ACTION 5B – FINAL REPORT

FLOOD RISK ASSESSMENT AT TWO PILOT SITES – METHODS AND MEASURES

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Betriebsstelle Norden-Norderney
Geschäftsbereich Planung und Bau

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gez. Thorenz	gez. Blum	gez. Burg
Baudirektor Betriebsstellenleiter	Dipl.-Ing. Aufgabenbereichsleiter Grundsatzplanung, Geoinformationssystem	Dipl.-Ing. Bearbeiterin

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– Betriebsstelle Norden-Norderney –
Jahnstraße 1
26506 Norden
Germany

phone: +49 (0) 4931 / 947 - 0
FAX: +49 (0) 4931 / 947 - 125
Email: poststelle@nlwkn-nor.niedersachsen.de

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1. Introduction

Natural phenomena only become sources of risk and cause natural disasters with the presence of people or values in the effected area. In the past, increase of damages due to floods had not primarily originated from cumulating flood events but from growing damage potentials (Meyer, 2005). With future accelerated sea level rise the situation will partly change and is already changing. Especially coastal lowlands will even more be flood-prone by storm surges and hence will be focussed by future flood protection policies.

Within the project SAFECOAST coastal managers of North Sea riparian states were cooperating and dealing with the question: 'How to manage our North Sea coasts in 2050?' The aim of the project was to exchange knowledge and existing approaches, in order to be prepared for future challenges. SAFECOAST is co-financed by the European Union and is part of the Interreg IIIb North Sea programme for transnational projects.
Besides the more general objective of knowledge exchange, explicit products regarding risk assessment, communication, and coastal management were obtained in SAFECOAST. For this purpose, the project members were working in certain work packages called actions. Different types of actions include different ways to deal with the before mentioned subjects. While cohesion actions compare between countries and focused actions translate knowledge to pilot sites by applying risk assessments or plans, the synthesis action has to combine the great variety of actions and emphasises knowledge and findings.

Action 5B has been accomplished by the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (NLWKN) which belongs to the Federal State of Lower Saxony, Germany. Action 5B is a focused action, since its major target was the application of state-of-the-art risk assessments to pilot sites. Two German pilot sites were chosen to be the investigation area. Both belong to the Federal State of Lower Saxony and are located at the North Sea. The sandy barrier island of Langeoog represents the first pilot site and is located off the coast of East Frisia whose mainland is the second pilot site and the most north-eastern region of Lower Saxony.

In the former project COMRISK was shown that there was a lack of knowledge concerning complex numerical flood models and concerning applicability of meso-scale risk assessment methods. Therefore, the present investigations concentrate on these topics as well. In a first step, flood-prone areas were determined and necessary information and data were collected. A hydrodynamic numerical flood model was used to simulate flooding in a great amount of scenarios. Previously, a parameter study was carried out in order to set the boundary conditions for the flood model and to gain an impression of given uncertainties.

A meso-scale damage potential analysis was carried out to provide the values at risk for the subsequent flood damage analysis. For the determination of damage potential the so-called Method I after Meyer (2005) was applied, while depth-damage functions from the KRIM project (KRIM, 2004) were used for the actual damage assessments.

By means of these investigations flood and damage maps for different scenarios in both pilot sites were obtained. Additionally, the impact of sea level rise and of certain possible flood mitigation measures could be qualified and quantified. On this base, recommendations for future risk analyses and for potential mitigation measures are given.

The methodology of investigations and the results are described in this report. Chapter 2 gives general information on the topic and provides theoretical background of all applied

approaches. Different types of numerical flood models are illustrated as well as the aspects to be considered in order to find an appropriate approach for a flood damage evaluation.

The explanation of theoretical background is followed by a description of the two pilot sites. The characteristics of the investigation areas were analysed with respect to the subsequent damage analysis. Therefore, only relevant information on the pilot sites is given in Chapter 3 of this report.

Chapters 4 and 5 deal with the actual conduction of the different parts of flood damage evaluations. From Figure 1 can be seen that the workflow of a damage analysis mainly consists of two paths, the damage potential analysis and the flood simulation. The results of these two paths are combined in the actual flood damage evaluation. Chapter 4 gives a description of the flood model setup and the previous parameter study. The great variety of applied scenarios is summarised. Scenarios were carried out for the present state (2007) and for future floods in 2050 and 2100. In Paragraph 4.3, the simulation results are analysed and interpreted. Beside the standard scenarios, modified coastal defence systems were tested and special effort was put into the understanding of the influence of linear topographic elements and into the identification of potential flood mitigation measures.

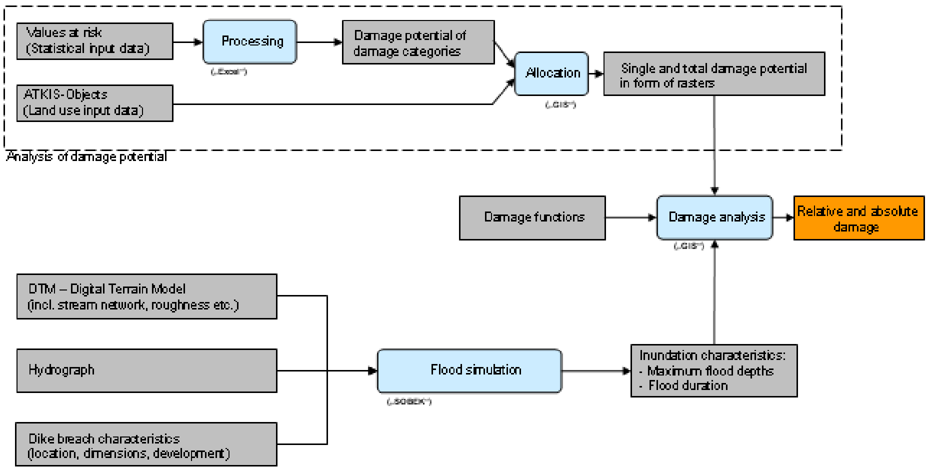


Figure 1: Possible workflow of a damage analysis

The damage potential analysis and damage evaluation are described in Chapter 5. This includes the processing of input data, the allocation of values to the investigation area and the application of depth-damage functions for the calculation of relative and absolute damages.

In Chapter 6, the principle of local contact groups (LCG) is illustrated and first experience with a LCG on the Island of Langeoog is described.

Key findings and the resulting recommendations are given in Chapter 7, while Chapter 8 provides an outlook on future work. Chapter 9 contains a summary of the investigations carried out in Action 5B and of the results gained thereof.

2. Theoretical background

Flood risk or flood damage evaluation studies include a number of different methods, approaches, and assumptions which are to be chosen carefully, since they strongly influence the results of the study. An applied method should fit both the conditions due to characteristics of the investigation area and demands on the complexity and precision of the results. Moreover, the effort to be spent on a certain method and the budget of the study need to be consistent.
This chapter gives necessary background information on numerical flood simulations in general and the applied software SOBEK (SOBEK Manual, 2004). In a second paragraph the basics of risk analyses and the different levels of choosing an appropriate approach are described.

2.1 Flood simulation

Flood simulations are the part of a risk analysis which provides quantification of impacts of storm surges and resulting failures of protection measures. Outputs of a flood model are flood maps, including inundated areas, and other flood characteristics like flow volume, flow velocity and direction, or the inundation depth at every place of the investigated area. Flood simulations themselves do not consider any probabilistic approaches, and therefore the failure of a flood defence system has to be set in the model as well as the related hydrograph. Both the characteristics of the failure and of the flood hydrograph are necessary boundary conditions for the simulation of flood events.

For the simulation of floods different types of numerical models are available. Model types mainly differ in the number of considered flow directions and in the way related processes are implemented in the model. In this respect, also the complexity of applied physical laws increases with the consideration of more dimensional flow directions. An introduction into the different types of numerical flood models and their characteristics is given in the following paragraphs. The model applied here is put into the context of this classification.

An approach which can be conducted by means of geographic information systems belongs to the group of so-called 0D models. These do not include any physical laws and cannot actually be considered as simulations. Using this method, a digital terrain model (DTM) in form of uniform grids is superposed with the determined high water level of the flood. The distance between the water level and the surface represents the inundation depth or the distance of dry surface to water level. It is assumed that the high water level seawards the protected area is able to occur also landwards and in the whole investigation area. This assumption is based on inexistent flood defences, since physical laws determine the extent of failures in flood defence system, the inflowing volume, and the spatial flood propagation. Velocity and direction of flow propagation cannot be simulated in such kind of flood model. These are the reasons, why they lead to overestimated flood characteristics.

Both, the volume of water flowing through the breach and the velocity of flow propagation are considered in models of the 1D type. Here, the flow can be simulated by solving the one-dimensional St. Venant equations. A so-called 1D+ method additionally includes a storage cell approach.

Methods of the 2D type solve two-dimensional shallow water equations. If they neglect the law of conservation of momentum for the floodplain flow, they are called 2D-. In case of considered vertical velocities by using continuity in addition to the 2D method, the

model is referred to as 2D+. A common 2D model admits the simultaneous flood propagation in both horizontal directions. Flow characteristics and surface roughness are also considered.

A 3D modelling approach includes the full solution of the three-dimensional Reynolds averaged Navier Stokes equations. But due to complex calculation algorithms and a great effort for data storage those methods are hardly appropriate for the application to investigation areas of meso or even macro level. This classification is based on the one used in the project FLOODsite (2007) which deals with similar flood simulations.

The numerical flood simulation model used in this study is called SOBEK and is developed by the Dutch company WL | Delft Hydraulics. The 1D module for channel flow and the module for two-dimensional overland flow of SOBEK were applied. The approach for the simulation of one-dimensional flow is described by the momentum equation and the continuity equation. The conservation of momentum is guaranteed by an implemented advection term and phenomena like drying and flooding or super-critical flow are taken into account (SOBEK Manual, 2004). Similar to the 1D flow, the flow in two dimensions over the surface is also described by the momentum and the continuity equation. But here the momentum equation has to be solved in x-direction as well as in y-direction. Hence, the number of considered equations is equal to three for 2D flow. Unsteady calculations are available in the flood simulation of SOBEK. Bed friction and the related roughness of river beds and soil surface can be set by the user. Since no shallow water equations are solved and the related turbulent stress terms are neglected (SOBEK Manual, 2004), the 2D overland flow module cannot be referred to as a full two dimensional approach. For this reason, the overland flow module of SOBEK can be classified as a 2D- flood model. In FLOODsite (2007) it is even classified as 1D.

A project in SOBEK consists of numerous cases representing different model configurations and therefore different simulated scenarios. A schematisation module provides the opportunity to setup a model in a GIS environment. After model settings like calculation time steps, duration of simulation, or output options were set, the module Netter is used to develop the actual model. The software provides 1D or 2D simulations or a combination of both. River networks or rainfall-runoff calculations are simulated one-dimensionally, while for the surface flow two-dimensional equations are solved.

River networks are modelled by digitising line elements which are connected by flow connection points. Every reach, a segment of the river network, modelled this way requires the definition of at least one cross section. The amount of available cross section shapes ranges from simple squares and trapezoids over closed circle or elliptical forms to cross sections given by pairs of coordinates. The dimension of every cross section and the position relative to the surface can also be altered. Additionally to cross sections, a great variety of structures is available to be built at or in a network reach. 1D boundary conditions are either set in form of changing water levels or by given discharges per time. Via the definition of calculation points on the reaches the spatial resolution of calculation is determined. In case of simultaneous use of 1D and 2D simulations both model parts are connected by means of calculation points and other defined structures. At those locations, the exchange of flood water is simulated for every time step.

The two dimensional surface flow is modelled by using uniform grids. For each grid cell the flow parameters are calculated at every time step. Input grids contain elevation data of a digital terrain model (DTM). Depending on the cell size of the grid and the total number of grid cells, a stream network can either be modelled by lowering the cells belonging to the river bed to the bottom level and setting an initial water level or by applying additional one dimensional calculations. While with high resolution grids a river cross section can be built by many grid cells, the cell size of coarser grids is often larger

than the stream width. In that case the stream network or drainage system cannot be modelled accurately and the 1D module needs to be used additionally.

The failure of flood defence structures can be implemented into the model also by either a one-dimensional or two-dimensional method. With the 2D-method grid cells belonging to the flood defence structure are lowered in every time step until the maximum breach depth is reached. The values of crown height reduction have to be given in form of time series. In the 1D-breach development two different empirical approaches are implemented in SOBEK, the formulae after Van der Knaap (2000) and the formulae by Verheij and Van der Knaap (2002) (SOBEK Manual, 2004). The advantage of the one-dimensional approach is that the breach extent is independent from the cell size of the DTM and the breach development is modelled in both the horizontal and vertical direction. The allowed influence of the user on the calculation is larger, but the sources of errors are more diverse as well. For further information on SOBEK, it is referred to the software manual or directly to the developer.

With respect to risk analyses, the most important output from the flood simulations of this study was the maximum inundation depth at every location in the investigation area. The information is also provided by SOBEK in form of grids. So the inundated area is given as well as the spatial distribution of inundation depth. The latter information is important, because the inundation depth at every value at risk is provided, if the location of value is also known. Hence, within the framework of the damage analysis the affected assets can be identified and their damage can be determined.

2.2 Risk analysis

Risk is equal to probability of failure times consequences of this failure. For flood risk the probability of failure is determined by the occurrence probability of the failure causing event and by the characteristics of the failing structure itself. The consequences depend on the vulnerability of affected values.

The source-pathway-receptor approach describes the course of events in case of floods chronologically and causally. The North Sea, actually its water, represents the source of risk. Risk is transferred through the pathway to the receptor. With floods the land itself is the pathway, including protection measures as dykes or flood barrages as well as the hinterland. If the pathway is not locked for danger coming from the source, the flood is transported to receptors, that is the people and the values at risk, and leads to consequences for them. In case of coastal floods, the combination of probability of storm surges and failure of the coastal defence system with an estimated damage results in a predicted flood risk.

For probabilistic approaches is assumed that floods of a certain return period lead to damages of same probability. Nevertheless, this study is focussed on the term of flood damage analysis, which should be distinguished from risk analysis. A flood damage evaluation does not include probabilistic calculations and therefore no information on risk. Sufficient information for calculating the probability of failure of the investigated dykes was not available due to the reason that these analyses are not part of the standard design process for coastal defence systems. The official design approach for flood protection measures to be used in Lower Saxony does not include probabilistic calculations. The recent Master Plan Coastal Defence for Lower Saxony (NLWKN, 2007) states that dykes in Lower Saxony are designed to withstand a defined design water level and the related wave run up. The design water level is determined by means of the so-called “Einzelwert-Verfahren” (NLWKN, 2007). Since the “Einzelwert-Verfahren” is a

deterministic method, no information is given about related risks or occurrence probabilities for failures of the flood defence system.

The term “flood damage” refers to all varieties of harm caused by flooding (FLOODsite, 2006). Flood damage includes a wide range of harmful effects on humans and their environment. There are different types of damages existing. They can be categorised in terms of direct or indirect damages as well as in terms of tangible and intangible values. A third distinction is drawn between primary and secondary damages.

Direct flood damage evolves from the immediate physical contact of flood water to humans or to assets at risk, while indirect damages harmfully disrupt or start processes. A typical indirect damage is, for example, the loss companies have to bear, if their production is intermitted. Flow figures or flow values like the gross value added are affected by indirect damages, since they are not vulnerable to direct contact with flood water.

Tangible damages are those who can be quantified in monetary terms. This includes direct damages to buildings as well as indirect damages to flow values. Casualties or affects on ecosystems for instance are either nearly impossible to quantify or are due to ethical and political reasons not subject of risk analyses. Hence, those and other not traded values are referred to as intangible values.

The terms primary and secondary damages are not clearly defined in literature. For this study the following terminology is valid. Primary damages occur during the flood event and secondary damages are chronologically and causally subsequent.

Every form of damage can be classified by the combination of these three differentiations. Nevertheless, since especially intangible and secondary damages are hardly predictable and therefore uncertainties are even higher than for the other types of damages, the major part of flood damage assessment studies only evaluates direct, tangible damages. Few damage categories of other types are additionally taken into account. For that reason, this report focuses on methods for the evaluation of direct, tangible damages.

An analysis of damage potential is defined as valuation of assets at risk and spatial distribution of these values. Damage potential is nearly independent from any hazard. But the extent of the area at risk and therefore the values to be considered is determined by type and magnitude of the hazard.

In this regard, an important decision to reach is which scale is applied to the vulnerability assessment. The extension of the pilot site, available and required data, and the objective of the study, including required detailedness, determine the scale of the methods to be chosen. Micro-, meso-, and macro-scale methods for risk or damage analyses are available. Suitable approaches are chosen based on the three above criteria, usually starting with the spatial scale of the area of interest. The most important argument for an appropriate approach is not necessarily the one providing the highest precision, but the efficiency and the ratio of required precision to related effort. The characteristics of methods of different scales are summarised below (Table 1).

In many studies the decision is to make, whether a micro- or a meso-scale approach is appropriate to the study area. Damage evaluations on the meso level have to deal with a lack of precision in their results, but micro-scale methods usually are not available to investigation areas of a meso level due to their great effort in terms of time and money. Meso-scale methods have a great advantage in comparison to those on micro level. They allow the use of aggregated official input data which leads to a greater transparency and

comparability between results of different studies. Furthermore, updating and maintenance of databases containing the values at risk requires less effort with meso-scale approaches.

Table 1: Comparison of method types for flood damage evaluations

characteristic	scale of approach		
	micro	meso	macro
spatial scale	local	regional	national, international
required data	object based inquiry	aggregated official statistics, differentiated by land use categories and municipalities	aggregated official statistics, differentiated by municipalities or higher administrative levels
study objective / precision	assessment of local coastal defence measures	assessment of flood defence strategies, insurances	decision support for national flood defence policies, reinsurances
conclusion	high precision, high effort	less precision, less effort	low precision, less effort

(after Meyer, 2005)

The conditions of the pilot sites investigated in Action 5B fit the characteristics of damage evaluations on the micro and meso level. But only a meso-scale method was applied to the damage potential analysis in the pilot site of East Frisia. A description of the applied approaches is given in Chapter 5. For the Island of Langeoog a micro-scale damage potential analysis was carried out in the former COMRISK project.

The damage potential represents the probable maximum damage, since a total loss of values results in damage equal to the sum of all values. A total loss of all values is hardly reached, as the major part of assets at risk is usually partly damaged. The damaged ratio of values mainly depends on the vulnerability of the type of value and on the inundation depth. Due to this correlation, values at risk are subdivided into categories of equal vulnerability. Examples for damage categories are the private buildings or the private inventory in the investigation area. With meso- and macro-scale studies, the classification of values into damage categories is also determined by the differentiation of values in official statistics, the source of input data in that kind studies. The definition of value or damage categories facilitates the spatial allocation of values. Besides this benefit, the assessment of damage to values aggregated in categories of equal vulnerability requires less effort than the assessment of every single inundated asset. In this regard, for each of those damage categories depth-damage functions were developed, in order to predict the damaged ratio depending on the inundation depth. Other influencing parameters usually are neglected.

There are different types of damage functions available. So-called direct damage functions deliver damages in absolute units without a prior evaluation of the damage potential. Other functions result in relative values, that is the damaged percentage of an inundated asset is calculated. The damage in absolutes terms is gained, when this percentage is multiplied with the actual value of the asset. The definition of damage categories and the applied depth-damage functions are explicitly described in Chapter 5 as well.

Flood damage evaluations follow a certain work flow which is exemplified in Figure 1 by the work flow followed in this study. The first step of all analysis is the definition of the area of interest, the investigation area. This determines the extent of subsequent procedures. In coastal protection studies usually the investigation area is consistent with the area at risk or the assumed flood-prone area. As mentioned above, these areas are limited by their topography.

The damage potential analysis, which represents the first branch of a flood damage evaluation, starts with the evaluation of all values to be considered within the investigation area. In most cases, the resulting data have to be processed to meet the requirements of the chosen method. After the allocation of the values either during the evaluation or in a separate procedure the total damage potential and its spatial distribution is obtained. This geo-coded damage potential is here combined with the inundation depth at each location via depth-damage functions to calculate the relative and the absolute damage.

For nearly all parts of a flood damage evaluation the application of geographic information systems is appropriate. Only first data preparations are easier to operate by means of spreadsheet programs. Furthermore, only 0D+ flood simulations can be carried out in a GIS. Hence, more complex flood simulations require separate software (see Paragraph 2.1). The use of GIS in this study, including the development of a new tool for estimating damage potentials and calculating damages, are described in Paragraph 6.2.

Above explanations on risk analyses and flood simulations as a part of it show the multiple decisions to be made and distinctions to be drawn before the actual flood damage evaluation is started.

3. Pilot sites

The Master Plan Coastal Defence for Lower Saxony states that an equal safety level is to be guaranteed for every person living in the flood-prone areas at the North Sea coast of Lower Saxony (NLWKN, 2007). In this policy, risk is referred to as hazard. With present design approaches for coastal structures no values of assets at risk or their vulnerability are taken into account. Coastal defence structures are built based on deterministic design rules. The height of defence systems is determined by adding design water level and design wave run up at the structure. The design water level is calculated by means of the Deterministisches Einzelwertverfahren (combined criterion for design water level) including an expected secular sea level rise (NDG, 2004 and COMRISK, 2005).

The protected flood-prone area of Lower Saxony covers about 6,600 km^2 and the Federal City of Bremen which includes the cities of Bremen and Bremerhaven has another 360 km^2. About 1.2 Million inhabitants are living in this low lying areas of Lower Saxony and 0.57 Million in Bremen (NLWKN, 2007). Hence the population density of 182 inhabitants per km^2 in Lower Saxony and ca. 1583 in Bremen show the different rural and urban characteristics of these federal states. The two pilot sites are located in the northwest of Lower Saxony (Figure 2). The first one called Langeoog is a small sand barrier island off the coast and the second one is the major part of the region of East Frisia. Both pilot sites are partly low lying, especially East Frisia contains great areas below the sea level.

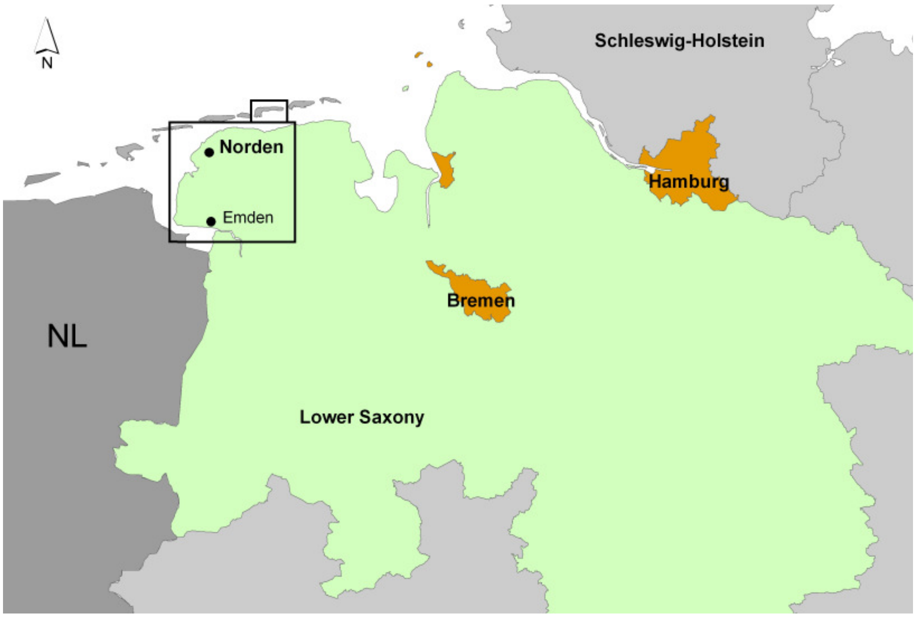


Figure 2: Location of the pilot sites East Frisia and the Island of Langeoog

An overview over the present flood defence system is given in Figure 3. It can be seen from the figure that the islands have a shielding effect concerning waves from the North Sea, similar to breakwaters. The islands and the shallow Wadden Sea cause a reduction of wave impact at the mainland coast. The coastal protection system varies, basing always on a min dyke line as primary flood protection element. The dykes consist of a sand core and covering clay layers. The height of the dykes ranges from NN + 5.6 m to NN + 9.0 m, depending on different design water levels and wave run up. The main dyke line has a total length of about 610 km (NLWKN, 2007).

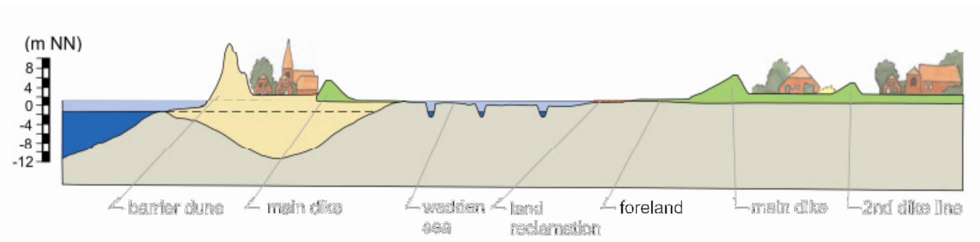


Figure 3: Coastal flood defence system in Lower Saxony (NLWKN, 2007)

Additionally, groyne fields, dyke forelands, summer dykes, and secondary dyke lines are found in differing combinations. While measures seawards the main dyke line reduce loads on it, the secondary dyke line provides an additional line of defence in case of failure in the first line.

The subsequent paragraphs give a description of characteristics of the two pilot sites and an explanation how the areas of investigation have been chosen.

3.1 Island of Langeoog

Langeoog is one of seven inhabited sand barrier islands located off the East Frisian coast. The distance from the mainland coast is only few kilometres. Between mainland coast and barrier islands the Lower Saxony Wadden Sea is found. All East Frisian Islands are sandy barrier islands naturally developed from former sand banks. They are characterised by a flat low lying topography on their wadden sea side partly protected by dykes and dune belts which typically protect the northern and western coasts from floods. The topography of Langeoog is given in Figure 4.

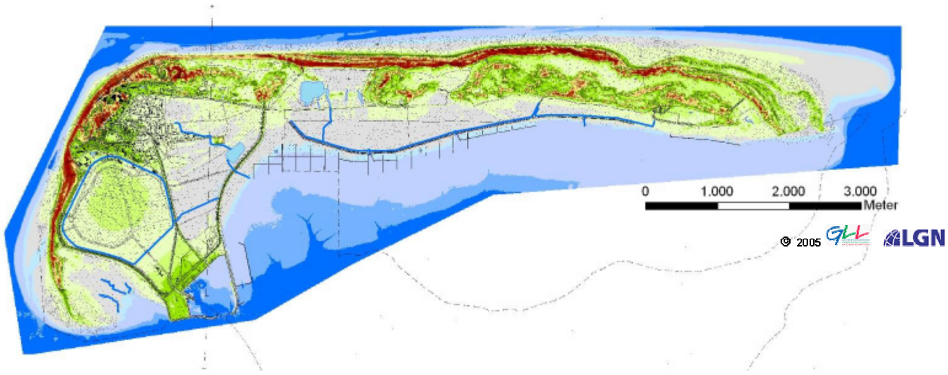


Figure 4: Topography of the Island of Langeoog

As can be seen from Figure 4, the brown parts are the higher areas of the island and represent a dune belt of varying height and width. The parts of the coast protected by dunes are suffering from wave attacks a lot harder than the southern coasts. The reason for this is that the northern part of the island is directing to the open sea while the southern coast is bordering the Wadden Sea where wave energy has been dissipated by the high lying tidal flats between the islands and the mainland. Moreover, the main wind direction causing storm surges is west-north-west.

Dunes are naturally nourished by landing sand banks due to morphological movements in the coastal environment. Most of the sand naturally nourishing the dunes originates from the eastern end of the neighbour Island of Baltrum, lying westwards of Langeoog. Due to morphological changes of the surrounding environment the system of sediment transport is not constant but dynamically balanced. Hence the amount of sediment, arriving at the island's coast is changing as well. If the ratio of deposited and eroded sand is negative over a longer period of time and if the area landwards this location belongs to the officially protected area, artificial beach and dune nourishment is conducted. Compared to other available coastal defence measures nourishment is the most suitable for this type of coast. The reasons are cost-benefit calculations and aspects of nature protection and tourism.

The only larger settlement on Langeoog is a village located in the western part of the island. This area is protected by a ring of dykes and dunes and is classified by the coastal defence authority as protected flood-prone area (see Figure 5). In the eastern part a wide belt of natural dunes exists, sheltering the island from floods in the north but no artificial coastal defence measures are carried out and flooding can occur from the wadden sea in the south. The western part of Langeoog contains the village, rural areas, and infrastructure, while the very narrow eastern part is mainly unused. In the eastern part of the island some other inhabited assets are located close to the dune area and are protected by small flood defence systems. These assets are not part of the study area. Hence, only the protected western part of Langeoog is defined as the first pilot site. Its

extent is about 6.62 km² and the number of inhabitants permanently living on the island is equal to 2009 (in June 2007) (NLS, 2007). This leads to a population density of 303 inhabitants per km². Additionally to the inhabitants, many tourists are staying there, depending on the season. Tourism is the most important economic sector on the island.
The southern coast of the western part of Langeoog is protected by a ring dyke connected to the dune belt at its ends. The total length of dunes and dykes around the project area is equal to 10.6 km. The crown height of the dyke ranges from NN + 5.40 m at the harbour to NN + 8.0 m. There are two major openings existing. One is a sluice in the eastern part of the dyke ring, representing the outlet of the main drainage system which also dewaters the village. This sluice has one gate at each side of the dyke and thus dual safety. The second significant opening in the line of defence is a dyke opening for trains in the harbour dyke in the south. It consists of only one gate and no secondary line of defence exists. Therefore, and because the base of the gate is extremely low this point is assumed to a weak part in the flood defence system.

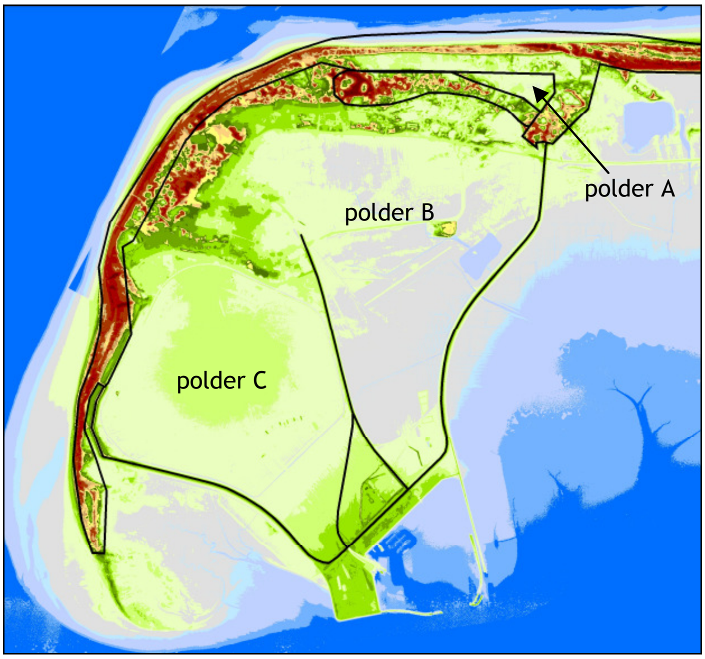


Figure 5: Study area on Langeoog and definition of polders

A secondary dune belt and a street dam subdivide the flood-prone area into three polders. The first polder lies between two parallel dune belts in the north and hence has the shape of a valley, called the Pirola Valley. The Valley is agriculturally unused but wells for the self-sustaining water supply of Langeoog are located here. This is the reason why the protection of the Pirola Valley from flooding with salt water is very important. Salt water intrusion will severely affect water supply. The flood impact on the fresh water lens under the valley had been investigated in the previous COMRISK project. The first polder represented by the Pirola Valley is small compared to the second and the third one. The area bordered by dunes and dyke ring is divided into two parts of nearly the same extent by a street and railway dam (see Figure 5).

There is no river existing on the Island of Langeoog. The drainage system only consists of smaller ditches dewatering the village and the surrounding rural areas.

3.2 East Frisia

A major part of the East Frisian mainland was chosen to be the second pilot site. East Frisia is not defined by administrative borders but is a historically grown region in the northwest of Lower Saxony. The Landkreis Aurich (Landkreis ≈ County), the Landkreis Wittmund, the Landkreis Leer, and the city of Emden form the region of East Frisia. A Landkreis is separated into municipalities, containing rural areas and at least one village or small city.

The area of investigation was defined to be consistent with the major part of the flood-prone area in East Frisia. For this purpose, the coast line, two channels with high river dams in the south and in the east, and the contour line of NN + 7 m are bordering the extent of the study area. The border of the investigation area is given in the following Figure 6.

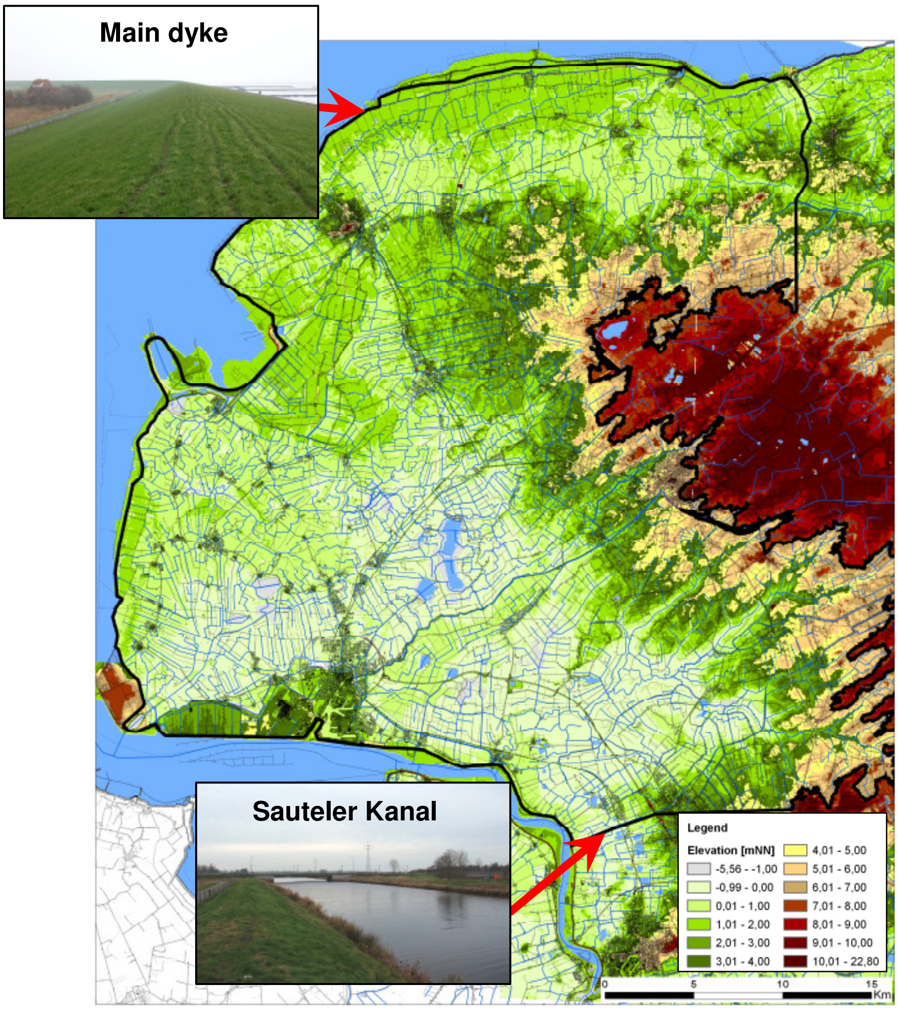


Figure 6: Extent and topography of the second pilot site East Frisia

East Frisia is surrounded by the North Sea on its northern and western coast. The estuary of the river Ems borders the project area in the south. The entire coast line of East Frisia is protected against coastal floods by dykes, forming a flood defence system with a length of about 109 km. The Ems-Jade-Kanal, a channel with high embankments, subdivides the project area into two parts. The channel runs from the city of Emden in south west to

north-eastern direction. The hinterland is characterised by low lying areas and a dense drainage network (see Figure 6 and 7). From Figure 7 can be seen that about 90 % of the pilot site has an elevation below NN + 5 m. This area belongs to the flood-prone area defined in the Master Plan Coastal Defence for Lower Saxony (NLWKN, 2007). Especially areas in the southern and eastern parts of the region are lying below the mean sea level. Moor land had been drained in former time to reclaim land for agricultural use and as a result the surface elevation had decreased. Due to the low lying surface the land has to be drained until this day. Other parts of slightly higher elevation are former salt marsh areas which were artificially increased by land reclamation measures and then had been embanked.

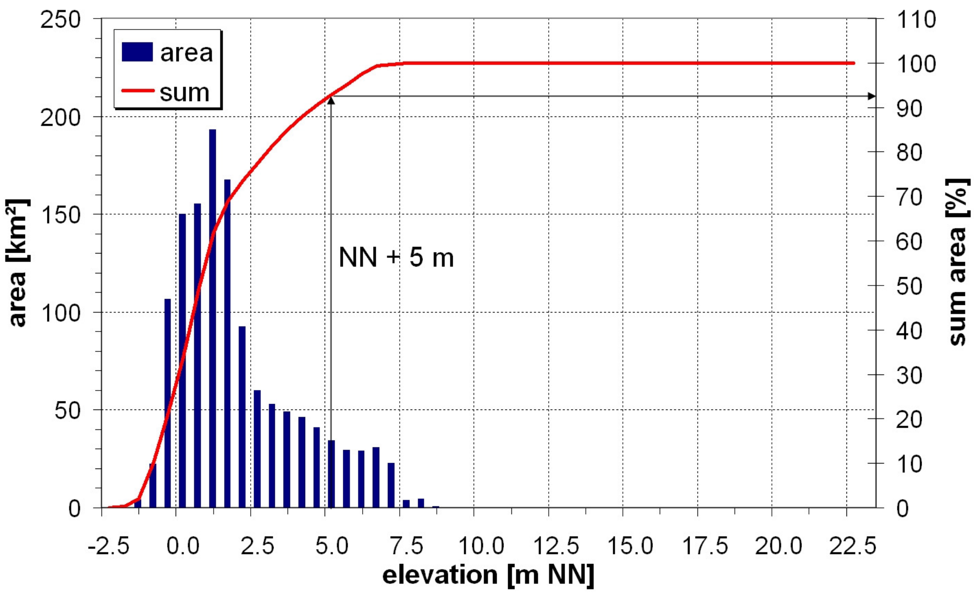


Figure 7: distribution of elevation within the pilot site of East Frisia

Several steps of embanking new land led to more than one dyke line at some parts of the coast. Major parts of the old dyke lines are parallel to the present main dyke line. A minor part of the old dyke line still exists and has the legal status of a Secondary Dyke Line, according to the Lower Saxony Dyke Law (NDG, 2004). The existence of secondary dyke lines provides additional protection, since in case of a failure of the primary dyke line the flood water is stored in the polder between the first and second line. Another measure, probably providing additional protection against floods, is the existence of dyke foreland which can also be found at different parts of the East Frisian coast. The influence of polders and dyke forelands on the development and propagation of floods is also investigated in this study. From the results conclusions on the effect of these two types of measures could be drawn.

The investigation area is mainly situated in the officially protected area which contains the land up to a level of NN + 5 m. Within this area inhabitants have to pay taxes for dyke maintenance works which are task of dyke boards. Thus, these dyke boards represent an important group of stakeholders of this study.

The sum of inhabitants, permanently living in the study area, is equal to 304,640. With an extent of 1,292 km² of land at risk, the population density becomes 235 inhabitants per km². The city of Emden with 51,000 and the city of Norden with 25,000 inhabitants are the largest settlements (NLS, 2007).

The entire region is characterised by its agricultural history and agriculture still is a very important economical sector. But the development of the tertiary sector, especially tourism, is much stronger at present. Some smaller harbours are found, mainly providing transportation for supplying the East Frisian Islands and for the transportation of tourists. Manufacturing industry is less important in the investigation area. Only in Emden, a major facility of car industry and a refinery is located. The harbour of Emden is of supra-regional importance. A more detailed description of values at risk is given in Chapter 5 where also the damage estimation is illustrated.

Above descriptions of the two pilot sites offer an overview over the characteristics as far as they are important for subsequent investigations. Therefore, the type and extent of coastal protection measures is illustrated and the design approach presently used in Lower Saxony is roughly summarised.

4. Flood simulations

Numerical flood simulations can require great effort, if they are conducted very detailed. Nevertheless, a careful development of flood model is necessary, due to uncertainties in all parts of the simulation and an unknown sensitivity of the model concerning different parameters. The development of models for both pilot sites, a previous variation of model parameters, and the resulting test programme are described in the following chapter. The application of models and the analyses of simulation results are illustrated as well as the conclusions drawn from this part of the study.

4.1 Model setup

The first work step of flood modelling is an analysis and interpretation of the characteristics of the project area which was done here previously. Necessary input data need to be collected and processed to fit the requirements of the model. In case of this study a basic model was developed and then adapted to different scenarios. In order to gain information on the sensitivity of the model concerning certain parameters, a parameter variation was conducted before actual simulations were carried out.

4.1.1 Data aquisition and processing

For the application of numerical flood models several types of input data are required. In this respect, it is distinguished between data which is constant over the time of simulation and data which is changing over time.

The first type usually provides the basis for the model and can only be altered from one scenario to another but not while the model is running. The so-called digital terrain model (DTM) is the most important example for constant data in this kind of numerical model. A DTM basically contains elevation data for every location within the investigation area. DTMs are often available as uniform grids. These are rasters of an equal cell size for all cells. If the spatial resolution differs from one raster to another, the level of detail will also vary. The cell size of a uniform grid often lies in a range from 1 to 100 m. The detailedness of topographic elements like river beds or small ridges in the model is depending on the chosen cell size.

Other forms of DTMs are irregular grids or TINs (Triangulated Irregular Network). Although these have some advantages, they are not used in this model due to the reason that laser-

scanning and other modern surveying techniques often also use uniform raster formats. Furthermore, uniform grids are easy to handle in GIS-based evaluations.

Besides elevation data, the surface roughness for the entire investigation area has to be considered within the model. The surface roughness strongly influences the flow velocity and therefore the propagation of the inundation front. This parameter can either be determined homogeneously or for each single raster cell of the DTM. The surface roughness mainly depends on the type of land use, for vegetation and artificial constructions act as flow influencing elements. The surface roughness is assumed to maintain the same value during a flood event. Hence this parameter is referred to as constant input data as well.

In the case that the spatial resolution of the DTM is not fine enough to represent the stream network sufficiently or the flow through the stream network should be simulated separately, the network's location and characteristics must be known in form of line elements, representing stream segments. The characteristics to be given are the cross-section of each segment and the related bed roughness.

With numerical models for floods due to storm surges also the flood defence system must be implemented. The different elements of the system can be modelled at their actual location. Often typical structures like for example weirs are predefined in the model software, so they are also represented with their function. If all flood defence structures keep the same parameter values during the entire simulation, the related data is also referred to as constant input data. Otherwise the structures determine unsteady boundary conditions for each time step of simulation.

Initial conditions represent the second type of input data required for the application of numerical flood models. Initial conditions are defined as the state of a time-dependent dynamical system or parameter of this system at the start time of a simulation or forecast. These parameters change over time but their initial value is needed to start the calculation. A typical example for this kind of data is the initial water level of the stream network. The water level is changed in each time step of the simulation and is also input for the calculation of the next time step. Therefore, at least the first value of the time $t = 0$ s is to be given.

The third important type of input data consists of boundary conditions. Boundary conditions are specified for the solution of equations implemented in the model in every time step of the simulation. In case of a dynamic numerical flood model the water level at or discharge through the failure in the flood defence system must be known at every time of the simulation. The value of this parameter is used to determine the water levels at every location in the model and for each time step. Every parameter which is set by the user and which is changing over time is referred to as a boundary condition of an unsteady calculation. Other examples for boundary conditions are the precipitation in a rainfall-runoff-model or the temperature in an evaporation model.

All data used in the models described here were derived from official sources. This has the benefit that the refresh period and homogeneity of data is guaranteed. The basis for flood simulation models, dealing with flood propagation over the soil surface, is a digital terrain model. In Lower Saxony, the DTM and also data of the stream network of second order are provided by the State Survey Agency of Lower Saxony (Landesvermessung und Geobasisinformation Niedersachsen, LGN).

The DTM is available in a GIS format which easily can be converted into ASCII-data compatible to SOBEK. Due to different extents of the two project areas the cell sizes of the DTMs were also different. The maximum number of cells for one model grid is

restricted due to limitations of SOBEK. Therefore, a cell size of 5 m for the model of Langeoog and 50 m for the model of East Frisia were chosen. In both cases the final elevation grid contained about 800,000 cells. The elevation data delivered by LGN had a resolution in height of one centimetre.

The data of the DTM were processed to fit the requirements of the software SOBEK and to keep the effort as small as sufficient for obtaining valuable results. All data was reduced to the extent of the pilot sites, so the calculation time was not unnecessarily long.

Additional processing of the DTM was necessary, because break lines which were not included in the first place should be considered. Break lines are linear elements whose elevations are significantly higher or lower than those of the surrounding surface. Break lines higher than its surrounding terrain are referred to as positive break lines. A dyke is a typical example for a positive break line. Sections of a stream network, including rivers, channels, and ditches, are representing negative break lines. Especially for coastal lowlands, break lines were assumed to be important in the 2D model, simulating surface flow, since they are influencing the flow propagation.

All available official information on break lines (ATKIS-data) was collected and implemented into the DTM by means of a geographical information system. Positive break lines implemented in the model of East Frisia are given in Figure 8.

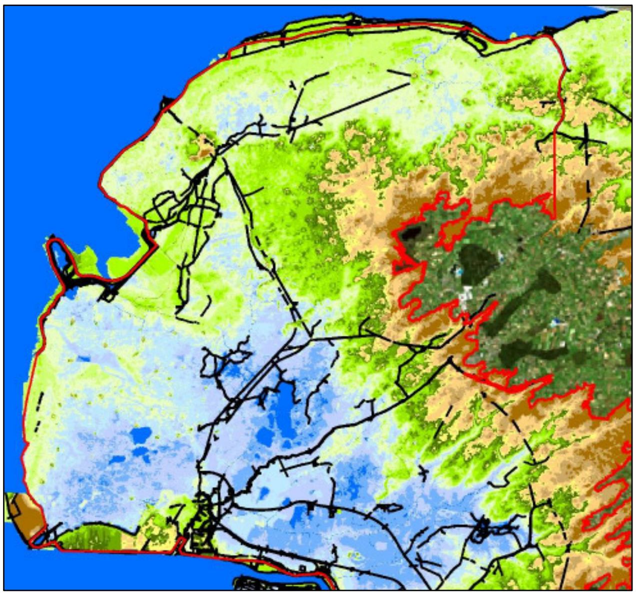


Figure 8: Break lines in the flood model of the pilot site East Frisia

It can be seen from the map that the distribution of positive beak lines in the investigation area of East Frisia is inhomogeneous. On the Island of Langeoog only the dyke and the railway dam were considered as break lines. The actual influence of break lines in the hinterland like secondary dyke lines, street dams, or railway dams has been investigated in this study as well (see Paragraph 4.3.2).

With the digital terrain model the basis for two-dimensional part of the flood simulation model was available. It was combined with the 1D stream network in the way described in Chapter 2. The drainage system of both the Island of Langeoog and East Frisia were digitised manually, since the data provided by LGN were not compatible with the GIS environment of SOBEK.

The DTMs of East Frisia and Langeoog, including additionally implemented break lines and the digitised drainage system, represent the basis of the numerical flood model applied to the two pilot sites. Nevertheless, at this stage of the model development no settings concerning model parameters or boundary conditions were made.

4.1.2 Parameter study

In this study the numerical flood model was used in order to deliver parameters of flood characteristics for the subsequent damage evaluation. Since the damage evaluation is based on the simulations described here, the flood model was developed with much effort. This means that model parameters and boundary conditions were chosen carefully and that the required level of detailedness was analysed before application of the model.

In order to gain information on the model's sensitivity, a variation of parameters was carried out for the model of East Frisia. The parameter study consisted of two different parts. In the first part, the general influence of the 1D drainage network and of the implemented positive break lines were assessed. As a result the required level of detail concerning these parts of the model was obtained.

One result from the parameter study was that the existence of a 1D flow model has great influence on the flood propagation. The drainage network initially damps the propagation of the flood over the surface, for it can store a certain volume of water before the water level in the system exceeds its embankments. The storage volume and therefore the damping effect strongly depend on the stream's cross-sections and the initial water level. With respect to the fact that severe storm surges occur from October to March and that drainage channels at that time of the year are usually filled, the initial water level is set to the maximum in the final model and the storage effect of the drainage system is assumed to be insignificant.

The second important effect of a drainage system in a flood-prone area is that the flood water is transported much faster than it could propagate over the surface. Therefore, low lying areas in a distance from the breach location are flooded, even if the surface flow has not arrived yet. Flood propagation is accelerated by the drainage network.

It was found that only the existence of the drainage network was very important for the resulting simulated inundation but not the extent of the cross sections. In order to prove this assumption a test area around the city of Norden was analysed with a drainage network and actually measured cross sections. Simulation results were compared to those of uniform cross section in every flow reach. It can be concluded that the dimensions of cross sections of the drainage network for these coastal lowlands have small influence on the defined flood characteristics, since the results of the simulations with the detailed drainage system and different simulations with uniform cross sections differed very little. Therefore, the use of actual cross-sections in the stream network is only recommended, if the effort of implementation is low or the structure of the topography differs from the one investigated in this study. Otherwise, a mean cross-section is sufficient for a study area similar to the current.

The influence of positive break lines was found to be significant as well and it was decided to implement them with the best resolution available.

A parameter variation was conducted in the second part of the parameter study. From the variety of different parameters which can be optionally changed in SOBEK those of major importance were chosen for the parameter variation. The model parameters surface roughness and roughness of river beds were changed as well as the extent of the dyke breach. The tested range of each parameter was taken from common literature. In the

parameter variation, each parameter was changed separately and in combination with others. For every configuration, a simulation was executed and the influence of every single parameter was statistically evaluated. The values used for the assessment were represented by defined flood parameters like the inundated area or the flood volume.

The result of this variation of model parameters was a ranking of parameters regarding their influence on the defined flood characteristics. The ranking of model sensitivity found in the parameter study was:

- Breach width
- Roughness
- Cross section

It was found that breach width, representing the breach extent, is by far the most influencing parameter for this pilot site. It was followed by roughness and stream cross sections of minor influence. The approach used for the development of the breach was developed by Verheij and Van der Knaap and is implemented into SOBEK (SOBEK Manual, 2004).

The benefit from this parameter variation was that the sensitivity of the model regarding its parameters was known for the application on the two pilot sites and therefore sources of uncertainties could be identified and assessed.

Based on these results from the parameter study, the model parameters for the actual simulations were set. Since the average surface roughness and bed roughness were not known for the inhomogeneous pilot sites and a detailed analysis of these parameters would have required too much effort, the medium values of the parameter study were chosen. The cross section implemented in the final model of East Frisia was of nearly square shape and was 5 m wide. It approximately represents an average value of the existing few larger and the many smaller channels. On Langeoog the stream network consists of few drainage channels of medium size and many of small size in the agricultural area. Due to the absence of rivers and the small amount of medium channels, the stream network of second order was implemented in the model with its actual cross sections.

The extent of a dyke breach could neither be predicted, nor could the breach location. Due to the fact that no probabilistic calculations were carried out in this study, assumptions had to be made concerning these parameters. For the breach width with 150 m also the medium value of the parameter study was chosen. The depth of the breach was simulated to grow from the crown of the dyke which uniformly lay at NN + 8 m in the model of East Frisia and was varying on Langeoog. It was assumed that the maximum breach depth was reaches at one meter below the elevation of the surrounding surface seawards and landwards the breach. This way the occurrence of a scour was modelled. The duration of breach development was stated to be one hour which is supported by observed dyke breaches reported in literature.

4.1.3 Tidal hydrograph

With the setting of these model parameters the basic models were completed. All steady values were implemented. Another type of necessary input parameters are time series of unsteady input parameters, the boundary conditions. In case of flood simulations the tidal hydrograph at the breach is the most important boundary condition.

The preparation of tidal hydrographs could not be done without a selection of possible dyke breach locations, for at every part of the coastline different wave parameters and therefore design water levels are valid. Additionally, the shape of the tidal hydrograph is changing from one place at the coast to another. While for the relatively small Island of Langeoog one hydrograph was sufficient, for the pilot site of East Frisia individual time series were prepared. For this purpose, possible dyke breach locations were selected by means of criteria defined previously. The selection of breach locations is described in the following paragraph dealing with different scenarios.

At Langeoog no tidal gauge is maintained and therefore no tidal data measured directly in front of the island was available. The next official tidal gauge is located at the Island of Norderney about 20 km westwards. Due to similar environmental conditions for both islands, the data from that gauge was assumed to be valid for Langeoog as well. Hence, the mean tidal hydrograph of Norderney was taken and a storm surge effect found to be typical for Norderney by Gönnert (2003) was added. This storm surge effect has a rise rate of 3 hours per meter water level, a peak duration of two hours and a decreasing velocity of 6 hours per meter water level. The available gauge data was earlier processed and statistically analysed (see COMRISK, 2005). The data was found to fit best a LOG Normal frequency distribution. Based on these calculations, an event with a return period of 10,000 years was extrapolated. Due to a relatively large confidence interval, it must be considered that the exceedance probability of this water level is the mean value of a wide range. This is also valid for the water level of a given exceedance probability. The tidal hydrograph related to this event is given in Figure 9.

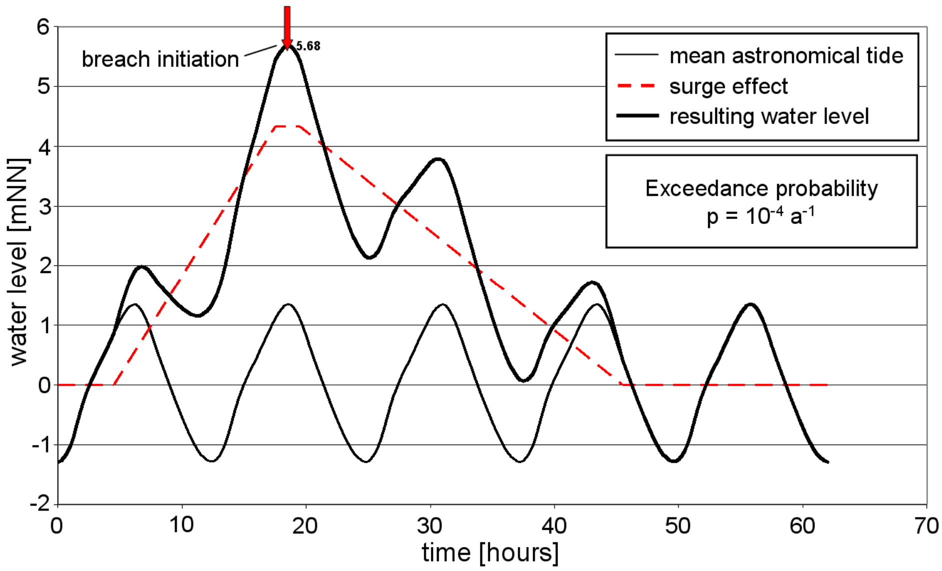


Figure 9: Tidal hydrograph applied to the Langeoog flood model

Beside this hydrograph of an extreme event, the hydrograph belonging to the actual design water level of NN + 5.35 m (DWL NN + 5.10 m and an additional factor of 25 cm for accelerated sea level rise) was used in the model of Langeoog. For the peak water level of the event with a return period of 10,000 years was higher than that of the design water level, the impact of this extreme event could be compared to those of the design state. With the model of Langeoog the characteristics of this pilot site should be analysed. For this reason, no future sea levels and no related hydrographs were used. In all flood scenarios the design water level of 2007 was assumed.

For the flood simulation model of East Frisia, the actual mean tidal hydrographs of every assumed breach location was used. Mean tidal hydrographs were available all breach locations but two. Therefore, the hydrographs of those stations were gained by interpolating the hydrographs from the closest breach locations. For these calculations the approach of inverse distance weighting was applied. Since no individual storm surge effect was analysed for each breach location, to all tidal hydrographs the storm surge effect after Gönnert (2003) was added. As a last step of preparing the standard case, the peak water levels were set equal to the actual design water level at every breach location (see Figure 10).

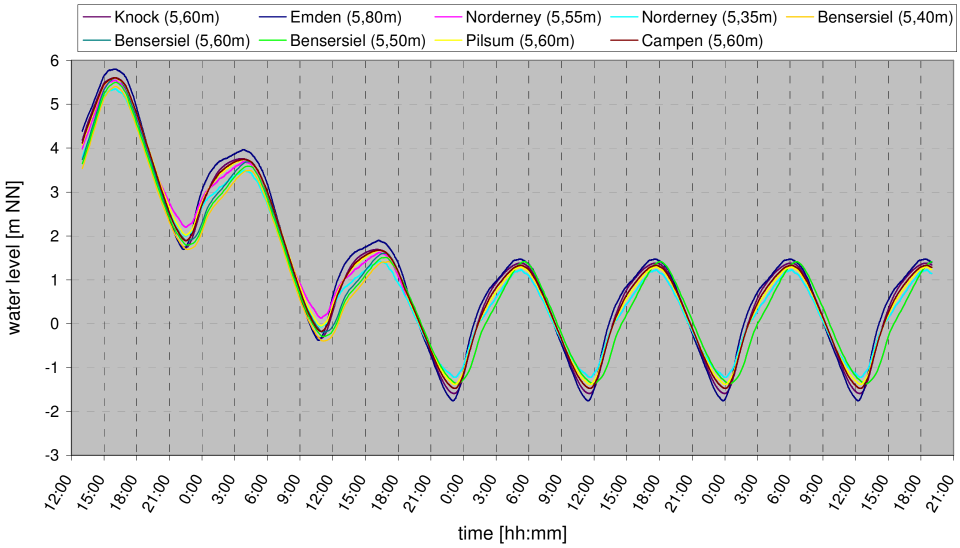


Figure 10: Tidal hydrographs for breach locations in East Frisia and scenario 2007

The start of breach development was set to occur at high water level. The simulation time was restricted to 79 hours, in order to cover the whole duration of setup by the storm surge and due to the fact that after this period very little changes in flood propagation occurred or even a drying of surfaces could be observed.

For the simulation of scenarios of the states in 2050 and 2100, a sea level rise of 25 cm and 50 cm, respectively, were simplifying added to the tidal hydrograph of the standard case described above, since no calculations of changes in the shape of tidal hydrographs were carried out. The value of sea level rise lies in the range of water level rises given by for example the present IPCC study and is conform to the Master Plan Coastal Defence for Lower Saxony (NLWKN, 2007). Since no fixed value could be currently predicted, a water level rise of 50 cm in one hundred years has to be referred as an assumption.

4.2 Flood scenarios

The model described above and the tidal hydrographs of 2007 were decided to be the standard case for simulations. The different model configurations and scenarios are explained in this paragraph. In the next paragraph, results of the flood simulations are described and discussed.

After the model of the second pilot site of East Frisia was used for the accomplishment of the parameter study, the actual flood simulations were started with the model of Langeoog. Since this project area was investigated in the former COMRISK project by

means of a relatively simple hydraulic approach and more complex flood simulations by SOBEK were run in this study, a comparison of the two methods for the simulation of floods due to storm surges was possible. The island of Langeoog could be referred to as the reference area for the subsequent simulations of the second pilot site. Conclusions from these results could be tested and verified with flood simulations of the second pilot site.

All model configurations of the Langeoog model contained the hydrograph representing the present state of design storm tides or representing a 10,000 a^{-1} extreme event. No scenarios were conducted for the years 2050 or 2100 like it was done with the model of East Frisia. In the different scenarios only the location of possible failure of flood defence system was changed. The reason was that in the former study COMRISK only the present state was evaluated as well. Hence, no flood data of future states would be existent to compare to the new results from the simulations with SOBEK.

Figure 11: Dunes at the Pirola Valley and dyke opening in the Harbour Dyke

Unlike the situation in East Frisia, for the island of Langeoog the weakest points of the flood protection system were known from investigations conducted in COMRISK. Therefore, these locations could be taken for possible failures in the protection system. Two different scenarios were carried out for two locations which were earlier identified to be critical. The first breach location in the model of Langeoog was positioned in the main northern dune belt protecting the Pirola Valley. The second breach represented a failure of the railway dyke opening in the Harbour Dyke (see Figures 11 and 12). Three additional possible breach locations were chosen, in order to represent every type of flood defence structure and every part on the island. The additional breach locations are also shown in Figure 12.

From the five locations two represent the failure of a protective dune belt. At the northern location the hinterland is a narrow, relatively low lying valley, the Pirola Valley, while the hinterland at the western location (Kinderkur) is higher and surrounded by other dunes. A breach at a location in the south-western dyke, called Flinthörndeich, was simulated, in order to assess the impact of a failure in the flood defence system from this direction as well. Like all dykes on the Island of Langeoog the Flinthörndeich is in very good condition. A failure of the sluice in the eastern dyke (Ostdeich) is also very unlikely due to its double safety. Nevertheless, failures at these locations are taken into account to get information on the hydraulic answer of the investigation area to flood hazards from all directions.

The failure of the railway dyke opening in the Harbour Dyke and a subsequent breaching of the Harbour Dyke was chosen to be another scenario. This scenario was assumed to be possible due to the fact that only one gate is existing to prevent flood water from entering the southern polder in case of floods. No second parallel gate or any other measure is existing and therefore no second line of defence.

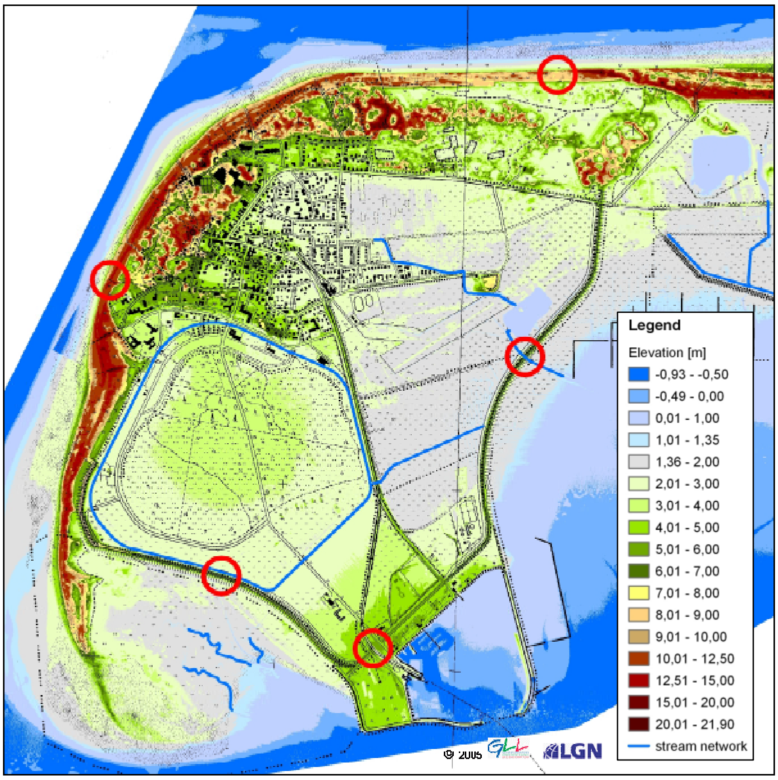


Figure 12: Locations of possible failures in the flood protection system simulated in the flood model

In addition to the standard scenarios of the breach location described here, the effect of current dune reinforcement in the Pirola Valley was assessed. Furthermore, two scenarios, representing flood mitigation measures in form of positive break lines, were accomplished. Those two measures came up in the first meeting of a Local Contact Group on Langeoog. The measures were roughly tested in supplementary scenarios and the results were discussed in the following meeting of the LCG. Further information on the aim of and the experience from LCGs are given in Chapter 6.

A lot more scenarios were simulated with the model of the pilot site of East Frisia. Several different scenarios with varying model configurations were accomplished. The goal of flood simulations of East Frisia were to obtain representative results for the region and to receive information on a great variety of investigated aspects.

For this purpose a standard case, representing the state in the year 2007, was created for different assumed breach locations. The development of the model was described afore. The selection of breach locations to be modelled was done in different steps. At first, the coast line of the study area was subdivided into quasi-homogeneous sections. The division was depending on predefined criteria. One criterion demanded the same type of coast line within one section, including the type of flood defence system as the type of dyke as well as the existence of a dyke foreland, a summer dyke, or a secondary dyke line. Another criterion was considering the topography of the hinterland, especially the elevation. Harbours and other areas with special functions were also treated separately. The result of this subdivision was a number of 47 quasi-homogeneous sections of coast line. The average section length was 2.5 km but the actual length strongly varied from one section to another.

From this sections eleven were selected and breach locations inside were chosen (see Figure 13). The selection was carried out with the aim to provide a representative

overview over the pilot site. Therefore, all different types of coast lines were included in the selection and some types were covered twice to obtain comparable data.

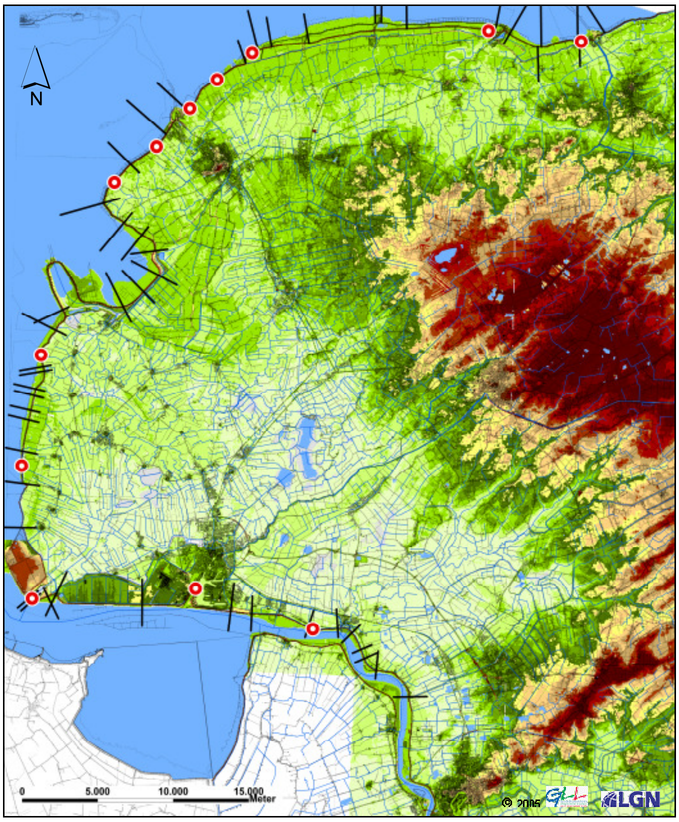


Figure 13: Sections and locations of dyke breaches simulated with the flood model of East Frisia

Different types of coast line, as they were defined in this study, are shown in Figure 14. Station 0 of the profiles was always set at the crown of the main dyke. The profiles are directly taken from the DGM. Hence, the profiles have a spatial resolution of 50 m (cell size of the DTM) as well. This can lead for example to dykes with a crown width of 50 m in the profile, although it is much smaller in reality.

The upper left graph represents a flood defence system consisting of a single main dyke. No dyke foreland or additional dyke lines are providing further protection, as it can be seen in the other graphs. All profiles have in common that the hinterland has an elevation about NN + 1 m. The direct hinterland is low lying in the entire investigation area, only interrupted by secondary dyke lines or channels.

Since the goal of SAFECOAST is to obtain knowledge about the coast and possible hazards in 2050, scenarios representing this year were conducted at all breach locations. For this purpose, an average sea level rise of 50 cm per hundred years was assumed. This means, present tidal hydrographs were added with 25 cm to simulate boundary conditions in 2050. In order to evaluate the influence of the sea level rise in a longer period of time, also scenarios of the year 2100 were accomplished and the hydrographs were increased by 50 cm from the present state. Simplifying the shape of the hydrograph curves have not been changed due to complex interactions between hydrology and morphology of the Wadden Sea area which requires further scientific investigations.

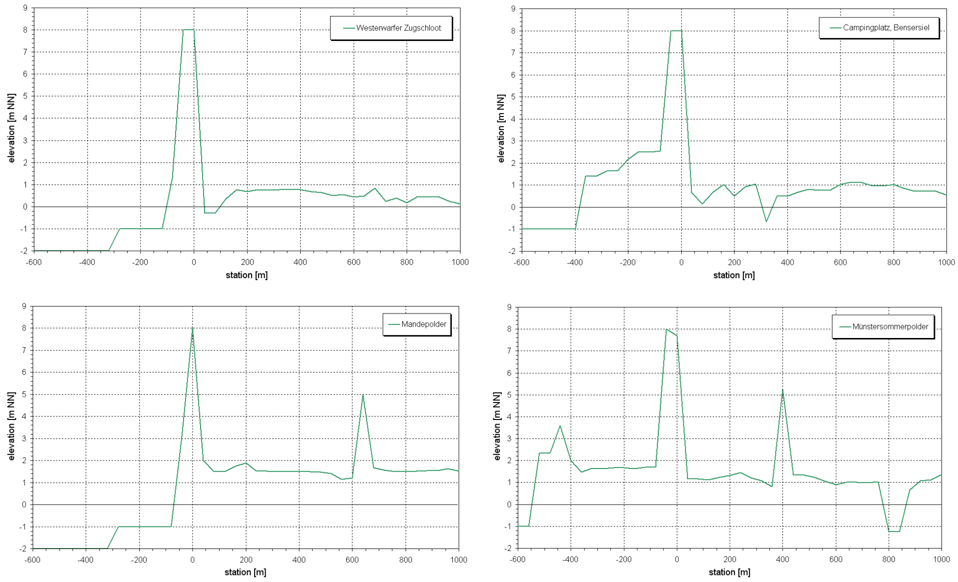


Figure 14: Profiles of selected breach locations in East Frisia

In addition, problem-oriented scenarios were tested with simultaneous dyke breaches, with a modified flood defence system, and with potential flood mitigation measures. The variation of the flood defence system was carried out by changing the digital terrain model, in order to simulate the presence of a summer dyke, a dyke foreland, or a secondary dyke line. At some breach locations, where none of these measures were existent, they were added. At other locations they were removed in the model. The results from scenarios with the altered DTM were compared to those from the standard case and hence the impact of the changes could be assessed. Other potential flood mitigation measures like break lines were tested the same way.

4.3 Analyses and results

The great variety of simulated flood scenarios in this study and therefore the great amount of output data led to the fact that the major part of analyses had to be repeated for each scenario. For this reason, standard analyses were identified which had to be accomplished for every scenario. They were necessary for the subsequent flood damage evaluation or for the supervision of the model. Other analyses were only carried out for certain scenarios, for they were not required or the effort would have been too high to apply them for all scenarios. Standard analyses are described in this Paragraph 4.3 as well as the most important additional investigations like the assessment of potential flood mitigation measures.

4.3.1 Standard analyses of flood characteristics

Many types of results analysed in this study were provided directly from the flood model SOBEK, while others needed preparation by means of GIS or spreadsheets. SOBEK directly delivers raster data for each simulated scenario, including inundation depths in every grid cell and for every simulation time step. They can be reviewed in the GIS environment of SOBEK or they can be exported from the SOBEK model. There, also animations and videos of flood propagation, inundation depths and vectors of flow velocity in each grid cell are available. The analysis of those animations led to the identification of flow paths and

locations of high flow velocities. By means of an additional function, the maximum inundation depth per grid cell, independent from the time of occurrence, is evaluated.

Standard analyses conducted for the results of each scenario were:

- Review of simulation in SOBEK and check on plausibility
- Determination of flood volume and inundated area
- Determination of frequency distribution of inundations depths per grid cell
- Preparation of flood map containing maximum inundation depth in each grid cell
- Identification of flow paths

The inundation characteristics volume and area gave a first impression on the magnitude of simulated flood. The distribution of inundation depths provided additional information which was valuable especially for the comparison of different scenarios. With regard to the subsequent flood damage evaluation, the flood map was of great importance. It provided inundation depths for each cell of the DTM which were required as input data for depth-damage function applied in the damage assessment (see Paragraph 5.3). Apart from the check on plausibility and the identification of flow paths all standard analyses were accomplished by means of a GIS.

Below, selected results of the standard analyses and their use for the interpretation are described. For the pilot site of Langeoog one focus lay on the comparison of flood models used in COMRISK and in SAFECOAST and on the improvement of knowledge regarding this area. For the pilot site of East Frisia the latter was also important, though comparisons of scenarios delivered information on special questions of Action 5B.

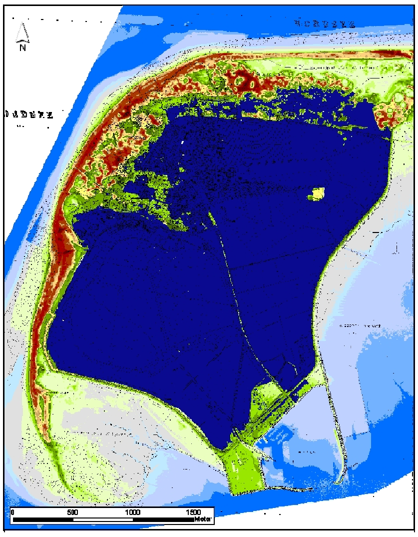
Langeoog:
In the former project COMRISK floods due to storm surges had been simulated for the island of Langeoog by means of hydraulic calculations and a GIS approach. This relatively simple method was now compared to the more complex application of SOBEK to the pilot site of Langeoog. Due to recommendations from the investigations on Langeoog, the application of a meso-scale damage potential analysis and the use of SOBEK as a complex flood model for the second pilot site East Frisia were decided.

The first scenario carried out with the model of Langeoog was the failure of the railway dyke opening in the Harbour Dyke. The results of this scenario were chosen to exemplify the differences between the 0D+ calculations done in COMRISK and the 1D2D model SOBEK. The resulting inundations are shown in Figure 15.

From the graphics can be seen that there are great differences between the two results. While the inundation determined by the GIS approach of superposing water levels and elevation grid is uniform and distributed over nearly the entire study area, inundation characteristics like flooded area or inundation depth, resulting from the application of SOBEK, are much more detailed. The extent of the flood especially differs in the second polder which is very important due to fact that the village is located in this area. This has great impact on the damages resulting from the simulated flood (see Chapter 5).

The differences in resulting flood characteristics can be explained by the approaches and considered parameters and processes of both models. Although the water volume flowing through the breach into the southern polder is calculated using the Poleni-formula for weirs and the flood water level is determined by the relation between water level and reservoir volume in the 0D+ approach, the resulting water level is uniform over the entire inundated area. Flow propagation including surface roughness and flow velocity is neglected. Only the transition of flood water from one polder to the second is calculated by the weir formula as well. This way the flood is assumed to be able to propagate into

the area which is lying below the flood water level and which is connected to the surface flow.



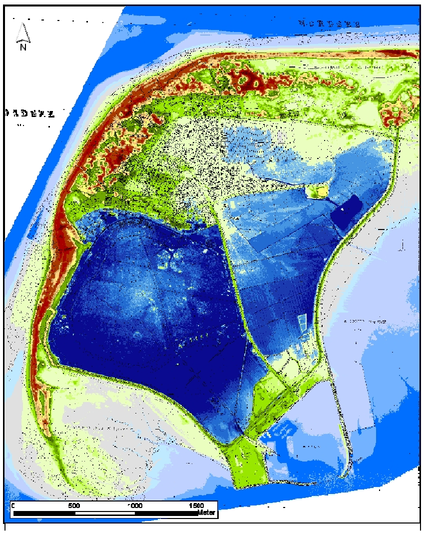


Figure 15: Comparison of flood maps from former COMRISK calculations (left) and from application of SOBEK (right), failure in Harbour Dyke

The results of SOBEK are calculated under the consideration of roughness of both, the surface and the stream network. This restrains the volume of inflowing water on the one hand and the propagation of the water on the other hand. Additionally, the water level inside the breach and in every next cell of the flow path limits the water flowing into this cell in the following time step. Since the calculations of SOBEK are unsteady, the conditions and results of former time steps are considered in every new time step.

The area of the breach location at the Pirola Valley has just been subject of a flood protection measure. A strengthening of flood protection dunes at the assumed breach location has been started in the summer of 2007 and is completed in 2008. The benefit of this measure could be verified by the results of the flood model. Erosion of the northern dunes of the Pirola Valley was found to result in severe inundations, also affecting the village. The animation of flood propagation from the dune breach showed a total filling of the Pirola Valley in the first hours after the breach occurs. After the water level inside the valley reaches a certain value, the flood propagates through a low lying path in the secondary dune belt, the Herrenhus Dünen. Close to the path other smaller gaps in the dune belt are filled as well and contribute to the inundation of very low lying areas south of the Pirola Valley. When this area is reached by the inundation, the flood water quickly arrives at the periphery of the village. Severe inundations in the eastern part of the village are the result.

With accomplishment of the recent flood protection measures at the northern dune, this scenario becomes unlikely at least for the next storm seasons. By using a complex flood model for the simulation of this scenario, a comparison of cost and benefit of this certain measure can be made.

The need for another measure, namely the closure of the three small gaps in the Heerenhus Dünen, was identified in COMRISK first (COMRISK, 2005). The recommendations of COMRISK led to a realisation of this adaptation measure in 2007. The simulation and the results from this flood mitigation measure are illustrated in Paragraph 4.3.2.

From the application of SOBEK to the Island of Langeoog and the subsequent comparison to results of a former study the conclusion was drawn that the application of complex models like SOBEK is costlier but useful due to more detailed and more accurate results.

East Frisia:
For the analysis of the results from the flood model of East Frisia nearly all output obtained from SOBEK were used. Only flow velocities were not considered in this state of the investigation, for it was assumed and earlier proved that high flow velocities only occur in the vicinity of the breach or small gaps. So, no influence on the resulting damage needed to be taken into account in the major part of the investigation area.

The standard analysis in form of a flood map was used for the assessment of the impact of the assumed sea level rise. Therefore, flood maps, containing comparisons of scenarios of 2007, 2050, and 2100 for all breach locations, were prepared. The cell size of the grids in the maps was equal to the input DTM (50 m). An example for a flood map is given in Figure 16. Here, the failure in the coastal defence system due to a storm surge was assumed to occur in the western main dyke near the village of Pilsum.

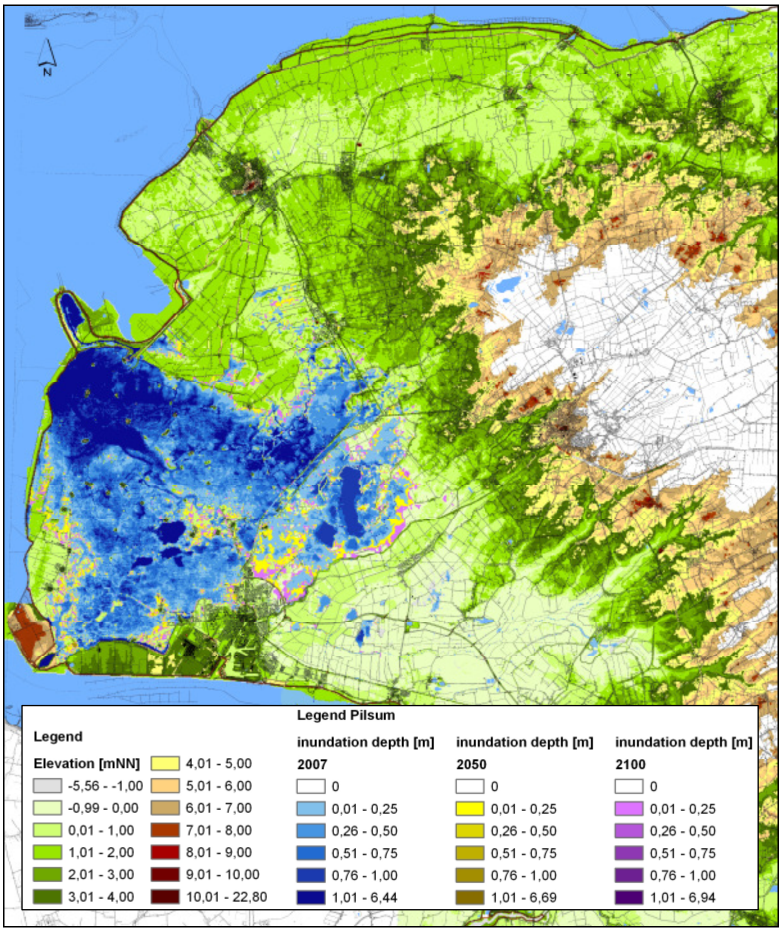


Figure 16: Comparison of inundated areas for scenarios of 2007, 2050, and 2100 and for a breach location near Pilsum

For all simulated scenarios the frequency distribution of inundation depths in all grid cells within the investigation area were obtained and interpreted. By means of a comparison of flood scenarios from 2007, 2050, and 2100 the influence of a rising sea water level could be assessed. Conclusions could be drawn, regarding the range of occurring inundation

depth and their future development. The development of frequency distribution of inundation depths related to the above breach location near Pilsum is shown in the following Figure 17.

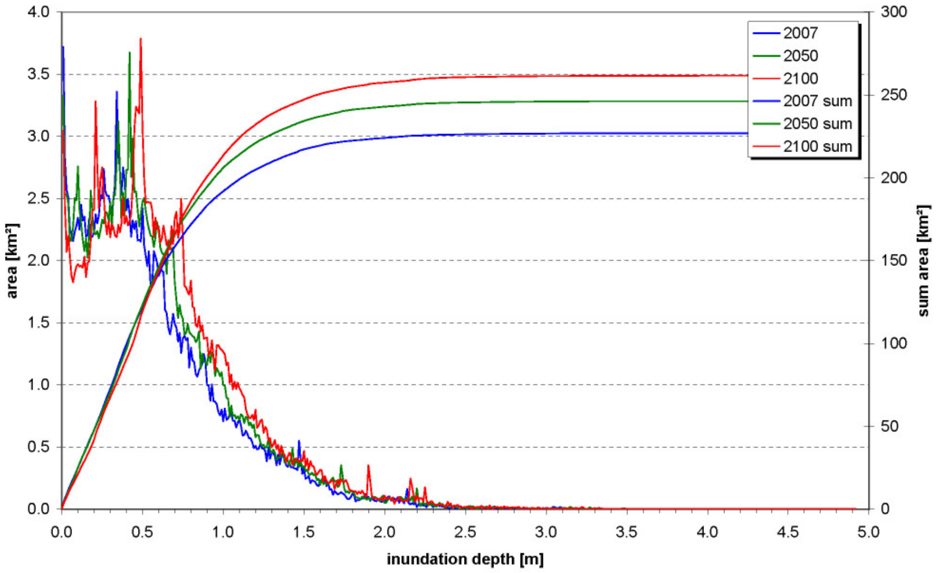


Figure 17: Inundation depths of flood scenarios for 2007, 2050, and 2100 (breach location "Pilsum")

Figure 17 illustrates that observed inundation depths were not significantly increased from the state of 2007 to the future scenarios but the frequency of especially the medium inundation depths have risen. For other breach locations the increase of inundation depths was found to be even lower. This means that especially the inundated area is affected by sea level rise and not that much the inundation depth. This finding is also very important for the assessment and prediction of flood damages. This future development of flood characteristics will result in a greater amount of affected assets at risk, though the damage of every single asset will not significantly increase.

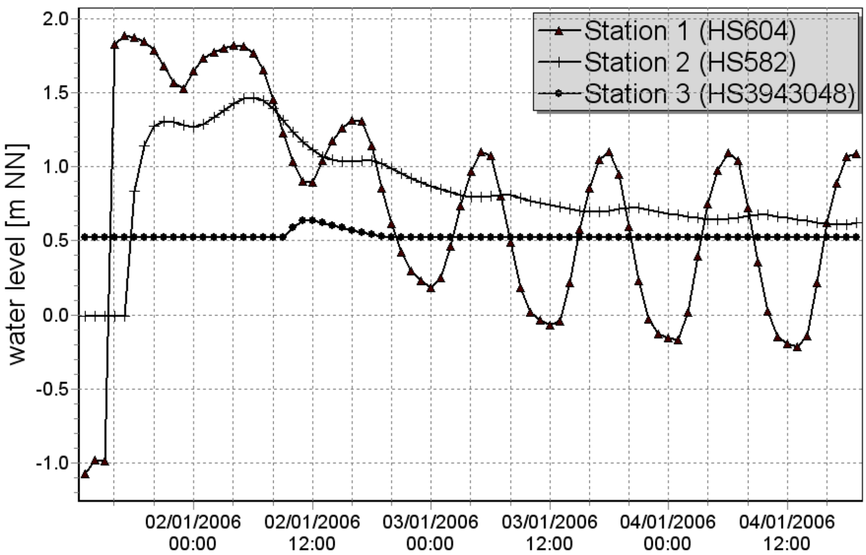


Figure 18: Water level over time at virtual gauges with different distance to the breach

The propagation velocity of the inundation front was analysed by means of gauging stations which were set in regular distances from the breach location. An example for virtually measured hydrograph curves is given in Figure 18.

From this kind of graph the propagation of the flood can be determined as well as the development of the flood hydrograph with increasing distance from the breach. A damping effect was found here. For the analysed scenarios of East Frisia the propagation velocity, exclusive of inside the breach, was determined to be in the range from 0.03 to 0.3 m/s. The increase of propagation velocity due to a greater flood volume in the scenarios of 2050 and 2100 was found to be insignificant.

The inundated area and the frequency distribution of inundation depth were determined by means of GIS tools. Additional analyses were carried out using spreadsheets. For example the dependency of calculation time on different model parameters was investigated. It was found that the time the model needs to accomplish a certain simulation strongly depends on the number of active cells. An active cell is defined as a cell which is wetted or already inundated in a time step. The higher the number of active cells the longer the duration of simulation. Other parameters were found to minor influence on the calculation time.

4.3.2 Potential flood mitigation measures

The impact of certain flood mitigation measures was also studied by means of flood scenarios in the pilot site of East Frisia. Potential mitigation measures investigated in this study were dyke forelands, summer dykes, secondary dyke lines, and break lines in the hinterland. The additional scenarios were conducted using the standard case of 2007. At those breach locations where dyke forelands or summer dykes were existent, these had been modelled in the standard case. For the new scenarios they have been removed, in order to compare flood characteristics from configurations with and without these measures.

Besides the amount of sea level rise the rate of change of inundation characteristics strongly depends on the breach location. This is explained by the fact that the topography of areas seawards and landwards the breach location strongly influences the inflowing volume and the flood propagation. This means for areas seaward a dyke the existence and height of a foreland and a summer dyke is important, whereas landwards the elevation of the hinterland and linear structures like secondary dyke lines or embankments are very important parameters. This finding is a result of scenarios conducted with high or low foreland at the same breach location. Another comparison is made between scenarios with or without a summer dyke in front of the main dyke line. Dyke forelands or summer dykes have the same function with respect to floods. They decrease the inflowing volume, since with their presence only very high tides enter the breach location. The effect is a decreased flood volume compared to low forelands without summer dykes. The function of dyke forelands and summer dykes corresponds to the sensitivity of inundation characteristics concerning breach extent. The cross section, representing inflowing flood water, is limited either by the breach extent or like mentioned afore by the elevation level of a dyke foreland or by the crest height of a summer dyke.

A failure in the main dyke line of a polder and the related effect of the secondary dyke line was investigated by additional scenarios at two breach locations. At the northern coast of East Frisia a secondary dyke line of several kilometres length is existent. This dyke and the main dyke represent the borders of a line of polders, separated by small dykes with low crown heights. Two of the assumed breach locations of this study lay in the main dyke line of the Mandepolder and the Münsterpolder. They have been analysed concerning the function of their secondary dyke line. Since both polders are not directly

drained into North Sea but into the hinterland, an opening in form of a culvert is found in the secondary dyke line of both polders. In order to assess the effect of these opening as well as the effect of the secondary dyke line, scenarios were carried out with a secondary dyke line in the present state, with a closed culvert, and without a secondary dyke line. Figure 19 shows the results of the scenarios "Mandepolder" in form of flood maps.

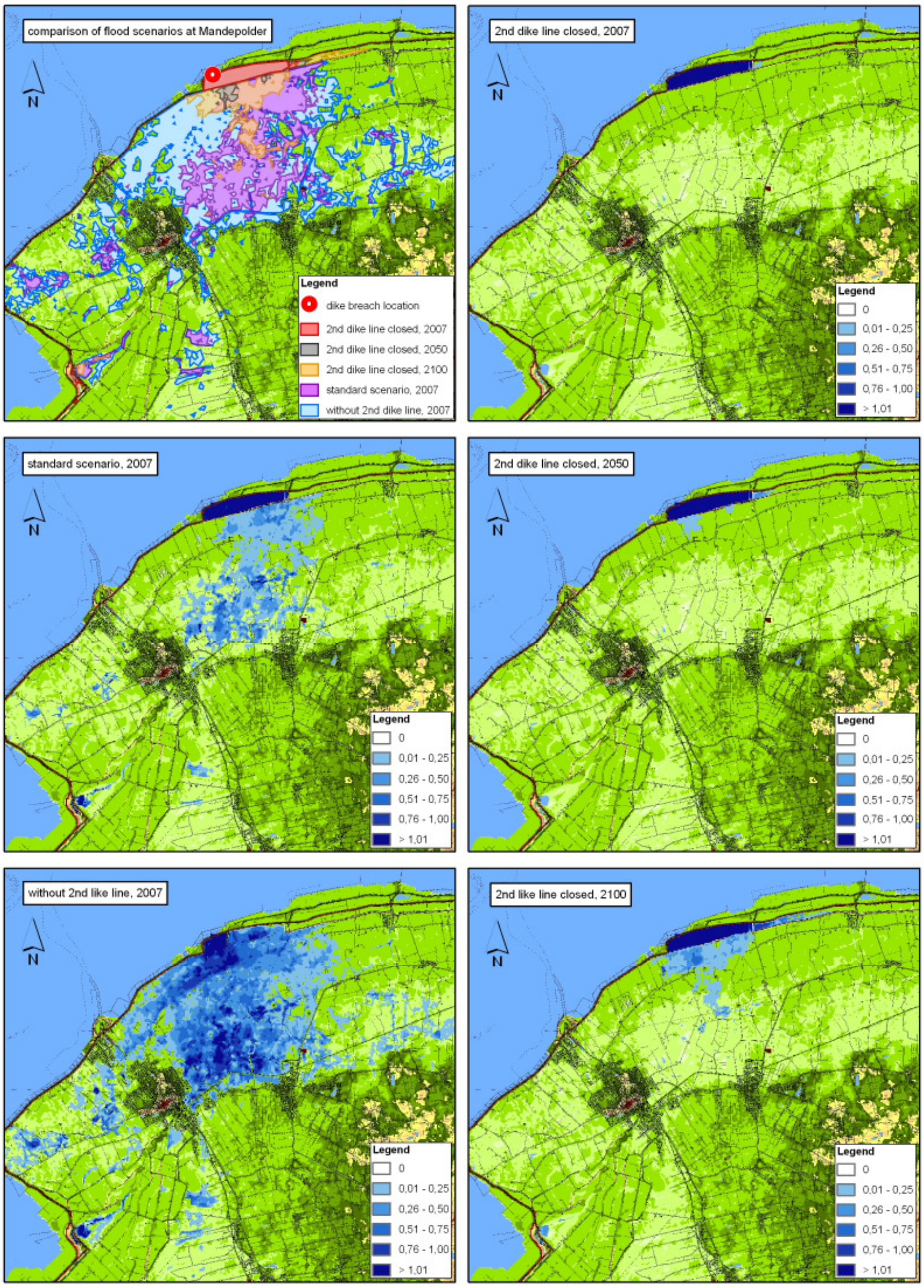


Figure 19: Comparison of scenarios for the assessment of the effect of secondary dyke lines

It can be seen from Figure 19 that the closure of the dyke opening has a great effect compared to the standard case. The total volume of flood water could be kept inside the polder in the state of 2007. No water reached the hinterland and therefore no damage would have occurred there. The inundation depth inside the polder is very high, since

flood propagation is prevented over a certain period of time. Assumed that no failure in the secondary dyke line occurs, the water level inside the polder has to reach the crown height of the secondary dyke line before flood water enters the hinterland. The high inundation depth inside the polder is in this case not that problematic due to the fact that only agricultural use is present in these polders. From this result the conclusion is drawn that the maintenance of the lock in dyke openings is of major importance for flood protection. Even with higher water levels like in the scenarios of 2050 and 2100 inundation areas are very small compared to the present state. The great effect of the secondary dyke line is shown by the scenario without it. Here, the inundation covered a wide area in the hinterland and residential areas were flooded.

It could be proved that secondary dyke lines and especially polders are considerable flood mitigation structures.

Positive break lines like street or railway dams represented another type of flood mitigation measures which had been assumed to have great influence on inundation characteristics, especially on flood propagation. The influence of break lines has been proved previously in the parameter study (see Paragraph 4.1.2).

The idea of using other break lines than secondary dyke lines as flood mitigation measures came from the fact that in some scenarios the identified flow paths had taken course through gaps in existing break lines. The question to be investigated was how flood characteristics will change in case of closed break lines. This was tested in the scenarios mentioned above. Another possibility was the construction of new break lines or the heightening of existing ones. This possibility was also analysed by means of scenarios, using the state of 2007. The results of these scenarios were compared to those of the standard case with the same breach location.

Figure 20 exemplifies the impact of new break lines. They were implemented into the model or gaps in existent break lines were closed in the DTM by means of a GIS. One scenario was conducted with new break lines near the city of Emden. The course of the new virtual break lines was chosen by the given conditions in the northwest of Emden. A highway was recently built in this area, surrounding the city like a ring. The highway was not built on a dam but on concrete pillars. It was assumed that this street could be used to protect the city of Emden from flooding from northern directions. In the scenario the gaps between the pillars were filled by a small dam of one meter height above the surface. Connected to this dam another small dam in north-south direction was built in the model in order to protect a village north of Emden. The dyke breach occurs in the south-western corner of the study area, called Knock. Coming from this direction, the flood affected the city of Emden in the standard case and led to severe damages in the north-western suburban areas.

The comparison of flood characteristics, especially the inundated area, showed a significant effect of the new positive break line (Fig. 20). A constant dam elevation of one meter was sufficient to prevent flooding in the city of Emden from the north-western direction. The total inundated area was not much decreased, but flow propagation into an area, containing a great amount of values at risk, was avoided. This effect could also be observed in the comparison of predicted resulting damages (see Paragraph 5.4).

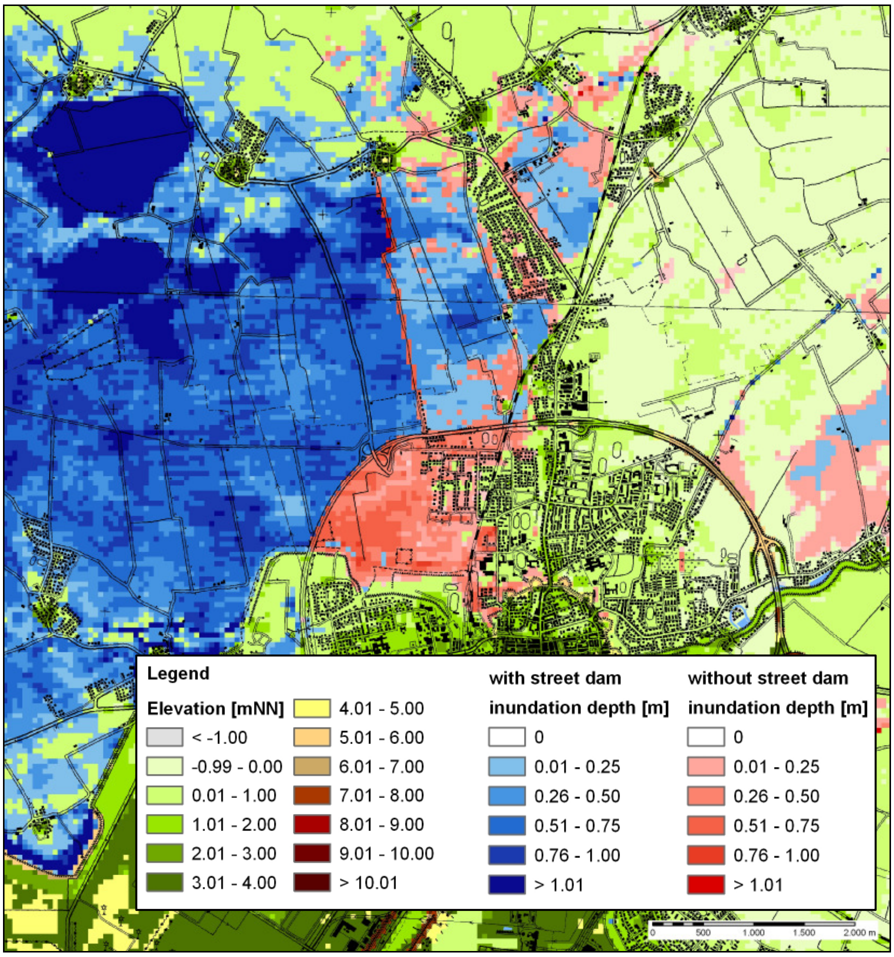


Figure 20: Comparison of scenarios with (blue) and without (red) new break lines

The effect of the new break line in northern direction was not as large as the ring dam around the city. Here, the inundated area was only slightly increased compared to the one from the scenario without a break line, although inundation depths were lower ($d_{mean} \approx 0.2$ m with break line; $d_{mean} \approx 0.5$ m without break line). The reason for the small reduction of inundated area was the opening in the break line due to a crossing drainage channel.

Another scenario included the closure of a gap in the break line between the cities of Norden and Norddeich. A railway dam which has a low lying part of several hundred meters is represented by this break line. This location was chosen, for the results from the standard simulations have shown that the only flow path connecting both sides of the break line is running through this gap. It was assumed that a closure would have great influence on the flood characteristics. This could be proven by the results of additional scenarios. The flow through the gap was avoided and also no overflowing over the dam was observed. Therefore, the values which lie in flow direction behind this break line were protected. But also the negative effect was found that the water level in front of the break was slightly higher and small parts of the close city of Norden were flooded which had been dry in the standard scenario. This originates from the fact that the flooded area westwards of Norden is bordered by break lines in three directions and therefore is similar to a semi-polder.

4.4 Conclusions from flood simulations

The results of the conducted flood simulations for the pilot areas were analysed in detail. The main conclusions drawn from the application of state-of-the-art flood simulation to the two German pilot sites are also summarised in Chapter 7.

The obtained flood maps for each scenario were required as input data for the subsequent flood damage evaluation, since the maximum inundation depth determines the damage an asset sustains. The estimation of damages due to a flood is described in the following Chapter 5. Beside the function of delivering input data for flood damage evaluations, the flood maps were valuable for answering certain questions like the influence of sea level rise or potential flood mitigation measures on flood characteristics.

Concerning the sea level rise it was found that especially the inundated area in the investigated coastal lowlands will increase. Inundation depths will not change significantly, unless the inundation area is restricted like in polders. This result is valuable for future spatial planning and for disaster control, since settlement in future flood-prone areas can be avoided or for example the inundation depth in certain areas can be taken for evacuation plans.

From the investigations on the influence of dyke forelands, summer dykes, secondary dyke lines, and break lines in the hinterland the conclusion is drawn that the development and management of forelands as well as the maintenance and expansion of embankments in the hinterland are potential flood mitigation measures. Especially dyke forelands and summer dykes have the positive effect to reduce the inflowing flood volume through the dyke breach. They can be referred to as structures, mitigating a flood before all other measures can take effect. Secondary dyke lines and break lines in the hinterland have the effect to reduce the flood propagation or to lead it into a certain direction.

In case of openings in the secondary dyke line of polders or in other positive break lines, flood water was transported by the drainage system into the area behind the break line, while in the investigated cases the dyke or dam itself was not overrun by the flood. This shows the influence of an existing drainage network implemented into the model on the one hand. On the other hand, the effect of break lines as flood mitigation measures could be demonstrated.

Nevertheless, an aspect to be discussed is the influence of new break lines on other parts of the investigation area than the newly protected. It was also found that, depending on the topography of the affected area, the flood is propagating into other directions and thus assets can be damaged which have been unaffected before. In order to prevent undesirable effects of new break lines as flood mitigation measures a detailed study and simulation with high spatial resolution is recommended.

It should be mentioned that the results described in this study were obtained from pilot sites of certain characteristics, namely coastal lowlands. The possible transfer of results to other regions is restricted and should be done very carefully.

5. Damage estimation

With accomplishing flood simulations, the effect of source and pathway of the SPR approach have been determined. The resulting inundation characteristics at every location in the investigation area, especially inundation depths, have to be combined with

the receptor of risk in the next step. Since in this case the receptor is considered to be the sum of all affected values, they have to be evaluated in the first place.

The application of a damage potential analysis to the pilot site of East Frisia is described in this chapter. The actual flood damage evaluation was conducted for both pilot sites by application of a GIS and is also illustrated in this chapter.

5.1 Adapted methodology

A common methodology for the application of flood damage assessments is described in Paragraph 2.2. Although the illustrated work flow is universally valid, methods and approaches of single work steps have to be adapted to the actual circumstances of each study. In this case minor adaptations of existing flood damage evaluations methods were necessary. For this reason, the actual adopted methodology for the two pilot sites is explained here.

As described in Paragraph 2.2, appropriate methods for flood damage evaluations have to be chosen based on different criteria. One of them is the extent or scale of the investigation area. In flood damage evaluations at least the flood-prone area should be included in the investigation area. This means that in coastal regions the scale of an investigation area is determined by the area of the hinterland but as well by the length of the coast line (Meyer, 2005). While the seaward boundary of a flood-prone area is given by the coast line, the landward border has to be specified. For this purpose, contour lines, administrative borders or a combination of both can be used for borders of the investigation area.

The investigation areas of the two pilot sites were already determined for the development of the flood simulation models. The study area at Langeoog was clearly defined by the northern and western dune belts and by the south-eastern ring dyke, since it was stated that only the protected western area of the island was to investigate. The Island of Langeoog is relatively small and the village located in the west has only few inhabitants. Due to this fact the damage potential for this pilot site was evaluated by means of the micro-scale so-called MERK method (Reese et al., 2003). The analysis, including an object-oriented assessment of values at risk, was conducted within the previous COMRISK project in 2003. For detailed results it is referred to the final report of that study.

In COMRISK, a concentration of values in the village of Langeoog was found. The surrounding rural areas in polder B are of low value and mainly used as pasture for horses. Polder C in the south of the island consists of unused land covered with low forest. Thus, values of damage potential are low there as well. Polder A, the northern dune valley "Pirolatal", is ecologically valuable and essential for the protection of the drinking water supply. Nevertheless, both aspects were not part of this study. The special aspect of impacts of storm surge induced floods on the drinking water supply of Langeoog was also investigated within the scope of the COMRISK project. For information on this subject is referred to the related reports.

For the second pilot site of East Frisia a detailed damage potential analysis was carried out. Due to the extent of the investigation area and the length of its coast line, a meso-scale method was chosen. The applied approach was based on the so-called Method I developed and described in Meyer (2005). This method had to be slightly modified due to the fact that the conditions in the present study area differed from the one in the investigation of Meyer.

Like the major part of available meso-scale methods, the values had to be evaluated on the municipal level. While in macro-scale approaches all values are allocated uniformly over the entire area of a municipal unit, meso-scale methods are characterised by the additional differentiation of land use within the municipal unit. The main assumption in the applied damage potential evaluation method is that values of a certain category are concentrated on certain land use types. Within one type of land use values of one category are equally distributed. A fixed allocation for every value category on land use types was defined by Meyer (2005). Therefore, the land use for each parcel within the investigation area has to be known as well as all values located there.

The land use data used in this study are called ATKIS-objects (Amtliches Topographisch-Kartographisches Informationssystem). ATKIS-objects represent official data which guaranties accuracy in a given range and therefore comparability of results. Nevertheless, not all land use types available in ATKIS are used in the method after Meyer (2005). Thus, a selection of required ATKIS-objects was made. Some ATKIS-objects were additionally differentiated by their attributes. For example the land use type green land was subdivided into green land of agricultural use and other forms of use. Processing of land use data and the subsequent allocation of values was carried out by means of a GIS. An example for resulting land use data in form of ATKIS-objects as required for the Method I is given in Figure 21.

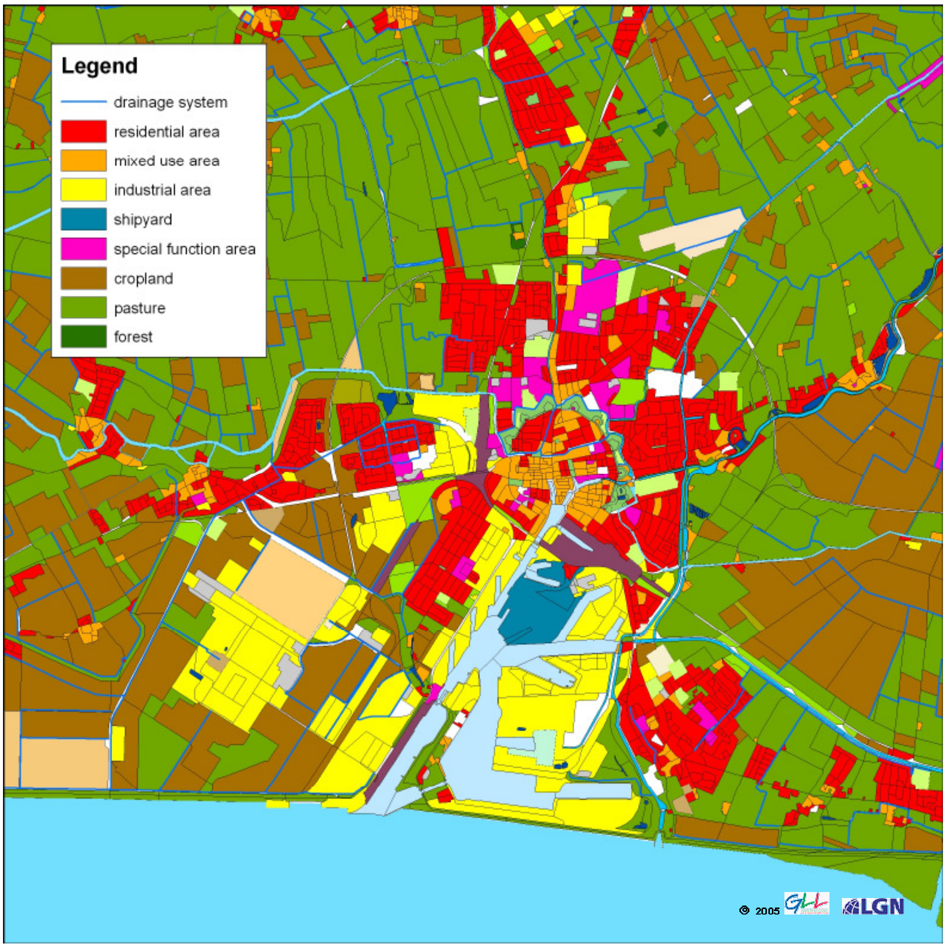


Figure 21: Land use in the city of Emden (ATKIS-data)

The values to be allocated on the determined categories of land use data was mainly obtained from the Niedersächsisches Landesamt für Statistik (Lower Saxony State Office for Statistics) which provides the major part of required information. Different types of data concerning population, economy, employment, or others are provided. While some data could directly be taken for the damage potential analysis, others necessitate the consultation with local experts or other sources.

The following value categories were evaluated in the damage potential analysis, for they could easily be combined to fit the damage categories applied in the actual flood damage evaluation:

- Inhabitants
- Private buildings
- Private inventory
- Vehicles (only private cars)
- Life stock
- Fixed assets in 12 different economic sectors
- Stock values in 11 different economic sectors (stock value of agriculture is represented by life stock)
- Infrastructure
- Land values

According to the damage potential evaluation after Meyer (2005), Action 5B was mainly dealing with the direct, tangible, primary damages (Paragraph 2.2). Therefore, only values, belonging to considered damage categories, were collected. The population living in the flood-prone area represents the direct, intangible and primary type of damage. Due to reasons mentioned above, the population was not considered in form of casualties but in form of inhabitants at risk as part of the damage potential. Only the number of people affected by a certain flood scenario was determined from the damage evaluation. The type of indirect, tangible, primary damage was represented by the loss of gross value added which is a result of flood water disrupting economical processes in the flood-prone area. The damage to the value of agricultural land due to flooding can be referred to as direct, intangible and primary or secondary. A classification as tangible might be theoretically possible but hardly practicable. While primary damages to cropland in form of crop failure can be quantified in monetary terms, primary damages to pasture and secondary long-term damages due to salt water and sediment on the land is difficult to predict or calculate sufficiently. For this reason, agricultural land is treated similar to the population at risk. Land values are evaluated for agricultural land and for settlements. Agricultural land was subdivided into cropland and pasture. Damages resulting from the subsequent flood damage assessment were given in form of value of affected land. No relative or absolute damage is assed.

The allocation of resulting damage potential on the ATKIS land use data was based on the Method I of Meyer (2005) and is described in the following Paragraph 5.2.

After the damage potential was allocated and analysed, the flood damage evaluation was conducted using depth-damage functions. The used depth-damage functions were taken from the earlier KRIM project and represent a statistical combination of certain other damage functions (KRIM, 2003). Graphs of the five depth-damage functions for the fixed assets of different economical sectors are provided in Figure 22. Stock values of all considered economical sectors are evaluated with one single function (Figure 23) due to their similar vulnerability.

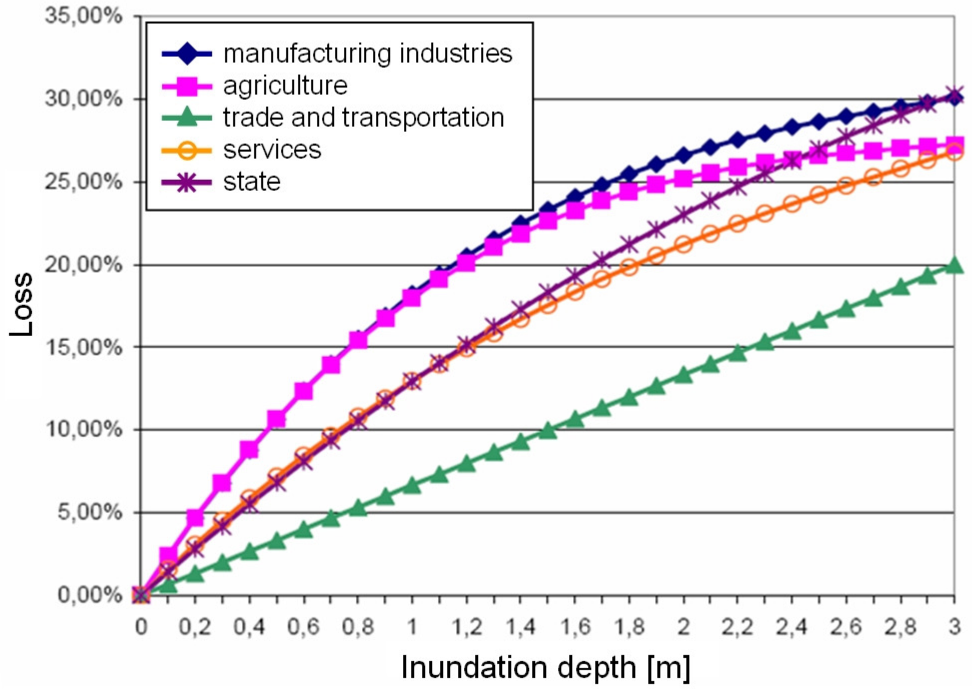


Figure 22: Depth-damage functions for different branches of industry

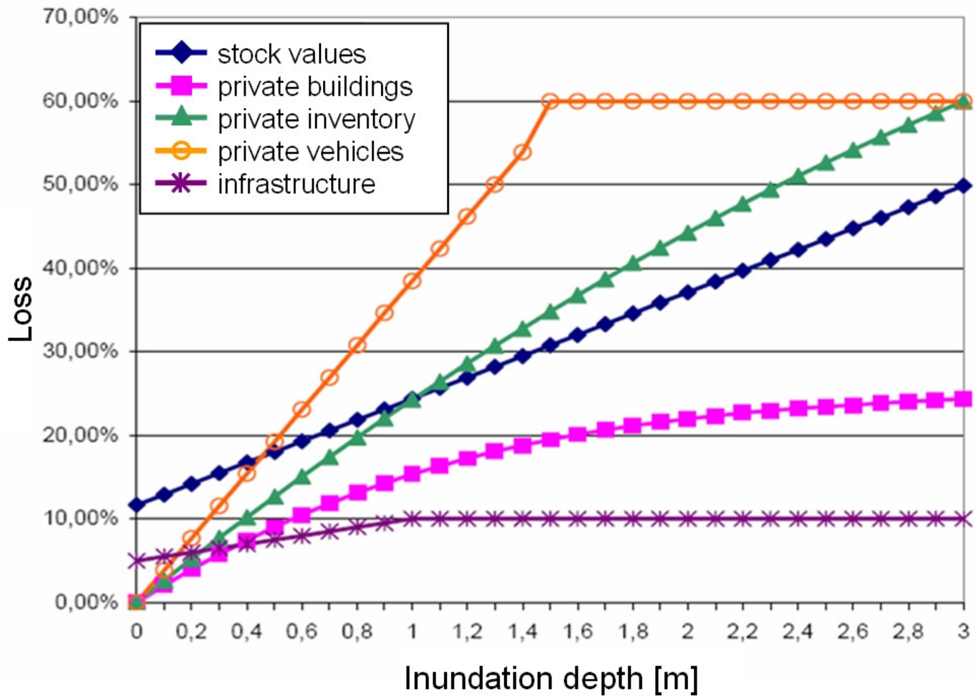


Figure 23: Depth-damage functions for stock values, private buildings, private inventory, vehicles, and infrastructure

The functions for the damage evaluation of private buildings, private inventory, vehicles, and infrastructure are also given in Figure 23. Some of the functions do not run through the origin which is physically incorrect. The functions were determined in the KRIM project by analysing and statistically combining depth-damage functions from former

studies. This means they do not represent a homogeneous set of recorded depths and damages and an illogical is therefore possible. Nevertheless, they were implemented physically correct into the analysis by allowing the occurrence of damage only with inundation depths greater than zero.

5.2 Damage potential for the pilot site of East Frisia

In order to evaluate the damage potential of the second pilot site "East Frisia", Method I after Meyer (2005) described above was applied. At first statistical data, representing the values at risk, were collected. These data were analysed and processed by means of a GIS.

Following the different work steps of the flood damage evaluation accomplished in this study, different types of results were obtained. Since the analysis of damage potential needs to be conducted before the actual damage evaluation, the first results were damage potentials for the different categories of values and the total damage potential of the investigation area. In this state of the study no allocation of values were carried out. Hence the spatial distribution of damage potential was unknown at that time. From the analysis a total damage potential of 33.6 billion € for the entire study area was determined. The distribution of values in categories is given in Figure 24.

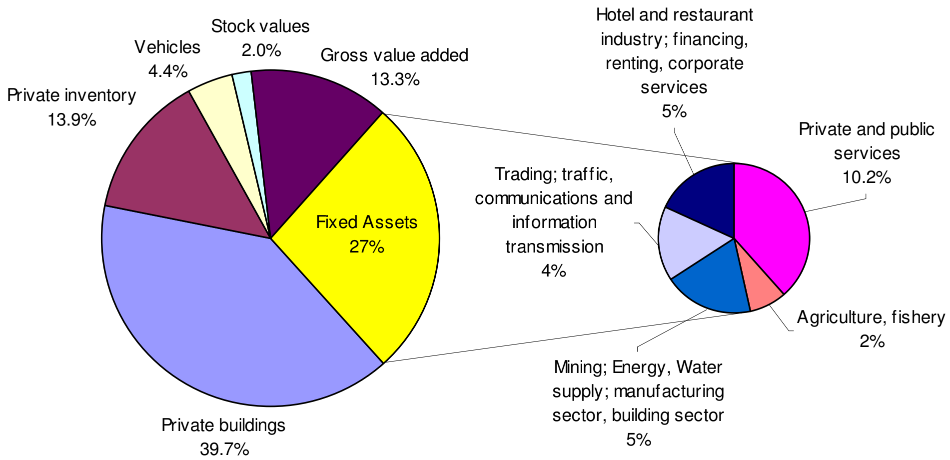


Figure 24: Distribution of damage potentials on categories of values for East Frisia

Regarding the distribution of values, a concentration of damage potential in four damage categories was detected (Figure 24). Those categories were private buildings, private inventory, fixed assets, and gross value added. Other investigated categories have been of minor importance (less than 5 % each). This fact was also found in the damage potential analysis of Langeoog (COMRISK, 2005) and is supported by outcomes of other studies.

The conclusion was drawn that these categories provide a sufficient estimation of predicted direct tangible damage potential, assuming that this distribution of values is more or less applicable for all regions comparable to the rural pilot site of East Frisia and supported by comparisons to other studies. For this reason, a possible approach for future damage potential analysis can be the estimation of only these four categories of values. In order to assess the total damage potential, the missing ten percent might be added to the 90 % of already known values. This findings are presently also discussed in other projects, for example FLOODsite.

After applying a GIS, the damage potential of East Frisia was also available in form of maps, including the damage potential per grid cell and per value category. The spatial distribution of values at risk could now be assessed. Another type of damage potential map provided information on the total damage potential in each grid cell (see Figure 25).

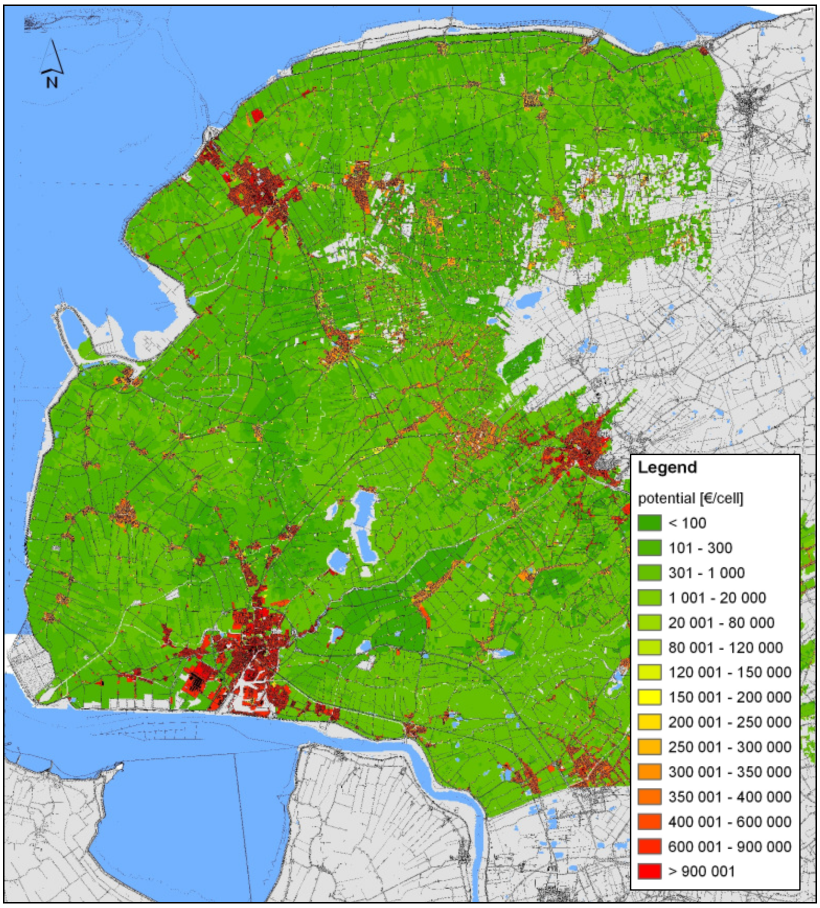


Figure 25: Damage potential per raster cell (50 x 50 m), sum of direct tangible values and GVA

The damage potential map (Figure 25) shows a significant concentration of values in cities and villages. This was expected, since the four categories including about 90 % of all values are also concentrated there. Private buildings and private inventory are allocated on residential areas and on areas of mixed use, while for these categories the density of values in residential areas was set to be twice as large as in mixed use areas (Meyer, 2005). Fixed assets are similarly distributed on industrial areas and areas of mixed use. Only the gross value added (GVA) is also allocated on agricultural areas and forests. Nevertheless, GVA is analysed for each sector separately. The fact that the GVA of agriculture and fishery is only one-tenth of the GVA of nearly all industrial sectors contributes to the concentration of values in settlements. The spatial distribution of values can be referred to as typical for rural regions with few smaller centres.

The micro-scale MERK method for damage potential analysis had been applied to the island of Langeoog in the former project COMRISK. Since this method is micro-scale, it is represented by a high level of detail in both space and height. The resulting total values up to 19.5 m above sea level were found to be about 1.1 billion € in 2004. For further information on methodology or results of that study is referred to the final report of COMRISK (2005).

5.3 Flood damage assessment

With the damage potential of the two pilot sites the amount of damage is known which will occur, if all values at risk gain a total loss. Since this is unlikely even in case of extreme flood events, certain flood events are applied to the investigation area and therefore to its damage potential. Via depth-damage functions the loss of values, the damage, can be determined as described above.

Langeoog:

For the pilot site of Langeoog actual damage evaluations for different flood scenarios were conducted by means of spreadsheet calculations. Damage potential and method of flood damage evaluation have not been changed in Action 5B. Only the flood simulation model was different. While in the previous study a 0D+ approach was applied, here a more complex numerical model was used. Since the results of the flood simulations, namely the inundations characteristics, were the only modified components of the flood damage evaluation, the determined damage of the same flood scenario in both studies were used to assess the influence of the flood simulation method.

Figure 26 shows a comparison of the results of both studies for the scenario “Harbour Dyke” in terms of absolute damage for each grid cell.

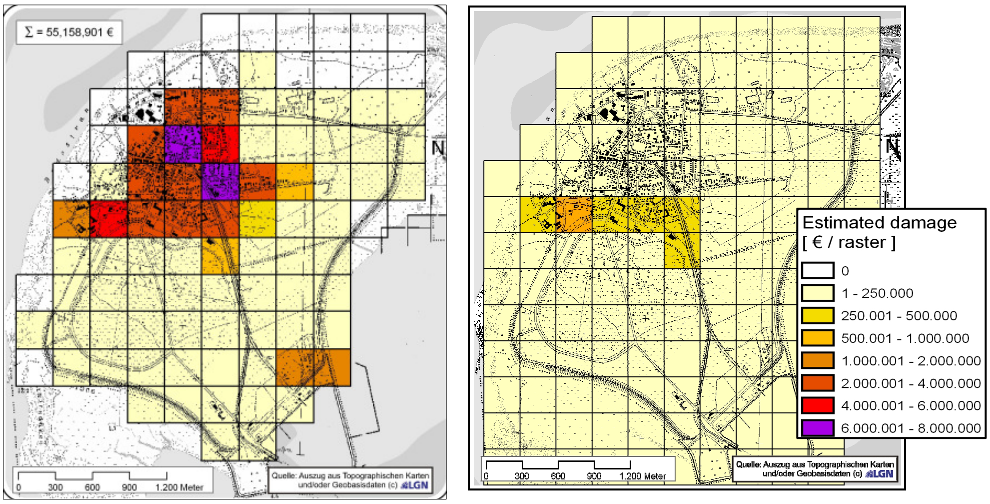


Figure 26: Comparison of damages from the damage potential analysis of MERK (2003) and from the COMRISK (left) and the SAFECOAST (right) flood simulations

The grids cells have a spatial resolution of 300 m. It is obvious that predicted damages resulting from SOBEK are significantly reduced compared to those of the former study. This can also be seen from Figure 27 where sums of absolute damages are given divided into the applied damage categories. The difference of flood impact was found as well when the number of affected inhabitants is checked. While the number of affected inhabitants was equal to 214 in the COMRISK study, the number was reduced to 34 in the present investigation for the same flood scenario.

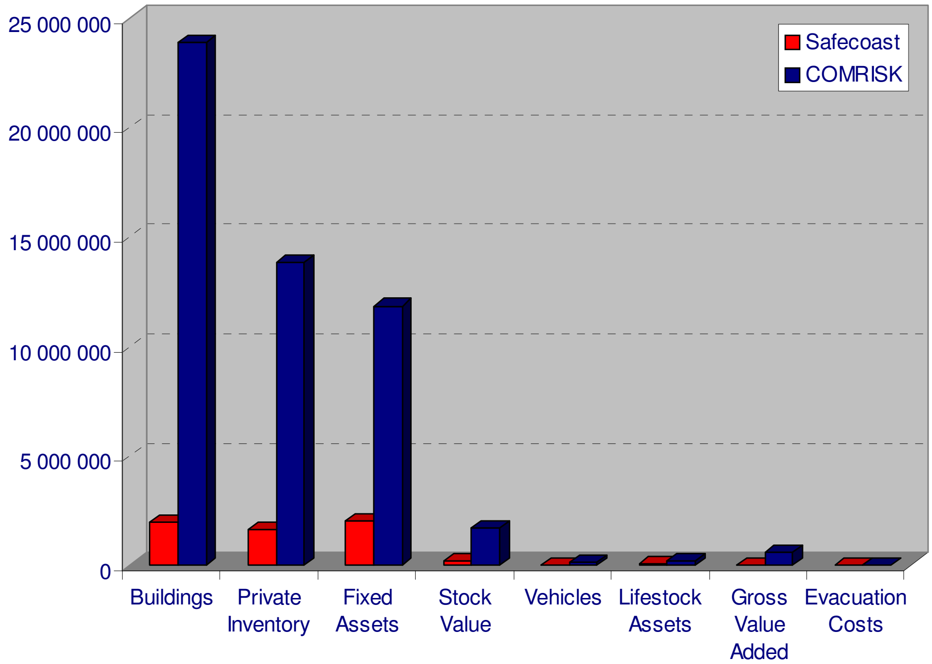


Figure 27: Comparison of absolute damages resulting from different flood simulations

It was found for this pilot site that a more complex flood simulation model provides more differentiated flood characteristics. Due to the reasons discussed in Chapter 4, it can be assumed that reduced floods and therefore reduced damages are also obtained in other pilot sites, when the results of a simple GIS approach and a complex model are compared.

East Frisia:

As afore mentioned, the actual flood damage evaluation for the pilot site of East Frisia was conducted by using depth-damage functions developed within the KRIM project. Resulting damages were obtained in form of maps for the total damage per grid cell and for each damage category as well as in form of sums, representing the total damage predicted to occur in the study area for a certain flood scenario. An example for a damage map is given in Figure 28. Here the predicted direct tangible damage for the scenario of a lock failure in the harbour of Emden is shown. From the map, a concentration of damage on residential areas close to the harbour is obvious.

The prediction of damages for the remote future suffers from great uncertainties. The prediction of future socio-economical changes in flood protected areas and therefore the development of assets at risk are highly uncertain. Only population developments are studied in more detail. A forecast of NLS (2007) states a slightly declining or constant population in the region of East Frisia. Increased moving in of older people and increased tourism are expected. This may especially cause a shift of values from the first and second to the third economical sector is predicted and will affect the resulting damages. A quantification of these effects is not available at the moment and further investigations on this topic are necessary. Nevertheless, measures and plans are indispensable in order to keep the flood risk at an equal level or to actually decrease it.

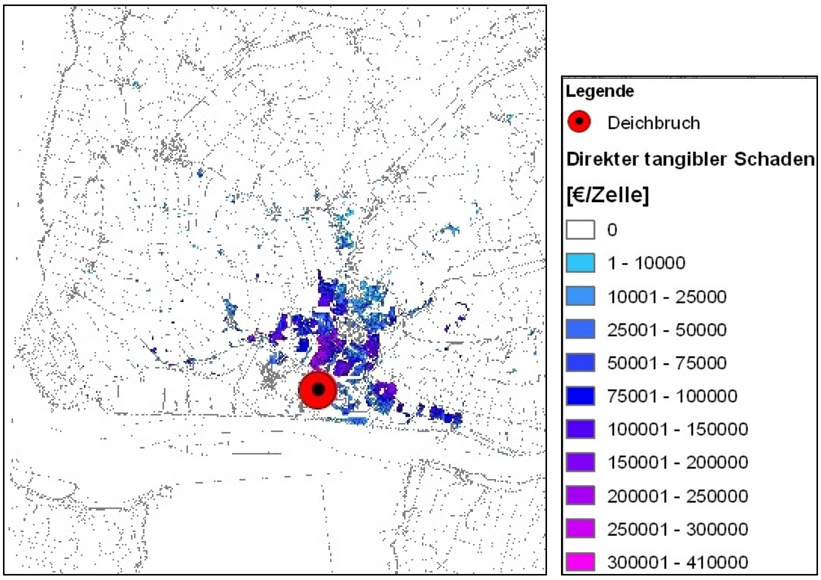


Figure 28: Direct tangible damages due to failure of a lock in the harbour of Emden

For this reason, damages in 2050 and 2100 were assessed by using the method of simulating scenarios again. Damage potential scenarios were combined with the inundation characteristics from the flood simulations for 2007, 2050, and 2100. In a first combination was assumed that the sea water level will rise, while the damage potential remains at its present value. This scenario is possible, for the population in the study area is predicted to slightly decrease in the future (NLS, 2007). If the values belonging to each inhabitant are increasing in the same time, a similar total damage potential is achievable. The total direct tangible primary damages, resulting from these scenarios, are compared in the following Figure 29.

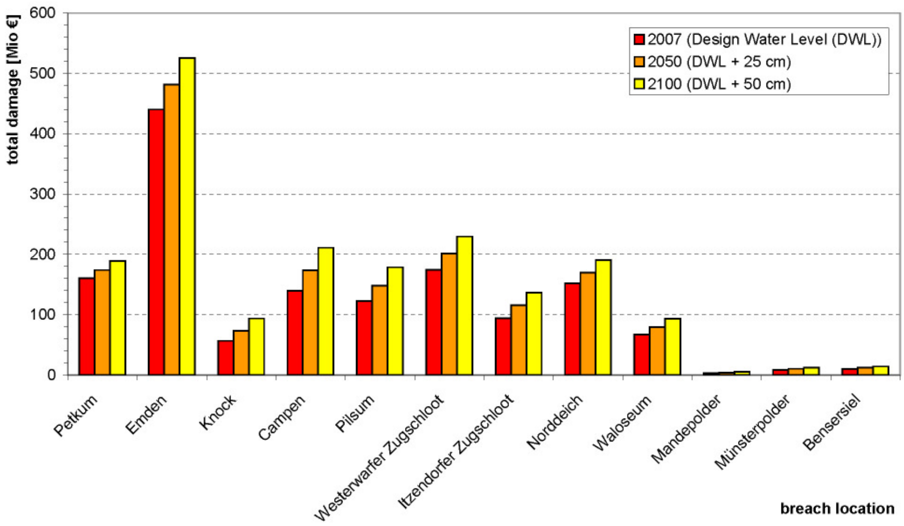


Figure 29: Total direct tangible damages from scenarios of constant damage potential but varying water level

The graph shows the increase of damages with a rising water level for every breach location. Three magnitudes of damages can be observed which origins from the varying topography and therefore flooded area in the pilot site on the one hand and from the distribution of damage potentially on the other hand.

The influence of topography has already been seen in the results of the flood model. Especially, if the breach occurred in a small polder area, the inundated area was also small compared to those of other breach locations. The difference of damages of other scenarios is even larger than the difference of inundated areas, because the density of values is very low in the investigated polder areas. Nearly all land is agriculturally used, only few farmers are permanently living there. Hence, the influence of hydraulic characteristics is superposed by the influence of damage potential distribution in the determination of damages. This explains the large total damage in the scenario with a failure in the harbour of Emden. Although inundation area and depths are not significantly different from those of the other non-polder scenarios, total damages are more than two-times higher. In that case an area of concentrated values, a city, is affected, while in other scenarios inundations in settlement play a minor role.

Concerning the results of scenarios with different water levels, the comparison in Figure 29 shows that the increase of damages is different at every breach location. The reason again is the superposition of the two mentioned influences. On the one hand, slope of land and break lines affect the propagation of floods and therefore the inundated area (Chapter 4). On the other hand, the inhomogeneous distribution of values in the investigation area may lead either to an intensified or a mitigated increase of damages. For example, only agricultural land with some small villages was affected in the scenario of 2007 for the breach location Campen. In the following scenarios of 2050 and especially 2100 the inundation also affected the city of Emden which results in an intensified increase of damages.

In order to cover a wider range of possible developments of damage potential for each flood scenario of 2050 additional damage evaluations with modified damage potential were considered. The values of all damage potential categories were increased by 10 % in a first series of scenarios and decreased by 10 % in a second series. But since no shifting of values from one potential category to another was taken into account and the depth-damage function have not been changed in that state of the study, the resulting damages were also increased or decreased by 10 %. Nevertheless, it was found that the change of damages due to a sea water level increased by 25 cm in 50 years is in the same order of magnitude as the change of damages, resulting from the tested range of damage potential. In Table 2, sums of damages in Emden from four different combinations of scenarios are given. It can be seen that a decrease of damage potential by 10 % is balancing the influence of the sea level rise.

Table 2: Damages from different scenarios for the breach location “Lock Emden”

Flood scenario	Damage potential scenario	Resulting damages [Million €]
2007	2007	366.576
2050	2007	401.341
2050	2007 + 10 %	441.124
2050	2007 – 10 %	361.207

5.4 Conclusions from the damage analysis

Uncertainties are significant in all parts of damage analyses. One major source of uncertainty is the definition of damage potentials. The scale of applied methods and

therefore the detailedness influence the determined damage potential as well as the considered types and categories of values at risk.

As in the major part of flood damage assessments, this study concentrated on the evaluation of direct tangible primary damages. The type of indirect damages was only represented by the gross value added and intangible damages were considered by the determination of affected inhabitants. Since the quantification of lives is difficult also for ethical reasons and evacuation or health care costs are hardly predictable, impacts on inhabitants are not further considered. The affected soil was also treated as intangible due to the fact that the impact of salt water on agricultural land, garden land, or forests cannot be quantified so far. Even the qualitative description of impacts on those values still suffers from insufficient knowledge. Other environmental of socio-economic effects of flooding due to storm surges are also neglected, although damage potentials might be large. Correlations between values of these types are complex and especially long-term effects are difficult to predict. For this reason, much effort is necessary and uncertainties are extremely large, if intangible, indirect, or secondary values should be taken into account.

In the kind of study the NLWKN conducted in Action 5B, no additional scientific investigations on certain types of values could be carried out. For practical reasons the damage categories analysed here were found to be sufficient. Nevertheless, the results must be interpreted, keeping in mind the unconsidered values and effects. Hence, absolute damages in monetary terms do not represent the total damage an affected area sustains. But it might be stated that damages will be at least as high as determined in this study.

Although absolute values of possible damages must be used very carefully, they are valuable for comparisons of different scenarios. By means of scenarios an assessment of the response of an investigated area on a flood event is achievable. The effect of coastal protection systems and flood mitigation measures can be analysed.

In this regard, an effective methodology is required for practical use of damage assessment. It was found in this study that Method I after Meyer (2005) is applicable for coastal lowlands like the pilot site of East Frisia. Minor adjustments of the method were done due to characteristics of the investigation area. Adjustments are assumed to be always necessary which implies a detailed analysis of every new investigation area. Nevertheless, the effort for the application of Method I is acceptable compared to the obtained information.

One result of this study is that the damage potential analysis after Meyer (2005) might be simplified due to a concentration of values at risk in only four categories, depending on the objectives of the analysis. Effort can be saved, if only values of those categories are collected and residual values are considered by a factor. Some of the more time-consuming evaluations, for example of life stock, can be avoided with this approach. The study showed that detailed state-of-the-art flood models can be combined with a simplified damage assessment, because a detailed damage analysis does not necessarily lead to much more accuracy, while a detailed flood model provides additional valuable information (Chapter 4).

Concerning the evaluation of damages, the expected sea level rise will lead to an increase of damages due to coastal flooding, even if the future development of damage potentials is not taken into account. It was found that the topography of the investigation area as well as the spatial distribution of values at risk is influencing the increase of possible damages. This is an important aspect for the assessment of additional flood mitigation

measures and corresponds to the identified possible negative effects of those measures (Chapter 4).

This finding can also be explained by the source-pathway-receptor approach. Every part of the approach influences the resulting damage or risk. Both, flood simulations representing the pathway and damage assessments representing the receptors, are essential for a complete analysis of flooding in coastal lowlands due to storm surges.

6. The local contact group

One important target of SAFECOAST was communication. This means on the one hand learning from each other on an international and on a local level and on the other hand communicating results and raising awareness. The former could be realised between the various partners inside the project by means of workshops with varying subjects. Policies and methods of different countries were discussed and personal contact was made. However, communication on a local level requires contact to the society outside the project. For this reason, a so-called local contact group (LCG) was set up in Action 5B.

The local contact group was established in order to involve the society. The LCG is aiming for two main objectives: getting in contact with local experts and stakeholders on the one hand and informing and hearing the public on the other hand. Since these objectives apply to different parts of the society, i.e. different target groups, the composition of LCG has to depend on the aim to reach. Besides actually informing the society, the present study was expected to benefit from LCGs. The exchange of thoughts and concerns might lead to new ideas and possible solutions.

One major difference from one target group to another is the level of expertise on flood risk and the related existing awareness. While with experts a raise of awareness is usually unnecessary and discussions might be objective and purposeful, knowledge and awareness are rather inhomogeneous in the general public. For this reason and due to fact that members of a LCG are directly affected substantiated and adequate information is highly important for the latter (see Final Report of Action 2, “The informed society”). In LCGs, including the general public, discussions were assumed to be more subjective and emotional than those on an expert level. It became clear that the participants of Local Contact Groups have to be chosen carefully. Invitations must be extended with respect to aims and target groups, but also with respect to societal circumstances.

The pilot site of Langeoog was chosen to be the scope of the first Local Contact Group established within the framework of SAFECOAST Action 5B. So, the associated area was limited to the island, more precisely to its inhabitants and municipality. The municipal authority was represented by the mayor of Langeoog and the heads of municipal administration, while the members of the municipal council can be referred to as elected representatives of the public.

On Langeoog the municipal administration is at least partly in charge for spatial planning, disaster control, and tourism. The NLWKN amongst others is responsible for coastal defence and nature protection. Hence, all important stakeholders of flood risk due to storm surges were participating in the LCG.

Due to the reasons illustrated above the LCG was decided to consist of two different parts or public levels. In both the NLWKN represented the federal state of Lower Saxony in form of a state agency and was the informing party. In the first meeting of the LCG, the other

party was the municipal administration, including the mayor. In the second meeting the municipal council was attending instead of the municipal administration.

In the first meeting, detailed questions on the relevance of this study for spatial planning and disaster control were argued. The provided information was found to be important for updating evacuation plans in the near future. Also suggestions for possible flood mitigation measures were taken openly. In the discussion even new ideas were brought up. One of these ideas for preventing the flood from inundating the village was subsequently tested with the flood model and the results were presented in the second meeting.

There, also general questions on climate change and coastal defence asked. The members of the municipal council stated that information on climate change via the media is exaggerated and confusing sometimes. Their main concern was the question: "How severe will the consequences of climate change be?" For this reason, one major target of that meeting was the communication of uncertainties. Much interest but also positive reactions were evoked by animated flood simulations. Small movies were presented, showing the flood propagation for certain scenarios. Thus, discussions became less hypothetically, although it had to be pointed out that those scenarios were assumptions and that uncertainties were there.

Experiences from both meetings were valuable for the accomplishment of this study. The overall finding was that the interest in the topic of flood risk and the demand for information was very high on all levels of society. Discussions were vivid and in depth in both meetings.

7. Key findings and Recommendations

The key findings and recommendations arising from the results of the investigations carried out in Action 5B are summarised below. The key findings are referring to the main subjects of this study, flood simulations and flood damage evaluations. The key findings to be seen in a more global context are listed separately.

Flood simulations

Key finding 1. The use of state-of-the-art numerical hydrodynamic models for simulations of flooding due to the failure of coastal defence structures is recommended. In comparison to simple hydraulic models they provide additional and more detailed information concerning flood propagation and time-dependent inundation depths. Moreover, they are considered to deliver more accurate results, since for example the characteristics of flow on surface and in rivers or differentiated roughness parameters are additionally taken into account.

Key finding 2. Simulations of coastal lowland's floods should include a 1D-stream network in addition to the 2D-overland flow. Dense stream networks, mostly drainage channels, are characteristic for coastal lowlands. They were found to have significant influence on the flood propagation and to be best modelled by an additional 1D-stream network. Especially with coarse grid resolutions finer river beds cannot be well represented and mere 2D-calculations will lead to insufficient results.

Key finding 3. The extent of a dyke breach, that is its width and depth, and the number of simultaneous breaches in a certain area were found to be the most influencing parameters. They directly determine the volume of water entering and flooding the hinterland. Other parameters as the roughness of the surface and of the river beds or stream cross sections also affect flooding but by far less significant.

Key finding 4. Additionally, the topography of areas seawards and landwards the breach location strongly influences the inflowing volume and the flood propagation. This means for areas seaward a dyke the existence and height of a foreland and a summer dyke is important, whereas landwards the elevation of the hinterland and linear structures like 2nd dyke lines or embankments are very important parameters.

Key finding 5. The sea level rise affects coastal flooding in a significant way. Flood characteristics such as inflowing volume, inundated area, and mean inundation depth are significantly rising. However, besides the amount of sea level rise the rate of increase strongly depends on the breach location.

Risk analyses

Key finding 6. About 90 % of the direct tangible values at risk are concentrated in four damage categories. Those are private buildings, private inventory, fixed assets and the gross value added. The conclusion was drawn that these categories provide a sufficient estimation of predicted direct intangible damage, assuming that this distribution of values is more or less applicable for all regions comparable to the rural pilot site of East Frisia and supported by comparisons to other studies.

Key finding 7. The prediction of future economical changes in flood protected areas and therefore the development of assets at risk is highly uncertain. Nevertheless, measures and plans are indispensable in order to keep the flood risk at an equal level or to actually decrease it.

General

Key finding 8. Development and management of forelands as well as maintenance and expansion of embankments in the hinterland, including 2nd dyke lines, street dams etc., are found to be potential flood risk mitigation measures. Those measures take effect by hindering flood propagation and therefore strengthening the area's resistance against flooding.

Key finding 9. Uncertainties in risk analyses and resulting predicted damages are considerable. Considerable uncertainties are found in all parts of risk analyses, for example statistics of values at risk, occurrence probabilities of flood events and failures, and numerical modelling of floods.

Key finding 10. Due to the former mentioned uncertainties the recommended methodology for flood simulations and damage analyses is based on scenarios which cover the whole span of possible parameters and values. These are the model's boundary conditions, breach locations, breach extents, and breach number as well as different assumptions for future changes of values at risk.

Key finding 11. Despite great uncertainties, for certain target groups the received information is suitable. For example, flood propagation maps are necessary for disaster control. And decision support for spatial and building planning and for integrative management of the coastal zone is provided.

8. Perspective

In near future the EU Flood Directive "Directive on the assessment and management of floods" will engage coastal managers all over Europe. The results and findings from Action 5B and the entire SAFECOAST project represent valuable contribution to the implementation of the Flood Directive. But they can only be seen as a first step and further investigations are essential in both the application of suitable flood simulations and flood damage evaluations.

9. Summary

For coastal defence risk management will become an instrument of growing importance management within the next years. For this reason, methods and methodologies of risk assessments and their applicability was one major subject in the EU-funded Interreg IIIb project safecoast. Action 5B of safecoast was conducted by the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency, Division Norden-Norderney. As a so-called focussed action, Action 5B concentrated on the application of a state-of-the-art flood damage evaluation on two pilot sites at the North Sea coast of Lower Saxony in Germany. The first pilot site was the Island of Langeoog, a sandy barrier island off the East Frisian coast. The second pilot site was the major part of the region of East Frisia located on the mainland and in the north-western part of Lower Saxony.

In a first step of the investigation, characteristics of both pilot sites were analysed with respect to present socio-economic values, topography, existing coastal protection system, and vulnerability to coastal floods. The methodology of the flood damage evaluation accomplished in this study consisted of two branches, a damage potential analysis and hydro-numerical flood simulations, which represented the basis for the actual flood damage assessment. Damage potential and inundation characteristics in the affected area were combined in the flood damage assessment via depth-damage functions. Results were estimated relative and absolute damages in table form as well as in form of damage maps.

Since the focus laid on the vulnerability of the pilot sites and their response to coastal flooding, investigations were carried out based on scenarios. Flood simulations were conducted by means of a numerical hydro-dynamical flood model which allows the simultaneous application of a 1D channel flow and a 2D overland flow module. Twelve breach locations were chosen for the pilot site of East Frisia and five for the pilot site of Langeoog. The different locations could be regarded as representative for the varying

coastal protection system along the considered coast line. For each breach location a standard case of present state was simulated. A future sea level rise of 25 cm for the state of 2050 and by 50 cm for the state of 2100 was set as scenarios. So, for each location three scenarios using the standard DTM were accomplished. Additionally, scenarios were conducted with which either the influence of a varying coastal protection system or the impact of potential mitigation measures was assessed.

Results from numerical flood modelling in this study were flood maps, including flooded area and inundation depths. Besides these parameters, flood volume, spatial distribution of inundation depths, and flow velocities were analysed. Valuable information was also gained from the development of these values over time. For example, flow paths could be identified and velocities of flood propagation were obtained. Concerning sea level rise, it was found that especially the inundated area in the investigated coastal lowlands will increase. Inundation depths will not change significantly, unless the inundation area is restricted. Analyses of simulation results regarding the influence of dyke forelands, secondary dyke lines, and break lines in the hinterland led to the conclusion that these structures are potential flood mitigation measures. Especially, dyke forelands and summer dykes have the positive effect of mitigating the flood volume. Concerning embankments in the hinterland as flood mitigation measures, also possible negative effects must be taken into account.

The method of damage potential analysis was chosen to be meso-scale for the pilot site of East Frisia, due to the extent of flood-prone area, due to available data, and due to the required detailedness of results. A method developed by Meyer (2005) was applied with minor adjustments related to characteristics of the pilot site. Geographical information systems were found to be suitable instruments for such kind of analysis. For the pilot site of Langeoog a micro-scale damage potential analysis had been carried out during the previous project Comrisk.

For praxis applications the damage potential categories analysed in this study were found to be applicable, since inter alia official statistical and land use data were available. About 90 % of the considered damage potential was concentrated in four damage potential categories.

Based on the results of flood simulations and damage potential analysis, the actual flood damage assessment was conducted for each scenario simulated with the flood model. Resulting relative and absolute damages showed that the expected sea level rise will lead to an increase of damages due to coastal flooding in the investigated coastal lowlands. In this regard, the topography of the affected area and the spatial distribution of values were identified to be the most influencing factors.

Due to large uncertainties in all parts of a flood damage assessment, absolute values of possible damages must be used very carefully. Nevertheless, flood damage assessments using scenarios are valuable for estimating the response of coastal lowlands on flood events. By comparing different scenarios the effect of coastal protections systems and possible flood mitigation measures can be assessed as well as the effect of a future sea level rise.

A local contact group was established, since one important target of SAFECOAST was risk communication. This means on the one hand, awareness of the public should be raised for the risk of coastal flooding. On the other hand, communication with local communities and experts could lead to an increase of acceptance for coastal protection measures as well as to useful contributions by the public. The interest in coastal flood risk of both, local experts and the public, was very high. The LCG provided valuable input for the study, especially concerning local circumstances, building planning, and disaster control.

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Ministry of Transport, Public Works and Water Management VenW [NL]
National Institute for Coastal and Marine Management
Rijkswaterstaat RIKZ (project management)

PO Box 20907
2500 EX Den Haag
The Netherlands

Contact: Niels Roode
E-mail: niels.roode@rws.nl
Tel: +31 70 311 4368
Fax: +31 70 311 4600

Road and Hydraulic Engineering Division
Rijkswaterstaat DWW

PO Box 5044
2600 GA Delft
The Netherlands

Contact: Wout Snijders
E-mail: wout.snijders@rws.nl

Tel: +31 15 251 8428
Fax: +31 15 251 8555

Ministry of the Interior of the Land Schleswig-Holstein [D]
Emergency Planning & Disaster Management Division

PO Box 7125
D-24171 Kiel
Germany

Contact: Matthias Hamann
E-mail: matthias.hamann@im.landsh.de
Tel: +49 431988 3470
Fax: +49 431988 3480

Schleswig-Holstein State Ministry for Agriculture, Environment
and Rural Areas [D]
Coastal Defence Division

PO Box 7125
D-24171 Kiel
Germany

Contact: Jacobus Hofstede
E-mail: jacobus.hofstede@mlur.landsh.de
Tel: +49 431 988 4984
Fax: +49 431 988 66 4984

Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency / NLWKN [D]
Division Norden – Norderney

Jahnstraße 1
DE-26506 Norden
Germany

Contact: Holger Blum
E-mail: holger.blum@nlwkn-nor.niedersachsen.de
Tel: +49 4931 947 158
Fax: +49 4931 947 125

Danish Coastal Authority [DK]

Højbovej 1
PO Box 100
DK-7620 Lemvig
Denmark

Contact: Thorsten Piontkowitz
E-mail: tpi@kyst.dk
Tel: +45 99 6363 63
Fax: +45 99 6363 99

Flemish Ministry of Transport and Public Works [B]

Agency for Maritime and Coastal Services
Coastal Division

Vrijhavenstraat 3
B-8400 Oostende
Belgium

Contact: Tina Mertens
E-mail: tina.mertens@mow.vlaanderen.be
Tel: +32 59 55 42 49
Fax: +32 59 50 70 37

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerp
Belgium

Contact: Toon Verwaest
Email: toon.verwaest@mow.vlaanderen.be
Tel: +32 3 224 61 87
Fax: +32 3 224 60 36

Environment Agency [UK]

National Flood Risk Management Policy Team

79 Thorpe Road,
Norwich NR1 1EW
United Kingdom

Contact: Rodney Hicks
E-mail: rodney.hicks@environment-agency.gov.uk
Tel: +44 1473 706 521 (office)
Tel: +44 7900 678460 (mobile)