Integrated Risk-Based Design and Management of Coastal Flood Defences

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Summary

The main obstacles encountered in the practical implementation of a sustainable protection against coastal floods and the peculiarities of coastal systems and processes are first discussed from the view point of the deficiencies in scientific knowledge, predictability and modelling tools.

The main requirements for a new design and management concept for sustainable flood defences are then derived, leading to an integrated probabilistic risk analysis (PRA)-based conceptual framework for the design and safety assessment of coastal flood defences. This concept is based on the risk source-pathway-receptor model, including (i) the prediction of flood risk, (ii) the assessment of tolerable flood risks and the risk analysis and (iii) the management of residual risk as an integral part of the overall design process. The scientific and modelling challenges within each component of the integrated concept (risk sources, risk pathways, risk receptors) are systematically addressed, also including the assessment of risk acceptances

Zusammenfassung

Zunächst werden die Hauptschwierigkeiten bei der praktischen Implementierung eines nachhaltigen Hochwasserschutzes im Küstenraum sowie die Besonderheiten der küstenbezogenen Systeme und Prozesse aus der Sicht der Defizite im Wissensstand, der Vorhersagbarkeit und der operationellen Modelle aufgezeigt.

Die Formulierung der Hauptanforderungen an ein neues Konzept für die Bemessung nachhaltiger Hochwasserschutzwerke führt zu einem integrierten probabilistischen und risikobasierten Konzept für die Bemessung neuer und die Sicherheitsprüfung vorhandener Hochwasserschutzwerke. Das Konzept basiert auf dem Modell „Risikoquellen-Risikowege und Risikoauswege" mit drei Hauptkomponenten: (i) Vorhersage der Flutgefährdung und der Vulnerabilität der geschützten bzw. zu schützenden Gebiete (berechnetes Flutrisiko); (ii) Evaluierung der tolerablen Flutrisiken und Risikoanalyse; (iii) Management der Flutrisiken als integraler Bestandteil des gesamten Konzeptes für die Bemessung bzw. Sicherheitsüberprüfung. Die Diskussion der wissenschaftlich/technischen Herausforderungen hinsichtlich der Risikoquellen, Risikowege und Risikoempfänger bilden den Hauptteil des Beitrages, wobei auch auf den wichtigen, noch offenen Aspekt der Riskoakzeptanz eingegangen wird.

Keywords

Coast, risk management, flood defence, probabilistic risk analysis, risk source-pathway-receptor model

Contents

1. Design of Flood Defences in the Context of Sustainable Development and Protection of Coastal Zones

Coastal zones, including estuaries, represent unique and vital transition areas between the marine and terrestrial environment and are therefore favoured as valuable habitats by both humans and wild life. In fact, almost 40 % of the world population are concentrated within a 100 km wide coastal strip, including 65 % of the large cities with more than 2.5 million inhabitants (OUMERACI, 2000). Worldwide, coastal, river and flash floods are responsible for more than 50 % of the fatalities and for about 30 % of the economic losses caused by all natural disasters. Moreover, the increasing storm surge activities which are observed since many decades will certainly continue to increase in terms of frequency, duration and intensity. This may lead to the increase of the probability of flood hazards.

On the other hand, the still increasing socio-economic pressure on the use of coastal zones with the subsequent increase of the needs for more infrastructures (industry, transportation, amenities, housing, etc.) has led to an increasing conversion of these vital zones to a built environment, and thus to a vulnerability increase. Subsequently, flood risks which consist of both flood hazard probability and vulnerability are expected to dramatically increase if no appropriate countermeasures are undertaken.

It is obvious, that appropriate solutions to mitigate coastal flood risks can only be found within the general context of sustainable development and protection of coastal zones. Some of the challenges towards the development of future models which are implied by the application of the sustainability principles to flood protection are briefly mentioned in Fig. 1.

The search for appropriate solutions meeting the sustainability principles becomes even more difficult due to some peculiarities and conundrums of the coastal system which may be summarized as follows (Fig. 1):

1) Although coastal zones occupy only 6 % of the total surface of our planet, the value of the coastal ecosystems represent almost 40 % of the value of all marine and terrestrial ecosystems (OUMERACI, 2000). This would suggest that conservation and preservation of coastal ecosystems should have a higher priority than the socio-economic use of coastal zones which is generally associated with an increasing need for more infrastructure and coastal defence structures. This will particularly require integrated methodology tools to achieve a proper balance between socio-economic needs and environmental integrity.
2) The coastal processes (hydrological, hydrodynamical, morphological and ecological) and their interactions are highly complex and stochastic. They are essentially non-linear, dynamic and three dimensional with a high level of spatial and temporal variability. They occur at a very broad range of space and time scales and are very sensitive to climate variability and human inferences. These will particularly require models with a high level of

integration of the diverse physical, ecological and socio-economic issues and interactions over a broad range of scales. Moreover, these models should account for the high temporal/spatial variability of the processes, for possible 3D-effects and the inherent stochastic variability of the influencing parameters and processes.

3) The use and protection of coastal zones, including prioritization, will always be subject to changes (moving target in both time and space!) as well as to conflicts and compromises. This will require adaptive tools/models to account for the evolving socio-economic demands and the evolving impact of human interventions on the apparently natural processes. Account should also be made for the sudden dramatic changes which might result from decadal to centennial/millennial slow changes and accumulations.
4) The knowledge, data and models used at any stage of decision making (design, operation, management) are never complete, permanently evolving and always subject to large uncertainties from diverse sources. Therefore explicit account should be made for these uncertainties, including the inherently low level of predictability of the modelling tools, the inherent stochastic variability of the input parameters as well as the human and organisation errors.

Given these peculiarities and the requirements implied by the sustainability principles it is obvious that a protection against flooding which fulfils both socio-economic efficiency and environmental integrity at longer term can only be achieved by within an integrated design and management framework which is based on probabilistic risk analysis (Fig. 1).

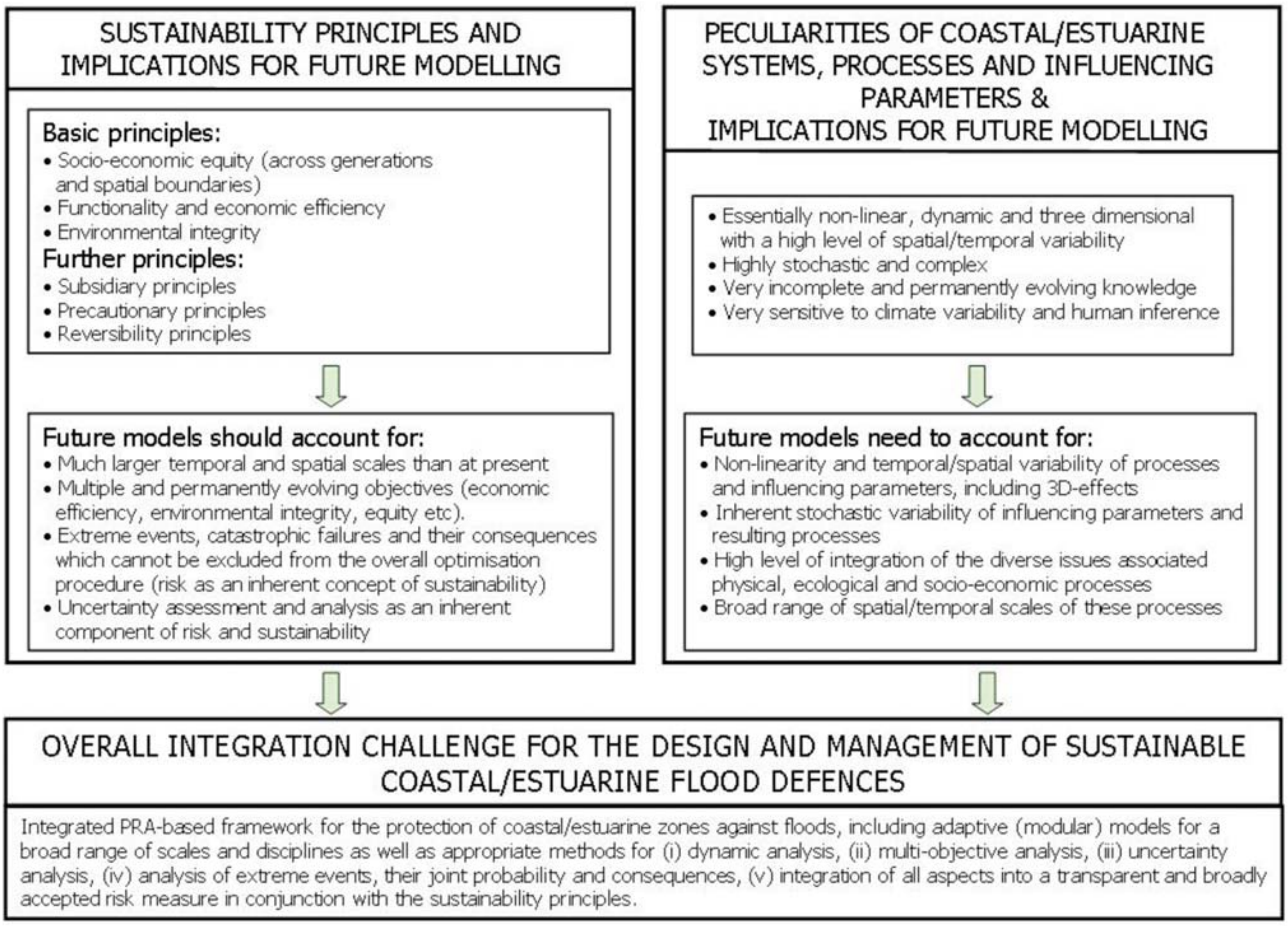


Fig. 1: Research and modelling challenges for the design of sustainable of coastal flood defences

2. PRA-Based Integrated Concept for the Design of Sustainable Coastal Flood Defences

Beside the general motivations mentioned in the introductory section, the necessity of a more rational and integrated design approach, fulfilling the sustainability requirements will be briefly outlined before starting with the description of the suggested design concept.

2.1 Necessity of New Design Concept

The protection against floods and the design of coastal flood defences have a long tradition worldwide. In spite of the wide variety of design methods and safety standards adopted in each country, the design criteria for flood defences structures are still essentially based on the so-called design water levels associated with exceedance frequencies which are specified by design standards and regulations. The specified exceedance frequency is implicitly interpreted as a probability of failure of the defence which is again equated to a flooding probability. Such approaches are too simplistic as:

1) they may lead to too high and expensive defence structures, because the structure must not necessarily fail when the design water level is exceeded;
2) they may result in an incorrect safety assessment, because the defence structure may also fail, even if the design water level will not be exceeded. The adopted safety coefficients are often arbitrary, lacking rationality and transparency;
3) they do not only ignore totally or partially the failure mechanisms likely to lead to flooding, but also the vulnerability of the flood-prone areas. Only in few countries such as in the Netherlands, the vulnerability is implicitly considered by allocating different exceedance frequencies, depending on the vulnerability of the flood-prone areas.

2.2 Basic Requirements for the New Design Concept

In order to substantially help moving the design of sustainable flood defences from an academic debate into the realm of concrete work, performance and return, a new design concept in line with a sustainable flood protection is urgently needed, including all the necessary methods and modelling tools, which should at least fulfil the following requirements:

1) To ensure that the prospective design approach and associated tools are consistent and transparent enough for a wide acceptance in practice, they should be based on a sound knowledge of all relevant processes and interactions at any stage – from the sources to the receptors of the flood risk –, including all constraints, possible changes and their predictions. Therefore, the prospective design approach/tools should possibly be based on *process-oriented* research.
2) To account explicitly in the design process for all uncertainties, including those associated with the prediction over a brad range of scales under the constraints of evolving socio-economic demands and human inferences as well as under the constraints of the more uncertain climate variability and its local implication, *reliability analysis and reliability-based tools* are necessarily required.
3) To offer more choices and transparency in the design process and to bridge the gap between technician and non-technical decision makers, the reliability analysis must be extended to *risk analysis*. The flood risk being defined as a combination of the probability

of the flood hazard (risk sources and risk pathways) and the vulnerability of the flood areas (risk receptors), the risk analysis should preferably be carried out according to the *risk source-pathway-receptor approach*, thus allowing to act on both risk components (hazard and vulnerability) to reduce flood risk.

4) To reduce flood risk, a proper balance of all options (retreat, accommodation and protection) and measures (structural and organisational; prior, during and after flood event) is required. Therefore, *risk management* must be an *integral part of the design* of new flood defences and of the safety assessment of existing defences.
5) To ensure that all processes and conflicting interests, which may affect one or both risk components (hazard and vulnerability), are properly assessed and accounted for, an *integrated approach* is required.
6) To help developing unified safety concepts and thresholds between sustainable and non-sustainable flood protection schemes, an appropriate measure for acceptable vulnerabilities and risks should be developed which also allows a comparison with tolerable values in other sectors such as transportation, chemical industry, nuclear power plants, etc. This will also be particularly important in the case of risk analysis associated with multi-hazards. Therefore, a *transparent framework for the assessment of acceptable flood risk with appropriate methodologies/modelling tools* and with clear implications for regulatory actions should be an integral part of the new design concept.
7) To make the new design concept broadly applicable at various levels, the entire approach for a detailed design level should be simplified for a feasibility and a preliminary design level, including the associated requirements for the data and the modelling tools to be used. *(Tiered approach).*

A possible design concept which can fulfil most of the aforementioned requirements is suggested in Fig. 2. This concept is based on risk-source-pathway-receptor approach, including four major steps:

1) *Prediction of flood risk:* It consists of the predicted flooding probability which is obtained from the risk sources and the risk pathways and of the predicted potential damages and losses which require a sufficient knowledge of the vulnerability of the flood-prone areas, including their temporal variability and uncertainties.
2) *Evaluation of the tolerable flood risk:* It consists of the tolerable damages and losses and of the tolerable probability of their occurrence. Both require a very good knowledge of the socio-economic/ecological resilience and of the risk perception/communication in the flood-prone areas which depend on a large variety of aspects, including individual, societal, political and legal issues. The variability of these aspects and the uncertainties associated with their assessment should be properly accounted for.
3) *Evaluation of the residual risk* through comparison of the predicted and acceptable flood risk. An appropriate measure for the level of residual risk should be developed which clearly describes the penalty associated with both underdesign and overdesign. This of course will have clear implications for future safety factors to be adopted in the design standards and regulations.
4) *Management of the residual risk* through structural and non-structural measures before, during and after the flood event. One of the key features of this design concept is the incorporation of the risk management as an integral part of the entire design process. In fact, no optimisation over the life-cycle of the flood defences is possible without the knowledge of the residual risk and its management.

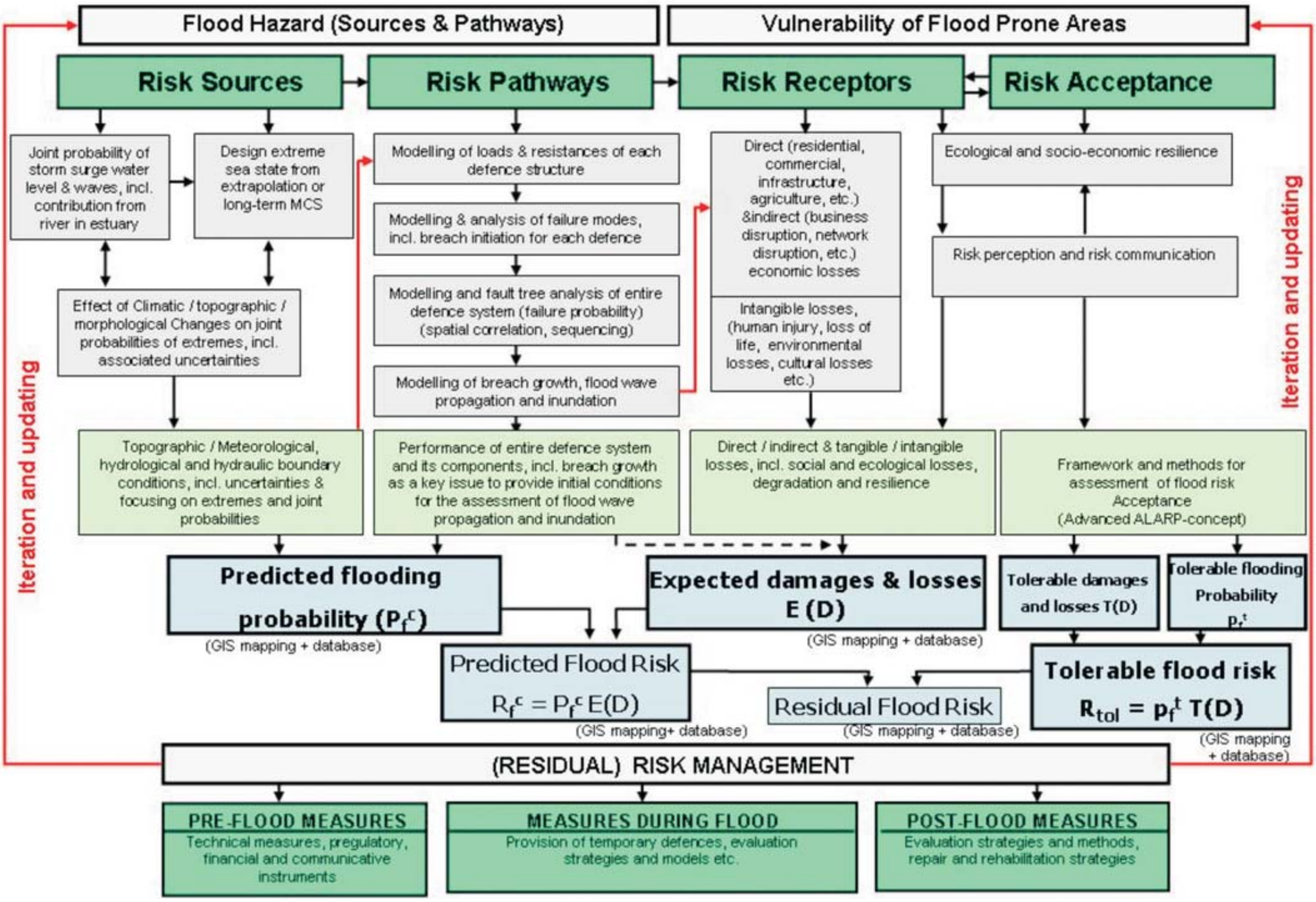


Fig. 2: Integrated PRA-based concept for the design of sustainable coastal flood defences

The practical implication of these four major steps require, however, a scientific knowledge, methodologies and modelling tools which are not yet sufficiently available and which therefore need to be developed. The research challenges associated with the risk sources, pathways, receptors and acceptance are discussed in Section 3 below.

3. Scientific, Modelling and Further Challenges

3.1 Challenges Associated with Risk Sources

The "risk sources" essentially provide the hydraulic boundary conditions which are required to assess the design loads and the probability of failure of the flood defence components. These are generally dependent on the prevailing tidal, meteorological and topographic conditions.

On coastlines with shallow shelf areas (e.g. North Sea) a combination of high tides storm surges, wind waves and mutual interactions generally represent the major sources of coastal flood risks:

$$\eta_{WL} = \overline{\eta}_{MSL} + \eta_{tide} + \eta_{surge} + \eta_{waves} + \eta_{topo} + \eta_{inter} \qquad (3.1)$$

The resulting water level (η_{WL}), which is temporarily and spatially variable, may be considered a resulting sea state.

The mean sea level component $\overline{\eta}_{MSL}$ essentially varies over long time periods as a result of climate changes (10–25 cm in past century) and is therefore subject to very large uncertainty. For a given climate change scenario the effect of changes in water depth due to MSL-rise on the tidal, surge and wave components can be quantified with some confidence for a well-defended (not morphologically very active) coast.

The astronomically generated tidal component η_{tide} is rather deterministic and much easier to quantify. The same applies for topographic effects on tides.

Much more difficult to determine is, however, the meteorologically induced surge component η_{surge} (BODE & HARDY, 1997). Although simultaneous computation of the tidal and surge components are now routine in present 2D and 3D baratropic storm surge models (SSM) which seem to hindcast water levels with acceptable accuracy, there is still a serious lack in the understanding/modelling of the processes involved in the interaction of the surge and wave components η_{waves}. In fact, the latter is still calculated separately (RESIO & CARDONE, 1999).

The wind wave and wind wave-induced component η_{waves} is calculated by high resolution wave models, including wave transformation over and by rather simple topographic features. Methods also exist to estimate the joint probability of wave heights and wave periods, but higher resolution models for wave transformation over a more complex topography, including the effects on the joint statistics of wave heights, periods and directions are urgently needed.

The contribution of the topography-induced effects η_{topo} to the resulting sea state η_{WL} is generally considered by means of models for the transformation of the tidal, surge and wind waves. Although morphological models are available to predict the topographic changes during storms, the susceptibility of sea bed and coastal features to progressive changes (e.g. migration of sand bank) and to sudden changes (e.g. breaching of barriers islands) is still not properly considered in the long-term simulations of sea state. Coupled surge, wind-wave and morphological models over a broad range of scales represent an ideal alternative for this purpose and are thus to be kept in perspective. Meanwhile, considerable improvements of the assessment of the extreme design sea state may be achieved through the joint run of existing models.

The contribution η_{inter} of the mutual interactions between the various components still remains the most unknown, despite the now routine linking of tidal and surge components in present operational storm surge models and despite the substantial progress in recent research on the physics of air-sea interactions and on the coupling of surge and wind-wave models. The coupling will certainly take a long way to be implemented in operational prediction models. Meanwhile, rather pragmatic approaches for the assessment of the joint probability of extreme water levels and waves for coastal engineering design emerged (HAWKES et al, 2002; DE VALK et al, 2001). These approaches certainly represent an important step toward the practical implementation of the PRA-design concept in Fig. 2, although much more remains to be done. In further research focus should rather be put on those approaches in which the critical step of extrapolation of the multivariate input data to extreme values is undertaken at the earliest and prior to any transformation, i.e. at the level of the offshore or regional climate. This is in fact more generic than extrapolation at the level of local nearshore climate or structure variables. In fact, the extrapolations offshore can be used for any type of sea defences at any location and for any structure function. This is also potentially more accurate as structure variables and nearshore climate are subject to much mort constraints which may result in anomalies in the tails of the distribution function. In contrast, tails of offshore climate are generally smoother and easier to extrapolate. Substantial improvement of the predicted extremes is achieved through Monte Carlo simulations of large samples of wave height, wave period and water level, using fitted distribution and by incorporating additional non-simultaneous data (HAWKES et al, 2002).

Within the particular context of such joint probability approaches the greatest research challenges are directed towards the following aspects:

1) Assessment of the uncertainties associated with transformation of the multivariate distributions functions through a sequence of models up to the failure probability function, including their explicit incorporation in the latter. This is particularly important, because it is much more difficult than transforming data.
2) Physical justification of the extrapolation of the fitted distribution to high extremes.
3) Introduction of the time factor, including the temporal dependence between successive variables and their time dependence. This is particularly important for failure tree analysis as well as for many failure modes which depend on the entire load history during a storm or which are caused by stepwise deterioration (e.g. dune regression, dike breaching).

Within the context of Eq. (3.1) the greatest challenge is to overcome the difficulties toward a complete understanding and modelling of all components, possibly also including contributions from other sources (e.g, from river discharges). These difficulties essentially arise from the very large differences in scales of the temporal (and spatial) variability associated with the formative components, of which the last two in Eq. (3.1) are present over a very broad range of scales (up to millennia). Particular challenges worth to be mentioned are:

1) Investigation of the effect of the increasingly high non-stationarity of the climate signals suggesting that the assumption is no longer defensible and that long-term changes in the distribution models are very likely even for time scales in the decadal range. This is particularly crucial for very vulnerable flood-prone areas where design return period of 103–104 years and design life time of 100 years are not uncommon.

   While sensitivity studies might indeed provide a first useful insight into the effect of climate changes on the extreme distributions, the systematic deviation from the fitted distribution, suggesting further population in the extreme distributions, can only be quantified through long hindcast simulation and a joint run of storm surge models, wave models and morphological models forced by (a) routine meteorological and other data which will provide the "natural" variability and (b) data including the results from a high resolution regional climate model which will provide the effects of climate changes. First attempts in this direction recently started to emerge, but without any consideration of the morphological changes. The effect on the tidal range was found negligibly small (FLATHER & WILLIAMS, 2000). The runs with the climate effect on extreme wind and extreme surge level estimates from observational records were found to dramatically deviate from the fitted distribution (VAN DEN BRINK et al, 2003; VAN DEN BRINK et al, 2004).
2) Improvement of the physical understanding of the relative contributions of the components in Eq. (3.1) and the underlying formative factors, including the range of their variability, their limits compatible with the physical laws and within the context of the geophysical and anthropogenic processes. Rather than mainly focusing on more sophisticated distribution models which will doubtfully be useful, this should have the highest research priority, because the results will build the basis for a physically sound combinatorial approach. The latter will enable the extreme joint probabilities to be obtained from the simulation of a large number of physically possible and unusual combinations of the constitutive factors and components compatible with the geophysical and anthropogenic context rather than

only from curve fitting and extrapolation without any explicit and complete account of the physical causes of observed records and of the possible changes of the climatic, morphological and other conditions circumscribing the potential of extreme sea states. It is in fact rather surprising that extrapolations to 103, 104 and even 105 years events determined in this manner are still accepted – even in regulatory documents – although it is widely known that decisions based on wrong numbers resulting from sophisticated mathematical analyses (extreme value theory and multivariate analysis) represent themselves an additional hazard which may substantially contribute to increase the flood damages and losses.

3.2 Challenges Associated with Risk Pathways

The main goal of the risk pathways is to predict flooding probability EMBED Equation. DSMT4 P_f^c which results from the failure of one or more components of the entire defence system (Fig. 2). This will particularly require reliable methods and models to predict:

1) the loading and resistance parameters of the defence components
2) the associated failures, including their interdependence and contribution to the initiation of the top failure event (e.g. breaching, flooding)
3) the breach growth, the subsequent flood propagation and the damaging effects
4) the overall performance (failure probability) of the flood defence system which may become very complicated, depending on the number, configuration and degree of interdependence of the defence components.

Among the R & D challenges associated with these four issues the following are worth to be mentioned.

3.2.1 Wave Overtopping, Breach Initiation and Growth from Landward Side

Except in the case of particular (moveable) defence structures such as storm surge barriers where flood may occur as a result of malfunctions due to human and organisation errors (Oumeraci et al., 2001) disastrous floods generally result from the breaching of flood defences. Keeping in mind that most sea dike breaches in the past (e.g. storm surge of 1953 in The Netherlands and 1962 in Germany) were initiated from the landward side by wave overtopping (Schüttrumpf & Oumeraci, 2004a) the highest research priority with respect to wave loading should be directed towards a proper modelling of wave overtopping, possibly in combination with overflow (Oumeraci et al, 1999).

The available empirical/analytical wave overtopping formulae (e.g. Schüttrumpf & Oumeraci, 2004b) and numerical models (e.g. Hubbard & Dodd, 2002) are restricted to a 2D-situation, including a number of further limitations which make their application in limit state equations for the failure modes associated with breach initiation questionable. Fig. 3 illustrates the 3D-structure of the overtopping flow with a complex tongue shape. Not only the 3D-modelling of such a single overtopping event is required (Fig. 3), but also the sequencing and distribution of the overtopping tongues along the defence (Fig. 4). For the inception of the erosion on the rear slope (Fig. 6a) it is also important to know, whether the overtopping tongue falls on a water free slope or on the water layer of the previous overtopping tongue (Fig. 4). Moreover, the effect of the incipient erosion on the crest and rear slope on the overtopping flow distribution may also become significant (Fig. 5). In this case, the

Fig. 3: Three-dimensional structure of overtopping flow

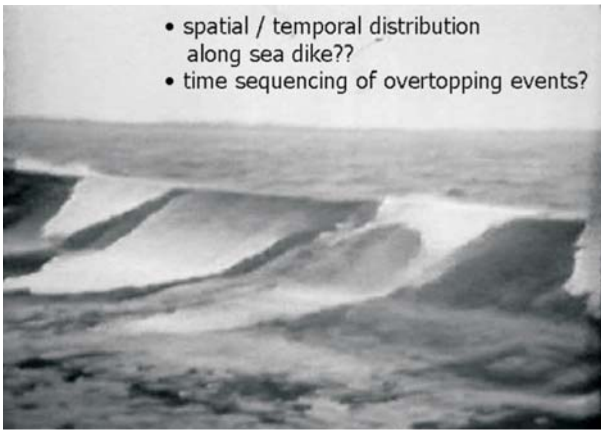


Fig. 4: Distribution of wave overtopping flow along a sea dike

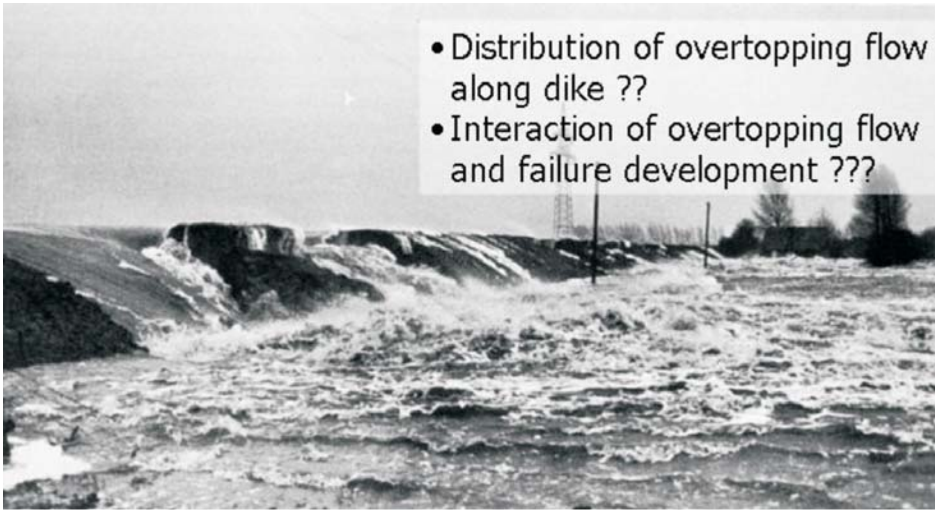


Fig. 5: Wave overtopping and erosion along an estuary dike

interaction between the flow and the development of the erosion should also be modelled, if a reliable prediction of breach initiation has to be achieved.

Furthermore, the prediction of breach development induced by wave overtopping still represents an unsolved problem, although the initial conditions at the defence line constitute one of the greatest uncertainties in flood propagation models and thus in the assessment of the warning time and the damaging effects.

The large experience available in dam engineering with dam-break flood wave models (Morris & Hassan, 2002) cannot be simply extrapolated to coastal flood defences, due to several reasons such as (i) the initial conditions of the flood wave which interacts with the breach growth, (ii) the limited breach width along the defence line and (iii) the 3D-character of the flood wave in a coastal plain. Therefore, substantially new knowledge towards the physical understanding and proper modelling of the breaching process must be generated before embarking into the detailed modelling of flood propagation and its damaging effects on typical obstacles in the protected areas.

Due to the very strong interaction between the expected extreme hydrodynamic conditions (high water levels, strong currents and high storm waves) and soil strength parameters (large Shield's parameter, variable shear strength, etc.) associated with very high erosion and transport rate during the breaching process, serious scale effects would be expected, if common small-scale models are used. On the other hand, it will not be possible to achieve the required understanding of the physical processes by using only field experiments for which the control of the forcing functions (water levels, currents and waves) and the boundary conditions cannot be controlled. Therefore, hydraulic model tests at almost full-scale in a large wave facility remains the sole alternative. Based on the experimental results, generic models of the development of the breach initiated by wave overtopping (Fig. 6c,d) must be developed from a structural and hydro-geotechnical engineering perspective for a class of typical flood defences, including homogenous and non-homogeneous earth structures.

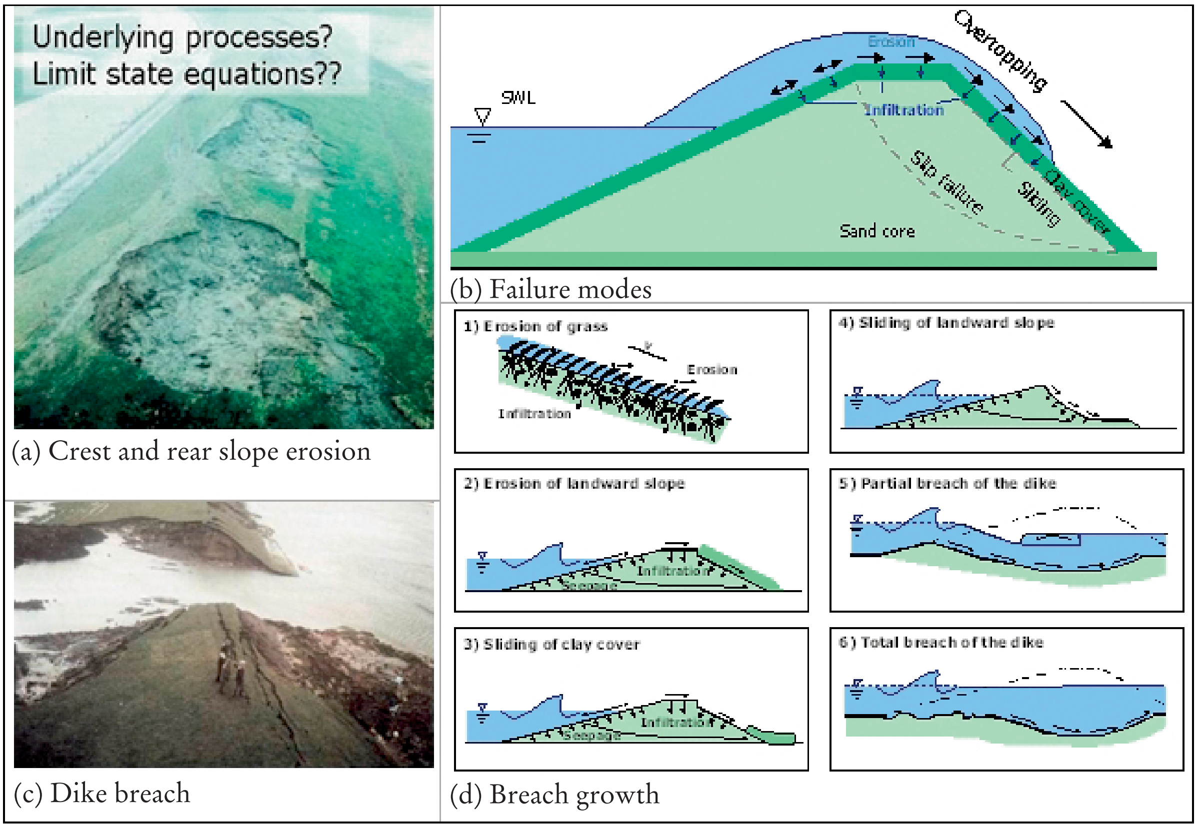
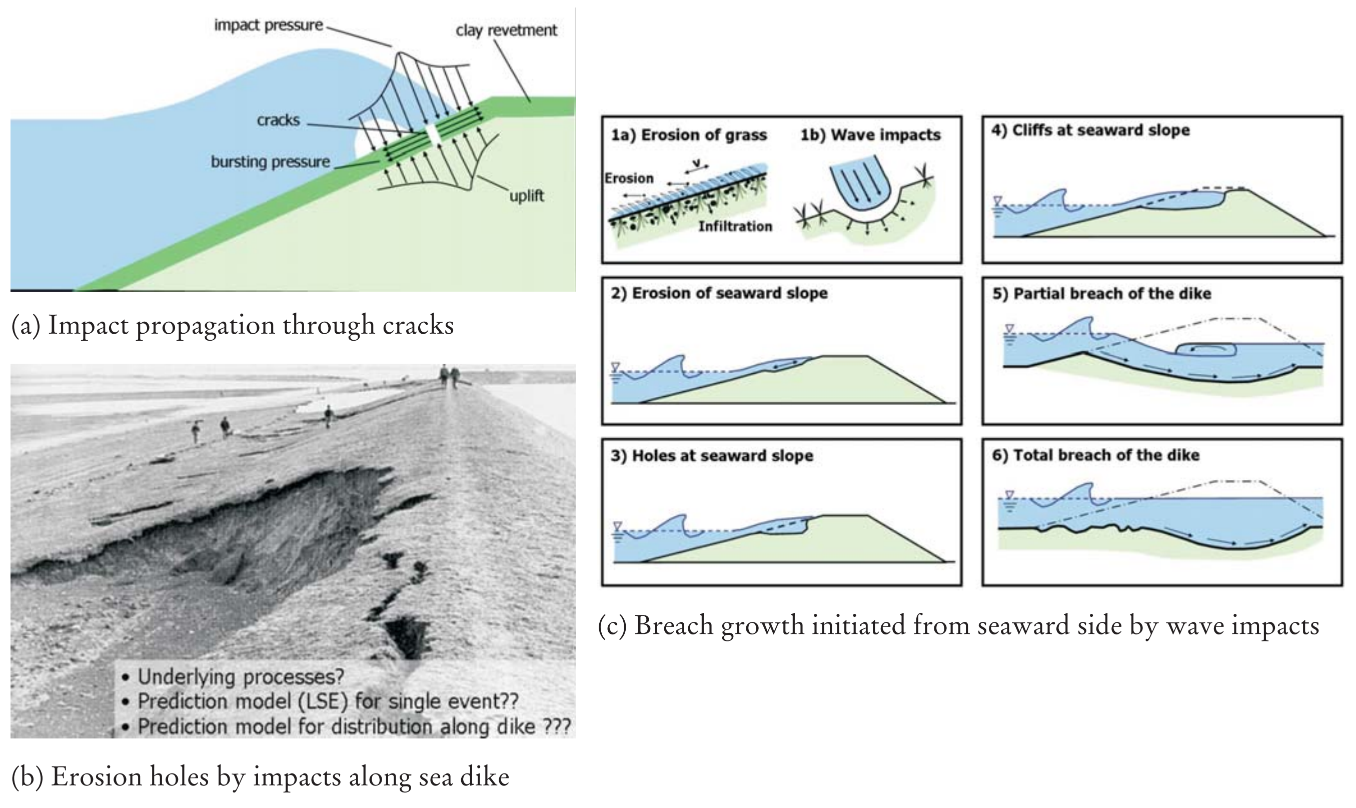


Fig. 6: Development of breach initiated from landward side by wave overtopping

3.2.2 Wave Impact, Breach Initiation and Growth from Seaward Side

A breach may also be initiated from the seaward side by various mechanisms, depending on the type of slope revetment. For most of the revetments and particularly for clay-covers of sea dikes as widely used in The Netherlands, Germany, Denmark, etc., the most common failure mode consists in erosion holes induced by breaching wave impacts along the dike (Fig. 7a,b).

It is therefore needed to develop a better understanding of the propagation of the impact pressure through cracks/voids (Fig. 7a) in the revetment into the dike core (Bruce et al,



(a) Impact propagation through cracks

(b) Erosion holes by impacts along sea dike

(c) Breach growth initiated from seaward side by wave impacts

Fig. 7: Erosion holes induced by wave impacts along a sea dike

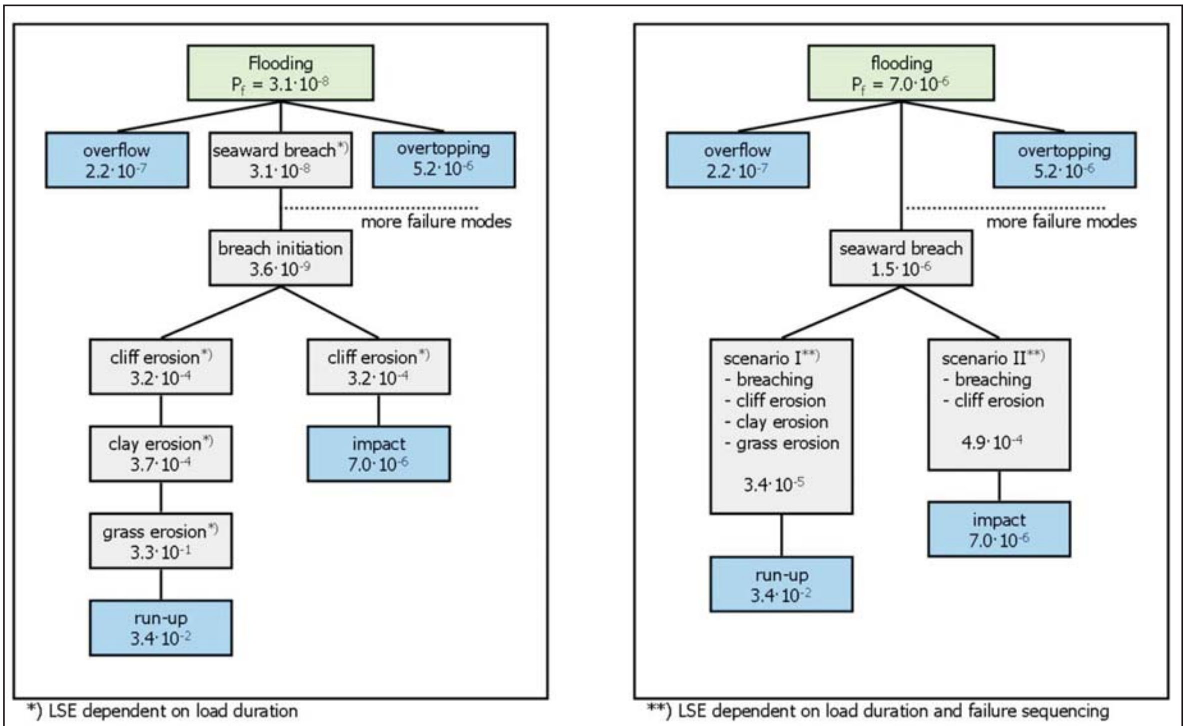
2000) and of the mechanisms by which the revetment is "blown out" by the pressure pulses. Generic limit state equations can then be developed for these failure mechanisms and a set of typical defences and revetments. There is also a crucial need to develop a prediction model for the distribution of the holes along the defence and to understand under which conditions theses holes may lead to breach initiation (Fig. 7b in the back). Since the breach will develop differently from the case shown in Fig. 6d, generic models are required for the development of the breach induced from the seaward side by wave impacts for a class of typical flood defences and revetments (Fig. 7c).

3.2.3 Advanced Fault Tree Analysis

Conventional fault trees describe the occurrence probability of a specific failure mode (top event) and all the ways in which that top event can be reached; i.e. the relative contributions of prior failure modes to the probability of the top event. Particularly for the cases where the load and resistance parameters are time dependent, the time duration of the failure mechanisms as well as their time sequencing and actual links which are not taken into account by conventional failure tree analysis may be crucial for the outcome. Kortenhaus (2003) performed a fault tree analysis, including 25 failure modes of a sea dike with flooding as a top event, by comparatively applying a conventional approach and a so-called "scenario approach". In the latter, time sequencing of the time dependent failure modes is achieved by building "scenario blocks" in the fault tree. A "scenario block" consists of a combination of those non-discrete failure modes which strongly depends on the time duration and on each other (e.g. progressive erosion and breach initiation). As expected the annual probability of the top event obtained by an improved fault tree including "scenario blocks" was more than two orders of magnitude higher than that obtained from a conventional fault tree (Kortenhaus, 2003). A more recent case study for a North Sea dike performed by Kortenhaus (2004) has shown that the difference between the two approaches may indeed reach two orders of magnitude with respect to the probability of the top event or even three orders of magnitude with respect to the probability of the failure immediately following the "scenario blocks" (see simplified fault trees in Fig. 8).

Moreover, fault trees must also include the key failure modes which are not or hardly amenable to common limit state equations (e.g. failures of moveable barriers due to human and organisation errors). "Quantification" of the failure probability by elicitation of expert opinions or/and simulations may considerably improve confidence (COOKE, 1991; OUMERACI et al., 2001).

To further reduce the drawbacks of conventional fault tree analysis which is time consuming and rather subjective as the outcome is strongly dependent on the expertise and skills of the analyst, innovative methodologies and techniques are urgently needed. These should particularly help moving this conventional analysis from an art to science, from a fragile and very sensitive tool to a more robust and widely affordable approach for practitioners. Complementarily the research should also be directed towards examining the feasibility of integrated system dynamic models and GIS-approaches to obtain a modelling framework capable of coping with space and time dependent processes (see Section 3.2.4 below).



a) Conventional fault tree analysis

b) Fault tree analysis with "scenario" approach

Fig. 8: Fault tree analysis: conventional vs. "scenario" approach

3.2.4 Failure Probability of Entire Defence Line and Phased Defence Systems

In practice, a flood defence rarely consists of a single or homogenous structure over its entire length. Generic methodologies and techniques are still lacking for the definition of "homogenous" segments of the defence line with respect to the load and resistance parameters as well as for the specification of the degree of interdependence of adjacent segments with respect to various mechanisms (structural support offered to adjacent segments, simultaneous hydraulic load effects, flood propagation, etc.). The same holds true for the modelling of the performance (probability of failure) of the entire defence line. The occurrence of a breach along a certain defence segment may be stochastically independent, but the breach along the nearby segment may strongly depend on the breach which occurred along the adjacent segment (Fig. 9).

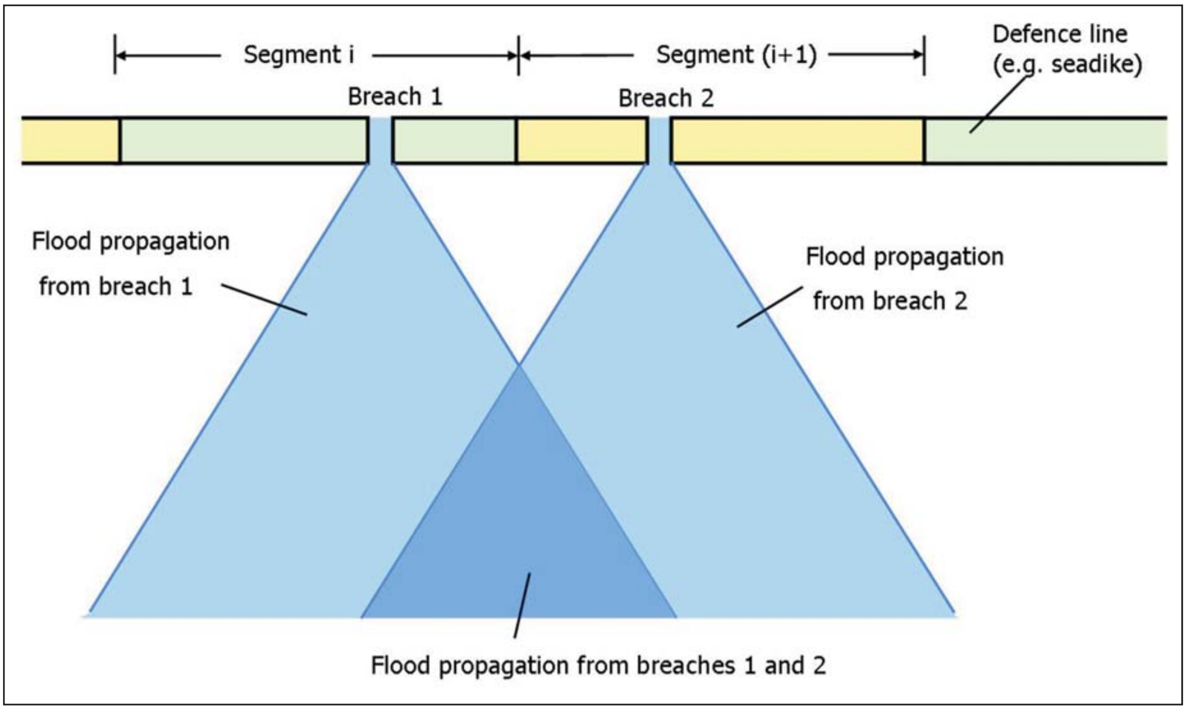


Fig. 9: Distribution of breaches along a defence line

Moreover, the time sequencing of both breaches will have a significant effect on the flood propagation and thus on the subsequent damages in the protected area. Therefore, the prediction of the defence performance must be conducted in close connection with the risk receptor analysis (Fig. 11).

Beside the "segmentation" and the modelling of the performance of the entire defence line, specification of the degree of a phased defence system and modelling of the performance of the entire defence system represent a further and much greater research challenge. Examples of such coastal flood systems as commonly applied in Germany are given in Fig. 10, showing for instance that the performance of the main defence line strongly depends on the high foreshore or dune fronting it.

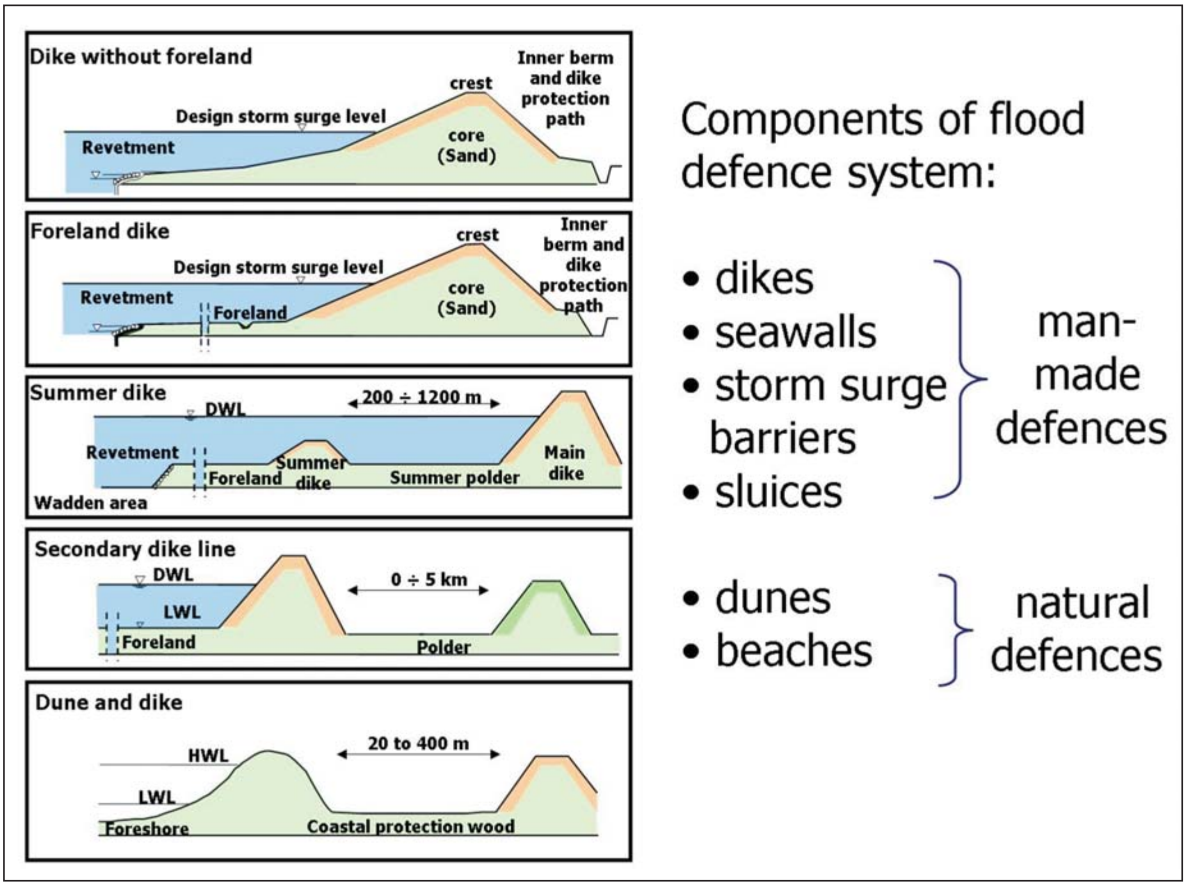


Fig. 10: Example of coastal flood defence systems in Germany (North Sea and Baltic Sea)

The degree of spatial correlation between the defence components will also depend upon the respective along and across shore distance between the components and how they are tied to each other in plan view (links, bonds, etc.). Therefore, due consideration of both cross sectional and along shore (plan view) representations of the defence components is required to formulate appropriate correlation functions. Keeping in mind the research challenges associated with advanced fault trees mentioned in Section 3.2.3, the simplified flow chart in Fig. 11 is tentatively suggested to illustrate the degree of complexity and the range of difficulties of the problems associated with the prediction of the performance of entire and complex defence systems. These difficulties are also well illustrated by a case study (BUIJS et al, 2003) which represents one of the first serious attempts in this direction. That and further case studies show that the performance of an entire defence system is too complex to be addressed by conventional approaches and modelling. Therefore, an appropriate modelling framework is needed which is capable to cope with the complex failure mechanisms in time and space, including all interactions between the component of the defence system and integrating the expected damages directly caused by flood propagation. Such a framework might be obtained by coupling system dynamic models to cope with the time dependent processes and GIS-based approaches to cope with spatial modelling. Cellular automata have also been suggested, but they are appropriate for discrete event simulations rather than for continuous time simulations.

Such a modelling framework will also enable to simulate the performance of the entire defence system over the intended design life time and thus to account explicitly for the long-term change of the failure probabilities which would necessarily result from the long-term changes of the load and resistance parameters. This issue is particularly crucial for probability discounting as optimisation can only be achieved by considering life-cycle costs.

3.3 Challenges Associated with Risk Receptors

The prime objective of the risk receptor analysis is to predict the expected damages and losses which will result form the predicted flood event (Fig. 2) This will require a consistent methodology with the necessary models and predictive/analytical tools for the vulnerability at multiple levels of the receptors, including the resilience of the ecological and social systems. Among the variety of candidate research issues the following research and modelling challenges may be mentioned: (i) physics of direct damages caused by flood propagation, (ii) loss of life and human injuries, (iii) environmental and cultural damages induced by inundation, (iv) integration of all expected flood losses.

3.3.1 Physics of Direct Damages Caused by Flood Propagation

The research efforts should primarily be directed towards modelling the interaction between breach growth and flood propagation from one or more breaches (Fig. 9), but also towards the damaging effects of the flood wave on a variety of a set of typical obstacles and topographic features, including scour, erosion, sedimentation and infiltration. As a result, a set of high resolution models (including modelling of turbulence and fluid-sediment-structure interactions) for the prediction of direct physical damages should be obtained.

3.3.2 Loss of Life and Human Injuries

Besides the socio-economic and ecological importance of the flood-prone area, the safety of flood defences primarily depends on the number of people at risk. Among the so-called intangible losses, human injuries and loss of life are, however, the most difficult to predict and to valuate.

The difficulties associated with the prediction essentially arise from the fact that the probability of drowning/injuries is not only a function of the flood propagation and inundation characteristics (depth, discharge, rising rate, etc.) but also of the warning, evacuation and further risk reducing measures. Therefore, appropriate models are urgently needed for the prediction of loss of life and human injuries by simulating the hydraulic conditions of the flood together with the associated risk reduction measures, including the explicit account for all other influencing factors such as reaction time, infrastructure capacity, traffic management, etc. A first step in this direction has been undertaken by Jonkman et al. (2003). The lack of appropriate data for validation will, however, constitute a crucial bottleneck. In fact, the international flood disaster database (www.cred.be) is not appropriate for the detailed assessment of loss of life given certain flood and risk management circumstances. Although the valuation of human life is questionable from the ethical view point, the problem is often formulated in terms of the amount society is willing to pay for saving life. Values between 1 to 10 million US$, depending on considerations associated with aversion of risk, have been reported.

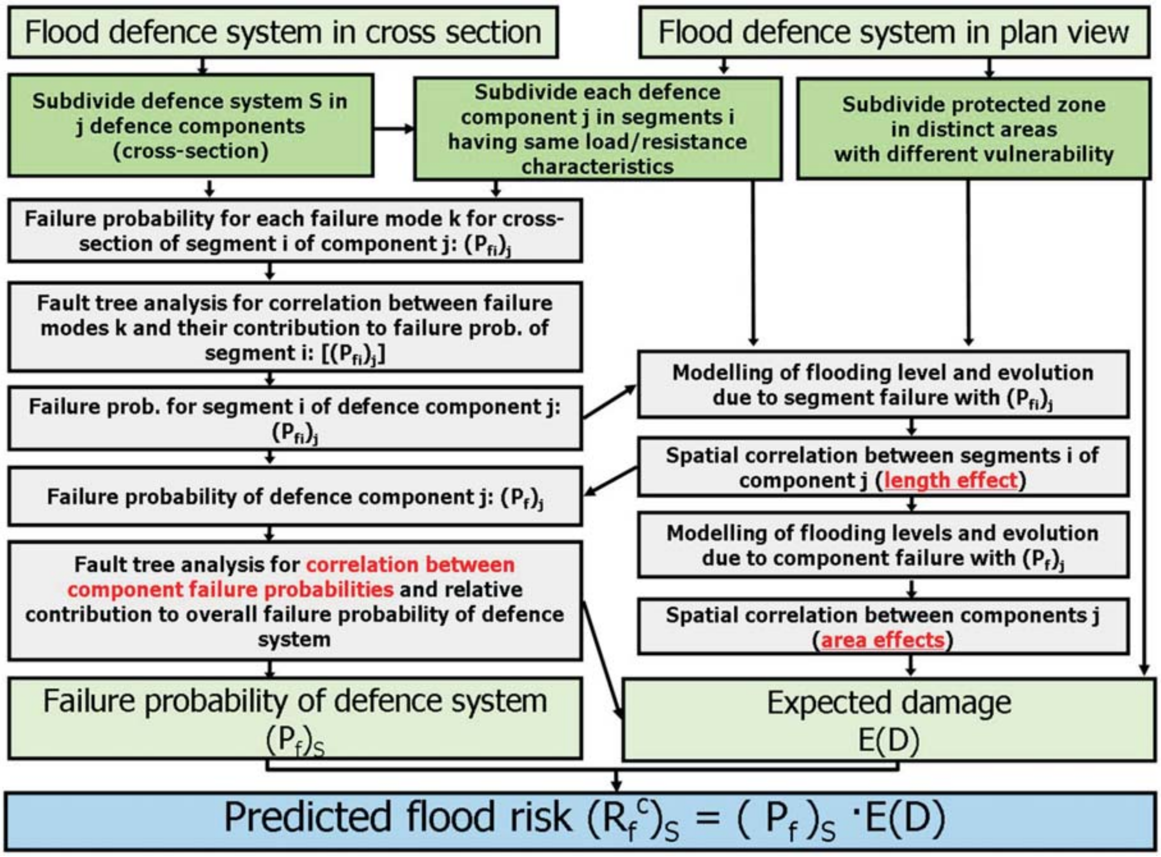


Fig. 11: Performance of entire flood system and integration methodology for flood risk prediction

Various methods to predict and to valuate intangible losses are available in the literature. A systematic review and analysis will help to derive the approaches which are most appropriate for coastal flood and the need for improvement/new development.

3.3.3 Environmental and Cultural Damages Induced by Inundation

Quantitative assessment of the damages caused by flood propagation and inundation in terms of degradation of natural resources such as ground/ground water contamination, loss of ecosystem integrity and functioning (including ecosystem services and goods such as organic matter production, nutrient cycling, physical structuring, biodiversity and loss of visual amenity). A key research challenge is the development of reliable methodologies/tools to assess the degree of degradation and the resilience of the damaged ecosystem. The damage to historic buildings and further cultural goods may also represent a substantial part of the flood damages and must therefore also be assessed.

3.3.4 Integration of Expected Flood Losses

To quantify and integrate the expected flood losses from various sources, new methodologies/techniques must be developed which are widely accepted by decision-makers, politicians and public at large. Tangible direct/indirect economic losses are generally tractable with common CBA-techniques. The key challenges are rather the methods (i) to evaluate the so-called intangible losses such as human injuries, loss of life, environmental and cultural losses, social and psychological impacts and (ii) to integrate these with the more tangible economic losses in order to get a complete overall picture of the vulnerability which is then fully quantified on a sound and transparent basis. In fact, previous experience has shown that common CBA-techniques supplemented by Utility Analysis and Life Quality Methods are often not very appropriate.

3.4 Challenges Associated with Risk Acceptance

The prime goal of the risk acceptance analysis is to assess the acceptable flood risk which may be considered as target flood risk R^t_f. This target risk and its comparison with the predicted flood risk R^c_f are required to develop an appropriate measure of the residual flood risk (Oumeraci, 2001), which can be used for design, safety assessment and decision-making on the most appropriate risk reduction measures. Due to the socio-cultural, legal, political and socio-economic dimensions of the issue, the assessment of acceptable flood risk certainly represents one of the most complex, most difficult and most important steps in any risk-based design and safety assessment. Therefore, this problem can only be solved within a coherent, transparent, adaptive and widely accepted framework for tolerable flood risk assessment. A good starting point for the development of such a framework is the so-called ALARP-concept (As Low As Reasonably Practicable) which is widely accepted across many disciplines (Fig. 12).

The key research challenges will be (Figs. 12 & 13):

1) *to define the lower and upper bound of the ALARP-zone for flood risks*. To achieve a wide consensus in accordance with the acceptable risks in other sectors (e.g. dam engineering, offshore engineering, nuclear power plants, transportation, etc.) it is indispensable that the prospective assessment methodologies and modelling tools are robust, coherent and transparent, enabling a comparison with the risk tolerated in other sectors. For this purpose, it would be useful to assess the acceptable probability of the flood hazard P^t_f and the acceptable vulnerability T(D) separately. This might also be important from the legal point of view. In fact, from the human rights perspective the responsible authorities have to reduce the vulnerability to an acceptable level, but not necessarily the flood risk.
2) *to explicitly account for risk aversion*. Weight factors have often been suggested, but more consistent methods are required to account for differences in acceptance/penalisation of certain risks as compared to others and to help achieving a better consensus on acceptable risks across many sectors and disciplines.
3) *to explicitly account for uncertainties in both components of the acceptable flood risk*. This is particularly important for high risks near the upper bound of the ALARP-zone where large uncertainties might shift the assessed acceptable risk outside the ALARP-zone (Fig. 12 right)

A tentative generic flow diagram which may also be used for the assessment of acceptable flood risks is roughly outlined in Fig. 13 to show that for the various steps, use can be made of techniques/tools already available in Cost Benefit Analysis (CBA), Reliability and Multi-Criteria Decision Theory, but also to point out that a number of further improvements and new developments are still needed.

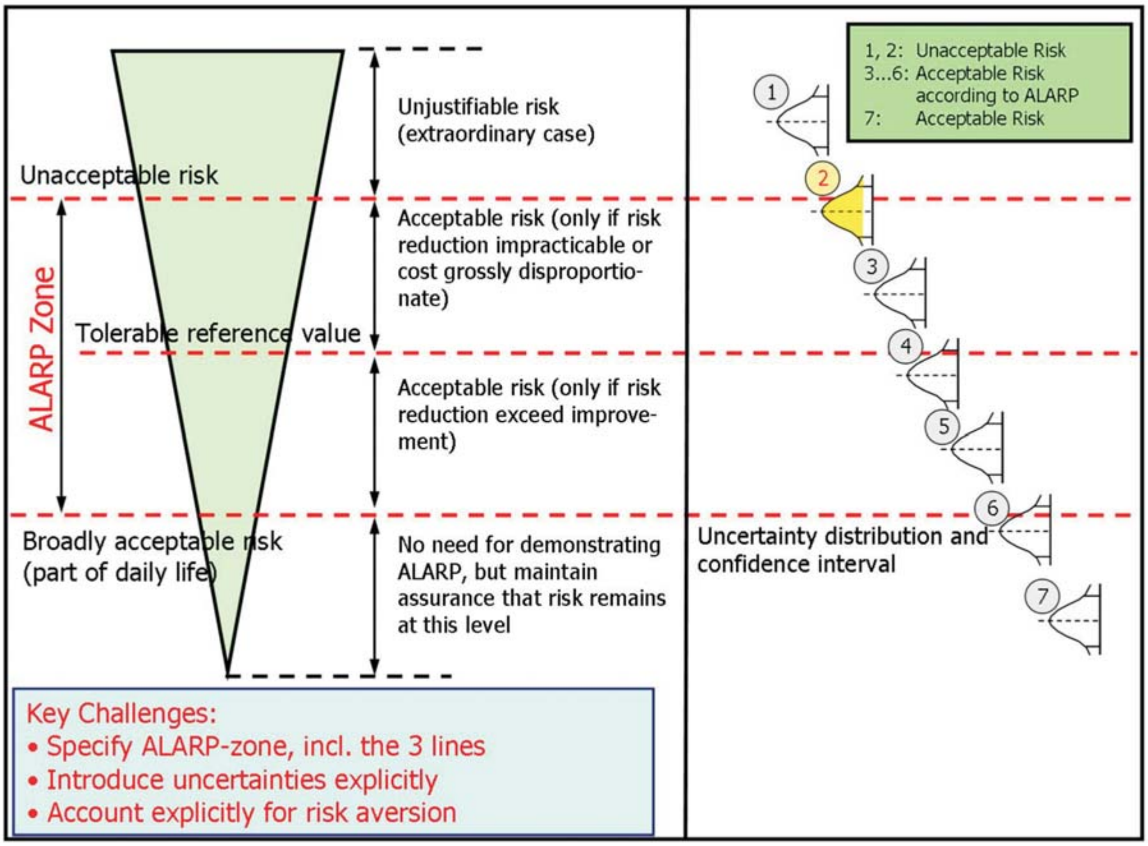


Fig. 12: Key challenge towards an advanced ALARP-concept for acceptable flood risk assessment

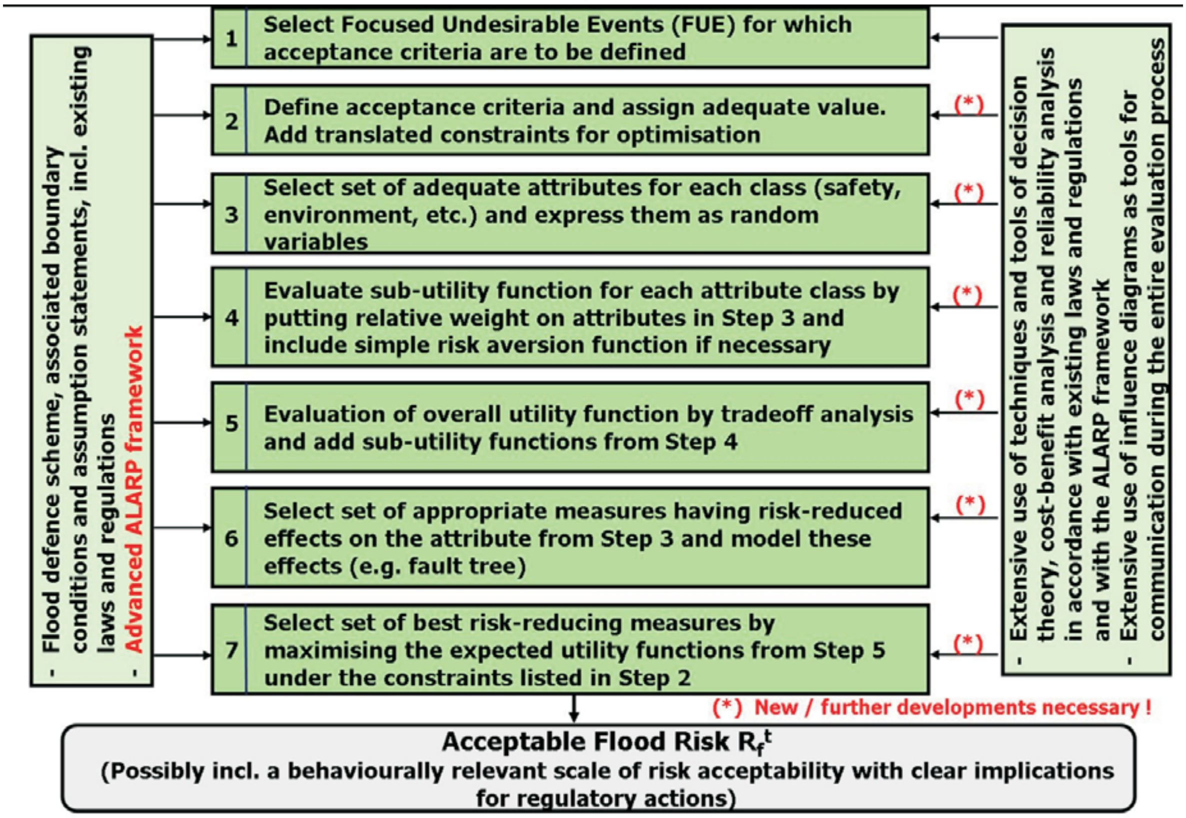


Fig. 13: Tentative flow diagram for a framework of acceptable flood risk assessment

4. Concluding Remarks

Keeping in mind that one of the key features of the proposed PRA-based design framework is the focus on the improved understanding/modelling of the underlying processes which may lead to disastrous floods (e.g. joint probabilities of risk sources, breach initiation, breach growth, subsequent flood propagation and damages), including the explicit account of all uncertainties at every design stages, the following key research challenges may be stressed:

1) To overcome the major problems encountered in *risk source prediction* (Fig. 14), a consistent modelling strategy with proper models and uncertainty analyses is required to predict the effects of climate/geophysical/morphological interdecadal changes on the joint probability distributions of storm surge water levels and waves, including joint design extremes. For the long-term, coupling of improved climate/storm surge/wind waves/morphological models must be kept in perspective. Meanwhile, substantial improvements might be achieved by the joint run of these models in their available or improved versions. This will at least provide the physical insight needed for instance to justify/improve the extrapolation to high extremes.
2) Most of the problems associated with *risk pathway analysis* are due to the lack of consistent modelling strategies, proper models and integration methodologies. With respect to the loading issue, the modelling of wave overtopping and wave impact, including their temporal/special distribution along the defence lines represents the greatest challenge. A further challenge is the modelling of the interactions between the various failure modes

Description		Typical values (years)
➢ Design life time of coastal flood defences	(t_{life})	100
➢ Length of observed/hindcasted records	(t_{obs})	10 - 100
➢ Design return period	(t_{RP})	100 – 10.000 (exceptionally: 100.000)
➢ Extrapolation beyond t_{obs}	(t_{extr})	$(10 - 1000) \times t_{obs}$

⇩

Major Problems in Practice

- ➢ Extrapolation of fitted distributions to extremes still lacks physical support, i.e.:
  - without explicit and complete account for physical causes, underlying processes and overall context which have led to the observational records used for fitting the distributions
  - without any account of anthropogenic climate changes and their effects on storminess and morphological changes in coasts, rivers and estuaries
- ➢ Extrapolation to 10^3, 10^4 and even 10^5 years events are even accepted in regulatory documents, although
  - associated extreme values may be completely wrong
  - decisions based on wrong numbers presented as good estimates from sophisticated analysis (extreme value theory, multivariate analysis) represent an additional hazard which may substantially increase the flood risk, particularly when no provision is made of associated uncertainty range

Fig. 14: Practical problems associated with risk source prediction

and of all the ways leading to breach initiation from both landward and seaward side by wave overtopping and wave impact, respectively. Generic models for the prediction of breaches, their growth and their temporal/spatial distribution along the defence components, including the effect of breach growth on flood propagation for a set of typical defence components and systems. Advanced fault trees or other alternative tools will be needed to account for the time duration, the time sequencing and the actual links of the failure mechanisms within each defence component and within more complex defence systems.

3) Most difficulties encountered in the *vulnerability analysis and risk acceptance assessment* primarily arise from the high degree of complexity and multi-disciplinarity of the various processes/issues involved. Therefore, research should be oriented towards developing consistent methods and models to predict and valuate the intangible flood losses, more coherent methodologies to integrate tangible and intangible losses, direct and indirect costs, but also a robust and transparent framework with the required modelling and analysis tools for the assessment of acceptable flood risks.

Besides all these challenges which are primarily associated with modelling and integration methodologies the greatest challenge will be to simplify as much as reasonably practicable (e.g. without loosing any important issue!), so that the prospective design and safety assessment approach will be comprehensible and affordable by practitioners and further prospective end users. Many of these challenges are expected to be met within the next five years by the recently initiated EU-Integrated Project "FLOODsite" on river, flash and coastal/estuarine flood management (SAMUELS et al, 2004), including 36 leading institutions from 13 EU-countries (www.floodsite.net). This synergetic transnational partnership and collaboration will substantially contribute to forge the transition to a more integrated design and safety assessment of flood defences, which includes risk management as an integral part of the design process and which is based on an interdisciplinary sound ground to meet the sustainability requirements.

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