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Assessing the impact of climate change on the Weser estuary region: an interdisciplinary approach

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ABSTRACT: In an interdisciplinary project involving life, engineering and socio-economic sciences, the sensitivity to climate change of the hydrologic, ecological and socio-economic properties of the inner Weser estuary and its marshes are analysed and different response strategies are developed and evaluated. To manage the complex interdisciplinary research process, the project has been organised with a stringent 'vertical' and 'horizontal' structure. The 'scenario approach' is used to take uncertainty into account. The climate change scenario for the year 2050 includes a sea level rise, an increase in tidal amplitude and mean temperature (especially in spring and winter) and an increase in precipitation and wind speed. In the absence of countermeasures a multitude of 'negative' primary effects can be expected, including overtopping of dikes by waves, submersion of forelands, changes in freshwater inflow, residence time and water quality in the estuary and water levels in the drainage systems of the marshes. However, the overall impact for the region can primarily be assessed as 'medium' and, if possible mitigating measures are taken into account, overall impact should be 'low'.

KEY WORDS: Climate change · Impact · Estuary · Regional scale · Interdisciplinary · Uncertainty

1. INTRODUCTION

In the first IPCC Assessment Report (IPCC 1990) it was already deemed necessary to apply a multidisciplinary approach to the evaluation of climate change in assessing the consequences of both environmental and socio-economic impacts. For coastal regions a 'Common Methodology' has been developed by IPCC, focusing on the environmental, socio-economic and political consequences of a rise in sea-level of 1 m, the consequences of flooding and on the ability of the socio-economic system to take adaptive measures.

A study using this 'Common Methodology' has been carried out for the German coast by Ebenhöh et al. (1997). They evaluated the possible consequences in the absence of counter-measures as 'medium' on a global scale. If countermeasures are taken into account, the consequences are evaluated as 'low'. However, it is obvious that the German North Sea coast has to expect major impacts if countermeasures are not taken (for The Netherlands see Den Elzen & Rotmans 1992) and that a more detailed analysis of sensitivity and vulnerability on a reduced spatial scale will be necessary, incorporating other climatic factors as well as adaptation or mitigation strategies and possible political developments (see also Warrick & Rahmann 1992).

Thus the German Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF) has initiated the research programme 'Klimaänderung und Küste' (Climate Change and the Coast), which includes 2 interdisciplinary studies in representative areas of special interest. One is related to the island of Sylt in the northern part of the

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Wadden Sea; the other (KLIMU) focuses on the region of the Weser estuary in northern Germany. The 3.5 yr study was concluded at the end of 2000.

2. THE STUDY AREA AND ITS ANTICIPATED VULNERABILITY

The assessment of climate change impact was performed for the region in and around the Weser estuary in Germany, a typical North Sea coastal area (Fig. 1). The study area covers ~1400 km^2 and includes the inner estuary, the accompanying lowlands (mostly used as agricultural land) and several cities and villages along the shores.

The Weser river drains into the German Bight, developing a 120 km long funnel-shaped estuary, running through the north German lowlands and the Wadden Sea. The catchment area extends over 44 000 km^2 between the central highlands of Germany and the North Sea coast. Climate is influenced predominantly by the Atlantic; the average discharge of the Weser amounts to about 320 m^3 s^{-1}, with high discharge (1–2 $\times$ 10^3 m^3 s^{-1}) in February and March, and low discharge ($<$100 m^3 s^{-1}) in August and September.

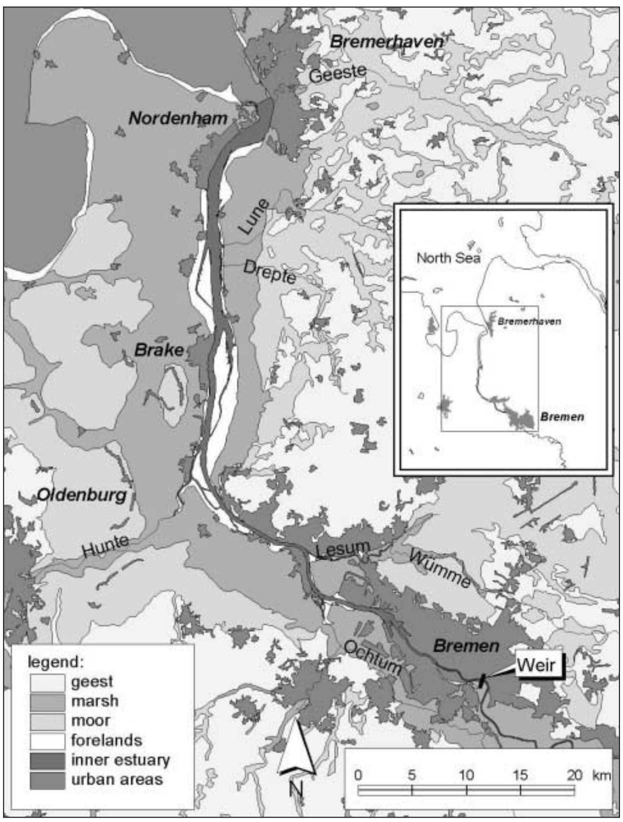

Fig. 1. Map of study area

The mesotidal to macrotidal coastal plain estuary has 3 distinct parts: the outer estuary, stretching from the port of Bremerhaven to the outer limits of the Wadden Sea (55 km) with a salinity greater than 18 psu (for average discharge); the middle estuary, between Bremerhaven and the tributary Lune (~15 km), dominated by brackish water of 1 to 18 psu; and the 50 km long inner estuary, with freshwater under tidal influence. The tidal range is 3.6 m in Bremerhaven and increases to about 4.2 m in Bremen as a result of several deepening measures, mainly of the inner estuary, for shipping purposes. In Bremen the tides are confined by a tidal weir (Grabemann et al. 2001, this issue).

The region considered in this study comprises coastal and estuarine lowlands (the 'Wesermarsch') with elevations of 0 to 2 m above sea level. The overall coastline is protected by dikes, which prevent tidal and storm-surge flooding of the lowlands. The 'Wesermarsch' is densely streaked with ditches and a complex drainage and irrigation system. Irrigation with fresh water derived from the inner estuary is in fact needed in order to suppress brackish groundwater and to keep the ditches filled with freshwater in summer (Kunz 1993). In the plains, pastures prevail for the production of cattle and milk. Rural villages lie along the estuarine banks, along old routes and on the slightly elevated bordering glacial hills. Two ports dominate the region, Bremen and Bremerhaven, with populations of 560 000 and 125 000 respectively. About 1 million people live in the region as a whole.

Regional sensitivity to climate change is caused by (Schirmer & Schuchardt 1993, Sterr & Simmering 1996): low elevation, from below sea level to only a few metres above; the dependence on dikes for flood control; the dependence on irrigation and drainage systems; the transfer of marine signals, such as tides and storm-surges, <70 km inland via the deepened Weser estuary; the exposure of the river mouth to northwesterly gales; additional impact from changing river discharge; the existence of rare brackish water habitats; and densely populated urban areas, with high economic activity and value.

3. AIM AND APPROACH OF THE PROJECT

3.1. Aim

The aim of the study is to perform an integrative analysis of the sensitivity to climate change of the hydrologic, ecological and socio-economic properties of the inner Weser estuary and its marshes and to develop and evaluate different response strategies. The results of the study are intended to form the scientific basis for an action-oriented public discussion in the region on how to handle the risks, the uncertainties and the consequences of climate change and on the response options. It can be regarded as a part of an 'Integrated Coastal Zone Management' process (EC 1999). The project is to provide answers to the following questions: what changes in hydrologic, ecological, economic and social properties can be expected from a change in climate that manifests itself through accelerated rise in sea level and ambient temperature, changes in precipitation and in prevailing winds; what will be the impact of climate change on the region as a whole; can we identify especially sensitive features of the natural system and in society; what consequences for individual and collective action can be expected; what may be the responses of coastal protection and what secondary problems could arise from their implementation; what social conflicts can be expected due to climate change; what will be the trends in future development of the region and what might be the consequences for climate change impact?

3.2. Approach and structure

To answer this complex set of questions, an interdisciplinary approach was required and a group of 8 subprojects, including natural, engineering and socio-economic sciences as well as a subproject for integration, has been put together (see Table 1). Four subprojects are directly concerned with different aspects of hydrology and coastal protection. Estuarine water levels and water quality aspects are handled by GKSS, Geesthacht, using a 1-dimensional numerical hydrodynamic and water quality model. The main task involves determination of the change in water level, the tidal signal and additionally of the water quality in the inner Weser estuary (see Grabemann et al. 2001). River discharge and the water management systems in the adjoining marshes are modelled by the Leichtweiss Institute at the Technical University of Braunschweig, while the Universität Hannover is responsible for modelling the groundwater system, including water levels and salinity. Another important aspect, coastal protection, is dealt with by the Franzius Institute at the Universität Hannover. It analyses the probability of overtopping by waves, with regard to future water levels and the additional impact of modelled wind-generated wave heights.

The impact on regional ecological systems, including the aquatic, the amphibious and the terrestrial range, are analysed by a subproject based at the Universität Bremen (see also Osterkamp et al. 2001, this issue). Two other subprojects at the University of Bremen are

Table 1. Participating groups (subprojects) in the KLIMU project

Task (key words)	Methods	Leader(s) of working group	Institution
Modelling of estuarine water level & quality	Numerical modelling	A. Müller I. Grabemann	GKSS Research Centre, Geesthacht grabemann@gkss.de
Modelling of inland water level, river discharge, water exchange between estuary & inland waters	Numerical modelling GIS	U. Maniak	Leichtweiss Institute, Technical University of Braunschweig u.maniak@tu-bs.de
Modelling of groundwater levels & salinity, soil moisture	Numerical modelling	B. Hoffmann	Universität Hannover meinken@mbox.iww uni-hannover.de
Coastal protection, probability of overtopping by waves, measures, costs	Numerical modelling Risk analysis	C. Zimmermann N. von Lieberman	Franzius Institute, Universität Hannover nicole@fi.uni-hannover.de
Ecological aspects, biotope types, species composition, land use	GIS	M. Schirmer	Department of Biology Universität Bremen schi@uni-bremen.de
Spatial demands, regional planning, agriculture, tourism	Interviews	G. Bahrenberg	Department of Geography Universität Bremen gbah@uni-bremen.de
Regional economic structure & consequences, social dynamics	Interviews Econometric modelling	W. Elsner	Department of Economics Universität Bremen welsner@uni-bremen.de
Integrative analysis, coordination, interdependencies, evaluation of impact	GIS	M. Schirmer B. Schuchardt	Universität Bremen schi@uni-bremen.de BioConsult schuchardt@bioconsult.de

working on socio-economic consequences, using *inter alia* expert interviews and an econometric model of the region. For the purpose of integrating the various groups and methodological approaches, a separate integration sub-project was launched.

3.3. Interaction between natural and socio-economic systems

Both traditional and modern approaches for the analysis of changes in natural systems, and their consequences for and the reactions of the socio-economic system, are based on direct causal relationships. Examples of this are the Global Environment and Society model (GES, Hasselmann 1990) and the Pressure-State-Response (P-S-R) approach used by the Land-Ocean Interactions in the Coastal Zone (LOICZ) project of the International Geosphere-Biosphere Programme (Turner et al. 1998). Luhmann (1986) pointed out that society has put a sort of 'filter mechanism' between environmental changes and social reactions: the perception of the changes. Thus we included this filter mechanism in our approach, similar to the extension of the GES model to a Perceived Environment and Society (PES) model by von Storch & Stehr (1997). The function and quality of this 'filter mechanism' are primarily evaluated using a large number of interviews conducted with regional experts and stakeholders.

3.4. Handling uncertainty

Uncertainties are common in science and are a main driving force behind any research. However, in future-oriented climate impact research, and especially in interdisciplinary research integrating long-term socio-dynamics, the handling of a cascade of uncertainties must be included in the methodological approach. The sequence begins with uncertainties in predicting future global climate change, it continues with the problems of downscaling to regional climate scenarios before becoming biased by all aspects of uncertainties which arise from running hydrological and other models on a regional scale (Frederick et al. 1998). The cascade proceeds with an overall increase of uncertainties when analysing the possible response at the ecosystem level and, especially, when looking at the impact on and the reactions of the constantly developing socio-economic system (see Pahl-Wostl 1995). This cascade of uncertainties is only partly due to insufficient knowledge and lack of data, but is also a result of complex non-linear dynamics in natural systems and the non-deterministic nature of perception and reaction by humans and of society (Bechmann et al. 1995).

To handle the main aspects of these uncertainties, we use the 'scenario approach' by formulating definite sets of assumptions without regard to predictions, avoiding any statements about their probability. For future climate change we have formulated a scenario based on a downscaling operation but fitted to our sensitivity assessment needs (see below). Another important aspect is that climate change will unfold its full impact less on the natural and socio-economic systems of today, but rather on a yet unknown future status, a problem that is too often neglected in climate impact studies (Arnell 1998). To take this into account, we not only simulate and analyse the consequences of the impact of the climate change scenario on the present situation, but also formulate 'possible futures' (i.e. scenarios) for some of the most relevant aspects (e.g. changed intensity in agriculture, restricted funding of coastal protection, different coastal protection strategies, different developments of marine transport, etc.). In an additional loop, we then analyse the consequences of the climate change scenario for these future situations.

This means that our research project will not produce a *mechanistic forecast* of the impact of climate change (which would certainly not be possible), but it will generate an array of possible consequences and adaptation measures. It will produce a 'new type' of knowledge that does not neglect or conceal uncertainties, but includes them as a necessary ingredient of the future (Bechmann et al. 1995, Pahl-Wostl 1995).

3.5. Integration

An interdisciplinary approach requires dissection of a complex problem as well as re-integration of the primarily disciplinary results (see Hübenthal 1991). According to our experience, this must be understood as a process beginning in the conceptual or planning phase of such a project. During this phase the structure of the project and the interrelationships between the subprojects have to be defined. To enhance integration, we have implemented a stepwise structured 'guiding concept' (Fig. 2), where each milestone requires input from each of the subprojects, thus forming the basis necessary for the next working step. To integrate the different disciplines, we analyse different multi-level subsystems, so-called 'relation networks', similar to Becker et al. (1998). In addition, we use a Geographical Information System as an integrating tool.

4. THE CLIMATE SCENARIO

As the main basis for the climate change impact analysis, we have formulated a climate scenario which is derived from model predictions but adapted to a time horizon of 5 decades, i.e. for 2000 to 2050. For sea level. a rise of 55 cm by 2050 has been set, which is derived from the IPCC (1996a) and represents the 'business as usual — high estimate'. Expecting reduced energy dissipation, we added 30 cm to tidal amplitude; +15 cm to the mean high water level and –15 cm to the mean low water level.

The other climate parameters were provided as a result of a downscaling exercise (von Storch et al. 1998). They used the climate model ECHAM4/OPYC3 with 'business as usual — best estimate' and 2 × [CO_2] assumptions for monthly calculations of near-ground air temperature and air pressure. From these data they derived a regionalised climate scheme using canonical correlation analysis for downscaling. The KLIMU scenario for 2050 for Bremen has been formulated on the following basis: sea level rises by 55 cm; tidal amplitude increases by 30 cm; temperature rises by an average of 2.7°C, especially in spring and winter (these assumptions are probably too high according to recent model results, but are used nevertheless for reasons of methodology and precaution); precipitation increases by ~10%, with the strongest increase in spring (22%) and a 6% reduction in summer; wind speed increases by <6% in autumn and winter, but is reduced by 4% in summer — stronger winds in winter will add ~14 cm to the levels of storm surges. To gain a more realistic basis, the predicted changes have been added to the real weather data for 2 reference years, i.e. 1991, a cold and dry year with low runoff and 1994, a warm, humid year with high runoff in spring.

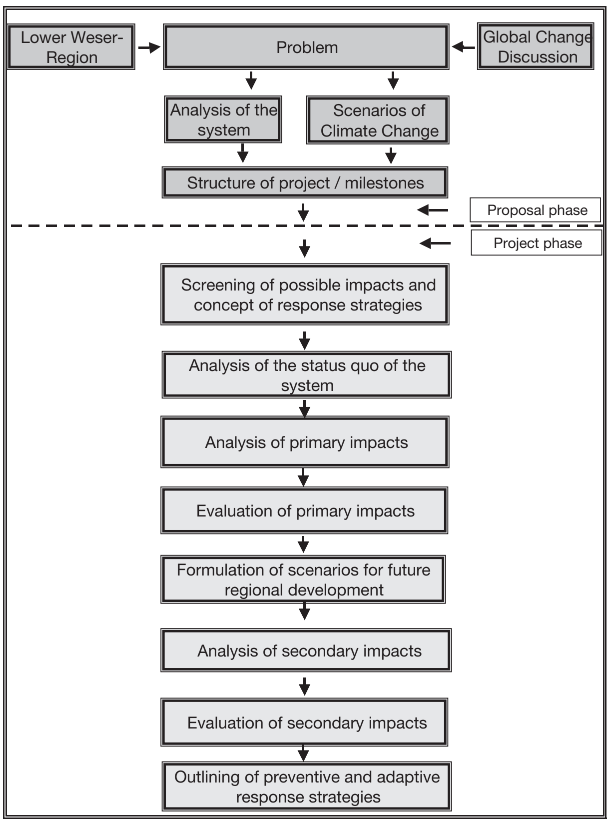

Fig. 2. Guiding concept for the research process

5. INITIAL RESULTS

After an extensive analysis of the status quo of environment and society in the Lower Weser region we simulated the impact of the scenario 'climate change without adaptation measures' and thus identified the sensitivities of the present day system to climate change.

5.1. Hydrographic situation of the estuary

Results show that the rise in mean sea level as well as the increase in tidal amplitude at the seaward border of the study area will advance into the inner estuary more or less 'undisturbed' as a consequence of the extreme deepening of the inner estuary. But due to changing river discharge as a consequence of the climate change scenario (simulated by the Leichtweiss Institute), the residence time of water in the estuary in summer and its temperature will increase, and salt water will penetrate further upstream with a consequent impact on water quality and utilisation (Grabemann et al. 2001).

5.2. Water management and river discharge

The climate change scenario will lead to lower river discharge in summer and higher discharge in winter/spring, mainly due to changes in precipitation and evapotranspiration. Thus the seasonal cycle in amplitude will become greater, with an increasing risk of flooding in early spring. During summer the consequences will be as mentioned in Section 5.1 above.

In the lowlands behind the dikes, an impact on the artificial drainage system must be expected. Increasing precipitation will lead to more water needing to be drained out of the system into the estuary. This presently occurs in a free-flow manner because of the difference in water-level at tidal low water. This will become more difficult with water level raised in the estuary. However, most sluices are already equipped with an electrically powered pumping station and the modelling shows that it should be possible to handle the additional water using these pumps more frequently. This will create increasing costs mainly to be paid by the farmers (see Section 5.6 below). However, the results indicate that in general the existing system will be able to handle the problems arising without overly serious consequences; the drainage system, developed over ~800 yr, will be adaptive and flexible enough and the contention that these low-lying areas are dangerously sensitive to climate change is not confirmed. However, additional costs and salinity problems for irrigation will arise from the advance of the brackish water zone into the inner estuary.

5.3. Groundwater system

The groundwater within the study area is used as drinking water only at the landward borders of the area due to the higher salinity resulting from intrusion of seawater. Initial results of the large-scale groundwater model show that the impact on the groundwater system will probably be relatively weak and slow. Neither strong propagation of the salinity intrusion front nor significant changes in the renewal of groundwater seem likely, due to partial balancing of higher precipitation and evapotranspiration. However, it is expected that during summer, with increasing temperatures and decreasing precipitation, soil moisture will decrease, with consequences for the ecological system and agriculture.

5.4. Coastal protection

After analysing the sensitivity of the actual coastal protection system (mostly dikes and storm surge barriers in the tributaries) using a probabilistic approach and taking wave heights into account, it becomes obvious that future adaptation of the system will be necessary under the climate change scenario. The probability of wave-overtopping will increase from 1 in 1000 yr to ~1 in 100 yr, without taking local problem areas into account. Different response strategies will be examined under a wide variety of aspects in further work (see Section 6 below).

5.5. Ecological complex

Substantial impact on ecological systems can be expected in foreland areas, due to rising water levels leading to inundation and a lateral shift of foreland biotopes, as well as upstream migration as a result of propagation of the brackish water zone (Osterkamp et al. 2001). New species will migrate into the region, mainly due to increasing temperatures, accelerating the natural shift in species composition. Behind the dikes, direct impact on the ecological system (mostly grassland) will probably be reduced by the capability of the water management system to keep the water levels in the drainage system more or less stable. However, increasing temperature and reduced soil moisture during summer will create changes in animal and plant species composition.

5.6. Socio-economic situation

Economic consequences and demands on space will occur mainly as a result of implementation of the coastal protection measures, which will be evaluated in detail in further work. The current climate change impact assessment indicates that, besides the need for coastal protection, direct consequences of climate change for society will be relatively weak. Major problems must be expected for urban waste-water management, if precipitation during winter and intensity of thunderstorms in summer increases. The use of river water for cooling purposes in power plants will be further restricted by temperature limits, and additional demands for electrical power by the pumping stations in the drainage system and for air conditioning are to be expected. Overall, a moderate socio-economic impact can be foreseen, as long as the community as a whole supports coastal protection efforts. The increasingly weak coupling between the natural and the socio-economic system in our industrial society and a fairly strong economy seem to be the main reasons for this.

6. RESPONSE STRATEGIES

An increase in sea-level is anticipated to be a major impact of global change (IPCC 1992, Warrick & Rahmann 1992), which will require further adaptation of coastal protection systems, e.g. in the Lower Weser region considered here. Three response strategies have been outlined, all of which are already under consideration as possible coastal protection schemes. The first option is the reinforcement and protection of the present front dike, second option is the construction of a huge storm surge barrier upstream of Bremerhaven, and the third is a partial retreat, with relocation of the main dike in one area and the construction of 'polders' in other areas.

However, the full impact of climate change will not hit the region and the society as they are today. Looking ahead to the year 2050, the specific development of future social and economic conditions is as yet unknown. To take this uncertainty into account, we use the 'scenario approach' again in formulating different future developments, in the hope that that reality will be somewhere in the range considered. These scenarios are supposed to represent the range of possible futures and to serve as a methodological tool for analysing future sensitivity to climate change. The impact of climate change and various coastal protection measures will then be analysed and evaluated considering those different aspects of future developments. This will reveal a wide range of possible consequences, response strategies and social conflicts or benefits, and will thus provide a basis for future public discussion.

7. COMPARISON WITH THE APPROACH AND RESULTS OF IPCC 'COMMON METHODOLOGY' STUDIES

As mentioned in the Introduction, IPCC has developed a standard approach to assess the vulnerability of coastal regions to climate change. This has initiated and stimulated many studies all over the world, showing that nearly all coastal zones of the world are vulnerable to the possible impacts of sea-level rise, but to very different degrees. The 'Common Methodology' approach for assessing coastal vulnerability to climate change is a multidimensional concept, encompassing biogeophysical, socio-economic, and political factors. It defines vulnerability as 'the degree of incapability to cope with the consequences of climate change and accelerated sea-level rise' (IPCC 1992). It integrates the sensitivity of the natural system with the vulnerability of socio-economic systems and includes their potential capability to develop active response strategies. Three segments have been specified in the methodology: impacts on the natural coastal systems, impacts on socio-economic development, and the implications of possible response strategies for adaptation (IPCC 1996b). This includes considerations of the present situation and a rise in sea level of 0.3 to 1.0 m by the year 2100, corresponding to the low and the high IPCC estimates. For the German North Sea coast, a recently completed study (Ebenhöh et al. 1997) shows that the consequences without countermeasures can be evaluated as 'medium', when compared on a global scale, and 'low', when taking adaptive (i.e. protective) measures into account.

However, there are some limitations of the approach that have been outlined in part by the IPCC (1996b) itself: no climate change factors other than sea-level rise have been considered (i.e. no changes in temperature, storms, precipitation, etc.); all studies have assumed that the socio-economic situation is constant until 2100, which is, of course, unrealistic; studies have focused on market values — non-market values have been largely ignored; the identification and handling of many levels of uncertainty was only incidental.

The regional study presented here is in partial agreement with the IPCC framework, especially with the methodological approach. However, by focusing on a specific region, we were able to include changes in other climatic variables (i.e. temperature, wind speed/storm, carbon dioxide, etc) and their seasonal variations and to analyse their interrelations in detail. As we consider our future socio-economic system to be still capable of avoiding 'catastrophic' situations such as the failure of dikes, we focused on adaptation strategies and on indirect secondary effects, e.g. on hydrology and water management behind the dikes, on agriculture, biota and nature conservation, etc. Thus the KLIMU approach can be regarded as the essential second, more detailed step following the 'Common Methodology', on the basis of which discussions of the above action scenarios may be started. Overall we agree — given the present state of knowledge — with the assessment of the 'Common Methodology' study cited (Ebenhöh et al. 1997) on the consequences for the region concerned being 'medium' or even 'low', taking the capability to respond into consideration. However, specific effects might only be detectable to their full extent if analysed on a small-scale basis (Sterr et al. 2000).

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