from the dunes out to the point where the water is too deep for waves to have a significant impact on the bottom (generally a depth of about 10 m, shown in Figure 2.3). By comparison, inundation depends only on the slope immediately above the original sea level. Because beach profiles are generally flatter than the portion of the beach just above sea level, the 'Bruun rule' generally implies that the erosion from a rise in sea level is several times greater than the amount of land directly inundated.

As Bird (in Titus 1986) emphasizes, processes other than sea level rise also contribute to

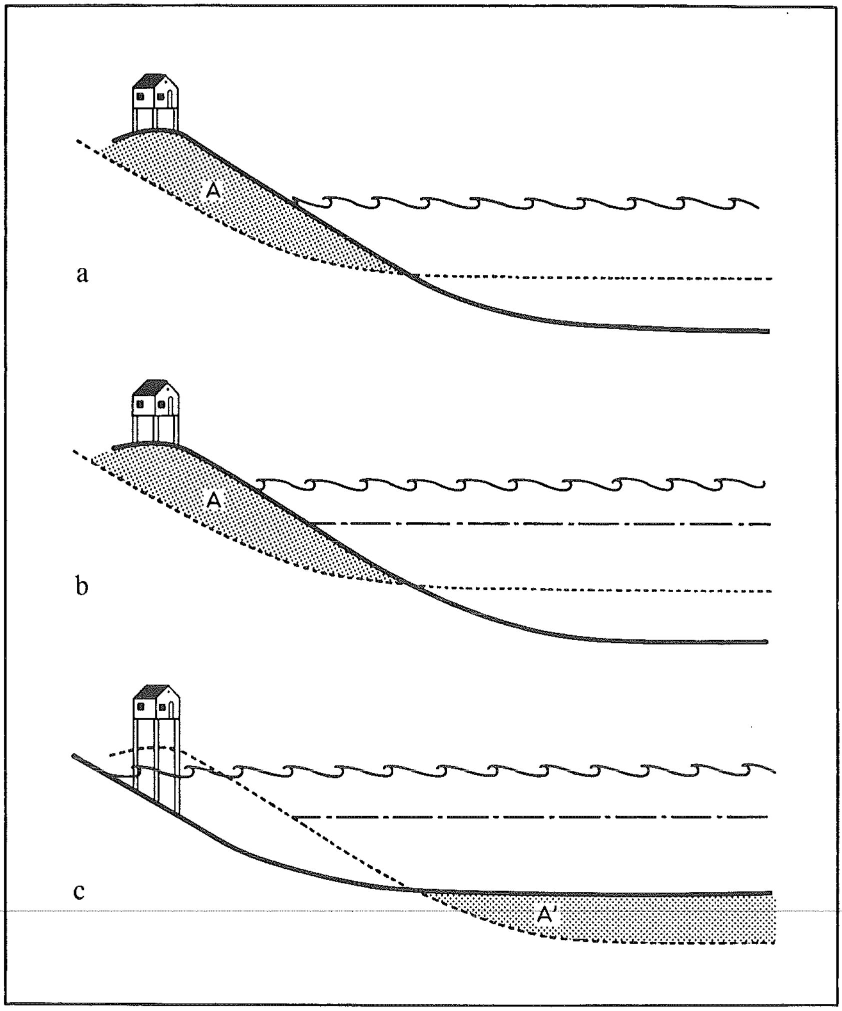

Figure 2.3. The Bruun rule: a) initial conditions, b) immediate inundation when sea level rises, c) subsequent erosion due to sea level rise.

erosion, including storms, structures, currents, and alongshore transport. Because sea level has risen slowly in recent centuries, verification of the Bruun rule on the open coast has been difficult. However, water levels along the Great Lakes can fluctuate over one metre in a decade. Hands (1976, 1979 and 1980) and Weishar & Wood (1983) have demonstrated that the Bruun rule generally predicts the erosion resulting from rises in water levels there.

The Bruun rule has been applied to project erosion due to sea level rise for several areas of the United States where it is believed to adequately project future erosion. Bruun (1962) found that a 1 cm rise in sea level would generally result in a 1 m shoreline retreat, but that the retreat could be as great as 10 m along some parts of the Florida coast. Everts (1985) and Kyper & Sorensen (1985), however, found that along the coasts of Ocean City, Maryland, and Sandy

Hook, New Jersey, respectively, the shoreline retreat implied by the Bruun rule would be only about 75 cm. Kana et al. (1984) found that along the coast of South Carolina, the retreat could be 2 m. The US Army Corps of Engineers (1979) indicated that along the coast of San Francisco, where waves are generally larger than along the Atlantic coast, the shore might retreat 2-4 m for a 1 cm rise in sea level.

Dean & Maurmeyer (1983) generalized the Bruun rule approach to consider the 'overwash' of barrier islands. Geologists basically believe that coastal barriers can maintain themselves in the face of slowly rising sea level through the landward transport of sand, which washes over the island during storms, building the island upward and landward. Because this formulation of the Bruun rule extends the beach profile horizontally to include the entire islands as well as the active surf zone, it always predicts greater erosion than the Bruun rule. However, the formulation may not be applicable to developed barrier islands, where the common practice of public officials is to bulldoze sand back onto the beach after a major storm.

The potential erosion from a rise in sea level could be particularly important to recreational beach resorts, which include some of the world's most economically valuable and intensively used land. Relatively few of the most densely developed resorts have beaches wider than about 30 m at high tide. Thus, the rise in relative sea level of 30 cm projected in the next 40 to 50 years could erode most recreational beaches in developed areas, unless additional erosion response measures are taken.

Bruun (in Titus 1986) examines potential responses to erosion in considerable detail (see also Magness 1984, US Army Corps of Engineers 1977). The responses fall generally into three catagories: Construction of walls and other structures, the addition of sand to the beach, and abandonment. Although sea walls have been used in the past, they are becoming increasingly unpopular among shore communities because erosion can proceed up to the wall, resulting in a complete loss of beach, which has happened in many areas (Kyper & Sorensen 1985, Howard et al. 1985). A number of other structures have been used to decrease the ability of waves to cause erosion, including groynes (jetties) and breakwaters. Bulkheads are often used where waves are small (Sorensen et al. 1984).

A more popular form of erosion control has been the placement of sand onto the beach. Although costs can exceed one million dollars per km (US Army Corps of Engineers 1980, Howard et al. 1985), it is often justified by the economic and recreational value of beaches. A recent study of Ocean City, Maryland, for example, concluded that the cost of holding back the sea for a 30 cm rise in sea level would be about $0.25 per visitor, less than 1% of the cost of a trip to the beach (Titus 1985). That community also provides an example of the practical consequences of sea level rise. Until 1985, the State of Maryland's policy for erosion control was the construction of groynes, which curtail erosion caused by sand moving along the shore, but not erosion caused by sea level rise. Sea level rise was cited as the motivating concern for the state to abandon the groyne plan and use beach replenishment, which can effectively control erosion caused by both types of erosion (Associated Press 1985).

Although shore protection is often cost-effective today, the favourable economics might change in the future. A more rapid rise in sea level would increase the costs of shore protection. A number of states have adopted erosion policies that assume a retreat from the shore. North Carolina requires homes that can be moved to be set back from the shore by a distance equal to shoreline recession from 30 years of erosion, while high-rises must be set back 60 years.[1] Maine requires people to demonstrate that new structures will not erode for 100 years.[2] Other jurisdictions discourage the construction of bulkheads and sea walls (Howard et al. 1985). As Bird (in Titus 1986) discusses, in many undeveloped countries, small, relatively inexpensive houses are found very close to the shore. Because the value of

[1] North Carolina Administrative Code, Chapter 7H, 1983. Raleigh, North Carolina: Office of Coastal Management.

[2] Fred Michaud, Office of Floodplain Management, State of Maine, pers. comm.

these houses is less than the cost of protecting them, they must be moved as the shore erodes. An accelerated rise in sea level would speed this process of shoreline retreat.

The need for anticipating erosion caused by sea level rise varies. Where communities are likely to adapt to erosion, anticipation can be important. The cost and feasibility of moving a house back depends on design decisions made when the house is built. The willingness of people to abandon properties depends in part on whether they bought land on the assumption that it would eventually erode away or had assumed that the government would protect it indefinitely. Less anticipation is necessary if the shore will be protected; sand can be added to the beach as necessary. Nevertheless, some advanced planning may be necessary for communities to know whether retreat or defending the shore would be most cost-effective.

2.4 FLOODING AND STORM DAMAGE

A rise in sea level could increase flooding and storm damages in coastal areas for three reasons; erosion caused by sea level rise would increase the vulnerability of communities; higher water levels would provide storm surges with a higher base to build upon; and higher water levels would decrease natural and artificial drainage.

The impact of erosion on vulnerability to storms is generally a major consideration in projects proposed to control erosion, most of which have historically been funded through the US Army Corps of Engineers. The impact of sea level rise, however, has not generally been considered separately from other causes of erosion.

The impact of higher base water levels on flooding has been investigated for the areas around Charleston, South Carolina, and Galveston, Texas (Barth & Titus 1984). Kana et al. (1984) found that around Charleston, the area within the 10 year flood plain would increase from 33% in 1980, to 48, 62 and 74% for rises in sea level of 88, 160 and 230 cm, respectively, and that the area within the 100 year flood plain would increase from 63% to 76, 84 and 90% for the three scenarios. Gibbs (1984) estimated that even an 88 cm rise would double the average annual flood damages in the Charleston area, but that flood losses would not increase substantially for higher rises in sea level because shoreline retreat would result in a large part of the community being completely abandoned.

Leatherman (1984) conducted a similar analysis of Galveston Island, Texas. He estimated that the area within the 100 year flood plain would increase from 58-94% for an 88 cm rise in sea level, and that for a rise greater than one metre, the Galveston sea wall would be overtopped during a 100 year storm. Gibbs estimated that the damage from a 100 year storm would be tripled for a rise of 88 cm.

A wide variety of shore protection measures would be available for communities to protect themselves from increased storm surge and wave damage due to sea level rise (Sorensen et al. 1984). Many of the measures used to address erosion and inundation, including sea walls, breakwaters, levees, and beach restoration, also provide protection against storms. In the case of Galveston, which is already protected on the ocean side by the sea wall, Gibbs hypothesized that it might be necessary to completely encircle the developed areas with a levee to prevent flooding from the bay side; upgrading the existing sea wall might also be necessary.

Kyper & Sorensen (1985) examined the implications of sea level rise for the design of coastal protection works at Sea Bright, New Jersey, a coastal community that currently is protected by a sea wall and has no beach. Because the sea wall is vulnerable to even a 10 year storm, the US Army Corps of Engineers and the State of New Jersey have been considering a possible upgrade. Kyper & Sorensen estimated that the cost of upgrading the sea wall for current conditions would be $3.5-6 million/km of shoreline, noting that if designed properly, the sea wall would be useful throughout the next century. However, they estimated that a rise in relative sea level of 30-40 cm would be likely to result in serious damage to the sea wall during a major storm, due to higher water levels and the increased wave heights resulting from the erosion of submerged sand in front of the sea wall. To upgrade the sea wall to withstand a

1 m rise in relative sea level would cost $5.7-9 million/km (50% more). They concluded that policy-makers would have to weigh the trade-off between the cost of designing the wall to withstand projected sea level rise and the cost of subsequent repairs and a second overhaul.

In addition to community-wide engineering approaches, measures can also be taken by individual property owners to prevent increased flooding. In 1968, the US Congress created the National Flood Insurance Program to encourage communities to avoid risky construction in flood-prone areas. In return for requiring new construction to be elevated above expected flood levels, the federal government provides flood insurance, which is not available from the private sector. If sea level rises, flood risks will increase. In response, local ordinances will automatically require new construction to be further elevated, and insurance rates on existing properties will rise unless those properties are further elevated. As currently organized, the National Flood Insurance Program would react to sea level rise as it occurred. Various measures to enable the program to anticipate sea level rise have been proposed, including warning policy-holders that rates may increase in the future if sea level rises; denying coverage to new construction in areas that are expected to be lost to erosion within the next 30 years; and setting premiums according to the average risk expected over the lifetime of the mortgage (Howard et al. 1985, Titus 1984).

Kuo (in Titus 1986) describes case studies in Charleston, South Carolina, and Fort Walton Beach, Florida, which examined the implications of sea level rise for rainwater flooding and the design of coastal drainage systems. Waddell & Blaylock (n.d.) estimated that a 25 year rainstorm (with no storm surge) would result in no damages for the Gap Creek watershed in Fort Walton Beach. However, a rise in sea level of 30-45 cm would result in damages of $1.1-1.3 million in this community of 4000 residents during a 25 year storm. An upgrade costing $550,000, however, would prevent such damages.

LaRoche and Webb who had previously developed the master drainage plan for Charleston, South Carolina, evaluated the implications of sea level rise for the Grove Street watershed in that community. They estimated that the costs of upgrading the system for current conditions would be $4.8 million, while the cost of upgrading the system for a 30 cm rise would be $5.1 million. If the system is designed for current conditions and sea level rises, the system would be deficient and the city would face retrofit costs of $2.4 million. Thus, for the additional $300,000 necessary to upgrade for a 30 cm rise, the city could ensure that it would not have to spend an additional $2.4 million later. Noting that the decision whether to design now for a rise in sea level depends on the probability that sea level will rise, they concluded that a 3% real social discount rate would imply that designing for sea level rise is worthwhile if the probability of a 30 cm rise by 2025 is greater than 30%. At a discount rate of 10%, they concluded, designing for future conditions is not worthwhile.

2.5 INCREASED SALINITY IN ESTUARIES AND AQUIFERS

Although most researchers and the general public have focused on the increased flooding and shoreline retreat associated with a rise in sea level, the inland penetration of salt water could be important in some areas.

As De Sylva (in Titus 1986) describes, a rise in sea level increases the salinity of an estuary by altering the balance between freshwater and salt water forces. The salinity of an estuary represents the outcome of (a) the tendency for the ocean salt water to completely mix with the estuarine water and (b) the tendency of freshwater flowing into the estuary to dilute the saline water and push it back toward the ocean. During droughts, the salt water penetrates upstream, while during the rainy season, low salinity levels prevail. A rise in sea level has an impact similar to decreasing the freshwater inflow. By widening and deepening the estuary, sea level rise increases the ability of salt water to penetrate upstream.

The implications of sea level rise for increased salinity have only been examined in detail for Louisiana and the Delaware estuary. In Louisiana and other river deltas, salt water intrusion is causing the conversion of cypress swamps (which cannot tolerate salt water) to open water lakes, and increasing the salinity levels of fresh and intermediate marshes. Accelerated sea level rise would speed up this process.

The impact of current sea level trends on salinity has been considered in the long range plan of the Delaware River Basin Commission since 1981 (DRBC 1981). The drought of the 1960's resulted in salinity levels that almost contaminated the water supply of Philadelphia and surrounding areas. Hull & Tortoriello (1979) found that the 13 cm rise projected between 1965 and 2000 would result in the 'salt front' migrating 2-4 km farther upstream during a similar drought. They found that a moderately sized reservoir (57 million m^3) to augment river flows would be needed to offset the resulting salinity increases.

Hull et al. (1986) examined the potential impacts of an accelerated rise in sea level due to the greenhouse warming. They estimated that 73 cm and 250 cm rises would result in the salt front migrating an additonal 15 and 40 km, respectively, during a repeat of the 1960's drought. They also found that the health-based 50 ppm sodium standard (equivalent to 73 ppm chloride) adopted by New Jersey would be exceeded 15 and 50% of the time, respectively, and that the EPA drinking water 250 ppm chloride standard would be exceeded over 35% of the time in the latter case.

Lennon et al. (1986) examined the implications of increased estuarine salinity for the Potomac-Raritan-Magothy aquifer system, which is recharged by the (currently fresh) Delaware River and serves the New Jersey suburbs of Philadelphia. During the 1960's drought, river water with chloride concentrations as high as 150 ppm recharged these aquifers. Lennon et al. estimated that a repeat of the 1960's drought with a 73 cm rise in sea level would result in river water with concentrations as high as 350 ppm recharging the aquifer, and that during the worst month of the drought, over one-half of the water recharging the aquifer system would have concentrations greater than 250 ppm. With a 250 cm rise, 98% of the recharge during the worst month of the drought would exceed 250 ppm, and 75% of the recharge would be greater than 1000 ppm.

Hull & Titus (1986) examined the options by which various agencies might respond to increased salinity in the Delaware estuary. They concluded that planned but unscheduled reservoirs would be more than enough to offset the salinity increased from a one foot (30 cm) rise in sea level, although those reservoirs had originally been intended to meet increased consumption. They noted that construction of the reservoirs would not be necessary until the rise became more imminent. However, they also suggested that, given the uncertainties, it might be advisable today to identify additional reservoir sites, to ensure that future generations retained the option of building additional reservoirs, if necessary.

A rise in sea level could increase salinities in other areas, although the importance of those impacts has not been investigated. Kana et al. (1984) and Leatherman (1984) made preliminary inquiries into the potential impacts on coastal aquifers around Charleston and Galveston, respectively. However, they concluded that in-depth assessments were not worthwhile because the aquifers around Charleston are already salt-contaminated because of overpumping, and pumping of groundwater has been prohibited in the Galveston area as it causes land subsidence. The potential impacts on Florida's Everglades and the shallow aquifers around Miami might be significant, but these have not been investigated.

2.5.1 *Economic significance of sea level rise*

Only two studies have estimated a dollar value of the likely impacts of sea level rise for particular nations. Schneider & Chen (1980) estimated the economic impact of what was once (but is no longer) thought to be a plausible scenario: rises of 4.6-7.6 m (15-25 ft) occurring with little or no warning during the early part of the twenty-first century. They estimated that these scenarios would result in real property losses of $100 to $150 billion, representing 6.2-8.4% of all real property in the nation.

The only comprehensive attempt to place a dollar value on the impacts of sea level rise for particular communities was the study by Gibbs (1984) of the Charleston and Galveston areas, summarized in Titus 1986. Gibbs' analysis, which considers scenarios ranging from 0.9 to 2.4 m rises through 2075, estimates what the economic impact would be if actions are taken in anticipation of sea level rise versus the cost of responding to sea level rise as it occurs. Gibbs also modeled how investment decisions might respond to floods and erosion, and explicitly considered community-wide strategies to limit losses, including shore protection and abandonment.

In the Charleston study, Gibbs assumed that in anticipation of sea level rise, efforts would be made to avoid developing some vacant suburban areas likely to be flooded in the future; that a partial abandonment would take place; and that the existing sea walls protecting Charleston would be elevated to provide additional protection. For a rise of 28-64 cm through 2025, Gibbs estimated that present value of the cumulative impact would be $280-1065 million (5-19% of economic activity in the area for the period), which could be reduced to $160-420 million if sea level rise was anticipated. Most of this impact would result from a 10-100% increase in expected storm damages, although Gibbs also estimated $7-35 million in losses as a result of erosion. For the period 1980-2075, Gibbs estimated that the economic impacts would be $1250 to $2510 million (17-35%) and could be reduced to $440 and $1100 million through anticipatory measures. Gibbs performed a similar analysis of the Galveston area, concluding that the impacts of sea level rise through 2025 would represent $115 to $360 million (1.1-3.6%) if not anticipated, and $80 to $140 million if anticipated.

Other studies can be used to understand the economic significance of particular classes of impacts. As discussed above, a 30 cm (1 ft) rise in sea level would erode most recreational beaches back to the first row of houses. The studies cited in our section on erosion indicate that the typical beach profile extends out about 1000 m implying that 300,000 m^3 of sand per km of shoreline are required to raise the beach profile 30 cm. If sand costs are typically $3-10/$m^3$, the beach rebuilding costs of a 30 cm rise in sea level would be $1-3 million/km. If the United States has a few thousand km of recreational beaches, then it would cost billions and perhaps tens of billions of dollars to rebuild these beaches in response to a 30 cm rise in sea level. This estimate considers only the beaches themselves; raising people's lots to avoid inundation would further increase the costs. The US Army Corps of Engineers (1971) estimated that in 1971, 25,000 km of shoreline (exclusive of Alaska, the Great Lakes and Hawaii) were eroding, of which 17% were 'critically eroding', and would require engineering solutions. If 17% of all shorelines require erosion control, that would imply protection of close to 10,000 km of shoreline. Sorensen (1986) describes dozens of engineering options for preventing erosion, the least expensive of which costs $300,000/km, implying a cost of at least $3 billion for protecting shorelines.

2.5.2 *Other impacts of the greenhouse warming*

The impacts of sea level rise on coastal areas, as well as their importance, are likely to depend in part on other impacts of the greenhouse warming. Although future sea level is uncertain, there is a general consensus that a global warming would cause sea level to rise; by contrast, the direction of most other changes is unknown.

One of the more certain impacts is that most areas will be warmer. For coastal resorts in mid-latitudes, the beach season would be extended by a number of weeks. For densely developed communities like Ocean City with a three-month peak season, such an extension might increase revenues 10 to 25%, far more than the estimated cost of controlling erosion. Some areas where the ocean is too cold to swim today might have more tolerable water temperatures in the future. Warmer temperatures in general might encourage more people to visit beaches in the summer.

Warmer temperatures might change the ability of wetlands to keep pace with sea level rise. Mangrove swamps, which are the tropical equivalent of salt marshes, generally accrete more rapidly than salt marshes. If warmer temperatures enable mangroves to grow at higher latitudes, the loss of wetlands to sea level rise might be reduced. On the other hand, marsh peat formation is generally greater in cooler climates; warmer temperatures might reduce the rate of vertical accretion for these wetlands.

De Sylva (in Titus 1986) suggests that changing climate could alter the frequency and tracks of storms. Because hurricane formation requires water temperatures of 27°C or higher (Wendland 1977), a global warming might result in an extension of the hurricane season and in hurricanes forming at higher latitudes. Besides increasing the amount of storm damage, increased frequency of severe storms would tend to flatten the typical beach profile, causing substantial shoreline retreat unless additional sand was placed on the beach. A decreased frequency of severe winter storms might have the opposite impact at higher latitudes.

Because warmer temperatures would intensify the hydrologic cycle, it is generally recognized that a global warming would result in increased rainfall worldwide. Thus, rainwater flooding might be increased because of both decreased drainage and increased precipitation. The impact of sea level rise on salt water intrusion could be offset by decreased drought frequency or exacerbated by increased drought frequency (Rind & Lebedeff 1984).

2.6 CONCLUSIONS

The studies reviewed in this paper appear to support the following conclusions regarding the causes and effects of sea level rise:

2.6.1 *Causes*

The projected global warming would accelerate the current rate of sea level rise by expanding ocean water, melting alpine glaciers, and eventually, causing polar ice sheets to melt or slide into the oceans.

Global average sea level has risen 10 to 15 cm over the last century. Ocean and glacial studies suggest that the rise is consistent with what models would project, given the 0.4°C warming of the past century. However, no cause and effect relationship has been conclusively demonstrated.

Projected global warming could cause global average sea level to rise 10 to 20 cm by 2025 and 50 to 200 cm by 2100. Thermal expansion could cause a rise of 25 to 80 cm by 2100, Greenland and alpine glaciers could each contribute 10 to 30 cm through 2100. The contribution of Antarctic deglaciation is likely to be between 0 and 100 cm; however, the possibilities cannot be ruled out that (a) increased snowfall could increase the size of the Antarctic Ice Sheet, thereby offsetting part of the sea level rise from other sources; or (b) meltwater and enhanced calving of the ice sheet could increase the contribution of Antarctica to as much as two metres.

Disintegration of the West Antarctic Ice Sheet might raise sea level an additional six metres over the next few centuries. Glaciologists generally believe that such a disintegration would take at least three hundred years, and probably as long as five hundred years. However, a global warming might result in sufficient thinning of the Ross and Filcher-Ronne ice shelves in the next century to make the process irreversible.

Local trends in subsidence and emergence must be added or substracted to estimate the rise at particular locations.

2.6.2 *Effects*

A substantial rise in sea level would permanently inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

Bangladesh and Egypt appear to be among the nations most vulnerable to the rise in sea level projected for the next century. Up to 20% of the land in Bangladesh could be flooded with a two metre rise in sea level. Although less than 1% of Egypt's land would be threatened, over 20% of the Nile Delta, which contains most of the nation's people, would be threatened.

A large fraction of the world's coastal wetlands may be lost, threatening some fisheries. A rise in sea level of one to two metres by 2100 could destroy 50-80% of US coastal wetlands. Although no study has been taken to estimate the worldwide impact, this result is probably representative.

Erosion caused by sea level rise could threaten recreational beaches throughout the world. Case studies have concluded that a 30 cm rise in sea level would result in beaches eroding 20-60 m or more. Because the first row of houses or hotels is often generally less than 20 m from the shore at high tide, if available studies are representative, then recreational beaches throughout the world would be threatened by a 30 cm rise unless major beach preservation efforts are undertaken.

Sea level rise would increase the costs of flooding, flood protection, and flood insurance in coastal areas. Flood damages would increase because higher water levels would provide a higher base for storm surges; erosion would increase the vulnerability to storm waves; and decreased natural and artificial drainage would increase flooding during rainstorms.

Future sea level rise may already be an appropriate factor to consider in the designing coastal drainage and flood protection structures.

Increased salinity from sea level rise would convert cypress swamps to open water and threaten drinking water supplies.

The adverse impacts of sea level rise could be ameliorated through anticipatory land use planning and structural design changes.

Other impacts of global warming might offset or exacerbate the impacts of sea level rise. Increased droughts might amplify the salinity impacts of sea level rise. Increased hurricanes and increased rainfall in coastal areas could amplify flooding from sea level rise. Warmer temperatures might enable mangrove swamps – which can accrete vertically more rapidly than salt marshes – to advance further north, perhaps decreasing wetland loss caused by sea level rise.

River deltas throughout the world would be vulnerable to a rise in sea level, particularly those whose rivers are dammed or leveed.

Economic studies of Bangladesh, Egypt, and the United States suggest that sea level rise would be economically important to coastal areas.

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3 SEA LEVEL RISE ON THE AWAKENING EARTH

H.Tennekes

3.1 FRAGMENTS OF A VISION

3.1.1 *Fragment 1: It's not nice to fool Mother Nature!*

In a favorite US television commercial of the early seventies, a salesman asks Mother Nature to try a fancy new margarine. He does not tell her anything about the source of the product. She puts a little on her tongue, tastes it carefully, and says: 'Oh, that's my own sweet butter!' When she learns that she has been offered a substitute, her temper turns violent. Against a background of thunder and lightning, she exclaims indignantly: 'It's not nice to fool Mother Nature!'

We should keep in mind that Mother Nature may act in unexpected ways when she is confronted with the impact of technological progress. The current consensus in the meteorological community is that the steady increase in atmospheric carbon dioxyde levels, which is caused by the mindless way in which mankind consumes fossil carbon resources, will lead to a certain amount of warming of atmosphere and oceans. This may accelerate the melting of the Antarctic ice sheet. But this is merely a consensus; the danger (or the pleasant surprise!) of some unexpected turn of events, in my opinion, cannot be ignored.

3.1.2 *Fragment 2: The Gaia hypothesis*

Twelve years ago, James Lovelock and Lynn Margulis developed the Gaia hypothesis. Gaia (or Gaea, whence e.g. geology) is the Greek earth goddess. In the Gaia hypothesis, the Earth is seen as a living creature, perfectly capable of fending for herself. The planet on which we live has a tremendous self-organizing potential. She has, for example, changed the chemical composition of her atmosphere to suit the plants and animals that live on her surface. The present level of oxygen is much higher than millions of years ago. All living creatures need this basically very toxic gas in their carbon-based energy cycles. According to this point of view, photosynthesis is not a stroke of good luck, a random accident, but an act of wisdom on the part of the planet. The oxygen production of green plants in sunlight is an excellent example of the self-organizing power of our planet.

What is Mother Earth up to, as she contemplates the increasing carbon dioxyde level in her atmosphere? We know that greenhouse crops grow faster and better when CO_2-levels are increased. The water use efficiency of soy beans doubles when the carbon dioxyde level doubles, and that of corn increases by at least 35%. Will our planet allow us to increase the carbon dioxyde concentration so much that she can restore the forests on her surface? Will she hit back before the CO_2-level is too high? And in what way? Is she going to lower or raise the sea level? And in which way should mankind respond?

The self-organizing potential of the planet on which we live should not be underestimated. This is not to say that mankind can continue to ignore the brutality and utter carelessness with which we dump waste products in air, water and soil. But the suggestion of an extremely fragile ecological balance, to be protected by advanced technology, has to be rejected: It does not fit the facts. The point is that the regenerative powers of our planet are poorly understood. We know far too little of the nonlinearities and unpredictabilities of the uncountable feedback loops in the climate system.

3.1.3 *Fragment 3: The Genesis strategy*

In his 1976 book, Stephen Schneider of the US National Center for Atmospheric Research advocates the adoption of a global Genesis strategy. He feels that the fluctuations of weather and climate will remain largely unpredictable, and suggests that governments should protect their nations by preparing for possible setbacks, for example by stockpiling food during good years. This is what Joseph advised the Faraoh after his dream about the succession of seven good years and seven lean years.

Again, the emphasis is on a flexible response to unpredictable circumstances. The issue at hand is not only to work out a strategy to deal with the consequences of one of the many possible scenarios (i.e. a 1 m sea level rise), but also to develop a meta-strategy on the great variety of scenarios that can be envisaged.

3.1.4 *Fragment 4: Toward the limits of predictability*

The limited predictability of the weather reminds us every day that there is a limit to the powers of science and technology. The atmosphere is a complicated nonlinear system; it exhibits chaotic behaviour (to use the jargon of current nonlinear dynamics theory). Weather forecasting is a disappointing process. The theory of predictability offers no relief: It states unequivocally that more technology, better observations, bigger computers and better science will not be able to improve the average prediction range by more than a few days.

In the atmosphere (and in all nonlinear systems that exhibit chaotic behaviour because they suffer sensitive dependence on initial conditions) the reliability of computer calculations decreases in time. Two calculations starting from slightly different initial conditions gradually become uncorrelated. This is not simply a matter of error amplification: the spectral flux of error variance plays a crucial role in this process. The finite resolution of any computer simulation introduces inevitable errors at the small-scale end of the spectrum. These errors propagate toward the larger scales and ultimately contaminate the energy-containing eddies, even if there is a strong spectral flux of kinetic energy toward the small scales. It turns out that the average period over which the evolution of a phenomenon can be predicted with some reliability is comparable with the typical life time of phenomena at that scale. The total range of predictability is comparable to the characteristic life time of the most energetic phenomena (processes, coherent structures).

The other side of the coin is that nonlinear systems with chaotic behaviour routinely create new coherent structures. The great mid-latitude cyclones in the atmospheric circulation demonstrate time and again that the atmosphere is capable of creating impressive order out of the daily chaos. Nonlinear systems have a tremendous self-organizing potential.

We stand at the end of the Newtonian era. The limited predictability of many dynamical systems destroys the last remnants of the determinism exemplified by Laplace's 'Mécanique Céleste'. The very meaning of the word 'exact' has become questionable: What is the use of a great many decimal places in a measurement or calculation, if that does not materially improve the predictability horizon?

We should not overestimate our predictive powers. There are countless ways in which calculation errors may propagate up or down the spectrum of phenomena. A mistake in modeling one component of the climate system may show up with great amplitude in one or several of the countless other components.

3.1.5 *Fragment 5: The awakening Earth*

One very unpredictable process that has to be dealt with when developing scenarios for the 21st century and beyond is the accelerated rate at which the planet Earth is developing a global consciousness. This symposium is a good example: It is organized from a global perspective. The chance that the equivalent of an unpredictable phase transition in the brains of our planet will occur in the next century can no longer be dismissed offhand. In 1939, Teilhard de Chardin predicted a future in which an integrated awareness, the 'noosphere', would span the planet, much like the biosphere has gradually covered the planet millions of years ago.

Teilhard did not predict when this would occur, but (to give just one example) the technology of satellite communication systems and computer links has grown so fast that the wiring for the brains of the 'global village' can be considered nearly complete. We are rapidly approaching the moment when the light can be turned on.

For a recent exposition of this view see Russell (1982) and the next section which is taken in its entirety from pp.18-21 of his book.

3.1.6 *Fragment 6: Humanity on Gaia*

Russell writes:

'If the entire biosphere has evolved as a single living system, in which all the numerous subsystems play diverse and mutually dependent roles, then humanity, being a subsystem of this larger planetary system, cannot be separated from it or treated in isolation. What then is its function in relationship to Gaia? There seem to be two common and opposing responses to this question. The first is that humanity is like some vast nervous system – a global brain in which each of us are the individual nerve cells. The second, more pessimistic, possibility is that we are like some kind of planetary cancer.

Considering the first response, human society, like our own brain, can be seen as one enormous data collection, communication and memory system. We have grouped ourselves into clusters of cities and towns rather like the way nerve cells cluster into ganglia in a vast nervous system. Linking the 'ganglia' and the individual 'nerve cells' are vast information networks. At any instant there are millions of messages flashing through the global network, just as in the human brain countless messages are continually flashing back and forth. Our various libraries of books, tapes and other records can be seen as part of the collective memory of Gaia. These parallels relate to the higher mental functions, to thinking, knowing, perceiving and consciousness, to the functions associated with the cortex of the human brain – the thin layer of nerve cells wrapped around the outside of the brain – and it might be more accurate to liken humanity to the cortex of the planet.

In evolutionary terms, the cortex is a relatively late addition, most of its development occurring with the mammals. It is not necessary for the maintenance of life; the cortex of an animal can be removed, yet the heart, lungs, digestion and metabolism will continue. In a similar way the planet Earth has survived perfectly well without humanity for over 4,000 million years, and could continue very well without it.

This brings us to the second possibility – that humanity might be some form of recently-erupted malignant growth, which the planet would be better off without. The analogy with cancer cannot be ignored. Modern civilisation seems to be eating its way indiscriminately across the surface of the planet, consuming in decades mineral resources which Gaia herself inherited billions of years ago. At the same time humanity is threatening to destroy the biological fabric which took millennia to create. Technological civilisation really does look like a rampant malignant growth blindly devouring its own ancestral host in a selfish act of consumption.

This view might seem to be in opposition to the idea of humanity being some form of global brain. It is entirely possible, however, that both these perspectives of humanity's role on Gaia may be valid. Perhaps we are part of some global nervous system, currently passing through a very rapid phase of development, capable of being to the planet everything that our own brains are to us. Yet this nervous system has, at a very critical stage, appeared to have gone out of control, threatening to destroy the very body which supports its existence.

If we are to fulfill our role as a part of the planetary brain, our malignant behaviour must be stemmed and the negative trends reversed. If we are to achieve this, it is imperative that we change, in the most radical way, our attitudes towards ourselves, others and the planet as a whole.'

3.1.7 *Fragment 7: Beware of the technological fix*

More than ten years ago Julian Heicklen, a former colleague of mine at the Pennsylvania State University, proposed that the photochemical smog over Los Angeles could be fixed simply and easily by daily spraying a few tons of a certain chemical over the basin. One aircraft flight a day would be sufficient for the purpose. Need I make a biting comment?

Strengthening coastal defences may be an appropriate reaction to a dangerous sea level rise. Again, this could turn out to be as stupid as the US escalation of the Vietnam war. What if the sea level continues to rise, so that all coastal plains on the planet have to be evacuated eventually, anyway? And why does Nature have to be viewed as the Great Enemy? Are natural disasters so much worse than man-made ones?

I have lost my belief in technological fixes. I am not even sure I would want an artificial heart if that were necessary to keep me alive. As Russell says: 'We must change, in the most radical way, our attitudes towards ourselves, others, and the planet as a whole'.

3.2 INTERMEZZO: THE EARTH SCIENCE

A continuing sea level rise at the rate of one metre per century will most likely help to cause a substantial increase of funding for the earth sciences. Gaia will become one of the main sources of inspiration for physics in the next century. This will require new institutes, research organizations, and laboratories. The funding for research that explores the universe (astronomy, astrophysics) and for research that explores the world of the elementary particles (high-energy physics, quantum mechanics) will decrease by comparison, and perhaps even in absolute magnitude. All disciplines will focus on the relations and interactions between processes. Science will attempt synthesis; as the global awareness increases, even social science and physics will rediscover each other.

The potential impact of climate fluctuations will also create a need for a comprehensive data base on all processes in atmosphere, hydrosphere, biosphere and lithosphere. Satellite-based remote sensing of the planet will evolve into an international undertaking by all government agencies that are responsible for environmental and ecological policy development. Obviously, international cooperation will have to increase. Should the United Nations create a Planetary Environment and Climate Organization?

3.3 THE VIEW FROM METEOROLOGY

The view from meteorology is that nature is not necessarily our enemy. The impact of sea level rise on society is a grave question, a problem that has to be studied thoroughly, from several points of view. But the noun 'impact' suggests an act of aggression, as a bomb hitting people in a Vietnamese rice field.

If we seduce ourselves into thinking that mankind has a duty to defend itself against Nature's aggression, we can conveniently forget that the original aggressor is mankind itself. It is the industrial world that is robbing the planet of her carbon resources: Why should she not create a climate with extensive coastal swamps where the carbon can be stored again?

Perhaps the lowlands of the world ought to be evacuated soon, so that coastal countries can contribute effectively to the future international program for carbon storage in the biomass.

Perhaps the cheapest solution to the sea level rise problem is to begin massive reforestation of the tropics, including the Sahara and other tropical deserts.

If we make Nature our enemy, we do not realize that we are part of Nature, too. The distinction between Gaia and her children is utterly artificial. Why do we not finally wake up? With a bit of luck, it is not yet too late. Not yet.

3.4 THE VIEW FROM CHAOTIC SYSTEMS THEORY

In systems that have a strange attractor, infinitely many orbits describing the evolution of the system in phase space pass through the little volume that represents the accuracy with which the present state of the system can be determined. All of these orbits diverge sooner or later; all calculations of the future evolution of the system become useless in due time. Nonlinear systems have a finite predictability horizon.

There is, however, no information whatsoever on the predictability horizon of the current generation of climate models. A sea level rise of one metre per century is a scenario that has to be reckoned with, but for how long? When will the trend reverse? Will it accelerate, or will it flatten out as mankind switches to other energy sources? In a nonlinear world, we should beware of making linear extrapolations. Linear extrapolations are bound to be unreliable in the long run. Perhaps their only usefulness is to scare us into contemplating the potential consequences of our own stupidity. We may wake up in time after all.

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4 THE DATA ACQUISITION OF AND TRENDS OBSERVED IN GLOBAL MEAN SEA LEVEL

Philip L.Woodworth

The following contribution attempts to describe the main sea level research interests at the Institute of Oceanographic Sciences (together with the Permanent Service for Mean Sea Level). Primarily these comprise sea level data collection and analysis for oceanographic, geological and geodetic research purposes and the study of tides and surges. Each part of our work, insofar as it applies to the ISOS study, is described below with recommendations for future research.

4.1 THE PSMSL

The Permanent Service for Mean Sea Level (PSMSL) has since 1933 been responsible for the collection and distribution to research workers of worldwide monthly and annual mean sea level data obtained from tide gauges. It is partly funded by the Federation des Services Permanents d'Astronomie et de Geophysique and the Intergovernmental Oceanographic Commission of UNESCO and is based at the Institute of Oceanographic Sciences, Bidston, UK. At present the PSMSL database contains sea level information from approximately 1300 stations worldwide with the longest record from Brest which commenced in 1807.

Data from each station is entered as received from national sea level authorities into the PSMSL 'Metric' file for that station. The monthly and annual means so entered for any one year are necessarily required to be measured to a common land datum, although at this stage datum continuity between years is not essential. However, in order to construct time series of sea level measurements at each station, the monthly and annual means have to be reduced to a common datum throughout the sea level record.This reduction is performed by the PSMSL making use of the tide gauge datum history provided by the supplying authority. Approximately 700 stations in the PSMSL database have had their data adjusted in this way, forming the 'Revised Local Reference' (or 'RLR') dataset. For the study of sea level secular trends, it is usually only stations included in the RLR dataset which are of use. In recent years a particular effort has been made to encourage the establishment of sea level measurements with good datum control in the tropics and in the southern hemisphere, where historically few tide gauges have operated. It is still true, however, that North America, Japan and Europe remain the three areas where the most sea level information is to be found.

4.2 EXISTING SEA LEVEL DATA FROM THE ISOS CASE STUDY AREAS

Existing mean sea level information available from the PSMSL for the case study areas selected for the ISOS project are shown in Table 4.1. For the Netherlands, all the data included in the Metric dataset are measured with respect to the National Levelling System ('NAP') and for the purposes of sea level secular trend studies can be used as if they had been in the RLR dataset. The fact that they are not in the RLR dataset stems from the preference of the PSMSL to express all data with respect to local and not national datums thus avoiding levelling errors. A description of Dutch data can be found in Van Malde (1986). Hoek van Holland, which is typical of Dutch stations, shows a rise of 2.5 mm/year averaged over the 119 years 1864-1984; no evidence for acceleration in the rate of sea level rise can be observed for recent years. For the Bangladesh data, however, no detailed datum information at all is available to enable connected series to be made. In addition, the Maldive Islands contain very little data. The result is that no sea level data from the ISOS case study areas appear in the PSMSL RLR dataset.

Table 4.1. Existing mean seal level available from the PSMSL for the case study areas selected for the ISOS project.

	RLR	Metric
Netherlands		
Delfzijl	53°20′N, 06°56′E	1865-1984
Terschelling	53°22′N, 05°13′E	1921-1984
Harlingen	53°10′N, 05°25′E	1865-1984
Den Helder	52°58′N, 04°45′E	1865-1984
IJmuiden	52°28′N, 04°35′E	1871-1984
Hoek van Holland	51°59′N, 04°07′E	1864-1969 1972-1984
Maassluis	51°55′N, 04°15′E	1848-1936
Hellevoetsluis	51°49′N, 04°08′E	1861-1968
Brouwershaven	51°44′N, 03°54′E	1872-1968
Zierikzee	51°38′N, 03°55′E	1872-1983 1985
Vlissingen	51°27′N, 03°36′E	1862-1984
Maldive Islands		
Gan	00°34′S, 73°13′E	1962-1963
Bangladesh		
Dublakhal	21°51′N, 89°32′E	1951
Chittagong (Sadarghat)	22°20′N, 91°50′E	1937-1948 1956-1961
Chittagong (Patenga Point)	22°40′N, 91°48′E	1954-1960
Chittagong (T.M. Compound)	22°19′N, 91°49′E	1960-1968
Chittagong (Juldia Point)	22°15′N, 91°50′E	1961-1968

4.3 COMMENT ON DETERMINATIONS OF 'GLOBAL' SEA LEVEL RISE

Attempts to derive a 'global average' value for the rate of sea level rise have been made in the last few decades by many authors, with the consensus of opinion in favour of a rate of rise between 1 and 3 mm/year [for a list of authors, see Lisitzin (1974) and Barnett (1983a)]. The individual analyses are not independent, however, as they have all used essentially the same sea level dataset obtained, directly or indirectly, from the PSMSL. The result of the most recent, and most sophisticated, analysis is from Barnett (1984a). The slope of the global trend for the period 1881-1980 is 1.43 ±0.14 mm/year, a value close to that observed by previous workers. However, little or no trend is apparent in the first half of the record, while in the second half, 1930-1980, a trend of magnitude 2.27 ±0.23 mm/year is obtained. This result, while providing evidence for the increasing trend from the beginning of the century, also demonstrates the difficulty of defining a current value of sea level trend independent of the epoch in question. Barnett concludes,and we would agree, that the present absolute rate of global mean sea level rise is uncertain to within at least a factor of 2.

4.4 STEPS TO BE TAKEN TO IMPROVE GLOBAL ESTIMATES

There are three major improvements in the acquisition of sea level-related data which must be made in order to provide more reliable estimates of global secular changes.

4.4.1 *Better geographical distribution of tide gauges*

The distribution of tide gauges around the world is heavily biased towards the northern hemisphere. Additional tide gauges, particularly in the tropics and the southern hemisphere, are planned for installation in the near future for a variety of oceanographic purposes (Wyrtki & Pugh 1985, Pyle 1985), and it is to be hoped that such gauges stay in operation for a considerable time in order to monitor sea level trends on a more genuinely global basis.

4.4.2 *Independent measurements of land movements*

Tide gauges measure the rate of sea level change relative to the land on which they are situated and even in a small area, such as the UK, different sea level trends arising from spatial variations in land movements can complicate estimates of true sea level rise (Woodworth 1986). Consequently an independent measure of change in the level of the land, in a geocentric coordinate system, is required to decouple land and ocean variability. Gauges in the future therefore should be fully equipped with the necessary modern geodetic measurement techniques (e.g. via the Global Positioning System and Very Long Baseline Interferometry) as recommended in IAPSO (1985).

A parallel approach to the problem of land movements is through improved geodynamic modelling. In areas of obvious glacial recovery, geodynamicists have made definite progress in recent years in quantifying the rate of rise or fall of the land (Peltier 1982). For example, it is clear that along the US east coast sea levels have larger than average secular trends owing to a contribution from glacial isostatic subsidence (IAPSO 1985). In principle, geodynamic models, as described in Peltier (1982), could be used to remove the contributions of isostatic disequilibrium from the tide gauge records. Lambeck & Nakiboglu (1984) suggest that 30-50% of the 'global' trend measured by Barnett (1983a), which did not include isostatic disequilibrium corrections, does not arise from ocean volume change but from the ongoing rebound of the earth's crust following the melting of the Pleistocene ice sheets, and from the uneven geographical sampling of the tide gauges.

4.4.3 *Removal of 'noise' from the sea level records*

The removal from each station's sea level record of the principally high-frequency meteorologically-induced variability sometimes, but not always, results in significantly more precise secular trend estimates. For example, Thompson (1986) shows thirty years of data from Newlyn (UK) as observed and after the removal, using linear regression fitting, of the combined influence of local wind, air pressure and oceanic sea level slope. The trends in the observed and residual records are 1.0 ±0.5 and 1.4 ±0.2 mm/year respectively. The standard errors clearly indicate the increased confidence that can be placed in the latter estimate enabling a change in the trend to be identified more readily in the residual, rather than the observed, series. A converse example concerns the western boundary of the North Atlantic for which Thompson (1986) has shown that it has not been possible to obtain by these simple means a 'cleaner' signal for detecting a change in the rate of rise of sea level. It is conceivable that such variability may eventually be removable via more sophisticated ocean numerical modelling, provided that the essential datasets (temperatures, salinities, meteorology, etc.) are also available.

In the very long term the problem of measuring truly global sea level changes may be solved by precise satellite altimetry with altimeter experiments repeated every 10 or 20 years (Born et al. 1986). This will also remove a difficulty arising from possible bias in the estimate of global levels arising through the chance of significant gyral spin-up and through gauges being situated principally on continental coastlines. Altimetry over the polar ice-caps and mountain glaciers will also provide measurements relevant to sea level rise through monitoring of the world's store of ice.

4.5 EXPLANATION OF ESTIMATED GLOBAL SEA LEVEL CHANGES OF THE LAST CENTURY IN CLIMATIC TERMS

There is some difficulty in accounting for the magnitude of the estimates of global sea level rise over the last century. Most of these problems are discussed in the recent report of Robin (1986). The situation can be summarised as follows.

Air temperatures are known to have increased during the last century (e.g. Jones et al. 1982), probably associated with the increase in atmospheric CO_2 concentrations and with a number of other forcings, such as volcanic activity. However, the evidence for a corresponding rise in sea temperatures is controversial (Barnett 1984b), and is not capable of explaining all the estimated sea level rise through thermal expansion of the ocean (Barnet 1983b).

Reduction in size of the polar ice-caps, with the consequent increase in ocean water volume, has also been suggested as a contributor to global sea level rise. Oerlemans (1981), for example, has suggested that irregular quasi-random fluctuations in Antarctic precipitation can produce changes in global mean sea level of the order of 5 cm, much as is observed in the present data. In principle, any large decrease in polar ice-store will also have an effect on the earth's rotation rate and on polar motion through the transfer of mass from the poles to lower latitudes (see Barnett 1983a for a good summary of changes in polar motion and length of day to be expected from sea level rise). Etkins & Epstein (1982), using the global sea level trend calculation of Emery (1980) to estimate the magnitude of the mass transfer, proposed that this mechanism could be consistent with a large fraction of the observed reduction in the earth's rotation rate since 1940. However, the rate of rotation is also subject to large fluctuations through variable motion in the earth's core and to deceleration through tidal friction (Hansen et al. 1983). In addition, the Emery sea level rise estimate was weighted heavily by the large number of stations on the east coast of the United States, and is much larger than those calculated by other authors. A contribution to the variability in earth rotation through change in global sea level is therefore extremely difficult to establish. Recent estimates of the mass balance of the Greenland and Antarctic ice sheets suggest they are in approximate balance, while the latter may even be subtracting water from the ocean (Meier 1984). In the future it will be essential to monitor the ice-caps through techniques such as satellite altimetry (e.g. Brooks & Norcross 1984), particularly if global temperatures rise significantly. At the present time, however, the contribution of polar melting to the observed rise in global mean sea level does not appear to be as large as was once thought.

A small fraction (about 1%) of total land ice is stored in glaciers other than those of the polar ice sheets. Over the epoch 1900-1961 almost all such glaciers have been in retreat as air temperatures have risen and, although the errors involved in the calculation are large, water from these glaciers can account for a third to a half of the observed (Gornitz et al. 1982) rise in sea level during that time. Meier (1984) suggests the possibility of explaining the Gornitz et al. estimate by a combination of thermal expansion of the ocean and glacier melting. The estimates of glacier melting are once again biased by almost all data coming from the northern hemisphere but do indicate an important, and hitherto largely, ignored, source of sea level rise.

In summary, the best estimate that one can make suggests a current rate of rise of global sea level of around 2 mm/year, although with unknown systematic errors (probably a factor 2 or more) arising from the uneven distribution of worldwide tide gauge records. Thermal expansion of the ocean, driven by global warming, can account for part of this rise. However, additional sources of ocean water volume (e.g. from polar ice-caps, glaciers etc.) are required to obtain even an approximate description of the observed effect. Other mechanisms, such as circulation changes, groundwater loss, trapping of water behind large dams, harbour sedimentation and civil engineering, earthquake activity etc. also contribute to the secular changes observed in the tide gauge records (for example, Newman & Fairbridge (1986) estimate that an effective 0.75 mm/year global sea level rise has been removed over the last half-century through trapping of water into reservoir storage and irrigation projects). Until all these various mechanisms are better understood in the overall context of climatic change, predictions of global sea level rise into the next century will be extremely uncertain, although such extrapolation exercises have already been attempted by brave authors; the most recent set of predictions can be found in Robin (1986). Several studies agree on the order of a metre rise in sea level over the next century but quantatively disagree on the relative importance of each forcing [e.g. compare Robin (1986) with Revelle (1983), Hoffman et al. (1983) and PRB (1985)]. One might ask, therefore, if these projections are to be assigned any degree of confidence at all.

A major improvement in the quality of global sea level predictions can only be obtained from more reliable monitoring of the various parameters and more realistic climate modelling. The future rate of sea level rise due to thermal expansion, in particular, appears to be poorly understood at present (PRB 1985). Improvements in the modelling of the ocean-atmosphere general circulation are urgently required. These are at present held back, partly by limitations of the required computing resources and partly by lack of data from which to develop the necessary algorithms. Significant improvements in this situation are to be anticipated in the next decade as a result of up-coming research programmes.

4.6 DETECTION OF ACCELERATION IN SEA LEVEL SECULAR TRENDS

If one accepts the approximate scenario of sea level forcings described in the previous section, then the prediction of future sea levels is best made through projections of the contribution from each forcing by means of (hopefully) increasingly more-reliable climate models, rather than by direct observations of accelerating trends from an unevenly globally-distributed network of tide gauges. In particular the major forcing, an increase of ocean temperatures, can be expected to lag behind the corresponding rise in global air temperatures (or CO_2 concentrations) by one or two decades thereby providing some degree of sea level warning. Rising air temperatures will also raise sea levels through glacier and polar ice melting which will be a relatively 'instantaneous' process. However, over the next 50-100 years this component is considered to be somewhat less important than thermal expansion [if one believes Robin (1986)] and warming can be provided not only by the air temperatures themselves but also by precise monitoring of ice sheets by satellite altimetry.

If one ignores other climatological data and concentrates on sea level information alone, then the observation of a statistically significant acceleration in the records over the next 50 years or so appears extremely difficult. Barnett (1984a) concluded that the possibility of observing a low-frequency contribution to sea level rise, such as anticipated from CO_2 build-up, on top of the existing low-frequency climatic and geological signals is rather unlikely. On the other hand, if a significant change in sea level trend does take place, it should be easily and routinely detectable from the available data given sufficiently long sea level records.

An important statistical point to be made here is that the 'global' trend data for this century, at least as observed in the principal components analysis of data from many stations by Barnett (1984a), seems at present to be well-described by a linear trend and the residuals about the fitted trend are observed to be approximately normally-distributed. This means that the standard error of the trend is well estimated, and one can speak with some confidence (systematic errors aside) of the magnitude of the trend. For individual stations, however, this is often not the case. Most station records show inter-annual variability, for example on decadal time-scales, which should be removed from the residuals by means of regression or other forms of modelling in combination with other climatic variables. If this is not done, the residuals will not be normally-distributed and the standard error on the observed trend in sea level at that station will be badly estimated. This effect often manifests itself in different standard errors on the secular trends being obtained from annual and monthly mean sea level values, even though the monthly mean sea level data may have been deseasonalised prior to analysis. It is important, therefore, to remove the inter-annual variability as far as possible, as discussed above.

4.7 THE ISOS CASE STUDY AREAS

The following short remarks apply to the Bangladesh, Maldive and the Holland case study areas. The latter we feel may be worth expanding to include the entire southern North Sea as Holland and south-east England have similar rates of sea level rise and suffer from the same storm surges.

4.7.1 *The Bangladesh case study area*

Bangladesh comprises an obvious area for a case study of the effect of rising sea level with the average height of the country a mere 7.6 m above present sea level (defined by a tide gauge at Chittagong). MSL at the coast varies by approximately 2 m throughout the year (Woodworth 1984) with a maximum at the monsoon in August. An additional metre in sea level obviously implies increased flooding, erosion and widening of the estuaries [damming of the rivers may also worsen the problem, see Broadus et al. (1986)]. In addition, the coastline suffers severely from storm surges generated by cyclones in the Bay of Bengal, in particular in the pre- and post-monsoon seasons (i.e. around May and November). Notable examples of surges are that of November 1970 in which 300,000 people were killed and the recent May 1985 surge which devastated the NE corner of the Bay, also with large loss of life. Furthermore tides and surges can be observed in the river levels of the entire southern half of the country. The major effect of a sea level rise in this region, therefore, is the increased likelihood of storm surge damage rather than 'simple' flooding.

The origins of the Bay of Bengal cyclones and the production of surges in the shallow waters at the head of the Bay have recently been reviewed by Murty et al. (1986). In principle, surge predictions can be calculated by means of numerical models provided that the models can be supplied with the relevant forecast meteorological information and the correct ocean tide and bathymetric data. In areas of large ocean tides, such as the Bay of Bengal, the tide and the meteorological surge cannot be considered as independent quantities but interfere in a nonlinear fashion to give significant 'tidesurge interaction'. The requirements for an operational surge-forecast facility can be summarised as:

a) A numerical model which takes all terms (including the nonlinear terms) properly into account. At the coasts the scheme should include high resolution estuary models;

b) accurate meteorological data from new coastal and space radars as well as existing routine observations of air pressures and winds;

c) accurate meteorological forecast data and the conversion of forecast surface wind velocities into surface wind stresses;

d) accurate bathymetric information. In shallow water the major forcing is wind set-up which is proportional to the wind stress divided by water depth. Inaccuracy in depth data in the shallow waters of the Bay will result in incorrect surge estimates;

e) accurate knowledge of the astronomical ocean tides, in particular the large lunar M2 component. In fact the tides of this region are badly known (it is proposed that ISOS participate in a series of pelagic tidal measurements in the deep part of the Bay during 1987 as part of a WMO/UNDP programme for the area. Together with an ongoing programme of coastal tide measurements, this should result in better tidal models for the area).

f) accurate surge measurements. Approximately 50 float tide gauges are known te be in operation in Bangladesh at present from which valuable surge data should be obtained for model tuning (there are of the order of 3 or 4 largish surges along this coast every year). The largest surges, however, are usually outside the range of recording of normal tide gauges and alternative efficient monitoring of high water marks on buildings etc. is also required. The development of tide gauges with a sufficient recording range, capable of withstanding very harsh treatment during the violent surges, is a major priority.

At present there are difficulties in providing all (a)-(f). However, in a short period (compared to the time-scale of sea level rise considered in this study) it can be anticipated that considerable improvements in all factors will take place and that the storm surges of the area will be better understood.

Adding an additional one metre to sea level obviously changes slightly the bathymetry of the Bay and the effective coastline of this low-lying region. In addition, it changes the river discharge of water and sediment and alters the tide, surge and interaction components of sea level predictions. It is impossible at this stage to speculate on the physical consequences of this adjustment to the new sea level (aside perhaps from simple estimates of increased land area at risk). However, they could be studied in some detail assuming that a model such as (a) above, which adequately reproduces the present data, could be modified to anticipated future conditions. The model would have to assume as a first approximation that all other factors (e.g. regional precipitation and evapotranspiration of plants) remain the same, although global CO_2 effects may well alter these quantities also. Such numerical modelling exercises should be a major recommendation of this study group.

4.7.2 *The Maldive Islands case study area*

While tides have been measured at several locations in the Maldives, there have been few measurements of mean sea level or extreme levels. The only mean sea level record in the PSMSL archive is from Gan (see Table 4.1); no records exist from the populated island capital of Male. Islands in the open ocean are unlikely to suffer large surges (other than in tsunami areas) such as those observed in the other case study areas. However, in view of the importance of sea level rise to these low-lying islands, the provision of tide gauges to record extreme levels and the local relative sea level trends would appear to be a worthwhile long-term investment (perhaps $20,000). The ISOS group should communicate such a recommendation to the appropriate agencies.

4.7.3 *The Holland and southern North Sea study area*

The changes in the level of the North Sea are considerably better understood than those of the Bay of Bengal or the Maldives. Tide gauges have operated for a century or more, meteorology and other variables are routinely monitored, and sophisticated tidal and storm surge models already exist. The effects of a change in mean level due to corresponding changes in the open ocean, however, remain largely unexplored so far, although preliminary studies for the open North Sea have been made by the Rijkswaterstaat (1986). These have shown that a sea level rise even as large as 5 m is unlikely to significantly change open sea tidal patterns.

In shallow-water areas, especially estuaries, bottom friction plays an important role and as the mean depth increases the tidal regime is changed. The River Thames estuary can be taken as an example (Rossiter 1969). The rising level of the river implies less bottom friction and, therefore, faster propagation of the tide up-river.This has been confirmed by comparison with data from Southend and Tower Pier which show the travel time of the tide between the two stations to be decreasing at a rate of approximately 16 minutes/century. Lower friction should also lead to less distortion of the tidal profile, and an increase in the major diurnal and semi-diurnal components at the expense of the higher frequency terms (Amin 1983). Larger semi-diurnal amplitudes produce larger HW-LW ranges. This feature is also observed in Holland (e.g. see the Vlissingen data in Van Malde 1986) but with an order of magnitude smaller secular trend than is observed in the Thames estuary. In turn, larger amplitudes increase extreme levels (in addition to the mean sea level contribution to extreme levels) and alter the tide-surge interaction. Although attempts have been made to model such tidal dependence on bottom friction and water depth, detailed results have sofar not exactly matched the observations (the modellers in question were trying to reconcile observed tidal secular changes with bottom stress variations to be expected from a few decimetres change in level. It would be interesting to run the models again with a one metre change).

Changes in the pattern of flooding in Holland and certain areas in eastern England will arise from the modification of the 'still water level' (tide and surge and mean sea level) together with increased erosion of the natural defences (i.e. sand dunes in Holland). This erosion and consequent sediment transport arise from the effects of surge and of wave action. Model tests by Bijker & Van der Graaff (1983) have shown that the storm surge is more important in affecting erosion (and hence causing flooding) than wave height. However, as the sea level at any specific defence site rises, the maximum wave height also increases as the water depth determines whether a wave will break or fully run-in. This suggests that the consequences of a metre rise in sea level should be studied further using the high resolution surge-wave models for the area under development at present together with models of beach processes.

It would also be valuable to know how future changes in the regional climate from the 'greenhouse effect' would affect storm surges through shifts in the tracks of cyclonic disturbances. Unfortunately, general circulation models (GCM's) are unable to provide reliable simulation of climate at such a regional scale, and thus cannot directly provide predictions of how the detailed climate of the region will change in the future [MacCracken & Luther (1985), Wigley & Santer 1986)]. However, there is scope for empirical investigations of the relationships between observed or simulated storm surges and the large-scale climate parameters which can be generated more reliably from GCM's in CO_2 experiments, and ISOS and collaborators will be participating in such research projects in the near future.

4.8 SUMMARY

The above remarks represent one view of the current state of research into global sea level changes. In short, the magnitudes and time-scales of future sea level changes are poorly estimated at present. Furthermore, the detailed consequences of a rise in level are largely unknown other than through some very simple calculations of the amount of flooded land etc. However, these effects are in principle quantifiable if the required modelling effort can be devoted to the subject. In addition, the oceans and atmosphere have to be instrumented sufficiently to enable the gathering of the necessary datasets. The conclusions of the ISOS study must certainly include recommendations along these lines for, without such research, discussions of impacts will always be based on false assumptions.

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5 ESTIMATING THE IMPACT OF INUNDATION

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The physical effects of climatic change are likely to be serious and pervasive. They could include significant alteration of radiation regimes, hydrological patterns, weather extremes, and other aspects of the environment. Unfortunately, our ability to assess even the qualitative implications of such effects for human welfare is extremely limited. It is unclear, for example, how present-day crop strains would respond to concurrent changes in growing seasons, ambient temperatures, solar radiation, moisture stress, carbon dioxide levels, and so forth. Even more uncertain is how well agricultural systems in general would be able to cope with differential changes in crop productivity within the context of national agricultural policies and global agricultural markets (Liverman 1986).

However, in the case of accelerated increases in global sea levels induced by a climatic warming, the impact is to a certain degree easier to quantify. In particular, it is fairly straightforward to assess the land, population, and wealth at risk of inundation. That is, we can look at the present landscape to see what resources and structures could be affected by rising sea level. Presumably, protective actions would only be taken to the extent that they cost less than the value of saved property. The present value of the 'immovable' property in a potentially inundated area thus represents a first-order estimate of the possible impact of inundation.

This static approach has been applied to the coastal areas of the United States for a 4.6-7.6 metre (15-25 feet) sea level rise (Schneider & Chen 1980). A rise of this magnitude could occur if the entire West Antarctic Ice Sheet were to collapse (Mercer 1978). We determined the area of the US at risk by examining small-scale (1:24,000) topographic maps produced by the US Geological Survey (USGS). Isolines on these maps are defined as elevation above mean seal level (MSL), typically with intervals of 1.6 m (5 feet). MSL is defined as the mean high water mark. The 4.6 and 7.6 m isolines thus represent conservative indicators of the 'new shoreline' that would result from sea level rises of the same magnitude.

Using these indicators, we estimated the area potentially subject to flooding as a proportion of an individual US county using index maps available from the USGS. This step is particularly crucial because virtually all detailed demographic and economic data in the US are tied to these political units. We were then able to combine county-level data from various US censuses with the estimates of the proportion inundated, assuming that population, income, wealth, and other attributes are evenly distributed throughout each county. On average, counties with population concentrations in low-lying areas tend to be balanced by those in which such areas are relatively under-developed (e.g. wetlands). This same technique has also been applied at the township level in the State of Massachusetts where more detailed data are available, and obtained results consistent with the county-level analysis.

An important element of our assessment was a set of estimates of property values collected as part of the US Census of Governments (Bureau of the Census 1973). This census includes figures on the total assessed value of all land and structures within each county. Since assessment values tend to be low relative to actual market values, the Bureau of the Census also conducts surveys to determine the prevailing ratio between market and assessment values within each jurisdiction. This permits estimation of the total market value of all private property at risk of inundation. These estimates agree quite well in the aggregate with independent wealth estimates derived from national-level data (Kendrick et al. 1976).

Unfortunately, the value of publicly owned land and structures, including roads, sewers, public buildings, and parks, is much more difficult to estimate. However, their value in the aggregate is probably of the order of 50% of the value of private property in an area (Balk 1971).

The result of the analysis for a 4.6 metre sea level rise using 1970-71 census data is

Table 5.1. Summary of estimated geographic, demographic, and economic impact of a 4.6 m (15 ft) rise in sea level in the continental United States.

Region/state	Percent flooded	Population (millions)	Percent of state population	EMV[1] (billions of $)	Percent of state EMV[1]
Florida	24.1	2.9	43	33.4	52
Gulf Coast	4.7	2.7	–	21.3	–
Texas	2.2	0.9	8	14.3	14
Louisiana	27.5	1.7	46	6.5	51
Mississippi	1.0	<0.1	2	0.2	3
Alabama	0.8	<0.1	2	0.3	2
Mid-Atlantic	5.3	1.8	–	11.6	–
Georgia	2.4	0.8	4	0.8	4
South Carolina	6.7	0.3	10	1.6	12
North Carolina	7.9	0.2	3	1.4	4
Virginia	3.1	0.7	16	4.1	12
Maryland	12.3	0.2	6	1.5	5
District of Columbia	15.0	0.1	15	1.2	15
Delaware	16.0	0.1	19	1.0	18
North Atlantic	0.9	3.6	–	33.3	–
New Jersey	9.5	0.7	9	6.2	9
Pennsylvania	0.1	0.4	3	2.0	3
New York	0.6	2.1	12	22.0	12
Connecticut	1.2	<0.1	2	0.6	2
Rhode Island	3.5	<0.1	3	0.2	3
Massachusetts	2.1	0.3	4	2.2	5
New Hampshire	0.1	<0.1	0	<0.1	1
Maine	0.2	<0.1	1	0.1	2
West Coast	0.6	0.8	–	7.8	–
California	1.0	0.7	4	7.3	3
Oregon	0.1	<0.1	1	0.3	1
Washington	0.4	<0.1	1	0.2	1
All regions	–	11.6	–	107.5	–
Percent of continental US	1.5	5.7	–	6.2	–

1. Estimated Market Value, derived by dividing the 'locally assessed taxable real property' in each county by the 'aggregate assessment sales price ratio' based on a sample of market values.

summarized in Table 5.1. Florida and Louisiana are threatened by the most extensive inundation. Due to their heavy coastal development, much higher proportions of their populations and wealth are concentrated in the areas at risk. In Louisiana, large areas are already as much as 1 m below sea level and are protected by levees. Other areas of Texas and California are similarly protected.

Since the Census of Governments is conducted every five years, it should now be possible to estimate US property values at risk of inundation over a ten-year period, 1971-81. Results of the 1986 census will not be available for a year or two. Of particular interest would be the degree to which coastal areas are developing more rapidly than interior areas.

The above results should be useful even for lower levels of sea level rise. Additional shoreline recession would be likely as erosional processes work to bring beach profiles to equilibrium. This recession could be 100-300 m or more for each 1 m of sea level rise, depending on underlying slopes (Bruun 1962, Dean et al. 1984). In addition, much interior land would become vulnerable to infiltration by seawater and storm surge flooding. In Texas, for example, hurricanes have caused extensive flood damage up to 7 m above m.s.l. or more. Actual flooding levels and associated damage depend greatly on coastline geometry, storm tracks, and beach, tide, and wind conditions.

Current market values may not of course accurately reflect the net societal losses that would accrue from a rising sea level. Inundation of some low-lying areas could increase the market value of interior areas expected to become the new coastline. Actions to prevent or ameliorate damage by regional and national governments would essentially redistribute costs across much wider areas. The disruption and relocation of large populations would undoubtedly result in significant economic, psychological, and sociological costs.

Market values may also not account for the 'true' value of various monuments, cemeteries, wildlife preserves, and educational institutions that may be threatened. For example, in the Washington DC area, a 7.6 m rise would endanger the Lincoln and Jefferson Memorials, much of the Washington Mall, the Smithsonian Institution, and the National Gallery of Art. Although it might be possible to protect or move these resources, some decrease in historical, cultural, and/or aesthetic value would undoubtedly occur in the process. Quantifying such losses in monetary terms is problematic.

Finally, an important issue is whether individuals or firms in a market assign the same value to future benefits that society does, i.e. whether the private discount rate utilized in market decisions is identical to the social discount rate. It may be that society should value land more highly than individuals because of its presumably longer time horizon.

Given the above limitations, dynamic approaches to impact assessment are required, i.e. approaches that take into account the timing and magnitude of sea level rises and possible socio-economic interactions. One such approach is the analysis of analogous situations and, in particular, hazards such as coastal erosion, storm damage, land subsidence, and lake-level increases.

For example, damage from coastal erosion is of the order of $300 million in the United States annually (White & Haas 1975). Much of this stems from the erosion of beaches that protect interior land and structures from severe storms. The effectiveness and economic feasibility of beach nourishment and other protective techniques are known to vary considerably (Dean et al. 1984). Moreover, some non-structural measures such as flood insurance programs may fail to reduce flood losses as intended because they encourage coastal development, e.g. Cross (1986). Closer examination of the responses of individuals and governments to the long-term loss of land due to coastal erosion would therefore be valuable. However, this is likely to be difficult since existing coastal planning mechanisms are extremely diverse in influence and effectiveness (Coccossis 1985).

Another useful analogy is the subsidence of the land surface due to the withdrawal of groundwater, petroleum, or minerals from below the surface. In Texas, subsidence of more than 2.4 m has led to the inundation of about 8 km that contained 450 homes on Galveston Bay. Notably, the US Army Corps of Engineers decided that relocating the area's residents would be easier than constructing an expensive protective levee (Neighbors 1981). This supports the assumption that protective actions will only be taken to the extent that they cost less than current market values, at least in the US where land is relatively plentiful.

This assumption might not hold true in Japan, where subsidence due to the extraction of groundwater has affected almost 10,000 km^2, some 12% of the habitable land in the nation (Carbognin 1984). Subsidence in Tokyo has reached about 4.5 m, necessitating the construction of dikes along Tokyo Bay to prevent flooding. Extensive protective works have also been constructed in Osaka.

The city of Venice has experienced an apparent rise in sea level of about 25 cm over the past century due to the combined effects of eustacy and subsidence (Ghetti & Batisse 1983). The acque alte, or high waters, associated with the tides have increased significantly in frequency and severity. For example, in 1920-23, the acque alte rose to 0.8 m above the 1897 m.s.l., an average of only once a year, but by 1966-69 this had increased to an average of 12 times per year and by 1970-79 to some 50 times per year. Flooding of more than 60% of the city has become increasingly frequent, occurring only 5 times in about 5 decades (1915-1965), but 12 times in the last 2 decades (1966-1982). Since Venice is not exposed to the open ocean, Venetians have been able to live with periodic flooding. Nevertheless, the frequent flooding is still a serious disruption and contributes significantly to the erosion and deterioration of the city's unique and historic infrastructure. Plans to construct expensive movable barriers to protect against storm surge have been adopted, but these will not be effective against most occurrences of the acque alte (Ghetti & Batisse 1983). It is also unclear to what extent the possibility of accelerated sea level rise has been considered.

Other cases where subsidence threatens low-lying coastal lands include Ravenna, Italy and Bangkok, Thailand (Carbognin 1984).

A natural-hazard 'experiment' of a different kind is currently underway at the Great Salt Lake in Utah. Increased runoff, high precipitation, and low evaporation have combined in recent years to raise the lake to its highest level in over a century. This rise has swamped large sections of beach, highway, and wildlife habitat and threatens many other public and private facilities. In part because of uncertainty about future rises, governmental responses have been slow to materialize. Indeed, uncertainty about possible preventive measures may be hampering adaptive responses such as the relocation of facilities (Riebsame 1985). A similar experiment is in progress in the North American Great Lakes, where lake levels have also risen significantly.

Natural hazard analogies such as these are perhaps the best source of information about possible 'real-world' responses to a climatically induced acceleration of sea level rise. In-depth investigation of a variety of analogous situations would shed light on the importance of the many different environmental, economic, psychological, cultural, legal, and other factors that could affect both short and long-term impact. In essence, such analogies constitute a valuable body of experience that can be used to improve and test the realism of other assessment approaches such as simulation modeling and interactive gaming.

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6 CONSEQUENCES OF SEA LEVEL RISE: IMPLICATIONS FROM THE MISSISSIPPI DELTA

J.W.Day Jr

6.1 INTRODUCTION

Numerous reports have recently emphasized the potential impact of global warming trends on future sea level rise in coastal areas. Predictions are that many low-lying coastal areas, especially those dominated by wetlands, will be flooded as sea level rises from 1-3 m over the next century. The latest information available indicates that the rise will likely take place and that the rise may be more rapid than earlier indicated. Thus there is a critical need to consider the impacts of sea level rise and possible policy responses to these impacts. One area which can provide valuable information on both impacts and responses is the Mississippi Delta. This area has been experiencing an 'apparent sea level rise' of about a metre per century for a very long time due to regional subsidence. In this contribution, the effects of this rise on coastal ecosystems in Louisiana and how public and private groups have responded to the problem will be discussed.

6.2 WHAT WILL BE THE IMPACT OF SEA LEVEL RISE?

It seems to me that in many coastal areas there will be at least two major direct impacts on coastal systems of sea level rise: Submergence and salinity increase. For low-lying wetland and terrestrial areas submergence brings about poorer drainage and increased waterlogging of soils. These, in turn, lead to lowered plant productivity and vegetation death. This latter factor is very important because production of biomass by plants plays a quantitatively important role in vertical accretion. In many coastal areas there will be a general increase in salinity because there will be relatively less freshwater input and there will be salt water intrusion into formerly fresh areas. These impacts will be most pronounced in large areas at or near sea level such as deltas and lagoon-like systems. Because these areas are very important for fisheries and agriculture, especially locally, the impact on local economies may be pronounced.

6.3 THE MISSISSIPPI DELTA AS A METAPHOR

The Mississippi Delta is a large area of lakes, bays, near sea level wetlands, and low-lying uplands. It can serve as a metaphor for the sea level rise question because there has been a significant historical 'apparent' sea level rise. The term metaphor will be used because the sea has not been rising, but the land has been sinking due to regional subsidence. But the impact on natural and social systems is the same whether the land is sinking or sea level is rising. Thus the Mississippi Delta is an excellent place to consider the effects of sea level rise for three major reasons:

1. The area has experienced an 'apparent' sea level rise for a very long time; thousands and even millions of years.
2. In spite of this apparent sea level rise, over the last several thousand years, a large deltaic plain of several million hectares has formed.
3. In recent decades, the historical trend of net land gain has reversed and there is a high net loss of land.

Each of these points are considered below in more detail.

6.3.1 *Apparent sea level rise*

A number of studies have shown that there is a regional subsidence rate averaging about 1.0 cm/yr in the Mississippi deltaic plain. Deep layers of sedimentary rocks thousands of metres thick indicate that this process has been going on for millions of years. This is a regional phenomenon due to such factors as downwarping, compaction, and dewatering. This rate has increased locally due to withdrawals of water, oil, and gas, but the major factor is regional subsidence. This sinking leads to the 'apparent' sea level rise. Almost all of this is due to subsidence, with eustatic sea level increase accounting for only 10-15%. In effect, from both ecological and social points of view, there has been a historical rise in water levels of about a metre per century.

6.3.2 *Long term growth of the Delta*

Sea level stabilized at about its present level about 5000-7000 years ago after being about 100 m lower during the last glaciation. Since that time, sedimentation from the Mississippi River has created a large deltaic plain of about 5×10^6 ha (50,000 km^2) of which over 2×10^6 ha (20,000 km^2) are wetlands. The great majority of these wetlands lie within 1 m of sea level. The rest of the deltaic plain is made up of shallow aquatic systems and low (up to 5-6 m) upland ridges.

Thus, despite an 'apparent' sea level rise of about a metre per century, there was a rapid net growth of the delta. This growth rate over the past 5000 years has been somewhat greater than 4 km^2/yr. This land has been formed by a series of shifting delta lobes. There were high growth rates in active delta lobes and deterioration in abandoned lobes. But the net growth was positive.

6.3.3 *Recent high land loss rates*

Over the past several decades, the long term net land gain has been reversed and there is an accelerating land loss which is now about 100 km^2/yr. This dramatic reversal is the result of a number of factors, all of which relate to the inability to maintain surface elevation in the face of rising water levels. This phenomenon has been studied in detail over the past decade. In other words there is an aggradation deficit; 'apparent' sea level rise is greater than vertical accretion. This situation is not unique to the Mississippi Delta. It is happening to a lesser degree on the eastern shore of Chesapeake Bay in Maryland and in several other locations. The aggradation deficit is due to a number of factors which are discussed in the following section.

6.4 CAUSES OF WETLAND DETERIORATION IN THE MISSISSIPPI DELTA

6.4.1 *Lack of sediment input*

There are two sources of allochthonous sediments which accrete on the surface of wetlands in the Mississippi Delta. One source is direct input of riverine sediments during the annual spring flood. This source has been eliminated for most of the coastal zone by dikes along the Mississippi River which extend almost to its mouth. In addition, a number of distributaries which carried lesser amounts of sediments to coastal wetlands have been dammed. In the one area of the coast where there is significant sediment input, Atchafalaya Bay, a new sub-delta is growing and loss of existing wetlands has been slowed or reversed.

A second source of sediments is the deposition of resuspended bay-bottom sediments. These sediments are resuspended during high energy events such as winter frontal passages and tropical storms and deposited on the surface of wetlands. These resuspended materials are the major source of new sediments for most of the coastal zone. Resuspended sediments alone do not appear to be sufficient to maintain surface elevation against 'apparent' sea level rise, but they greatly slow wetland loss. Along the Wadden Sea, the Dutch have used brush fencing baffles to encourage settling of resuspended sediments and prevent resuspension to create wetlands.

In the Mississippi Delta, the input of resuspended sediments has been greatly reduced by canal construction. Over the past 30-50 years, over 15,000 km of canals have been constructed for navigation, drainage, but mostly for oil and gas exploration and production. This network of canals has changed the regional hydrology of the coastal zone. Canals are generally straight and along one or both sides there is a low spill bank resulting from the deposition of material excavated to construct the canal. Since spoil banks are generally higher than mean high water, flow across the wetland surface is greatly altered and the input of resuspended sediments is reduced. Studies have shown that canals and associated spoil banks alter hydrology, reduce productivity of wetlands, cause salt water intrusion, and cause the deterioration of natural channels. A number of studies have correlated canal density to wetlands loss.

6.4.2 *Salt water intrusion*

The dikes along the Mississippi River have stopped most direct freshwater input into the coastal zone and resulted in salt water intrusion. The canals have allowed more rapid movement of salt water into fresher areas. The intrusion of salt water into abandoned delta lobes is a natural process, but diking and canalization have greatly accelerated it. Salt water kills or reduces the productivity of fresher vegetation directly causing loss of wetlands.

6.4.3 *Death or lowered productivity of wetland vegetation*

The health of vegetation is a critical factor in maintaining surface elevation since biomass production (roots and above ground material) can contribute significantly greater than 50% of vertical accretion. Studies in the Netherlands have shown that vertical accretion increases by a factor of 2-3 times when vegetation becomes established.

In the Mississippi Delta a number of factors have combined to reduce the role of wetland vegetation in augmenting vertical accretion. It is known that coastal wetland vegetation will grow within a rather narrow elevation range which is related to local tide range. Thus if subsidence lowers the surface elevation below this range, vegetation death will occur. There is a large body of literature which shows the impact of waterlogging and submergence on wetland plant production and health. We have studied this specifically for Louisiana. In the Mississippi Delta, it has been shown that the most important single source of new nutrients for salt marsh vegetation accompanies sediment input. Therefore, a reduction of sediment input lowers productivity and hastens wetland deterioration. As noted above, salt water intrusion causes death or reduces productivity.

In summary, in the Mississippi Delta a number of human impacts have interacted to reverse delta growth and cause widespread wetland loss. These factors are related to the inability of maintaining surface elevation in the face of 'apparent' sea level rise. Input of both riverine and resuspended sediments has been greatly reduced. Wetland productivity has been reduced or wetlands have been killed resulting in a reduction of accretion due to biomass production. An extremely important point to appreciate when considering the effects of sea level rise (and institutional response to it) is that there is a considerable lag period (of the order of decades) before effects become apparent. For example, dikes along the lower Mississippi were substantially completed in the 1930's and widespread canal construction had taken place by the 1960's. It was not until the mid-1970's, however, that the problem of land loss began to be appreciated and not until the early 1980's that the role of 'apparent' sea level rise was understood. The rate of wetland loss also appears to be exponential. Losses were low at first but are increasing very rapidly at present.

6.5 SPATIAL RESPONSES

The results from the Mississippi Delta indicate that rising sea level will not simply lead to a retreat of the edge of the sea. This is especially true in broad areas near sea level which will be most affected by sea level rise. Most wetland loss is not due to lateral erosion at the land-water interface, but, in more isolated areas due to an ever increasing aggradation deficit. Areas furthest from lakes, bays, and tidal streams deteriorate first due to sediment deficits. Freshwater wetlands, which are furthest from the coast, can be killed due to salt water intrusion. Thus wetland loss is greatest in isolated, stagnant, waterlogged, sediment-starved areas especially in fresh areas with salt water intrusion. In the Mississippi Delta, wetland loss occurs as small ponds open up as vegetation dies. These ponds coalesce to form large areas of shallow open water. These results suggest that sea defences will not stop such land loss unless there is active water level control.

6.6 THE INSTITUTIONAL RESPONSE IN LOUISIANA

Coastal and wetland management in Louisiana is very complex, and federal, state, and local public agencies and private groups (landowners, sportmen, commercial fishermen and trappers, conservationists) are involved. In addition, management is done for a variety of reasons (marsh management, aquaculture, waterfowl enhancement, fur mammal management, timber production) and only recently has it been focused on the problem of land loss and 'apparent' sea level rise.

Considering what has happened in the past and the prospects for future sea level rise, it appears that most management actions taken are almost completely the opposite to what is necessary to solve the long term problem. Different management approaches, however, have become popular and accepted because they produced at least some positive results or were not immediately or obviously harmful in the short term (10-20 years). The lag time in the response of the natural system to 'apparent' sea level rise is of the order of decades. And the degree of impact (e.g. the rate of land loss) is low at first but accelerates exponentially. Thus the effects of inappropriate management practices (in terms of addressing the sea level rise question) are cumulative. They were small at first but now changes are taking place rapidly. Some of these management approaches and their impacts are considered below.

6.6.1 *Flood control*

Flood control in the Mississippi Delta area must contend with the threat of flooding from the river and from the sea during tropical storms. To protect developed areas, the Mississippi River has been almost completely 'walled in' by dikes. Early flood control along the river was accomplished by ring (encircling) dikes, and the city of New Orleans is still protected by ring dikes because it faces flooding threats from both the river and the sea. The dikes prevented the introduction of sediments and freshwater into much of the coastal zone with the resulting problems discussed above. The protection from flood control also stimulated agricultural and urban development into low-lying areas. What is obviously needed now is the reintroduction of freshwater and sediments into the coastal areas. However, development makes this difficult and the widespread network of canals (with attendent spoil banks) retard the easy movement of sediment-laden water over wetlands. A clear lesson from the Mississippi Delta is that flood protection in response to sea level rise should not diminish the introduction of freshwater and sediments to affected coastal areas.

Because of continuing subsidence and 'apparent' sea level rise, many low-lying areas are experiencing increased flooding. Gravity drainage systems are still being proposed which involve the construction of many more km of canals which make problems of land loss (and water quality) worse. But institutional inertia and reliance on approaches used in the past make change difficult. For example, the State of Louisiana recently approved a gravity drainage system in the Lake Verret region of the coast, despite the fact that evidence was presented that water levels in the area would likely rise more than a metre (due to the combined effects of subsidence and eustatic sea level rise) over the 50 year life of the project.

6.6.2 *Impoundment and semi-impoundment*

Wetland impoundment, that is the encirclement by dikes for water management, has been carried out for over 100 years in the Mississippi Delta. New Orleans first developed on the higher natural levees of the river. However, by the late 19th century it began to spread into adjacent wetlands. The city is now completely surrounded by dikes and protected by an extensive and expensive drainage system. Despite this, the city experiences severe flooding due to periodic extremely heavy short-term rainfall which occurs along the Louisiana coast (the record 24-hour rainfall in south Louisiana is of the order of 625 mm and 24-hour rains of about 250 mm occur almost annually). During the second half of the 19th century and the early part of this century, extensive areas of wetland were reclaimed for agriculture. Most of these failed due to a combination of subsidence (due to regional sinking and oxidation of peat) and heavy rains. Most are visible today as large rectangular ponds in the coastal marshes.

More recently, semi-impoundment has become common as a technique for wetland management. In this approach, wetland areas are surrounded by low dikes and water movement is controlled by water control structures such as wiers, sluices, and gates. This has been done since the 1950's to encourage the growth of grasses which are beneficial for waterflow. Recently, semi-impoundment has become much more widespread as a form of marsh management done specifically to address the problem of land loss. One of the main objectives is to control salt water intrusion and thus death of wetland vegetation. Such plans are even being proposed in areas of salt marsh vegetation where salinity is clearly not a problem. A main objection to marsh management plans is that such plans retard the introduction of resuspended sediments which are so important to maintenance of marsh elevation. Any future plans to introduce riverine sediments (which surely must come) will be hampered by the dikes surrounding these management areas. Even though there are questions about the effectiveness of this kind of marsh management, there are plans for projects which will include perhaps one-third to one-half of the coastal wetlands.

A complicating problem in the management of the delta is that of land ownership. Most of the area is privately owned and the objectives of landowners may not necessarily coincide with that of public agencies. For example, an important consideration in Louisiana is revenues from oil and gas production. If wetland deteriorates into open water, revenues from any mineral production changes from the landowner to the public. One way a property owner can define ownership is with a system of low dikes (such as used in marsh management plans). Thus even if wetlands within a surrounding dike deteriorate to open water, revenues are retained by the landowner. Thus questions of property rights can be an important factor to take into account when considering what to do about sea level rise.

6.7 IMPLICATIONS FROM THE MISSISSIPPI DELTA FOR OTHER COASTAL REGIONS

A number of lessons can be learned from the situation in the Mississippi Delta which may be of importance in understanding and addressing the problems of sea level rise. From the standpoint of the natural ecosystems, the following findings seem important.

1. A very important lesson is that coastal regions with significant sediment input can withstand considerable sea level rise and still not undergo deterioration. The Mississippi Delta region has experienced an 'apparent' sea level rise of about 1.0 metre/century for thousands of years and has still built a large deltaic plain. The critical factor is that the system remained

open and dynamic. Thus sediments and water from the river were distributed widely over the deltaic plain.

2. Two critical problems which will result from sea level rise are submergence and salinity increase. Submergence occurs when vertical accretion cannot keep pace with the rate of water level rise.

3. A number of factors contribute to the rate of vertical accretion. Sediment input is an obvious one. In the Mississippi Delta region both riverine and resuspended sediments are important. Biomass production by vegetation can contribute more to vertical accretion than mineral sediment input. Therefore, maintenance or establishment of vegetation is critically important.

4. There is a lag time of several decades before the effects of sea level rise becomes apparent. Changes are slow at first but later become exponential.

5. The effects of sea level rise will obviously be more critical where there are large areas near sea level, such as deltas. What is not so widely understood is that coastal areas with low tidal ranges will probably be more quickly affected because the vertical distribution of vegetation is related to local tide range. Thus, the impacts of sea level rise (at least on wetland ecosystems) will first become apparent in large flat areas with low tidal range. This suggests that the world's deltas, especially those which occur in areas of low tidal range, should be monitored for impacts. Areas in the Gulf of Mexico (Grijalva-Usamacinta Delta and the Everglades), the Mediterranean (Ebro, Camarque, Po, and Nile Deltas) and the Black Sea (the Danube Delta) as well as the Ganges-Bramaputra Delta should be monitored. The eastern shore of the Chesapeake Bay in Maryland is another area where effects are currently being felt.

6. A coordinated monitoring program should be established in such systems as above to gain information on sea level rise.

From the standpoint of institutional response, the following should be considered.

7. Those responsible for management should recognize that there is likely to be a considerable lag time before the effects of sea level rise become clear and that the rate of change will likely be exponential. Thus action should be taken early. This may be difficult because many will not see the need.

8. Initial responses are likely to be wrong unless the problems are very carefully considered over the long term. Since effects will be minimal and change slow initially, approaches to addressing the problem may make the situation worse in the longer term. As an example, semi-impoundment may be suggested as a way to deal with sea level rise. If this approach is not considered very carefully, it may make longer term solutions much more difficult.

9. Flood protection to combat rising waters should not eliminate widespread sediment and freshwater input to coastal areas. These are needed to counter submergence and salinity increase.

10. Problems associated with land ownership may complicate efforts to address the effects of sea level rise.

11. Agriculture in low-lying areas will present a special problem. How can such areas be maintained with increasing sea level. The construction of dikes and drainage of peat soils will make the problem worse in the long term. A rotating system in which riverine sediments are introduced into specific fields might maintain accretion and help fertilize crops. Productive crops may also be important in maintaining vertical accretion.

12. Maximum use should be made of natural energies such as winds, river currents, and tides. For example, currents should be used to distribute sediments. Vegetation should be used to enhance vertical accretion. This is the principle of ecological engineering where small levels of fossil energies are used to channel much larger flows of natural energies.

13. An extremely important point is that there should be coordinated, long term planning when addressing the sea level question.

6.8 A COORDINATED MONITORING PLAN

A coordinated monitoring plan should be started soon in a number of coastal areas of the world to gather data on the effects of sea level rise. In many cases, there are on-going programs which could be integrated and coordinated. Some possible areas include the following: Mississippi, Grijalva (Mexico), Ebro, Po, Nile, Camarque, Danube, Netherlands, Bangladesh, Maryland.

A number of factors should be measured including vertical accretion rates, rates of water level increase, vegetation response (productivity, tree ring growth, physiological stress indicators), habitat change over time (mapping), shoreline retreat.

A powerful tool has evolved over recent years which can help in predicting the spatial response of low-lying areas to sea level rise. This is spatial modeling. Spatial modeling has been used to consider the effects of a sea level rise in coastal Louisiana and the impacts of different management scenarios.

7 ECOLOGICAL EFFECTS OF A RAPID RELATIVE INCREASE OF SEA LEVEL

W.J.Wolff

7.1 INTRODUCTION

It is a well-known ecological law that the environment determines which species of plants or animals can occur at a particular place. The conditions of climate, hydrology, soil, etc. define the limits of the fluctuations of the environmental factors and only if the tolerance of a particular species includes those limits, is the continued existence of this species at that place likely.

What sea level rise does in the first place, is to change the environment of all coastal species of plants and animals. For terrestrial species especially the hydrological environment changes i.e. it becomes wetter. For aquatic species the change of other factors, such as exposure to wave action, will be more important. If the change is large enough to result in environmental conditions beyond the tolerance limits of a species, that species cannot longer occur at that place. Sometimes only part of the life-cycle of a species, for example the reproduction, will be affected. In such a case the adult individuals can continue to live.

Sea level rise is not an isolated event. It is part of a complex of changing factors, all of which will have an effect, small or large, on the environment of plants and animals. The increased levels of CO_2 influence the process of photosynthesis. The change of climate has effects on temperature, irradiation, precipitation, wind, etc. The changing sea level itself may influence tidal ranges and wave patterns. Any of these factors may have a decisive influence on the occurrence of a particular species of plant or animal.

7.2 SEA LEVEL RISE AS A NORMAL GEOLOGICAL PROCESS

In the course of geological history changes in sea level have been normal geological processes. During the last Ice Age each glaciation was accompanied by a drop of many tens of metres in sea level and consequently each interglacial period started with a rise of the same order of magnitude. The rate of these processes has varied with maximum values of about 0.5-1.0 m per century. The latest sea level rise has occurred during the last 10,000 years.

The rate of evolution of most coastal organisms is slow. In fact, sea level variations during the last Ice Age have occurred at a shorter time scale than evolutionary processes in the majority of coastal organisms. This means that a large share of the species of plants and animals occurring along the world's shorelines today, have survived all sea level variations of the last Ice Age. Nearly all species have survived the rapid sea level rise after the last glaciation 10,000 years ago.

There are a few exceptions, however. We know a few species of organisms which originated in recent times, in most cases due to human interference. An example is the marsh grass *Spartina anglica* which originated through the combination of the American *S.alterniflora* and the European *S.maritima* in Great Britain. However, there is little reason to assume that this species would react differently to sea level rise.

Coastal species of plants and animals live in ecosystems which usually occur in zones parallel to the coastline. For example, along the Dutch coast the original zonation of ecosystems consisted of:

- open North Sea,
- shallow area off the beaches,
- barrier island beaches,
- barrier island dunes,

- barrier island salt marshes,
- estuarine tidal flats,
- salt marshes along mainland coasts,
- freshwater marshes and swamps,
- peat moors.

The geological record as well as some archaeological and historical data show that the reaction of these ecosystem zones to sea level rise has been a landward shift. For example, the salt marshes along the mainland coast moved to the position of the fresh marshes and peat areas further inland, as appears from the occurrence of various forms of peat below these marshes.

It can be assumed that the reaction of coastal ecosystems will be identical during a future rise of sea level.

7.3 EFFECTS OF FUTURE SEA LEVEL RISE

It is unlikely that many species of plants and animals will become extinct due to future sea level rise. Sea level rise may contribute to extinction of a species only in exceptional cases, when the continued existence of a species is already threatened by other factors. One of the principal reasons will be the temporary absence of habitat within the range of dispersal.

The majority of plants and animals will, as part of the ecosystems they live in, move shoreward with the rising sea level. Some communities will be able to follow sea level very closely, since their organisms have strong powers of dispersal. This applies, for example, for the tidal flat community whose members all have spores or larvae which are distributed by the water. In other cases a time lag might occur, especially in case of rapid sea level rise. For example, some salt marshes are dependent on vegetative reproduction. This is a slow process which may easily lead to disappearance of marsh vegetation.

It is not only water level per se which determines the ecological effects of sea level rise. Higher water levels also result in intrusion of seawater into estuaries and other coastal ecosystems. This leads to the replacement of species adapted to fresh conditions by other adapted to brackish circumstances and eventually to the occurrence of salt water species.

Another aspect to consider is that other processes can keep up with sea level rise. Salt marshes may increase their level through sedimentation. Sedimentation rates of 1 cm per year and more have been observed at many places. Moors may increase in height through growth of *Sphagnum*.

Along shores without human interference it may be assumed that in most cases sea level rise will simply lead to a shoreward shift and a redistribution of the coastal ecosystems. Local topography will determine which ecosystems will increase their area and which will become smaller. Of course, terrestrial and freshwater ecosystems will be lost during this process.

Along shores with human interventions entirely different results are possible. For example, when the coast is protected by sea walls or dikes, situated on what originally were salt marshes, the shoreward migration of ecosystems will still occur. However, since these ecosystems cannot 'pass' the dike, they will disappear once the dike has been reached. Hence, in front of the dike in our example, one will observe firstly the change of marsh into tidal flats, later the flats will become shallow water, and finally marine ecosystems will border immediately the dikes. The result is that the gradient from the marine environment to the terrestrial environment becomes steeper. Other defensive activities, such as beach nourishment, also will lead to a steepening of this gradient.

Another effect will be shown by populations of migrating shorebirds. Species bound to tidal flats as feeding areas are likely to lose part of their resources and at least in some species population size might be influenced.

Hence, the ecological effect of sea level rise will differ in relation to human interference with the process. Along shores without human interventions major changes and redistribution of ecosystems will occur, but viewed over larger areas, no essential changes are likely to occur. If the coast is protected by human activities, the result will be in many cases that the area of coastal ecosystems decreases and in some regions some types of ecosystems will even disappear.

Within the dikes everything will be dependent on the conditions created by human activities. If they change, ecological changes will be the result. In a country such as the Netherlands, no major ecological effects are expected as long as sea level rise does not exceed 1-2 m.

7.4 ECOLOGICAL EFFECTS ON HUMAN USE OF THE ENVIRONMENT

The coastal zone is the site of many human activities. The effects of rapid sea level rise on some of these are considered in other contributions to this workshop. Here some words will be spent on fisheries, agriculture, forestry and nature protection.

Along shores without human interference fisheries resources will change. The outcome of this change will depend on local topography and hydrography and can be either positive or negative. On the large scale no net change is likely to occur. This is expected to be different along shores with human interference. Due to the decrease and eventually disappearance of coastal ecosystems it may be expected that nurseries of fish and shrimp will decrease in size and that eventually this will be reflected in a decrease of the catches offshore. Similarly, the possibilities for several forms of coastal mariculture, especially shellfish, are likely to decrease.

Agriculture will be forced to move landwards along unprotected coasts, which in many cases will result in a reduction of the cultivatable area. Along protected coasts the possibilities for salt-marsh grazing will be reduced, but inside dikes no major changes will occur unless drainage is affected. In this case adaptation to wetter conditions, for example through change from crops to grassland, will be required. It is conceivable that in the long run agriculture will become impossible and that the land will be flooded.

Forestry will be subjected to the same changes as agriculture, but there will be a difference because of the low turn-over rate of forests. Adaptation to changing conditions takes much more time.

Nature conservation is likely to lose at least part of its reserves and parks in the coastal zone. One cause will be the increasing competition with other human uses in coastal areas, such as agriculture. Secondly, in the case of protected shores a number of reserves and parks will be drowned (salt marshes, tidal flats) or eroded away (e.g. barrier islands). Finally, wetlands along rivers in coastal plains will be threatened, because of a general rise of water level in drainage systems.

8 SOME POLICY-ORIENTED OBSERVATIONS CONCERNING SEA LEVEL RISE

Tom Goemans

Before discussing the impacts of sea level rise a number of remarks can be made concerning its relationship with other phenomena. Sea level rise is, after all, only one of the possible consequences of the increasing atmospheric CO_2 concentration. It may be true that sea level rise is more directly noticeable than most of the climate changes, especially in the Netherlands. But then the time horizon for our considerations is in the order of one hundred years and it is fairly certain that within such a period the societal context will change considerably. One only has to think about the socio-economic developments in the past hundred years (with a reasonably stable climate). The reaction to climatic changes and sea level rise will also depend upon other controversial matters that fight for our attention: unequal distribution of natural resources and affluency, deterioration of the natural environment, transboundary pollution, population increase and food strategies, and possibly armed conflicts. Although it is necessary to see things in perspective and consider all the aforementioned problems in context, for practical reasons the impacts of sea level rise are considered separately in this paper. Although the impacts of climate changes are uncertain, it is clear that there will be regional differences and that there will be winners and losers. Sea level rise, however, seems to cause only losers. No single country with a coastline can escape the phenomenon through measures of its own. It should be stressed that it is not a natural phenomenon; the increasing concentration of CO_2 and other greenhouse gasses is the result of human activities. The long-term costs connected with this are a typical example of external costs, i.e. costs not included in the costs of present fossil fuel burning.

What are the impacts of a rising sea level on society? First the situation without protection measures will be considered.

1. Loss of land: Land can be lost in two ways. Firstly by inundation of unprotected river deltas, like those of the Ganges, Indus, Yangtse, Nile, Mississippi, Magdalena, Amazon, Mekong, etc. These deltas are generally very fertile and densely populated. Secondly by erosion of coastal areas which are in dynamic equilibrium; presently this happens at several locations at present e.g. the Dutch coast and the eastern and the southern coast of the US. The impacts of all this may be felt for:

- nature reserves along the coast (swamps, marshes, mud flats) which will probably disappear faster than they develop,
- (historical) buildings along the coast, e.g. in old harbour cities like Venice but also houses built directly at or even on the beach like in the US,
- infrastructure like harbour facilities, sewage drains, airports and power plants using seawater cooling,
- (hazardous) waste facility sites located on flood plains,
- recreational facilities at and on the beach, e.g. in the Mediterranean and Florida.

2. Storm damage: For areas protected against flooding through dikes, dams, dunes and barriers, high water will start at a higher mean sea level. With respect to the excess frequency line (giving the relationship between high water level and exceedance frequency) two possible things may happen:

- the line simply shifts to higher water levels; hence sea level rise would result in a decrease in the level of protection for the existing construction,
- the shape of the line changes as a result of different storm patterns at the coast (the climate will change as well).

3. Morphology and ecology: Any change in water flows along the coast will influence the morphology of the foredelta (dynamic equilibrium of the sand banks), the abundance of food in fishing areas and the distribution of pollution supplied by the rivers. In estuaries the tidal

volume will increase and because of higher currents more erosion will occur.

4. Salt water intrusion: With a retreating shoreline the salt-freshwater interface will rise which will influence the environment in the coastal area and the possibilities for drinking water extraction. Through the rivers salt water will migrate further inland, which may cause:

- a threat to any of the freshwater inlets used for agriculture and drinking water supply,
- a change in the character of nature reserves,
- more salt water seepage.

5. River water levels: With a rising sea level the river water level will rise accordingly and especially for flat river deltas this is felt far inland. River dikes may, in fact be too low for a specified level of protection; bridge clearance will decrease and tunnels will be deeper under water. Sedimentation patterns will change, especially in nature reserve areas. Draining the polders along the rivers will require adjustments to the pumping stations.

Assuming that the impacts mentioned above can be mapped reasonably accurately for the different areas in the world threatened by the sea. Then the local policy-makers will have to choose an appropriate protection strategy; in general two different strategies can be conceived:

a) Accepting shoreline retreat: This means loss of land and possibly buildings, and of the environmental and cultural values that cannot be expressed in monetary terms. If little money is available this may be the only strategy possible. People living in the relevant areas will have to migrate to other areas, with all the psychological and social problems involved. This should include the regulation of the coastal areas, i.e. choosing where developments can take place. This means giving up short-term advantages in order to avoid future losses.

b) Protection of the coast: If coastal retreat is unacceptable some kind of defence must be introduced. This can be artificial stabilization of the coast through suppletion of sand, construction of groins, dams, etc. With a rising sea level stabilization gets more and more expensive and should be carefully assessed against the value of the property to be defended. Vested interests will call for continued stabilization, once started.

Fixed constructions can be made insensitive to sea level rise (relatively high costs at beginning of the life cycle) or can be adjusted during the life cycle on an ad-hoc basis (costs spread over the life cycle). Once the location of certain infrastructural items has been chosen, the developments in an area are fixed for an extended period of time (in the order of 100 years). To keep open the possibilities for raising the level of protection structures, this has to be taken into account in the design of the construction and its foundation.

The countries along the West European coast chose for protection long ago and on the basis of the value of the area to be protected a certain protection norm was determined. The number of people in Belgium, the Netherlands, Germany and England protected by sea walls is enormous (in the order of 20 million) and the economic value of the area gigantic. Giving up this area is as yet unthinkable, and replacing the people unfeasible. Where several countries share a coastline, multilateral cooperation will be needed when responding to sea level rise. It should be mentioned here that living behind a very high dike can cause severe psychological pressure. Moreover, requirements for evacuation plans will be more severe, because the larger the area threatened the more difficult it will be to evacuate.

At this moment the sea level rises about 1.5 mm per year. If present predictions about the greenhouse problem are correct, this rate will increase to 5-10 mm per year within several decades. In order to manage the uncertainty various rise scenarios have to be used. The impacts can then be determined roughly for a chosen coastal section and the costs of alternative protection strategies calculated. Our aim is to learn about sensitivities and not to declare one particular scenario to be the most probable. It is especially important to learn how key impacts will change with sea level rise rate.

To get an indication for the costs involved the following should be considered. For several years the Netherlands has spent about one tenth of a percent of its GWP (gross world product) on the Delta Project. The GWP is estimated to be $10,000 billion; 0.1% equals $10 billion. Can we defend the world's coastlines for this annual amount of money? Three observations may be useful.

Firstly, the recent past has taught us that both individual and collective decision-makers only react to discrete events and most hesitantly to slow cumulative developments. For example: energy conservation in developed countries only gained momentum after the energy crisis of 1973-78; reaction to the acid rain phenomenon, where the natural system seems to have been pushed over a threshold with nonlinear deterioration of the environment, is mostly lukewarm; did the 1953 flood disaster have to occur in the Netherlands before a real long-term protection strategy could emerge? Countries that have not experienced such a traumatic experience will react very differently to sea level rise. Consequently we may be too late once there is consensus that the signal is 'loud and clear'. Important factors seem to be:

- the way information is presented and handled (uncertainty, inevitability, predictive power),
- the small interest of the present for the coming generations (high discount factor), unless fed by traumatic experiences,
- the apparent latitude for pushing unpleasant decisions ahead.

Secondly, the burden of protection against sea level rise will be unequally distributed over the various coastal countries. No doubt some of these countries will lack the necessary money for protection; a number of countries will put the question why they have to pay for it themselves. Remember that it is a man-made phenomenon we are talking about. Laying the blame on others for sea level rise may, however, prove very difficult and deciding on compensation payments a long and tiresome struggle. Much will depend upon the international relations in the next century.

Thirdly, we have only considered the impacts of sea level rise. Once the sea level rises, however, climate changes will also occur and this may complicate the battle for monetary resources considerably.

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9 SEA LEVEL RISE, EVALUATION OF THE IMPACTS OF THREE SCENARIOS OF SEA LEVEL RISE ON FLOOD PROTECTION AND WATER MANAGEMENT OF THE NETHERLANDS

W.van der Kley

9.1 INTRODUCTION

The Ministry of Transport and Public Works is investigating the consequences of sea level rise for flood protection and water management schemes in the Netherlands. With the best of present knowledge three scenarios have been adopted as an exogenous variable, ranging from extrapolation of current trends to more serious increases of sea level rise. These scenarios are the following:

9.1.1 *Scenario 1 (S1)*

The present sea level rise of 0.2 m/century is maintained. This rate has been chosen as first scenario because the physical processes causing sea level rise are actually unknown. This scenario serves as reference for Scenarios 2 and 3.

9.1.2 *Scenario 2 (S2)*

An additional sea level rise of 1 m in a period of hundred years is superimposed on the current trend of 0.2 m/century. After this period the present rate is assumed to continue again. The extra rise of 1 m is ascribed to thermal expansion of the oceans, caused by global warming up, melting of glaciers and volume reduction of polar ice masses.

9.1.3 *Scenario 3 (S3)*

The above extra sea level rise will continue after the hundred years' period, eventually resulting in a sea level rise of 5 m in 300 years as from the year 2000. Decay of the West Antarctic ice cap is accounted for in this scenario.

The respective scenarios are graphically presented in Figure 9.1.

Sea level rise is closely related to climate changes. It is believed that changes of climatological conditions surely will impact on nature and society. However, for the time being there is little knowledge about such changes. Therefore the present study focusses on direct consequences of sea level rise.

9.2 SCENARIO 1

9.2.1 *General*

This scenario will only cause some local problems in the next two centuries. Generally countermeasures can be implemented in line with the present strategy for flood protection and water management. The coastal zones of the Netherlands comprise approximately 400 km of sea dikes and 200 km of sand dunes. In the deltaic areas of Rhine and Meuse Rivers about 400 km of embankments protect the low-lying areas from flooding.

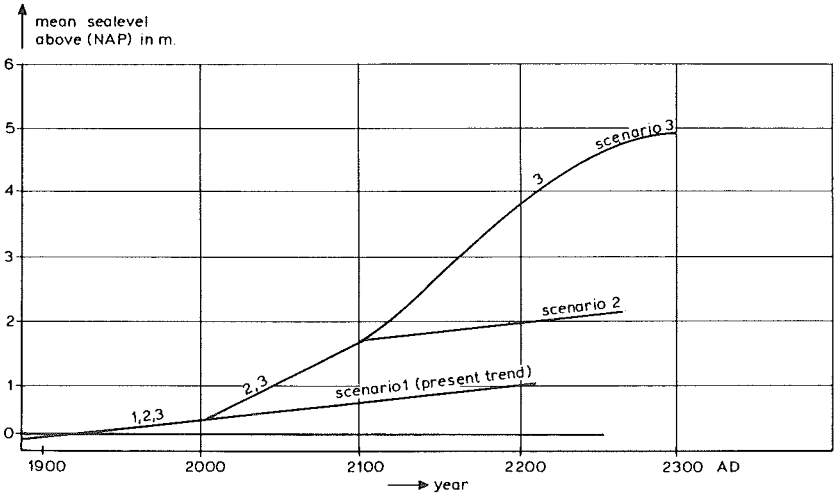

Figure 9.1. Scenarios sea level rise.

9.2.2 *Water management*

Tidal drainage in the coastal zone will not be endangered significantly by a sea level rise according to this scenario. In areas of increased seepage drainage by pumplifting might become necessary. The Province of Groningen represents a special situation in view of the ongoing land subsidence caused by gas mining. Salinity intrusion will not aggravate seriously.

9.2.3 *Flood protection*

With the present maintenance and construction program, which is based upon the present knowledge, the required safety will be reached in 1990. Special attention should be given to the problem of land subsidence in Groningen and maintenance of the coastline. Further it is necessary to anticipate on future heightening and widening of dikes by maintaining sufficient clearance when constructing buildings, pipelines, etc.

The morphology of the Wadden Sea will react on sea level rise by sedimentation to the same extent. This means that the intertidal areas will be preserved.

9.2.4 *Harbours and navigation*

Sea level rise following Scenario 1 will not induce significant changes of the coastal morphology. Sedimentation patterns will remain practically unaltered and no serious problems will arise for the existing harbour facilities.

Thus from the point of sea level rise no special attention is required for navigation channels and ports.

9.3 SCENARIO 2

9.3.1 *General*

In the case of Scenario 2, which implies an extra rise of 1 m in the year 2100, countermeasures will have to be taken in large parts of the Netherlands. In a general sense, the face of the

Netherlands will not change. However, the dynamic equilibrium between present sea level rise and the morphology of the Wadden Sea and the deltas of the Rhine and Meuse rivers will be disturbed. Considerable morphological changes might develop, such as disappearance of intertidal zones and offshore shoals. Consequently current and wave impact on the coastal zones will increase. Necessary countermeasures will be based upon traditional and well-tried design principles and will involve an estimated amount of Hfl. 10 billion (Dutch guilders).

9.3.2 *Water management*

In the coastal zone tital drainage will have to be replaced by pumplifting to maintain sufficient capacity. Due to increased pump head, existing installations will operate at lower efficiency and will consequently have to be modified or redesigned.

For Lake Yssel, a 1200 km^2 fresh water lake separated by a 30 km long barrier from the sea, a decision has to be made about the water level. Probably the solution will include a combination of a higher water level compared to the present situation, tidal drainage and pumplifting. It will be necessary to allow for enhanced water level variations to keep up with the demands for drainage and flushing.

Water levels in the delta areas of the rivers Rhine and Meuse will be influenced by the sea level rise. It is expected that this influence will extend far upstream, consequently followed by a rise of the river bed. The impact will be large and affect numerous civil engineering structures like bridges, sluices, embankments, etc.

Salt water seepage will intrude further landward. A policy analysis will have to show which countermeasures are required in the different areas of the country. Measures can be of a combating or accepting nature. Examples of this first type are:

- raising of bed level of Nieuwe Waterweg;
- increase of flushing discharges;
- protective measures in shipping locks and discharge sluices;
- regional differentiation; and
- constructive measures (screens).

Acceptation type of measures can be:

- replacement of intake structures in upstream direction;
- fresh water supply through pipelines for agriculture, horticulture, industry and drinking water;
- acceptation of reduced productivity levels and growing of less salt-sensitive crops;

The cost of the above-mentioned measures are in first instance estimated at Hfl. 3 billion. Extra exploitation costs are in the order of Hfl. 10 million per year, excluded are the extra costs involved in operation of the Yssel Lake.

9.3.3 *Dikes*

Dikes will have to be heightened and special measures will have to be taken in the case of defence systems like the Wadden Sea. Sea level rise will cause an erosion in the order of 100 to 200 m of the dune area which forms part of the Dutch coastal defence system. Choices have to be made between placing of sand fills, construction of dikes and other possible innovative solutions.

The construction of a storm flood barrier in the Rotterdamse Waterweg Channel might be considered in relation to heightening of dikes in this area. Probably such a solution has to be combined with shipping locks. The 'newly' (1972) constructed Haringvliet sluices have to be abandoned in that case.

The Easterscheldt storm surge barrier will be used frequently. This will have far-reaching consequences for environment and fishery. A possible compromise might be found in designing an operation scenario of the barrier in combination with heightening of dikes.

The total cost of the measures related to heightening of dikes in two steps of 0.5 m each is as first approximation estimated at Hfl. 6 billion.

9.3.4 *Harbours and navigation*

Harbour facilities, shipping locks, discharge sluices, fixed bridges, etc. will have to be adapted to the higher sea level. It will be necessary to review tunnel design in view of the increased top load. Obviously the cost involved can be reduced when such adaptations can be taken up in ongoing renovation or construction programs. Problems related to disposal of dredged material will become more important.

The total cost of the above measures are, in first instance, estimated at Hfl. 1 billion.

9.3.5 *Unprotected coastal zone*

Intertidal areas will reduce and sometimes disappear completely as a consequence of sea level rise. In this respect special attention will have to be paid to the Wadden Sea.

9.4 SCENARIO 3

9.4.1 *General*

The sea level rise following Scenario 3 will coincide with Scenario 2 until the year 2100. Hereafter disintegration of the West Antarctic icecap will boost the sea level rise up to +5 m in the year 2300. Although the reality of this scenario is being discussed, the possibility is not to be ruled out yet.

The prevailing opinion is that, if the important functions of the Netherlands are to be maintained, very large, integrated measures of broad scope are necessary. In political sense this will have great impact and intensive national and international efforts will be required.

Although no large-scale abandonment of the west of the Netherlands and migration to for example the areas of the Veluwe and Limburg will be necessary, some measures as rising taxes might have to be taken to promote migration. It is anticipated that as a psychological effect of sea level rise a general feeling of unsafeness will grow and stimulate the inhabitants of coastal zones to move to higher places.

On small scale, non-profitable parts of the country will be abandoned and get the function of coastal storage reservoir.

All in all the face of the Netherlands will change dramatically, especially in the coastal zone. The environment will be affected to a large extent in areas as the Wadden Sea, the delta areas of Rhine and Meuse rivers and the dune zone of the coast. There will rise an urgent pressure to 'close' the coast between Belgium and Germany.

The total cost of the consequences and measures resulting from sea level rise is estimated at Hfl. 40 billion at the lowest, in the 22nd and 23rd century.

9.4.2 *Consequences and countermeasures*

It is expected that in the north of the country the Wadden Islands will migrate to the mainland. East of this area a barrier will have to be constructed between Eemshaven and East-Friesland, a part of Germany. This barrier has to be provided with shipping locks and discharge sluices.

On a large scale, adaptations and new regulations in harbour areas will become necessary. New shipping locks have to be constructed. For the protection of the town and harbour of Antwerp a storm surge barrier has to be constructed in the Westerscheldt river, east of the town of Terneuzen.

The problem of disposal of dredged material will need special attention because of loss of traditional dumping sites. Possibly dredging work will increase because of changing morphological patterns and required adaptations of shipping channels.

Inevitably pump-lift systems have to be constructed for drainage of the Yssel Lake. New regulation of the water systems of the Rhine, Waal and Meuse rivers will have to be applied.

The increasing sea water level will endanger the fresh water reservoirs under the dunes, being a major supplier of drinking water. New fresh water sources have to be found and new supply systems will have to be created. Large parts of the dunes will be replaced by dikes. Functions as recreation and environment will be lost then for those areas.

Construction problems will be faced in some areas when heightening the dikes and more and more there will be a change from dike to barrage. Also in Belgium and Germany attention will have to be paid to the dikes.

Only in some areas of Noord-Holland and Zuid-Holland, e.g. Alblasserwaard, maintenance of dikes and water management will become too costly in relation to the productivity.

Quite some adaptations will be required in the delta areas of Rhine and Meuse Rivers. In the following two variants are elaborated which differ significantly in the respect of navigation, river, dike and water management.

9.4.2.1 *Variant a* (see Figure 9.2a)
This variant includes an open connection between the sea and the hinterland of Rotterdam port, formed by a resistance channel between Hoek van Holland and Rotterdam. East of this channel up to the town of Tiel a buffer reservoir is created with the following functions;

- navigation;
- damping the tide to limit the required dike heights;
- sedimentation reservoir; and
- water management.

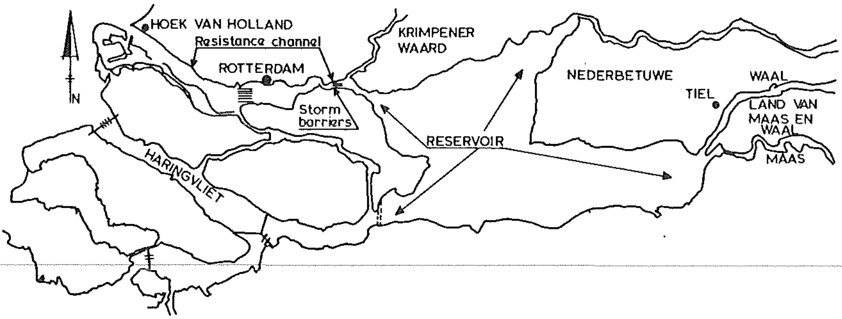

Figure 9.2a. Variant a of S3.

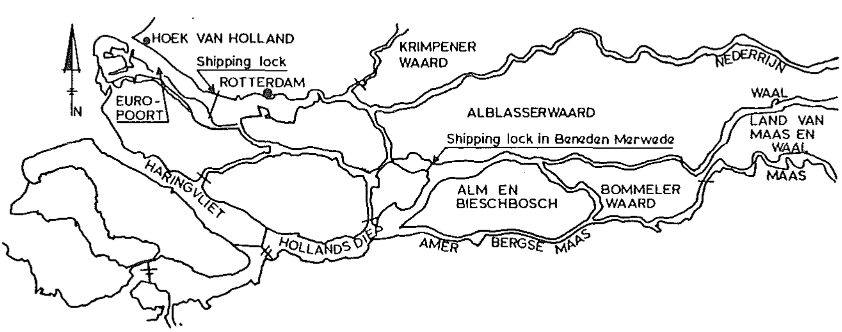

Figure 9.2b. Variant b of S3.

A possible but highly speculative measure would be that after a long period of sedimentation a new buffer reservoir has to be created elsewhere.

Further Variant a involves rebuilding of the Haringvliet sluices and also shifting of highway RW 27.

9.4.2.2 *Variant b* (see Figure 9.2b)

In this variant Waal and Meuse Rivers will be connected near Tiel and the river discharge will flow through the Haringvliet. The Haringvliet sluices will be abandoned and not rebuilt.

Europoort will remain open to sea but Rotterdam will be closed off by a system of shipping locks in the Rotterdamse Waterweg channel near Maassluis. The shipping route to Waal River and Germany will go via a shipping lock in Beneden Merwede River.

Compared to Variant a, heightening of the dikes will be less. However, navigation is more affected by the extra shipping locks to be constructed.

In both Variants a and b the Easterscheldt storm surge barrier will remain permanently closed and reconstructed to a 'real' dike. The Grevelingen lake and the Easterscheldt will become fresh water basins and could be connected to the buffer reservoir.

9.5 STRATEGY

9.5.1 *General*

The scientific explanation of the present rate of sea level rise is still very poor (De Ronde 1982, Barnett 1983, Lambeck & Nakiboglu 1984). The same holds for a possible 'rapid' rise (Oerlemans & van den Veen 1984, Titus 1986). However, it is necessary to anticipate possible future scenarios of sea level rise. For example dikes will be most probably heightened in steps of 0.5 m, each step requiring some decades for construction. In this respect there might be a critical situation when sea level rise will speed up.

It is very important to monitor the sea level rise. This will provide essential data for theory development concerning the physical mechanisms and processes playing a role. Increasing knowledge must feed the need to obtain consensus on possible countermeasures.

It should be realized that sea level rise, at least a substantial part of it, is induced by mankind. Therefore scenarios including high rates of sea level rise should not be rejected beforehand. Preventive measures should be developed and sanctioned in the international political forum. Especially development of a global emission and reforestation policy is possible.

The effectiveness of such measures will appear in the long run only. However, the scale of the impact of sea level rise on society is such that only joint-efforts on global scale can influence sea level rise and avert the longterm dramatic consequences.

In the Netherlands processes of land subsidence due to tectonic movements, peat oxydation, drainage, mining of gas and minerals and surface loads, play an important role. Sea level rise and possible countermeasures can not be isolated from these effects.

9.5.2 *Detection of the signal*

The more gradually the acceleration of sea level rise will elapse, the more difficult detection of it will take place. Eventually, when the conclusions are sufficiently solid and well-based, the increase of sea level rise will be assessed by surprise. Therefore computations of trends of sea level rise and monitoring must be continued on a global scale, as an international effort.

If sea level rise develops according to Figure 9.3b decisions are to be made around the year 2030. However, before this time it might be considered to adapt design criteria of ongoing or planned projects in view of increased sea level rise. Or, to find flexible designs so that future adaptations are relatively easy and cheap (Ymuiden shipping locks).

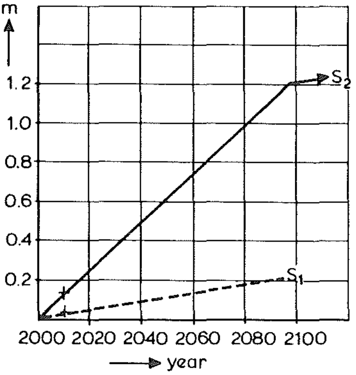

Figure 9.3a. 2010 detection if sea level rise is linear.

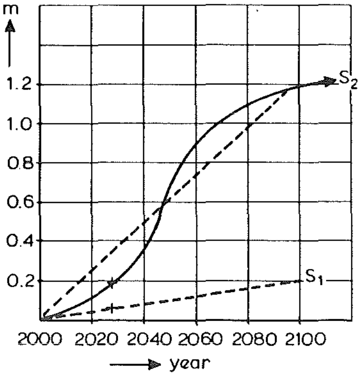

Figure 9.3b. 2030 detection if sea level rise is gradually accelerating.

In case of increased sea level rise the problem is which scenario is active. Such a problem demands a policy analysis.

Problems and uncertainties concern especially water management aspects and to a lesser extent dikes. However, reconstruction of the dikes is the most expensive. The approach of navigation problems generally depends on the chosen water management and flood protection policy.

The cost involved in measures following from Scenario 2 is estimated at approximately Hfl. 6 billion for (re)construction of dikes and dunes, Hfl. 3 billion in the field of water management and Hfl. 1 billion for adaptations in rivers and ports. Thus a first approximation of the total cost related to measures in case Scenario 2 evolves is Hfl.10 billion.

The total cost of measures involved in Scenario 3 is estimated at Hfl.40 billion in the period between the years 2100 and 2300. Apart from the higher capital investments required the exploitation cost (operation, maintenance) will be higher as well. This, however, has not been elaborated on in detail in view of the approximative character of the above figures.

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10 IMPACTS OF A RAPID RISE OF THE SEA LEVEL ON FLOOD PROTECTION AND WATER MANAGEMENT OF LOW-LYING COASTAL AREAS

A.Volker

10.1 INTRODUCTION

A rapid rise of the mean sea level will have a considerable impact on the morphological, hydrological and, in general, environmental conditions of the coastal zones of the globe. Such a 'rapid' rise is assumed to be of the order of 1 to 2 metres in 100 years.

The present notes deal with the impact of a rise of this magnitude on the flood protection and water management of the low-lying coastal regions of the world, such as deltaic areas, coastal marshes and embayments in coastal lowlands. These level areas are exposed to sea and river floods and their situation is most vulnerable because of the low elevation of the land. In Denmark, Japan and the Netherlands tidal embayments have been reclaimed which are situated as low as 5 to 7 m below mean sea level (m.s.l.). Deltaic areas are not only threatened by floods but also exposed to intrusion of seawater into the surface waters and the groundwater. Water management of these areas therefore poses special problems which are related to the mean sea level.

Low-lying coastal areas are densely populated and highly productive in the agricultural sector, especially in Europe, Asia and North-America. In these continents industrial development has also taken place. Large cities and harbours have been built in alluvial areas like Shanghai, Jakarta, Bangkok, Calcutta, Tokyo, Osaka, Rotterdam, London, Venice, New Orleans, etc.

The effects of a rise of the sea level on the flood protection and water management of the low-lying coastal areas should be considered jointly with the effects of land subsidence which occurs almost everywhere.

Like the rise of the sea level land subsidence is caused by two groups of factors: Natural effects and man-induced effects. Land subsidence is caused by geosynclinal and tectonic subsidence and in some cases isostatic compensation as natural effects. Man has increased subsidence by agricultural drainage, groundwater abstraction, mining of gas and minerals and also by loads on the surface. Natural subsidence takes place at a low rate (centimetres per century) and extends over thousands of years; man-induced subsidence may amount to a few metres within a period of a few decades.

The present notes focus on the effects of a rapid rise of the sea level although it should be noted that a rapid drop of the sea level, and similarly an upheaval of the land areas, will also have adverse effects on the water management and other sectors.

On a global scale the impacts of a sea level rise are different for different coastal areas. The magnitude of the rise may be different in different places and the effects of a given rise will vary according to land elevation, the local morphological and hydrological conditions and the degree of development of the flood protection and water management system.

A rapid rise of the sea level will be accompanied by a change in climate of the land areas. This may affect the river flow and the precipitation-evaporation conditions of these land areas. In the present considerations this point has not been taken into consideration.

10.2 MORPHOLOGIC PROCESSES AND HUMAN INTERFERENCE

From a geological point of view deltas belong to the most rapidly changing parts of the crust of the earth. A common situation in cases where man has not yet interfered or only to a limited extent is that of a growing delta. This is a delta which is extending into the sea entailing a rise

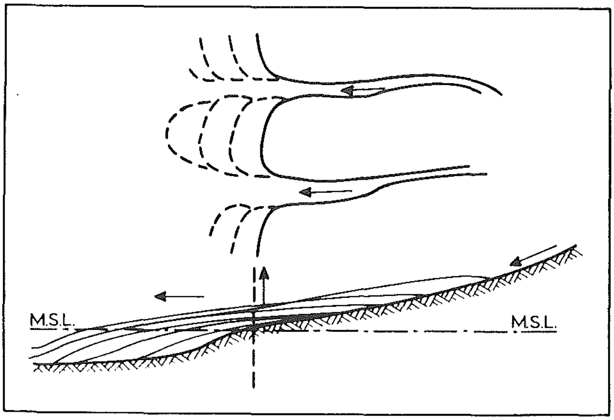

Figure 10.1. Delta extension.

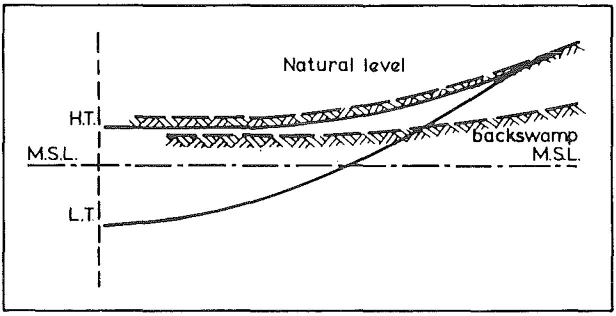

Figure 10.2 Tidal levels and land elevation.

of the riverbed and hence of the levels of the river floods (Fig. 10.1). The land areas are built up by sediments from the river and from the sea.

Under normal conditions the land in the coastal strip is built up to an elevation slightly above high tide level. Beyond the tidal reach the river builds up the natural level to approximately the level of the 1 to 5 years' flood (Fig. 10.2). The annual rates of extension vary widely but often amount to a few tens of metres horizontally and to some centimetres vertically; actual rise is a fraction of this figure because of compaction and subsidence.

A rapid rise of the sea level within a certain period will upset the present dynamic equilibrium. There will be a gradual adaptation of the morphology to the new sea level. Because of the time lag the water depths of the river channel and the sea floor will initially increase slowing down the rate of building up. The tidal currents in the shallow coastal waters will increase and cause erosion of sandy coasts. The mangrove belt which exists along the coasts of most tropical deltas will deteriorate or even disappear. This belt has a high commercial value and effectively protects the landward banks against wave attack. In the case of Bangladesh-West Bengal the mangrove forest (some 12,000 km^2) reduces the cyclone levels from the sea at inland Khulna.

In deltas where flooding has been excluded by the construction of embankments the natural building up of the land areas has been arrested. Agricultural drainage has caused a land subsidence. The effect of a rapid rise of the sea level will be a still lower land elevation with respect to the tidal levels. When the river bed has adapted itself to the new situation the flood levels will be accordingly higher.

In deltas where the distribution of the upland discharge over the tributaries has not been stabilized by hydraulic works, a river branch may be cut off from the supply of sediments (moribund river). The part of the delta which was supplied with sediments by that branch will be exposed to erosion in the case of a rapid rise of the sea level (parts of the delta of the Mississippi River).

An extreme case is that of the drowning delta like the (former) delta of the Rhine and the Meuse in the Netherlands. Low supply of sediments, natural and man-induced subsidence and a rise of the sea level have led to an artificial situation where man is constantly fighting the destructive forces of the sea. Man has learned how to cope in this area with a continuing relative rise of the sea level which, if man-induced subsidence is included, amounts to some 3 metres during the past 1000 years.

10.3 IMPACTS ON FLOOD PROTECTION

10.3.1 *Protection in the coastal zone*

Coastal embankments are exposed to high water levels and, depending on the situation, to impact of waves. High sea levels are caused by astronomical spring tides and, along a number of coasts, by wind-induced set-up of the sea level (storm surges, cyclones, typhoons and hurricanes).

A rise of the sea level will affect these conditions in different ways. The propagation of the astronomical tides in shallow coastal waters will be modified, increasing, in general, the tidal range. The set-up will decrease but, in general, this effect will be small. The wave uprush may substantially increase, especially in those cases where under the original conditions, the depths in front of sea dikes are small or where tidal foreland exists (Fig. 10.3).

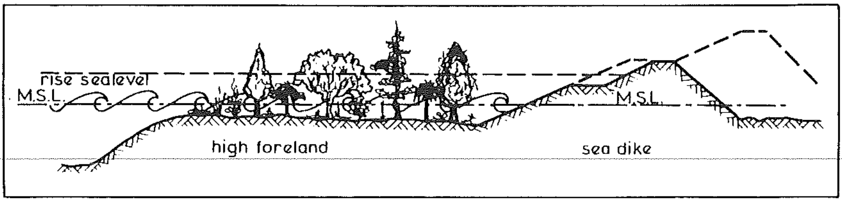

Figure 10.3. Impact of waves.

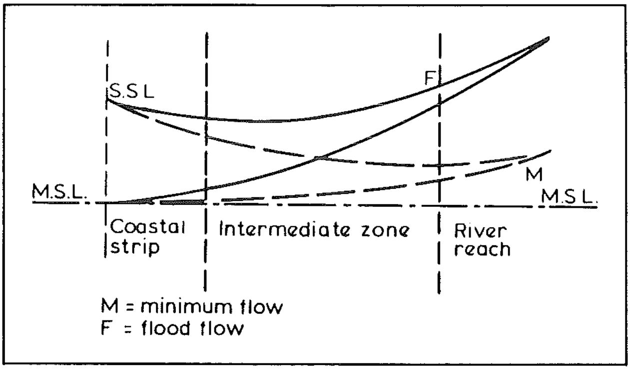

Figure 10.4. Sea and river floods.

The result is that the sea-dikes will have to be raised to a greater height than the rise of the sea level to maintain the same degree of safety.

In many deltas embankments have been raised periodically to cope with the relative sea level rise. The motive has often been not so much this rise but the desire to ensure a greater degree of safety, especially after disasters (1953 in the Netherlands and 1959 in Japan). This was also the motive for the implementation of schemes aiming at shortening the lines of defence by enclosures near the mouth of estuaries and other tidal embayments (Japan, the Netherlands and, on a smaller scale, Bangladesh).

10.3.2 *Protection upstream*

In a delta three zones can be distinguished with respect to flood levels. In the coastal strip the extreme levels are governed by the storm surge levels at sea. In the river reach the effect of the river floods is predominant. In the intermediate zone the highest floods occur when sea and river floods coincide (Figure 10.4).

A rise of the sea level will affect the levels in all three reaches with different time-scales. The rise of the sea level and the related back-water effects increases the depths of the lower river reach and facilitates the propagation of the storm surges in this reach. In a later stage the effect of the rise of the river bed will be felt, firstly downstream and then propagating in upstream direction. This will be most pronounced in deltas and lower river reaches with very small slopes (10^{-5}) like the Paranà and the Mekong rivers.

10.4 IMPACTS ON SURFACE- AND GROUNDWATER

10.4.1 *Seawater intrusion into open estuaries*

In all estuaries where a freshwater river debouches into a basin with saline water the heavier saline water will penetrate into the estuary and move in an upstream direction in spite of the flow of freshwater in the opposite direction. Depending on various factors, in the first place the tidal range in the basin, the estuary will show a distinct interface between the freshwater near the surface and the saline water near the bottom or a situation will occur where there is partial or complete mixing. The saline intrusion renders the water unsuitable for various purposes and is a maximum when the riverflow is a minimum during dry periods when the need for freshwater is high. An extreme case is the Gambia river in West Africa where at minimum flow the saline effect is felt up to 235 km upstream from the sea.

A rise of the sea level will increase the intrusion of saline water because of the increase in water depths, at least in a first phase, and the increase in tidal flood volumes. The shift of the saline reach in the upstream direction will affect the intake of water from the river for irrigation and water supply (see also Section 10.5) and the ecological conditions of the channel and the adjacent land.

It should be noted that this process is already taking place in a number of estuaries where because of dredging in connection with port development the saline effect has moved further upstream. A classical example is the Rotterdam Waterway giving access to the port of Rotterdam where the saline reach moved over 35 km in a period of about 60 years.

10.4.2 *Seepage*

In the subsoil of most large deltas pervious strata are found through which groundwater can move under the effect of differences in elevation of the surface waters. As a result of marine transgressions in the geological history the groundwater under deltas is often brackish or saline so that when seepage occurs water with a high salinity will ooze at the surface.

In many cases, however, the seepage in deltas is not a salient feature because of small

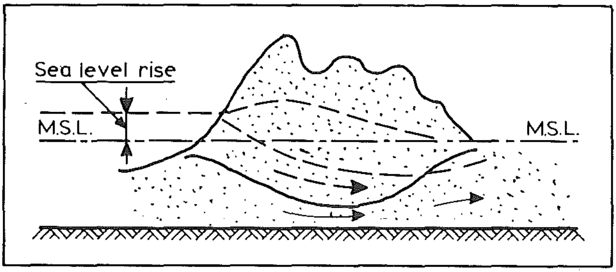

Figure 10.5. Seepage flow.

differences between the level of the land and the level of the sea. This changes with a rising sea level. Seepage of water with a high salinity (ultimately seawater) will occur where the semi-pervious top layers are absent or poorly developed. This is often the case under the sea and in the land areas at the location of incised rivers, filled-in tidal creeks and abandoned natural levees.

The presence of a sandy ridge (e.g. dunes) with fresh water pockets will not prevent seepage from the sea because of the deformation of the pocket resulting from a rise of the sea level (Fig. 10.5).

Seepage water has to be drained from land areas by pump-lift and this involves additional costs. The saline water causes considerable problems especially in deltas in the arid zone like the delta of the Nile and the delta of the Indus.

10.5 IMPACTS ON WATER MANAGEMENT SYSTEMS

10.5.1 *Drainage of agricultural lands*

Non-embanked areas

Lowland rice is grown in many deltas in the humid tropical zone where storm surges occur and where there is no protection against river floods. In these areas, often there are only low coastal embankments to protect the coastal strip from flooding with saline water during high astronomical spring tides. Local rice varieties are grown which are adapted to the depth of flooding caused by the river. Near the coastal strip the depths of flooding are small and relatively high yields are obtained. Further upstream the depth of flooding may be as much as 3-4 m and 'floating rice' is grown with low yields. These conditions occur in many parts of the large deltas of South-East Asia and especially in the delta of the Mekong-river.

A rise of the sea level of, say 1 m or more, would upset these conditions. The sea-dikes will have to be raised and in the tidal reach the depth of flooding will increase affecting the productivity. To maintain the present productivity levels protection against flooding will become necessary and embankments will have to be erected. Although, in itself, this is a simple operation it will change the environment profoundly and will entail many hydrological and morphological side effects (rise of the flocd levels, rise of the river bed and increased meandering). Embanking makes it necessary to lay out a system of drainage canals and outfalls. Because of the elimination of the beneficial effects of the floods (supplemental irrigation and flushing) it may become necessary to provide irrigation facilities.

Under the present conditions with the continuing relative sea level rise and the desire to increase the yields and to grow other crops than rice there is a tendency to carry out development schemes in the deltas aiming at flood protection, drainage and irrigation. An uncertain economic feasibility often hampers actual implementation. A rise of sea level which far exceeds that occurring at the present will either ruin many agricultural areas or accelerate the developments which are already taking place.

Embanked areas
Depending on the land elevation, relative to tidal levels, and on the drainage requirements (lowland rice or dry food crops) either gravity drainage or pump-lift drainage can be applied. In the coastal zone of many deltas all over the world tidal drainage is applied on a large scale when the land is not too low. The system often consists of simple wooden box sluices with flap gates. If there is a significant rise of the sea level this system will have to be replaced by pump-lift. This will entail high installation and operation costs in deltas in the humid tropical zone with their high amounts of rainfall.

Where pump-lift drainage is applied like in the Netherlands, Italy, Japan, USA and India the pumps will operate at lower efficiency if there is a substantial rise of the sea level and the structures may have to be modified or redesigned.

10.5.2 *Irrigation*

As mentioned in Section 10.4 the sea level rise will increase the salt water intrusion threatening the intake points of irrigation water along the river. Unless the drastic solution of enclosure of the estuaries near the mouth is applied, the intake points will have to be shifted upstream beyond the salinity limit during periods of low river flow (Figure 10.6).

New canals will have to convey the irrigation water from the new locations of these intakes to the downstream areas and, when the slopes are small, booster pumping stations in the canals will be necessary.

A benefit of the sea level rise will be the increase in head for the flow of irrigation water from the river to the land.

10.5.3 *Urban areas and harbours*

If there is a rapid rise of sea level cities in low-lying coastal areas as mentioned in Section 10.1 will have to be protected from flooding by encircling embankments ('pocket dikes') and, in any case, will have to be drained by pump-lift. This is an operation which is already under way in a number of large cities mainly as a consequence of man-induced land subsidence. Typical examples are New Orleans and Osaka; Bangkok as a recent case. In Osaka a (local) maximum

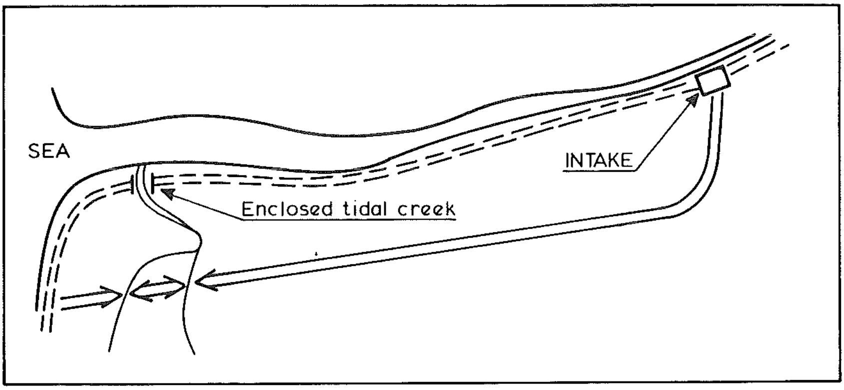

Figure 10.6. Location intakes.

subsidence of 2.8 m occurred in a period of about 30 years. This probably is a greater rate than any conceivable rate of rise of the sea level. The walls along the city canals and the entrances from the sea have been raised by 1 to 3 m. Check-sluices (some with vizor gates with a span of 60 m) have been built which can be closed when high typhoon levels occur on the Pacific Ocean. The city area is then isolated from the surrounding waters and excess water from local typhoon rainfall has to be removed by pumping. The Kema pumping station, probably the largest of the world, with a capacity of 330 m^3/s (6 pumps of 55 m^3/s) and a head of 3-4 m has been constructed for this purpose

The response of the Japanese to this challenge has been immediate and vigorous. Because of financial and organizational problems this however would probably not be possible for cities like Shanghai and Calcutta should a rapid relative rise of the sea level occur which would be similar in effect to the subsidence of Osaka.

The case of Osaka demonstrates that, from the technical point of view, a rise of the sea level of, say 2 to 4 m within a period of 100 years, would not cause unsurmountable problems. The costs have been justified because of the high economic value of an urban place like Osaka.

In tidal harbour basins it will be necessary to raise the heights of quay walls and landing stages. Attention should also be paid to ensure that there is sufficient headway under bridges. In the case of dock harbours the access locks may have to be adapted to a rise of sea level.

10.5.4 *Coastal storage reservoirs*

In a number of coastal areas in France, India, Japan, the Netherlands and to a lesser extent Bangladesh and the Mekong-delta coastal or estuarine reservoirs have been formed by damming off tidal embayments or estuaries. Excess water from the rivers is discharged into the sea through sluices and the enclosed basins have been transformed into reservoirs with freshwater by the inflow of river water (Figure 10.7).

The discharge to the sea is effectuated by tidal drainage, see Section 10.5. The low-lying areas around the reservoirs can abstract water from these reservoirs during dry periods; generally, they also drain to these reservoirs during rainy periods, either by gravity or by pump-lift.

A rise of the sea level of say 0.5 m or more will completely upset the present operation of these reservoirs since gravity drainage into the sea will no longer be possible. There are two basically different solutions which could be considered. According to the first the reservoir levels would be maintained at the original level. This implies that excess water from the reservoir would have to be removed by pumping and that the sluices would be closed. Since the volume of flood waters from the river may be quite high this could be an expensive solution.

In order to reduce the volume of flood water to be pumped out it may be possible to divert a major portion of the water to a river branch which debouches freely into the sea (Figure 10.8).

A drawback of this solution would be any seepage of seawater under the dam which may affect the quality of the water in the reservoir.

In the second solution the normal operational level of the reservoir would be raised so that gravity drainage to the sea remains possible. This would require a modification or redesign of the existing sluices. The drainage of the surrounding low-lying areas on the reservoir would be hampered and pump-lift may be necessary. Embankments would have to be raised, not only along the reservoir but, because of backwater effects, also along the rivers debouching into the reservoir. Indeed in a delta, with its system of interconnected water courses, the rise of the reservoir level would propagate in the entire system unless partitions are made.

There would also be a seepage flow from the reservoir with its high level to the surrounding low-lying areas, but after a long period of time this seepage water would have the same composition of the water in the reservoir.

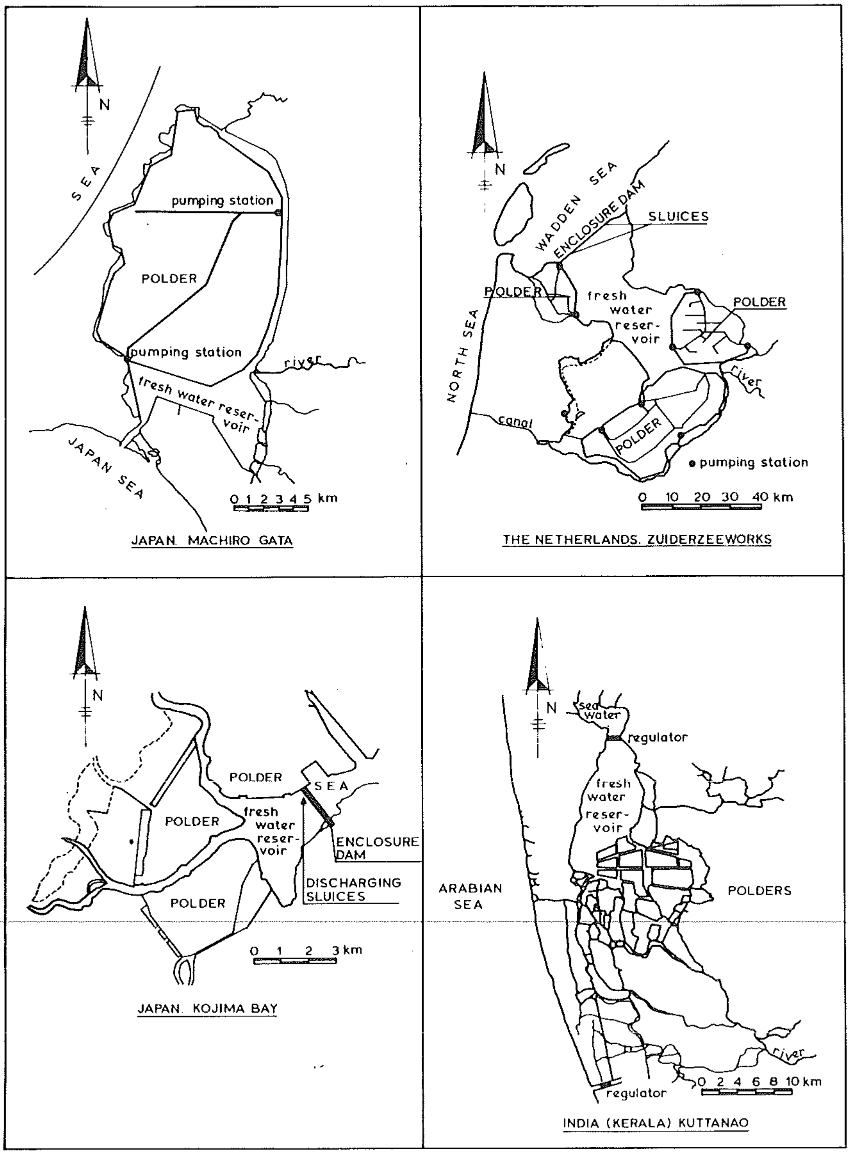

Figure 10.7. Coastal reservoirs.

10.6 PLANNING OF REMEDIAL MEASURES AND RECOMMENDATIONS

In the foregoing an outline has been given of the adverse effects of a rapid rise of sea level on flood protection and water management of low-lying coastal areas. Some remedial measures have also been indicated. Evaluation of the technical and economic feasibility of technical measures is a very time-consuming task and requires an enormous amount of design work to

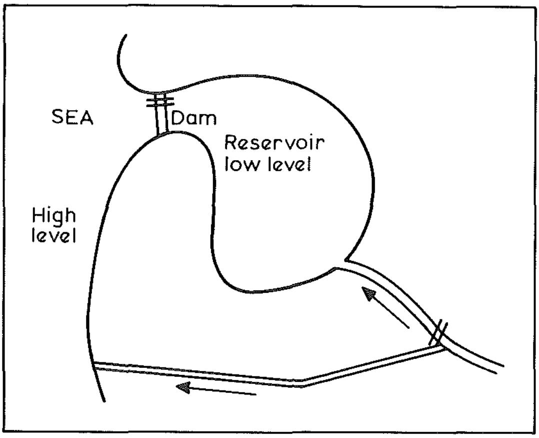

Figure 10.8. Flood diversion.

enable alternative solutions to be compared with respect to their technical, environmental and economic merits. Two fundamental difficulties are encountered in such an exercise.

The first difficulty stems from the fact that to date the predictions of a possible sea level rise have been most uncertain and that an accurate prediction of magnitude and time-scale cannot be expected within the forthcoming two or three decades. It is, none the less necessary to examine the implications of a number of scenarios of the sea level rise. This almost precludes the application of large scale remedial measures, such as enclosure of embayments, large scale embanking, river diversion, which would fit into a masterplan for the long-term development of the delta.

The second difficulty is related to the monitoring of the actual sea level rise. There is at present a sufficient number of well-founded tidal gauges all over the world and adequate international coordination for a global analysis. The problem is, however, complicated because the annual averages of the tidal levels from year to year show considerable variations which are due to variations in the wind patterns and temperature distributions in the sea and the ocean-waters. As a result neighbouring stations may show different short term trends. Even rapid rises of the mean sea level can only be detected after, say 5 to 10 years. This means that even ad-hoc remedial measures will always lag behind actual hydrographic developments.

It has been proposed that the implications of possible sea level rise should be examined and that remedial measures should be planned more concretely and in greater detail for three different deltaic areas for which adequate data are available. The following three areas could be considered:

a) the drowning delta of the Rhine and Meuse as a case of a very vulnerable situation with the threat of storm surges;

b) the growing delta of the Mekong river in the southern part of Vietnam as a case of a delta in the humid tropical zone which is densely populated but still in a primitive stage of technical development;

c) the delta of the Nile in Egypt as a case of a delta in an arid zone.

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11 SOME REMARKS ON ECONOMIC IMPACTS OF SEA LEVEL RISE AND THE EVALUATION OF COUNTER-STRATEGY SCENARIOS

Rolf H.Funck

11.1 INTRODUCTION: THE STRUCTURE OF THE DECISION PROBLEM

An evaluation of the economic impacts of sea level rise (SLR) and of possible counter-strategies must be based on a clear description of:

- the meaning of the term SLR,
- the point of view from which the evaluation takes place,
- the strategy scenarios which form the quantity bases for the evaluation,
- and the methodological framework in which the evaluation procedure is carried out.

11.1.1 *Definition of SLR*

For the limited purpose of this note, it is assumed that, due to irreversible human action in the past and the present, an SLR of height $\Delta h = 1$ m will occur over the next century. In addition, we presume that, as awareness of the existence of the greenhouse effect and its environmental impacts spreads, measures will be determined and put to work on a world-wide scale in order to limit the effects. Consequently then, Δh will be the maximum SLR. Also since these measures will presumably be taken independently of the strategy chosen to counter the impacts of SLR, they can be considered to be an undifferentiated element of any such strategy, and thus can be neglected for the purpose of this note.

The distribution of SLR over the time axis t between the years 1986 ($t = 0$) and 2086 ($t = T$) can then be described by a probability function P(x) (see Klaassen, this volume) $P(\Delta h(t))$ which is basically unknown, except for $P(\Delta h(T)) = 1$, since we do not know at present whether SLR will follow a linear, a decreasing or an increasing path. For matters of convenience, however, we may assume the function to be of logistic form, see Figure 11.1. This would mean that the probability of a serious SLR occurring during the next thirty or so years would be sufficiently low to constitute an acceptable risk. This would enable sufficient periods of planning (say ten years) and execution (say twenty years) of strategies to be made in reaction to the anticipated SLR. Also, it would coincide with the above mentioned measures to limit the greenhouse effect to gradually take effect in the future.

In Figure 11.1, the point in time at which the planning should be completed is labelled τ_1, while the point at which counter-SLR strategies should be in effect at time τ_2.

11.1.2 *Point of view of evaluation*

SLR will have effects on individuals, on the regional and national economic levels, and on a world-wide scale. As far as effects for individuals – households or enterprises – are concerned, these are included as impacts on the regional or national economy. Gains or losses of one individual, however, that are compensated in monetary terms by losses or gains of another individual, will not be considered (see also Gibbs 1984), although, in utility terms, the sum of losses and gains may differ from zero. Consideration of utility changes through an inter-individual redistribution of wealth would, however, make it necessary to construct a national (or a series of regional) welfare function(s) which include(s) a distribution term, and also to make a sensible assumption about the interpersonal distribution of economic impacts from SLR. While fulfilling the former condition seems a difficult task of its own, fulfilling the latter seems virtually impossible.

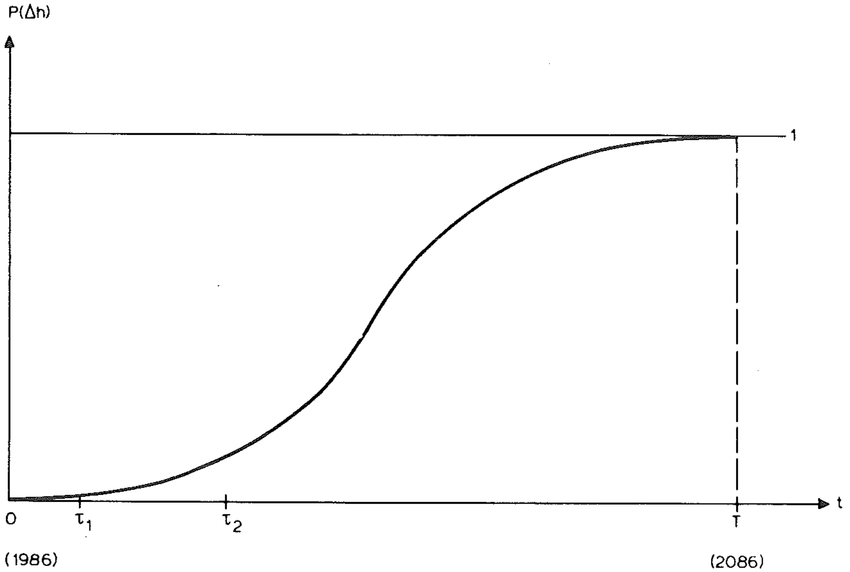

Figure 11.1. Time distribution of probability of occurrence of SLR.

Impacts of SLR on the world economy are not discussed in this note, although they may be very serious. Ecologic changes resulting from the flooding of low-lying coastal areas, the opening up of areas – predominantly in third-world countries – previously untouched from human activity, the securing of a minimum supply of food for the world population under changing conditions in coastal plains, the financing of defence strategies in densely populated, however, economically poor, predominantly third-world lowlands, are just a few keynotes to be mentioned in this respect. Elaborating on these aspects of SLR would, however, go far beyond the scope of this note.

Instead, a national economic point of view will be adopted, considering also regional differences in economic structure as well as in settlement distribution and geographic characteristics. In particular, we assume that, in the country under consideration of total area L, a certain area $L_n < L$ exists which, due to topographical considerations, is not directly affected by an SLR of height Δh. Also, L_n is assumed to be sufficiently large and economically viable as to, in principle, allow for a physical relocation of people and production sites from the endangered area (L-L_n). Finally, the production possibility of the national economy must be sufficiently large to allow for investments in either defence or resettlement strategies, or both, to take effect at time τ_2 at the latest, assuming a national financing of these strategies, which allows for interregional redistribution of investment funds.

A scenario like this seems to fit best to a highly developed country like, among the countries used for case studies in the workshop, the Netherlands. It could be fitted to a situation of underdevelopment if international migration and financing were allowed for.

11.1.3 *Counter-strategy scenarios*

Basically, three strategies are considered: Land saving (Strategy S), land abandoning (Strategy A), and a combination of both where the land endangered by SLR is partly defended from the sea and partly abandoned (Strategy P).

Strategy S calls for a raising of the level of existing dikes (by $\Delta > \Delta h$), possibly supported by other engineering solutions[1] like building or improving storm gates for the protection of river mouths, or replacing by the construction of new dikes in front of the existing ones (vanguard dikes). If the engineering measures are completed in time and successfully, no other measures, as for example, resettlement, need be taken.

Strategy A, on the other hand, consists primarily of measures for the relocation of inhabitants and their personal belongings as well as machinery and other movable production facilities (including livestock) to new sites. Also, in order to reduce to a minimum the physical loss[2] of infrastructure and fixed supra-structure, a building code would have to be put into effect at time τ_1[3], preventing construction or even reinvestment in fixed structures on land to be abandoned (L_a). In addition, plans would have to be made and implemented to adequately regulate the spatial and social adaption of immigrant population and enterprises into L_n. Finally, it may be necessary or advisable to shield the not-endangered area L_n against the rising sea in the same way as the now-to-be abandoned area has been protected originally; thus, dike building or other engineering solutions may be advisable to a similar though lesser degree as described in Strategy S.

In view of this it is clear that the combined strategy P is in fact a sub-strategy to strategy A, compared to which engineering solutions have to be implemented at a somewhat higher degree of priority, although relocation measures still must be realised, though for a somewhat smaller area. At the same time, the area L_n for which spatial and social adaptation planning is necessary, will have to be extended to enclose the area defended from SLR, that is L_s. Thus, only strategies S and A (including sub-strategy P) have to be differentiated.

11.1.4 *Methodological framework of evaluation procedure*

Basically, three kinds of methodological approaches to the evaluation of the economic impacts of SLR and feasible counter-strategies seem possible:

- a purely market economy-oriented investment calculation which only takes into account the nationally aggregated market effects;
- a cost-benefit approach, see e.g. Dasgupta & Pearce 1973, which, in addition to the market effects, allows certain societal effects like possible loss of life, see e.g. the procedure suggested by Klaassen (this volume), calculated or transformed, however, into monetary expressions;
- a multi-criteria evaluation procedure, see e.g. Hwang & Masud 1979, which allows for a

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[1] Non-engineering solutions, like relying on a natural adjustment of the environment to SLR are not considered here, but may well be adequate to the situation in underdeveloped countries or in large river deltas, where the cost (including the cost of environmental damage) of engineering solutions would clearly be excessive.

[2] Monetary loss will always tend to be zero, since prices for abandoned land and property will drop to zero, precisely at time $\tilde{\tau}(0 < \tilde{\tau} < \tau_2)$ when the discounted value of future (expected) profits can no longer offset the investment outlay, that is when the following expression holds:

$$0 = -K(\tilde{\tau}) + \int_{t=\tilde{\tau}}^{t=\tau_2} [1-P(\Delta h(t))] \cdot \pi \cdot e^{-r \cdot t}\, dt$$

where K = capital investment to be taken at time t in order to yield average annual expected profits of π, and r = interest rate. In order to determine $\tilde{\tau}$, the expression must be calculated for alternative points in time $(0 < \tilde{\tau} < \tau_2)$.

[3] Alternatively, at the latest, at a time as (indirectly) determined in the previous footnote, that is when considering the period of depreciation d_j for a particular type of investment j, the following expression holds: $\tilde{\tau} = \tau_2 - d_j$.

non-monetary evaluation of social effects relative to market and other monetary effects, which cannot reasonably be expressed in monetary terms, except at the cost of serious des-information; this holds particularly, for environmental, distributional (these will, however, be disregarded here, as stated above) and socio-structural effects such as the emotional loss and the social disturbance connected with land abandoning and the reorganization of social structures necessary as a reaction to a (massive) intrusion of the relocated population into (densely) populated areas, the change in accessibility as a result of relocation, etc.

The first approach is clearly insufficient with respect to the problem at hand. The third approach calls for a complex socio-political procedure which, in the relevant literature, see e.g. Funk 1985, is still disputed regarding its theoretical structure, empirical requirements, and scientific-theoretical implications. Thus, for the purpose of this note, we will, for the sake of convenience, assume a cost-benefit approach, but will keep in mind multi-criteria evaluation as a class of procedures for the determination of relative social values for such societal effects to which price-tags cannot be attached through any reasonable argument.

The decision problem which we face can then be described as the task of determining the delineation between L_s and L_a, based on an evaluation of the socio-economic effects of SLR and reasonable counter-strategies on the national and regional levels.

11.2 THE IDENTIFICATION OF STRATEGY ALTERNATIVES

In general, there are two different approaches to the identification of the particular strategy alternatives to be included in the evaluation procedure:

- an approach based on a spatially continuous evaluation of impacts, and
- an approach inhibited by pre-determined socio-geographic restrictions.

11.2.1 *Spatially continuous evaluation*

In this approach, every conceivable line of defence against SLR is considered, from the saving of all endangered land (Strategy S) to total retreat to the border line of L_n (Strategy A proper). Strategy choice is then made on the basis of the comparative social desirability of the alternatives as determined by the results of the valuation procedure described in Section 11.5, below.

This approach would be sharply focused on the objective of neo-classical theory of economic welfare, that is, determining a Pareto optimum solution for the economy as a whole (see Van de Graaff 1963). The approach, however, does not seem to be very practical in two senses: an indefinite number of scenarios cannot be dealt with in reality, and it would include a large number of cases which cannot be considered as alternatives if they are not really distinctly different or pose obvious technical difficulties, or are policitally unfeasible. Thus, it is sufficient to identify a limited number of feasible alternatives for socio-economic evaluation.

11.2.2 *Pre-determined socio-geographic restrictions*

An identification of feasible alternatives might be based on a consideration of socio-geographic criteria which, probably, can be most easily described by using a constructed example. Such an example is provided in Figure 11.2: in addition to showing the actual coast line, the figure shows the sites of a big city, B, where central service production for the country as a whole, and a large urban population are concentrated, and of a rural town R which serves as an administrative and service centre for the (northern) agricultural region. It is also assumed that manufacturing is concentrated mainly in the southern region with B as the main service centre. North and south are interchangeable, in principle, as agricultural and manufacturing

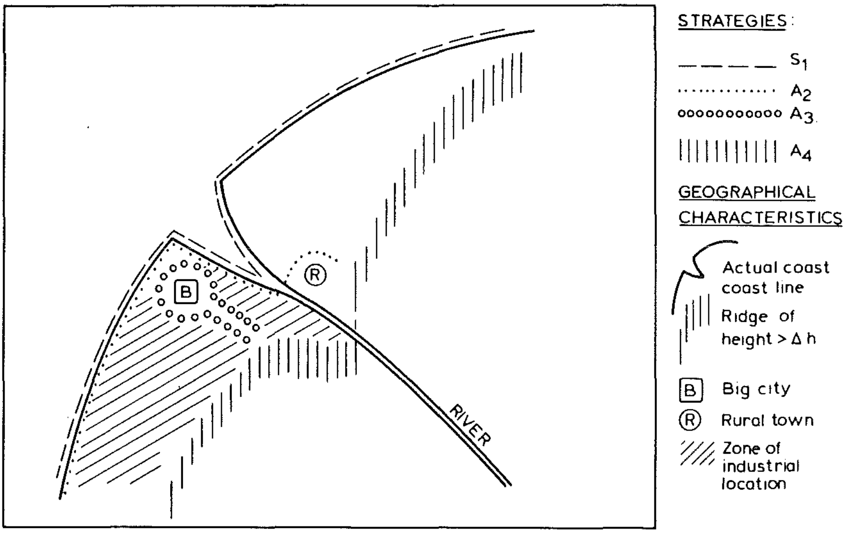

Figure 11.2. Determination of strategy alternatives under socio-geographic restrictions.

regions for the purpose of this evaluation, that is depending on the relative social values attached to the prevailing economic activities.

A natural ridge of height >Δh is assumed to extend in a north-south direction somewhere inland, while a river provides the geographical distinction between north and south.

Obviously, a number of alternatives for feasible defence strategies can be determined in Figure 11.2. These are labelled Strategies S_1, A_2 and A_3: Strategy S_1 involves total defence of endangered land; Strategy A_2 involves the defence of two centres (City B and Town R) as well as the manufacturing area, the southern region, while Strategy A_3 restricts defence activities to the central City B, allowing for abandoning to the rising sea all other areas outside L_n. Strategy A_4, involves total retreat against SLR (Strategy A proper).

In a real situation, socio-geographic restrictions other than those included in the example are conceivable. Basically, however, the possibilities seem to be as described in the example if we allow for an interchange of 'manufacturing' and 'agricultural' in the description of the Northern and Southern regions, where the actual labelling would depend upon the socio-economic evaluation.

11.3 SOME ELEMENTS OF THE SOCIO-ECONOMIC FRAMEWORK FOR THE EVALUATION

In this section, selected elements of the socio-economic framework are discussed, within which the evaluation and the consequent strategy choice to counter SLR take place. In particular, the following questions are considered which seem of special importance to the topic of this contribution:

- the social rate of discount,
- the problem of capacity restrictions in the construction industry,
- the problem of budget constraints on the national level, and
- the necessity of interregional redistribution of impacts from SLR.

Table 11.1. Present social value of future (real) income. (Present social value of Y_0 of (real) income to be produced in future period t (Y_t) will be equal to or less than 1% of Y_t for the following social rates of discount).

Social rate of discount (r_s)	After t years
0.02	230
0.03	154
0.04	115
0.05	92
0.06	77
0.07	66
0.08	58
0.09	51
0.10	46

The calculation is based on the following reformulations of the compound interest formula:

$$\frac{Y_0}{Y_t} = \frac{1}{e^{r_s \cdot t}} \leqslant 0.01$$

$$t = \frac{\ln 100}{r_s}.$$

11.3.1 *Social rate of discount*

The social rate of discount is assumed to reflect the relative value the society puts on current over future availability of goods. Obviously, the interest rate on capital serves – among other objectives – the same purpose from a private business point of view, but is also influenced by a variety of factors such as short term supply and demand on the money market, state of the balance of international payments, profitability of current investment, to name just a few. Thus, the capital interest rate is not an easy substitute of the social rate of discount but only an indicator of the range in which this rate is floating. Also it is obvious, that any decision on a counter-strategy to SLR, and thus, on possibly heavy investment in dike or/and resettlement construction, will in itself influence the capital interest rate.

The social rate of discount, therefore, has to be determined through a socio-political evaluation procedure in which the real interest rate (deflated for increases in general price level, the rate of inflation) will be one element among others, e.g. the scarcity of non-reproduceable factors[1] such as land for residential, manufacturing, food-producing, recreational or other purposes.

Depending on the value society places on current against future availability of goods, that is, on the social rate of discount r_s, goods available beyond a certain point in time only will become socially practically worthless today, or at planning time τ_1. This is a very important element in long-term societal decision-making for determining SLR-counter strategies. From Table 11.1 it can be seen that (real) income, which can be produced a century from today (or ninety years from planning time τ_1) will influence current decisions on SLR-counter strategies only, if the social rate of discount r_s, does not rise over four to five percent. Thus, it should be noted that caring today for the well-being or even for the possibility of a continuation of life of future generations is theoretically equivalent to a low rate of social discount.

[1] Rothengatter et al. (1984) use drinking-water and air of certain quality standards as restricting factors.

11.3.2 *Capacity restrictions in the construction industry*

Massive investment in dike raising, building of new dikes or other defence devices against SLR or in residential or commercial resettlement may pose serious demands upon the capacity of the construction, and related industries. In order to avoid either exorbitant price increases or heavy, temporary expansion of capacity – and the problems arising necessarily in the following contraction period – a careful priority planning of the various construction tasks is advised. In the following, it is assumed that the capacities of the construction-related industries are sufficiently flexible to allow for an implementation of a carefully planned construction-reconstruction program without excessive market reactions.

11.3.3 *National budget constraints*

From a national economic point of view, budget constraints may have to be considered regarding the choice of strategy alternatives. Assuming, e.g. that Strategy S_1 (in Figure 11.2) requires huge investments in the construction of vanguard dikes as compared with all other feasible strategies, then the societal (un)willingness to pay for land saving might push the line of defence against SLR inland. A societal attitude like this would be expressed in a broad-ranged political resistance against higher taxes, possibly combined with a re-channelling of public funds from other uses to the purpose of land saving. It would, however, reflect the lower, and possibly negative, social value attached by society to a massive diversion of production factors to this task, thus reducing the possibilities of producing other (consumer) goods[1], and raising the wage and price levels, creating inflation.

11.3.4 *Interregional redistribution of impacts*

The impacts of SLR, particularly if a strategy of partial or total land abandoning is adopted, will affect the various sectors of the national economy in different ways and to different degrees: defence investment, by their very nature, have to be concentrated in certain areas, resettlement of residents and enterprises must be planned to be carried out in locations adequate to the particular purpose. Thus, economic and social structures, see Section 11.4, will change, possibly dramatically in certain regions, while remaining basically unaffected in others. An interregional balancing of SLR impacts seems, therefore, necessary. This would possibly take the form of an interregional redistribution of public funds ('horizontaler Finanzausgleich') in order to offset financially the different levels of social and economic disturbance, or to provide (part of) the funding for such social activities as might be considered necessary to ease situations of regional or local social unrest.

11.4 THE SOCIO-ECONOMIC EFFECTS OF SEA LEVEL RISE AND OF COUNTER-STRATEGIES

The socio-economic impacts for the various strategies, that have been identified as feasible for a specific country, see Section 11.2 and Figure 11.2 above, have to be determined and evaluated. The main effects are, in particular:

- construction,
- change of (real) national income,
- migration,
- loss of land in production,
- environmental change, and
- social disturbance.

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[1] Unless all construction could be provided by activating factors otherwise idle, that is through an increase of employment and capacity use (see Section 11.4).

All costs and benefits, if any, must be calculated for an identical point in time, e.g. $t = 0$ or $t = \tau_1$, see Section 11.1, employing the pre-determined social rate of discount r_s, see Section 11.3.

11.4.1 *Construction*

Two factors have to be taken into account: construction costs of dike raising, including the building of new dikes or other engineering devices for defence against SLR ($C_d(t)$), and the costs of reconstruction of residential and/or production-oriented facilities including infrastructure at new sites if land is abandoned ($C_r(t)$). The costs of dike raising or building may be considered as dependent on the length of the defence line with the unit cost of construction as a constant factor for each particular engineering solution (see the expression for K as calculated by Klaassen (this volume)). Reconstruction costs, on the other hand, will depend on the settlement structure in the abandoned area as well as on the type and the spatial density of those activities already present in the area of immigration. Thus, a resettlement and reconstruction plan will be necessary to determine the costs involved for each feasible strategy.

11.4.2 *Change of (real) national income*

If, at time τ_1, unemployment exists in the national economy, the implementation of construction-reconstruction plans under the adopted SLR counter-strategy may greatly improve the employment situation in regional or national labour markets on a medium to long term basis, that is for the construction period ($\tau_2 - \tau_1$). Employment effects may spread from the construction industry to the building materials and other supply sectors as well as to the industries producing consumer goods and services. Since, from a national point of view, the real cost of defence against SLR should be calculated as the use of productive factors diverted from other productive employment, that is on an opportunity cost base only, the total cost of construction as determined in the previous paragraph, should be (partially) offset by the increase in (real) national income ($Y_{dr}(t)$) which results from increased employment. It, then, becomes clear that the cost of saving land from SLR may become small, or even tend to zero, if a substantial raise in total employment occurs as a result of the increase in construction related activities.

11.4.3 *Migration*

The cost of migration of population and enterprises to new sites ($C_m(t)$) should be based on the actual moving costs of persons and their personal belongings, of machinery, livestock, and other movable assets. It is assumed that fixed structures have to be abandoned, but will, in general, have been depreciated to zero-value, if the building code suggested in Section 1 has been followed. Obviously, the migration costs to be determined for each strategy alternative will depend on the number of migration population, and on the economic structure prevalent in the area to be abandoned L_a.

11.4.4 *Loss of land and production*

The economic value of the loss of land, and abandoned structures not completely depreciated, should be calculated based on:

– the reduction in (real) income from agricultural production ($Y_{agr}(t)$) for an indefinite period, and

– the reduction in (real) income from manufacturing, housing and other service production etc. ($Y_{ms}(t)$) during the period of removal of the activity to a new site, that is until full production can be resumed.

It is clear that property values are relevant only insofar as they no longer secure the creation of future income. Land values at time t = 0 should not be considered adequate indicators of losses to occur as results of SLR (see Section 11.1). Also, it should be noted that as a result of resettlement of activities land prices will rise, possible dramatically, in areas where migrators intend or are supposed to settle. However, monetary changes in land prices mean simply a redistribution of wealth between owners, and non-owners; these redistributory effects, which may affect the social capital in utility terms only, are not considered for this contribution, see Section 11.1.

11.4.5 *Environmental change*

Both SLR and the implementation of feasible counter-strategies will lead to serious environmental changes in endangered lowlands and estuaries, the particular kind and intensity of change depending on the strategy adopted. Changes will also occur in areas where the relocated population settle and take up production and other activities.

In principle, the social costs (or benefits) of environmental changes should be calculated as the relative value society places on these changes, based on the evaluation of the results of the various strategies, compared with the situation which would prevail if an uninhibited SLR of height h were accepted (Strategy A_4 in Figure 11.2). In this evaluation, economic losses (gains) from changes in fishing grounds and beach tourism should be considered[1]. The main task, however, would be to determine the relative social importance of non-marketable environmental alternatives.

This latter problem can only be solved on the basis of a complex socio-political evaluation procedure, which should produce a strategy-specific environmental factor σ_E. Since this factor in the evaluation procedure, would be handled in the same way as the societal factor, see the following paragraph, both factors are dealt with together in Section 11.5.

11.4.6 *Social disturbance*

In the evaluation of alternatives a societal factor (σ) should be included to account for:

– a safety margin in order to prevent or minimize loss of life (σ_S); in our concept, loss of life would occur only if an SLR of height Δh takes place at time $t < \tau_2$,

– the emotional cost and the cost of social disturbance connected with the loss of land and the reorganization of social structures as a reaction to a (massive) intrusion of migrators into already (densely) populated areas (σ_D),

– the change in social accessibility as a result of spatial redistribution of migrators (σ_A), and

– the social value of environmental change (σ_E), as described in the previous paragraph.

Obviously, the societal factor σ is a complex parameter which has no monetary value in itself, but is intended to correct or reconsider the relative social importance of the various (real) monetary elements of the evaluation procedure, through which the decision on strategy alternatives is to be structured using social efficiency criteria.

11.5 THE EVALUATION PROCEDURE

In the evaluation procedure the various cost and benefit elements must be evaluated, for each strategy alternative, that is for S_1, A_2, A_3, A_4 as determined in Section 11.2 for an imaginary case. The results can then be compared, and the best alternative, or rather the alternative which requires the least social diseconomies, identified.

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[1] For the sake of simplicity of the calculations in Section 11.5, these cost (or benefit) elements will be assumed to be absorbed in the costs of loss of land and production.

11.5.1 *Calculation of costs and benefits for each strategy alternative*

A simplified version of the procedure can be described as follows for each alternative:

Calculate construction costs at time t, first the costs of dike raising (see Klaassen, this volume)

$$C_d(t) = K_d(t) + l \cdot \Delta h' \cdot c_d(t) \tag{11.1}$$

where

K_d = fixed costs of dike raising to be provided at time τ_1,
l = length of dike,
$\Delta h'$ = height of dike raising,
c_d = marginal costs of dike raising per unit of dike length
and all other symbols already explained.

and then the costs of reconstruction

$$C_r(t) = K_r(t) + \sum_{i=1}^{n} c_r^i \cdot L_a^i(t) \tag{11.2}$$

where

K_r = costs of reconstruction as determined by socio-economic characteristics of area of resettlement,
i = type of activity to be resettled, e.g. residential by quality type, agricultural, manufacturing by sector, service etc.,
c_r^i = costs of reconstruction of activity i per unit of abandoned land where activity i was prevalent.

The total societal value of construction costs (C_{dr}), at time τ_1, is then

$$C_{dr}(t) = \int_{t=\tau_1}^{t=\tau_2} [C_d(t) + C_r(t)] \cdot e^{-r_s \cdot t}\, dt \tag{11.3}$$

Calculate the change in national income $Y_{dr}(t)$, due to increased employment, as

$$Y_{dr}(t) = \int_{t=\tau_1}^{t=\tau_2} w \cdot E_{dr}(t) \cdot e^{-r_s \cdot t}\, dt \geqslant 0 \tag{11.4}$$

where

E_{dr} = change in employment as a result of dike raising and reconstruction activities,
w = average (real) wage rate per unit of employment (e.g. per man/year).

Calculate migration costs of population and enterprises as

$$C_m(t) = \int_{t=\tau_1}^{t=\tau_2} [POP_a \cdot c_m^{pop}(t) + \sum_{i=1}^{n} c_m^i \cdot L_a^i(t)] \cdot e^{-r_s \cdot t}\, dt \tag{11.5}$$

where

POP_a = population in area to be abandoned,
c_m^{pop} = costs of moving of population and personal belongings per capita,
c_m^i = costs of moving of movable assets for productive use per unit of abandoned land where activity i is prevalent.

Calculate the costs of loss of land and production, first as the reduction in income from agriculture for an indefinite period:

$$Y^{agr}(t) = \int_{t=\tau_1}^{t\to\infty} y^{agr} \cdot L_a^{agr}(t) \cdot e^{-r_s \cdot t}\, dt \leqslant 0 \tag{11.6}$$

where

y^{agr} = average annual income from agricultural production per unit of land,
L_a^{agr} = abandoned agricultural area,

then as the temporary reduction in income from manufacturing and other economic activities:

$$Y^{ms}(t) = \int_{t=\tau_1}^{t=\tau_2+\Theta} \Big[\sum_{i=1}^{n-1} y^{ms,i} \cdot L_a^{ms,i}(t) \Big] \cdot e^{-r_s \cdot t} dt \leqslant 0 \qquad (11.7)$$

where

$y^{ms,i}$ = annual income from non-agricultural production of type i per unit of land where activity i is prevalent (for non-agricultural production: $i \epsilon \{1, \ldots\ldots, n-1\}$; for agricultural production: $i \epsilon \{n\}$),
$L_a^{ms,i}$ = abandoned area where non-agricultural production of type i prevails,
$\tau_2 + \Theta$ = point in time at which full production can be resumed.

As stated in Section 11.1, it is expected that the probability of an occurrence of SLR of height Δh is negligible up to time τ_2. Thus, for the sake of simplicity, we can assume that $P(\Delta h(t)) = 0$ for $0 \leq t \leq \tau_2$. Also, the assumption is made that any SLR-counter strategy will be completed at time τ_2, which means that the actual value of $P(\Delta h(t))$ for $t > \tau_2$ is irrelevant as far as the socio-economic consequences of SLR are concerned. Therefore, the term $P(\Delta h(t))$ has already been omitted from Equations (11.6) and (11.7).

Determine the societal factor as

$$\begin{aligned} &\sigma = s \cdot \sigma_S + d \cdot \sigma_D + a \cdot \sigma_A + e \cdot \sigma_E \\ &\text{with } s + d + a + e = 1 \end{aligned} \qquad (11.8)$$

where the parameters s, d, a, and e indicate the relative social importance of the various elements which are included in the societal factor. The determination of these weighting parameters is a result of the socio-political evaluation procedure mentioned in Section 11.4.

Then, the results of the various partial calculations can be combined in such a way that, for each strategy alternative $\upsilon(\upsilon \varepsilon \{S_1, A_2, A_3, A_4\})$, the following equation holds:

$$V^\nu = [C_{dr}(\tau_1) + C_m(\tau_1) + Y^{agr}(\tau_1) + Y^{ms}(\tau_1) - Y_{dr}(\tau_1)] \frac{1}{\sigma^\nu} \qquad (11.9)$$

Finally, the lowest value V^υ

$$\min V^\nu V_\nu \qquad (11.10)$$

is identified.

11.5.2 *Final remarks*

It should be noted, however, that the strategy which fulfils Equation (11.10) must not necessarily be accepted as the optimal counter-SLR strategy. The evaluation procedure proposed in this contribution should, rather, be interpreted as a quantitative system of identifying the socio-economic impacts of SLR, and the various feasible counter-strategies, and thus as an attempt to supply structured information on the relative desirability of these strategies under the stated aspects. This information does not replace, it rather underlines the necessity of a final, political decision on strategy selection. This decision must take particular regard of the socio-economic framework in which it is embedded, and some important elements of which have been discussed in Section 11.3.

Also, it should be kept in mind, that the analysis in this contribution is based on the probably rather optimistic assumption that $\Delta h = 1$ m will be the maximum SLR. In Chapter 1 of this volume it is stated, that SLR 'estimates for the next century range from 0.5 to 2 metres', and that there are fears and doubts expressed, particularly in the meta-scientific and popular literature, which go far beyond the upper limit of even this range. Clearly, therefore, during the planning period (from $t = 0$ to $t = \tau_1$), a more precise view of the maximum height of SLR, the time-path which it is expected to follow, and the consequent time-distribution of probabilities for SLR must be established. Then, in a real decision situation, public pressure may push the value of the societal factor σ so high that any technically feasible strategy alternative other than total land saving (Strategy S_1) becomes politically unfeasible.

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12 SOME SOCIETAL CONSEQUENCES OF THE RISING SEA LEVEL

L.H.Klaassen

Costs related to raising the height of a dike are often justified by the resulting increase of safety behind the dike of both population and of property. In the present contribution a theoretical framework is developed in which some of the factors determining the balance between costs of dike raising and gains due to increased safety are incorporated. The theoretical consequences of some ethical standpoints on adding values to human life are explained.

Theoretical framework

Let the costs of raising dikes be

$$K = K_o + k \Delta x l \tag{12.1}$$

where

K = total costs of dike raising,
K_o = fixed costs of dike raising,
k = marginal costs of dike raising by unit of length,
Δx = extent of raise,
l = length of dike
(all at time t).

Furthermore, let

$$S_t = P(x)C_t + (P(x) \cdot (v_{to} + v_t\bar{L}_t)P_t) \tag{12.2}$$

where

S_t = damage in year t,
$P(x)$ = probability of catastrophe at a level x of dike,
C_t = capital (in monetary terms, or value of production means, stocks and consumption goods in family households),
v_{to} = value of human life irrespective of age,
v_t = value of a year's life (quality-adjusted life-year),
P_t = total population in the region protected by the dike,
$\bar{L}_t$ = average life expectancy.

The underlying thought behind the second term of Equation (12.2) is that human life has a value irrespective of age as well as a value dependent on the number of life years still to be expected (adjusted to the quality of these years – twenty healthy years are worth more than twenty years of infirmity). Those who believe that only the value of life as such should be counted, not wishing to discriminate between younger and older people, will set $v_t = 0$. Those who are of the opinion that only the years to be expected count, so that at loss of life only the years lost (few with older people, many with younger ones) should be taken into consideration, will set $v_{to} = 0$. The general formulation of Equation (12.2) permits both points of view.

We assume that

$$\begin{aligned} C_t &= C_o e^{\gamma t} \\ v_{to} &= v_{to}^{o} e^{\nu t} \\ v_t &= v_t^{o} e^{\mu t} \\ P_t &= P_o e^{\pi t} \\ \bar{L}_t &= \bar{L}_o e^{\lambda t} \end{aligned} \tag{12.3}$$

where

C_o = initial capital,
v_{to}^{o} = value of a life in year 0,
v_t = value of a life year (quality-adjusted) in year 0,
γ = growth factor of capital,
ν = growth factor of the value of life (dependent on societal and income developments),
μ = growth factor of the value of a life year (dependent on societal and income developments),
π = growth factor of population,
λ = growth factor of average life expectancy.

Total damage then is

$$\Sigma = \int_0^\infty P(x)\,[C_o e^{\gamma t} e^{-rt} + \{v_{to} e^{\nu t} + v_t e^{\mu t} \overline{L}_o e^{\lambda t}\} P_o e^{\pi t} e^{-rt}]\, dt \qquad (12.4)$$

where

r = long-term level of interest (discount rate).

The following constraints apply:

$r > \gamma$
$r > \nu + \pi$
$r > \mu + \lambda + \pi$

From Equation (12.4) follows

$$\Sigma = P(x) \left[\frac{C_o}{r - \gamma} + \frac{v_{to}^{o} P_o}{r - \nu - \pi} + \frac{v_t^{o} \overline{L}_o P_o}{r - \mu - \lambda - \pi} \right] \qquad (12.5)$$

Total damage defined as the costs of dike raising K plus the damage to life and capital Σ is thus equal to:

$$Z = \Sigma + K = P(x) \left[\frac{C_o}{r - \gamma} + \frac{v_{to}^{o} P_o}{r - \nu - \pi} + \frac{v_t^{o} \overline{L}_o P_o}{r - \mu - \lambda - \pi} \right] + K_o + klx - klx_o \qquad (12.6)$$

where

$x - x_o = \Delta x$, and
Z = damage plus costs of dike raising.

Z reaches a minimum for

$$\frac{\delta Z}{\Delta x} = 0$$

or

$$P'(x)\,[A] + kl = 0 \qquad (12.7)$$

from which

$$-P'(x) = \frac{kl}{A} \qquad (12.7a)$$

where

$$A = \frac{C_o}{r - \gamma} + \frac{v_{to}^{o} P_o}{r - \nu - \pi} + \frac{v_t^{o} \overline{L}_o P_o}{r - \mu - \lambda - \pi}$$

On the assumption that

$$P(x) = e^{-\alpha(x-\bar{x})} \tag{12.8}$$

where

$P(x)$ = probability of a water level higher than x,
x = water level,
$\bar{x}$ = minimum water level,

so that $P(x) = 1$ for $x = \bar{x}$, in other words, that the chance of a water level above minimum is equal to one, the following equation applies:

$$P'(x) = \frac{dP(x)}{dx} = -\alpha e^{-\alpha(x-\bar{x})} = -\alpha\, P(x) \tag{12.8a}$$

so that Equation (12.7a) becomes

$$\alpha P(x) = \frac{kl}{A}$$

or

$$P(x) = \frac{kl}{\alpha A} \tag{12.9}$$

Substituting

$$P(x) = e^{-\alpha(x-\bar{x})}$$

into Equation (12.9), we find after some processing that:

$$x - \bar{x} = -\frac{1}{\alpha} \ln \frac{kl}{\alpha A} \tag{12.10}$$

where

$$\ln \frac{kl}{\alpha A} < 0$$

$$(\frac{kl}{\alpha A} = \text{excess probability } P(x)).$$

Written out in full, Equation (12.10) reads

$$x = \bar{x} - \frac{1}{\alpha} \ln \frac{kl}{\alpha} \left[\frac{C_o}{r-\gamma} + \frac{v_{to}^{o} P_o}{r-\nu-\pi} + \frac{v_t^{o} \bar{L}_o P_o}{r-\mu-\lambda-\pi} \right]^{-1} \tag{12.11}$$

In the foregoing the assumption was that the flooded land and the capital on it would be brought back into use. If, on the contrary, the land is abandoned, the above remains valid except for the costs of the dike, which does not have to be constructed, and the value of the land lost.

If in the foregoing the value of the means of production is measured as replacement value, the amounts of lost production remain the same, but if the land is abandoned, there should be added the constant value of that part of total production that can be attributed to the land; in principle that is the price of the land.

Equation (12.11) indicates a relationship between the value of human life (and a life year) and the level of the dike. The inverse interpretation, namely, establishing the level of the dike (for instance on the basis of a flooding chance of 10^{-5}), implies the valuation in money terms of a human life (or a life year), for at given values of the (measurable) variables and coefficients in Equation (12.11) the value implicitly attributed to a human life can be calculated.