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Source: Journal of Coastal Research, 2008(242) : 380-393

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/07A-0011.1

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Journal of Coastal Research	24	2	380–393	West Palm Beach, Florida	March 2008

Assessment of Vulnerability and Adaptation to Sea-Level Rise for the Coastal Zone of Germany

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ABSTRACT

STERR, H., 2008. Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. *Journal of Coastal Research,* 24(2), 380–393. West Palm Beach (Florida), ISSN 0749-0208.

Germany's coast extends over 3700 km on both the North and Baltic Seas and is shared by five coastal states. Major seaport cities, Hamburg and Bremen, form two of these states, whereas rural areas and small and medium-size coastal towns comprise the other three coastal states. Along the coast large low-lying areas are already threatened by recurring storm flood events and erosion. Accelerated sea-level rise therefore exacerbates a high-risk situation. It is estimated that under a 1-m accelerated sea-level rise scenario the recurrence of devastating storm floods that presently have a probability of 1 in 100 will decrease to a 1 in 10 or even 1 in 1 probability. Vulnerability assessments have been carried out in Germany at three scales: (i) the national level, *i.e.,* for all coastal areas lying below 5 m (Baltic Sea Coast) and 10 m (North Sea Coast), (ii) the regional level for the coastal state of Schleswig-Holstein, and (iii) the local level for selected communities within this state. When comparing findings from these analyses, the results show that the economic risks of flooding and erosion are highest when detailed studies covering the full range of infrastructure assets are used. However, the actual risk areas in detailed studies may be more confined when considering local topography and infrastructure such as road dams. Nationally, an accelerated sea-level rise of 1 m would put more than 300,000 people at risk in the coastal cities and communities, and economic values endangered by flooding and erosion would amount to more than 300 billion US$ (based on 1995 values). This is why German coastal states are following a strategy based on hard coastal protection measures against flooding, although authorities realize that maintaining and/or improving these defence structures might become rather costly in the long-term. Although additional investment in flood and erosion protection will be considerable (estimated at more than 500 million US$) this seems manageable for the national and regional economies. On the other hand, hard coastline defence and accelerated sea-level rise will increase "coastal squeeze" on the seaward side, endangering important coastal ecosystems such as tidal flats (Wadden Sea), saltmarshes, and dunes. Currently there is no strategy to remedy this increasing ecological vulnerability.

ADDITIONAL INDEX WORDS: *Storm floods, coastal risks, assessment scales, North Sea, Baltic Sea.*

INTRODUCTION

Coasts have long been recognized as potentially hazardous regions where the population concentrated in low-lying areas frequently face extreme events. With oncoming global climate change and the threat of accelerated sea-level rise (ASLR) the existing risk of flooding and storm surges will be exacerbated significantly. Climate change may not only enhance the most threatening extreme events (*e.g.,* through increased storminess) but also aggravate long-term biogeophysical effects, such as rising of mean water tables, shoreline erosion, sediment deficits, saltwater intrusion into coastal aquifers, and the loss of coastal wetlands (BIJLSMA *et al.,* 1992). Unlike many other anticipated consequences of climate change, global sea-level rise is already taking place. During the last 100 years, global sea level rose by 1–2.5 mm/y. Present estimates of future sea-level rise induced by climate change, as presented in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report, range from 20 cm to 86 cm for the year 2100, with a best estimate of 49 cm (including the cooling effect of aerosols) (WARRICK *et al.,* 1996). According to the IPCC Third Assessment Report, (IPCC, 2001) global warming might occur faster than previously assumed, with a possible maximum temperature rise of 5–6° C within the next 100 years. If so, earlier ASLR projections also need to be upgraded. Moreover, model calculations 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. In light of these existing hazards and the 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 increases in risk related to future sea-level rise and climate trends. Thus, it is essential to carry out analyses of the biogeophysical responses of coastal systems to climate-change impacts as well as to assess the threats posed to human society (WCC '93, 1994).

The assessment of coastal vulnerability to climate-related impacts is a basic prerequisite for obtaining an understand-

DOI: 10.2112/07A-0011.1 received and accepted in revision 19 April 2007.

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ing of the risk of climate change to natural and socio-economic coastal systems. At global level, vulnerability assessments (VAs) can serve to underpin the overall significance of sea-level rise for coastal societies and enable comparisons of regional variations of sea-level rise–related risks (HOOZEMANS, MARCHAND and PENNEKAMP, 1993; NICHOLLS and MIMURA, 1998). At a global scale, VAs demonstrate that anticipated impacts might exceed the coping ability of some coastal regions and nations. At national and local levels, VAs are needed to identify specific vulnerable areas and sectors and to 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 at global level will not be sufficient to achieve all of these objectives. Instead, higher resolution is needed to describe more meaningfully the conditions that lead to site- or area-specific exposures to risks of inundation, erosion, or saltwater intrusion (STERR, KLEIN, and REESE, 2003). 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. This implies the selection of the most suitable response strategy, between protection, accommodation, or retreat options, to minimise risks while optimising future coastal resource use (PEERBOLTE *et al.,* 1991). This is why in Germany, where adaptive policies are generally the responsibility of state governments, it has been decided to elaborate on an initial (first-order) national VA and refine the information base by means of a downscaling analytical procedure. Decisions on flood defence schemes taken at state level can now draw on specific topographic and economic data obtained from meso-scale studies (EBENHOEH, STERR, and SIMMERING, 1996; SCHELLNHUBER and STERR, 1993). Furthermore, for particularly vulnerable coastal sections, even more detailed (microscale) databases are being assembled to encourage informed evaluation of adaptation options.

This article aims at a thorough analysis of anticipated impacts of ASLR on Germany's low-lying coastal regions. First, the German coastal zone, including its socio-economic and ecologic characteristics, is described in detail. Then scenarios for climate change, ASLR, and storm flooding are considered in comparison with past records, and data requirements for VAs are summarised. The different VA scales in Germany are compared, which demonstrates that estimates of vulnerability and adaptive options are largely scale-dependent. Then, VA results are considered, and an outline of the overall risk with respect to ASLR and related effects is presented. Finally, the past, present, and future strategies for adaptations are critically reviewed.

CHARACTERISTICS OF THE GERMAN COASTAL ZONE

The first components needed for a vulnerability analysis are the physiographic characteristics of the German coastal regions. Germany has coasts both on the North Sea to the west (1600 km) and on the Baltic Sea to the east (2100 km), thus the total length of the coastline amounts to *ca.* 3700 km, of which approximately two-thirds are eroding (Table 1). In political and administrative terms, five states (out of 16 states making up the Federal Republic of Germany) border these coasts: Lower Saxony, Bremen, and Hamburg belong to the North Sea region; Mecklenburg-Vorpommern belongs to the Baltic Sea region; and Schleswig-Holstein shares coasts with both seas. The Baltic region was morphologically shaped during and after the last glaciation of Northern Europe (Weichselian Glaciation) and is composed of glacial drift material. The North Sea coast, on the other hand, remained free of ice and was an area of widespread deposition of glacial outwash deposits during Pleistocene times and of littoral marshland formation during the Holocene. Thus, the German coastline is mainly shallow, *i.e.,* marsh, dune coast, or beach wall, while only approximately 11% of the coast (420 km) is steep. On the Baltic, more than half of the coastline belongs to the so-called Bodden Coast (Bodden are shallow bays and inlets cut off from the open Baltic Sea by islands, peninsulas, and narrow spits). An overview of the morphologic and hydrologic features of the two coastal zones is given in Figure 1 and Table 1. Few sections of the Baltic coast, mostly the densely populated areas, are protected by dikes. Along the

Table 1. *Physiographic features of the North Sea Coast and Baltic Coast of Germany.*

Coastal Features	North Sea	Baltic Sea	Total
Coast length (km)	1590	2110	3700
[including length of eroding coast]	[1110]	[1150]	[2260]
Share of total coast length			
Shallow Coast			
a) Marshland Coast	1220	1100	2310
	[880]	[350]	[1230]
b) Beach Ridge or Dune Coast	340	600	940
	[210]	[450]	[660]
Cliff Coast	20	400	420
	[20]	[350]	[370]
Islands	530	930	1460
Estuary	870	—	870
Bodden (= semi-enclosed inlets)	—	1350	1350
Tidal range (m)	1.7–4.0	0.1–0.2	—
Length of protected sections (km)	1340	560	1900
a) First-grade dikes	630	270	900
b) Other dikes and dunes	590	190	780
c) Other protective structures	120	100	220
Artificially drained areas (km²) (an estimated 30% of the total flood-prone area [(see Table 2])	3370	—	≈3400
Extent of wetland area (km²)	4800	1800	6600
Intertidal	4300	—	4300
Saltwater-influenced	500	1800	2300
Observed secular sea-level rise (cm)	20–25	15	—
Years of highest storm surge	1906/1962/ 1981	1872/1913	—
Design water level (cm above MSL)	500–770	170–370	—
Probability of flooding			
a) 1995	1/100	1/250–1/1000	—
b) 1995+ 1 m (ASLR)	1/5	1/2 to 1/10	—
Extent of low-lying areas (km²)			15,060
a) Up to +10 m above MSL	15,060	n.a.	n.a.
b) Up to +5 m above MSL	11,020	2560	13,580

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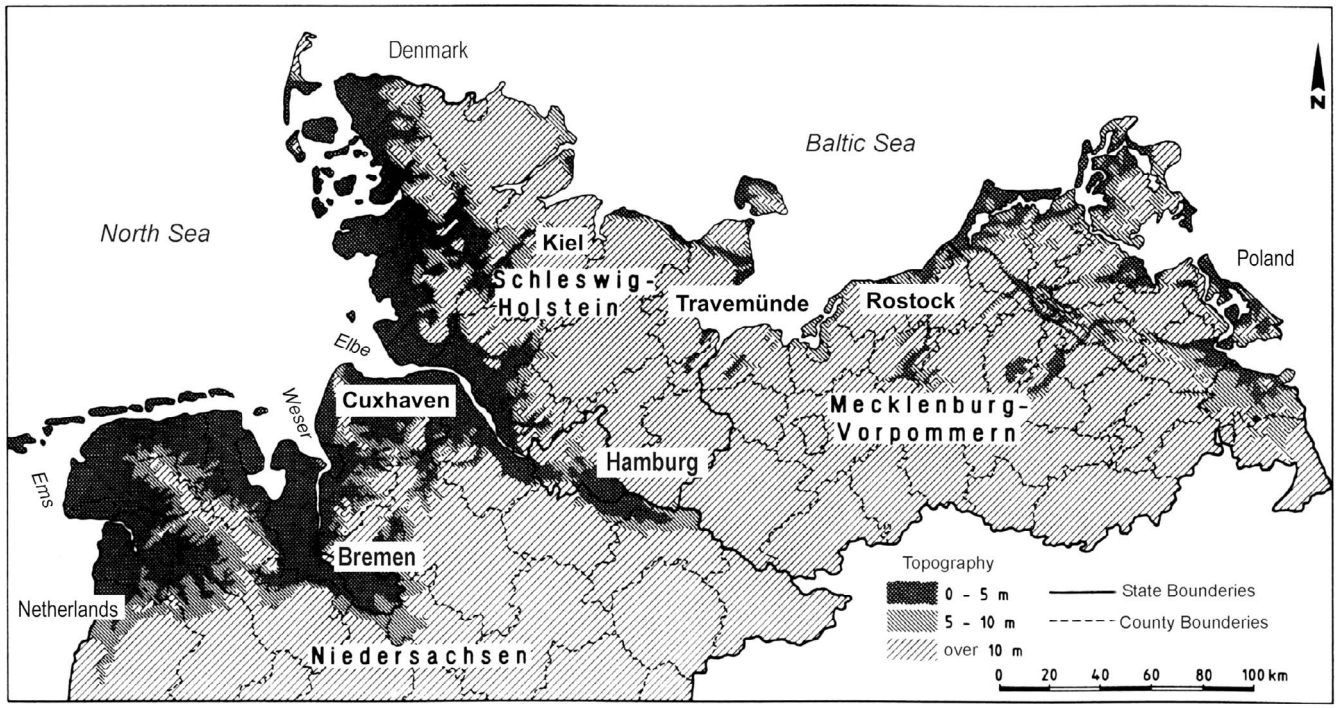


Figure 1. Map of German coastal regions showing the low-lying coastal areas at risk from sea-level rise and the three large coastal states. Locations of tide gauge stations of Cuxhaven and Travemuende are also shown.

cliffed coast and around the inlets, there are no protective (hard) structures (Table 1). In total, only 560 km, or 27%, of this coast is protected by dikes. This is in strong contrast to the North Sea coast, where 1340 km, or 85%, of the coast is dike-protected. For the entire German coastline, 1900 km, or 52%, is protected by dikes, dunes, or other constructions (Table 1). Table 1 also provides expert-based estimates of the size of the artificially drained areas behind the dikes (EBENHOEH, STERR, and SIMMERING, 1996; KUNZ, 2003) and data on the extent of coastal wetlands, the range of calculated water levels, and the probability of flooding. Statistical flood risk is calculated from tidal gauge statistics of extreme water levels, derived from the recorded storm surges during the 20th century and from designed dike heights according to Coastal Protection Master Plans. Finally, Table 1 contains information on beach erosion. Recent coastal morphological investigations have shown that approximately 75% of all (sandy) coasts are subject to erosion. On the Baltic coast, the average rate of shoreline retreat is approximately 40 cm/y.

From a socio-economic perspective it is essential to delineate the coastal zone threatened by impacts of ASLR and storm flood events as precisely as possible (KLEIN and NICHOLLS, 1999; TURNER and ADGER, 1996). Judging from previous extreme flood events and the design water levels used for defining dike heights, it seems clear that the landward boundary of the coastal zone is to be assessed according to the regional topographic setting. For the North Sea coast, which has a meso-tidal regime (tidal range of 1.5–4 m), the landward boundary was taken at the 10-m contour line; for the microtidal environment of the Baltic Sea (tidal range 0.1–0.2 m) historic storm surge levels are significantly lower and, thus, the 5-m contour line was considered to appropriately delineate the flood-prone area. The total size of this area is more than 15,000 km^2, the largest portion of which lies on the North Sea coast. However, this only represents 4.2% of the country's total land area. The surface area below the 5-m contour line represents 3.8% of the German territory. Table 3 shows how the areas at risk are distributed among the five coastal states in political and administrative terms.

The low-lying coastal region is densely populated and intensely used. As many as 3.2 million people live within this coastal strip, concentrated mainly in a number of large coastal towns. The four biggest of these are the port cities of Hamburg (1.6 million inhabitants, of which 180,000 are in the risk area), Bremen (630,000), Kiel (245,000), and Rostock (180,000). Moreover, there are about 10 seaboard towns with between 50,000 and 120,000 inhabitants, most of them with historic city centers, *e.g.,* Luebeck, Flensburg, Wismar, Stralsund, Greifswald (Baltic area), Cuxhaven, Wilhelmshaven, and Emden (North Sea area). The most important economic sectors in the coastal region are harbours (commercial and military), harbour-related industries (shipyards, refineries, *etc.*), tourism, and agriculture, whereas the fishery sector has lost much of its previous importance in modern times. The overview assessment showed that nearly 1.2 million jobs are located within the risk area as defined above (STERR and SIMMERING, 1996).

In addition to its high socio-economic importance, Germa-

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ny's coastal region contains an abundance of valuable coastal ecosystems. Typical coastal ecosystems of the North Sea and Baltic Sea are extensive tidal flats (Wadden Sea), dunes, salt marshes, brackish wetlands, and shallow coastal waters. Their diverse functions include being a recreational asset, nutrient and pollutant filters and buffers, biomass and biodiversity production and preservation, food chain regulation, and protection. These ecosystems have nature reserve status under a number of national and international directives and regulations. They show an extreme sensitivity toward the effects of climate change and sea-level rise although it is still uncertain to what extent their functions will be affected by climate-related impacts (KLEIN and NICHOLLS, 1998; TURNER, ADGER, and DOKTOR, 1995). In this respect the risks threatening Germany's coastal zone do not differ considerably from the dangers experienced elsewhere (NICHOLLS and LEATHERMAN, 1995; NICHOLLS and MIMURA, 1998). Therefore, the IPCC's overall considerations of coastal vulnerability, which state that the functional stability of coasts will diminish as a result of climate change impacts, is also valid for the German coastal zone (Table 1) (BIJLSMA *et al.,* 1996).

SCENARIOS OF CLIMATE CHANGE AND SEA-LEVEL RISE FOR GERMANY

A description of plausible climate and sea-level rise scenarios depends on three criteria: (i) the observed trends of sea-level rise and storm flooding; (ii) appropriate global sea-level scenarios (IPCC, 2001); and (iii) the results of hydronumerical modelling of (future) climate-driven storm flood activity. Along the North Sea coast, a long-term (so-called secular) rise of 20–25 cm/100 y has been recorded on a regional scale (GOENNERT and FERK, 1996). Along the Baltic coast, the average secular rise has been slower (*i.e.,* average 15 cm/100 y), as suggested by the records from several tide gauges (HOFSTEDE, 1997; STIGGE, 1997). These values include regional effects of slow isostatic subsidence (following the last glaciation of northern Europe) of approximately 5 cm/100 y, which add to the climate-related effects of sea-level rise. According to IPCC estimates, global sea-level rise will accelerate significantly in upcoming decades, increasing to three to four times the current rate by 2100. The mid IPCC estimate for sea-level rise during this period amounts to 49 cm (WARRICK *et al.,* 1996). However, in shallow seas like the North and Baltic Seas, sea-level rise caused by thermal expansion alone is thought to be proportionally higher. Consequently, combined with the above mentioned geological effects, a 60-cm rise of mean water level is assumed to be more plausible for this area. The recorded trend of sea-level rise in the southern North Sea appears to be accompanied by a simultaneous increase of the tidal range by 0.15 cm/y (HOFSTEDE, 1996). Therefore, in the German Bight, the change in mean high water (MHW) levels is foreseen to be greater than mean water-level change. From the comparison of all hydrographical parameters, the current assumption of the coastal authorities in Schleswig-Holstein is that MHW might rise by 0.65 cm/y during the 21st century.

Quantitative observations at tide gauges along the North and Baltic Sea coasts show that an increased frequency of extreme water levels is related to the rising sea-level trend. It cannot be inferred from statistical analysis whether the increase in storm flood frequency indicated by the hydrographical trend is further emphasized by changes in the regional wind fields. Only a moderate shift from the dominating southwesterly wind direction to a northwesterly direction is likely to bring about a considerably higher water table setup and wave energy input, in particular within the German estuaries of Elbe, Weser, and Ems (GOENNERT, 2003).

Maximum water levels during extreme weather situations are much more dangerous for the coastal population, coastal use, and infrastructure than a mean increase in sea level. According to recent tide gauge observations along the North Sea coast, extreme water levels have reached greater heights during the last four decades than before the so-called "flood of the century" that occurred in February 1962 (large portions of Hamburg City and the neighbouring North Sea coastal lowlands were flooded). The storm flood levels for both 1976 and 1981 were up to 50 cm higher than those in the 1962 event. Six storm surges higher than the 1962 level have also been recorded at the tide gauge station in Hamburg; four since 1990. In the Ems estuary near the border to The Netherlands, the storm surge of January 1994 was the highest ever recorded (BEZIRKSREGIERUNG-EMS, 1997). A significant increase in the frequency of (moderate) storm floods can be shown statistically for the North Sea and the Baltic (GOENNERT and FERK, 1996; STERR, 2002). Significant trends are not currently available for strong and extreme storm floods, partly because of the lack of longer data series (LANGENBERG and VON STORCH, 1996; STIGGE, 1997). The "baseline scenario" of the common methodology developed by the IPCC Coastal Zone Management Subgroup assumes a sea-level rise of 1 m by the year 2100 (BIJLSMA *et al.,* 1992). This generic scenario is intended to allow for the cross-regional comparison of vulnerability case studies carried out across the world. When applying this scenario to the storm flood frequency distribution, the recurrence of extreme (*i.e.,* hazardous) water levels shows a significant reduction of return periods. For example, at Cuxhaven, the 1-in-100-year flood event today is reduced to a 5-year flood event (Figure 2). Similarly, along the Baltic coast the long-term records show a significant increase of storm surges. At Travemuende, which has had surge records since 1830, there is an increasing trend of storm surges through the 20th century (Figure 3). There, the 1-m ASLR scenario would lead to an even higher increase in the frequency of storm surges, as the absence of tides generally leads to a gentler storm flood frequency curve. Therefore, maximum flood levels, showing a frequency of 1 in >250 years in the past (as estimated from morphological-geological investigations) would be reduced to a 1 in 2–10 year period (Figure 4).

Having described the morphologic, hydrologic, and ecologic features of the German coasts in sufficient detail (see Table 1), the next crucial step of the VA is to describe and quantify socio-economic values and overall importance of the coastal zone. However, the collecting of relevant socio-economic data often proves more difficult. A number of socio-economic variables need to be considered:

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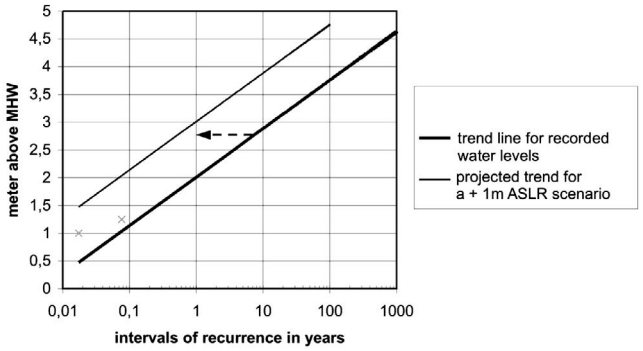


Figure 2. Recurrence intervals of storm surge water levels at Cuxhaven, North Sea coast (data from BSH-statistic and Goennert and Ferk, 1996). An assumed 1-m ASLR would reduce the storm surge interval by at least one order of magnitude.

- socio-demographic patterns, in particular distribution of coastal population
- current economic resource use and likely economic development
- land use patterns
- infrastructural and other economic assets
- cultural assets
- institutional arrangements
- accumulated capital and ecological values within the risk area.

The key elements used for the socio-economic assessment in German studies are shown in Figure 5. A baseline scenario was developed from current economic trends that were derived from reliable statistical information for the period between 1994 and 2000. A "development scenario 2100" would be more appropriate in combination with the ASLR and hydrographic trends outlined above for the 21st century. However, it is not currently feasible to produce meaningful quantitative estimates of long-term regional socio-economic trends for German coastal regions.

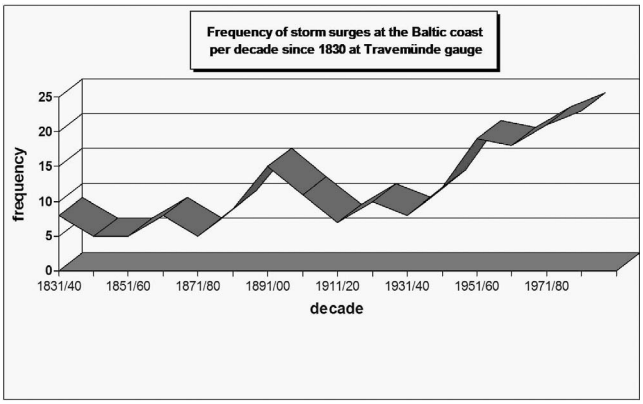


Figure 3. Number of storm surges (water levels of >1.5 m above mean water) on the Baltic coast since 1830 for tide gauge station at Travemuende (from Ebenhoeh, Sterr, and Simmering, 1996).

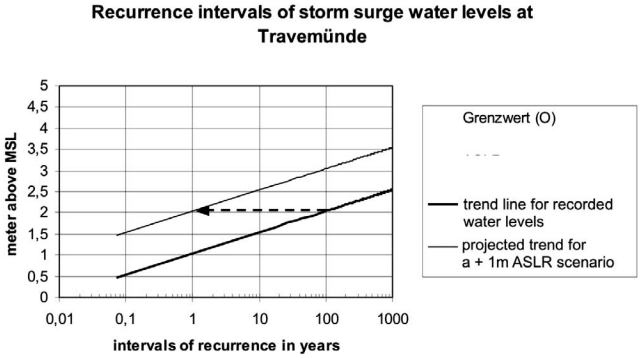


Figure 4. Recurrence intervals of storm surge water levels at Travemünde, Baltic Sea coast (data from Stigge, 1994). An assumed 1-m ASLR would reduce the storm surge interval by two orders of magnitude.

ASSESSING VULNERABILITY AT THREE SCALES: THE GERMAN EXPERIENCE

The issues and questions that have been raised in the previous sections are now considered and discussed in the con-

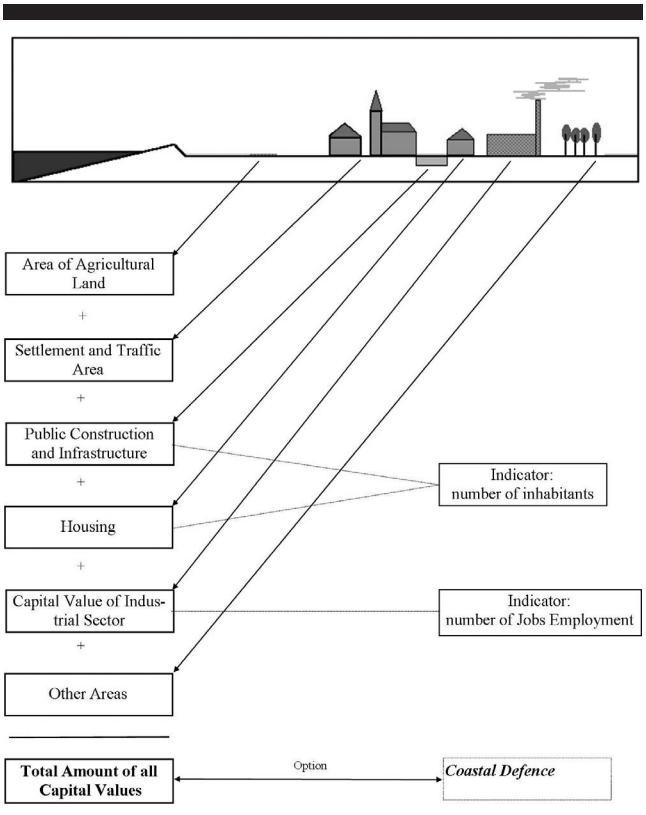


Figure 5. Quantitative approach to the economic vulnerability assessment for the German coast.

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Table 2. *Vulnerability assessments carried out on three levels of scale for the German coastal regions.*

Scope of Vulnerability Assessments Foci of Research	Macroscale Assessment (following Common Methodology)	Meso-Scale Assessment	Microscale Assessment
Vulnerable areas (size, boundaries, localities) (see Figures 1 and 7)	All low-lying areas below the +10 m along the German coast; hazardous area below the +5 m contour line (as shown in Figure 1)	For State of Schleswig-Holstein only. All areas below +5 m at the North Sea and the Baltic Sea coast (as shown in Figure 7)	Two North Sea, three Baltic case study sites selected in S-H; +5 m and +3 m contour lines used as respective landward boundary
Sea-level rise	1-m sea-level rise by 2100	A more moderate sea-level rise (of approximately 0.5 m) is considered likely	Same as in meso-scale assesment
Storm flood scenario	Storm flood recurrence growing by one to two orders of magnitude		
Coastal protection scenario	Inspite of full protection in 1995 failure of existing dikes is assumed to be possible	Failure of major dikes is considered as possibility	Failure of major dikes is considered as possibility
Socio-economic scenario	The 1995 situation is maintained	The 1997 situation is maintained	The 2001 situation is maintaned
Primary hazards assessed	-Number of people in vulnerable areas (aggregated data)	-More precise number of people	-Detailed local topography
	-Potential damage to capital values	-Socio-economic damage potential described in greater detail (*e.g.*, including coastal tourism)	-Exact number of people in the risk areas
	-Change of risk for people and values up to 2100	-No change of risk assessed	-Exact and very detailed damage potential in each of the communities
Key results	High socio-economic risk potential for Germany's coasts, especially in urban areas (>3 Mio people; >400 Mio $)	Assessment of socio-economic risk potential is based on more detailed statistical and topographic data	Assessment of all socio-economic risks within study site topography (established from field surveys, community and insurance statistics); appraisal of full range of possible damage; vulnerability described in urban, rural and tourism localities
	Strongly rising costs for improvement of defence installations	Results are in agreement with macroscale analysis	
	Large wetland areas (30–50% of existing area) could be lost	Most vulnerable areas are pinpointed, with focus on urban areas	
Comments	Scoping study for first-order evaluation of coastal vulnerability of Germany (in comparison to neighbouring countries); rough appraisal of coastal defence (range and focus) and of risk to coastal wetlands	More accurate statistical and topographic (GIS-based) data base provides guidelines for future priorities of coastal protection schemes; assessment is still too coarse for community-based measures	Most accurate community-based data show that socio-economic risk potential differs from meso-scale: more capital values are found in vulnerable area while people affected could be less

text of the vulnerability of the German coastal zone. In Germany, assessments have been carried out at three different resolutions (see Table 2):

- Macroscale: a national VA covering the entire German coastal zone (Figure 1) (EBENHOEH, STERR, and SIMMERING, 1996).
- Meso-scale: a more detailed assessment for the State of Schleswig-Holstein (commissioned by the state government). This aimed at comparing the potential hazards along the North Sea *vs.* the Baltic Sea coast and at providing a basis for regional coastal defence planning (Figure 6) (HAMANN and HOFSTEDE, 1998).
- Microscale: high-resolution assessments were carried out in five communities within the State of Schleswig-Holstein. Three different types of communities found to be representative for northern Germany were chosen. The case studies considered two rural communities, two tourism resorts (both on North Sea and Baltic Sea), and one urban area (city of Kiel). Here the aim was to describe typical site-specific vulnerabilities along the North and Baltic Seas to reveal the concrete needs and opportunities for adaptation to ASLR at community level (STERR, KLEIN, and REESE, 2003).

At all three levels of analysis, the primary focus for ASLR-related risks was on increased flood risk with special attention to possible socio-economic impacts. Erosion was treated mainly in the context of adaptive strategies and costs. Effects of ASLR on water resources, possible deterioration of farmlands, and possible loss of valuable wetlands were considered in a qualitative, first-order approach. Table 2 gives an overview of the foci of research and major results for the three different scales of assessment.

The National Study

In 1992, a multidisciplinary research project was launched by the Federal Ministry of Research to study the full range of climate-change implications for the coastal region. In this context a national case study was carried out between 1993 and 1996 as part of an international effort to encourage the generic assessment of coastal vulnerability. The IPCC common methodology (BIJLSMA *et al.*, 1992) was applied and tested, and the results obtained for a number of countries around

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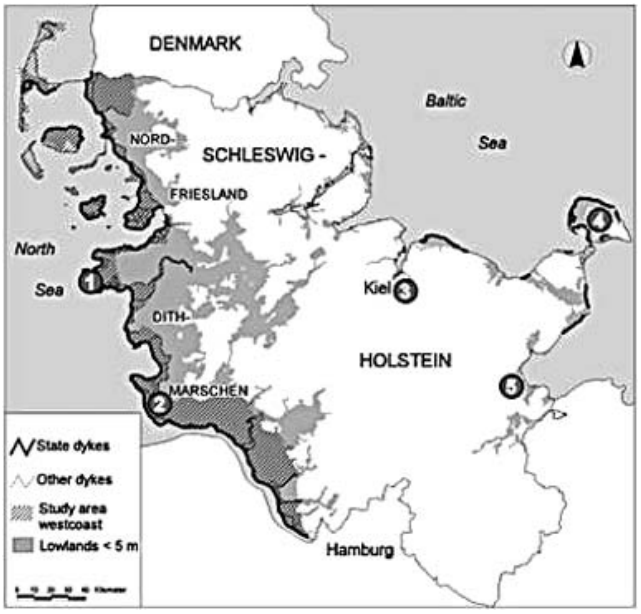


Figure 6. Flood risk areas in the state of Schleswig-Holstein calculated from the meso-scale vulnerability assessment. All shaded areas (below 5-m OD) are potentially flooded lowlands, striped areas are particularly vulnerable in case of dike breakage. Microscale VA: the numbers 1–5 indicate localities where microscale assessments were carried out: (1) St. Peter-Ording: major tourism-oriented community on the North Sea Coast; (2) Kaiser-Wilhelm-Koog: reclaimed farmland secured by dikes, rural character; (3) City of Kiel: largest coastal agglomeration of residents, houses and infrastructure in state; (4) Island of Fehmar: mixed orientation towards agriculture and tourism & recreation; and (5) Timmendorfer Strand: major tourism-oriented community on the Baltic Sea coast.

the world were compared (NICHOLLS, 1995; NICHOLLS and MIMURA, 1998; WCC '93, 1994). Besides serving as an IPCC case study, the German national study had several policy-related objectives, the most important of which were

- 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 1 m sea-level rise to the year 2100)
- to determine the critical flood water levels along the North and Baltic Sea coasts in terms of past and future damage potential
- to estimate the likely socio-economic vulnerability in each of the five coastal states (Figure 5)
- to determine the subregions most susceptible to flooding within these states
- to assess to what degree coastal protection schemes (dikes, seawalls, dunes, *etc.*) would be insufficient with the assumed scenario
- to determine the approximate costs of adjusting the coastal protection schemes so they could withstand a higher sea level
- to assess additional vulnerability of the low-lying coastal areas, in particular with respect to local drainage and decreasing wetland stability (Wadden Sea and other wetlands).

The data collected for the national vulnerability study were put together in a Geographic Information System (GIS) database, combining, for the first time, contingent topographic and economic information for the whole coastal region of Germany across state boundaries (EBENHOEH, STERR, and SIMMERING, 1996 map scale 1:200,000; see Table 3). The data were aggregated on the basis of statistical information at state and county level (macroscale), but were not found to be sufficiently specific and conclusive to enable regional authorities to consider in detail the existing coastal defence and adaptation schemes.

Meso-Scale Assessment of Schleswig-Holstein

A more detailed analysis of the state of Schleswig-Holstein was undertaken. This region was chosen for two reasons. First, it contains all the types and elements of vulnerable coastal systems in both the North and Baltic Sea regions. Second, in the late 1990s 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 considering sea-level rise and climate change in future planning (HOFSTEDE, 1997).

Schleswig-Holstein is the most northerly state in Germany and has an area of 15,731 km² and a population of about 2.7 million (Figure 6, Table 3). The state is situated between the Baltic Sea in the East and the North Sea in the West (Figure 1). A large part of the state lies in the coastal zone, where most of the population is concentrated. The largest cities, Kiel and Luebeck, are important harbours at state level. The Baltic Sea coastline of Schleswig-Holstein measures 535 km and is composed of coastal lowland (348 km), cliffs (148 km), and various (anthropogenic) coasts (39 km). The total area of coastal lowlands (below 5.0-m contour line) is 480 km²; 178,000 people live within this area.

The west coast of Schleswig-Holstein is part of the Wadden Sea and lies between Skallingen in Denmark and Den Helder in The Netherlands. Today the Wadden Sea of Schleswig-Holstein occupies an area of 2759 km², 434 km² of which are islands and saltmarshes. The total length of the coastline measures 564 km, 297 km of which belong to the mainland and 267 km are island coastlines. Intensive diking in the last nine centuries has resulted in the reclamation of an area of about 3514 km² of former intertidal areas.

The assessment for the state is based on aggregated data sets. The following data from different sources were compiled and processed to create a homogeneous, geo-referenced database (Figure 7) (HAMANN and HOFSTEDE, 1998).

- Physical geographical data such as elevation from a digital terrain model (DTM)
- Topographical structures from maps, scale 1:50,000–1:25,000 (roads, settlements, *etc.*)
- Land-use data (Landsat-TM images)
- Socio-economic data (municipal and district statistics)
  - inhabitants
  - houses
  - roads/infrastructure
  - motor vehicles
  - livestock

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Table 3. *Vulnerability assessment with a 1-m sea-level rise scenario for each of the five coastal states and all of Germany (from Ebenhoeh, Sterr, and Simmering, 1996).*

	Coastal States						
VA Parameters	Niedersachsen	Bremen	Hamburg	Schleswig-Holstein	Mecklenburg-Vorpommern	Total Costal Region	Whole Germany
Length of coastline (km)	880 (23.8%)	55 (1.5%)	60 (1.5%)	995 (26.9%)	1710 (46.2%)	3700	100%
Total area (km²)	47,430	404	755	15,650	23,400	87,640	23.4%
Affected area (km²)							
a) Up to +10 m above MSL (OD)	9400 (20%)	372 (92%)	227 (30%)	5062 (33%)	n.a.	15,061	4.20%
b) Up to +5 m above MSL (OD)	6900 (15%)	323 (80%)	150 (20%)	4000 (26%)	2210 (9%)	13,583	3.8%
Affected population (= people living in area b above)	1.46 Mio (19%)	631,000 (92%)	180,000 (11%)	633,000 (23%)	319,400 (17%)	3.22 Mio	3.9%
People at risk (in 1995) (affect. population * flooding probability)	14,600	6300	1800	5600	1480	29,800	0.03%
People at risk in 2100							
a) Without measures	146,000	63,000	18,000	45,000	37,000	309,000	0.32%
b) With measures	14,000	7000	2060	5000	2000	30,000	0.04%
Affected values (billion DM)							
a) Below +10 m contour	331.4 (18%)	174.2 (92%)	75.4 (16%)	165.2 (24%)	75.2 (17%)	821.4	4.5%
b) Below +5 m contour	244 (13%)	151 (80%)	51 (9%)	124 (18%)	80 (9.5%)	650	3%
Statistical yearly loss (billion DM) in 2100 given 1 m SLR (affect. values * flooding probability)	3.3	1.7	0.75	1.5	0.35	7.5	0.05%
Value at change = other impairments							
Increase of artificially drained area	1070 (50%)	—	—	550 (30%)	100 (100%)	1720 (km²)	
Increase of area with salinization	+10%	+10%	—	+10%	+5%	—	—
Loss of wetland area (tidal flats, salt marshes in km²)						estimated	
a) Without measures	1100 (52%)	—	—	1250 (45%)	45 (−20)	2400	—
b) With measures	1200 (57%)	—	—	1530 (55%)	110 (50%)	>2800	—
Annual protection costs (million DM): (presently)	90	no data	60	60	50	>26	
Projected annual protection costs (until 2100)	>120	>20	>100	>90	>80	>410	
Additional costs for artificial drainage and groundwater management by 2100	+50%	—	—	+60%	+200%	estimated >500 Mio DM	

- quality of agricultural soils
- touristic capacity of coastal communities (number of beds)
- number of jobs and employees for 10 different sectors of economy
- gross increment value and tax yield (running economic results)

This study indicated that the areas defined by the 10 m/5 m contour lines (*i.e.,* the inward boundaries at the macroscale) would not entirely be at risk from a further sea-level rise of 0.5–1 m. Instead, local topographic features such as second dike lines or road dams would provide inland flood protection, and these were used to define more accurately the vulnerable areas (see Figure 6). In the case of a dike-breach, only the area between the first and second dike-line was assumed to be flooded. This area represents 1500 km² and has a population of 142,000. Furthermore, there are a number of detailed socio-economic elements, such as technical, tourist, and traffic infrastructure, which are relevant for risk assessment, but these could not be included in the macroscale (national) study. Consequently, the potential risk in economic terms increases when the resolution of the analyses is higher (see Table 2). Moreover, available information on the prevailing adaptation to storm flood hazards, in particular on the existing dikes, needed to be considered in greater detail to realistically describe the present and future exposure of coastal segments to flooding and erosion 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 VA (HAMANN and HOFSTEDE, 1998; see Figure 7).

This analysis was particularly useful to emphasise to what extent (improvement of) coastal protection and accommodation strategies may be necessary when considering sea-level rise and storm flood scenarios on a subregional scale. With respect to the assessment of economic and ecological vulnerability as well as possible options for improvement of adaptation, there were still shortcomings found in the meso-scale results. Even on the state level the socio-economic assessment used aggregated (usually statistical) data to quantify the values possibly threatened by sea-level rise. Therefore, even more detailed information is needed to precisely deter-

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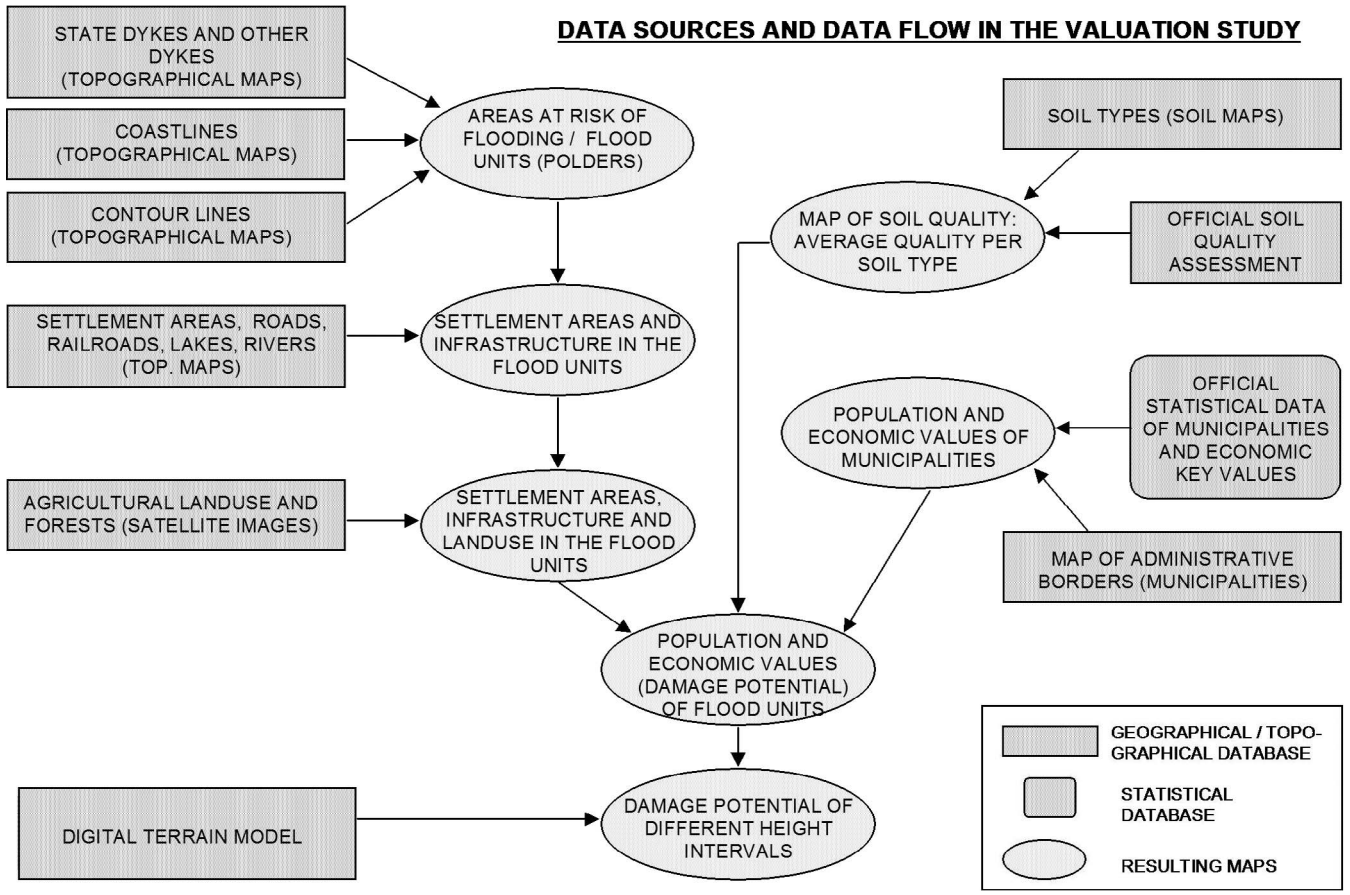


Figure 7. Data sources and step-wise GIS procedure in the meso-scale vulnerability study of the State of Schleswig-Holstein.

mine the full range of risks from flooding, erosion, or saltwater intrusion for individual communities. Recent studies by YOHE *et al.* (1998) and WEST and DOWLATABADI (1999), who studied sea-level rise impacts on developed coasts in the United States at the community scale, showed that it is not sufficient to consider only the incremental depreciation of existing values and the benefits of gradual adaptation processes. Instead, the local effects of all impacts, including extreme storm events, must be taken into account and balanced against the incremental adjustments likely to occur in coastal communities.

Microscale Assessments (Within Schleswig-Holstein)

In Germany, a number of "close-up assessments" have been carried out since 1998 to define the full range of expected ASLR-related impacts at the local level and to describe detailed options for protection and adaptation at community scale. Two examples are the local studies carried out by REESE (1997) for the tourist town of St. Peter-Ording on the North Sea coast and by MARKAU (1998) for the town of Eckernfoerde on the Baltic Sea coast. These studies confirmed the observational trend from the meso-scale study that more economic assets are detected to be at risk when the focus of the assessment is narrowed (Table 2).

RESULTS

Vulnerability within the coastal zone is scale-dependent, at least from a socio-economic perspective. When comparing results from national, state, and community assessments (as shown in Table 2) the relevant assets and values describing economic vulnerability increase whereas the size of the study area decreases. This must be considered when weighing costs *vs.* benefits of ASLR adaptation schemes for coastal communities.

The results of the national vulnerability study are summarized in Table 3 and include estimates for the potential area, coastal population, and total capital values at risk (see Figure 5). The five coastal states are listed separately (columns 1–5); the total coastal region is summed up in column six and related to the whole country (Federal Republic) in column seven. In all five coastal states a maximum of 15,061 km^2, corresponding to the land area below 10-m OD[1] is con-

[1] Amsterdam Ordnance Datum.

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sidered to be in danger of flooding. A second calculation was made for the flood area scenario by using the 5-m OD contour line for an inward boundary because the meso-scale study showed this approach to be more realistic. This scenario yields an area of 13,583 km² as potential risk area (in the following text the numbers relating to this smaller area are given in square brackets). This corresponds to 4.2% [3.8%] of the total land area in Germany. There are an estimated 3.22 [2.97] million inhabitants (*i.e.,* population affected) currently living in the area, and regional statistics show that just under 1.2 million jobs would be affected.

Bremen, with 92% of its area situated in the low-lying Wesermarsh, is conspicuously the coastal state most exposed to sea-level rise as it is followed by the state of Schleswig-Holstein, which has 33% of its state area exposed. Other states have less area at risk: Hamburg (30%), Lower Saxony (20%), and Mecklenburg-Vorpommern (9.5%). The picture for population affected in each state is similar to that of area at risk (see Table 3): *i.e.,* Bremen is again the most affected, with 92% of all inhabitants at risk according to this scenario, followed by Schleswig-Holstein (23%), Niedersachsen (19%), Mecklenburg-Vorpommern (17%), and Hamburg (11%). This low percentage for Hamburg is due to the fact that much of Hamburg's territory lies on higher ground, *e.g.,* on terminal moraines. However, virtually all of Hamburg harbour, by far the most important port of Germany, is within the potential flood zone.

In addition to the parameters of affected area and population, accumulated capital values were assessed for an overall estimation of the total vulnerability. In an overview analysis not all economic sectors could be considered independently. Therefore, values for the economic utilisation of an area were calculated using the cumulative capitalisation approach explained in Figure 5. It is important to note that the total sum of property values calculated in this way is a statistical quantity, which cannot be verified in practice. However, it is important as a basis for estimating and justifying efforts for the protection of coastal investments. The capital values calculated for the five states (in 1995 prices) are between 75 [51] billion DM[2] (Hamburg) and 331 [244] billion DM (Niedersachsen); the total sum of all capital values amounts to 821.4 billion DM [650 billion DM] (Table 3).

According to the IPCC common methodology, the exposure of population and capital values to ASLR, *i.e.,* to storm floods, erosion, and saltwater intrusion, describes the actual threat to a particular area from the probability of flooding and thus is equivalent to a likely estimate of loss. According to the Coastal Protection Master Plan (MLR SCHLESWIG-HOLSTEIN, 2001), this flooding probability is presently assumed to be 1 in 100 years for the North Sea coast, and a medium (hypothetical) frequency 1 in 250 (range from 1 in 100 to 1 in 1000) for the Baltic (Table 1). The (statistical) annual vulnerability of the coastal region is calculated by multiplying the population or capital values in the flood zone with the respective probability of flooding, termed "at risk". Following the common methodology, these figures show the number of people and capital values affected annually by flooding (Table 3). Nationally, fewer than 30,000 people are at risk based on the current probability of flooding, which includes a moderate historical sea-level rise of 15–25 cm (Table 1).

The probability of future flooding, if sea level rises by 1 m, is much greater and will grow by a factor of at least 10 in both coastal regions. Consequently, the currently valid numbers for people and capital values at risk would, without further coastal protection measures, increase tenfold by the year 2100. Therefore, 309,000 people and capital values of 7.5 billion DM are faced with an annual flood risk in the German coastal zone (Table 3).

When considering the overall damage potential of 650–820 billion DM (realistic *vs.* worst-case projection) in the German coastal zone, it becomes obvious that coastal protection on the North and Baltic Seas will continue to be extremely important for the coastal states' future economies. Even today, vast areas would be flooded daily or periodically in the absence of defence structures. Therefore, the VA also had to consider the condition and standards of coastal protection in the investigated region as well as the costs of future coastal protection improvements in accordance with the scenarios. Also, the costs of other accompanying measures, remaining risks, or resulting losses must be taken into account. In a local-scale pilot study for the Wesermarsh district a complex analysis and evaluation model was developed that considered coastal utilisation and existing coastal protection as well as investments necessary for further protection improvements and the respective cost–benefit relationship (EBENHOEH, STERR, and SIMMERING, 1996, Figure 8).

The national assessment also outlines further aspects of vulnerability of the coastal system in the region, such as the values at change referred to in the common methodology (BIJLSMA *et al.,* 1992). The term "values at change" (see Table 3) comprises the change or deterioration of coastal system components resulting from the effects of sea-level rise. This is particularly relevant for those components that cannot be easily valued in monetarily terms (KLEIN and BATEMAN, 1998; TURNER, ADGER, and DOKTOR, 1995). In the North and Baltic Sea regions, these components include

- the reduction of sandy beaches and of dune ecosystems by erosion
- the problem of higher water levels for the terrestrial drainage of flat areas
- increased intrusion of saltwater into groundwater and soil caused by higher mean sea level
- permanent submergence (*i.e.,* loss) of beach zones and coastal wetlands.

Although these sea-level related changes are of major concern in terms of coastal vulnerability, German coastal authorities have so far not considered them to the same extent as changing flooding risks. Beach and dune erosion, as well as terrestrial drainage, are addressed to a certain extent in the context of coastal defence schemes, as discussed later. The national assessment estimated that the area requiring artificial drainage after a 1-m sea-level rise will increase between 30% and 100% depending on regional topography. Overall, an area exceeding 1700 km² is likely to suffer from

[2] For reference; Euro conversion rate 1 € = 1.96 DM.

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severe drainage problems in this scenario (Table 3). Other values at change such as groundwater salinization within agricultural marsh areas have hardly been addressed. A first-order estimate indicates a 10% increase in saltwater intrusion, but the economic implications have yet to be evaluated. The most difficult and perhaps also the most crucial impact of future sea-level rise appears to be on coastal ecosystems. Along the North Sea, a decrease or total loss of coastal wetlands, such as tidal flats (Wadden) and salt marshes, seems likely as a result of "coastal squeeze" (the transgression of the sea across these wetlands, which are prevented from migrating landward by existing dike structures). It is possible that more than 2800 km² of wetland areas might be lost in Niedersachsen and Schleswig-Holstein. On the other hand, a rising sea level could lead to an extension of wetlands along the Baltic coast of Mecklenburg-Vorpommern if no new obstructing dikes are built (Table 3).

A comparison of the national assessment and the meso-scale vulnerability study of Schleswig-Holstein (Figure 6) produced three major results (HAMANN and HOFSTEDE, 1998).

- The vulnerability for the study region is of the same order of magnitude in both studies.
- For Schleswig-Holstein, the risk area is smaller in the meso-scale study, being about half the size of the previously defined area of 4000 km², because local topographic features are used for a more detailed delineation of the flood zone. Here, it was possible, for instance, to calculate the actual flood-hazard areas within coastal communities formerly considered to lie completely within the risk area.
- The sum of capital values within the risk zone is higher when compared to the (reduced) size of the affected area in the national study; the values calculated from the macroscale study are 31 million DM per km² within Schleswig-Holstein, whereas the meso-scale assessment for this state yielded 48 million DM per km². This is because more detailed information from state and communal economic statistics could be used. The overall sum of capital values from the meso-scale assessment yielded a risk potential of 95 billion DM for the State of Schleswig-Holstein. This study also enabled a more detailed delineation and description of coastal segments where the risk potential is concentrated.

The findings from Schleswig-Holstein are thought to be generally valid for the other coastal states; working with more detailed maps and data will yield a more realistic, *i.e.,* more confined exposure area, but identify a wider range of vulnerable assets. Thus the overall economic vulnerability remains approximately the same as calculated in the national assessment.

At the microscale level, the specific vulnerability for selected coastal communities can be assessed in even greater detail with a high input in research time and labour. By mapping local topography and the distribution of houses, infrastructure, and economy, it is possible to view site-specific hazard conditions in a three-dimensional pattern, *i.e.,* topographic discretion at 1-m contour intervals enables differentiation of risk levels according to vertical distribution as well. For example, in the local assessment for the town of Eckernfoerde on the Baltic coast (25,000 inhabitants), the economic/capital vulnerability amounted to 975 million DM, half of which is situated at the risk elevation zone between 2-m and 3-m elevation (MARKAU, 1998). However, a large part of the population living in the risk zone (about 3300) is situated at low levels, *i.e.,* below 2-m elevation. When calculating the amount of capital values at risk for people living in the risk zone, the microscale study yields a much higher figure, *i.e.,* 300,000 DM per capita *vs.* 200,000 DM per capita from the macroscale analysis.

The comparison of studies at different scales shows that results from socio-economic VAs greatly depend on the scale chosen for the assessment. From the observation that the specific vulnerability increases when "zooming-in" from the national to the local level, it is concluded that, with respect to adaptation policies, a community-based evaluation is preferable to an approximated national assessment. The approach taken in Germany, on the other hand, has been a rather time-consuming and expensive one. From the start of the national VA (in 1993) to the end of the microscale studies (in 2002) approximately one million US$ was spent over a period of nearly 10 years on the research described above and in Table 2, yielding an ample GIS database. The insights gained were derived by a step-wise procedure decreasing in scale. The macroscale VA served as basis for the meso-scale analysis from which microscale studies could finally be launched. Thus for countries or regions where no information on coastal vulnerability yet exists (and given the usual constraints in time and financial resources), a scoping study at the national level would be the best place to start. This would give a valuable overview of the general aspects of a coastal region's sensitivity to ASLR and assist in pinpointing vulnerable areas and socio-economic assets showing specific conditions of present and future risks.

ADAPTATION TO SEA-LEVEL RISE AND COASTAL ZONE MANAGEMENT IN GERMANY

Germany's coasts have suffered from severe storm flood impacts and related catastrophes for centuries. In the upcoming decades, the combined effects of an accelerated sea-level rise and likely changes in storminess will create a considerably increased danger of flooding along the Baltic and even more so for the North Sea coast. In many places, this problem is exacerbated by coastal erosion. Therefore, these risks need to be countered by extensive flood defence systems and also, locally, by protective measures for erosion (HOFSTEDE, 1996; STERR and PREU, 1996).

Along the North Sea, coastal communities and authorities have fought rising sea level for many centuries and established dike protection along the entire low-lying mainland coast (GOELDNER, 1999). Along the East and North Frisian islands, only the densely populated areas are protected by dikes. Additionally, almost all tide-influenced tributaries of the Ems, Weser, Elbe, and Eider have been protected by storm surge barriers since the 1950s. However, the slow subsidence of the older marsh areas (*i.e.,* the first ones to be protected by dikes) near the edge of the upland area creates a particularly difficult situation for coastal protection and

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terrestrial drainage. Furthermore, it has been observed that the heavy weight of dikes causes them to subside, while at the same time the calculated water level is rising. In the past, coastal engineering design had not taken these problems fully into consideration because acceleration of sea-level rise due to climate change had not been seriously considered by coastal authorities. As a result, coastal protection standards in some areas are now insufficient for a drastic sea-level rise scenario, requiring new evaluation of the required dike heights and the resulting costs. Taking a regional perspective, the dikes are not in an adequate condition in some areas of Niedersachsen (mainly in the district of Weser-Ems). Even without the extreme 1-m ASLR scenario, costs of 1.1 billion DM have been estimated for the reenforcement of the dikes there in the next 20 years and beyond.

Along the Baltic coast, little more than a quarter of the total coast is protected from flooding by dikes, revetments, and other protection systems. Many existing dikes do not fulfill the requirements for the calculated water level determined during the most catastrophic storm flood of 1872, and even without considering an increasing sea level, the costs for coastal protection total 200–300 million DM annually.

Consequently, based on a 1-m ASLR scenario, the current (annual) coastal protection costs of the five coastal states is generally <400 million DM/y. This sum does not yet include the so-called "soft coastal protection" (*i.e.,* beach nourishment, dune protection, *etc.*). Along the Baltic coast a 30–50% increase of the erosion on beaches and steep coasts has been observed as a long-term medium value. In the 1-m rise scenario, total protection costs will need to include measures that will address this problem at an estimated cost of 50–100 million DM/y. If the sea level on the North Sea were to rise significantly, efforts and cost requirements for the protection of the terrestrial drainage would be higher. Most floodgates currently allow the natural drainage of inland waters at low tide cycles. This would have to be changed to pumping drainage stations (as used widely in The Netherlands) in order to pump the water out continuously. Continuous pumping is the only way to avoid saltwater intrusion into the soil and groundwater and to protect agricultural utilisation. Expert opinion estimates that in the assumed extreme scenario, the cost of drainage measures in the three North Sea states might correspond to those of the dike construction costs and might possibly be higher (Table 3).

In Germany, responsibility for coastal adaptation measures is shared between local communities and the state government according to their coastal defence master plans. Decision-making for coastal protection with respect to adjusting to future threats from accelerating sea-level rise has not therefore followed a uniform path across state and community borders. Since 1995, however, the VAs reported here have sparked some fruitful discussions with some of the responsible coastal authorities about long-term adaptation strategies. Based upon our results and the findings from other local risk assessments, some coastal sections are less vulnerable than others according to the population and capital values distribution. With regard to the immense and growing costs for the maintenance of an adequate coastal protection standard, politicians and authorities are gradually looking for an optimising strategy to combine greatest benefits (*i.e.,* high safety) with reasonable expenses. Hence, whereas it is clear that protecting people's lives will remain the top priority, it also becomes obvious that in the long run, spatially differentiated adaptation strategies will be more appropriate, if not unavoidable. Consequently, defence strategies for economically less important coastal sections should be reconsidered and perhaps changed into a strategy of protecting only areas of greater importance. In addition to the obvious economic criteria, such future-oriented flexible strategies would also contribute to stabilizing the coastal ecological system. These measures could probably ensure that dramatic changes, in particular large-scale losses of wetland habitats, might be avoided and that the existing littoral ecosystem values and functions could be sustained (EBENHOEH, STERR, and SIMMERING, 1996; STERR and PREU, 1996; WCC '93, 1994).

First steps in this direction have been initialised in two states (Schleswig-Holstein and Mecklenburg-Vorpommern), which address the issues of possible retreat and natural coastal system adjustments in their protection master plans as possible long-term options. The coastal population, on the other hand, has thus far been strongly opposed to a strategy of "giving way to the sea" wherever specific measures toward this objective have been discussed so far (GOELDNER, 1995). In order to change coastal management practises it will therefore be crucial to follow a long-term participatory approach via coastal fora involving politicians, authorities, coastal communities, scientists, and nongovernmental organisations in a long-term dialogue about policy options. In this context, it is viewed as a positive sign that cooperation between coastal protection authorities and research institutions have greatly improved in recent years and more emphasis is now put on detailed scientific analyses of natural and socioeconomic vulnerability aspects. It has been recognized that decisions of how to respond to a given threat, for example by building a seawall or enhancing beach nourishment activities, ought to be based on community-based assessments of flooding or erosion risks and tailored to local needs. Similarly, it is only at this microscale level that the coastal population can make decisions on the possible benefits of flood insurance or on site-specific economic investments.

CONCLUSIONS

Germany is not a typical coastal nation such as Great Britain or The Netherlands, as most of its territory is both far from the sea and lying at elevations well above flood levels. Nevertheless, the length of coastline and sizeable areas of low-lying land near the North Sea and Baltic Sea are responsible for the significant vulnerability of this country to impacts from accelerated sea-level rise. Considerable risks exist for the German coastal population and economy (but less than in The Netherlands and higher than in Poland) (NICHOLLS and MIMURA, 1998; VAN KONINGSVELD *et al.,* 2008; PRUSZAK and ZAWADZKA-KAHLAU, 2008) as a result of the anticipated sea-level rise, which is bound to shorten the recurrence intervals of devastating floods. The long-term strategy of defending the coastline at its present position by dikebuilding and other costly structural measures has kept these

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socio-economic risks under fair control up to now, although storm floods have repeatedly caused serious damage. Accelerated sea-level rise from climate warming, however, will strongly increase future threats and costs for adaptation in upcoming decades. VAs on the national, regional, and local scale for Germany show that the range and extent of risk increases with the levels of detail. This means that specific adaptation measures, such as structural designs, have to be planned mostly at the community level. Generally, the costs for such measures will greatly exceed previous expenses for coastal protection. As these costs become an increasingly high burden to the national and regional economies, it might be preferable to reconsider the traditional adaptation policy of static defence. Instead, more flexible response options, such as partial set-back of dikes in areas with low population density, could offer more sustainable solutions to the aggravating problem of coastal squeeze, which is threatening coastal wetlands, mainly along the North Sea. Perhaps in view of the high vulnerability of these valuable ecosystems (tidal flats, salt marshes, and dunes) the coastal population and decision-makers in Germany will gradually adjust the long-term adaptation policies (MLR SCHLESWIG-HOLSTEIN, 2001).

The experience gained in Germany with three different levels of VA carried out on two differing coastal regions has provided interesting insights into coastal VA methodologies, which can hopefully be applied to other regions of the world. A scoping study at the national level usually serves the need for basic information to politicians and decision-makers on the overall risk situation in the coastal zone. Depending on the methodological approach chosen and on the amount of time and work invested, it should yield information on key aspects of vulnerability such as the nature of the most serious impacts (inundation, storm flood hazards, erosion, freshwater, and soil problems, *etc.*), the land area possibly affected, the number of people and approximate capital values distributed in this area, the most vulnerable coastal segments (*i.e.,* vulnerable "hotspots"), and the most likely increase in risk from ASLR. In many cases, information gained from a scoping study will suffice for the consideration of meaningful basic adaptation strategies at the (national) political level or for seeking monetary/technical assistance outside the country to counteract the recognized risk. On the other hand, such a macroscale assessment can consequently serve as a working basis for focusing on the coastal segments or communities found to be the most vulnerable ones. At these locations, where adaptation measures are considered urgent to save people's lives and valuable economic assets from threatening losses, local-scale assessments should be carried out in high detail (and if possible based on GIS-technology). This would provide guidance to local coastal managers for the consideration of adaptation measures (*e.g.,* community hazard maps, flood control structures, erosion control, warning systems, *etc.*) and the cost/benefit evaluation of such measures. In countries where general coastal defence and management responsibilities lay neither at a national nor at a local level, such as Germany, it can be helpful to also assess the regional vulnerability at somewhat greater detail (meso-scale) to assist the state or district administration on adaptive policy-making, *e.g.,* preparing coastal defence master plans. In Germany, results from VAs at all scales have greatly contributed to making the considered adaptive strategies more acceptable with the coastal population.

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□ ZUSAMMENFASSUNG □

Die deutsche Kuestenzone erstreckt sich ueber insgesamt 3.700 km (davon 1590 km Nordseekueste und 2110 km Ostseekueste) und ueber fuenf Bundeslaender. Zwei davon sind große Hafenstaedte (Hamburg und Bremen), die anderen drei umfassen laendliche Raeume mit einer Reihe von kleineren und mittleren Kuestenstaedten. Große Bereiche des Kuestentieflandes an der Nordsee ebenso wie an der Ostseekueste sind von Sturmfluten und Erosion bedroht. Daher stellt ein beschleunigter Meeresspiegelanstieg ein hohes Gefaehrdungspotential jetzt und kuenftig dar. Wasserstandsanalysen zeigen, daß bei einem Szenario eines Meeresspiegelanstiegs von 1 m die zerstoererischen Sturmfluten 10 bis 100 mal haeufiger auftreten koennten als bisher. Daher wurden in Deutschland Gefaehrdungsabschaetzungen vorgenommen und zwar fuer den gesamten Kuestenraum im groben (Gebiete unterhalb 5 m Hoehe), fuer das Kuestenland Schleswig-Holstein in groeßerem Detail und fuer einzelne Kuestengemeinden dieses Landes in hoher Aufloesung. Im Vergleich dieser verschiedenen Maßstabsebenen zeigt sich, daß der Umfang der oekonomischen Gefaehrdung bei großmaßstaeblicher Betrachtung am hoechsten ist, weil alle Detailstrukturen erfaßt werden koennen. Andererseits koennen die tatsaechlichen Risikoraeume auf lokaler Ebene genauer eingegrenzt werden, was die ueberflutungsgefaehrdete Flaeche verringert. Demnach waeren bei einem kuenftigen Pegelanstieg von 0,5 bis 1,0 m in den Siedlungsgebieten mehr als 300.000 Personen gefaehrdet und Sachwerte in Hoehe von mehr als 300 Mrd. US$ potentiell betroffen. Daher setzen die Kuestenlaender auf strikte Kuestenschutzmaßnahmen (v.a. Deichbau). Andererseits sehen die Behoerden weiter steigende Ausgaben fuer den Kuestenschutz voraus. Insgesamt ist mit mehr als 500 Mio US$ fuer Maßnahmen im Hochwasser- und Erosionsschutz in den kommenden Jahrzehnten zu rechnen, die allerdings von der Wirtschaftskraft der Bundes- und Laenderregierungen aufgebracht werden koennten. Dagegen wird sich bei steigenden Meeresspiegel und starrer Verteidigungslinie der Druck auf die Kuestenoekosysteme weiter verstaerken und diese zunehmend in ihrer Existenz bedrohen. Gegenwaertig ist noch keine Abhilfe gegen diese Art der oekologischen Kuestenverwundbarkeit in Sicht.

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