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Horst Sterr, Richard Klein and
Stefan Reese

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Corso Magenta, 63, 20123 Milano, tel. +39/02/52036934 – fax +39/02/52036946

E-mail: letter@feem.it
C.F. 97080600154

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(Why) Are Vulnerability Assessments Needed?

Human population is attracted to coastal zones to a greater extent than to other regions. Urbanisation and the rapid growth of coastal cities have therefore been a dominant population trend over the last decades, leading to the development of numerous megacities in all coastal regions around the world. At least 200 million people were estimated to live in the coastal floodplain in 1990 (in the area inundated by a 1 in 1000 year flood) and it is likely that their number increases to 600 million by the year 2100 (Nicholls and Mimura, 1998). Collectively, this is both placing growing demands on coastal resources as well as increasing people's exposure to coastal hazards. In historic times, but even more pronounced in recent years, coastal populations around the world have suffered from serious disasters caused by storm floods and related wave and wind attack and precipitation. A dramatic example could be seen in the coastal region of eastern India (State of Orissa), where a tropical storm in October 1999 caused thousands of deaths and displacement and impoverishment of millions of residents in a large coastal area.

Global climate change and the threat of accelerated sea-level rise exacerbate the already existing high risks of storm surges, severe waves and tsunamis. Climate change may not only enhance the most threatening extreme events (*e.g.*, through increasing storminess) but also aggravate long-term biogeophysical effects, such as sea-level rise, shoreline erosion, sediment deficits, saltwater intrusion into coastal aquifers and the loss of coastal wetlands.

Unlike many other anticipated consequences of climate change, global sea-level rise is already taking place. Over the last 100 years, global sea level rose by 1.0-2.5 mm/year. Present estimates of future sea-level rise induced by climate change, as presented in the IPCC Second Assessment Report and shown in Figure 1, range from 20 to 86 cm for the year 2100, with a best estimate of 49 cm (including the cooling effect of aerosols). Moreover, model projections show that sea level will continue to rise (although at a slower rate) beyond the year 2100, owing to lags in climate response, even with assumed immediate stabilisation of greenhouse-gas emissions.

[FIGURE 1]

In light of these existing hazards and increasing risks in coastal regions, there is a great need to gain as much insight as possible into the exact nature and extent of possible risk increases related to future climate trends. Thus, it is essential to carry out analyses of the coastal systems' biogeophysical responses to climate-change impacts as well as to assess the threats posed to human society. As Klein and Nicholls (1998) have stated, vulnerability to impacts is a multi-dimensional concept, encompassing biogeophysical, economic, institutional and socio-cultural factors.Vulnerability of coastal zones has been defined as „the degree of incapability to cope with the consequences of climate change and accelerated sea-level rise" (Bijlsma *et al.*, 1996). Thus, vulnerability assessment includes the assessment of both anticipated impacts and available adaptation options.

Knowledge of vulnerability enables coastal scientists and policy-makers to anticipate impacts that could emerge as a result of sea-level rise. It can thus help to prioritise management efforts that need to be undertaken to minimise risks or to mitigate possible consequences. In view of the high natural and socio-economic values that might be threatened and/or lost in coastal zones, it is therefore important to identify the types and magnitude of problems that different coastal areas may have to face, as well as identify possible solutions. In some cases, assistance may be needed to overcome these problems. Socio-economic data are of great importance for estimating the possible costs and benefits of possible adaptation strategies, such as protection, retreat or accommodation. Experience shows that these response options are best imbedded into the process of integrated coastal zone management (ICZM) but that developing an ICZM framework is usually a longer-term rather than a short-term issue in most coastal regions (WCC'93, 1994).

A Spatial Perspective on the Vulnerability of Coasts

Since 1990, a number of major efforts have been made to develop guidelines and methodologies to assess coastal vulnerability to sea-level rise. When assessing impacts of sea-level rise, it is the local change (or rate of change) in relative sea level that matters, not the global or regional average. Relative—or observed—sea level is the level of the sea relative to the land. While it is affected by absolute changes in sea level, relative sea level is also influenced by vertical movements of the land, which may be of regional or only local extent. These vertical movements are mostly natural phenomena, but human activities may be important as well. First, extraction of water and hydrocarbon can induce or enhance subsidence of coastal lowlands. In specific regions, this subsidence can equal or exceed the above-mentioned projected global sea-level rise. Often-quoted examples of cities that have subsided as a result of groundwater exploitation include Venice (Italy), Bangkok (Thailand), Shanghai (China) and Tokyo (Japan). Second, removal or reduction of sediment supplies in deltas makes natural subsidence more apparent, as it inhibits compensating accretion. Third, in reclaimed coastal lowlands, oxidation and compaction of peat can lead to considerable declines in land level which can equal or exceed the above-mentioned projected global sea-level rise (Klein and Nicholls, 1999).

Irrespective of the primary causes of sea-level rise (climate change, natural or human-induced subsidence, dynamic ocean effects), natural coastal systems can be affected in a variety of ways. From a societal perspective, the six most important biogeophysical effects are:

1. increasing flood-frequency probabilities and enhancement of extreme flood-level risks;
2. erosion and sediment deficits;
3. gradual inundation of low-lying areas and wetlands;
4. rising water tables;
5. saltwater intrusion;
6. biological effects.

It is clear that these effects would usually not occur in isolation. Along tropical coastlines such as in Senegal, for example, sea-level rise causes accelerated offshore transport of fine sediments (*i.e.*, erosion), leading to destabilisation of mangroves and, subsequently, to enhanced flood risks and rising water tables (Nicholls et al.1995).

Past VA Exercises: The Benefits and Drawbacks of the Common Methodology

In 1992, the former Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change (IPCC) proposed a Common Methodology for Assessing the Vulnerability of Coastal Areas to Sea-Level Rise. The Common Methodology was drafted to assist countries in making first-order assessments of potential coastal impacts of and adaptations to sea-level rise. The Common Methodology and similar approaches have been applied in about 25 national assessments and one global assessment. These studies have served as preparatory assessments, identifying priority regions and priority sectors and providing a first screening of possible measures. They stimulated a methodological debate on the estimation of climate change impacts in coastal areas, but also the development of alternative approaches.

In addition to the Common Methodology, the generic IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations have been developed (Carter *et al.*, 1994) and then elaborated into a form appropriate for coastal regions (Klein and Nicholls, 1998). Both the Common Methodology and the Technical Guidelines comprise seven consecutive analytical steps for vulnerability assessment. However, they are not identical. In Figure 2, the Common Methodology and the Technical Guidelines are compared.

[FIGURE 2]

The difference between the two approaches in large part reflects the fact that the Common Methodology was developed specifically for application in coastal zones, whereas the Technical Guidelines have been designed to serve as a more generic framework for any natural or socio-economic system. Therefore, some of the steps outlined in the Technical Guidelines do not appear in the Common Methodology. For example, the definition of the problem and the selection of the method are steps 1 and 2 of the Technical Guidelines, while they are only implied in the Common Methodology. Testing the method is also not included as an explicit step in the Common Methodology, although the wide application of the Common Methodology and other similar approaches has allowed for extensive evaluation (*e.g.*, WCC`93, 1994). Further, the assessment of autonomous adjustments is considered explicitly in the Technical Guidelines, but not in the Common Methodology. The final step of the Technical Guidelines, the evaluation of adaptation strategies, is again made up of seven consecutive steps, which approximate steps 5, 6 and 7 of the Common Methodology.

In spite of these differences, it is important to realise that no other methodology to assess coastal vulnerability has been applied as widely and evaluated as thoroughly as the Common Methodology. The Common Methodology has contributed to understanding the consequences of sea-level rise and encouraged long-term thinking about coastal zones. The results of comparative national vulnerability studies according to the Common Methodology show considerable variation in the degree of impacts from country to country, reflecting that certain settings are more vulnerable than other ones. Small islands, deltaic settings and coastal ecosystems appear particularly vulnerable (Bijlsma *et al.*, 1996).

With respect to the social and economical implications of sea-level rise and the issue of adaptation, a set of six vulnerability indicators has been outlined and applied in the Common Methodology. These are:

1. people affected;
2. people at risk;
3. capital value loss;
4. land area loss;
5. protection / adaptation costs;
6. wetland loss.

The indicators are used to establish national or regional vulnerability profiles, using the information of Table 1 for (semi-) quantification. In Europe, the countries that have carried out comprehensive assessments according to the Common Methodology are The Netherlands, Poland and Germany (Nicholls and Mimura, 1998).

[TABLE 1]

The available results all emphasise the large potential impacts of sea-level rise on coastal societies, economics and ecology in Europe, where large concentrations of population and economic infrastructure exist in coastal areas. Local studies (*e.g.*, Turner *et al.*, 1995; Nicholls and Leatherman, 1995; Hamann and Hofstede, 1998) further support the conclusion that sea-level rise alone, notwithstanding other climate-related impacts, should be of great concern to national and regional governments. In all three European countries, the socio-economic impact potential is rather high, yet in terms of adaptation costs, Poland appears to be more vulnerable than The Netherlands and Germany (Table 2; Nicholls and Mimura, 1998).

[TABLE 2]

In spite of the obtained valuable results, a number of problems have been identified with the Common Methodology (Klein and Nicholls, 1998). These problems can be summarised as follows

- Many case studies that have used the Common Methodology have faced a shortage of the accurate and complete data necessary for impact and adaptation assessment. In particular, it has often been difficult to determine accurately the impact zone in many countries owing to the lack of basic data, such as the coastal topography.
- Many studies have been directed towards a single global scenario of sea-level rise (1 metre by 2100), often owing to a lack of more detailed data on coastal elevations, while most studies have ignored the spatial distribution of relative sea-level rise and other coastal implications of climate change, owing largely to a lack of regional climate scenarios.
- Although the Common Methodology encourages researchers to take into account the biogeophysical response of the coastal system to sea-level rise, lack of data and models for describing the complicated non-linear coastal processes have hindered detailed quantitative impact assessment. Many case studies have carried out a simple linear, first-order assessment by shifting the coastline landward by an amount corresponding with the sea-level rise scenario.
- As to adaptation, the Common Methodology has been less effective in assessing the wide range of technical, institutional, economic and cultural elements present in different localities. There has been concern that the methodology stresses a protection-orientated response, rather than consideration of the full range of adaptation options.
- Market-evaluation assessment frameworks, as applied in the Common Methodology, have proved inappropriate in many subsistence economies and traditional land-tenure systems.

Unfortunately, these problems are quite fundamental for any approach to vulnerability assessment and cannot be solved overnight. Therefore, both the Common Methodology and the Technical Guidelines only represent a step in an ongoing process, rather than an endpoint. In the immediate future, a more comprehensive effort needs to be made to develop tools and techniques that more readily meet the requirements of vulnerability assessment in an environment as dynamic as the coastal zone. In particular, more attention has to be devoted both to the hazardous effects of changing frequencies, intensities and areal occurrences of extreme weather events and to the consideration of „residual“ risks reflecting existing adaptation policies.

A Conceptual Framework for Vulnerability Assessment and the Role of Adaptation

The potential socio-economic impacts of sea-level rise can be categorised as follows:

- direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructure and coastal habitats;
- increased flood risk of people, land and infrastructure and the above-mentioned values;
- other impacts related to changes in water management, salinity and biological activity.

Owing to the great diversity of natural coastal systems and to the local and regional differences in relative sea-level rise and other climatic changes, the occurrence of and response to these impacts will not be uniform around the globe. Vulnerability studies first need to analyse the extent to which the above biogeophysical effects will occur in the natural system of a study area before the potential socio-economic impacts can be assessed. Table 3 lists the most important socio-economic sectors in coastal zones, and indicates from which biogeophysical effects they are expected to suffer direct socio-economic impacts. Indirect impacts (*e.g.*, human-health impacts resulting from deteriorating water quality) are also likely to be important to many sectors, but these are not shown in the table.

[TABLE 3]

One can distinguish between natural-system vulnerability and socio-economic vulnerability to climate change, although they are clearly related and interdependent. Figure 3 shows a conceptual framework for coastal vulnerability assessment that makes this distinction explicit. This framework helps to define the various concepts involved in vulnerability assessment and shows how these are related (Klein and Nicholls, 1999).

[FIGURE 3]

As shown in Figure 3, proper analysis of socio-economic vulnerability to sea-level rise requires prior understanding of how the natural system would be affected. Hence, analysis of coastal vulnerability always starts with some notion of the natural system's *susceptibility* to the biogeophysical effects of sea-level rise, and of its natural capacity to cope with these effects (*resilience* and *resistance*). Susceptibility simply reflects the coastal system's potential to be affected by sea-level rise (*e.g.* a subsiding delta versus an emerging fjord coast), while resilience and resistance determine the system's stability in the face of possible perturbation. As applied in ecology, resilience describes the speed with which a system returns to its original state after being perturbed, while resistance describes the ability of the system to avoid perturbation in the first place. Susceptibility, resilience and resistance together determine the coastal system's *natural vulnerability* to biogeophysical effects of sea-level rise. Resilience and resistance are functions of the natural system's capacity for *autonomous adaptation*, which represents the coastal system's natural adaptive response to sea-level rise. As opposed to susceptibility, which is largely independent of human influences, resilience and resistance are often affected by human activities. The effect of human activities need not only be negative: *planned adaptation* can serve to reduce natural vulnerability by enhancing the system's resilience and resistance and thereby adding to the effectiveness of autonomous adaptation (Klein and Nicholls, 1999).

The biogeophysical effects of sea-level rise give rise to a range of potential socio-economic impacts. This *impact potential* is the socio-economic equivalent of the natural system's susceptibility (see above), although now it clearly is dependent on human influences. In parallel with a coastal zone's natural vulnerability, which is a function of susceptibility and resilience/resistance, *socio-economic vulnerability* is determined by the impact potential and society's technical, institutional, economic and cultural *ability to prevent or cope* with these impacts (*i.e.*, its capacity to adapt within the time-scale of natural changes). As with the natural system's resilience and resistance, the potential for *autonomous adaptation* and *planned adaptation* determines the social system's ability to prevent or cope.

Finally, it is important to acknowledge the dynamic interaction that takes place between natural and socio-economic systems. Instead of being considered as two separate systems that exist independently of each other, natural and socio-economic systems are increasingly viewed as developing in a co-evolutionary way. This co-evolution is shown in Figure 3 by the feedback loop from the socio-economic system to the natural system.

Information Gains from Vulnerability Assessments and the Issue of Scale

The assessment of coastal vulnerability to climate-related impacts is a basic prerequisite for obtaining an understanding of the risks of climate change to the natural and the socio-economic coastal system. At the global level, vulnerability assessment can serve to underpin the overall significance of sea-level rise for coastal societies and allows to compare the regional variations of sea-level rise-related risks (Hoozemans *et al.*, 1993; Nicholls and Mimura, 1998). At this scale, vulnerability assessment demonstrates that anticipated impacts might exceed the coping ability of some coastal regions and nations. At the national and local level, vulnerability assessments are needed to identify the specifically vulnerable areas and sectors and reflect on the status of adaptation strategies designed to cope with adverse impacts such as flooding and erosion.

It becomes clear that first-order assessments carried out on a global level will not be sufficient to achieve all of these objectives. Instead, descriptions and analyses are needed to describe in greater detail the conditions that lead to site- or area-specific exposures to risks of inundation, erosion or saltwater intrusion. Only on the basis of detailed and comprehensive information will it be possible for national and local policy makers to design the most appropriate response strategies, that is, to decide whether and which protection, accommodation or retreat options are most suitable for minimising risks while optimising future coastal resource use. This is why in Germany, where adaptive policies are the responsibility of state governments, it has been decided to elaborate on an initial (first-order) national vulnerability assessment and refine the information base by means of a downscaling analytical procedure. Decisions on flood defence schemes at a state level can now draw on specific topographic and economic data obtained from meso-scale studies. Furthermore, for particularly vulnerable coastal sections, even more detailed (micro-scale) databases are being put together, allowing for the informed evaluation of adaptation options.

Practical experiences in Vulnerability Assessment: Methods, Data and Time

In spite of the considerable interest in assessing coastal vulnerability to climate change, efforts are often hindered by the limited availability of data and resources for assessment. Sometimes there has also been a mismatch between the available data, the level of effort and the sophistication of the models utilised in vulnerability assessments. In some cases, this has led to inappropriate expectations concerning the outcomes of the assessment studies. To help to structure the approach, to optimise the level of effort, and to make the likely outcome of studies more explicit, it is useful to consider three levels of increasingly complex assessment (Table 4):

- screening assessment (SA);
- vulnerability assessment (VA);
- planning assessment (PA).

[TABLE 4]

As its name implies, SA is a screening approach, which—by its quick nature—focuses on one aspect of vulnerability: susceptibility. VA is a more comprehensive analysis, including explicit assessment of biogeophysical effects, socio-economic impacts and adaptation. PA involves analysis at an integrated level suitable for detailed coastal planning and would take place in the wider context of coastal management. This three-level approach relates to the issue of scale, as discussed in the section above, in that more specific (policy-relevant) results will be obtained by a downscaling procedure, as also known from climate modelling (*e.g.*, Warrick *et al.*, 1996).

Analysis in the framework of a country study should start with SA. The results of the SA can then be used to plan how VA might be most effectively implemented. VA will provide broad concepts and ideas concerning impacts and possible adaptation. PA might be viewed as the link between VA and detailed coastal planning and management (see below). PA asks more precise questions and hence, the recommendations concerning possible adaptation measures would be more precise.

The remainder of this section presents a summary overview of important steps of coastal vulnerability assessment and of methods and tools that are available to complete these steps, as presented by Klein and Nicholls (1998, 1999).

Delineation of the study area

The study area, at a minimum, needs to be defined so that it at least encompasses the areas that might be physically affected by sea-level rise. It is advisable not to delineate the area too narrowly so as to account for the broad range of uncertainty that is involved in vulnerability assessment. The Common Methodology suggests consideration of all the land area below the contour line that corresponds with the height of a once-every-1,000 years storm surge, given projected sea-level rise by the year 2100. In addition, the study area should consider saltwater intrusion and increased river flooding. In deltaic and estuarine areas, sea-level rise could cause these effects to extend tens of kilometres inland.

In the absence of the required data or other clear criteria to delineate the study area, it is recommended to use the contour line 2 metres above extreme high tide as the landward demarcation, unless the physiography or socio-economic structure of the area suggests that this arbitrary boundary will not suffice. This would be the case when impacts may also be expected to occur further inland (*e.g.*, because of saltwater intrusion, extreme storm surges or increased river flooding) or, conversely, only much closer to the coast. The seaward extension of the study area should be based on the area that is likely to be subject to biogeophysical effects of sea-level rise, such as coral reefs, intertidal areas and wetlands, but may also include coastal waters containing valuable living resources.

Scenarios for vulnerability assessment

Scenarios for vulnerability assessment reflect plausible future conditions of all environmental and socio-economic parameters of interest. Some parameters can be considered universally important, while other ones are more site-specific. Relevant parameters have two degrees of freedom: environmental or socio-economic, and climate-induced and not climate-induced. This defines the matrix that is shown in Table 5.

[TABLE 5]

Coastal vulnerability studies have focused primarily on scenarios of climate-induced changes in the environmental conditions—especially sea level—of a study area (*i.e.*, the upper left-hand box of Table 5). The lower part of Table 5 represents changes that will occur independently of climate change. As such, they form a reference case of what could be the environmental and socio-economic conditions in the absence of climate change. Scenarios of environmental and socio-economic developments not induced by climate change are increasingly being used in combination with climate scenarios. However, the fact that climate change will trigger socio-economic developments that in turn affect the manifestation of coastal impacts, is as yet often ignored (*i.e.*, the upper right-hand box of Table 5). These developments embrace autonomous and planned adaptation. The potential for adaptation and the dynamic effects of its implementation need to be considered as an integral part of vulnerability assessment, for example by linking impact and adaptation scenarios.

For some coastal areas it could be worthwhile also to consider climatic changes other than sea-level rise (Bijlsma *et al.*, 1996). In mid- to high-latitude regions, a decrease in the return period of extreme rainfall events appears likely. This will be especially relevant for low-lying coastal areas prone to flooding. For cold-temperate seas like the Baltic Sea but also for coral reefs and atolls, increasing seawater temperature could be important as this could affect the period of sea ice coverage and the coral growth potential, respectively. Reductions in sea ice and coral growth could reduce the coasts' ability to keep withstand wave impacts and erosion processes.

Other climatic changes that could have significant consequences for coastal zones, such as changes in wind direction and intensity, remain highly uncertain. The construction of plausible scenarios using the output of general circulation models is as yet impossible. However, sensitivity analyses using trend analysis (*e.g.*, Zeidler *et al.*, 1997) or arbitrary scenarios (*e.g.*, Peerbolte *et al.*, 1991) could be helpful in providing insight into the possible consequences.

Irrespective of the need to consider multiple scenarios, relative sea-level change remains the most important variable for coastal vulnerability assessment. As relative sea-level rise is the sum of global sea-level rise, regional oceanic effects and vertical land movements, it follows that scenarios for relative sea-level rise can be expressed as:

$$S_{r,t} = S_{g,t} + S_{o,t} + V \cdot t$$

where: $S_{r,t}$ = relative sea-level rise in year t (m);

$S_{g,t}$ = global sea-level rise in year t (m);
$S_{o,t}$ = regional sea-level change induced by oceanic changes in year t (m);
V = vertical land movement (m/year);
t = number of years in the future (base year 1990).

Given the uncertainties surrounding $S_{g,t}$, it is important that scenarios are selected such that they encompass the likely change (see Figure 1). Therefore, a maximum scenario in which $S_{g,t}$ equals 1 metre in 2100 is quite appropriate for a screening approach. Not much information is usually available on the value of $S_{o,t}$, in which case this parameter should be neglected. Values for V can be assessed from a number of different sources, including geological analysis, geodetic surveys and the analysis of long-term tide-gauge records. Note that the equation above assumes that (*i*) vertical land movement is responsible for all the deviation of relative sea-level rise from global sea-level rise, and (*ii*) vertical land movement is linear and will continue unchanged in the future. However, in areas subject to human-induced subsidence, future vertical land movements may be uncertain, as they will depend on human action, necessitating scenarios for subsidence.

Data collection

The fundamental starting point for any assessment study is the acquisition of basic data on a number of important parameters that characterise the study area. Relevant characteristics of the natural coastal system include the following:

- coastal geomorphology/topography;
- relative sea-level changes;
- trends in sediment supply and erosion/accretion patterns;
- hydrological and meteorological characteristics;
- meteo-oceanographic characteristics;
- ecosystem characteristics.

Additionally, it is necessary to collect data on the important socio-economic characteristics of the study area. These include:

- demographic developments;
- trends in resource use and economic development;
- land use and ownership;
- infrastructural and other economic assets;
- cultural assets; and,
- institutional arrangements.

First, it is essential to review critically any available material (maps, aerial photographs, satellite images) and previous studies that may have yielded results or contain background information relevant to vulnerability assessment. Various national and international organisations have developed sites on the World Wide Web that contain coastal bibliographies, databases and tools as well as numerous links to other relevant information and organisations on the Internet.

Assessment of biogeophysical effects

For five of the six coastal biogeophysical effects of sea-level rise identified above, assessment methods are presented. Each method is described in some detail, but given the scope of this paper, it is impossible to present all the peculiarities involved.

Increasing flood-frequency probabilities
One of the first consequences of a rise in sea level on low-lying coastal zones is an increased flood risk associated with storm surges and extreme precipitation and runoff events. The degree to which coastal land is at risk of flooding from storm surges is determined by a number of morphological and

meteorological factors, including coastal slope and wind and wave characteristics. Together these factors determine a coastal zone's flood-frequency probability curve (also referred to as flood-exceedance curve). The information provided by flood-frequency probability curves can be used to plot design water levels on a topographical map. Design water levels are contour lines that indicate with which probability a particular area could be flooded.

Hoozemans *et al.* (1993) defined the risk zone as the land area between the coastline and the „maximum" design water level, which is defined as a flood-frequency probability of once per 1,000 years, taking into account global sea-level rise and regional and local aspects such as subsidence, tidal range and storm characteristics (wind and wave set-up and minimum barometric pressure). Hence, the delineation of the risk zone requires the calculation of the maximum design water level.

Erosion and inundation
Sea-level rise can activate two important mechanisms that result in the loss of land: erosion and inundation. Erosion represents the physical removal of sediment by wave and current action, while inundation is the permanent submergence of low-lying land. The primary mechanism at any location depends on the geomorphology of the coast. Many other factors than sea-level rise can play a part in determining land loss (*e.g.*, vegetation, sediment supply), yet at the intended level of analysis it is justified not to consider them. More sophisticated analyses would require considerably more data on the coastal sediment budget, and the development of more site-specific models. Such analyses are therefore likely to face severe time and funding constraints in many coastal areas.

Sea-level rise contributes to the erosion of erodible cliffs, coral-reef islands and gravelly, sandy and muddy coasts by promoting the offshore transport of sedimentary material. The best known and most widely applied model to estimate erosion has been developed by Bruun (1962) for application on straight sandy shores. In other erodible coastal environments, alternative erosion models have to be used, which, however, are often based on the Bruun rule.

Low-lying coastal areas such as deltas, coastal wetlands and coral atolls may face inundation as a result of sea-level rise. Land loss resulting from inundation is simply a function of slope: the lower the slope, the greater the land loss. In addition, the survival of coastal wetlands is dependent upon sediment availability and/or local biomass production, as well as the potential for these ecosystems to migrate inland. Flood embankments can inhibit this natural adaptation of wetlands to sea-level rise. Healthy, unobstructed wetlands in settings with continuing sedimentation are expected to be able to cope with projected global sea-level rise, although ecosystem characteristics may change.

Rising water tables
Sea-level rise could be associated with a rise in coastal (ground) water tables. The distance inland that a water table will be affected by sea-level rise depends on a range of factors, including elevation and subsurface permeability. In some locations, particularly deltas, rising water tables can occur as far as several tens of kilometres inland. The need to assess rising water tables depends on the potential for saltwater intrusion in groundwater as well as impacts on foundations, drainage systems and underground services. As these impacts occur almost exclusively in urban areas, this is where attention should be focused.

Saltwater intrusion
As sea level rises, fresh groundwater and surface water could be displaced by saline water, which could have substantial adverse impacts on agriculture and drinking-water supply. To allow for these impacts to be assessed, it is essential to acquire knowledge on the spatial and temporal extent of saltwater intrusion. It is important to note that saltwater intrusion is already occurring in many coastal regions, owing to overexploitation of surface water and groundwater. With growing populations in coastal regions, saltwater intrusion of this cause is expected to occur more widely, and may enhance the rate of saltwater infiltration. Therefore, it is likely that sea-level rise will exacerbate an already adverse situation.

Assessing the extent of saltwater intrusion in groundwater is difficult as it depends on many factors that are locally variable, and often poorly understood. These factors include subsoil characteristics such as porosity and conductivity of the aquifer, hydraulic resistance of the aquitard and hydraulic variables such as groundwater flow and recharge. Also the geo(hydro)logy is important, as this determines whether a freshwater aquifer is confined, semi-confined or unconfined. Note that sea-level rise will not result in saltwater intrusion in confined aquifers. Saltwater intrusion in groundwater can be assessed using analytical methods or mathematical modelling.

Table 6 lists the methods that are available for assessments of biogeophysical effects of sea-level rise and indicates for which level of assessment they can be applied. It also shows the requirements for application—in terms of data, time, skill and resources—and gives an indication of the reliability and validity of results.

[TABLE 6]

Assessment of socio-economic impacts

In addition to the biogeophysical effects discussed above, the socio-economic implications of increased flood risk and potential land loss need to be considered. This will be done using a distinction between three fundamental socio-economic impact categories:

- (human) population;
- marketed goods and services;
- non-marketed goods and services.

For the latter two categories, the techniques considered here are aimed at expressing these impacts in economic terms, recognising that this may be impossible or undesirable for all values at stake. The first category applies a risk-based approach, using the design water levels calculated as suggested in the section above.

Population
Assuming no protection, the (human) population affected by sea-level rise can be divided into two categories: (*i*) population at risk (of flooding), and (*ii*) population to respond. Population to respond comprises people *potentially* displaced by land loss resulting from erosion and inundation.
The population at risk is defined as the number of people experiencing flooding in a typical year (Hoozemans *et al.*, 1993; Baarse, 1995). This number is estimated by multiplying the total number of people living in an area potentially affected by flooding by the probability of flooding in any year, as determined for each risk zone. For example, if 3 million people were exposed to a flood-frequency probability of 1/10 years, the population at risk would be 300,000 people per year (see also Tables 1 and 2).

Marketed goods and services
Assessment of the increased risk or potential loss of marketed goods and services is a somewhat more complicated exercise. In principle, an inventory needs to be made of all economic assets and activities that can be found in the coastal area affected (both now and in the future), as well as a quantitative assessment of the degree to which these assets and activities will be subject to damage as a result of sea-level rise. Sea-level rise may also lead to costs that are not related directly to the economic assets and activities identified (*e.g.*, evacuation). Further, benefits accruing from new opportunities, if any, should also be taken into account. Turner and Adger (1996) have provided specific guidance for the application of economic valuation methods in coastal zones Even more detailed, and originally written for application in the United Kingdom, is the manual by Penning-Rowsell *et al.* (1992).

The most important goods and services that could be at risk of sea-level rise, and which are readily quantifiable in monetary terms include:

- land;

- physical (building) structures;
- agricultural and industrial productivity.

Either these values can be irreversibly lost as a result of erosion or inundation, or they can be exposed to a higher risk of flooding, which can cause temporal losses. Also, rising water tables may result in increased likelihood of foundation failure, existing drainage services may be made obsolete and underground services in urban areas would be impacted.

If the risk zone's contribution to a country's gross national product (GNP), is known, the GNP at risk from sea-level rise can be estimated. An approach utilised by Turner *et al.* (1995) to assess GNP at risk assumes an equal annual incremental rise in sea level between 1990 and 2050, of which impacts are a linear function. Since a time horizon of 60 years is used, 1/60th of the total capital value and activity would be at risk after one year, 2/60ths after two years, and so on. In addition to estimating GNP at risk, it is important to assess potential losses in capital assets such as land, property and infrastructure. These are to be valued based on the accelerated depreciation cost of the capital assets, and, particularly in the case of land, their opportunity costs. Once an inventory has been made of the capital value in the risk zone, a similar analysis can be conducted as for population at risk. Thus, capital value at increased risk over time can be assessed.

Alternatively, the timing of the occurrence of losses can be estimated based on relative sea-level rise scenarios. All losses that would occur within the time horizon of interest are summed up to arrive at the total potential loss, which can then be discounted to their net present value. In addition, it could be useful to make a distinction between temporal and permanent losses, using threshold times at which permanent losses occur. Details of this approach can be found in Turner *et al.* (1995).

Non-marketed goods and services
As the term implies, non-marketed goods and services are not traded on markets. Therefore, they cannot be readily expressed in financial terms, because no pricing mechanism exists. This does not suggest, however, that they do not possess economic value. Examples of non-marketed goods and services include recreational values, cultural and subsistence values (*e.g.*, community structures), and natural values (*e.g.*, a wetland's capacity to buffer wave energy and assimilate waste). To date, economic assessment of non-marketed goods and services has been directed primarily at quantifying the value of coastal recreation and indirect-use values such as storm protection and waste assimilation (*e.g.*, Klein and Bateman, 1998). More guidance and references on the valuation of non-marketed coastal goods and services can be found in Turner and Adger (1996).

Working on Three Scale Levels: The German Experience

The issues and questions that have been raised in the previous sections are now briefly considered and discussed in the context of the vulnerability of the German coastal zone. In Germany, assessments have been carried out on three different scale levels. The various information bases and management strategies from the national down to the local level may shed some light on the use of assessment results.

Within the context of applying and testing the IPCC Common Methodology (IPCC CZMS, 1992), a national case study was carried out for the German coastal region. Northern Germany is subdivided into five coastal states (counties), three of which (Lower-Saxony, Hamburg, Bremen) border the North Sea, while one state (Mecklenburg-Vorpommern) borders the Baltic Sea and another (Schleswig-Holstein) shares a coastlines with both Seas. The state (regional) governments are individually responsible for policies on coastal development, protection and management, with the national government playing a subordinate part in most coast-related policies. The case study had primarily the following objectives:

1. to identify the coastal segments that would be exposed to risks from flooding – according to coastal topography - in case of an accelerated sea-level rise (Scenario of +100 cm sea-level rise to the year 2100);
2. to determine the critical flood water levels along the North Sea and Baltic Sea coasts;
3. to approximate the likely socio-economic vulnerability in each of the five coastal states;
4. to delineate sub-regions mostly susceptible to flooding within these states;
5. to assess to what degree coastal protection schemes (dikes, seawalls, dunes, *etc.*) will be insufficient in the case of the assumed scenario;
6. to determine the approximate costs of adjusting the coastal protection schemes so they could withstand a higher sea level;
7. to assess additional vulnerability of the low-lying coastal areas, in particular with respect to local drainage and decreasing wetland stability (Wadden Sea).

The data collected for the national vulnerability study were put together in a GIS database, combining (for the first time) contingent topographic and economic information for the whole coastal region of Germany (Ebenhoeh *et al.*, 1996; map scale 1:200.000). The use and application of GIS for risk assessment and management planning turned out to be as time consuming as valuable (see Textbox 1). From the case study results it soon became clear, however, that the data, aggregated on the basis of statistical information on county level (macro-scale), were not specific and conclusive enough for the regional authorities to consider in detail the existing coastal defence and adaptation schemes. Therefore, it was decided that a more detailed analysis should be done on a meso-scale level for the state of Schleswig-Holstein. This region was chosen for two reasons. First, it comprises all types and elements of vulnerable coastal systems in both the North Sea and the Baltic Sea region. Second, the state authorities were in the process of revising and adjusting the coastal defence master plan for the next 30 year period and were thus particularly interested in taking results from a specific vulnerability assessment for the state into consideration.

[TEXTBOX 1]

In the lower-scale study for Schleswig-Holstein (map scale 1:25.000) it could be shown that not the whole area up to the +5 metres contour line (which was the inward boundary at the macro scale) would actually be at risk of sea-level rise. Instead, local topographic features such as second dike lines or road dams were used to delineate the vulnerable areas more precisely. On the other hand, there are a number of elements in terms of socio-economic values at risk, such as technical, tourist and traffic infrastructure, which are relevant for risk assessment but could not be included in the overview study. Moreover, the detailed information on the prevailing adaptation to storm flood hazards, in particular on the existing dikes, needed to be considered in greater detail in order to realistically describe the present and future exposures of coastal segments to flooding risks. Technically, the previously established coastal GIS needed to be refined and specified to meet the requirements of policy-addressed conclusions from the state-wide vulnerability assessment (Hamann and Hofstede, 1998; see Figure 5).

[FIGURE 5]

The major benefit of the meso-scale analysis was to show to which extent coastal protection and accommodation strategies may be necessary when considering sea-level rise and storm flood scenarios on a regional scale. With respect to the assessment of economic and ecological vulnerability as well as possible options for improvement of adaptation, there were still shortcomings observed in the meso-scale results. A lesson learnt from recent studies by Yohe *et al.* (1998) and West and Dowlatabati (1999), who studied sea-level rise impacts on developed coasts in the United States on a community scale, it is not sufficient to look only at the incremental depreciation of existing values and the benefits of gradual adaptation processes. Instead, the local effects of all impacts, including extreme storm events, have to be taken into account and balanced against the incremental adjustments likely to occur in coastal communities.

When considering the German conditions, it is essential to know that a range of adaptation measures falls within the communities' responsibility, while other measures would be the responsibility of the state government (according to the master plan). Therefore, decisions of how to respond to a given threat, for example by building a seawall or enhancing beach nourishment activities, must be based on community-based assessments of flooding or erosion risks. Similarly, it is only at this micro-scale level that the coastal population can make decisions on the possible benefits of flood insurance or on site-specific economic investments. The complex interrelations between results from local risk assessment and economic as well as policy-oriented decisions are demonstrated in an ongoing case study for the German island of Sylt, the major tourist attraction along the North Sea coast of the state of Schleswig-Holstein. In Sylt, risks of sea-level rise are estimated to be rather high, but trust in local adaptation schemes has still led to ongoing tourist development. From a scientific point of view, the case of Sylt appears to be a critical issue where local private judgements towards adjustment to sea-level rise are not in line with those of the public and policy makers.

General Conclusions and Further Work on Vulnerability and Adaptation

To identify the most appropriate coastal-adaptation strategy, one must consider the full context in which impacts of climate change arise, and realise that the three dominant strategies—protect, retreat, accommodate—happen within a broader policy process. Within this process, increasing resilience by reversing maladaptive trends could be an important option to reduce coastal vulnerability to climate variability and change. This approach will often address more than climate issues alone and generally involve a change in adaptation strategy, for example, nourishing beaches instead of constructing seawalls, or introducing a building setback instead of allowing construction next to the coast (Table 7).

[TABLE 7]

Data collection and information development are essential prerequisites for vulnerability assessment as well as for coastal adaptation. The more relevant, accurate and up-to-date the data and information available, the more targeted and effective adaptation can be. Coastal adaptation requires data and information on coastal characteristics and dynamics, patterns of human behaviour, as well as an understanding of the potential consequences of climate change. It is also essential that there is a general awareness amongst the public and coastal planners and managers of these consequences and of the possible need to act (Table 8). In countries where the central government has neither the means nor the expertise to address problems in every part of the coast, the information is used most effectively when targeted at the most influential people in the community.

[TABLE 8]

FIGURE 1
Projected sea-level rise for the period 1990-2100, using scenario IS92a („Business-as-Usual“).

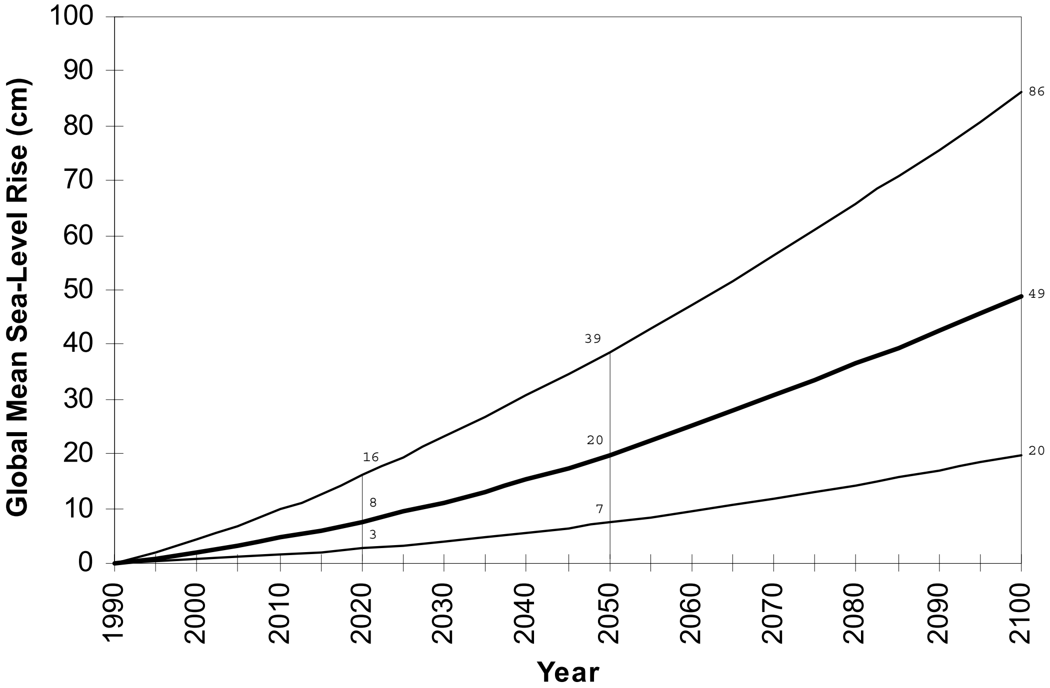

FIGURE 2
The IPCC Common Methodology compared with the IPCC Technical Guidelines.

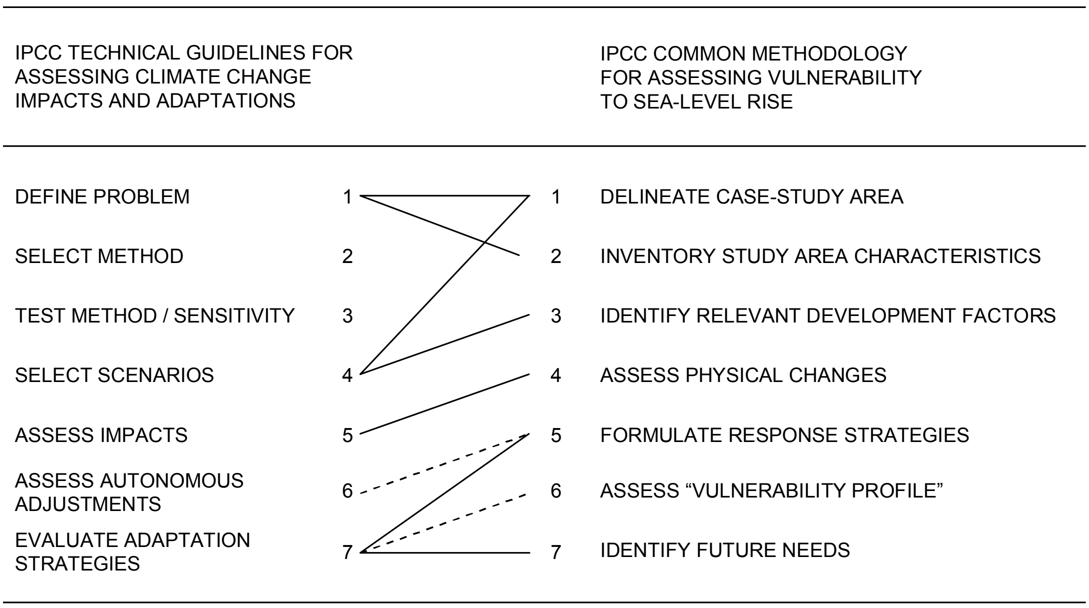

FIGURE 3
A conceptual framework for coastal vulnerability assessment.

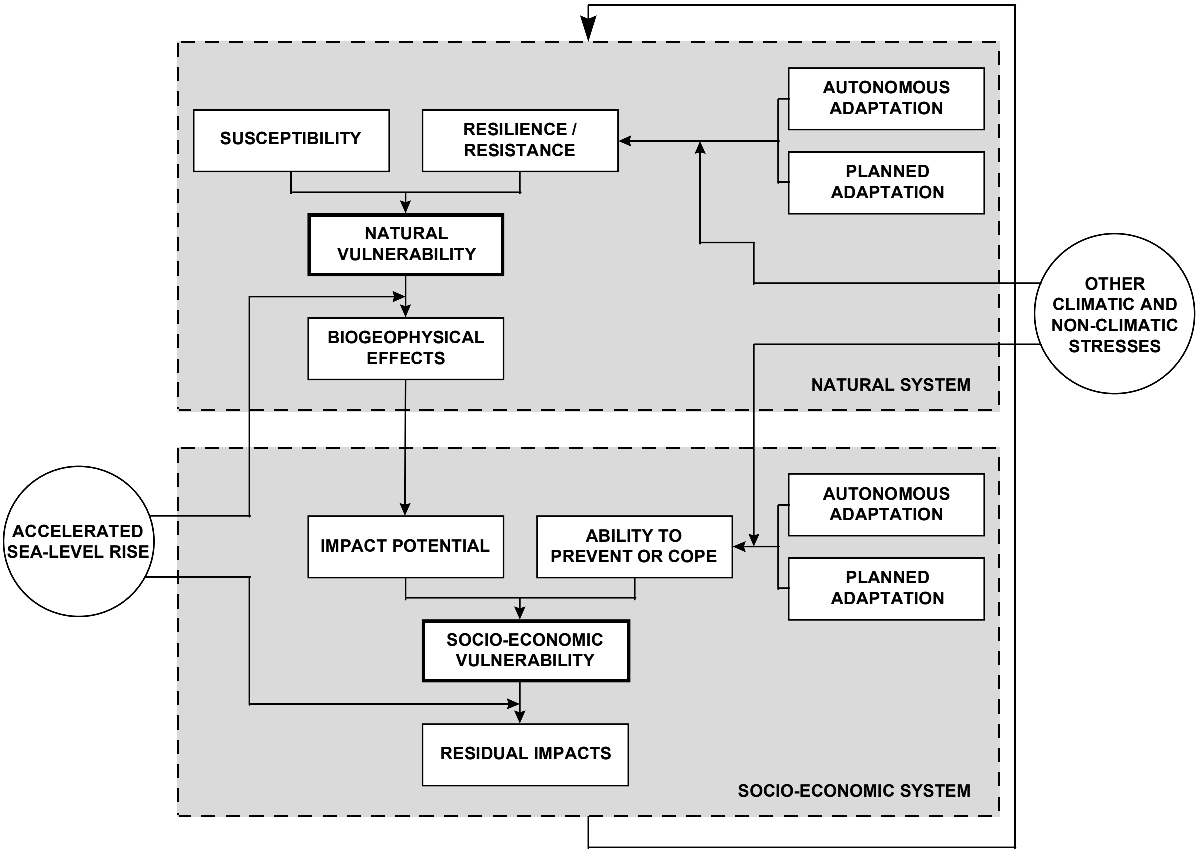

FIGURE 4
Flow diagram to determine the appropriate method to determine land at risk from erosion or inundation. Wetlands embrace marshes, mangroves and coral atolls/keys.

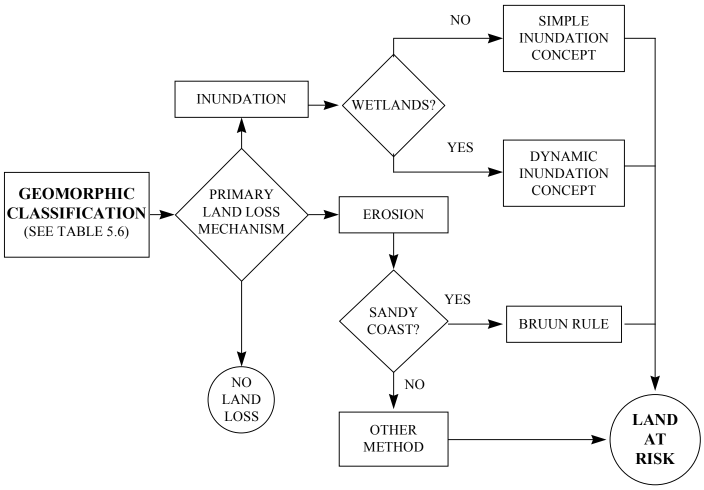

FIGURE 5
Data sources and step-wise GIS procedure in the meso-scale vulnerability study of the State of Schleswig-Holstein.

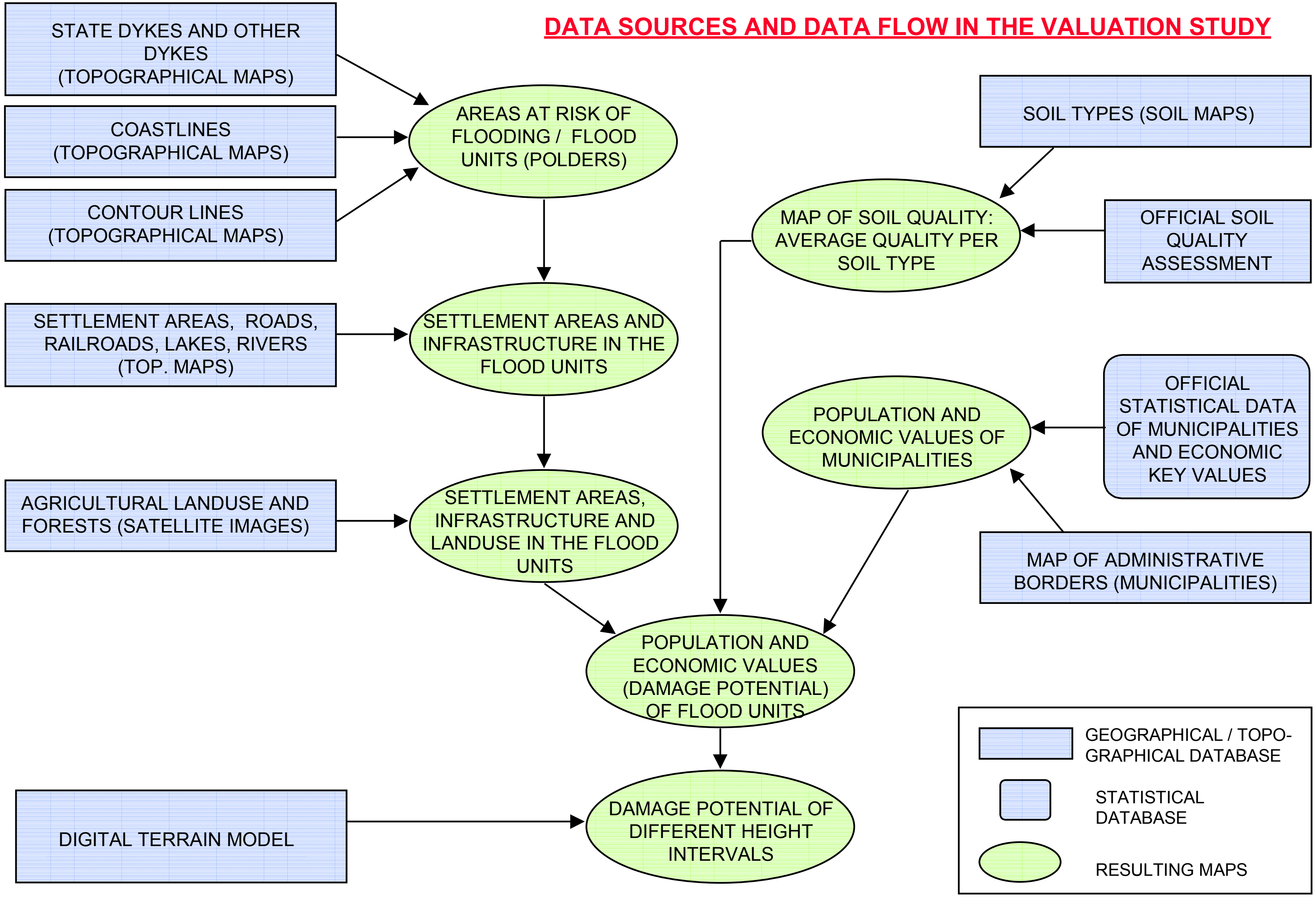

TABLE 1
Vulnerability classes developed and used in the Common Methodology.

Impact categories	Vulnerability classes			
	Low	Medium	High	Critical
People affected (no. of people/total population) x 100%	<1%	1-10%	10-50%	>50%
People at risk Σ (no. of people x flood probability) / 1000	<10	10-100	100-500	>500
Capital value loss (total loss/1990 GNP) x 100%	<1%	1-3%	3-10%	>10%
Land loss (area loss/total area) x 100%	<3%	3-10%	10-30%	>30%
Protection/adaptation costs (annual cost/1990 GNP) x 100%	<0.05%	0.05-0.25%	0.25-1%	>1%
Wetland loss (area loss/total area) x 100%	<3%	3-10%	10-30%	>30%

TABLE 2
Results from impact assessments using the IPCC Common Methodology, carried out for the coastal regions of The Netherlands, Germany and Poland.

Country	SLR scenario	People affected		People at risk		Capital value loss		Land loss		Wetland loss	Adaptation/ protection costs	
	(m)	No. of people (1000s)	% total	No. of people (1000s)	% total	Million US$	% GNP	(km^2)	% total	(km^2)	Million US$	% GNP
The Netherlands	1.0	10000	67	3600	24	186000	69	2165	6.7	642	12300	5.5
Germany	1.0	3200	3.9	309	0.3	7500	0.05	13900	3.9	2000	23500	2.2
Poland	0.1	N/A	N/A	25 (18)	0.1 (0.05)	1800	2	N/A	N/A	N/A	700+4	2.1+0.01
	0.3	N/A	N/A	58 (41)	0.1 (0.1)	4700	5	845	0.25	N/A	1800+8	5.4+0.02
	1.0	235	0.6	196(146)	0.5 (0.4)	22000	24	1700	0.5	N/A	4800+400	14.5+1.2

TABLE 3
Qualitative synthesis of *direct* socio-economic impacts of climate change and sea-level rise on a number of sectors in coastal zones.

Sector	Biogeophysical Effect					
	Flood Frequency	*Erosion*	*Inundation*	*Rising Water Tables*	*Saltwater Intrusion*	*Biological Effects*
Water Resources			✓	✓	✓	✓
Agriculture	✓		✓	✓	✓	
Human Health	✓		✓			✓
Fisheries	✓	✓	✓		✓	✓
Tourism	✓	✓	✓			✓
Human Settlements	✓	✓	✓	✓		

TABLE 4
Examples of the four different types of scenarios that can be used in coastal vulnerability assessment.

	Environmental Changes	Socio-Economic Developments
Climate-Induced	• Accelerated sea-level rise • Changes in rainfall patterns • Changes in sea-surface temperature • Changes in wind and wave patterns • El-Niño-related changes • Sediment-budget changes	• Autonomous adaptation • Planned adaptation
Not Climate-Induced	• Vertical land movement • Sediment-budget changes	• Population changes • Land-use changes • Changes in gross domestic product

TABLE 5
Three levels of assessment in coastal zones, showing the respective requirements and the factors to be considered.

Level of Assessment	Requirements			Factors to Consider		
	Time	*Level of Detail*	*Prior Knowledge*	*Socio-Economic Factors*	*Other Climatic Changes*	*Non-Climate Changes*
Screening Assessment	2-3 months	Low	Low	No	No	No
Vulnerability Assessment	6-12 months	Medium	Medium	Yes	Possible	No
Planning Assessment	Continuous	High	High	Yes	Yes	Yes

TABLE 6
Summary of the available methods to assess biogeophysical effects of sea-level rise. Scores from 1 to 5 indicate increasing requirements and reliability/validity.

Biogeophysical effect	**Assessment method**	**Requirements** *Data*	*Time*	*Skill*	*Money*	**Reliability and validity**
Increasing flood-frequency probabilities	• Use of current flood-frequency data	3	2	3	2	2
	• Individual-component method	3	3	3	2	2
Erosion	• Bruun rule of thumb	2	1	1	1	1
	• Bruun rule	3	3	3	2	2
	• Sediment-budget approach	5	5	5	4	3
Inundation	• Simple inundation concept	1	1	1	1	1
	• Dynamic inundation concept	2	2	3	2	2
	• Landscape modelling	5	5	5	5	3
Rising water tables	• Mazure equation	3	3	3	3	1
Saltwater intrusion	• Analytical methods (sharp-interface approach)	3	2	3	2	1
	• Mathematical modelling	5	5	5	5	3

TABLE 7
Examples of important technologies to protect against, retreat from or accommodate sea-level rise and other coastal impacts of climate change (see also Bijlsma *et al.*, 1996).

Application	Technology
Protect	
• Hard structural options	– Dikes, levees, floodwalls – Seawalls, revetments, bulkheads – Groynes – Detached breakwaters – Floodgates and tidal barriers – Saltwater-intrusion barriers
• Soft structural options	– Periodic beach nourishment – Dune restoration and creation – Wetland restoration and creation
• Indigenous options	– Afforestation – Coconut-leaf walls – Coconut-fibre stone units – Wooden walls – Stone walls
(Managed) Retreat	
• Increasing or establishing set-back zones	– Limited technology required
• Relocating threatened buildings	– Various technologies
• Phased-out or no development in susceptible areas	– Limited technology required
• Presumed mobility, rolling easements	– Limited technology required
• Managed realignment	– Various technologies, depending on location
• Creating upland buffers	– Limited technology required
Accommodate	
• Emergency planning	– Early-warning systems – Evacuation systems
• Hazard insurance	– Limited technology required
• Modification of land use and agricultural practice	– Various technologies (*e.g.*, aquaculture, saline-resistant crops), depending on location and purpose
• Modification of building styles and codes	– Various technologies
• Strict regulation of hazard zones	– Limited technology required
• Improved drainage	– Increased diameter of pipes – Increased pump capacity
• Desalination	– Desalination plants

TABLE 8
Examples of important technologies to collect data, provide information and increase awareness for coastal risk and adaptation to climate change.

Application	Technology
Coastal-System Description	
• Coastal topography and bathymetry	– Mapping and surveying – Videography – Airborne laserscanning (lidar) – Satellite remote sensing
• Wind and wave regime	– Waverider buoys – Satellite remote sensing
• Tidal and surge regime	– Tide gauges
• Relative sea level	– Tide gauges – Historical or geological methods
• Absolute sea level	– Satellite remote sensing – Tide gauges, satellite altimetry and global positioning systems
• Land use	– Airborne and satellite remote sensing
• Natural values	– Resource surveys
• Socio-economic aspects	– Mapping and surveying
• Legal and institutional arrangements	– Interviews, questionnaires
• Socio-cultural factors	– Interviews, questionnaires
Climate-Impact Assessment	
• Index-based methods	– Coastal vulnerability index – Sustainable capacity index
• (Semi-) quantitative methods	– IPCC common methodology – Aerial-videotape assisted vulnerability assessment – UNEP impact and adaptation assessment
• Integrated assessment	– Coupled models
Awareness Raising	
• Printed information	– Brochures, leaflets, newsletters
• Audio-visual media	– Newspapers, radio, television, cinema
• Interactive tools	– Board-games – Internet, world-wide web – Computerised simulation models

Textbox 1

The role of GIS in coastal risk assessment, adaptation and management

GIS combines computer mapping and visualisation techniques with spatial databases and statistical, modelling and analytical tools. It offers powerful methods to collect, manage, retrieve, integrate, manipulate, combine, visualise and analyse spatial data and to derive information from these data. One simple, first-order application of GIS in coastal adaptation would be overlaying scenarios of sea-level rise with elevation and coastal-development data to define impact zones. More sophisticated applications may include morphodynamic modelling. GIS technology is evolving rapidly and is increasingly used for sophisticated modelling. Hence, GIS can provide excellent support to coastal managers for making decisions about adaptation.

GIS can contribute to each of the steps towards vulnerability assessment and adaptation. Collected data can be stored in a GIS, combined to develop new insights and information, and visualised for interpretation and educational purposes. In combination with scenarios of relevant developments and models to assess and evaluate changes in important natural and socio-economic variables, GIS can assist planners to identify appropriate adaptation technologies as well as their optimal locations for implementation. It allows for the non-invasive, reversible and refinable testing of specific adaptation technologies before these are implemented in the real world. After implementation, newly acquired data can be analysed to evaluate technology performance. Once created, a GIS database will have further utility in other aspects of coastal management.

In spite of its clear utility, GIS cannot substitute for fieldwork or common sense. It will never eclipse the importance of economic, institutional, legal and socio-cultural factors in coastal management. In addition, true three-dimensional modelling in GIS (*e.g.*, for sediment budgets) remains problematic. Finally, some commentators have questioned whether GIS can always be used effectively in developing countries. Specific issues in this regard include:

- the costs of computer hardware and most GIS software;
- the lack of raw data to input to the system;
- the lack of consistency between data sets;
- restrictions on free access to information for strategic, political, economic or other reasons;
- limited salaries and career opportunities for GIS-literate operators compared to the industrialised world;
- the prevailing Western conceptual model of geographical space, which may be different from local ways of perceiving and interpreting spatial relationships;
- the fear that the introduction of GIS could lead to or facilitate oppressive government, misuse of power, civil unrest or other non-democratic activities.

The rapid ongoing developments of all aspects of GIS may remove some of these concerns. There is no doubt that GIS presents great potential for societies wishing to anticipate and understand the consequences of climate change and develop adaptation strategies to cope with the potential impacts.

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Authors:

Horst Sterr
Department of Coastal Geography
University of Kiel
24098 KIEL
Germany
Tel. 49 – (0)431 – 880 2944
Fax. 49 – (0)431 – 880 4658
E-mail: sterr@geographie.uni-kiel.de

Richard J.T. Klein
Potsdam Institute for Climate Impact Research (PIK)
P.O. Box 601203
14412 POTSDAM
Germany
Tel. 49 – (0)331 – 2882651
Fax. 49 – (0)331 – 2882695
E-mail: richard.klein@pik-potsdam.de

Stefan Reese
Research and Technology Centre West Coast
University of Kiel
Hafentörn
25761 Büsum
Tel. +49 (0)4834 604282
Fax: + 49 (0)4834 6772
E-mail: sreese@ftz-west.uni-kiel.de