FLOOD RISK ASSESSMENTS
RESULTS, APPLICATIONS AND FUTURE REQUIREMENTS

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This paper summarises and discusses the key results of two research projects one of which was a 4-year joint research project in Germany (XtremRisK) and the other comprised applications of the XtremRisK results to selected cases in Denmark (HARIMA-DK) within the framework of the European Flood Directive on the generation of hazard and risk maps for preselected areas. The former project focused on improving and expanding the existing knowledge, methods and models on flood risk assessments for extreme storm surges with respect to (a) extreme storm surge for current conditions and scenarios for climate change, (b) failure mechanisms of flood defences, (c) assessment of tangible and intangible losses, (d) integrated flood risk analysis involving the aforementioned developments and its implementation for two selected pilot sites (representative for an open coast and an urban estuarine area in Germany). The HARIMA-DK project used these results, applied it and produced flood risk maps for selected coastal areas in Denmark. The key results of both projects are briefly summarised, lessons learned are discussed and some conclusions for future flood risk studies are finally drawn.

Keywords: flood risk assessment; storm surge; extremes; intangible losses; risk mapping

INTRODUCTION

In the past, storm surges and river floods have frequently led to failures of flood defences which caused major damages, also along German rivers and coastlines. Due to climate change and increasing intensities of rainfall and storm surges it may be expected that the risk of flooding will still increase. However, taking into account the uncertainties associated with the impacts of climate change, the unpredictability of extreme events and the various combinations of loading conditions, it is inevitable to use a probability-based approach to account for any flood hazard assessment. Furthermore, mid- and long-term changes of the potential socio-economic consequences of any flood event are also impossible or very hard to predict but should be accounted for when dealing with any future impacts of hazards. Therefore, risk-based approaches are more widely used to date for assessing both future changes and their consequences in a very transparent and quantifiable way. However, definitions and methodologies are not consistent in literature and there is an ongoing discussion to which detail flood risk assessments need to and can be performed (see e.g. Oumeraci et al., 2012).

The EU Flood Directive (Directive 2007/60/EC) on the assessment and management of flood risks entered into force on 26 November 2007 and requires EU Member States a) to assess if all water courses and coast lines are at risk from flooding (until end of 2011), b) to map the flood extent and assets and humans at risk in these areas (until end of 2013) and c) to take adequate and coordinated measures to reduce this flood risk (until end of 2015). This sets the pace for any developments within the field of flood risk assessments and the use of up-to-date methods which can be used for their assessment.

Coastal flood risk assessments generally use storm surges as boundary conditions for the risk assessments performed. These extreme events have been assessed by principally two different approaches in the past which are a) deterministic methods and b) stochastic methods. Both methods were recently brought forward within the German XtremRisK project where for the deterministic methods a non-linear superposition of the storm surge components was achieved for the data-rich cases of Cuxhaven and the island of Sylt at the North Sea. Gönnert & Gerkensmeier (2012) have used analytic methods to derive new insights in the superposition of different contributions to maximum storm surge water levels and Tayel & Oumeraci (2012) have looked into a combination of numerical models and neural networks to derive non-linear effects for the North Sea region. It was concluded that non-linear superposition effects could either lead to lower or higher values rather than the linear superposition results and therefore have to be investigated very carefully. As for stochastic approaches Wahl et al. (2012) not only used the maximum storm surge levels but widened the statistical analyses to the full history of individual storm surges (up to five tidal cycles) and proposed bivariate joint exceedance probabilities for peak water levels and the 'fullness' of these curves using Copula functions.

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Naulin et al. (2012) discussed the reliability assessment of flood defences and more recent updates for failure modes and breach developments of dikes and dunes. The final outcome of this paper is a better understanding and description of different flood defences in two pilot sites in an estuary (Hamburg-Wilhelmsburg) and at the open North Sea (island of Sylt) where the overall failure probabilities of these flood defences were achieved for certain storm surge scenarios. Furthermore, shortcomings and future research needs were discussed to some detail.

Recent developments within assessment methods for vulnerabilities and economic consequences have also been achieved by using indirect economic losses (Kowalewski & Ujeyl, 2012), which were compared to the direct economic losses for the case study of Wilhelmsburg in Hamburg. This study was complemented by further analyses of intangible consequences (Dassanayake et al., 2012) who concluded that intangible consequences cannot be disregarded when looking into flood risk assessments and might become even more relevant than their tangible counterparts. Furthermore, methods from the literature were intensively reviewed, adopted, brought into a spatial GIS-based environment and applied to case studies to obtain a direct comparison with (traditional) tangible risk assessments.

The integration of different methods for flood risk assessments has been discussed within Burzel et al. (2012) in which the authors presented a so-called 'Cellbased risk assessment (CRA)' which allows for the integration of both tangible and intangible consequences for extreme storm surge scenarios. Furthermore, tools were discussed to finally present hazard and risk maps as requested by the European Flood Directive and this approach was illustrated by using different scenarios for the case of Hamburg-Wilhelmsburg.

The aforementioned approaches have all been used for one or two case studies in either Hamburg and/or the island of Sylt where data were available for most of the investigations within the XtremRisK project. This has allowed the research to focus on the development of new methods rather than data collection and analysis. A further step has then been described in Skov et al. (2014) where these methods were applied for the derivation of flood hazard and risk maps in Denmark for the second step of the European Flood Directive. Difficulties and shortcomings of this application were discussed and the final maps were presented.

This paper seeks to summarise the aforementioned recent developments of methodologies and tools as well as their applications to real case studies. The key objectives are to briefly summarise the recent developments and applications but mainly to come up with lessons learned from these studies and derive some future requirements for flood risk assessments. The paper starts with the underlying methodological approaches, will then present the key results of the basic research and report about lessons learned from both projects. Finally, the paper will discuss some of the research gaps and future developments still needed to provide better, faster, and more reliable outcomes.

METHODOLOGY

The German research project XtremRisK (Extreme storm surges at open coasts and estuarine areas: Risk assessment and mitigation under climate change aspects, www.xtremrisk.de) has defined the risk of flooding as the combination of the probability (hazard) that the flood occurs and the related consequences to people and assets (Oumeraci et al., 2012). The integrated risk analysis in XtremRisK was based on the well-known Risk Source-Pathway-Receptor Concept (see Figure 1).

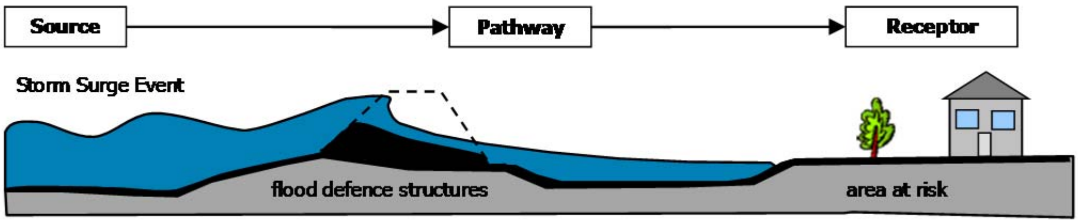


Figure 1. Source-Pathway-Receptor Concept after Oumeraci et al., (2012).

Following this concept model the work was structured in four parts which were a) Risk sources and extreme events; b) risk pathways; c) risk receptors and consequences; and d) integrated risk analysis. Each of these parts built on each other and developed updated methods and new tools to provide the required steps to produce hazard and risk maps for the two selected pilot areas. Within the integrated risk analysis a GIS-based tool and a cellbased risk assessment approach (CRA) was eventually developed which allowed to bring together all the different results from the previous steps and to apply them to the two pilot areas.

A second methodological concept was needed when the results were transferred to different coastal areas in a different country which mainly imposed the difficulties of a) different input data (bathymetry, topography, land-use, sea level, and wave data) available; b) different climate change scenarios; c) different adaption strategies and defence measures; d) different socio-economic data; e) different inundation modelling tools and results; and f) different scale and resolution requirements. Due to these differences a test case was defined for which the methods were adapted and then applied to the remaining case studies. This approach was successful at the end but has shown that considerable efforts due to the data requirements were needed (cf. Figure 2).

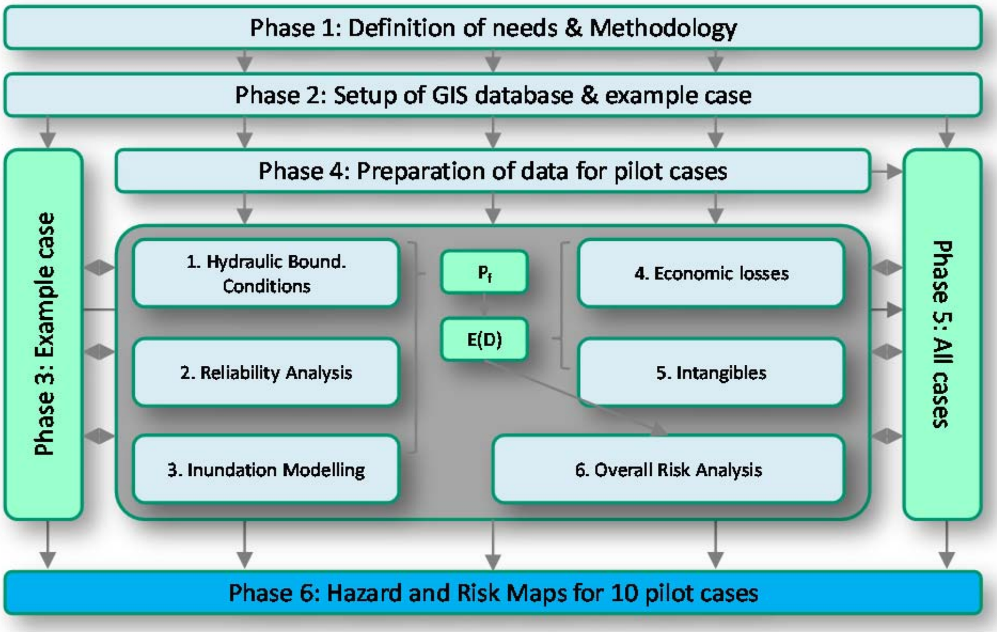


Figure 2. Conceptual approach for implementation of XtremRisK results in Denmark for requirements of the European Flood Directive.

More details on the projects and their results are described and discussed in the following sections and can be found in Oumeraci et al. (2012) for the XtremRisK project and Skov et al. (2014) for the HARIMA-DK project, respectively. In these papers, the methodological approaches are also discussed in more detail.

PROJECTS

XtremRisK Project

The primary objectives of XtremRisK were a) to particularly focus on the extreme storm surge events which are physically possible for the present time and at the end of this century, b) to perform a detailed modelling and reliability analysis of the entire flood defence systems, including both man-made and natural barriers, c) to assess the tangible flood damages including both direct and indirect losses, d) to assess the intangible losses including both social losses (loss of life, cultural losses) and environmental losses, e) to consider both tangible and intangible losses and to integrate them to assess the overall flood losses in the risk analysis, including a consistent framework and methodology for admissible flood risks.

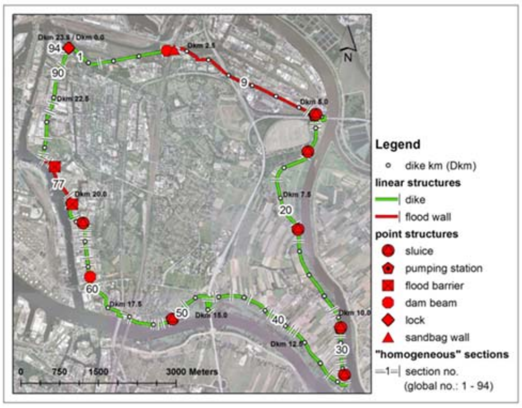
Two pilot sites were selected for the application of the developed methodologies, modelling tools and techniques, and finally for the practical implementation of the integrated risk analysis: a) the city of Hamburg as a representative urban area in the river Elbe estuary (Figure 3) and the Island of Sylt as a representative for an open (North Sea) coast (Figure 4).

The structure of the overall project with four subprojects (SPs) follows the SPR-concept and address risk sources (SP1), risk pathways (SP2), risk receptors (SP3) and their integration in a risk analysis (SP4), as follows:

a) Dike

b) Sluice gates

c) Flood protection wall



d) Defence line overview

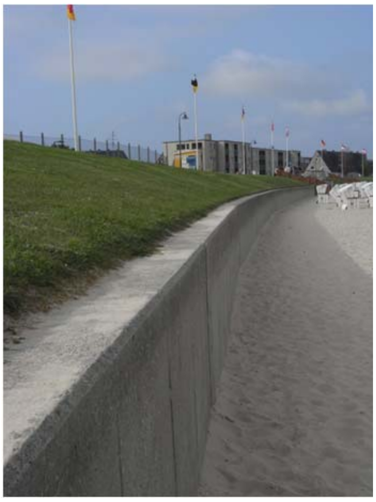
Figure 3. Case study 'Hamburg-Wilhelmsburg' with a) dike; b) sluice; c) flood protection wall; and d) map of defence line

- SP1a aims to develop scenarios of extreme storm surges for the selected pilot sites based on previous storm surges using the analysis of field data and numerical modelling. This comprised the analysis of all storm surge constituents (e.g. wind surge, tide and external surge) and their non-linear interactions as compared to their linear superposition.
- SP1b determined the exceedance probabilities of the extreme storm surge scenarios provided by SP1a. This was achieved through the development of a storm surge generator capable to reproduce parameterised storm surge curves combined with a multivariate statistical analysis of extreme storm surge water levels. Joint probabilities of storm surge maximum water levels and fullness of the extreme storm surge were determined using a bivariate Copula approach. Based on the extreme storm surge scenarios developed in SP1, SP2 aimed to determine the loading and the reliability analysis of all components of the flood defence systems for the two selected pilot sites. This comprised a failure analysis of these components, including breaching and breach development, eventually resulting into the failure probability of the flood protection systems (and thus the flooding probability). Moreover, the initial conditions at the breach location for the inundation modelling were also determined, including the breach development and the final breach width and depth.
- SP3 focussed on the assessment of the direct and indirect economic losses in the two selected pilot sites. This was achieved through the combined application of numerical modelling for flood inundation, damage models for the assessment of direct damages to residential and commercial buildings, equipment and infrastructures as well as an economic model for the indirect losses due to the disruption of economic and social activities as a consequence of the direct flood damages. The direct damages were assessed at a micro-scale level (buildings) and extrapolated to a group of similar items at a meso-scale level. A cluster-based approach was then used to aggregate the losses from the building level to the level of economic sectors in the

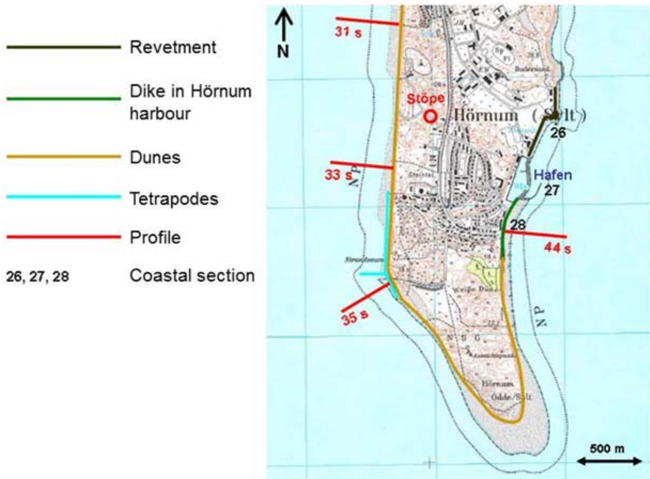
entire pilot site considered, so that they can be implemented in an economic modelling framework at a macro-scale level.

a) Dune at the west coast of Sylt

b) Storm surge wall in Westerland



c) Flood defence dike in Hörnum



d) Defence line in Hörnum at South end of Sylt

Figure 4. Case study 'Sylt island' with a) dune; b) storm surge wall; c) flood defence wall and dike in Hörnum; and d) map of defence line in Hörnum

- SP4 aimed to bring together all results from SP1-SP3 into an integrated flood risk analysis for the two pilot sites by considering the selected storm surge scenarios determined in SP1 for present (2010) and future climate conditions (2100). This required a methodology for the assessment of intangible losses (social, cultural and environmental losses), their GIS-based spatial modelling and their integration with the economic losses obtained from SP3 into integrated risk maps. This approach was also applied for the modelling of direct and indirect economic damages resulting from SP3 for the GIS-based mapping of the risk related to each damage category.

HARIMA-DK project

The Danish-German HARIMA-DK project (hazard and risk maps for Denmark) started after the end of the aforementioned XtremRisK project and used its results to produce hazard and risk maps for designated flood prone areas in Denmark most of which are at risk from coastal and/or river floods (Figure 5). The methodology comprised a scenario-based approach for different sea level rises and coastal developments, flood inundation modelling and a detailed procedure for tangible and intangible losses (see Skov et al., 2014) which will be explained in more detail below.

In Denmark, 10 locations have been selected within the first step of the European Flood Directive for further investigation and hazard and risk mapping within the second step (Figure 5). These locations are:

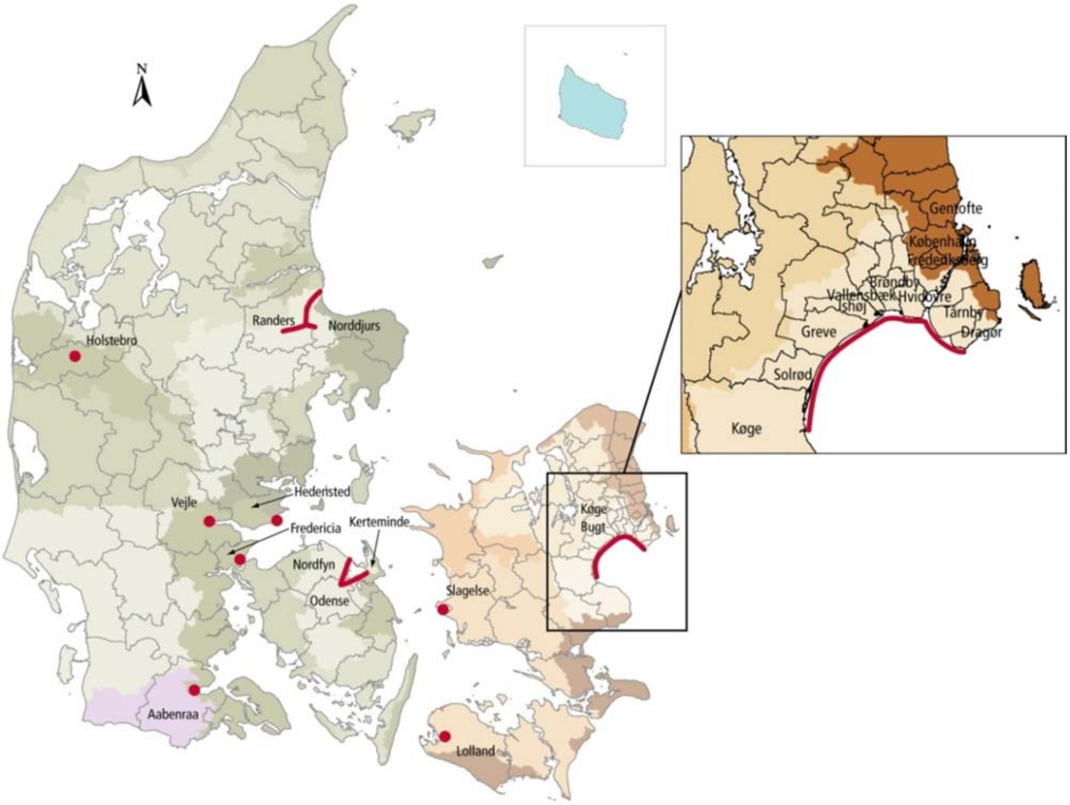


Figure 5. Locations of the 10 flood prone areas in Denmark selected under the first step of the European Flood Directive (Source: DCA)

1. Randers Fjord (Randers and Norddjurs Kommune)
2. Juelsminde (Hedensted Kommune)
3. Vejle (Vejle Kommune)
4. Fredericia (Fredericia Kommune)
5. Aabenraa (Aabenraa Kommune)
6. Odense Fjord (Odense, Nordfyn, and Kerteminde Kommune)
7. Korsør (Slagelse Kommune)
8. Nakskov (Lolland Kommune)
9. Køge Bugt (10 different municipalities)
10. *Holstebro (Holstebro Kommune)*

At 9 of the 10 flood prone areas the source for flooding comes from the sea or a combination of sea and rivers, since these areas include a river mouth. Only the area of Holstebro has a single fluvial flood hazard, and was therefore not considered in this study. All coastal areas (1 to 9 from the list above) are located at the Baltic Sea coast of Denmark. There are 22 municipalities involved in the aforementioned areas where 7 are on Jutland, three on Fyn, and 12 on Sealand, respectively.

Data for the HARIMA-DK project came from different sources and were either readily available from the Danish Coastal Authority (DCA) or were further collected and analysed by DCA. These data comprised information regarding the bathymetry (from digital chart maps), the topography (high resolution digital terrain model from 2007 with a horizontal resolution of 0.5 m and a vertical mean resolution of 3.5 cm (standard deviation)), water levels and statistics around the Danish coasts, wind data for more than 50 years, precipitation and discharge measurements from the rivers involved, wave heights and wave periods for deep water conditions from hindcast analysis, and relevant information for the coastal structures. However, the latter was scarce and had to be updated either by the DTM analysis or further investigations in the field.

The key objectives of the proposed work were to use the tools and methods developed from the XtremRisK project, adapt them to the available data and the required needs in Denmark and derive hazard and risk maps for the 9 pilot cases in Denmark. To reach these objectives the project ran in six phases as follows (cf. Figure 2):

- Phase 1: Methodology and data needs for the risk analysis: the approach was taken from the XtremRisK project and adopted to the pilot cases in Denmark. Data needs were defined after comparison of data required for the new tools developed under XtremRisK, a first test case was agreed to check whether the modified approach was working.
- Phase 2: Setup of a GIS database containing relevant input data for the pilot sites: most of the data were available in Denmark but not necessarily in the right format. DCA has therefore expanded their database to hold the data in a format available for the tools developed from XtremRisK
- Phase 3: Hazard and risk maps for an example case: it was agreed that the whole methodology would only be worked out and applied for one test case (Randers Fjord) before it would be applied to all cases. This would assist in solving any remaining issues with the data or the application of the models.
- Phase 4: Preparatory phase for all pilot sites: learning from the test case in Phase 3 DCA prepared all other cases in a similar way so that the analysis and hazard and risk mapping could start once this phase has terminated.
- Phase 5: Application to all pilot sites: taking the results from the previous phases a risk assessment study was performed for all pilot sites using the same hazard scenarios and the same methodology.
- Phase 6: Hazard and risk maps for all pilot cases: finally hazard and risk maps were produced for all the pilot sites and for all different scenarios as requested by the European Flood Directive. These maps were then forwarded to the municipalities involved in the pilot cases and were discussed with them in some detail.

RESULTS

This section discusses the key results from both aforementioned projects and focusses on the results of XtremRisK providing rather the scientific advances than the necessary adaptation during application. The section is split into four parts which are a) results for risk sources, b) risk pathways, c) risk receptors, and d) risk integration, so closely following the SPR-concept.

Risk sources

Within XtremRisK a deterministic approach has been developed which combines empirical methods and numerical modelling to analyse the *non-linear interaction between the storm surge constituents* and to determine extreme storm surge scenarios. This approach follows three main steps: (i) analysis of the highest event of each constituent, (ii) analysis of the interaction between tide and wind surge and the interaction between wind surge and external surge, and (iii) calculation of an extreme storm surge event based on the result of these analyses. In the case of Hamburg this consideration of the non-linear interaction of storm surge constituents has led to lower water levels than those resulting from a linear superposition. It should be noted that this conclusion is only valid for the data obtained from the tidal gauge of Cuxhaven (continuous time series of more than 100 years). However, the proposed approach has also been applied to the data of the tidal gauges in Hörnum (Sylt) which has proved that the approach is generally applicable to other areas as well (Gönnert et al. 2012).

A stochastic approach has been used to develop a *storm surge generator* which is not only capable of generating statistically based peak water levels from the available data but also allows to keep into account the full time history of a storm surge, including tidal elevations. This generator builds upon detailed analysis of parameterised storm surge curves and uses statistical analyses of 25 parameters of the time history (19 sea level parameters and 6 time parameters). It can stochastically simulate a large number of storm surge scenarios (in the order of 10^7) by using Monte-Carlo-Simulations (MCS) where the interdependencies of parameters were also considered to avoid inconsistencies. The capabilities of the generator have been demonstrated by comparing synthetically generated storm surge curves with those obtained from observed data, from hydrodynamic models and from empirical analyses. Furthermore, it should be noted that full time series of storm surges will allow for scenario-based analyses of flood risks, also considering the *joint probabilities of water levels and time-related parameters* (Figure 6) such as the fullness or duration of the storm surge (Wahl et al., 2012).

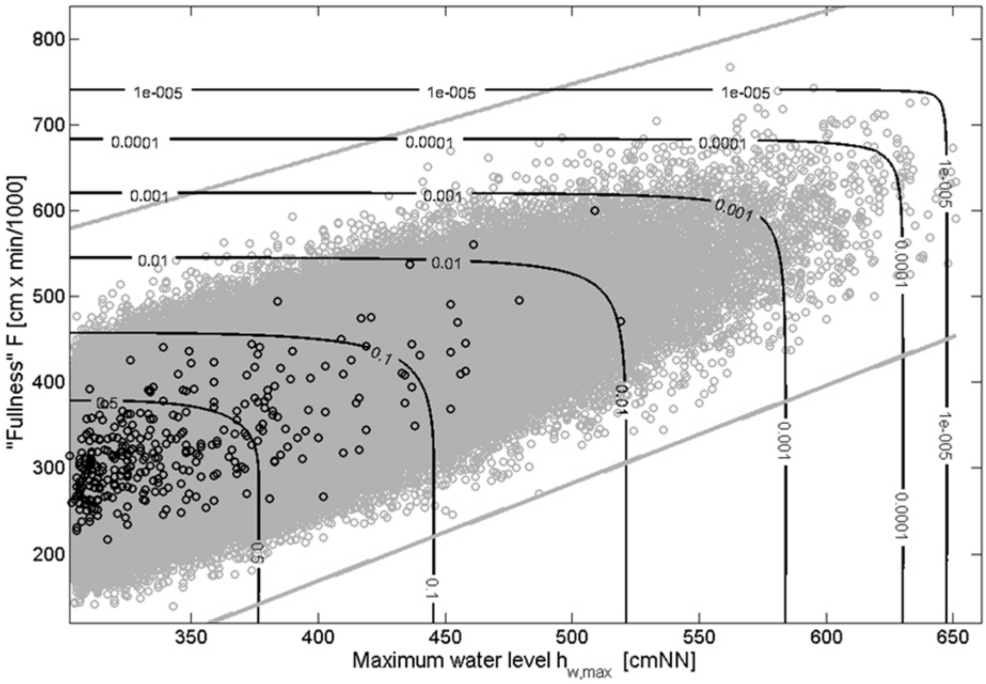


Figure 6. Joint probability of maximum water level and fullness (after Wahl et al., 2011)

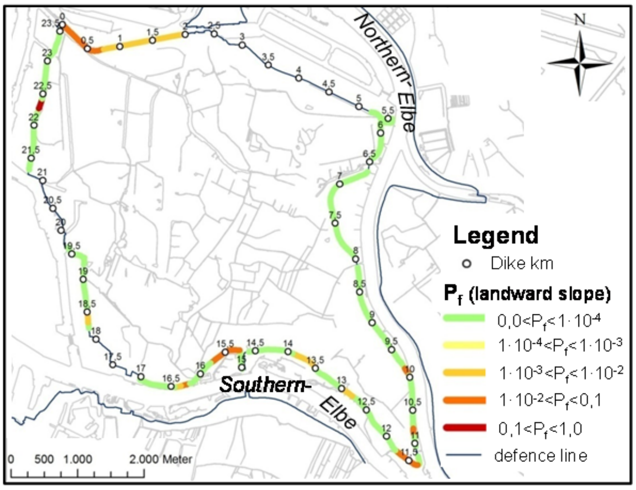
Risk pathways

A reliability analysis of the flood defences in the pilot sites of XtremRisK and HARIMA-DK such as sea dikes, coastal dunes, and flood walls has been performed. As a result, a probability of flooding was obtained for the different extreme storm surge scenarios in the two projects, see example for the pilot sites in the XtremRisK project in Figure 7. As the defence lines in the pilot sites consist of different types of structures which are commonly non-homogeneous along their entire length, a segmentation was performed into approx. 300 homogeneous, but not equally long, sections in terms of both loading and resistance properties. For each section, about 80 parameters were required for the 35 limit state equations (22 LSE for dikes, 8 LSE for flood walls and 5 LSE for dunes) to perform the reliability analysis.

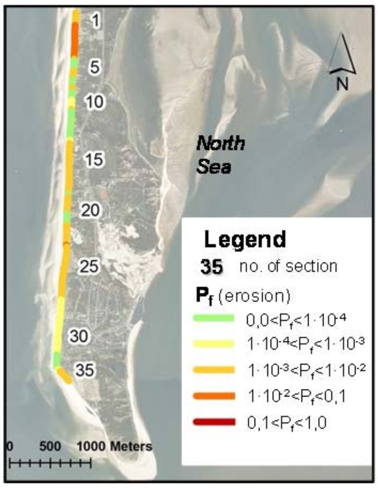
Additional limit state equations for cross-shore profile response of dunes due to wave impact and overwash by applying available analytical models were also included. Moreover, the common approach for the LSE which compares the admissible wave overtopping rate with the actual wave overtopping rate has been modified to consider instead the admissible volume of water and the actual volume of water in the floodplain. To do so, the time-dependent process of wave overtopping and related failure mechanisms could more accurately be assessed over the entire storm surge time history. More details are given in Naulin et al. (2012).

Risk receptors

Substantial results were achieved in the development/implementation of new approaches for the assessment of both *tangible and intangible losses* as well as for their aggregation in an integrated risk analysis. As for *tangible losses* the main achievements are related to the development of new methods for the micro-scale assessment of direct economic damages (caused by the physical contact of assets with water) based on actual market prizes and for their aggregation at a meso-scale level as well as for the assessment of indirect economic losses (caused by disruption of economic and social activities as a consequence of direct flood damages). The focus was put here on residential buildings as well as on commercial and industrial assets, but damages to infrastructure and agriculture were also considered. The micro-scale approach is mainly based on the damage assessment using the Flood Resilient Tool (FloReTo, TU Hamburg-Harburg, http://floreto.wb.tu-harburg.de/) for sample type buildings, e.g. for residential assets defined by the type of building, the occupancy of the ground floor and the wall construction (Ujeyl et al., 2012).



a) Hamburg-Wilhelmsburg



b) Hörnum, Sylt island

Figure 7. Failure probabilities for the storm scenario XR2010A for a) dike breaches in Hamburg-Wilhelmsburg and b) dune erosion in Hörnum at the south end of Sylt island (after Naulin et al., 2012)

Based on the results of a literature study the Adaptive Regional Input-Output (ARIO) model proposed by Hallegatte (2008) was identified as the most appropriate approach for the assessment of the indirect economic losses which result from production interruption and service losses in the housing sector. Its implementation for the pilot site in Hamburg has shown how indirect losses are related to the direct damages. It was found that the former remain negligibly small (even negative) for direct losses below a certain level, but increase nonlinearly with direct losses after exceedance of this level. The latter indicates the existence of a threshold in the coping capacity of economic systems. For Hamburg, the threshold was found to be about 2.5 billion Euros (Kowalewski & Ujeyl, 2012*).* The corresponding values obtained by Hallegatte (2008) for Louisiana are 50 billion and 200 billion U.S. $, respectively.

As for *intangibles losses* a systematic framework and methods for the assessment of intangible losses and their integration with tangible losses have been developed and implemented for the two pilot sites (Dassanayake et al., 2012; Burzel et al., 2012). Within this framework, the model proposed by Penning-Rowsell et al. (2005) for the assessment of *loss of life and human injuries* caused by river floods is applied by taking into account both flow depth and velocity as well as the characteristics of the population at risk (number, age, etc.) and those of the flood prone areas. For the evaluation of *cultural losses*, however, a new methodology based on physical damages due to flooding and the cultural values of the assets was developed (Dassanayake et al., 2012). The estimation of direct physical damages of cultural assets is based on both flow depth and flow velocity. The cultural value of the different types assets (heritage and non-heritages assets) are assessed by considering their historical (HS) and societal significance (SS). The results are then integrated in a cultural loss assessment matrix (CLAM) by using a five-point score scale varying from very low (1) to very high (5). For the *environmental losses*, an ecosystem services-based approach in two steps is proposed by making use of the classification of the ecosystem services developed by the Millennium Ecosystem Assessment in 2005. The identification of the ecosystems at risk and their services (1st step) is based on the analysis of CORINE land cover data and further available knowledge. The assessment of their changes (measured in percentage) induced by inundation (2nd step) is performed by considering flood depth, velocity and duration as well as salinity obtained from numerical modelling.

Risk integration

Cellbased Risk Assessment (CRA): A GIS-based approach has been developed for the spatial modelling of the different categories of flood losses as well as for their aggregation in the integrated risk analysis. Due to the considerable spatial variability of the characteristics of both hazard and vulnerability in the flood prone areas of the selected pilot sites, a polygon based concept for spatial risk analysis has been developed which makes use of the advantages of both raster and polygon concepts.

For the CRA based analysis the flood prone area is subdivided into uniform polygons (cells) of a given size which primarily depends on the size of the study area and the scale of the assessment. These cells build a uniform grid and are therefore termed as 'grid cells'. Resolutions of 100 m, 50 m and 10 m have been applied in the pilot sites. Comprehensive geoprocessing workflows are developed in a modular structure making the model highly flexible and adaptive to any study area and resolution. Hence, the CRA is performed in three main steps: a) conversion of all irregular shaped input data into the assigned compartment, b) application of the selected model for all cells within the investigation site, and c) visualisation of the results on a spatial basis.

Integration of tangible and intangible losses: a consistent integration methodology had to be developed since the different loss categories are measured in different units (economic losses in Euro, loss of life and injuries in number of people, cultural losses in a five-point score and environmental losses in a percentage). This was developed within a GIS-based multi-criteria analysis (MCA) framework. The methodology is performed in 8 steps and results into a single score scale of 0 to 1 allocated to each GIS-grid cell. Among the several MCA approaches, multi-attribute utility theory (MAUT) was selected using a pairwise comparison method for criterion weighting. This methodology has been implemented in the pilot sites and represents an important achievement within the risk receptor part of the project (Dassanayake et al., 2012; Burzel et al., 2012).

GIS-mapping: using the aforementioned MCA approach for the integration of the different losses, the CRA approach is applied to generate flood maps, maps for each category of losses and for aggregated losses as well as related risk maps by combining flood maps and loss maps. Typical examples of this approach for the city of Veijle, Denmark, for an overall flood risk for a 100 years return period flooding scenario and sea level rise are shown in Figures 8 and 9 for the present (2012) and the year 2050, respectively.

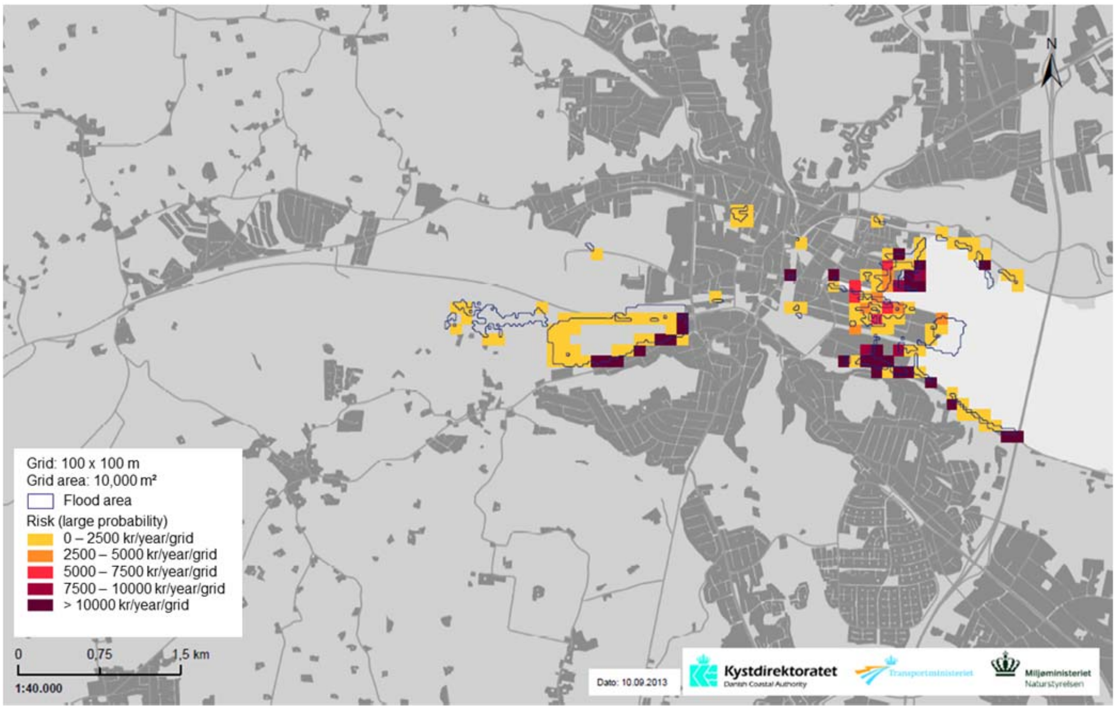


Figure 8. Flood risk mapping of Veijle, Denmark, for 2012 using flood risk assessment approaches from XtremRisK, units are in Danish crowns/year/grid cell.

More results were plotted for higher resolutions (grid sizes) and were made available to the municipalities involved. A close collaboration between the Danish Coastal Authority and the municipalities has assured a large acceptance of the results within the stakeholders group. The maps were submitted to the EU by the end of 2013 as planned. More details on the background, the generation of the maps, assumptions and achievements are provided in Skov et al., 2014.

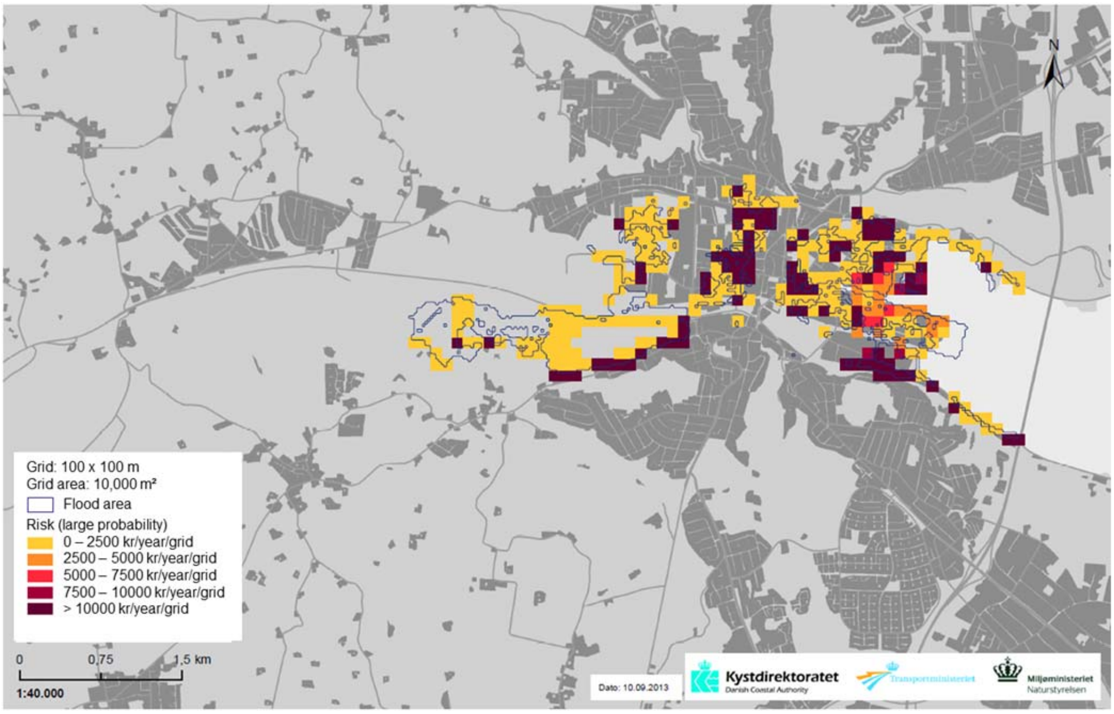


Figure 9. Flood risk mapping of Veijle, Denmark, for 2050 using flood risk assessment approaches from XtremRisK, units are in Danish crowns/year/grid cell.

LESSONS LEARNED

The research results developed under XtremRisK and their applications within the HARIMA-DK project have generated a series of questions for research and practical applications. The most relevant of these issues are discussed in the following:

- **Scenarios of climate change impacts:** in most studies scenarios of sea level rise and climate change impacts were used since there is hardly any information on future climate-related changes for local or regional studies. Although global and regional models are generally available it turned out that their results are not detailed enough for the micro-scale studies in the research projects described here. If those become available, future work should try to better relate the results to global and/or regional climate models and resulting consequences for input conditions along the coast;
- **Data availability:** most of the research projects performed to date were based on case studies where lots of data were readily available. This was understandable since these research projects were started to derive new methods and tools rather than collecting new data. However, data-rich case studies are not the majority of studies performed so that many of the models and tools still need to be adapted to cases where data are not or only scarcely available;
- **Simplification:** Many of the developed tools are complex, sometimes using sophisticated numerical models (e.g. in breach simulations). In order to use them for reliability analyses (e.g. Monte-Carlo simulations), more simplified tools are needed which can be run without significant expertise and which still generate sufficient accuracies for the cases in question;
- **Time dependencies in limit-state equations:** many of the limit-state equations which were used to calculate the failure probabilities of flood defences were based on time-independent (static) limit states. However, this would rather not be the case in reality and needs to be better described considering the short- and long-term variability of processes and parameters over time. Exemplary calculations within the aforementioned research projects have already suggested that the differences in the resulting failure probabilities may be significant. It is important to note that accounting for time dependencies might lead to even higher failure probabilities than without accounting for time. It is therefore essential to at least consider these cases.

- **Length effect:** whenever flood defences are split into different segments, this will either result in segments of constant lengths or in very different lengths of the segments depending on the criteria which were used for distinction. Whilst the former needs a proper selection of correlation between the various segments, the latter assumes that the sections are homogeneous and independent from each other. Both assumptions are wrong and a better and yet still simple approximation needs to be found to find a quantifiable way to determine this length effect.
- **Importance factor for segment probabilities:** if segments of a flood defence structure are differently long it should be considered if an importance factor for its contribution to the overall flooding should be introduced. Sometimes, depending on the flood defence line and the local differences, the lengths of the segments can differ fundamentally. Therefore, the difference of water flowing into the hinterland when a small or a large segment fails should be taken into account. As an example, the contribution of a failed gate in the defence line will be significantly different than the failure of a 2 km long dike stretch.
- **Scale of investigation:** depending on the scale of the investigation and the availability of data, different methods are generally used which calculate the consequences from extreme events. Very often in the recent past micro- or meso-scale approaches have been used for local studies which generally provide the highest accuracy. However, the data needs and calculation efforts may be significant. Therefore, it would be very beneficial if one can move to approaches which automatically account for different scales of investigations and then estimate the data needs and the associated inaccuracies;
- **Uncertainties of flood losses:** Most of the risk studies so far are using very similar approaches where the probability of flooding is calculated taking into account the uncertainties of the processes and the parameters involved. On the consequences side the losses are calculated deterministically by estimating the costs of the damages which may occur from any extreme event or hazard. However, also on this side the uncertainties are huge and should be considered which would result in a losses distribution function rather than a loss value;
- **Harmonised approaches in assessing flood risks:** To date, very different approaches exist on how to assess flood risks. These approaches may result from using different scales, different consideration of flood scenarios, different failure modes, other consideration of uncertainties, differences in the detail of tangible losses, and how to integrate intangible losses, etc. It is therefore more than logic that the results of such studies cannot be compared to each other easily. This requires a more uniform approach for risk analysis and management, a lot more than required by the European Flood Directive which principally stated that the member states have to deliver flood hazard and risk maps but never said in which way they should be derived.

The above list is not regarded complete. There are other lessons which have been learned during the development and the application / transfer of methods to different areas. Going into more detail, however, was not possible within the scope of this study but would be extremely beneficial for the future. It is believed here that other projects like the European THESEUS project (see e.g. Zanuttigh, 2014 and Zanuttigh et al., 2014) or the German HORISK project (see e.g. Grimm et al., 2013) have also achieved lessons in how to assess and how to not assess flood risks. These results should be brought together in a consistent way and may then result into a) recommendations for further research, b) improvements on how to apply available methods, and c) harmonisation of tools.

CONCLUDING REMARKS

The German research project XtremRisK (Extreme storm surges at open coasts and estuarine areas: Risk assessment and mitigation under climate change aspects) and the German-Danish project HARIMA-DK (Hazard and Risk Maps for Denmark) have developed new methods and tools for flood risk assessment studies which were used within the second stage of the European Flood Directive in Denmark where flood hazard and risk maps have been produced for 10 different flood-prone areas.

Various advancements have been achieved in the area of risk sources, risk pathways, and risk receptors where the most important ones comprise a) the improved understanding of the non-linear contributions of extreme storm surge constituents; b) the statistical descriptions of the time history of storm surges and their (joint) probability density functions; c) improved descriptions of limit-state equations of various flood defences; d) time-dependent description of selected limit-state equations; e) consideration of indirect tangible losses and their comparison to direct tangible losses; f) taking into account and quantification of intangible losses such as loss of life, cultural, and ecological losses; and g) bringing all different risk contributions together under a consistent framework and providing an ARC-GIS based cell-based risk assessment (CRA) tool.

Comparing these results with other ongoing research and achievements within other projects has led to 8 suggestions for improved risk assessment approaches as follows:

1. **Bring it together!** Numerous studies on national, European and international level exist but there is hardly any attempt to harmonise the different frameworks, approaches, methods, and tools. This should be done considering different spatial and temporal scales suggesting which method and which tool to use under which boundary conditions.
2. **Build one network!** Learning from the various research projects and from providing hazard and risk maps to the European Union there is a large expertise now between European researchers and risk analysts which should not be lost. Results of studies should be compared and lessons learned must be discussed and brought together. The additional knowledge and expertise from these experiences are believed to be significant.
3. **Be consistent!** A consistent approach for risk assessment studies should be used. A network of risk researchers should derive from available methods which tools are available for which boundary conditions. Guidelines should be provided to describe which details (details of sources, failure modes, indirect losses, or intangibles) should be included under which boundary conditions.
4. **Solve problems!** The recent research projects have filled some of the knowledge gaps but have also shown that there are still issues which need to be solved. Common efforts should be started to solve those and come up with intermediate and then long-term solutions. In the light of lacking guidance and yet still deterministic design rules of flood defences in many countries the priority should not only be to solve the issues but also to find acceptable and workable solutions now rather than waiting for final solutions.
5. **Define outcome!** It should be clear what the outcome of a risk assessment study is and what it includes. It is not regarded sufficient to define a hazard and/or risk map as an output, one also has to say what should be included and in which way. Only then the hazard and risk maps produced over Europe will get better comparable and understandable.
6. **Communicate risk!** Moving from a philosophy of ‘safety approach’ like used in many countries (as far as flood defences are concerned) to a ‘risk-based approach’ means a change in understanding and perception of people. It needs to lead towards a better understanding and then tolerance of risk which is not a very easy and short way to go. Only when this is achieved a risk-based design of flood defences can be implemented. This means the earlier this process is started the better it will be.
7. **Work together!** Risk is a manifold subject and nobody is an expert everywhere! The various disciplines involved in risk-based approaches still need to learn to understand each other better and collaborate for a more universally accepted risk approach. This is not easy to achieve since different disciplines are working in a different way. However, not even starting this process is the wrong way as history with its recurrent floods and yet insufficient improvements in flood risk management are permanently showing us.
8. **Keep it simple – Make it happen!** The European Flood Directive might not have produced consistent results all over Europe. However, it has produced results! This is a step forward which would have not been achieved without it. It is now time to make the next step and compare the results and improve the remaining issues. It will never be achieved without going the first step.

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