

Global Vulnerability Analysis

By

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Introduction

Climate can have great influence on our lives as shown by the great damage and loss of life in events such as Hurricane Mitch in Central America, the 1999 cyclone in Orissa, India and the flooding in Mozambique in 2000. Such events could be intensified by climate change, making this issue a major challenge for the 21st Century. This widespread concern has generated a global policy response including the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC), whose signatories are committed, among other things, to “avoid dangerous climate change”. The key policy issue is the relative merits of reducing greenhouse gas emissions (usually termed mitigation) and/or adapting to the impacts of climate change, with a mixed response being most realistic.

A major consequence of climate change is global sea-level rise that could cause serious impacts around the world's coast. In the context of coastal zones, the goal of vulnerability analysis for sea-level rise (and other coastal implications of climate change) is to assess the potential impacts on coastal populations and the related protection systems and coastal resources, including the ability to adapt to these changes. A range of methods for such analyses has been developed and these have been extensively applied at the national and sub-national level (e.g. IPCC CZMS, 1992; Klein and Nicholls, 1999). These varied studies are often based on different assumptions and scenarios, so they are difficult to synthesize to the larger scales most pertinent to the policy debate outlined above. Therefore, there have also been efforts at vulnerability analysis at the regional and global scale.

The first global vulnerability analysis was completed in 1992 and evaluated: (1) increased flood risk and potential response costs; (2) losses of coastal wetlands; and (3) changes in rice production, assuming a one-meter global rise in sea level (Hoozemans et al., 1992). This was rapidly updated with a second edition (Hoozemans et al., 1993). Here only results for this second edition are discussed and henceforth this analysis is termed GVA1. The IPCC Common Methodology (IPCC CZMS, 1992) was followed throughout. These results influenced the United Nations Conference on Environment and Development (Rio de Janeiro, Brazil, 1992) (IPCC CZMS, 1992), and the World Coast Conference (Noordwijk, the Netherlands, 1993) (WCC'93, 1994), and are included in the IPCC Second Assessment Report (Bijlsma et al., 1996). Subsequently, Nicholls et al (1999) made a major improvement relative to GVA1 for the flood and wetland analysis. This was upgraded to a dynamic form, including improved impact algorithms, which can consider variable sea-level rise scenarios, the implications of growing coastal populations, and rising living standards (this analysis is henceforth termed GVA2). It is widely cited within the IPCC Third Assessment Report and has also contributed to a series of impact studies based on common climate and socioeconomic scenarios (e.g., Parry and Livermore, 1999).

This following description firstly outlines the key concepts of global vulnerability assessment. It then presents some selected methods of analysis, considering coastal population and flood risk, adaptation to increased flood risk and wetland loss. The results together with their validation and use are then considered, including the differences between the methods used. Lastly, possible developments in the near-future are considered.

Concepts, Constraints and Approaches

In the present context, *vulnerability* is defined as the degree of capability to cope with the consequences of climate change and sea-level rise (Klein and Nicholls, 1999). As such, the concept of vulnerability comprises:

- the susceptibility of a coastal area to the physical and ecological changes imposed by sea-level rise;
- the potential impacts of these natural system changes on the socioeconomic system;
- the capacity to cope with the impacts, including the possibilities to prevent or reduce impacts via adaptation measures. (This last factor is often termed 'adaptive capacity').

However, there are four main barriers to the comprehensive vulnerability assessment, irrespective of the scale of assessment (Nicholls and Mimura, 1998):

- incomplete knowledge of the relevant processes affected by sea-level rise and their interactions;
- insufficient data on existing conditions;
- difficulty in developing the local and regional scenarios of future change, including climate change;
- the lack of appropriate analytical methodologies for some impacts.

For the global assessments, the availability of consistent and complete global databases on (1) the distribution, density and present status of the impacted resources and (2) the nature and probability of the impacting hazardous events was a major constraint. Coverage at a global scale was sometimes incomplete due to regional gaps, or only coarse resolution data was available.

All these problems necessitate careful consideration of what can realistically and usefully be assessed. After considering these limitations, global assessments have evaluated fairly simple parameters to date, with the main focus on impact assessment rather than adaptation assessment. GVA1 was limited to an assessment of the potential impacts on three distinct elements in the coastal zone and one possible adaptive response:

- *risk to population (and adaptation potential)* -- population at risk of flooding and also potential protection upgrade costs;
- *ecosystem loss* -- coastal wetlands of international importance at loss;
- *agricultural impacts* -- rice production at change (in south, southeast and east Asia only).

GVA2 refined the methods and results for the first two elements, but the underlying data is the same. Only these elements will be considered here.

In order to assess the vulnerability of a coastal zone to sea-level rise we need uniform procedures to compare and to integrate national and regional studies. To determine

impacts in measurable and objective terms, the concept of *values at risk*, *values at loss* and *values at change* were used. The concept of risk is defined as the consequence of natural hazardous events multiplied by the probability of the occurrence of these events, *excluding* the system response. The concepts of loss and of change are defined as the consequences of natural hazardous events multiplied by the probability of the occurrence of these events, *including* the system response. The 'risk'-approach is considered appropriate to assess the consequences of sea-level rise on the probability of episodic hazards such as flood impacts on the coastal population and economy. System response is excluded because it is difficult to predict how flood events may change the behavior of the population in the long-term. The concepts of 'loss' and 'change' are appropriate for impacts on ecosystems and agricultural production, respectively, because it is the long-term consequences of sea-level rise that are the most important factors influencing the magnitude of the impacts.

To examine the capacity to cope with flooding, a set of protection measures was developed with these impact studies to enable the comparison of the impacts of sea-level rise 'with- and without increased protection measures'. While one may be susceptible to increased flooding, if one can easily afford to upgrade defenses, there is little cause for concern and overall vulnerability is low.

Lastly, the scale of assessment needs to be considered. Much of the available data for these studies was only available at national resolution and was of uncertain quality. Therefore, some of the underlying data as well as the assumptions about physical processes, physical and socioeconomic boundary conditions, limit the accuracy of the national-scale results. This is especially true since the last major revision of the underlying databases was in 1993. However, the errors appear to be unbiased so regional and global estimates are expected to be more robust (Nicholls, 1995). Therefore, all the results are aggregated to 20 regions and the global scale, and this is the output of the analysis that has been utilized elsewhere. The national data and results are available in Hoozemans et al (1993) for reference purposes, although the limits of the accuracy and validity of these detailed results should be born in mind.

Some of the methods are now considered in more detail.

Coastal population and flood risk

Storm surges are temporary extreme sea levels cause by unusual meteorological conditions. The resulting coastal flooding is a major issue damaging livelihoods, causing great distress and in the extreme, loss of life. As many as 2 million people may have been killed by storm surges in the last 200 years, mainly in south Asia (Nicholls et al., 1995). Sea-level rise will raise the mean water level, and hence allow a given surge to flood to greater depths and penetrate further inland. Changes in storm tracks, frequencies and intensity would also be change surge characteristics, but in the absence of credible scenarios, this factor is considered constant in time within this analysis

The concept of risk is considered appropriate in the context of assessing the consequences of sea-level rise on flooding for the population in the coastal zone. As rising sea levels intensify flood hazards, some human response might be expected. However, this response is not considered as such a prediction was considered unrealistic

given that it involves human choice (ranging from migration to increased protection). Therefore, a high Population at Risk indicates the need for some kind of a response. Possible protection costs against flooding are considered in the next section.

Based on the definition of risk, Population at Risk (PaR) is defined as the product of the population density in a certain risk zone and the probability of a hazardous flooding event in this risk zone. The resulting number is interpreted as the average number of people expected to be subject to flooding events per time unit (/year). Hence, PaR has also been termed “average annual people flooded” (Nicholls et al., 1999). The 'risk'-value is able to reflect changes in:

- the population living in the risk zone (coastal flood plain);
- the flood frequency due to sea-level rise;
- the protection standard of defenses.

As a general approach, the following steps were undertaken in GVA1 to determine the PaR for the various scenarios:

- Assessment of the height of the maximum flood level theoretically threatening the low-lying coastal zone, taking into account present and possible future extreme *hydraulic and geophysical conditions*.
- Determination of the *flood prone area* and calculation of the area contained between the coastline and the maximum flood level.
- Assessment of the *present state of protection* against flooding.
- Determination of the coastal *population densities* for the present and future state.
- Determination of the *Population at Risk* with and without measures, with and without sea-level rise, and for conditions in the years, 1990 and 2020.

To estimate global PaR with a reasonable accuracy, the world's coast was divided into 192 coastal zones based on the 181 coastal countries (as existed in the early 1990s). For each of the 192 coastal zones, a database was developed and an identical step-wise calculation scheme was followed to arrive at a coastal zone-specific PaR-number for each scenario (e.g. Figure 1). The database contained the following elements:

- (1) the maximum area of the coastal flood plain after sea-level rise;
- (2) the flood exceedance curve for storm surges from a 1 in 1 year event to a 1 in 1,000 year event;
- (3) the average coastal population density in 1990;
- (4) the occurrence or absence of subsidence; and
- (5) the standard of coastal protection.

Three fundamental assumptions are that (1) the coastal flood plain has a constant slope, and (2) the population is distributed uniformly across the coastal zone, and (3) if a sea defense is exceeded by a surge, the entire area behind the sea defense is flooded.

Calculations proceed as shown in Figure 1. Estimates of four storm surge elevations (1 in 1 year, 1 in 10 years, 1 in 100 years, and 1 in 1,000 years) are raised by the relative sea-level rise scenario and converted to the corresponding land areas

threatened by these different probability floods assuming a uniform coastal slope. These areas are then converted to people in the hazard zone using the average population density for the coastal area. Lastly, the standard of protection is used to calculate PaR. These national estimates are then aggregated to regional and global results.

In GVA1, a 1-m rise in sea level was imposed on the 1990 (and 2020) world. Coastal population density was estimated and used directly. In subsiding coastal areas, 15 cm of subsidence was assumed. Protection standards were estimated indirectly as discussed below. Lastly, only impacts of the expansion of the flood plain were considered, although this was amended by Baarse (1995).

In GVA2, a more dynamic approach was followed in which climate and socioeconomic scenarios both reflect realistic timescales. The 1990 coastal population density was increased (or decreased) at twice the rate of national growth. This is simply projecting present trends (Bijlsma et al., 1996). In coastal areas subject to subsidence, a uniform subsidence of 15 cm/century was applied to the entire coastal area, although it is recognized that this is only a first approximation.

There are no global data bases on the level of flood protection. Therefore, GVA1 adapted the World Bank classification of less developed, middle and high developed nations to estimate this parameter indirectly and used the GNP/capita in 1989 as an “ability-to-pay” parameter (Table 1). GVA2 used the same concept, but the algorithm was improved to reflect: (1) existing defense standards, (2) the greater costs of protecting deltaic areas against flooding, and (3) the increasing risk of flooding within the coastal flood plain as sea levels rise. The minimum standard of protection in 1990 was assumed to be 1 in 10 years, reflecting that people do not choose to live in highly flood-prone areas. Deltaic areas have a longer land-water interface than elsewhere, and a greater need for water management within the extensive low-lying areas that are protected, substantially raising protection costs. Based on expert judgement, the protection classes shown in Table 2 were selected. Lastly, the increase in flood risk within the existing flood plain produced by sea-level rise is estimated by reducing the protection class as sea level rises.

In GVA2, two protection scenarios are considered:

- constant protection (i.e., constant 1990 levels); and
- evolving protection in phase with increasing GNP/capita.

The evolving protection scenario is more realistic based on observed trends during the 20th Century. It should be noted that evolving protection only included measures that would be implemented *without* sea-level rise -- i.e. there are no proactive adaptation measures to anticipate sea-level rise. These two protection scenarios allow us to examine how such evolving protection might reduce vulnerability to sea-level rise.

Adaptation to Flooding

To estimate realistic first order national-scale protection costs within the constraints of the GVA1, a simple modular approach was adopted (Hoozemans and Hulsbergen, 1995). This assumed that the protection class is upgraded by one class (e.g., PC 1

increases to PC 2 – Table 1). Then the revised PaR is calculated together with the protection costs as outlined below. The regional protection costs are compared to the regional GNP to quantify their relative cost, and hence the relative capacity to implement such measures.

The method aims to address the wide range of existing coastal defense types and their related costs. The following factors were used:

- the lengths of low-lying coastline (or coastal areas) to be protected,
- a set of six standardized coastal defense measures to be applied,
- standard unit costs for each type of defense measure,
- individual national cost factors, to take account of local cost factors.

For each country, the national costs (C_N) were found by applying the following summation at the national scale for all partial stretches of coastline in that country or coastal area which need protection:

$$C_N = \sum l_c \cdot c_m \cdot c_f \quad (1)$$

where l_c is the coastal length, c_m is the unit defense measure cost, and c_f is the national cost factor.

Regionally and globally, the aggregated cost is found by summing the respective national costs. This approach does *not* produce a basis for national coastal defense planning. However, the modular set-up provides a realistic and practical framework for subsequent, more detailed analyses, to improve the accuracy and local relevance of the individual modules.

For each coastal country, an evaluation was made of the present types of sea defenses. It was assumed that new or upgraded defenses will be based on this experience, and hence the preferred type of defense options were selected by expert judgement. This selection should also account of matters like soil conditions, elevation and wave-exposure of the shore, the availability of construction materials and the value of the direct hinterland.

The length of coastline vulnerable to flooding was determined from the earlier World Coast Estimate (WCE) study by adding the length of low coast, the length of city waterfronts and the length of low coast of islands. Because there were no suitable global databases on geomorphology/defense status (e.g., dunes, dikes, saltmarshes) within each country, a typical coastline was selected, based on the dominant coastline type per country.

Six types of defense measure were considered:

1. *Stone-protected sea dike*
2. *Clay-covered sea dike*
3. *Sand dune*
4. *Tourist beach maintenance (beach nourishment).*
5. *Harbors and industrial areas (upgrade).*
6. *Elevation of low-lying small islands.*

Defense measures 1, 2 and 3 apply in most cases. However, the effective implementation of any measures requires a well-functioning technical and organizational infrastructure (as this is a key element of adaptive capacity). More demanding coastal defense works like those used to close off large estuaries were deliberately omitted from the standard list, although their application will be the most economical solution in some cases, as experience in England, the Netherlands and Japan illustrates.

Cost estimates for the standard protection measures were established in 1990 US dollars. They are based on the following assumptions and conditions, which draw strongly on Dutch technical experience:

- Standard defense constructions are defined for each situations, including dimensions, construction material and construction methods.
- The schematized designs are based on well-established procedures.
- Standard unit costs are derived from the Dutch situation, including provisions for all the costs, including design, execution, taxes, etc.
- Construction methods and cost estimates are based on the assumption of construction in one continuous operation per project.
- The hydraulic regime determined in the flood analysis is considered in design, increasing adaptation costs in areas with large surges.

Coastal wetlands and loss

Natural systems may also be impacted by sea-level rise. Coastal wetlands are defined as saltmarshes, mangroves and associated unvegetated intertidal areas (and here exclude features such as coral reefs and shallow-water sea grasses). Wetlands are not impacted by short-term fluctuations in sea level such as tides and surges, but they are susceptible to long-term sea-level rise and show a dynamic and non-linear response (Nicholls et al., 1999). Therefore, we are considering potential losses. In this case it is important to consider the wetland response to sea-level rise to make credible impact estimates.

All the evidence shows that coastal areas with a small tidal range are more susceptible than similar areas with a large tidal range. Loss of coastal wetlands due to sea-level rise can be offset by inland wetland migration (upland conversion to wetland). However, in coastal areas without suitable low-lying areas, or in low-lying areas protected against flooding, wetland migration cannot occur, producing a coastal squeeze.

A database of the type, area and location of most coastal wetlands of international importance was created as part of GVA1. It mainly comprised sites recognized by the Ramsar Treaty. It is missing data for certain regions such as Canada, the Gulf States and the former Soviet Union.

GVA1 identified those wetlands that might be threatened by a 1-m rise in sea level, but did not project actual losses. These threatened wetlands were identified based on coastal geomorphology, tidal range and local population density.

A non-linear model of coastal wetland response to sea-level rise was developed in GVA2 (Figure 2). The modeling effort is split into two parts (1) vertical accretion and (2) wetland migration. To model vertical accretion, the availability of sediment/biomass for vertical accretion is parameterized using critical values of non-dimensional relative sea-level rise ($RSLR^*$):

$$RSLR^* = RSLR/TR \quad (2)$$

where $RSLR$ is the relative sea-level rise scenario and TR is the tidal range on spring tides. Hence, wetlands in areas with a low tidal range are more susceptible to sea-level rise than wetlands in areas with a higher tidal range. (The rate of relative sea-level rise was implicit being defined by the 95 year period of interest). A critical value of $RSLR^*$ ($RSLR^*_{crit}$) distinguishes two distinct wetland responses to sea-level rise in terms of vertical accretion:

- (1) $RSLR^* \leq RSLR^*_{crit}$, No wetland loss as wetland accretion \geq sea-level rise; and
- (2) $RSLR^* > RSLR^*_{crit}$, Partial or total wetland loss as wetland accretion $<$ sea-level rise.

If wetland loss occurs, it is modeled linearly using the excess sea-level rise up to $RSLR^* = RSLR^*_{crit} + 1$. Above this rise, (near-) total loss is assumed and wetlands will only survive if there is inland wetland migration. This simple model captures the non-linear response of wetland systems to sea-level rise and the association of increasing tidal range with lower susceptibility to loss. The literature stresses the large uncertainties concerning quantitative wetland response to sea-level rise, so a range of values for $RSLR^*_{crit}$ which encompasses the available information were selected (Nicholls et al., 1999). The wetland sites are aggregated to the 192 coastal areas defined in the flood analysis, except for eight continuous national coasts that were subdivided because of a large variation in tidal range.

To model wetland migration, the same approach as GVA1 was used. The natural potential for the migration of the coastal wetlands under sea-level rise was evaluated for each wetland site using the global coastal geomorphic map of Valentin (1954) (showing the limited work on global-scale coastal typology in the last 40 years!). Three classes of migration behavior are recognized: (1) migration is possible; (2) migration is impossible; and (3) migration is uncertain. In the latter cases, losses were calculated assuming both migration and no migration and this contributes to the uncertainty between the low and high range of the results. In areas where migration is possible, the population density was estimated for the 2080s in a consistent manner to the flood analysis. If this population density exceeded 10 inhabitants/km², it was assumed that wetland migration would be prevented by flood protection structures. In areas where wetland migration is possible, wetland losses are assumed to be zero (i.e. wetland migration compensates for any losses due to inundation).

Validation/Interpretation of the GVA

Validation of any model is a critical step, which increases confidence in the absolute quality and interpretation of the results. However, global assessments can also be interpreted as relative impact measures. Given that global assessments provide internally consistent results, the relative impacts may be more reliable than the

absolute impacts. Therefore, it is suggested that users interpret the results from both an absolute and a relative perspective.

For the flood analysis, an independent data set of the impact parameters was developed via national-scale vulnerability assessments (Nicholls, 1995; 2000). While these national-scale results consider the impacts of sea-level rise on the 1990 world without any socioeconomic changes, the results can be used to validate the global flood model for these scenarios. In broad terms, the results for GVA2 are of the right order of magnitude for the three parameters assessed, and are also an improvement over the results in GVA1 (e.g. Figure 3). Therefore, the changes to the methods in GVA2 are justified.

Validation of the protection cost estimates suggested they are broadly reasonable (Nicholls, 1995). The validation of the wetland loss models remains limited due to a lack of suitable calibration data.

Results

Globally, about 200 million people live in the coastal flood plain (below the 1 in 1,000 year flood elevation). GVA1 estimated that PaR is 50 million people/year in 1990. Most of these people live in deltaic areas in the developing world. The expansion of the flood plain due to a 1-m sea-level rise will increase PaR to 60 million people/year based on 1990 population. Allowing for the additional factor of increased flood frequency within the existing coastal flood plain, PaR doubles to 120 million people/year (Baarse, 1995). Upgrading coastal protection infrastructure against a 1-m rise in sea level as outlined above could collectively cost US \$1,000 billion (1990 dollars), or 5.6% of the 1990 Global World Income. In this case, PaR is reduced from 60 to 7 million people/year, so there would be substantial benefits to coastal inhabitants. As these cost estimates assume an instantaneous rather than a progressive response and do not consider erosion in non-tourist areas or the costs of water management and drainage, they are more useful as a relative cost rather than an absolute adaptation cost.

Coastal wetlands are already declining at 1%/year to indirect and direct human activities. They would decline further due to a 1-m rise in sea level: more than half of the world's coastal wetlands could be lost.

The coastal regions defined in Figure 4 have different problems in the GVA1. Six regions are vulnerable to the loss of coastal wetlands: North America; Central America; South America Atlantic Coast; North and West Europe; Northern Mediterranean; and Pacific large islands (GVA regions 1, 2, 4, 7, 9 and 18). Nine regions were considered to be vulnerable with respect to both flood impacts/response costs and loss of coastal wetlands: the Caribbean islands; West Africa; the Indian Ocean small islands; East Asia; the Pacific small islands; the southern Mediterranean; south Asia; southeast Asia; and East Africa (GVA regions 3, 11, 15, 17, 19, 10, 14, 16 and 12). Relative flood impacts are significant for small island settings, but the absolute impacts are highest in south, south-east and east Asia.

The improved and validated approach of GVA2 suggests that under the 1990 situation, PaR is 10 million people/year. Even without sea-level rise, PaR is likely to increase to the 2050s due to increasing coastal populations. A one-meter rise in sea level produces a 14-fold increase in PaR given the 1990 world, rather than a 3-fold increase as found by Baarse (1995). Therefore, in the absence of adaptation, the impacts of sea-level rise on flooding are much more dramatic than previously realized. Evolving protection reduces the magnitude of flood impacts, but the relative increase in people flooded given sea-level rise is still dramatic. Under a lower sea-level rise scenario of 38-cm by the 2080s, the global increase in flooding will be seven-fold compared to the situation without sea-level rise. Most of these people will be flooded so frequently that some response seems inevitable. The most vulnerable regions are similar to GVA1, comprising large relative increases in the small island regions of the Caribbean, Indian Ocean and Pacific Ocean small islands (GVA regions 3, 15 and 19), and large absolute increases in the southern Mediterranean, West Africa, East Africa, South Asia and South-East Asia (GVA regions 10, 11, 12, 14 and 16).

Wetland losses given a 1-m rise in sea level could approach 46% of the present stock. Taking a 38-cm global scenario by the 2080s, between 6% and 22% of the world's wetlands could be lost due to sea-level rise. When added to existing trends of indirect and direct human destruction, the net effect could be the loss of 36% to 70% of the world's coastal wetlands, or an area of up to 210,000 km². Therefore, sea-level rise is a significant additional stress which makes the prognosis for wetlands even more adverse than existing trends. Regional losses would be most severe on the Atlantic coast of North and Central America, the Caribbean, the Mediterranean and the Baltic. While there is no data, by implication, all small island regions are also threatened due to their low tidal range.

The major change in flood impacts from GVA1 to GVA2 reflects the more realistic assumptions in GVA2 concerning the present protection status, and its degradation as sea level rises. The most important effect on PaR is the increased risk of flooding in the existing flood plain, rather than the expansion in the size of the flood plain as sea levels rise. Wetland losses in GVA1 and GVA2 are difficult to compare, but results for the common 1-m scenario are similar. The main benefit of GVA2 is its more flexible form.

What have we Learned/Next Steps?

The analyses described here have proven the concept and utility of global vulnerability assessment for policy analysis. The results confirm that global sea-level rise could have a range of serious impacts on the world's coasts if we fail to plan for these changes. Further, these impacts will be greater in some regions than others with parts of Asia, Africa and small island regions most adversely impacted. This is an important result to be considered by the UNFCCC policy process. However, what to do is not evaluated by the existing analyses.

In scientific terms, the rigor of developing such models gives improved insights into the functioning of the coastal system and the relationship between different scales. For instance, this work explicitly considers the relationship between local measurements of wetland accretion rates and global wetland vulnerability. At this stage of development, the global modeling is raising as many questions as answers, but

continued efforts will provide important insights that will be useful to the International Geosphere-Biosphere Programme, Land-Ocean Interactions in the Coastal Zone Project (IGBP-LOICZ) (Holligan and de Boois, 1993) and related research programs.

Policy analysis for climate change requires flexible tools which can link different emission scenarios all the way to potential impacts and adaptation potential. This will allow exploration of a wide range of sea-level rise (and other climate change) and socioeconomic scenarios, including different mixtures of mitigation and adaptation options. The experience with developing GVA1, and its improvement to GVA2 provide the basis to develop such tools. Important needs for future models include operation at a finer resolution, a better description of impact processes and the facility to include different response and adaptation pathways, among other improvements. A European Union research project called Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-level rise (or DINAS-COAST) is exploring these issues and will report in 2004.

Bibliography

- Baarse, G., 1995. *Development of an Operational Tool for Global Vulnerability Assessment (GVA): Update of the Number of People at Risk due to Sea-level rise and Increased Flood Probabilities*. CZM-Centre Publication No. 3, Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands, 15pp.
- Bijlsma, L., C.N. Ehler, R.J.T. Klein, S.M. Kulshrestha, R.F. McLean, N. Mimura, R.J. Nicholls, L.A. Nurse, H. Perez Nieto, E.Z. Stakhiv, R.K. Turner and R.A. Warrick. 1996. Coastal zones and small islands. *Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, ed. R.T. Watson, M.C. Zinyowera and R.H. Moss. Cambridge University Press, Cambridge, pp. 289-324.
- Holligan, P., de Boois, H. (eds.) (1993) *Land-Ocean Interactions in the Coastal Zone: Science Plan*. IGBP Report No. 25. International Geosphere-Biosphere Programme, Stockholm.
- Hoozemans, F.M.J., Marchand, M., Pennekamp, H.A., Stive, M., Misdorp, R. and Bijlsma, L., 1992. The impacts of sea-level rise on coastal areas: Some global results. In: *Proceedings 'The Rising Challenge of the Sea'*, Margarita Island, Venezuela, March 9-13 1992. NOAA, Silver Spring, Md. pp. 275-292.
- Hoozemans, F.M.J., Marchand, M., and Pennekamp, H.A., 1993. *A Global Vulnerability Analysis: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production on a Global Scale*. 2nd edition. Delft Hydraulics, the Netherlands.
- Hoozemans, F.M.J. and Hulsbergen, C.H., 1995. Sea-level rise: A worldwide assessment of risk and protection costs. In Eisma, D (ed.) *Climate Change: Impact on Coastal Habitation*, Lewis Publishers, London. pp. 137-163.
- IPCC CZMS, 1992. *Global Climate Change and the Rising Challenge of the Sea*. Report of the Coastal Zone Management Subgroup. IPCC Response Strategies Working Group, Rijkswaterstaat, the Hague.
- Klein, R.J.T. and Nicholls, R.J. 1999. Assessment of coastal vulnerability to sea-level rise, *Ambio*, 28, 182-187.

- Nicholls, R.J. 1995. Synthesis of vulnerability analysis studies. *Proceedings of WORLD COAST 1993*, Ministry of Transport, Public Works and Water Management, the Netherlands. pp. 181-216.
- Nicholls, R.J. 2000. An analysis of the flood implications of the IPCC Second Assessment global sea-level rise scenarios. In: Parker, D.J. (ed.) *Floods*, Routledge, London, *in press*.
- Nicholls, R.J., Mimura, N. and Topping, J. 1995. Climate change in South and Southeast Asia: Some implications for coastal areas. *Journal of Global Environment Engineering*, 1, 137-154.
- Nicholls, R.J. and Mimura, N. 1998. Regional issues raised by sea-level rise and their policy implications. *Climate Research*, 11, 5-18.
- Nicholls, R.J., Hoozemans, F.M.J., and Marchand, M. 1999. Increasing flood risk and wetland losses due to global sea-level rise: Regional and global analyses. *Global Environmental Change*, 9, S69-S87.
- Parry, M. and Livermore, M. (eds.) 1999. A new assessment of the global effects of climate change. *Global Environmental Change*, 9, S1-S107.
- Valentin, H. 1954. *Die Kusten der Erde*, VEB Geographisch-Kartographische Anstalt Gotha, Berlin.
- WCC'93, 1994. *Preparing to Meet the Coastal Challenges of the 21st Century*. World Coast Conference Report, Noordwijk, Nov. 1993, Rijkswaterstaat, The Hague.

Figures

Figure 1. The flood model algorithm as used in GVA2 (modified from Nicholls, 2000).

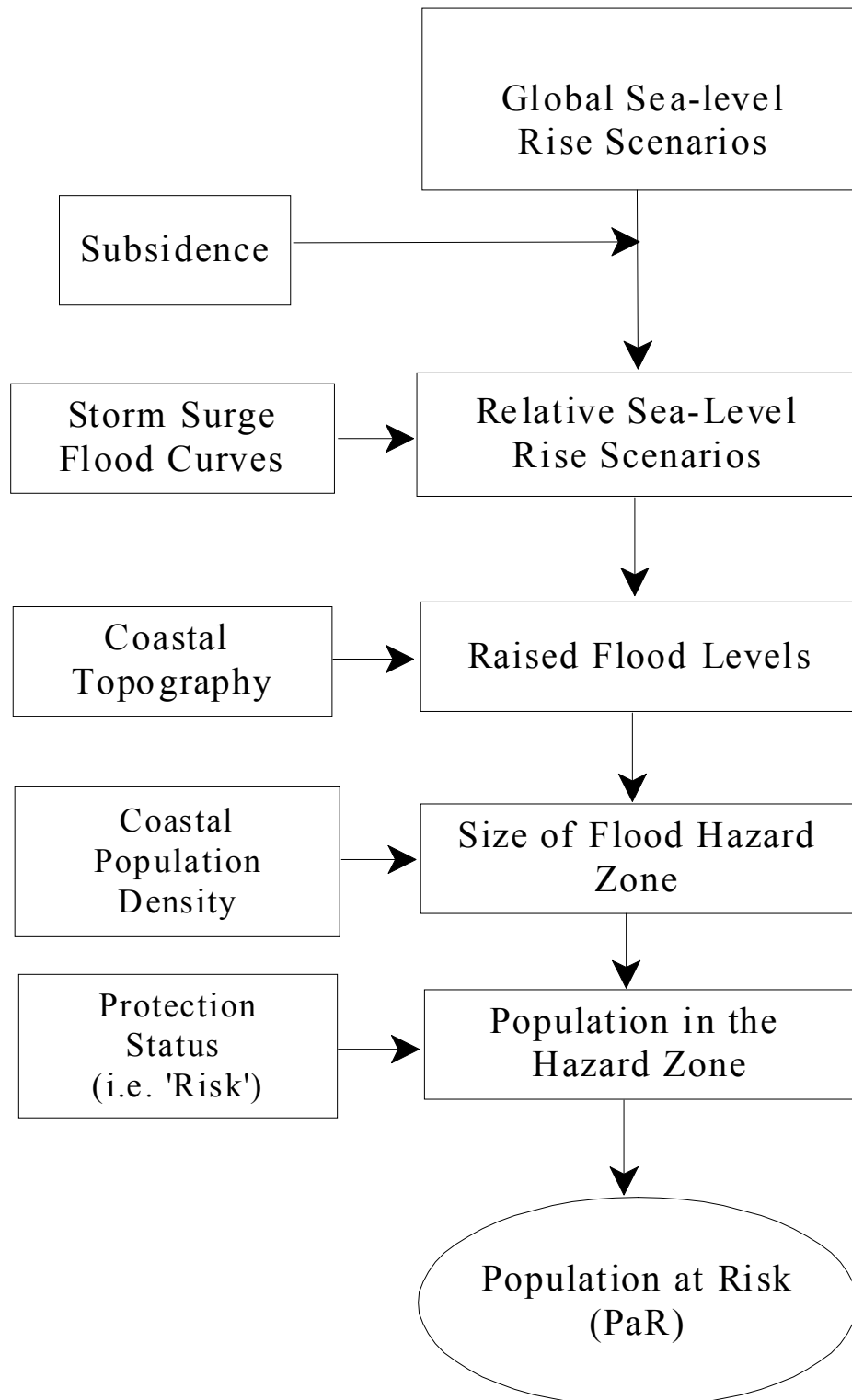


Figure 2. The wetland loss model algorithm used in GVA2 (modified from Nicholls et al., 1999).

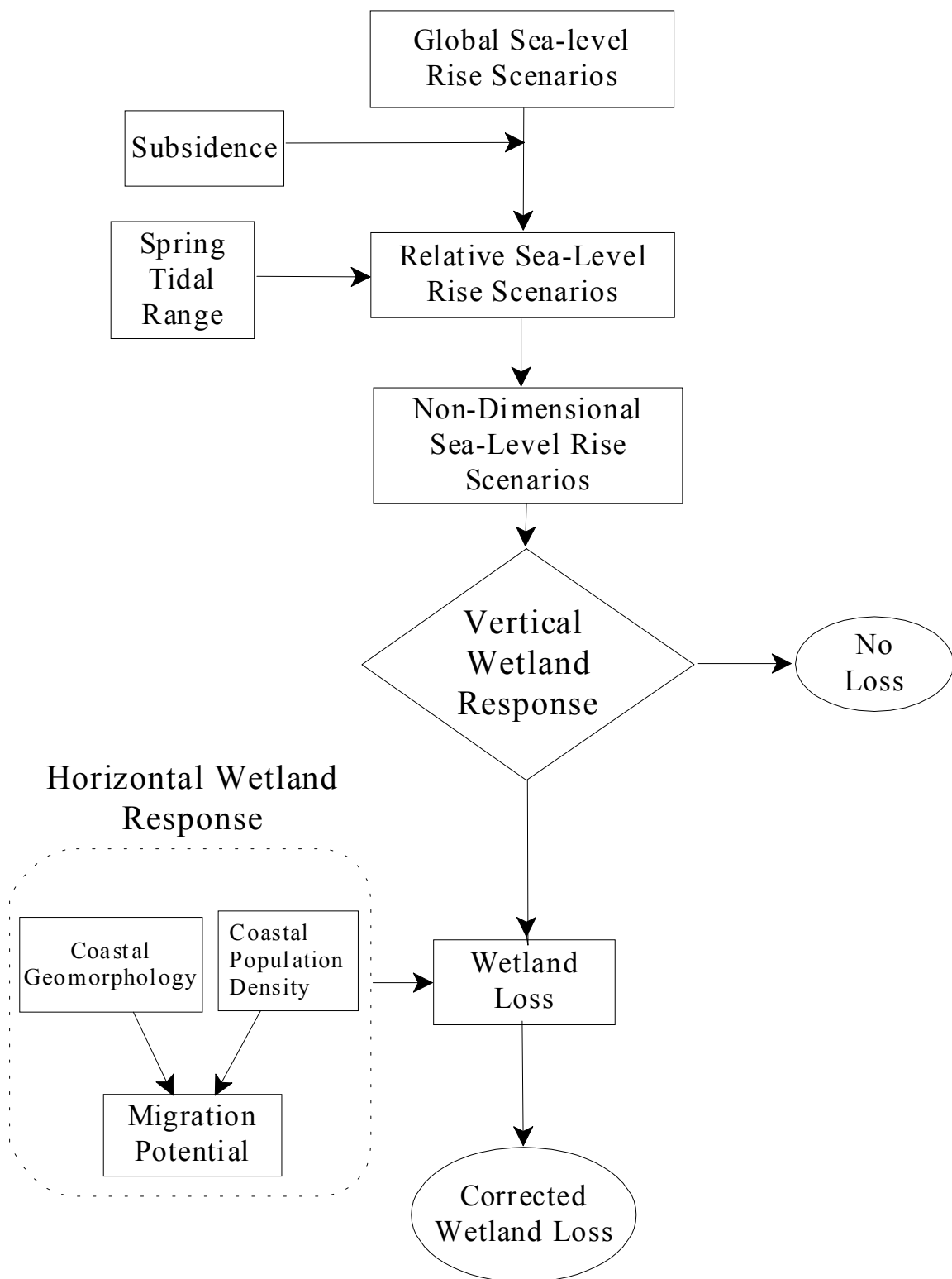
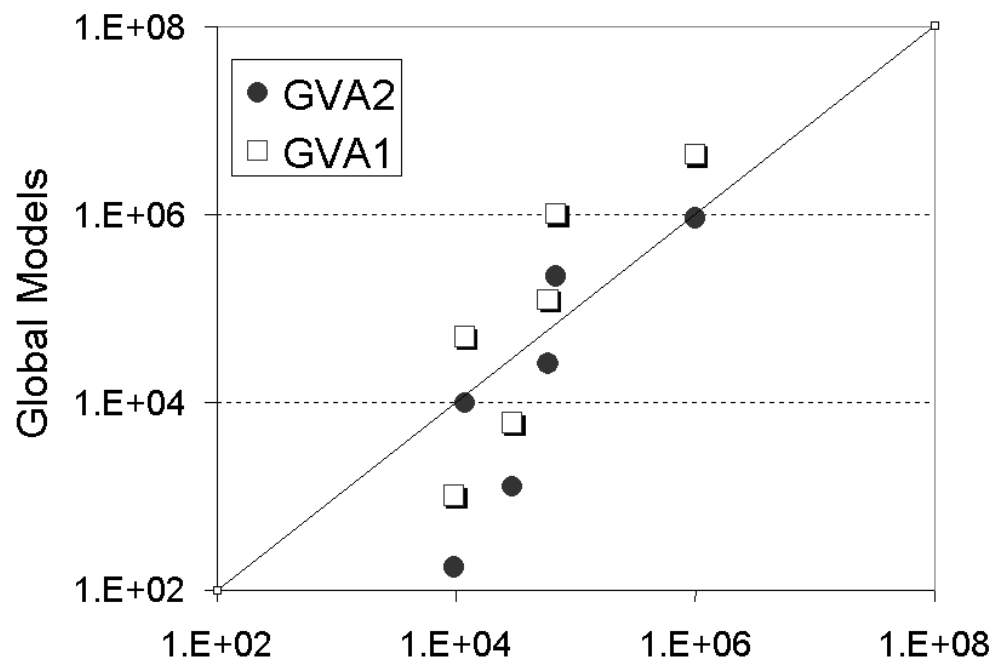
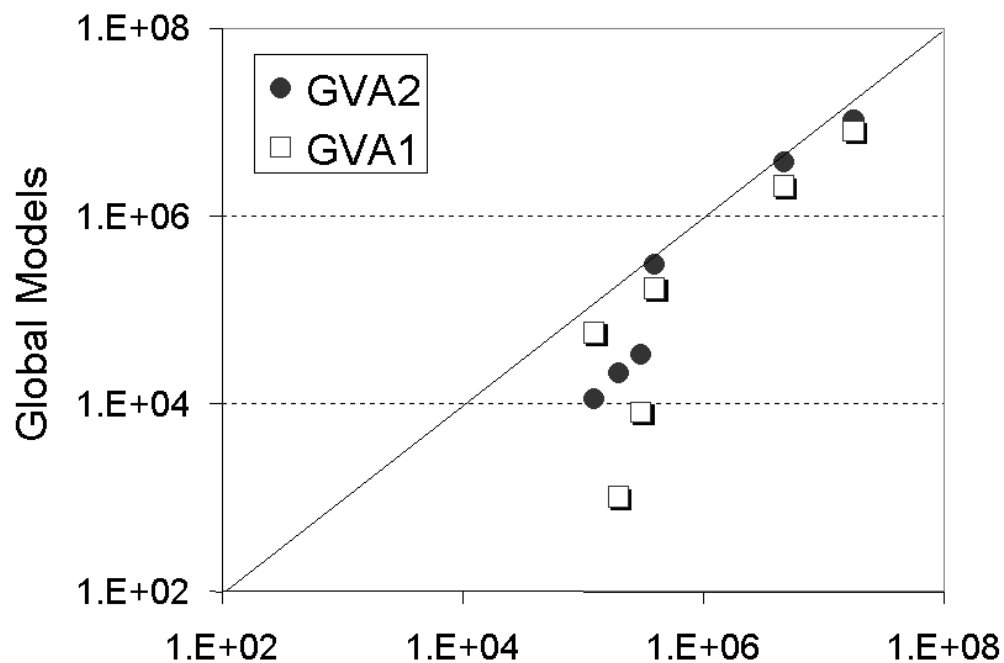


Figure 3. National PaR-estimates from GVA1 and GVA2 against independent national-scale vulnerability assessments for six countries (Egypt, Germany, Guyana, the Netherlands, Poland and Vietnam): (a) no sea-level rise in 1990, and (b) 1-m sea-level rise in 1990. (modified from Nicholls et al., 1999).



(a) National Assessments



(b) National Assessments

Figure 4. The 20 regions used in the GVA (from Hoozemans et al., 1993).

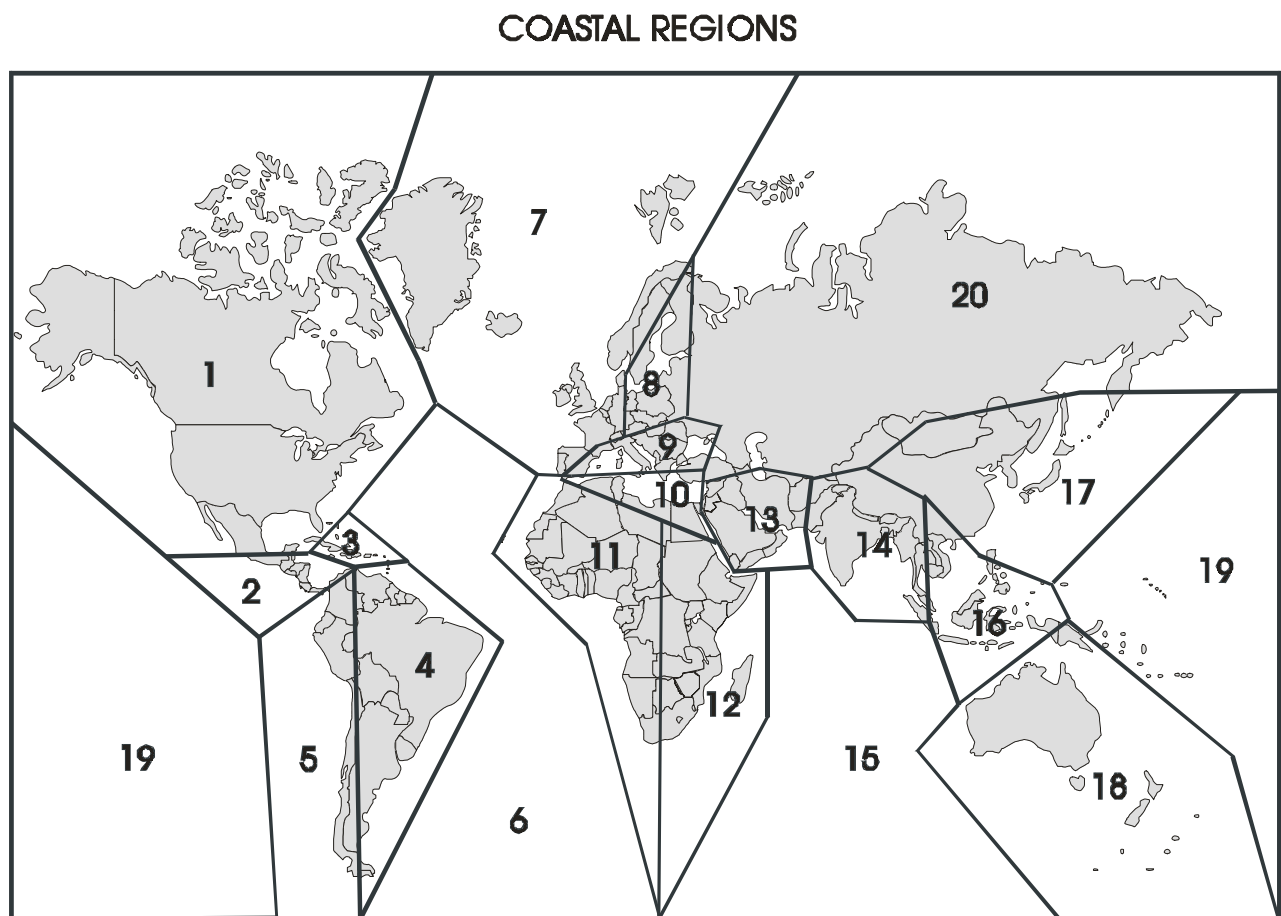


Table 1. Protection Classes used in GVA1

GNP/capita (US\$) (or ability-to-pay)	Protection Class (PC)	Protection Status	Design Frequency
<600	PC 1	low	1/1 to 1/10
600 to 2400	PC 2	medium	1/10 to 1/100
>2400	PC 3	high	1/100 to 1/1000

Table 2. Revised Protection Classes used in GVA2, allowing for deltaic and non-deltaic coasts.

GNP/capita (US\$)		Protection Class (PC)	Protection Status	Design Frequency
If deltaic coast	If non-deltaic coast			
<2400	<600	PC 1	low	1/10
2400 to 5000	600 to 2400	PC 2	medium	1/100
>5000	2400 to 5000	PC 3	high	1/1000
-	>5000	PC 4	very high	1/1000