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XtremRisK – Integrated Flood Risk Analysis for Extreme Storm Surges at Open Coasts and in Estuaries: Key Results and Lessons Learned

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XtremRisK – Integrated Flood Risk Analysis for Extreme Storm Surges at Open Coasts and in Estuaries: Key Results and Lessons Learned

H. Oumeraci, A. Kortenhaus, A. Burzel, M. Naulin, D.R. Dassanayake, J. Jensen, T. Wahl, C. Mudersbach, G. Gönnert, S. Thumm, B. Gerkensmeier, P. Fröhle, K.-F. Daemrich, E. Pasche and G. Ujeyl

Summary

A brief overview of the joint research project XtremRisK is given. The project has been focusing on developing/improving/expanding the knowledge, methods and models with respect to (i) physically possible extreme storm surge for current conditions and scenarios for climate change, (ii) failure mechanisms of flood defences, (iii) assessment of intangible losses (social and ecological) and their integration with direct/indirect economic losses, (iv) reliability analysis of flood defence systems and (v) SPR-based integrated flood risk analysis involving both tangible and intangible losses and its implementation for two selected pilot sites (representative for an open coast and an urban estuarine area in Germany). The key results are briefly summarised and the lessons learned for future flood risk studies are finally drawn.

Keywords

integrated risk analysis, SPR-Concept, extreme storm surge, flood defense structures and systems, reliability analysis, dike breach modelling, intangible and tangible flood losses, GIS-based spatial modelling

Zusammenfassung

Das Verbundprojekt XtremRisk wird zunächst kurz beschrieben. Schwerpunkte des Forschungsvorhabens waren die Entwicklung, Verbesserung und Erweiterung von Grundlagen, Methoden und Modellen hinsichtlich folgender Aspekte: (i) Physikalisch mögliche extreme Sturmfluten für verschiedene heutige und künftige Klimaszenarien, (ii) Versagensformen und -mechanismen von Hochwasserschutzwerken, (iii) Evaluation der intangiblen Flutschäden (soziale und Umweltschäden) sowie deren Aggregation mit direkten und indirekten Schäden in eine integrierten Risikoanalyse, (iv) Zuverlässigkeitsanalyse von Hochwasserschutzsystemen, (v) Implementierung der integrierten Risikoanalyse unter Berücksichtigung der tangiblen und intangiblen Schäden auf der Grundlage des bewährten SPR-Konzeptes (Source-Pathway-Receptor) am Bespiel von zwei ausgewählten Standorten an der deutschen Nordseeküste: Sylt repräsentativ für eine offenen Küste und Hamburg für ein urbanes Ästuar-Gebiet. Der Beitrag fokussiert lediglich auf einige Schlüsselergebnisse und die wichtigsten Lehren für künftige Forschungsvorhaben.

Schlagwörter

Integrierte Risikoanalyse, SPR-Konzept, extreme Sturmflut, Hochwasserschutzwerke und -systeme, Deichbruchmodellierung, Zuverlässigkeitsanalyse, intangible and tangible Flutschäden, GIS-basierte räumliche Modellierung

Contents

1 Introduction

Given the large uncertainties of the impact of climate changes on physically possible extreme storm surges and further unfavourable combinations of the loading conditions, as well as of the potential subsequent damages to be expected in the 21st century at open coasts and estuaries, it is obvious that an integrated reliability and risk analysis based on the Source-Pathway-Receptor (SPR) concept (OUMERACI 2004) represents the most appropriate approach to address this problem. Among the main obstacles for the practical implementation of such an approach are the remaining gaps of knowledge following the completion of the EU-FLOODsite project (KORTENHAUS and OUMERACI 2008), especially those associated with extreme storm surges, the failure mechanisms of flood defences, the intangible flood losses and their integration with tangible losses in a risk analysis.

With this background, the four -year project "XtremRisK", funded by the German Federal Ministry of Education and Research (BMBF), was initiated in October 2008. It brought together three partners from different German universities (TU Braunschweig, fwu Siegen, TU Hamburg-Harburg, hereafter LWI, fwu and TUHH) and one partner from the Agency of Roads, Bridges and Water in Hamburg (LSBG) as well as the end-users of the prospective results for Hamburg (LSBG and HPA) and the Island of Sylt (Schleswig-Holstein Agency for Coastal Defence, National Park and Marine Conservation LKN) as cooperative partners.

After a very brief overview of the project and a brief summary of the key results, the lessons learned for future flood risk studies are finally drawn, also including recommendations for future priority R&D topics.

2 Brief overview of overall project

The XtremRisK project follows the SPR-based integrated risk analysis and management approach proposed by Oumeraci (2004) and FLOODsite (www.floodsite.net), but differs from previous similar flood risk projects in the sense that (i) it was intended to particularly focus on the extreme storm surge events which are physically possible at the present time and at the end of this century, (ii) it is based on a detailed modelling and reliability analysis of the failure of entire flood defence systems, including both man-made and natural barriers, (iii) the assessment of the tangible flood damages includes both direct and indirect losses, (iv) the assessment of the intangible losses includes both social losses (loss of life, cultural losses) and environmental losses, (vi) both tangible and intangible losses are consistently considered and integrated to assess the overall flood losses in the risk analysis, including a consistent framework and methodology for admissible flood risks.

Two pilot sites, for which most of the required data already existed, were selected for the application of the developed methodologies, modelling tools and techniques, and, ultimately, for the practical implementation of the integrated risk analysis: for Hamburg, as a representative urban area in an estuary, and for the Island of Sylt, representative for an open coast.

The structure of the overall project (led by LWI) in four subprojects (SP1-SP4) follows the SPR-concept (Fig. 1) as they respectively address risk sources (SP1), risk pathways (SP2), risk receptors (SP3) and their integration in a risk analysis (SP4).

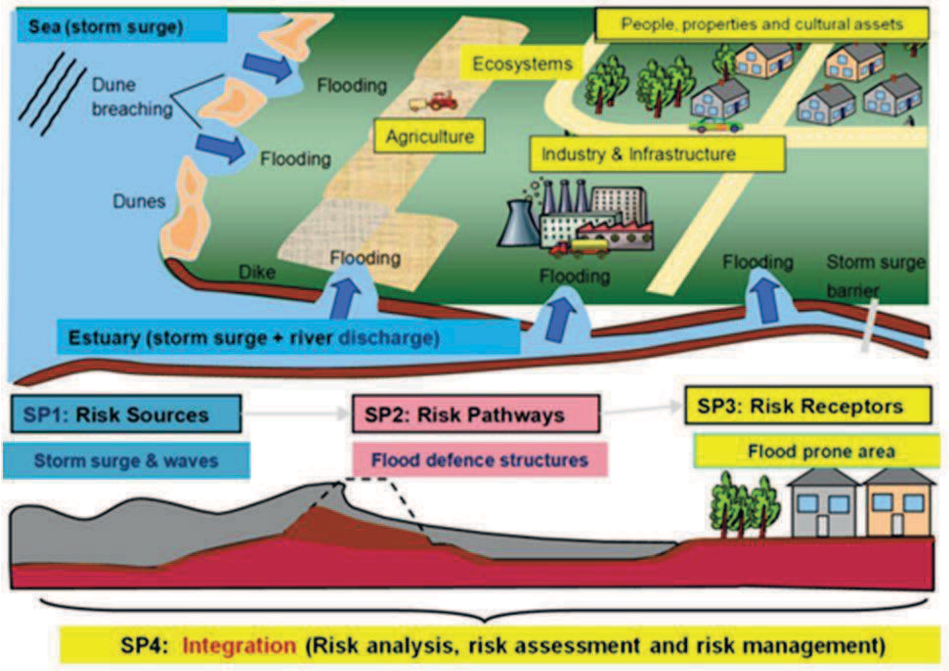

Figure 1: "Source-Pathway-Receptor" concept (SPR) and Subprojects (SP) in XtremRisK.

2.1 Subproject 1 – Extreme storm surges

Subproject 1 – Extreme storm surges (risk sources) is divided in SP1a, led by LSBG, and SP1b, led by fwu.

SP1a aims at the development of scenarios of the largest physically possible extreme storm surges for the selected pilot sites based on the analysis of field data (e.g. tidal gauge Cuxhaven) and numerical modelling by analysing all storm surge constituents (e.g. wind surge, tide and external surge) and their non-linear interactions as compared to their linear superposition (see Fig. 4).

SP1b aims at the determination of the exceedance probabilities of the extreme storm surge scenarios provided by SP1a. This is achieved through the development of a storm surge generator capable of reproducing entire parameterised storm surge curves combined with a multivariate statistical analysis of extreme storm surge water levels (field data and synthetic data obtained from storm surge generator). Joint probabilities of both peak values $h_{w,max}$ and fullness F of the extreme storm surge are determined using a bivariate Copula approach. A trivariate approach is required to also consider significant wave height H_s. The obtained joint probabilities are delivered to SP2 for the reliability analyses of the flood defences (risk pathways).

2.2 Subproject 2 – Reliability analysis and breach modelling of flood defences

Subproject 2 – Reliability analysis and breach modelling of flood defences (risk pathways) is led by LWI.

Based on the extreme storm surge scenarios developed in SP1, subproject 2 aims at the determination of the loading and the reliability analysis of all components of the flood defence systems for the two selected pilot sites. This will also comprise the full failure of these components, including breaching and breach development.

The ultimate goal will be the determination of a failure probability of the flood protection systems (and thus the flooding probability $P_{f,cond}$), which represents the first component of flood risk (defined in this project as the product of probability $P_{f,cond}$ and related consequences D). Moreover, the initial conditions at the breach location for the inundation modelling will also be determined, including the breach development and the final breach width and depth.

The results are delivered to SP3 for the numerical simulation of the flood inundation and the assessment of related damages in the two pilot sites.

2.3 Subproject 3 – Damage assessment/evaluation

Subproject 3 – Damage assessment and evaluation (risk receptors) is led by TUHH.

SP3 aims at the assessment of the direct and indirect economic losses in the two selected pilot sites. This is 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 sole consideration of direct economic losses is, indeed, not sufficient in the case of extreme event related risks.

The direct damages are assessed at a micro scale level of one item (e.g. building) and extrapolated to a group of similar items at a meso-scale level. A cluster-based approach is used to aggregate the damages 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.

The GIS-based direct and indirect economic damages are delivered to SP4 for the integration of all damage categories in a risk analysis.

2.4 Subproject 4 – Risk analysis/ risk evaluation

Subproject 4 – Risk analysis, risk evaluation and recommendations for risk mitigation (integration) is led by LWI.

SP4 primarily aims at bringing together all results from SP1–SP3 into an integrated flood risk analysis (see Fig. 1 and OUMERACI 2004) for the two pilot sites by considering the selected storm surge scenarios determined in SP1 for present (2010) and future climate conditions (2100). For this purpose, however, a proper 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 is required. Therefore, a consistent GIS-approach (Cellbased Risk Assessment (CRA)) for the spatial modelling of risk needs to be developed. The CRA approach is 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, and finally for the integration of all risk categories in an integrated risk map for the two pilot sites.

Moreover, the predicted flood risks for both conditions are evaluated based on tolerable risks estimated for each damage category in close collaboration with the prospective end-users of the results in the study areas. Finally, structural and non-structural mitigation measures are proposed to reduce predicted flood risks to a tolerable level.

The detailed analysis of the selected most appropriate mitigation measures in terms of technical and economic feasibility will possibly be conducted in a follow-up project, depending on the final outcome of discussions with the decision makers responsible for flood risk management at the two pilot sites.

3 Key results and lessons learned

3.1 Risk sources

3.1.1 Key results

A new approach combining empirical methods and numerical modelling to analyse the non-linear interaction between the storm surge constituents and to determine extreme storm surge scenarios has been developed and implemented for the study areas, including three main steps: (i) analysis of the highest event of each constituent and (ii) analysis of the interaction between tide and wind surge and the interaction between wind surge and external surge to (iii) calculate an extreme storm surge event based on the result of these analyses (GÖNNERT et al. 2012). Lower water levels are obtained by considering the non-linear effects between the storm surge constituents than those resulting from a linear superposition of constituents. This conclusion is, however, valid only for the data which have so far been analysed at the tidal gauge of Cuxhaven (continuous time series for more than 100 years). Moreover, the implementation of the proposed approach to the data of the tidal gauges in Hörnum (Sylt) has shown that it is also applicable to other areas (GÖNNERT et al. 2012). In order to better understand the relative contribution of the nonlinear effects and to check the validity of these important results, a PhD research programme for the implementation of a hybrid approach using hydrodynamic modelling and artificial neural networks was initiated, which is now nearing completion (see TAYEL and OUMERACI 2014).

A powerful and computationally efficient stochastic storm surge generator (SSSG) and an advanced Copula-based multivariate statistical analysis of extreme storm surge events (CMSA) have been developed and implemented for the two pilot sites.

The SSSG is capable to stochastically simulate a large number of storm surge scenarios (in the order of 107). It is based (i) on the observed storm surge water levels from the tidal gauges of Cuxhaven (Elbe estuary) and Hörnum (Sylt Island) which have been parameterised by means of 19 sea level parameters and 6 time parameters, (ii) the fitted parametric distribution functions to the data sets resulting from the parameterisation, (iii) the consideration of parameter interdependencies and the application of empirical filter functions to avoid inconsistencies and (iv) Monte-Carlo-Simulations (MCS) using the fitted parametric distributions and different filter functions are applied. The capabilities of the SSG have been demonstrated by comparing synthetically generated storm surge curves (time series with a 1-minute resolution) with those obtained from observed data, from hydrodynamic models and from empirical analyses. More details are given in WAHL et al. (2011) and WAHL et al. (2012a, b).

In contrast to most of the previous studies where only the highest peak water level $h_{w,max}$ (S in Fig. 2) is considered to be the sole parameter to statistically represent the storm surge event, the CMSA in its bivariate version additionally considers the "fullness" F (Fig. 2) of the entire storm surge curve.

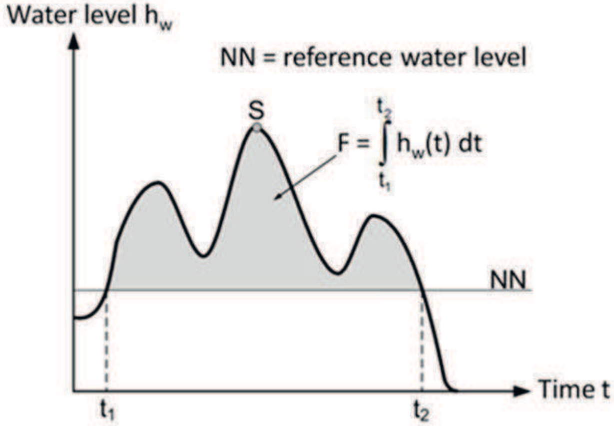

Figure 2: Storm surge curve with highest peak value S and "fullness" F (definition sketch) (modified from WAHL et al. 2011).

The "fullness" F may indeed be as crucial as $h_{w,max}$ for the stability of flood defences and flooding probability as it implicitly describes the residence time of the water levels from the reference water level NN to the maximum level $h_{w,max}$ (S). Therefore, the proposed CSMA and the obtained joint probabilities of $h_{w,max}$ and F as shown in Fig. 3 represent a significant advance in reliability and risk analysis.

By using a fully nested Archimedean Copula approach, the bivariate model is extended to a trivariate model which additionally accounts for the significant wave height Hs as one of the most important wave parameters.

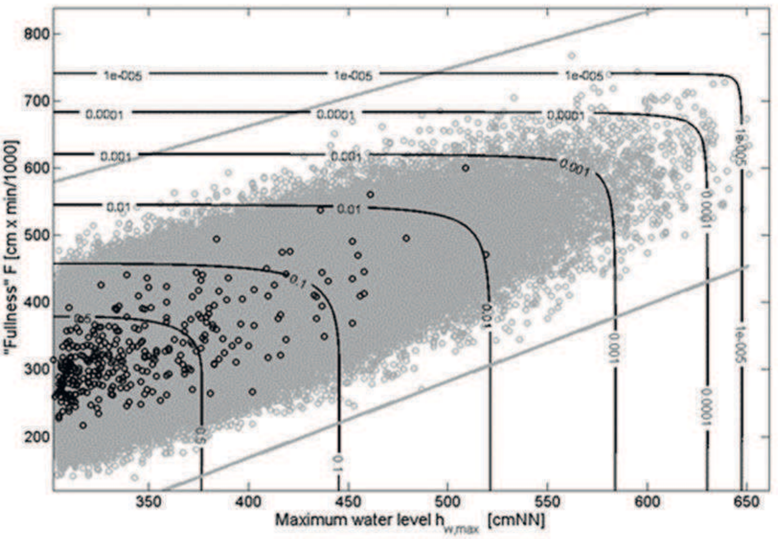

Figure 3: Joint probability of maximum water level and full-ness F (WAHL et al. 2011).

3.1.2 Lessons learned

Many of the conventional bivariate approaches available suffer from restrictions and constraints regarding the underlying data sets in terms of dependence or marginal distributions. Unlike the conventional models, Copula-based approaches are more flexible and able to handle dependent parameters with mixed marginal distributions.

Therefore, the proposed CSMA can be extended to account for further storm surge wave parameters. Moreover, Copula functions represent a promising alternative to address further classes of multivariate problems. The major issue, however, remains the considerable uncertainties associated with higher dimensional Copula-based models.

The attempt made in this study by considering only two sources of uncertainties, namely the Copula parameter θ and the stochastically generated synthetic storm surge data by using filter functions, has shown that the latter source is much more crucial and that the uncertainties can only be reduced through an improved physical understanding of the relative contributions of the storm surge constituents and their non-linear interactions (Fig. 4), the underlying formative factors, including their variability range and their limits compatible with the physical laws.

For this purpose, a consistent modelling strategy with proper models and proper uncertainty analyses will be required to predict the effects of climate/ geophysical/ morphological inter-decadal changes on the joint probability distributions of storm surge water levels and waves, including joint design extremes. A first step in this direction has been made by TAYEL and OUMERACI (2014) with the implementation of a combined 2D-hydrodynamic model and recurrent artificial neural network (ANN) to improve the understanding of the non-linear interaction between the storm surge constituents in the German Bight as illustrated by Fig. 4. The results are very encouraging, as they show that the developed hybrid modelling approach is efficient in the sense of its capabilities to capture the overall relative contribution of the non-linear interaction between the storm surge constituents as compared to the their linear superposition – and, thus, to predict extreme storm surges. As found by GÖNNERT et al. (2012) linear superposition generally results in higher water levels, but under certain circumstances which are still not fully clarified, the nonlinear effects may result in higher water levels (TAYEL and OUMERACI 2014).

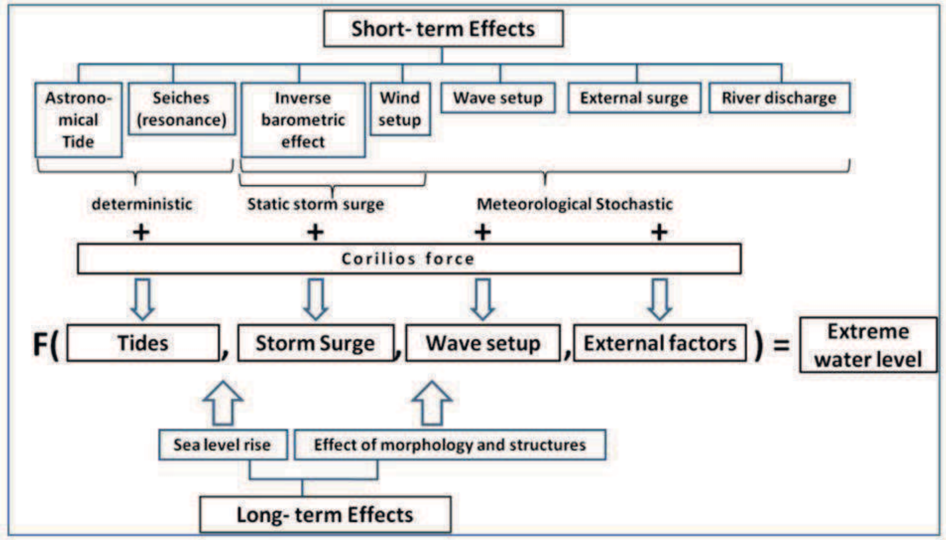

Figure 4: Storm surge constituents and their non-linear interactions (TAYEL and OUMERACI 2012).

3.2 Risk pathways

3.2.1 Key results

Based on the knowledge and modelling tools developed in previous projects such as FLOODsite (www.floodsite.net) and further improved/extended in XtremRisK, a reliability analysis of the linear flood defences such as sea dikes, coastal dunes and flood walls is performed for the two pilot sites. As a result, a probability of flooding P_f is obtained for the different extreme storm surge scenarios provided by SP1. This also includes (i) breach modelling for sea dikes by using the models developed by TUAN and OUMERACI (2010, 2011) and STANCZAK and OUMERACI (2012) for a dike breach initiated respectively by wave overtopping/overflow on the inner dike slope and by breaking wave impact on the outer slope and (ii) dune erosion and breaching by using the "X-Beach" code.

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 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) used to perform the reliability analysis. Most of the LSEs considered were taken from the previous studies, including some modifications and further developments in this project.

Beside the commonly applied limit state equations for dune erosion, additional limit state equations for cross-shore profile response of dunes due to wave impact and overwash by applying available analytical models are also included. Moreover, the common approach for the LSE, which compares the admissible wave overtopping/overflow rate q_{adm} with the actual wave overtopping/overflow rate q has been modified to, instead, consider the admissible volume V_{adm} and actual volume V (Equation 1)

$$V = \sum_{i=1}^{n,m} V_i = \sum_{i=1}^{n,m} q_i \cdot t_i \cdot l_i \tag{1}$$

with: t_i = time [s]; l_i = length of flood defence section [m]; n = number of time steps [-]; m = number of sections [-]. The consideration of time-dependent volumes has substantial advantages, as it represents a better approximation of the time-dependent process (unsteady conditions) and related failure mechanisms over the entire storm surge time history. Moreover, the storage capacity of the hinterland is taken into account in contrast to the common approach based on overtopping discharges. In fact, exceedance of the critical overtopping discharge might occur for a short period at the peak of the storm surge, but should not necessarily result in flooding. More details are given in NAULIN et al. (2012a, b). Due to the deficiencies of the available state of the physical knowledge, which is still very limited regarding the time dependency of the failure modes and their spatial correlation along the entire defence line, the reliability analysis could not fully consider the effect of time and the so-called "length effect", i.e. the failure modes were considered more or less separately for each section of the segmented defence line. Despite these simplifications, and though only conventional fault tree analyses have been performed without taking into account (i) the *duration* of the failure mechanisms as well as their *time sequencing* and *actual links* and (ii) the failure modes, which are hardly amenable to common limit state equations (e.g. failures of moveable barriers due to human and organisation errors), the results have clearly revealed the relative contributions of each failure mode to the probability of the top event (flooding), and, thus, have also provided valuable indications on the priority issues which need more elaboration and more R & D efforts. Traditional hierarchical reliability models such as fault/event trees and reliability block diagrams are neither capable of capturing the causality of failures, nor their interactions in time and space (ZIO 2009). For this purpose, new agent based modelling approaches are emerging which are capable of using the existing knowledge and models on the environmental loads and material properties to identify and model potential failures and their mutual interactions, including cascading effects (MACAL and NORTH 2010).

3.2.2 Lessons learned

In spite of the aforementioned and further simplifications required to make the reliability analysis practically feasible for entire flood defence systems, the obtained failure probabilities of the flood defence components/sections and the related conventional fault trees substantially contribute to identifying the weak links and to prioritising the issues being candidates for further detailed investigations. This also applies to risk mitigation for related possible structural countermeasures. Moreover, it was found that the performance of an entire defence system is much too complex to be addressed efficiently by current modelling approaches and by conventional reliability/fault tree analyses. This complexity is significantly increased by the high degree of temporal and spatial variability of the load and resistance parameters affecting the failure modes, as well as by their interaction for a single defence component and for an entire flood defence system.

Therefore, an *appropriate modelling approach* is needed which is capable of coping with the complex failure mechanisms in time and space, including all interactions between the components of the defence system and the integration of the expected damages directly caused by the flood propagation. Such a modelling approach might be obtained by coupling system dynamic models to cope with the time dependent processes and GIS-based approaches to cope with spatial modelling. Such an approach will also enable the simulation of the performance of the entire defence system over the intended design life time, and, thus, to also explicitly account for the long-term change of the failure probabilities which would necessarily result from the long-term changes in load and resistance parameters. This issue is particularly crucial for probability discounting, as optimisation can only be achieved by considering life-cycle costs.

Time-dependent reliability analysis: A structured approach to define statistical models for time-dependent processes of flood defences and a sophisticated modelling framework including hierarchical and stochastic process models have been proposed by BUIJS et al. (2009). This is indeed a very promising approach which may provide new insights into the time-dependent behaviour of flood defence structures, especially for failures associated with deterioration processes. However, the scientific knowledge available yet on the physical processes underlying time dependent failure mechanisms and their mutual interactions over time is still too poor to efficiently apply this or any other sophisticated time dependent reliability approach on realistic flood defence components and systems in engineering practice. Reliance upon sophisticated modelling approaches without sufficient knowledge on the underlying physical processes, deterioration mechanisms and other time dependent failure modes and their interaction might indeed represent an *additional hazard* which may substantially contribute to increase flood damages and losses. The practical implementation of modelling approaches enabling, for instance, the development of time-dependent fragility curves and their embedment in the reliability analysis of an entire flood defence system needs to proceed with the results of basic research on the most relevant underlying physical processes. Iterative refinements, based on these results and upon sensitivity analysis of the entire system, to each of these processes will also be required.

In a longer term, an improved understanding of the interactions between the diverse failure modes, the temporal and spatial correlation between the sections along a defence line and between the different components of the entire defence system is needed to overcome the drawbacks of conventional fault tree analysis. The latter is rather based on engineering judgment and therefore subjective, as the outcome is strongly dependent on the expertise and skills of the analyst. Moreover, advanced fault trees or other alternative tools will be needed to account for the time duration, the time sequencing and the actual links in space and time of the failure mechanisms within and along each defence component, as well as within entire flood defence systems. These will significantly help moving the conventional analysis from art to science, from a fragile and very sensitive tool to a more robust and widely affordable approach for practitioners. In this respect, the feasibility of integrated system dynamic models and GIS-approaches to develop a modelling framework capable of coping with space and time dependent processes and interactions needs to be examined.

Moreover, time-dependent fault trees or other alternative integrating tools must also include failure modes which are not or hardly amenable to common limit state equations (e.g. failures of moveable barriers due to human and organisational errors). For this purpose, a "quantification" of the failure probability by elicitation of expert opinions and/ or simulations may considerably improve confidence. Particularly in cases where the load and resistance parameters are time dependent and where the time duration of the failure mechanisms, as well as their time sequencing and links, are important, the final outcome of a conventional fault tree may be largely on the unsafe side.

Spatial variability and length effects: The different failures mechanisms are commonly assessed by considering a representative cross section of each segment resulting from a segmentation of the entire defence line. It is, therefore, obvious that the probability of failure will increase with the length of the defence lines, due to the spatial variability of both load and resistance terms of the limit state equations, as well as to the fact that "a chain is as strong as its weakest link" (*length effect*). The higher the spatial variability (i.e. shorter auto-correlation distances) of the load (e.g. waves and water levels) and resistance parameters (e.g. soil parameters), the higher the length effect. The relative contribution of the resistance parameters (e.g. soil properties) to the length effect are generally much higher due to their larger heterogeneity along the defence line as compared to that of the load parameters, which are commonly characterized by much larger correlation distances. The multiple breaches, which occurred as a result of weak spots along the defence lines in New Orleans during hurricane Katrina, have shed more light on the importance of these issues. Moreover, the resistance-dominated failure mechanisms generally govern the length effect and failure probability of a single segment and of the entire defence line may differ by more than two orders of magnitude (VRIJLING et al. 2011). A consistent framework for the modelling of the continuous spatial variability of soil parameters using random field theory already exists and has gained distinct importance in recent years, as spatial variability of soils represents one of the main damage (failure) sources of built-up systems in civil engineering (VROUWENVELDER 2006). Discrete spatial variability (e.g. weak spots) can be incorporated into modelling by using conditional probability based on scenarios (VRIJLING et al. 2011).

The large uncertainties associated with the spatial variability of the resistance parameters along the defence lines (heterogeneity in terms of shear strength, hydraulic permeability and soil layer thickness, weak spots at transitions and those caused by burrowing animals, etc.) are not only inherent (aleatory), but also epistemic in the sense that they exist due to the lack of measurement/observation data and are continuously and discretely changing over time. They represent the main obstacles to plausibly account for the length effect in the reliability analysis of entire flood defence systems. Targeted aerial reconnaissance, using infra-red and further geophysical surveys, can be used as a first step in detecting possible weak spots. In the long term, a consistent and systematic monitoring strategy will be required.

It should be kept in mind, that the omission or improper consideration of the aforementioned aspects (time dependence and spatial variability of the failure mechanisms and their interaction, single point structures), which is common in the current reliability analyses of flood defences, generally leads to lower predicted values of flooding probabilities, i.e. to results on the unsafe side.

3.3 Risk receptors

3.3.1 Key results

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.

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 is placed on residential buildings, as well as on commercial and industrial assets, but damages to infrastructure and agriculture are also considered. As a main input hydraulic parameter for damage calculation, the flood depth obtained from inundation modelling using MIKE21 is applied for the development of asset-based depth-damage functions (data obtained from building inspections, photos and floor plans of the buildings). Inundation modelling is based (i) on the storm surge scenarios provided by SP1 and (ii) on the overtopping/overflow volumes or the initial conditions resulting from dike breaches provided by SP2. The micro-scale approach is mainly based on damage assessment using the Flood Resilient Tool (FloReTo) 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. 2011, 2012). The calculated damages and the inundation depths are brought together using GIS-based spatial modelling (see Section 4) using the "develop depth-damage"- functions. A comparative analysis with commonly used meso-scale approaches is also performed to underpin the benefit of the proposed approach (e.g. for deriving efficient risk mitigation measures).

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 following exceedance of this level. The latter indicates the existence of a threshold in the coping capacity of economic systems. For the pilot site in Hamburg, the threshold was found to be about 2.5 billion Euros (UJEYL and KOWALEWSKI 2012). The corresponding values obtained by HALLEGATTE (2008) for Louisiana are 50 billion and 200 billion U.S. $, respectively (Fig. 5).

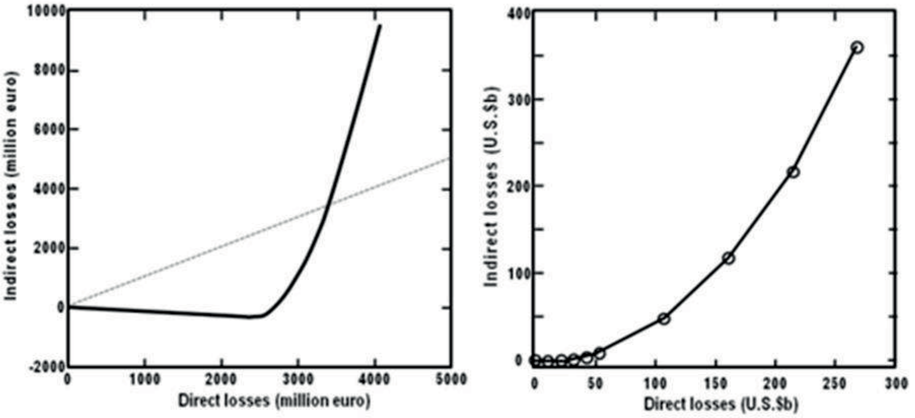

Figure 5: Indirect economic losses in terms of value-added losses vs. direct losses for Hamburg (UJEYL and KOWALEWSKI 2012, left) and for Lousiana (HALLEGATTE 2008, right).

Intangible Losses: The results of a comprehensive state of the art report (DASSANAYAKE and OUMERACI 2010) have revealed the gaps in the methodologies available (i) to assess the social losses (loss of life/injuries and cultural losses) and environmental losses incurred by floods and (ii) to integrate them with the tangible losses in a risk analysis. Moreover, the results have particularly contributed to identify the lack of appropriate methodologies for the evaluation of both cultural and environmental losses, as well as for their integration with other losses in risk analysis. Therefore, 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. Since this model has, as yet, been applied for river floods only, the model proposed by JONKMAN (2007) is also applied for comparison.

For the evaluation of cultural losses, however, a new methodology based on physical damages due to flooding and the cultural values of the assets is developed (DASSANAYAKE et al. 2011a). The estimation of direct physical damages to cultural assets is based on both flow depth and flow velocity. The cultural value of the different types of assets (heritage and non-heritages assets) is assessed by considering their historical (HS) and societal significance (SS). The results are then integrated into a cultural loss assessment matrix (CLAM) by using a five-point score scale, varying from very low (1) to very high (5). The spatial analysis of social losses was successfully performed in ArcGIS for the pilot site in Hamburg (BURZEL et al. 2012).

For the environmental losses, a two-step ecosystem services-based approach is proposed by making use of the classification of the ecosystem services developed by the Millennium Ecosystem Assessment in 2005, which is modified in the sense that supporting services are omitted so that only Provisioning Services, Regulating Services and Cultural Services are considered in order to avoid double-counting. 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. The approach has already been implemented for the pilot site Sylt. Spatial modelling of the losses is performed based on the Cellbased Risk Assessment (CRA) approach (BURZEL and OUMERACI 2011).

Integration of tangible and intangible losses: As 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) a consistent integration methodology had to be developed. This was developed within a GIS-based multi-criteria analysis (MCA) framework. The methodology is performed in 8 steps (1 - Problem definition, 2 - evaluation criteria, 3 - selection of spatial units and grid size, 4 - criteria evaluation, 5 - criterion weights, 6 - decision rules, 7 - ranking of alternatives, 8 - sensitivity analysis) and has the following objectives (i) integration of all tangible and intangible losses into a single score scale of 0 to 1, (ii) aggregation according to their relative significance and (iii) determination of the severity of the total flood loss within the study area as a final result in a score between 0 and 1, allocated to each GIS-grid cell. Among the several MCA approaches, multi-attribute utility theory (MAUT) is selected for step 6 and a pairwise comparison method for criterion weighting in step 5 (DASSANAYAKE et al. 2011b). This methodology has been implemented in the pilot sites and represents one of the most important achievements within the risk receptor part of the project (DASSANAYAKE et al. 2012; BURZEL et al. 2012).

3.3.2 Lessons learned

The results have shown that *the assessment of the direct economic losses* at a micro-scale level and their aggregation to a meso-scale, though requiring more data and efforts, is worthwhile, as compared to the common meso-scale assessment. Moreover, results have also clearly indicated (i) why the value of direct losses cannot represent a sufficient indicator for the severity of the losses and for decision making related to risk mitigation measures and (ii) why a consistent consideration of indirect economic losses and intangible losses, as well as their consistent aggregation, is crucial for the outcome of the integrated risk analysis. The results of *the indirect economic loss assessment* highlight the main difficulties in defining, measuring and predicting these costs as a function of the direct costs, and emphasize the need for a better understanding of the most important underlying economic mechanisms and market related processes in the recovery and reconstruction phase after an extreme flood event. This particularly includes abnormal solidarity and assistance at regional/national/international levels, as well as further governance/ political processes, which are not considered in the current assessments (HALLEGATTE 2008). Moreover, a better insight into the relationships between the mechanisms of the financial and business sectors and those of a natural disaster may help to better understand the underlying governing processes and the difficulties in assessing the impact of natural disasters based on macro-economic data.

Regarding *the intangible loss assessment*, beside the final results of the evaluation of the loss categories measured in different units and the severity of flood losses expressed in a score scale between 0 and 1 for each GIS-grid cell, it would also be desirable to define all the losses on a monetary scale based on the life quality index (LQI). This is important for the decision -making process, based on a cost/benefit analysis (CBA), but also to improve CBA-based assessments of the benefits resulting from different options for risk mitigation measures. A first encouraging attempt in the direction of an LQI-based approach for the assessment of statistical value of life (VSL) is in progress (DASSANAYAKE and OUMERACI 2012).

For the *determination of criterion values and weights* within MCA, a structured procedure should be developed to also include the opinions of experts and of the affected citizens within the flood prone areas. The latter group is also particularly relevant in determining the relative importance of the different loss categories. The multiplicity of terms to characterize the diverse categories of losses caused by extreme events, as well as the diversity of assessment methodologies and underlying assumptions, not only reflect the confusion in the published literature, but also make the selection of an appropriate methodology and a meaningful comparison or aggregation of the published results extremely difficult. The selection of the adequate methodology and the proper degree of detail of the analysis primarily depends on the purpose of the loss assessment (insurance, risk mitigation measures, etc.). Moreover, the difficulties are significantly increased by the inherent multi-dimensionality of the impact of extreme events and their significant redistributive effects, as well as by the large uncertainties involved, which are rarely assessed. Therefore, a *harmonization within the risk analysis community*, possibly at transdisciplinary and transnational levels, is urgently needed. Such a harmonization is expected to significantly contribute to the evaluation of the very large uncertainties, which currently represents the most critical bottleneck in any integrated risk assessment. These uncertainties are primarily due to the lack of sufficient knowledge on the interaction between the socio-economic dynamics and the impact dynamics of natural disasters, but also to insufficient data and inconsistent assessment methodologies.

3.4 Integrated risk assessment

The overall project was completed at the end of 2012, including the integration of the results from subprojects 1-3 in the risk analysis for different extreme storm surge scenarios, the risk evaluation and subsequent recommendations for possible mitigation measures for the two pilot sites. Some of the results related to the developed integration methodology are summarised below.

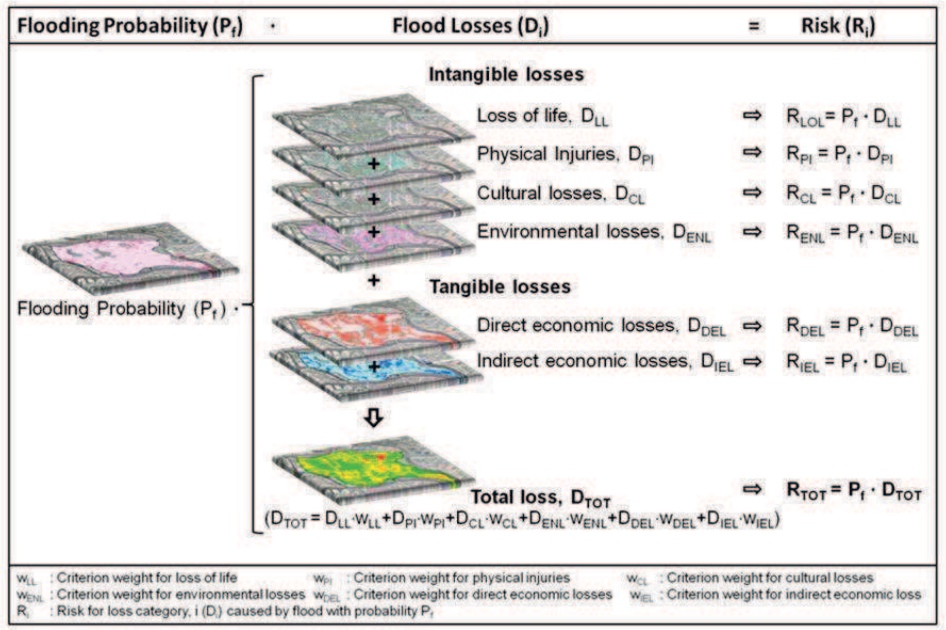

Figure 6: Risk related to the different categories of losses and their aggregation in the integrated risk analysis (modified from DASSANAYAKE et al. 2012a).

Cellbased Risk Assessment (CRA): A GIS-based approach has been developed as a flexible and robust framework 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 both selected pilot sites, the GIS raster concept, which has often been used in the past, is inadequate (e.g. only one attribute can be stored in one raster file). Therefore, 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 form 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 using the Model Builder environment in ArcGIS, thus making the model highly flexible and adaptive to any study area and resolution.

The CRA is performed in three main steps: (i) conversion of all irregular shaped input data into the assigned compartment, (ii) application of the selected model to all cells within the investigation site, and (iii) visualisation of the results on a spatial basis. The CRA approach has successfully been applied for the modelling of tangible losses (direct and indirect economic damages) and intangible losses (loss of life and human injuries, cultural losses and environmental losses) for different scenarios as described in Section 3.3 above.

Integration of tangible/intangible losses and GIS-mapping: Using the MCA based approach developed by DASSANAYAKE et al. (2011b) (see Section 3.3 above) 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 (Fig. 6). Particularly the risk maps for each loss category, together with the aggregated risk maps, which are obtained for different extreme storm surge scenarios, build the primary basis for the evaluation of the predicted risk as compared to tolerable risk, and finally for the recommendations of possible risk reduction measures for both considered pilot sites. For this purpose, a consistent and transparent framework, including the required methodology and tools to assess tolerable risks, is required.

4 Concluding Remarks

One of the key features of the XtremRisK project, which started 2008 and was completed at the end of 2012, is the level of detail which has been kept at the highest mark (practically feasible within the time frame of the project) for the analysis of the risk sources (e.g. effect of non-linear interaction of constituents on extreme storm surge), risk pathways (e.g. failures modes of flood defences and failure probabilities) and risk receptors (e.g. consideration of different categories of tangible and intangible flood damages) given the available knowledge/models and the available time/resources for further/new developments. Therefore, it is believed that this study represents one of the most process-based integrated risk analyses of coastal floods induced by storm surges with sample applications at two pilot sites, selected to represent an open coast and an urban estuarine area. This high level of detail was necessary in order to better identify not only the deficiencies of the current knowledge/models and the prioritization of further research, but also to find out where, how and to which degree simplifications over the entire risk analysis process are possible without losing sight of the essentials. Moreover, this study might also help to better assess the outcome of simplified or holistic approaches, such as those proposed in the joint HoRisk project (SCHÜTTRUMPF et al. 2012) and in the EU-THESEUS project (NARAYAN et al. 2013; ZANUTTIGH et al. 2013).

Beside closing the most relevant knowledge gaps which have been identified in the sections above, the ultimate challenge will be the simplification of the process, as much as reasonably practicable, i.e. without losing any important issue, so that the proposed integrated risk analysis methodologies and tools will be comprehensible and affordable by practitioners and further prospective decision makers (e.g. for the implementation of the EU flood directive). Making the best use of the outcome of the joint projects XtremRisk, HoRisk and THESEUS (ZANUTTIGH et al. 2013), it is intended to initiate a new R & D project in 2015 with the ultimate objective of developing a Living Decision Support System (LDSS) with a modular tiered structure for the three decision levels commonly encountered in engineering practice: the feasibility, preliminary and detailed levels. As a result, an integrated coastal flood risk assessment as a flexible and robust tool will be obtained, which can be used for risk-based design, safety assessment and monitoring/maintenance of flood defence systems, as well as for efficient flood risk management in coastal and estuarine areas. A particular focus will be placed on the damages to the so-called critical infrastructures in coastal areas. Such complex systems are generally designed to withstand events and threats such as storm surges and coastal flooding, which are predictable through existing modelling tools and in line with existing design standards for such conditions. However, for extreme low probability events, which are difficult to predict, a 100 % protection is neither technically nor economically feasible, so that these events generally result in catastrophic damages and losses, if a consistent and robust set of countermeasures are not provided. The efficiency of the types of countermeasures depends on the degree of complexity of the system considered together with its components (sub-systems) and its nesting in larger systems at regional, national and international scales, but also on the type, magnitude and frequency of the extreme event, the type and importance of critical infrastructure, the type and relative importance of possible cascading effects, the categories and magnitudes of potential losses (economic, social and environmental) and the local risk culture (risk acceptance). Critical infrastructures nested in their environment are highly complex and non-linear systems in the sense that the collective behaviour of their constituents entails emergence of properties that can hardly, if not at all, be inferred from properties of the constituents. This has significant implications on the conceptual and theoretical framework for the generation of the knowledge base, the methodologies, the modelling approaches and further analysis tools/techniques to understand the basic functioning of complex systems aimed at minimising the risk in the case of unexpected extreme hazards. These, together with the outcome of the aforementioned completed and further related projects, will build the basis for the new 3-stage LDSS. Whether the LDSS will be developed within an Agent-Based Modelling (ABM) framework or within a more conventional framework is still to be clarified. In both cases, a synergetic transnational partnership and collaboration would be desirable.

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6 References

BUIJS, F.A.; HALL, J.W.; SAYERS, P.B. and VAN GELDER, P.H.A.J.M: Time-dependent reliability analysis of flood defences. In: Reliability Engineering and System Safety 94, 1942-1953, 2009.

BURZEL, A. and OUMERACI, H.: Development of a Framework for the Spatial Modelling of Extreme Risks and the Consideration of Risk Acceptance: Progress Report. Leichtweiß-Institute, TU Braunschweig, 2011.

BURZEL, A.; DASSANAYAKE, D.R. and OUMERACI, H.: Spatial Modelling of tangible and intangible Losses in Integrated Risk Analysis – Results of the XtremRisK Proc. 2nd European Conference on FLOODrisk Management, Rotterdam, 2012.

DASSANAYAKE, D.R. and OUMERACI, H.: Framework and Methods for the Evaluation of Intangible Losses and their Integration in Coastal Flood Risk Analysis. State of the Art Report. Leichtweiß-Institute, TU Braunschweig, 80 p, 2010.

DASSANAYAKE, D.R.; BURZEL, A.; KORTENHAUS, A. and OUMERACI, H.: Evaluation of cultural losses due to coastal floods. XtremRisK Progress Report. Leichtweiß-Institute, TU Braunschweig 38 p, 2011a.

DASSANAYAKE, D.R.; BURZEL, A. and OUMERACI, H.: Integration of Tangible and Intangible Flood Losses: A GIS Based Multicriteria Analysis (MCA) Approach. XtremRisK Progress Report. Leichtweiß-Institute, TU Braunschweig, 40 p, 2011b.

DASSANAYAKE, D.R.; BURZEL, A. and OUMERACI, H.: Intangible Flood Losses: Methodologies for their Evaluation and Integration in Flood Risk Analysis. Proc. 2nd European Conf. on FLOODrisk Management, Rotterdam, 2012a.

DASSANAYAKE, D.R. and OUMERACI, H.: Value of statistical life based on life quality index. Progress Report. Leichtweiß-Institute, TU Braunschweig, 2012b.

GÖNNERT, G. and SOSSIDI, K.: A new approach to calculate extreme storm surges: Analyzing the interaction of storm surge components. In: BENASSAI, G., BREBBIA, C.A. and RODRIGUEZ, G.R. (Eds.): Coastal Processes II. Southhampton, pp.139-150, 2011.

GÖNNERT, G.; THUMM, S. and GERKENSMEIER, B.: Empirical analyses of extreme storm surges – Results of the XtremRisK project. Proc. 2nd European Conf. on FLOODrisk Management, Rotterdam, 2012.

GÖNNERT, G. and GERKENSMEIER, B.: A 2-method-concept to approach extreme storm surge events – Combination of deterministic empirical and numerical methods. Proc. 10th Intern. Conf. Hydroinformatics, Hamburg, Germany, 2012.

HALLEGATTE, S.: An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. In: Risk Analysis, Vol. 25, No. 3, 779-799, 2008.

KORTENHAUS, A. and OUMERACI, H.: Flood risk analysis and management in Europe – The way ahead. Proc. of the 31st Intern. Conf. Coast. Eng. (ICCE), ASCE, Hamburg, Germany, 2008.

MACAL, C.M and NORTH, M.J: Tutorial on agent-based modelling and simulation Journal of Simulation 4, 151-162, 2010.

NARAYAN, S. et al.: The SPR systems model as a conceptual foundation for rapid integrated risk appraisals: Lessons from Europe. In: Coastal Engineering 87, 15-31, 2014 (http://dx.doi.org/10.1016/j.coastaleng.2013.10.021).

NAULIN, M.; KORTENHAUS, A. and OUMERACI, H.: Reliability Analysis and Breach Modelling of Flood Defences in an Integrated Risk Analysis – Results of the XtremRisK Project. Proc. 2nd European Conf. on FLOODrisk Management, Rotterdam, 2012.

OUMERACI, H.: Sustainable coastal flood defences: Scientific and modelling challenges towards an integrated risk-based design concept. Proc. First IMA Intern. Conf. on Flood Risk assessment, University of Bath, UK, 9-24, 2004.

PENNING-ROWSELL, E.C.; FLOYD, P.; RAMSBOTTOM, D. and SURENDRAN, S.: Estimating Injury and Loss of Life in Floods: A Deterministic Framework. Natural Hazards 36, 43-64, 2005.

SCHÜTTRUMPF, H.; BACHMANN, D.; GIER, F.; GRIMM, C. and WÖFFLER, T.: Vulnerability and Risk Assessment of the coastal zone in a changing environment. 26th Umbrella Symposium for the Development of Joint Cooperation Ideas "Sustainable Urban Development" 2012, Haifa, Israel, 2012.

TAYEL, M. and OUMERACI, H.: Prediction of extreme storm surge water levels using recurrent artificial neural networks. Proc. 10th Intern. Conf. Hydroinformatics, Hamburg, Germany, 2012.

TAYEL, M. and OUMERACI, H.: A hybrid approach using hydrodynamic modelling and artificial neural networks for extreme storm surge prediction (submitted this issue), 2014.

UJEYL, G. and KOWALEWSKI, J.: Estimating Direct and Indirect Damages from Storm Surges: The Case of Wilhelmsburg/Hamburg. Proc. 10th Intern. Conf. Hydroinformatics, Hamburg, Germany, 2012a.

UJEYL, G.; FRÖHLE, P. and PASCHE, E.: Evaluating direct damages of residential and commercial assets on a micro scale – Results of the XtremRisK Project. Proc, 2nd European Conf. on FLOODrisk Management, Rotterdam, 2012b.

VROUWENVELDER, A.C.W.M.: Spatial effects in reliability analysis of flood protection systems. IFED Forum 2006, Lake Louise, Canada, 2006.

WAHL, T.; MUDERSBACH, C. and JENSEN, J.: Assessing the hydrodynamic boundary conditions for risk analyses in coastal areas: a stochastic storm surge model. Nat. Hazards Earth Syst. Sci., 11, 2925-2939, 2011.

WAHL, T.; MUDERSBACH, C. and JENSEN, J.: Assessing the hydrodynamic boundary conditions for risk analyses in coastal areas. Nat. Hazards Earth Syst. Sci., 12, 495-510, 2012a.

WAHL, T.; MUDERSBACH, C. and JENSEN, J.: Statistical assessment of storm surge scenarios within integrated risk analyses – Results of the XtremRisK project. Proc. 2nd European Conf. on FLOODrisk Management, Rotterdam, 2012b.

ZANUTTIGH, B. et al.: THESEUS decision support system for coastal risk management, Coast. Eng. 2013 (http://dx.doi.org/ 10.1016/j.coastaleng.2013.11.013).

ZIO, E.: Reliability engineering: Old problems and new challenges. In: Reliability Engineering and System Safety 94, 2, 125-141, 2009.