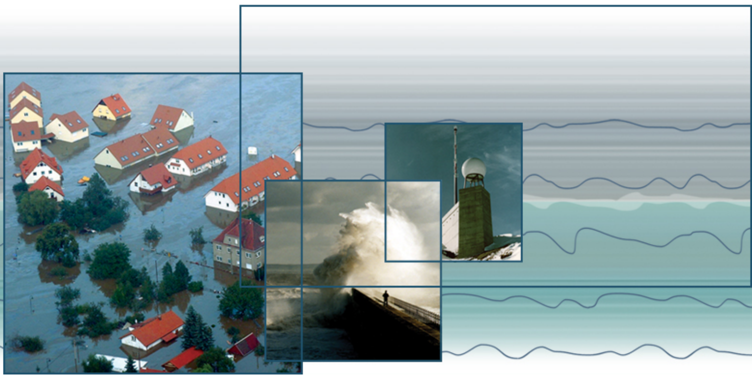
Integrated Flood Risk Analysis
and Management Methodologies



Methodologies for Integrated Flood Risk Management

RESEARCH ADVANCES AT EUROPEAN PILOT SITES

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0. Introduction

Floods are one of the most disastrous natural hazards in Europe. This is not only true for a historical perspective on European rivers, coasts and estuaries, but receives increasing evidence in the presence. Alone in the time period between 1998 and 2002 about 100 major damaging floods caused some 700 fatalities, the displacement of about half a million people and at least € 25 billion in insured economic losses (EEA, 2004). The real damage could be many times higher. During the 2005 European summer floods in Romania, the Alpine Region in Central Europe and other Eastern European countries 62 persons lost their lives. And, beyond these major disasters, numerous local events occurred as damaging flash floods or pluvial floods.

The risk of future flooding even exceeds the numbers of previous events if maximum probable losses are considered. For example, the potential damage along the River Rhine is calculated at € 165 billion (Day, 2006). And the total values of economic assets located within 500 metres of the European coastline is estimated at € 500 to 1,000 billion. The situation is supposed to worsen because of the ongoing climate and societal change. This may lead to an intensification of the flood hazards as well as to an increase of the vulnerability.

Against this background the management of flood risks reaches growing attention in science and policy on European, national, regional and local levels. In contrast to the previous paradigm of flood protection which focuses on the defence against floods and appeared to be unachievable and unaffordable, the paradigm of risk management is dedicated towards the reduction of risk to a tolerable and sustainable level. Basic ideas of this approach were developed during the International Decade of Natural Disaster Reduction (IDNDR) from 1990 to 1999 (UNDRO, 1991; Plate, 1999). They are now broadly considered in European and national research programmes and in legal regulations in a kind of transition process.

Under the European Flood Action Programme (EC, 2004) the European Commission combined activities to enhance knowledge and methodological skills for the scientific-based risk management on the one hand and to prepare a legal instrument for a common approach of societal flood risk management in the Member States on the other hand. The former initiated research efforts under the 6th Framework Programme. The latter led to the implementation of the European Directive 2007/60/EC on the assessment and management of flood risks (Floods Directive) which entered into force on 26 November 2007.

As one key research action the project “Integrated Flood Risk Analysis and Management Methodologies” (FLOODsite) was funded to comprehensively study the issue of flooding and associated risks and to develop and test innovative approaches to support flood risk management under real-world conditions. The thematic areas range from the understanding and statistical appraising of weather and marine extremes that generate flood hazards over the vulnerability analysis for all areas of sustainability to risk reduction measures and instruments with their inclusion in management strategies. The project involved about 200 scientists from 13 countries and has been the largest study on the topic in Europe ever since.

To ensure a principle applicability of the integrated methodologies, their development and testing has been carried out in a number of European pilot sites which reflect typical flood problems at mountainous and lowland rivers, estuaries and coasts. The following sites have been chosen:

- Pilot site “Elbe River basin”
- Pilot site “Tisza River basin”
- Pilot site “European flash flood watersheds”
- Pilot site “Thames River estuary”
- Pilot site “Scheldt River estuary”
- Pilot site “Ebro River delta coast”
- Pilot site “German Bight coast”

Research at the sites includes existing scientific knowledge and regional experience to make a significant step forward towards integrated flood risk management with its emergent tasks. This for example means that existing hydrodynamic models have been used to investigate the risks for additional social and ecological receptors. Moreover active links to ongoing projects were established. The envisaged final applicability of the new methodologies and techniques is ensured due to a close collaboration with experts from flood risk management practice.

The book provides an overview of major outcomes from developing and testing the integrated methodologies under the respective natural and societal conditions of the pilot sites. It shows both scientific advances in relevant disciplinary and interdisciplinary fields as well as their relevance for flood risk management practice. The site-specific approaches are complemented by an indicative cross-pilot consideration to facilitate the identification of common advances and lessons learnt. Due to the limited number of cases the book is meant to offer good examples instead of a general guidance.

Although the Floods Directive was negotiated in parallel to the course of the FLOODsite project, the research addressed many issues constitutive for the implementation of its legal requirements. This holds true for the preliminary flood risk assessment (chapter II of the directive), the preparation of flood hazard and flood risk maps (chapter III), and the elaboration of flood risk management plans (chapter IV). Maybe the available methods and data from the pilot sites together with the fruitful networks between scientist and experts from flood risk management practice, which both evolved during the project, may be used as a core for an exemplary implementation of the directive.

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1. Flood risk management – basic understanding and integrated methodologies

Jochen Schanze

1.1 Framework of flood risk management

Flood risk management deals with a wide array of issues ranging from the generation of the flood hazard over its impacts to the preventive interventions for risk reduction. Moreover it comprises a number of societal tasks including the management process itself. Because of the variety of aspects, managing flood risks needs some systematisation efforts to better understand the entire problem and to allow for a targeted development of supporting knowledge, methods and tools. Hence, this section provides a brief overview of key definitions and concepts which have developed in recent years and may serve as a basic framework for comprehending risk management and according integrated methodologies.

From a formal perspective of the disaster science community, risk can be defined as the probability of negative consequences (Schanze, 2006; cp. Helm, 1996; Samuels & Gouldby, 2009). Hereby it is assumed that both the uncertainty of the future occurrence and the causality of the impacts can somehow be determined. This already indicates that the definition is dedicated to quantitative risk analysis which is just one possible understanding of risk particularly if risk concepts from social science and daily life are considered. However, in the public domain of dealing with flood risk, a formal definition seems to be adequate to ensure transparency and inter-subjectivity of assessments. This is the reason why the above mentioned risk concept is used throughout the book. For a general discussion of the term risk see e.g. Knight (1921), Adams (1995) and Weichardt (2007).

In addition to basing risk on the uncertain occurrence of certain impacts, underlying principal processes can be used for a concept of risk as an interrelation between a hazard and vulnerable elements (Klijn, 2004, cited in Samuels & Gouldby, 2009). The hazard represents the physical trigger for the consequence as well as its probability, whereof the vulnerability depends on values or functions, susceptibility and coping capacity (Schanze, 2009a; Messner *et al.*, 2006). In this case risk originates if the vulnerable element is exposed to the hazard (Figure 1.1). Depending on the kind of vulnerability it can refer to social, economic and ecological domains of the society according to the triangle concept of sustainability (Serageldin, 1995).

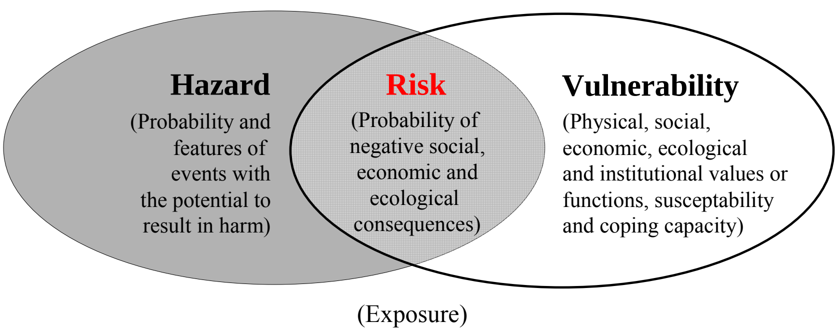

Figure 1.1 Scheme on risk as inter-relation of hazard and vulnerability (Schanze, 2009a)

To further specify the processes of risk generation the so-called source-pathway-receptor-consequence (SPRC) concept has been proposed by ICE (2001), Evans *et al.* (2004), Schanze (2006) and Samuels & Gouldby (2009) (Figure 1.2). It assumes that 'source' describes the triggering meteorological event and 'pathway' represents the wave propagation. Distinction between both is not always easy. In the case of a river flood the sources stand for the rainfall-runoff process, the pathways for the wave propagation in the river channel with its floodplain including the inundation process. Source and pathway together cover all water related phenomena of the flood hazard.

In contrast, ‘receptor’ and negative ‘consequence’ address all societal matters related with the flood risk generation. The receptors in principle can be human beings, animals and plants, objects such as buildings, infrastructure and mobiles goods as well as ecosystems or their components. Together they determine the vulnerability.

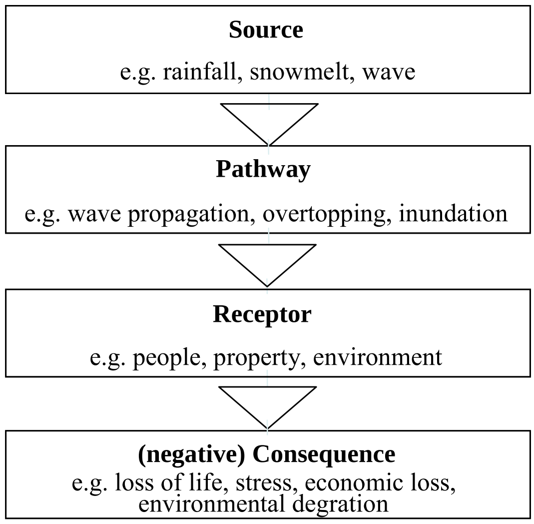

Figure 1.2 Source-Pathway-Receptor-Consequence Concept (Schanze, 2006)

Of course, risk generation in reality is much more complicated than the simple SPRC concept may suggest. It cannot be fully reproduced particularly on the scale of river basins, estuaries and coast lines. However, to indicate individual elements and processes, Schanze & Luther (2009) sketch a concept of a fluvial ‘flood risk system’ which is based on the SPRC concept but goes in some more detail. The idea is to identify major system elements and related processes for comprehensively modelling the immanent risk.

Figure 1.3 shows this concept with each box representing a group of system elements that influence flood risk as source, pathway, receptor or consequence. In the centre three river sections are depicted which stand for the wave propagation from the sources to the receptors. The elements displayed above are more or less of natural origin, whereof the ones below represent the anthropogenic provenance. On a more detailed level these system elements are considered with respect to their meaning as factors of future alteration. This covers three principal processes of change: (i) *autonomous change* due to external drivers, (ii) *controllable interventions* due to risk reduction policies, and (iii) *random states* due to various natural, socioeconomic and technological features. Identification of all relevant factors and their alteration provide the prerequisite for a consistent investigation of possible future developments in a medium and long-term perspective (e.g. based on the scenario planning approach; Luther & Schanze, 2009a,b,c).

Due to the number and particularities of processes within the flood risk system, modelling requires the inclusion of manifold approaches. Among others they comprise: regional climate models, digital terrain models, rainfall-runoff models, hydrodynamic and failure models, damage and vulnerability models, regional economic models, extreme value statistics, uncertainty analysis, remote sensing techniques for sampling hydrometerological data und land-use structures, measurements of e.g. precipitation, soil moisture, discharge, and water levels, fore- and nowcasting, trend analyses and projections, simulations models for risk reduction measures (e.g. effects of warnings and evacuation), and so forth. These approaches bear upon different mathematical and technological solutions and have to face different scales, different spatio-temporal resolutions and different areas and time spans of information.

The involvement and suitability of certain approaches predominantly depend on the site conditions and the respective issue of flood risk management. Therefore a general guidance on the required tools is impossible to provide. However all methods together should reflect the concept of the flood risk system and hence at least describe the source, pathway, receptors and consequences. Figure 1.4 shows how the methodological requirements can be systematised by formulating principal modules of flood risks analysis (and evaluation) from the view of model-based decision support (McGahey *et al.*, 2009). These modules can be operationalised applying alternative approaches. The latter are supposed to be influenced not only by methodological or technological aspects but also by the personal preferences of the investigators and maybe by previous work and results.

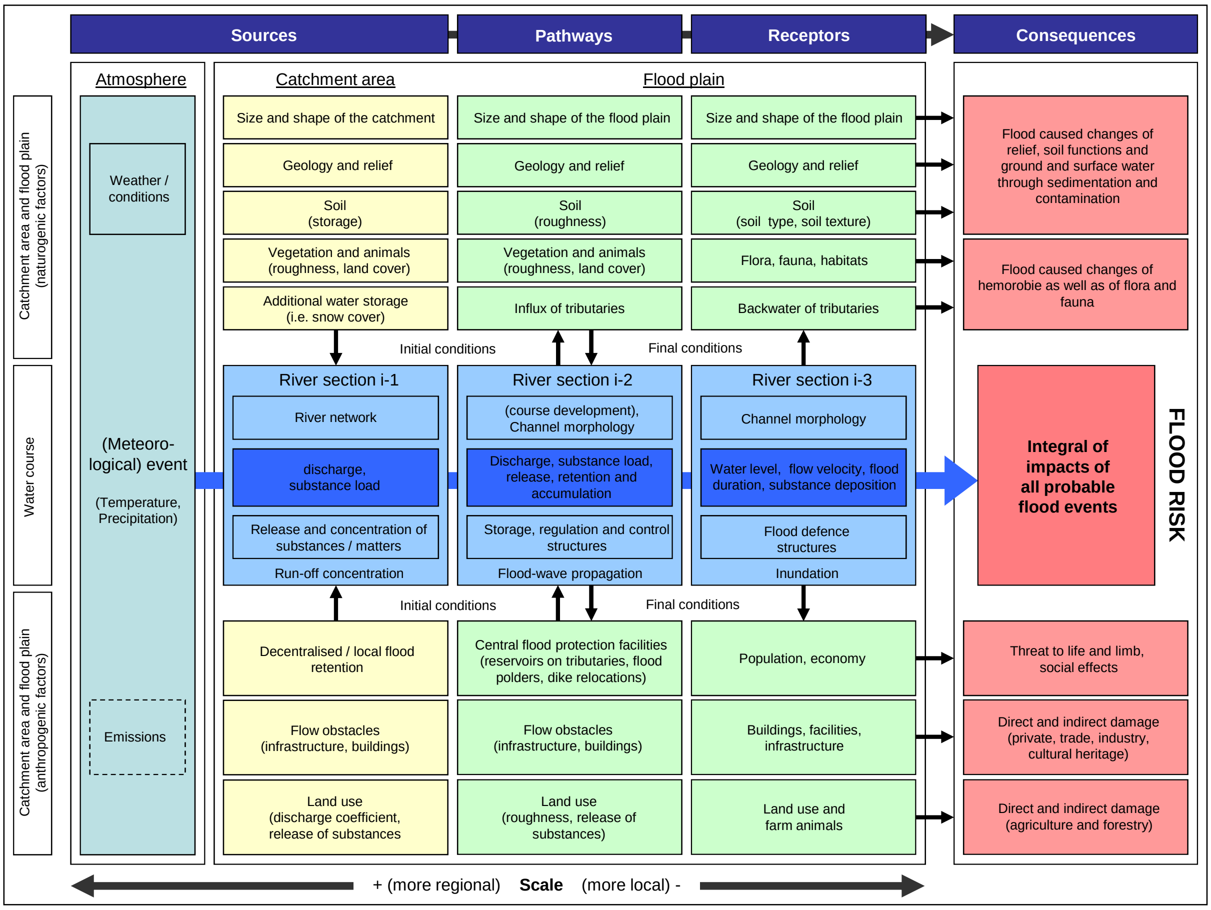

Figure 1.3 Concept of a principal flood risk system for river floods (Schanze & Luther, 2009)

To model an entire risk system, individual approaches need to be integrated including soft or hard coupling. Integration can range from using output data from a previous methodological step within a data flow diagram to online linking tools in a model system. A unique model for simulating the flood risk system would currently be a challenge because of complexity and reduced methodological flexibility.

While calculating the risks of a risk system already seems to be a major challenge, managing these risks encompasses even further tasks. To understand the scope of risk management − and more precisely managing the flood risk system − a close look into the field of business economics appears to be helpful. According to Weihrich & Koontz (1992) ‘management’ can be defined as all activities to effectively and efficiently control the decisions and actions of an actor, an organisation or a set of organisations (network). Such activities include planning (data gathering, analysing, goal setting, assessment of options, and so forth), organising, directing, staffing, monitoring, controlling, and learning (ibid.).

In this sense 'management' is also used in European Water Policy. As one example the requirements of river basin management plans (Art. 13) specified in Annex VII of the Water Framework Directive (WFD; 2000/60/EC) can be seen. Among others, they encompass:

- General description of the characteristics (section A, 1),
- Summary of the analysis of pressures and impacts (section A, 2),
- Results of the monitoring programmes carried out under those provisions for the status of surface water (ecological and chemical) and groundwater (chemical and quantitative) (section A, 4),
- Summary of economic analysis of water use (section A, 6),
- A summary of the programme or programmes of measures … including the ways in which the objectives of Art. 4 … are thereby to be achieved (section A, 7),
- A summary of the public information and consultation measures taken, their results and the changes to the plan made as a consequence (section A, 7),
- Updates (section B).

The annex of the European Directive 2007/60/EC on the assessment and management of flood risks (Floods Directive) analogue requests the following items for the elaboration of the flood risk management plans:

- Conclusions of the preliminary flood risk assessment (section A, I, 1),
- Flood hazard maps and flood risk maps (section A, I, 2),
- Description of the appropriate objectives of flood risk management (section A, I, 3),
- A summary of the measures … aiming to achieve the appropriate objectives (section A, I, 4),
- Description of the methodology of cost-benefit analysis (section A, I, 5),
- A description of the … way in which progress in implementing the plan will be monitored (section A, II, 1),
- A summary of the public information and consultation measures/actions taken (section A, II, 2),
- A list of competent authorities and … a description of the coordination process within any international river basin district and … with Directive 2000/60/EC (section A, II, 3),
- Updates (section B).

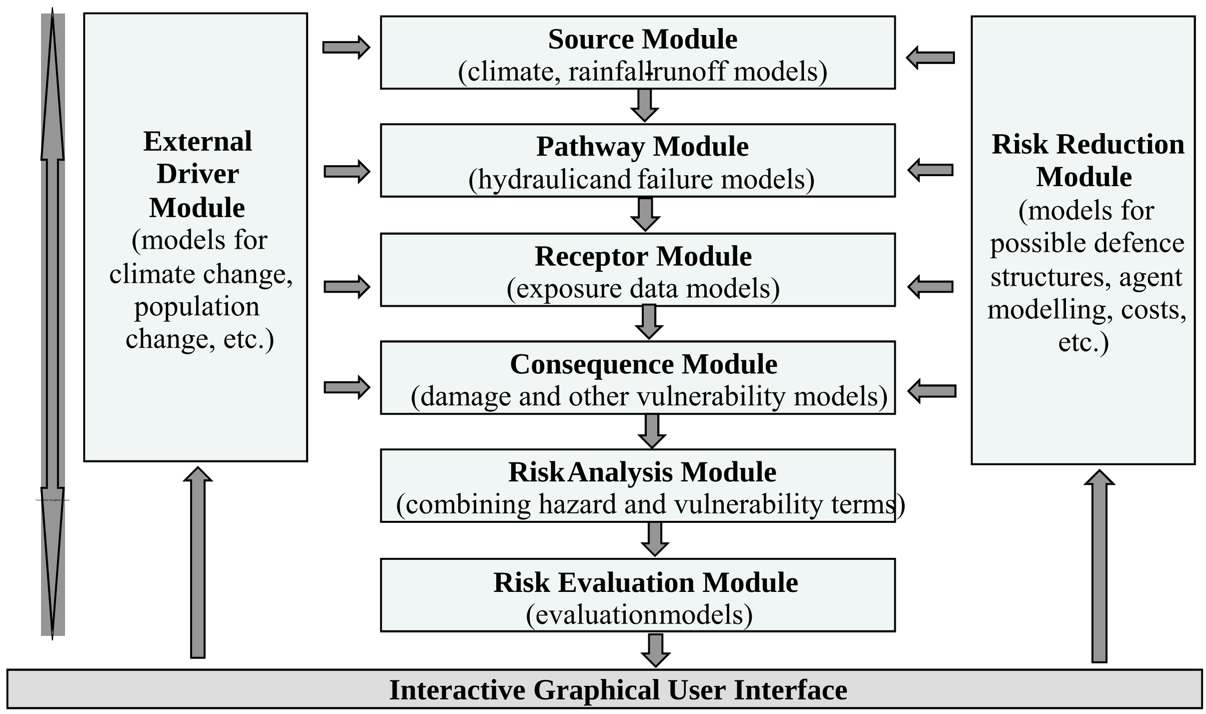

Figure 1.4 Overview of a methodological framework for flood risk management dedicated to a decision support tool (McGahey et al., 2009, adapted)

Against this background it becomes evident that flood risk management encompasses the analysis of the flood risk system, the evaluation of a certain system state (e.g. in terms of tolerability and risk reduction objectives) and the reduction of undesirable risk. Moreover it refers to the societal process of designing measures as well as implementing and monitoring their effects (for more details see Schanze, 2009). Thus, flood risk management has been defined as the *holistic and continuous societal analysis, evaluation and reduction of flood risk* (Schanze 2005a, 2006; cf. Sayers *et al.*, 2002; Hall *et al.*, 2003; Samuels & Gouldby, 2009).

Society, represented by politicians, experts and individuals, is the 'managing entity'. And there are multiple actors involved due to manifold interrelations between society and floods (Schanze, 2006, adopted from Parker, 2000). These representatives are perceiving flood risks and are evaluating whether a certain flood risk is acceptable, or tolerable respectively, or not (Adams, 1995). Flood risk management accordingly takes place as a decision making and development process involving actors from various fields (e.g. water authorities, spatial planning authorities), adjacent areas (e.g. communities) and different levels (e.g. local, regional or national).

Flood risks and related decision making processes of flood risk management differ depending on the types of waters (e.g. mountainous rivers, lowland rivers), flood types (e.g. flash floods, plain floods), land uses (e.g. rural, urban), planning and administrative systems (e.g. structuring according to catchments or communities) as well as natural (e.g. geomorphology, regional climate) and societal (e.g. social, economic, cultural, political) conditions (Schanze, 2005a, 2006).

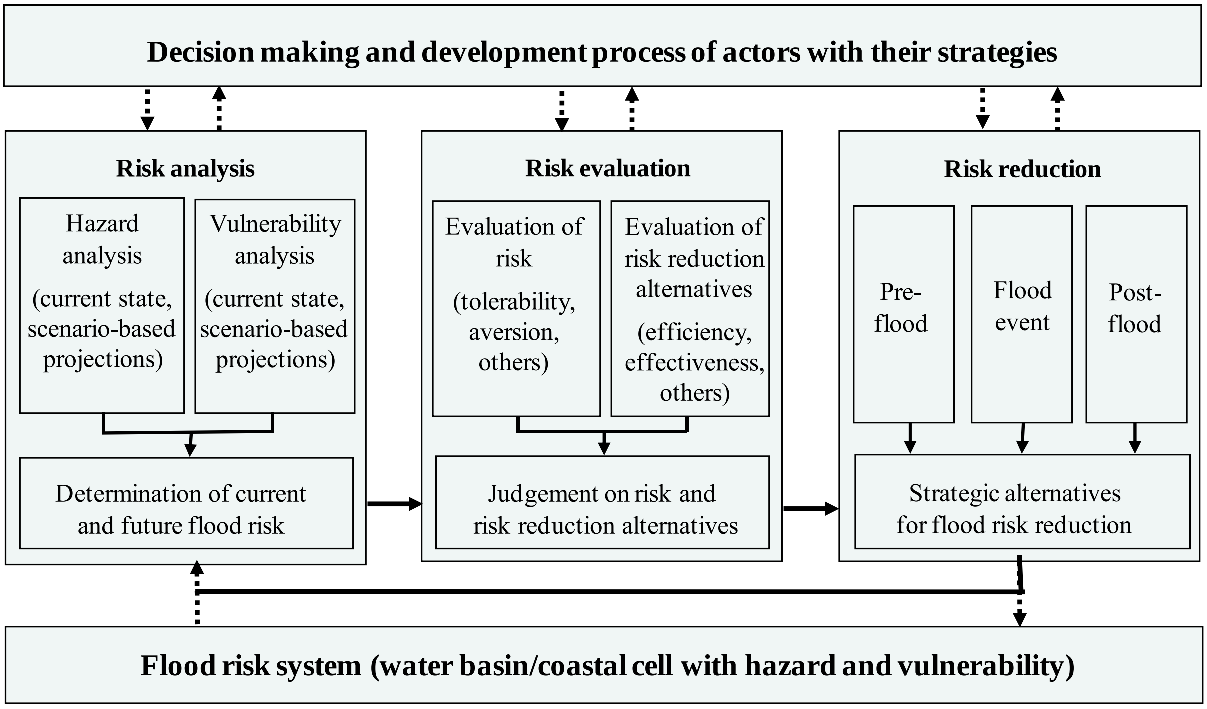

Figure 1.5 Basic framework of flood risk management (Schanze, 2009b)

To understand the relation between the three major tasks considering their functions for decision makers a basic framework of flood risk management has been sketched (Figure 1.5). On the bottom of the figure, the flood risk system is displayed as the subject of concern. On the top, the decision making and development process of actors of flood risk management with their strategies is shown (see below). It is assumed that actors do analyse, evaluate and reduce risks. In more detail this means that risk analysis bears upon the hazard analysis and the vulnerability analysis including projections of future developments. In comparison, the risk evaluation does not restrict itself to the description of risks but deals with their judgement or the judgement based on the comparison of risk reduction alternatives. On the scale of public risk management this evaluation needs the application of scientific methods.

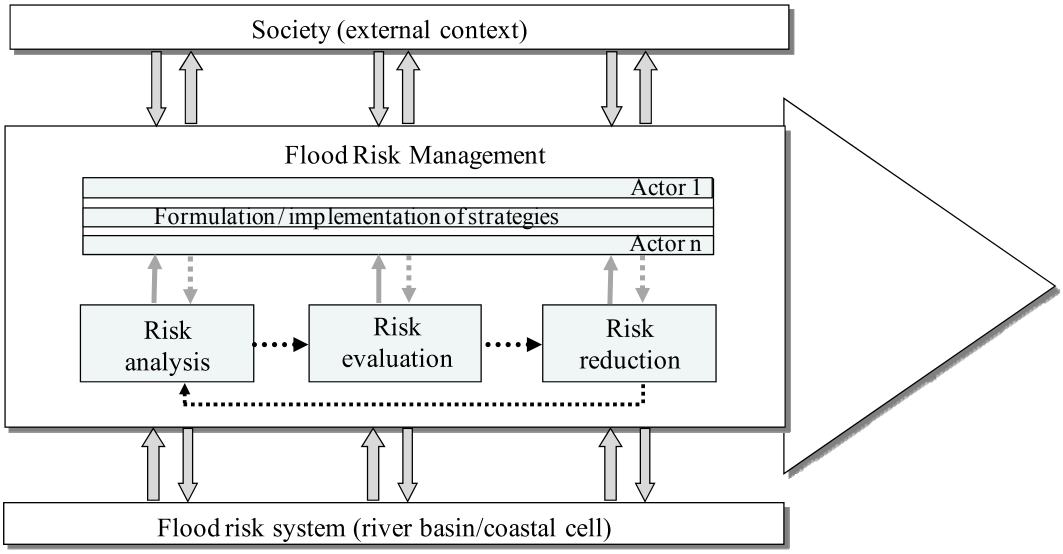

Figure 1.6 Scheme of the flood risk management process (Schanze, 2009b)

The task of risk reduction encompasses the identification of interventions in the flood risk system based on physical measures or policy instruments (Olfert & Schanze, 2007). Hereby different modes of flood risk management are distinguished: the pre-flood, the event and the post-flood management. Decision makers cannot only select individual options from a certain policy field but they need to combine them into strategic alternatives. Once such alternatives have been specified, the risk analysis and evaluation can be used to simulate their effects and to judge their suitability ex ante.

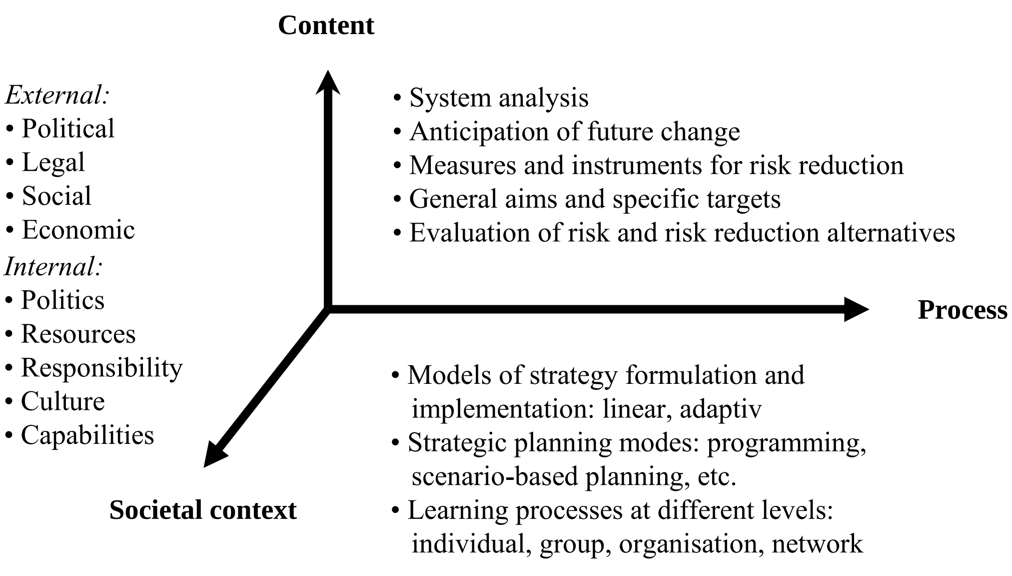

Figure 1.7 Content, context and process dimensions of strategies (Hutter & Schanze, 2008, adapted)

Although the framework brings together all tasks and required components of flood risk management, real-world observation suggests that one should draw additional attention to the decision making process itself. By doing so it becomes evident that management is oriented in time and not just an optimisation loop. Decisions in the past form the background for today's decision space and today's decision will determine the decision space of the future. Thus the arrow in Figure 1.6 expresses the directed procedure over time.

Moreover, it should be taken into account that public flood risk management involves multiple actors. These actors in principle operate independently, from the point of view of the required joint issue of tackling floods and related risks they act even fragmented (Bressers & Kuks, 2004). Figure 1.6 for that reason differentiates individual actors within the ‘managing entity’.

Like in the business sector also flood risk managers are embedded in a societal structure and behave in varying ways as far as the formulation and implementation of strategies is concerned. To provide a principle understanding in this respect, Hutter (2006) and Hutter & Schanze (2008) argue that strategy making in flood risk management has at least three dimensions: the content, the context and the process (cp. Pettigrew & Whipp, 1991; Volberda, 1998).

The content already stood in the foreground of the previous consideration up to the basic framework of flood risk management. The *context* dimension additionally takes into account that there are always internal constraints and conditions for actors such as limited resources, personal capabilities, cultural backgrounds and political beliefs. Furthermore, they are externally determined by political and legal provisions from higher (e.g. European, national) or adjacent (e.g. trans-boundary) levels of decision-making. The *process* dimension reflects features of learning and co-operation over time. It relates to certain phases (formulation, implementation) and modes of strategic planning (e.g. programming, scenario-based planning).

Although the argumentation line has so far touched some major aspects of flood risk management, of course, a single chapter cannot go into much detail. However, the presented understanding may assist in structuring the field as a basis for relating individual questions of science and practice. Moreover it indicates interrelations of topics which allows for addressing the emergent issues of the overall problem. Both purposes were relevant for the development and testing of integrated methodologies in European pilot sites of FLOODsite.

Before the objectives of the case studies are introduced, in the subsequent section one further item should be mentioned explicitly. The perspective of this section was determined by focusing on the management of flood risk. Therefore most aspects were treated within the light of describing, judging and altering the risk system. Beyond this perspective there remains at least the important aspect of governance irrespective. The theoretical background of governance provides the opportunity to also consider the societal structures around the management efforts. This can be illustrated by the following example.

Investigations of Kuhlicke & Steinführer (2006) proofed that the perception of risk and risk management by the people largely differs from the expert knowledge and strongly depends on own experience with flooding. Accordingly, information provided to the public probably cannot be properly interpreted and required actions for self-prevention are lacking. In contrast, investigations at the Scheldt showed that a few local people are well grounded in knowledge on flood risks, which even exceeds the scientific knowledge (see Chapter 6).

Of course these are just two examples. However they shed light on the meaning of the institutional structure and thus the embedding of flood risk management in the overall context of society. Risk governance therefore seems to be an important topic of mitigating flood risks. Due to the scope of the FLOODsite project it will not be addressed in too much detail in this book.

1.2 Developing and testing integrated methodologies in European pilot sites

To facilitate dealing with the comprehensive issue of flood risk management integrated methodologies have been developed in FLOODsite. In line with the framework described in the previous section these methodologies address risk analysis including hazard mapping, risk evaluation considering specific challenges due to future change of the flood risk system as well as risk reduction including physical measures and policy instruments. Moreover they encompass the design and implementation of decision support tools and the strategy making in the management process combined with the involvement of stakeholders and partly even the people directly affected.

Special emphasis was put on the description and modelling of various flood risk systems regarding both the hazard and the vulnerability. Hereby the different processes of risk generation at mountainous and lowland rivers, estuaries and coasts were embraced like, for instance, the rapid and uncertain onset of flash floods with related challenges for early warning, the large volume of lowland river floods with restrictions referring to prevention and defence, the storm-induced flood waves at coasts with the meaning of failure modes and coastal vulnerability, and the concurrence of riverine and coastal processes at estuaries. With respect to the management modes, research addressed the pre-flood and event management.

With the exception of topics of basic research most activities were related to real-world issues in a number of pilot sites (see Chapter 0). These cases studies were chosen for the following reasons:

- Development of integrated methodologies needs comprehensive subjects covering many aspects of flood risk management.
- Real-world conditions allow for immediate testing of the relevance of the outcomes with the aim of an ultimately applicability.
- Parallel investigations at rivers, estuaries and coasts ensure reflection of major flood risk issues in Europe.
- Concrete and well-documented cases facilitate the data acquisition together with valuable information on previous flood disasters.
- Co-operation with actors of flood risk management encourage in mutual learning of scientists and practitioners.
- Reference to ongoing management activities leads to an increased chance of uptake and effective contribution of research findings.
- Involvement of stakeholders (and the people) from the very beginning on fosters the information on regional flood risk issues and hence the risk awareness.

The selection of the sites involved several criteria such as

- coverage of typical riverine, estuarine and coastal flooding problems,
- geographic spread across Europe,
- interest for the relevant authorities and institutions,
- reasonable access to data and existing models,
- link to one or more partner institutes in the research team.

Finally seven pilot sites have been defined (Figure 1.8):

- The Elbe River basin, most of which is located in Germany and the Czech Republic,
- The Tisza River basin which includes Slovakia, Ukraine, Romania, Hungary and Serbia,
- Four flash flood watersheds, in Italy (Adige River), France (Cévennes-Vivarais Region), Spain (Besos River and the Barcelona Area) and a transnational river catchment in the Ardennes area covering the Netherlands, Belgium and Luxemburg,
- The Thames River estuary in the UK,
- The Scheldt River estuary in Belgium and the Netherlands,
- The Ebro River delta coast in Spain,
- A part of the German Bight coast including the community of St. Peter-Ording

As far as the research design is concerned the case studies have been used as single cases in the first place. Accordingly each case has been worked on mostly independent to enable in-depth investigations tailor-made for the issue of the site. This led to the supplementary advantage that regional conditions could influence the development of the integrated methodologies bottom-up. Because of the abandonment of a comparative approach, conclusions of common lessons are more indicative than systematic (Chapter 9).

1. Elbe River basin
2. Tisza River basin
3. European flash flood watersheds
4. Thames River estuary
5. Scheldt River estuary
6. Ebro River delta coast
7. German Bight coast

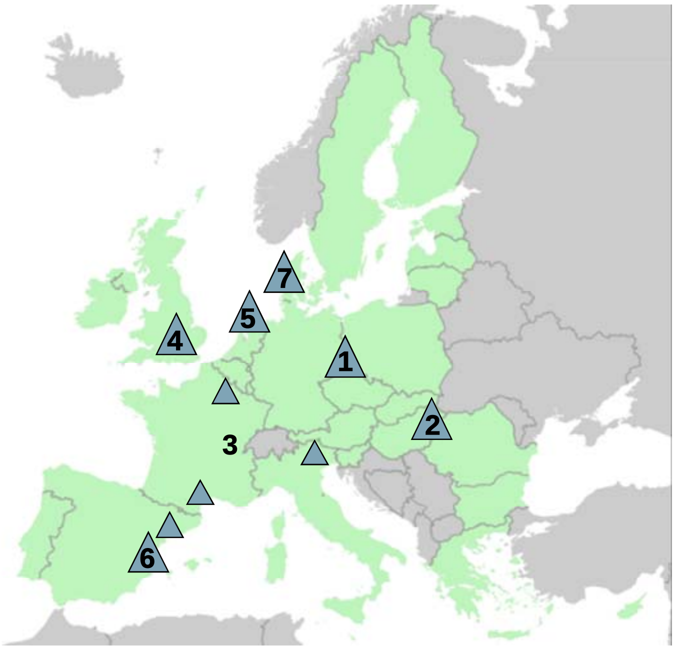

Figure 1.8 Location of the European pilot sites

The focus of developing integrated methodologies was rather site-specific. In none of the case it was feasible and intended to try to deal with the entire framework of flood risk management as presented in Section 1.1. Instead, the framework provided orientation and served for interpreting the research results in the context of the overall issue. In a number of cases the use of the framework has broadened the scope and has led to the inclusion of more relevant aspects of risk management.

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2. Pilot site "Elbe River basin"

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The transnational Elbe River (Czech: Labe) originates in the Czech Republic, traverses the Eastern Part of Germany in north-westerly direction and flows into the German Bight of the North Sea. In both languages, its name is derived from the old Nordic "elfr" ("river") which became Albis or Albia ("white") for the Romans and the ancient Germanic tribes. With a length of 1,094 km, the Elbe River takes place 14 among the rivers of Europe. Its catchment area covers approximately 148,000 km^2 and the average discharge is 860 m^3/s upon its mouth.

It runs through Northern Bohemia in a wide arc and pursues its course through Germany, passing the cities of Dresden, Magdeburg and Hamburg. Here it forms a small delta and widens to an estuary that finally converges with the North Sea near Cuxhaven. The tidal influence is still noticeable at Geesthacht, some 30 km upstream of Hamburg and about 142 km upstream of Cuxhaven. The discharge regime is largely influenced by rainfall and snowmelt in the Krkonoše, Bohemian Forest and Ore Mountains. Therefore discharge normally peaks in spring and then decreases continuously until October/November. However, this regime is often interrupted by the effects of strong summer rains.

Many flood-prone areas along the Elbe are dominated by agricultural and forest uses with a low population density. However, many smaller settlements and parts of larger cities might be exposed to flood waters during extreme events. After flowing in an often narrow valley through the České Středohoří (Bohemian Mountain Range) and Saxon Switzerland (Elbe Sandstone Mountains) and the hilly areas of Dresden and Meißen, the Elbe enters the North German Plain with floodplain widths of more then 11 km. Here, the Elbe receives with the Mulde and Saale Rivers two main tributaries that in the past have significantly contributed to the flood waters of the Elbe.

2.1 Flood risks and previous mitigation efforts

The hydrological situation of the basin can be characterised by measurements at Elbe River for the time period 1852 - 2007 until the mouth of the Saale River and for 1870 - 2007 further downstream. Especially during the "Little Ice Age" in the 18th and 19th century winter floods prevailed. In the relatively warm early decades of the 20th century frequent and extreme summer floods occurred, becoming less severe towards the end of the millennium (ICPER, 2005). This provides some evidence that extreme flood events have not increased along the Elbe River over the last centuries.

A number of reservoirs for flood control, drinking water and energy supply are located on several tributaries, whereas the main channel of the Elbe is free of dams and locks. In 2003, 292 reservoirs existed within the Elbe River basin with a total volume of 4.08 billion m^3 (of which 0.57 m^3 are common flood retention storage; ICPER, 2005). Although these figures are quite high compared to other European catchments, for floods with recurrence intervals of more than 50 years the effect of the reservoirs on downstream water levels is limited, as the reservoirs are full before the flood peak occurs.

A complex system of flood polders exists at the mouth of the Havel River. Six flood polders (101.9 km^2, 109.4 Mio. m^3) together offer a retention volume of 130 million m^3 and may lop the peak in the Elbe River significantly. This system has been operated successfully once so far (in 2002). Also the mouths of smaller tributaries along the Lower Elbe can be dammed in order to prevent backwater effects from flood waters of the Elbe River. Their waters are then retained in small polders.

Dikes are the main flood defence structures. It is planned to renew and enhance all existing dikes by 2015 so that discharges with a recurrence interval of 100 years (possibly even 300 years taking the freeboard into account) can be conveyed without causing harm, given no dike breach occurs. Due to different responsibilities and the historic development of dikes, protection levels often differ on the right and the left bank or from one federal state to the other.

Floodways exist near the cities of Dresden and Magdeburg. The large floodway near Magdeburg was created in 1869-73 and follows with a length of 21 km an earlier medieval course of the Elbe River. In August 2002 up to 1,050 m^3/s were diverted, corresponding to 24 % of the peak discharge in the Elbe River at gauge Barby (4,320 m^3/s), 6 km upstream of the branch-off and just downstream the confluence with the Saale River.

For navigation purposes, the Elbe River was equipped with groins, sills and longitudinal training walls between 1844 and 1900. In consequence of the 2002 flood event, the current practice is to merely avoid a deterioration of navigation conditions.

The socioeconomic conditions can be delineated by demographic, economic and land-use data as well as damage occurred during previous floods. The total population in all districts directly bordering the Elbe River was 3,156,809 in 2004. It is noticeable that large parts of the Elbe River basin are sparsely populated. In the past, loss of life has also not really been an issue when a flood happened along the Elbe. This, however, is an issue along some mountainous stretches of the tributaries which are prone to flash floods.

The event in August 2002 with a peak discharge in Dresden of 4,680 m^3/s slightly exceeded the 1890 flood (ICPER, 2005). Its return period is estimated with 150 to 200 years. The extraordinary high water level in Dresden with 9.40 m was partly due to large alluvial deposits at some bridges, rank riparian vegetation and to flow obstacles (buildings, roads, etc.). At 12 locations the embankments failed and breaches developed. Because large volumes of water gushed into the dike hinterland through these breaches, the discharge in the river itself decreased substantially. If the embankments upstream had been higher or stronger, the flooding further downstream would have been far more severe. Although damages were initially overestimated, the damage in Germany amounted to 9.1 billion € and in the Czech Republic to 3 billion €. The last important flood was observed in spring of 2006 with a duration of several weeks and an overall higher load (flood volume) than in 2002. The return period corresponded to about 1:15 years at the gauge Dresden and 1:200 years in the lowland part of the river (e.g. at the town of Hitzacker). In consequence of these events, weak points in the flood protection system were identified and flood risk management concepts were developed.

Past floods have already shown that even without the failure of certain measures, damage is generated. This applies especially for the Elbe stretch in Saxon Switzerland, where no permanent defence structures are possible, and for the vicinity of Dresden. In the middle and lower reaches of the Elbe River, mostly rural areas are affected. In these areas it is presently accepted that some dikes only provide protection from a 1:50 year flood.

The "Action Plan Floods" of 2003 (last updated in 2006) proposes a variety of future measures, including potential sites for dike relocations and additional flood polders. The suitability analysis for these areas was carried out under the INTERREG IIIB CADSES project ELLA. Measures for flood provision should also support the achievements of the good ecological status in accord with the EU Water Framework Directive.

2.2 Objectives and approach

2.2.1 Overall objectives

The research at the pilot site of the Elbe River basin aims at a *comprehensive developing and testing of the FLOODsite integrated methodologies on long-term flood risk management under the conditions of* *a large and transnational European river basin*. The principal idea is to better understand the complex problem of flood risk management in this basin and to provide tools for supporting real-world risk reduction practice. Although the ability to comprehensively consider the entire topic, the study is dedicated to address major factors of the flood risk system, all management tasks from risk analysis over risk evaluation to risk reduction as well as the process of strategy formulation and implementation. Due to limited resources research is carried out involving numerous FLOODsite tasks and matching with external research projects. Moreover a multi-level research design is applied ranging from the plot scale to the scale of the entire catchment (see Section 2.2.2).

The transnational basin provides the additional opportunity to foster collaboration between the Czech and German scientists with their embedding in the overall research network evolved under FLOODsite. Beyond intensive exchange with practitioners of flood risk management is being established on various levels to facilitate the mutual understanding and learning for the final applicability and uptake of the research results. At the local and regional levels, water and spatial planning authorities and municipalities are involved. At the national and international levels, collaboration focuses the International Commission for the Protection of the Elbe River (ICPE) and the German Elbe Board. Last but not least, research findings are also being disseminated to the general public through public events and via the media.

2.2.2 Research design

Developing and testing the integrated methodologies in the Elbe River basin draw upon a basic framework for flood risk management as it has been proposed by Schanze (2006, 2007, *et al.*, 2008, Ammann 2006; see Chapter 1). It encompasses risk analysis, risk evaluation and risk reduction as part of a societal decision-making and development process. Accordingly the research design considers the following topics:

A. Risk analysis
- Coupled modelling of the flood hazard, flood vulnerability and flood risk including the influence of land use on the runoff generation (plot and catchment scale)
- Formulation and parameterisation of long-term scenarios (e.g., climate change, land-use change) including the regionalisation of global climate change projections for flood modelling
- Multi-criteria analysis of current and future flood risks including risk for agricultural use in flood polders

B. Risk evaluation
- Ex-post evaluation of implemented risk reduction activities (e.g. effectiveness, efficiency)
- Ex-ante evaluation of strategic alternatives for risk reduction (e.g. robustness)

C. Risk reduction
- Explication of measures and instruments for risk reduction
- Combination of these options to strategic alternatives

D. Decision-making and development process
- Design of a scenario-based tool for strategic planning support
- Strategy development of stakeholder
- Risk perception of people at risk

As prerequisite for this comprehensive programme various links are ensured with other topics of the FLOODsite research (e.i. Tasks 1, 9 to 14, 18, 29 to 31). Externally, there are close co-operations with the projects VERIS-Elbe (Schanze *et al.*, 2007a), ELLA (www.ella-interreg.org), FLOOD-ERA (Schanze *et al.*, 2009), and others. Data were provided by many public authorities, in particular by the Czech Hydrometeorological Institute, the German Weather Service (DWD), the CEC Potsdam, the Free State of Saxony, the Bundesland Saxony-Anhalt, the municipalities Nové Hrady and Horní Stropnice, as well as the Vltava River Watershed Authority.

Because of the size of the Elbe River basin, research needs to focus specific sites. Thus five pilot areas have been chosen reflecting the sources, pathways, receptors and consequences of the Elbe River flood risk system. These sites are the headwaters of Moldawa River (Czech Republic) with the Horní Stropnice River (Aa) and the Trebon Basin (Ab), the Elbe tributary Upper (Ba) and Lower (Bb) Mulde River (Germany) as well as the Lowland Elbe River (C; Germany) (see Figure 2.1). Beyond the entire basin is considered in scenario planning and for the scenario-based decision support tool.

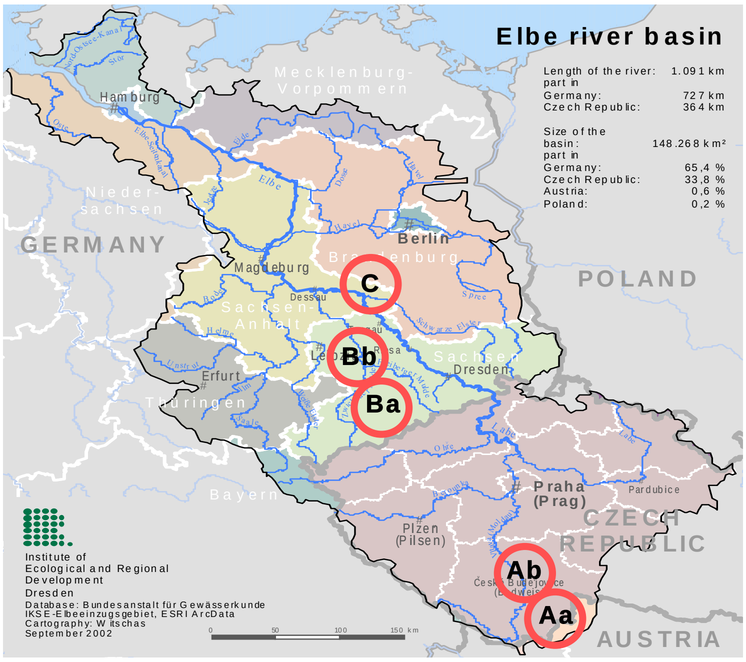

Figure 2.1 Pilot site Elbe River basin with five pilot areas

2.3 Major findings

Presentation of the outcomes from the pilot site Elbe River basin follows the multi-level structure of the research design. It starts with the results from the pilot areas and then reflects the level of the entire Elbe River basin with a focus on flood risks along the German Elbe floodplain. At last, key innovations the study are summarised.

2.3.1 Pilot areas Horni Stropnice and Trebon Basin

Research carried out along the headwaters of the Elbe River basin concentrate on the hydrologic conditions, the ecological vulnerability as well as on recommendations for municipalities and the public. As result for the *Horni Stropnice River* catchment (85 km²) it can be shown that existing dams in this rural region performed well during frequent flood events (5yrs), but not during rare events (50-100yrs), like the 2002 flood. At the same time, flood detention is increasing due to land-use change from arable land to forestry since 1990 (Table 2.1). Experiments with artificial floods show a minor ecological flood vulnerability of aquatic community in the study area because of life strategies of the species and natural pattern of flood occurrence (Komínková *et al.*, 2007). However, flood conveyance is reduced due to low bridges and congestions of sediment, garden waste and trees. Risk reduction options were developed in close cooperation with municipalities and governmental organisations.

The downstream *Trebon Basin* pond system of about 500 km² has originally detention function. Here, the change of land use and the detention capacity have been analysed based on historical, hydrologic, hydrogeological and LANDSAT 7 data (Zikmund & Kodrova 2006). An ecological vulnerability analysis allowed for an assessment of the current ecological risk. Flood hazard, ecological vulnerabilty and risk are presented in a GIS project. A set of recommendations to improve the flood risk management were derived and discussed with local authorities and the public.

Table 2.1 Primary retention capacity of the watershed

	Amount of retained water [m³]	
	1945	**1990**
Forest	1. 343 -2.417 million	1.75-3.15 million
Grass fields	0.6732-1.5147 million	0.29-0.65 million
arable soil	0.1065-0.426 million	0.13-0.5 million
Total	2.1227-4.4107 million	2.17-4.3 million

2.3.2 Pilot areas Upper and Lower Mulde River catchment

For the Czech-German Mulde River catchment (5,340 km²) a comprehensive flood risk system is described to test coupled modelling of the whole process of risk generation. This covers all methodological components displayed in Figure 2.1. According to the features of the catchment, research regarding the mountainous Upper Mulde River focuses the hydro-meteorological processes, whereof the Lower Mulde River is subject of hydrodynamic modelling and multi-criteria risk analysis. For the Lower Mulde a complete risk analysis has been carried out. This compromises (i) a hydrodynamic modelling of inundation depth (ii) a vulnerability analysis and damage evaluation and (iii) a multi-criteria risk analysis and mapping of potential social, economic and environmental impacts. Both parts of the catchment are linked by the hydrologic models and consistent scenarios.

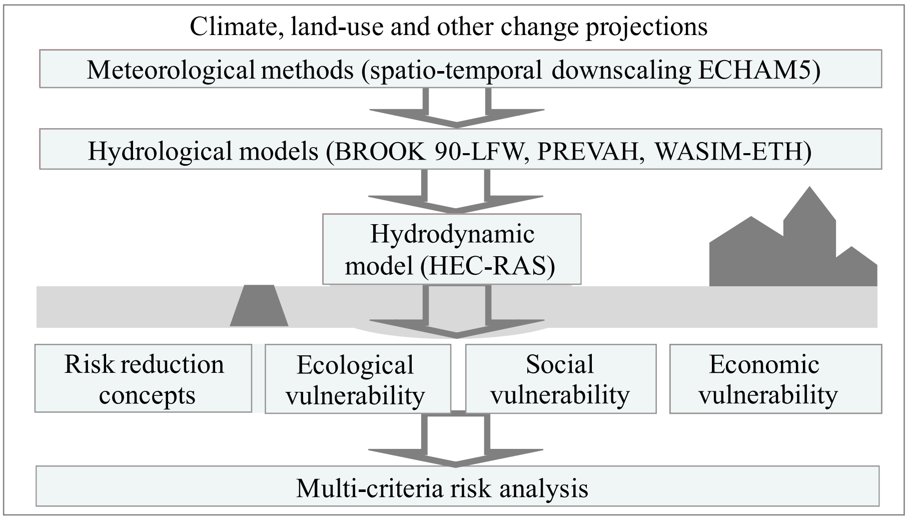

Figure 2.2 Coupled modelling of the flood risk system of the Mulde River catchment (Schanze, 2007b, adapted)

Meteorological investigations

Two meteorological drivers of the flood risk systems are investigated based on regionalised climate and climate change projections according to the IPCC scenarios: Pre-event moisture and heavy rainfall events. Research encompassed analyses of the daily climate scenario data (transient run) and the effects of climate change on design precipitation and return periods. Data are derived from the GCM base ECHAM5 (MPI-M Hamburg) for SRES scenarios A2 and B1 and the dynamical statistical downscaling using weather patterns (WETTREG). Three transient realisations (dry, mean, wet) for each station and decade between 2001-2100 were considered with mean realisation of 2041-2050 and 2091-2100.

Results indicate temperature and precipitation changes in the Mulde River catchment with higher precipitation changes in the lowlands in summer. Extreme precipitation (> 50 mm) is not covered by climate projections (like 2002) which may change the probability density functions. Historical 100a return period will probably be 65a (1d), 85a (2d), 97a (3d)… by the end of the 21st century. As an example Figure 2.3 shows the reduction in return period for a precipitation event with 48 hours duration and an actual return period of 100 years (reference period 1951-2000). Changes in pre-event moisture and snow melt floods are possible what should be investigated in further works. (Goerner *et al.*, 2007)

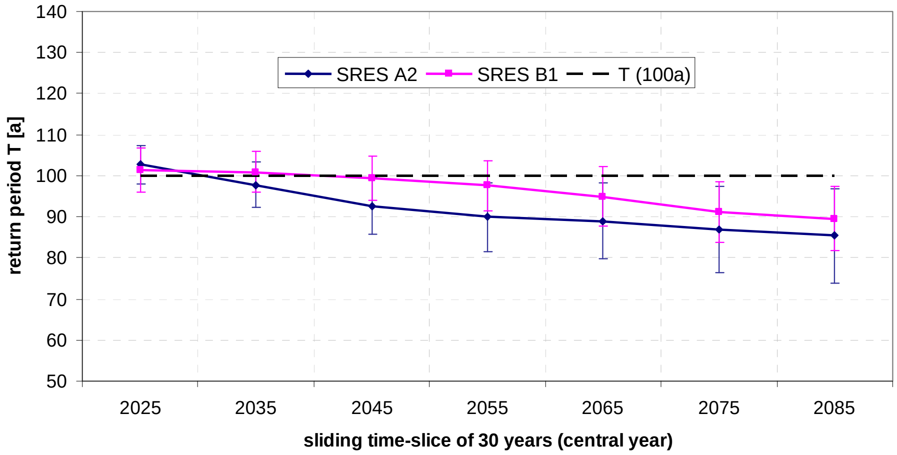

Figure 2.3 Changed return period of hN (48h,100a) for 1951-2000, summer period (may-sep), catchments "Zwickauer Mulde" and "Freiberger Mulde" (Goerner et al., 2007)

Macro-scale modelling the influence of land-use and climate change on the rainfall-runoff process

The aim of the study is (i) to assess land-use parameters of different model approaches, (ii) to analyse the effect of realistic land-use scenarios, and (iii) to simulate the impacts of climate change on the soil-water budget. As far as modelling the infiltration is concerned, BOOK90-LFW was applied.

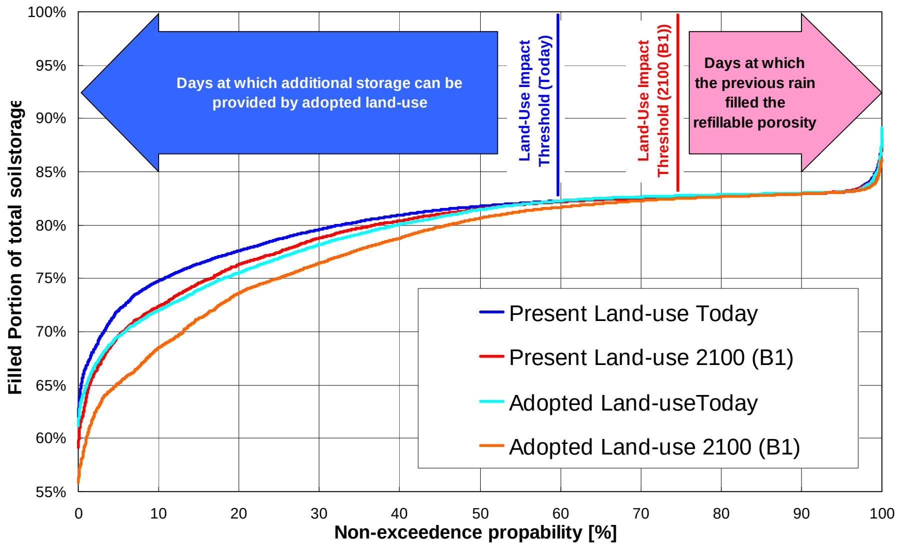

Figure 2.4 Soil storage depending on land-use and climate change scenarios (Wahren et al., 2007c)

Results confirm that adopted land use could be an efficient means of flood detention providing additional storage (see Figure 2.4) and transferring runoff into slower pathways. However, these effects are limited to events of lower recurrence probability, site-specific and not static. There is a considerable lack of data for model parameterisation particularly with respect to short-term vegetation changes and their long-term effects on soil properties. The corresponding investigations on false chronosequences circumstantiate that e.g. for afforestation an increased conductivity and a higher portion of coarse/middle pores can be observed. This causes an increased infiltration and soil water retention potential especially for the top soil layer (Table 2.2). Compared to the vegetation parameters these soil effects are generally not simulated in rainfall-runoff models concerning land-use scenarios. Existing assessment tools are scale-specific in accordance to their data requirements. In this respect one can distinguish point (site) models, expert systems and spatially distributed meso-scale rainfall-runoff models. A combination of such tools appears to be adequate. (Wahren *et al.*, 2007a, b)

Table 2.2 Pore distribution [Vol%], related field capacity (mm) and unsaturated hydraulic conductivity [mm d-1] in the top layers (30 cm)

Land-use	Horizon	Pore diameter [µm]			Field Capacity [mm]	Hydraulic Conductivity [mm d^{-1}] at pF 2,5
		> 50	50 - 10	10 – 0,2		
Arable land	Ap	6	5	3	106	0,11 ±0,02
Young afforestation	Ah	6	9	7	149	0,26 ±0,05
Old afforestation	Ah	5	14	10	179	0,43 ±0,10

Meso-scale hydrologic modelling
The rainfall-runoff model PREVAH has been set up for one part of the Upper Mulde River catchment and verified after comprehensive data analysis. A reservoir module was developed and implemented in the model system. The remaining parts of the catchment were calculated with the already running WASIM-ETH model. Following the meteorological investigations, rainfall series were used to analyse flood characteristics under possible future climatic conditions. Results of reanalysis show no significant change of the hydrologic characteristics compared to the average hydrologic characteristics of the last 90 years. Instead, future climate change projections indicate a decrease of the discharge. This would mean that the future flood hazard could be totally covered by the currently planned structural measures of the Saxon Flood Protection Concepts. Therefore, flood hydrographs were derived applying the mean standardised hydrographs (Dyck, 1979) as input for the subsequent hydraulic modelling and flood risk analysis. (Lennartz *et al.*, 2007)

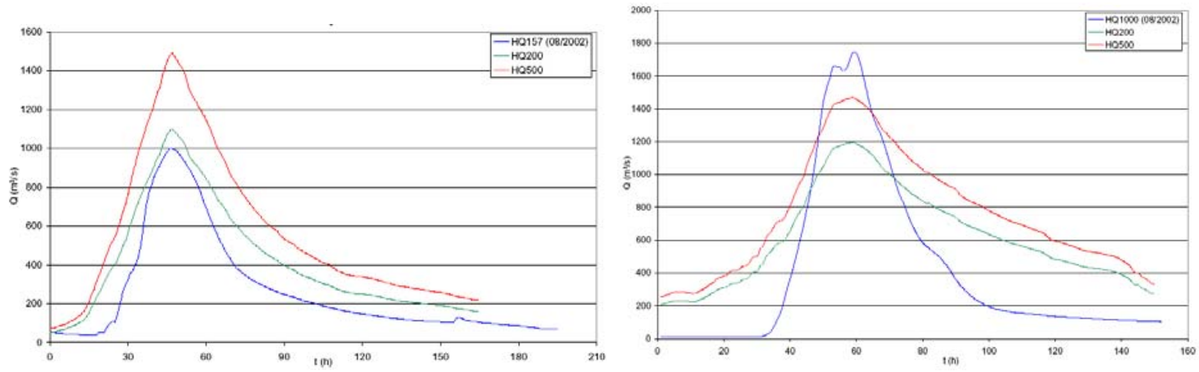

Figure 2.5 Flood hydrographs for return periods 200 and 500 years for gauge Wechselburg (Zwickauer Mulde, left) and gauge Erlln (Freiberger Mulde; right) (Lennartz et al.. 2007)

Hydrodynamic modelling
Using a quasi 2D-hydrodynamic modelling (HEC-RAS) discharge of different recurrence intervals (1:10, 1:25, 1:50, 1:100, 1:200, 1:500) is calculated for the Lower Mulde River for two risk reduction alternatives. Resulting inundation depth is mapped for the entire Lower Mulde applying a grid with a spatial resolution of 10 m.

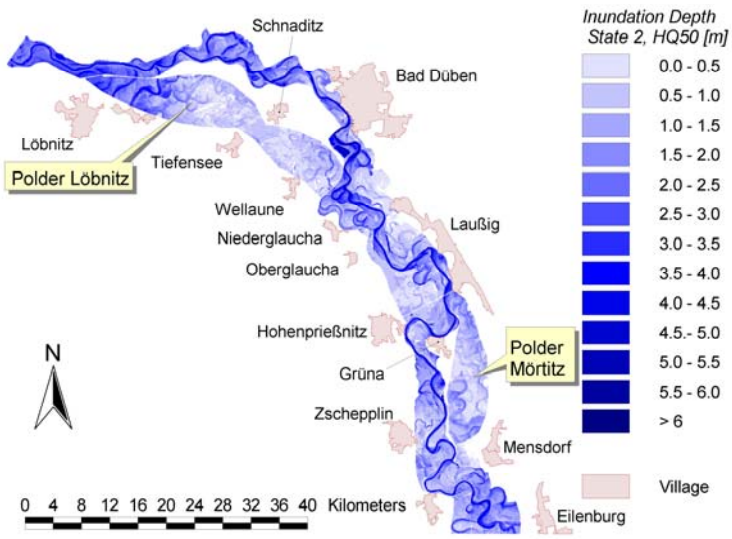

Figure 2.6 Flooded areas and water depths at a stretch between Eilenburg and Löbnitz of the Lower Mulde River (state 2, HQ_{50}) (Wenk & Rode, unpublished)

The two risk reduction alternatives are as follows: (1) protection like before the 2002 flood, (2) all measures planned in the current regional Flood Protection Concepts of the Free State of Saxony. As an example, Figure 2.6 shows the flooded areas and water depths for a stretch between Eilenburg and Löbnitz based on alternative 2 and a return period 1:50. For this recurrence interval the flood polders Mörtitz and Löbnitz are activated. Both flood polders are artificial water courses (diked grassland) which are flooded if the discharge exceeds a return period 1:25. Inlets and outlets are controlled hydraulic structures (controllable flood polders). Outside the urban areas long dike sections are relocated in this alternative. Compared with alternative 1 the inundated area for alternative 2 is clearly enlarged. The activated flood polders lead to an increase of the cross sectional area and hence to lower water levels compared to alternative 1. These inundation data are used as a basis for the vulnerability analysis and multi-criteria risk analysis.

Vulnerability analysis and multi-criteria risk analysis

For the analysis of the current and future flood vulnerability and risks, the GIS-based multi-criteria analysis and mapping approach of FLOODsite (Task 10) has been tested at the Lower Mulde River. The method allows for (i) considering flood risks in monetary and non-monetary terms, (ii) mapping of thematic flood risks (Figure 2.7), and (iii) deriving multi-criteria flood risks including different weights for the thematic risks (Figure 2.8). Two multi-criteria decision rules, a *disjunctive approach* and an *additive weighting approach,* are used for the analysis and mapping. Both, the risk calculation and mapping of single criterion as well as the multi-criteria analysis are realised by the software tool FloodCalc. A GIS dataset of economic as well as of social and environmental risk criteria has been built up for the pilot area. Moreover, the method is used to display the risk reduction effects of the regional Flood Protection Concepts of the Free State of Saxony.

While it is crucial for flood risk management to identify social hot spots, further findings from the sociological work in FLOODsite reveal that social vulnerability – as something related to local communities, social groups, households and individuals – is not restricted to certain socio-economic or socio-demographic criteria (Steinführer & Kuhlicke, 2007). These findings provide evidence in the Lower Mulde River floodplain that

- vulnerability is highly context- and event-specific
- there is no single variable which explains the vulnerability of specific groups coherently and for all the disaster phases
- no specific group is *per se* highly (or little) vulnerable
- the same group may be vulnerable in certain phases – anticipation, resistance and coping, recovery and reconstruction – and not vulnerable in others

- the same group may be vulnerable in relation to certain aspects – e.g. preparedness, risk awareness, capacity to receive help during the event, flood impact – and not vulnerable in relation to others
- some relations are not linear, it is rather extreme groups (e.g. the very young and the very old) which in certain respects turn out to be more vulnerable than the other groups "in-between".

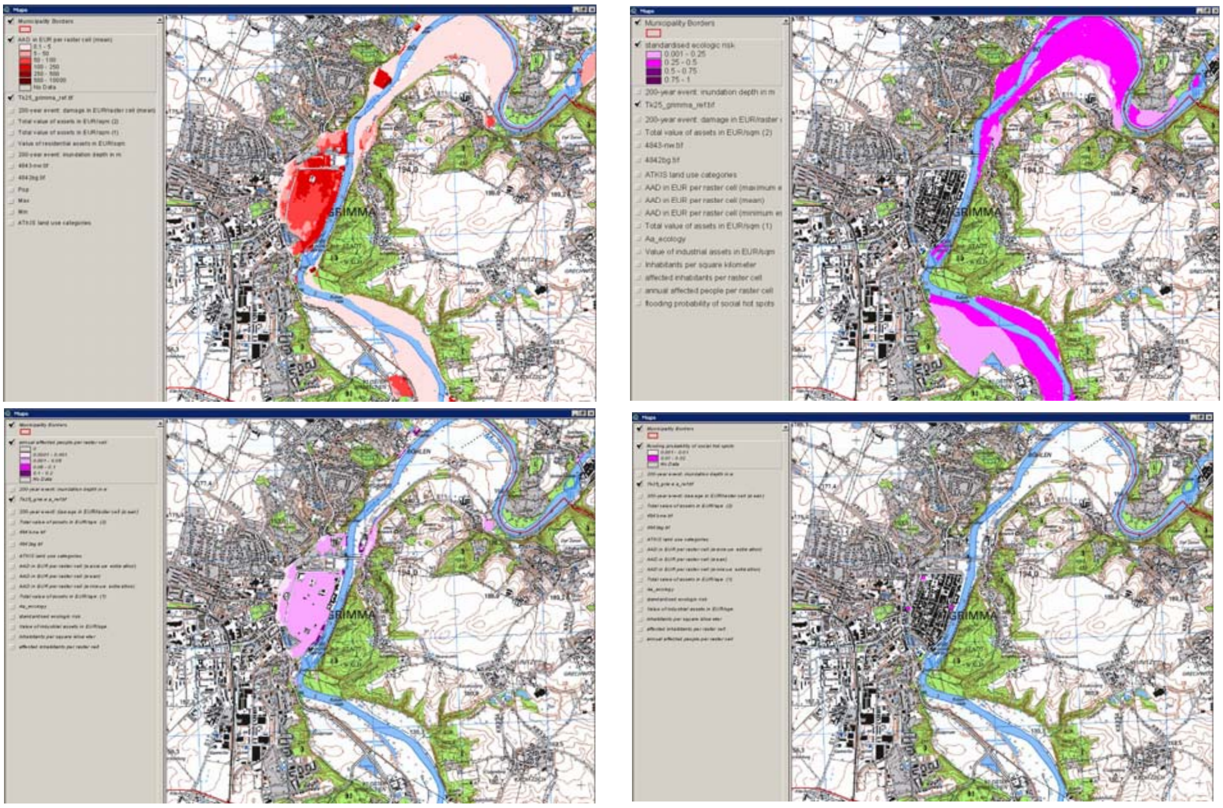

Figure 2.7 Economic (top left), environmental (top right) and social (population, down left; social hot spots, down right) risks (Meyer et al., 2007)

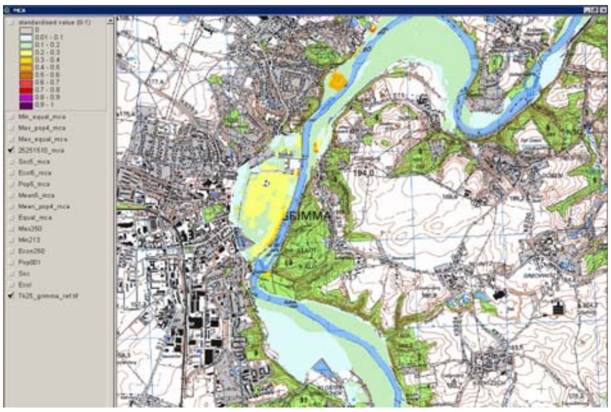

Figure 2.8 Multiple flood risk weighting economic risk (0.33), environmental risk (0.33), social (population; 0.20) and hot spots (social hot spots; 0.13) risks (Meyer et al., 2007)

Risk awareness and preparedness

In several locations of the Lower Mulde River floodplain questionnaire surveys and in-depth interviews with residents were conducted to better understand risk awareness and social behaviour before, during and after the 2002 flood (Kuhlicke & Steinführer, 2006; Steinführer & Kuhlicke, 2007).

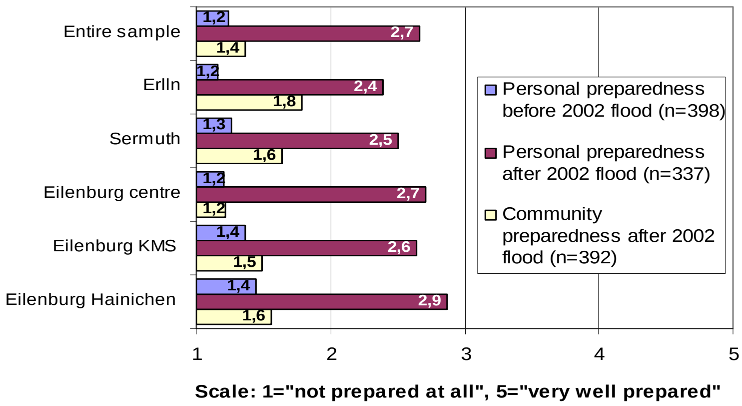

Figure 2.9 Perceived preparedness for an extreme flood by research location

As for *risk awareness*, results show that there is a need to question some desirable but rarely existing causal relationships: There is no automatism between being aware of the risk of flooding and actual behaviour – a crucial issue from the perspective of the European Floods Directive, since assumptions that preparedness is a direct result of awareness are widespread. This finding holds for further supposed relations, such as feeling informed and being prepared, too. Hence, there are no direct, immediate, and univocal links between perceptions, opinions, and attitudes on the one hand and actual behaviour on the other. Although from a social-science perspective this finding is not surprising, it is necessary to stress it.

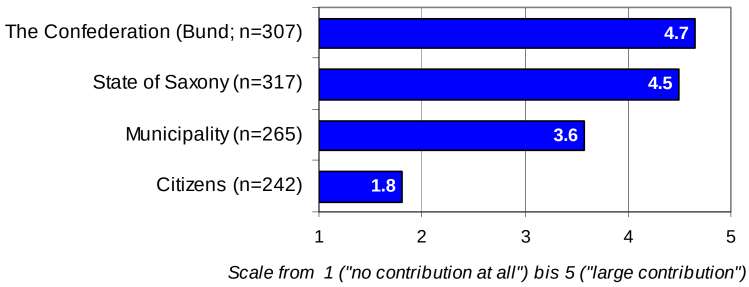

Figure 2.10 Answers to the question "Flood protection [...] is rather cost-intensive: How much should the following actors contribute to the costs?" (mean values)

Yet, there is a significant rise in *subjective preparedness*. In contrast with 2002, the residents feel better prepared for a disastrous event. But two restrictions need to be made: firstly, the majority of the residents still feel "not prepared" (all mean values below 3; Figure 2.9), secondly, this result contrasts with the perception of a very low degree of community preparedness. Moreover, also a rise in the actual application of preparatory measures can be reported. But the majority still do not apply any measure and among those mentioned, insurance and minor adaptations in the buildings prevail. A final focus was on the evaluation of *public measures*. The residents at risk were asked who in their minds should bear the costs for flood risk protection. The result (Figure 2.10) clearly points to clear distinction between personal and collective responsibility and its delegation to authorities.

The issue of private and public mitigation measures is a crucial one in the context of *flood risk management*, since this paradigm carries with it a *shift in responsibilities*. It expects the residents at risk to take active part in these efforts. Yet, the empirical findings underline that recent developments in the policy sector are not shared (or even understood) by the people at risk. While the demand that individuals should take responsibility and adopt private precautionary measures seems relatively well established within the scientific community and among flood-risk managers the research results show that among the residents at risk *traditional assumptions about flood protection*, both its structure (technical defence) and the responsible bodies (public authorities) dominate.

Thus a gap of knowledge between the scientific community and the policy makers on the one hand, and the local population on the other, is apparent. Probably even more important, there exists also a gap in the attribution of meaning to private preparatory measures since the residents at risk have their own clear comprehension about responsibilities for flood protection which, in their point of view needs to be borne by public authorities (similarly for the U.K.: Brown & Damery, 2002, 423). These findings underline that flood risk management also requires new partnerships and synergies, otherwise placing greater responsibility on private shoulders is likely to be ineffective.

2.3.3 Pilot area Lowland Elbe River

For large rivers like the Elbe, risk reduction through flood polders is one major option. Hereby, a flood polder is understood as a detention basin intended to reduce river peak flood flows through temporary water storage. Under the Elbe study effects and side-effects of the operation of the proposed flood polder Axien/Mauken (storage capacity 40 million m³) at the Lowland Elbe is analysed. Research encompasses hydrodynamic modelling using a 1D and coupled 1D-2D approach to simulate the flood hazard and particularly the peak discharge of the downstream Elbe River under different scenarios and control alternatives.

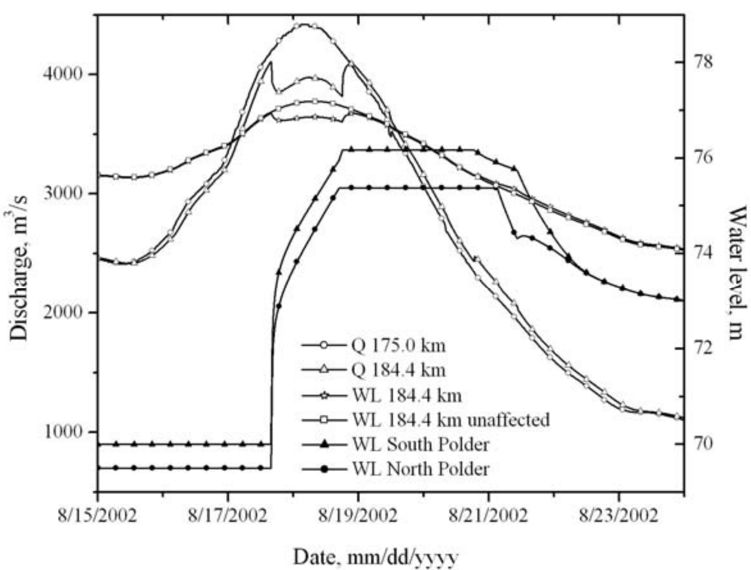

Figure 2.11 Simulated peak discharge reduction (approx. 310 m²/s), water level reduction (approx. 19 cm) and water levels in flood polders for the August 2002 flood event (Förster et al., 2008b)

Results indicate that during large floods the utilisation of the flood polder significantly reduces the Elbe River peak discharges (Figure 2.11). However, the magnitude of the attenuation depends on the steepness of the flood hydrograph and the applied control strategy with well-timed gate operations (Förster *et al.*, 2008b; Chatterjee *et al.*, 2008). Utilisation of flood polders can lead to environmentally harmful situations in the storage basin. One major problem is the depletion of dissolved oxygen concentrations due to the strong oxygen demand imposed by organic material in the water body and at the bottom. Based on the hydrodynamic model set-up, water quality was simulated focussing on the oxygen balance of the flood polder. In addition, flood vulnerability of and risk for the rural land use within the flood polder were determined as basis for ex-ante evaluation of the alternatives (Förster *et al.*, 2008a). In the context of a close co-operation with the regional water authorities, recommendations were derived for the future operation strategy depending on flood characteristics and land-use development within the flood polder.

2.3.4 Elbe River basin

The original scope of the pilot study Elbe River basin did not allow for the inclusion of the Elbe channel and the entire basin. However during the course of investigation this could be realised due to a close co-operation with the VERIS-Elbe project funded under the German RIMAX Programme (Schanze *et al.*, 2007). The latter project deals with change and management of risks due to extreme flood events in large river basins with the Elbe River basin as an example. Thus it scientifically addresses long-term flood risk management complementary and more detailed than the pilot study Elbe River basin. As a result the scenario planning approach of VERIS-Elbe could be tested in the Elbe pilot (under Task 14) and model runs from the former were used to design and programme an innovative decision support tool (under Task 18). Based upon the pilot study has been expanded to include an investigation on the decision-making and development process of practitioners of flood risk management practice reflecting the integrated methodologies.

Scenario planning approach

Research on long term futures of the flood risk system of the Elbe River basin led to a recommended approach which consists on the following steps: (i) conceptualisation, delineation and description of the flood risk system, (ii) coupled modelling for system analysis, (iii) Formulation and parameterisation of scenarios (as bundles of sectoral projections), strategic alternatives (as portfolios of risk reduction options) and random conditions (as set of random features), (iv) composition of futures (comprising scenarios, strategic alternatives and random conditions), and (v) ex-ante risk analysis and evaluation of futures (Luther & Schanze, 2009a,b). In line with this approach, scenarios, strategic alternatives, random conditions and futures are investigated for the Elbe River basin.

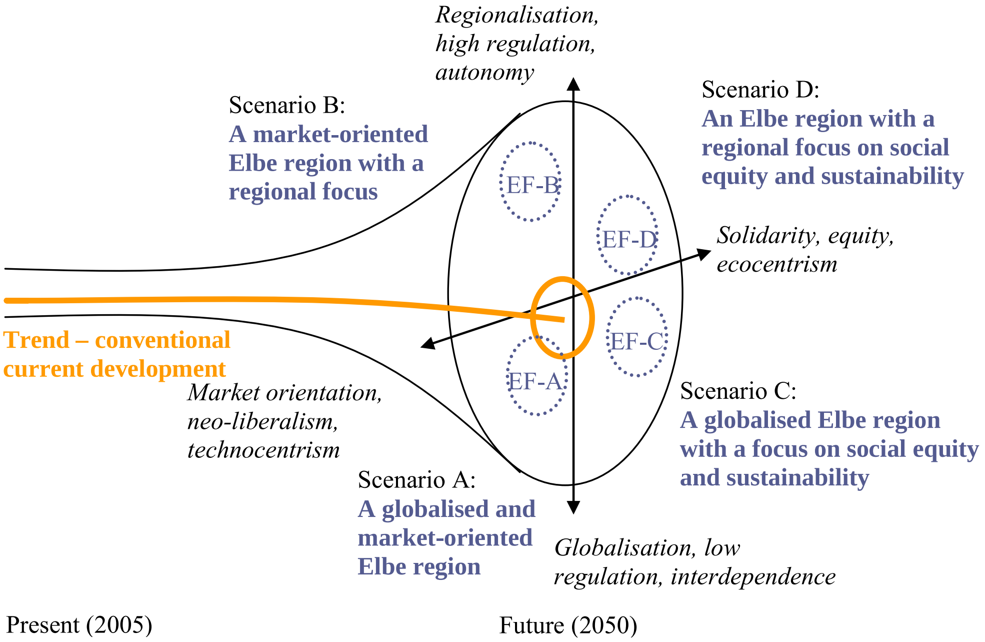

Figure 2.12 Schematic illustration of the scenario funnel with the storyline quadrants. Indicated are the four Elbe Futures resulting from selected combinations of scenarios and strategic alternatives (based on Luther & Schanze, 2009b)

Figure 2.12 presents an overview of storylines used for structuring thematic scenarios on climate change, demographic change, economic development and land-use change applying the discriminate-axes method. In a similar way a number of risk reduction measures and instruments such as flood polders, building provisions, flood proofing and so forth are combined to strategic alternatives. Figure 2.13 depicts the impact of the baseline scenarios and of the strategic alternatives on flood risks at the Elbe River channel displayed as frequency of damage. It can be seen that the influence of the aleatory uncertainty through the considered scenarios is much higher than the effect of all risk reduction alternatives.

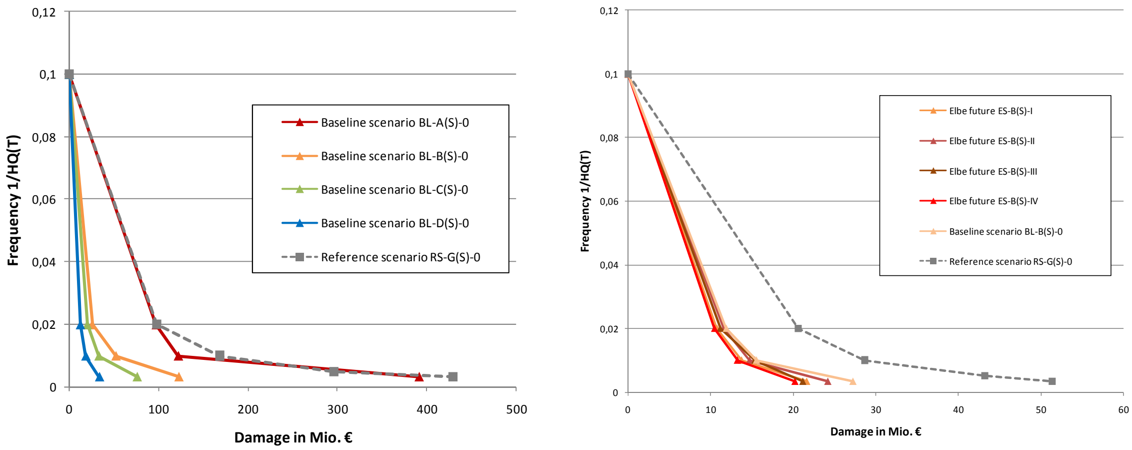

Figure 2.13 Influence of the baseline scenarios (left) and the strategic alternatives (right; without Saxony) on the flood risk along the German Elbe River floodplain (Luther & Schanze, 2009b)

Figure 2.14 illustrates the importance of an additional evaluation of the results from the ex-ante risk analysis. In this case the criterion 'robustness' addresses the emergent issue of the performance of strategic alternatives under the conditions of different scenarios. It is calculated as average expected annual damage (EAD). Results for the Elbe River floodplain are that the current practice which would save a lot of further investments could become critical in terms of future flood risks if the real development would follow scenario A (Luther & Schanze, 2009c).

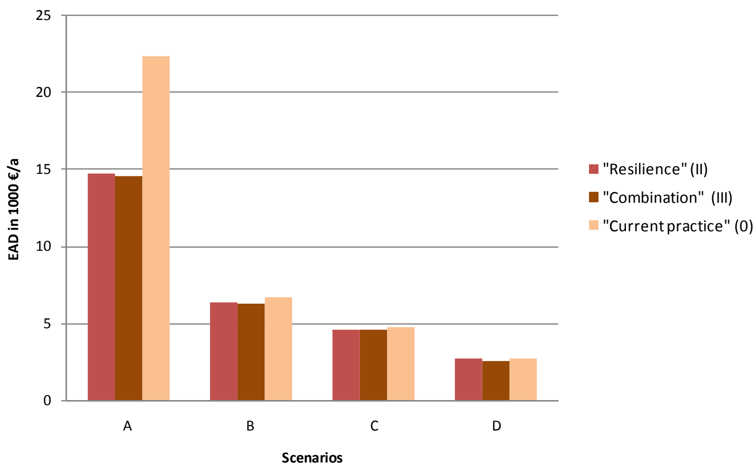

Figure 2.14 Robustness of three strategic alternatives for the German Elbe River floodplain expressed by the respective EAD under each scenario (Luther & Schanze, 2009b)

Webbased decision support tool for long-term planning

To facilitate the use of the modelling results for the Elbe River an actor-oriented and web-based DSS for long-term flood risk management has been designed and programmed. The tool allows all actors involved to explore scenario-based future flood risks and effects of risk reduction alternatives. Two aspects play a major role in the concept of the tool: firstly, an easy-to-understand and interactive applicable Graphical User Interface (GUI) is realised, secondly developing a sound technological solution based on the ArcGIS® Server 9.3 software and including all relevant model outcomes.

Figure 2.15 presents a screenshots of the tool. The GUI shows the step-wise approach which consist of (i) the selection of a guiding or key question respectively, (ii.) the choice of strategic alternatives and scenarios, and (iii) the final display of the results. The latter is based upon two maps. The map on the left hand side comprises spatial information on the chosen strategic alternatives and scenarios, the map on the right hand side provides the resulting water levels and risks. Numerous features allow for GIS functionalities, such as for example queries for manually edited polygons, even for a client accessing the website from a normal browser.

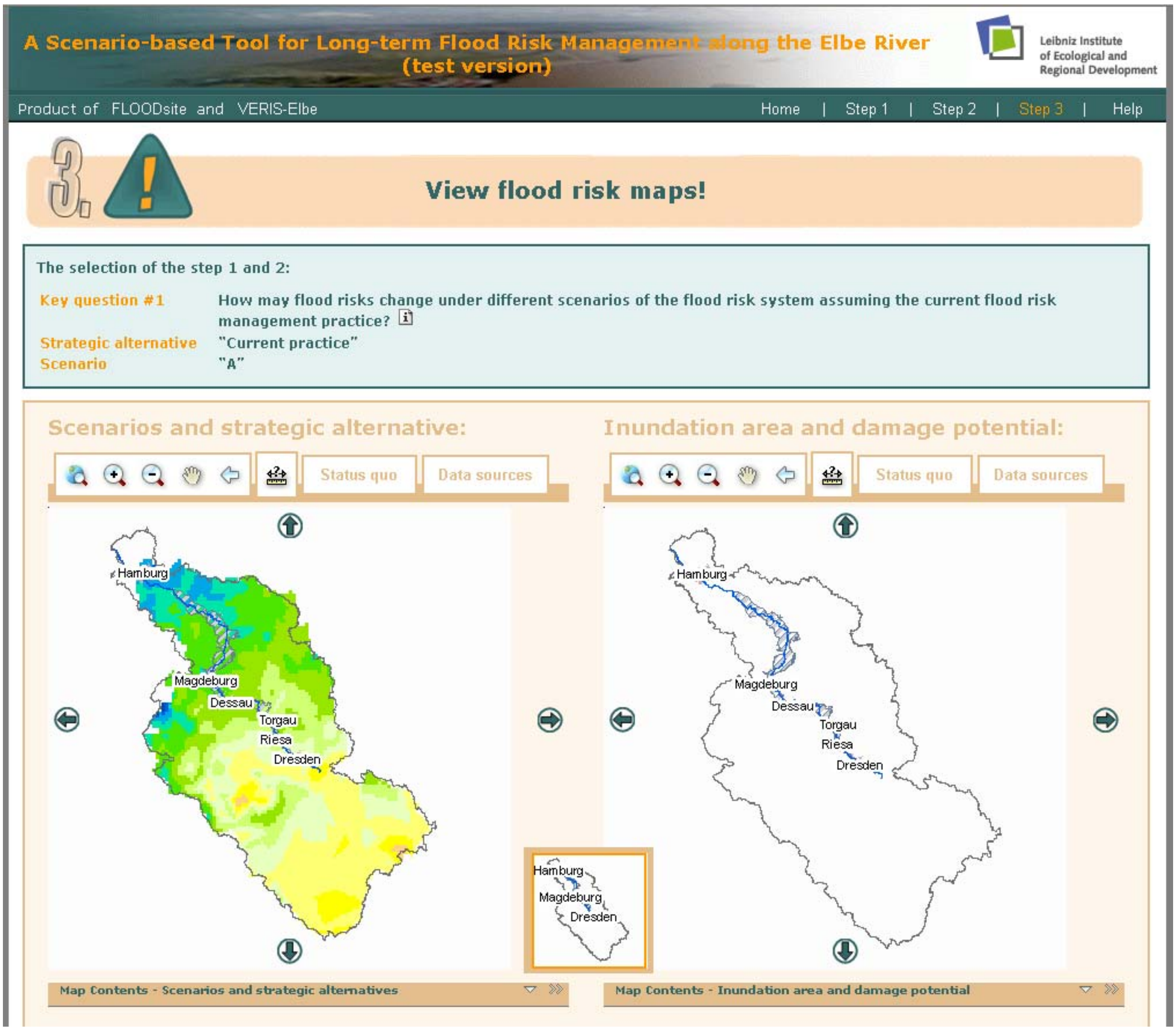

Figure 2.15 Screenshots of the scenario-based tool for long-term flood risk management for the Elbe River basin (Petroschka et al., 2009)

Decision-making and development process

Since all calculations of current and futures risk just build the evidence base for societal decision making, research also covered workshops with relevant experts and stakeholders in flood risk management. Uptake of the integrated methodologies towards effective risk reduction mainly depends on this people who are responsible for the formulation and implementation of flood risk management strategies (Hutter, 2006). The so-called stakeholders are often addressed in research but there requirements are not always met. The pilot site Elbe River basin therefore not only encompassed more generic investigations on major aspects (dimensions) of strategy making. Beyond it covered the organisation and accompanying analysis of workshops. Most important addressees were the International Commission for the Protection of the Elbe River (ICPE) and the German Elbe Board. In addition officials and experts with other affiliations, but similar cognitive orientations have been consulted representing all in all water authorities, spatial planning authorities, nature and environmental protection, as well as major municipalities and regional districts.

Findings can be interpreted as a confirmation that the principal approach of the tested integrated methodologies reached acceptance particularly with regard to a long term perspective. However the complexity of the topic and the scope of assumptions especially for the scenarios need clear guidance to facilitate the understanding and the application of the results. The DSS tool appeared to be a valuable tool in this respect. Due to its public accessibility decision makers strongly requested to provide sufficient information which indicates the difference between the scenario-based results and the existing official calculation as basis for the currently implemented risk reduction activities. Of course, time horizons on the current measures significantly differ from the scenario-based exploration. Therefore the latter should be seen as a means of understanding the flood risk system's behaviour to support current decisions.

2.3.5 Innovations towards integrated flood risk management methodologies

The scope of the study led to a considerable number of methodological developments, both disciplinary and interdisciplinary. Noteworthy particularly are the weather generator and the design precipitation transformation, a combined analysis of climate and land-use change impacts on the rainfall-runoff process on the plot and catchment scale, the novel reservoir module for the rainfall-runoff model PREVAH, the multi-criteria flood risk analysis developing the FloodCalc tool, the testing of the scenario planning approach from VERIS-Elbe, the actors-oriented and web-based DSS tool for long-term flood risk management, and the knowledge on risk awareness and preparedness of people at risk. Although some of the methods already address cross-disciplinary issues, the overall approach from the coupled modelling of the flood risk system to the relation of the results to the real-world decision making process particularly emphasis the comprehensiveness of the research.

2.4 Contribution to flood risk management practice

The impact of results from the pilot site Elbe River basin on the flood risk management practice is of course difficult to anticipate, especially from the scientific point of view. However, there are some aspects that may indicate the relevance of research findings:

- Researchers from FLOODsite were invited by the ICPE and the German Elbe Board manifold to present the research objectives, the entire approach and the preliminary results. This already shows a principle interest on the scientific endeavour to comprehensively deal with the flood risk system of the large basin and its management in the long term.
- Preliminary results were discussed in detail. Hereby the scenario planning approach together with the coupled modelling appeared to be a new level of evidence base for decision making in the basin.
- Since the matter is rather complex for both researcher and experts from flood risk management practice the web-based tool allows for a stepwise exploration of the findings. The use of the English language in the tool which was recommended for its accessibility all over Europe and beyond has been amended by German translations.
- In addition, there are a number of direct applicable outcomes such as climate change projections, flood hazard determination for extreme events, vulnerability and risk maps, recommendations for the flood polder operation, evaluations of measures and instruments, and so forth.

All in all, results from the pilot study together with the VERIS-Elbe and other projects can be seen as a significant step toward the implementation of a flood risk management plan for the Elbe River basin. Based on this, the basin may even become a pilot case for a good long-term flood risk management practice. In addition, knowledge and empirical examples from the study contribute to the curriculum, workshops and field trips of the international FLOODmaster course at the Technische Universitaet Dresden. In line with the approach for the entire pilot site the course is dedicated to a comprehensive understand and to integrated methodologies and thus involve lecturers from several disciplines.

2.5 Conclusions and outlook

Research at the pilot site Elbe River basin supported an in-depth understanding of the entire flood risk management issue in the major European basin from the physical processes to risk perception of the people. Furthermore it resulted in a successful development and testing of integrated methodologies for risk analysis, risk evaluation and risk reduction as well as on an actor-oriented and web-based decision support. Beside disciplinary innovations the comprehensive treatment of the problem led to particular advancements on the emergent level of an integrated approach. Hereby practical applicability seems to be ensured given the feedback from stakeholders.

However, it can be said that the interface between technological knowledge and evidence base on the one hand and the decision making and development process of responsible actors and the people affected on the other hand seems still to need further research efforts. Dynamic change of the flood risk system additionally requests for more long-term surveys on the feasibility and effectiveness of a strategic planning approach especially on the regional and national level. And finally beyond the formulation of future strategies, success factors and according instruments for better implementation in terms of good governance should be seen as crucial for future flood risk reduction.

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3. Pilot site "Tisza River basin"

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3.1 Flood risks and previous mitigation efforts

With its catchment area of 157,000 km², the Tisza River is the largest left-side tributary of the Danube. The uppermost part of the catchment is situated in the national areas of Slovakia, Ukraine and Romania, while most of its lowland part is divided between Hungary and Serbia. Although the Hungarian part of the catchment area is near to 48,000 km² and the length of the Tisza stretch itself crossing the country is 580 km, the runoff ratio of the precipitation is rather low in the Hungarian part of the catchment, due to its predominantly lowland character. Thus the floods of the Tisza Valley are triggered by the precipitations reaching the upper parts of its catchment, situated in the neighbouring countries of Hungary (Figure 3.1). Due to the considerable slopes of its tributaries, sudden and vehement swellings take place along the latter, while the flood waves resulting from their accumulation on the Hungarian river stretches with low slopes propagate down very slowly and with very high water levels.

As for the river system concerned, it can be stated that the flow discharge of the Tisza River entering the national area of Hungary is composed by the discharges of four major and a number of minor rivers. The extension of the catchment area belonging to the Ukrainian/Hungarian border cross section at Tiszabecs is 9,707 km². The four most important rivers within this sub-basin are the following: The Black and White Tisza Rivers; The Visó River; The Iza River; The Nagyág River.

Besides these four major rivers listed above, the discharge of the Tisza is being fed by a number of minor (mostly right-bank) tributaries, the most important ones being the Tarac and the Talabor. Just downstream the national border section, a right- and a left-side tributary join the Tisza River: the Borzsa and the Túr, whose discharges are insignificant during low flow periods, but may be considerable, particularly in the case of the Borzsa (reaching even several hundred m³/s) during flood periods. The most important tributary of the Upper Tisza, the Szamos River, joins its recipient at Vásárosnamény, arriving from Transylvania (in Romania), unifying along its upper stretch a number of branches, while the most important tributary of its middle and lower stretch is the Lápos River. The catchment area at border belonging to the Csenger gauging section of the Szamos River is 15,283 km² (thus surpassing by 50% that of the Upper Tisza itself at their confluence). Its slope, however, is considerably lower than that of the latter.

The Kraszna River, joining the Tisza just downstream the mouth of the Szamos, plays a considerably less significant role.

The Bodrog River joins the Tisza at Tokaj. It collects with its extensive, fan-shaped river system the waters from the northern part of Trans-Carpathia and from Eastern Slovakia. To its gauging section Felsőberecki belongs a catchment area of 12,385 km², its resulting discharges being composed mainly by those of its tributaries in Trans-Carpathia (Latorca, Ung), and in a smaller degree by those originating from Slovakia (Laborc, Ondava, Tapoly).

Not far downstream from the Bodrog-mouth there is the Tiszalök Barrage whose backwater effect, during low flow periods, can be registered up to Záhony. The Sajó River, joining the Tisza downstream of Tiszalök, and collecting the major part of its waters, together with its main tributary Hernád from Slovakia is characterised by a more tranquil flow regime than the so far mentioned other rivers of the Tisza system. Downstream from its mouth, at a distance of 85 km, there is the Kisköre Barrage, the second one on the Tisza River, which influences the water stages, depending on the actual replenishment of the riverbed, up to the Tiszalök Barrage. The small river Zagyva, joining the Tisza at Szolnok and collecting the major part of precipitation falling onto the Middle Hungarian Range, can have only a limited effect on the flow regime of the Tisza.

The Hármas-Körös River, reaching the Tisza just downstream Csongrád, collects the waters of Western Transylvania. The extension of its catchment area belonging to the gauging section Gyoma is 19,700 km². Its four main branches are, in a North to South sequence, the Berettyó, the Sebes-, the Fekete - and the Fehér -Körös. The flood waves of the Berettyó generally flatten out relatively soon whenever not coinciding with those of the Sebes-Körös, whose flood peaks, on the other hand, are considerably reduced by the effects of the storage reservoirs of huge capacities situated in Transylvania (Romania). The catchment areas of the Fehér- and particularly of the Fekete-Körös have less elongated forms, so that the waters reach practically at the same time these recipients, occasionally resulting in violent flood waves. Downstream the unification of the four branches, along the Hármas-Körös with its very mild bottom slope, the water levels depend increasingly on the actual water stages in the main recipient, the Tisza-River. The flow regime of almost the whole Hungarian part of the Körös River System is influenced, during the major part of the year, by the barrages situated therein. The discharges of the Berettyó - and in the low flow period also those of the Hármas-Körös - are considerably influenced by the irrigation canals joining them (mainly the East Main Canal and the Hortobágy-Berettyó).

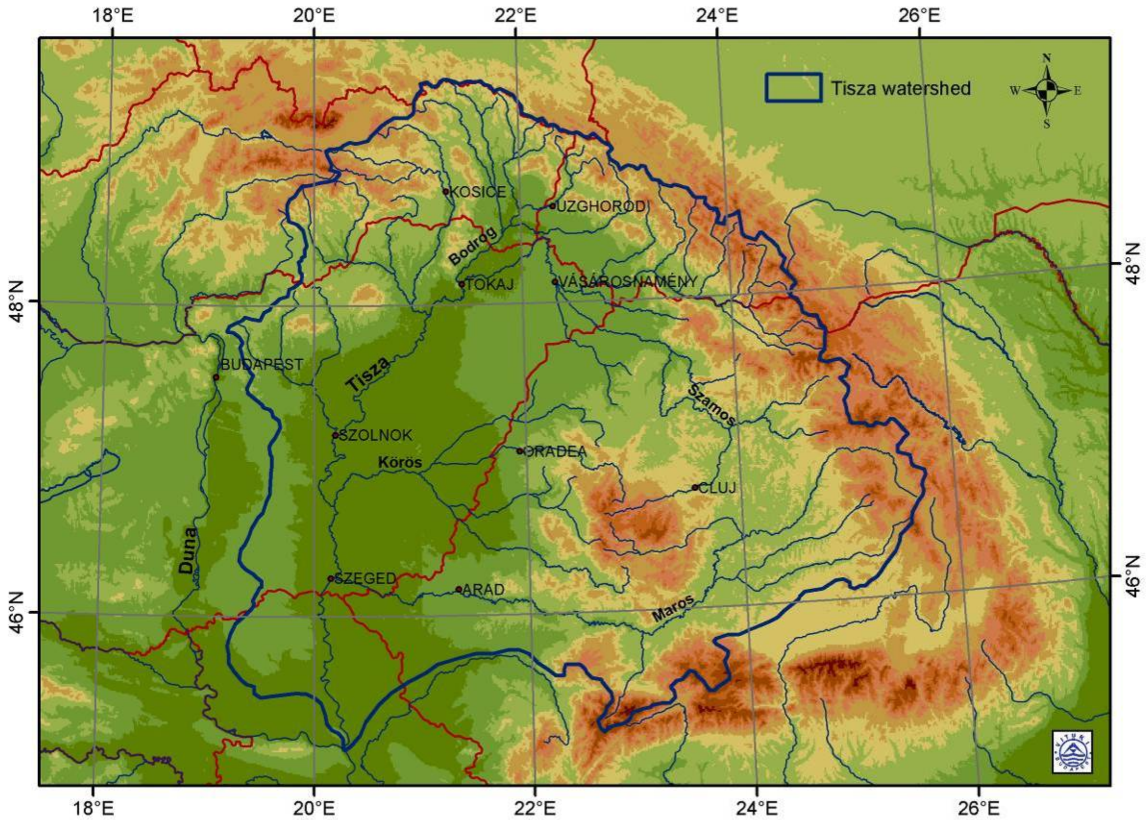

Figure 3.1 The Tisza River basin

Just upstream of Szeged the Maros River - the third main large Transylvanian tributary, besides the Szamos and the Hármas-Körös - joins the Tisza River. It collects the waters of Eastern, Central and Southern Transylvania. Its catchment area, belonging to the gauging section Makó, is rather considerable: 30,400 km². Its major Transylvanian tributaries are the Kis- and Nagy-Küküllő, the Aranyos and the Sztrigy Rivers. Before reaching the Romanian/Hungarian border, it makes a long way: the cross section of Gyulafehérvár (Alba Julia), which is the outlet of the upper part characterised by high runoff values, is in a distance of 350 km from the border. Along this long way, even the most violent flood waves of the upper stretches flatten out, so that the typical feature of the flow regime of the rather short Hungarian stretch of the river are its sluggishness and the prevailing backwater effect of the recipient Tisza River.

Along the mild-sloped lowest stretch of the Tisza River, the water levels may occasionally (e.g. during the flood wave of 2006) be significantly influenced also by the water stages of its recipient, the Danube.

A great part of the Hungarian Lowland was regularly inundated (blue regions in Figure 3.2), even during the 19th century, by the floods of the Tisza and its main tributaries. Flood protection works were started in 1846 and, with smaller and larger interruptions, the basis of today's flood protection system was created by 1900. At present about 2,700 km long dyke system along the Tisza River and its main tributaries protects 17,300 km^2 land and about 1.5 million people.

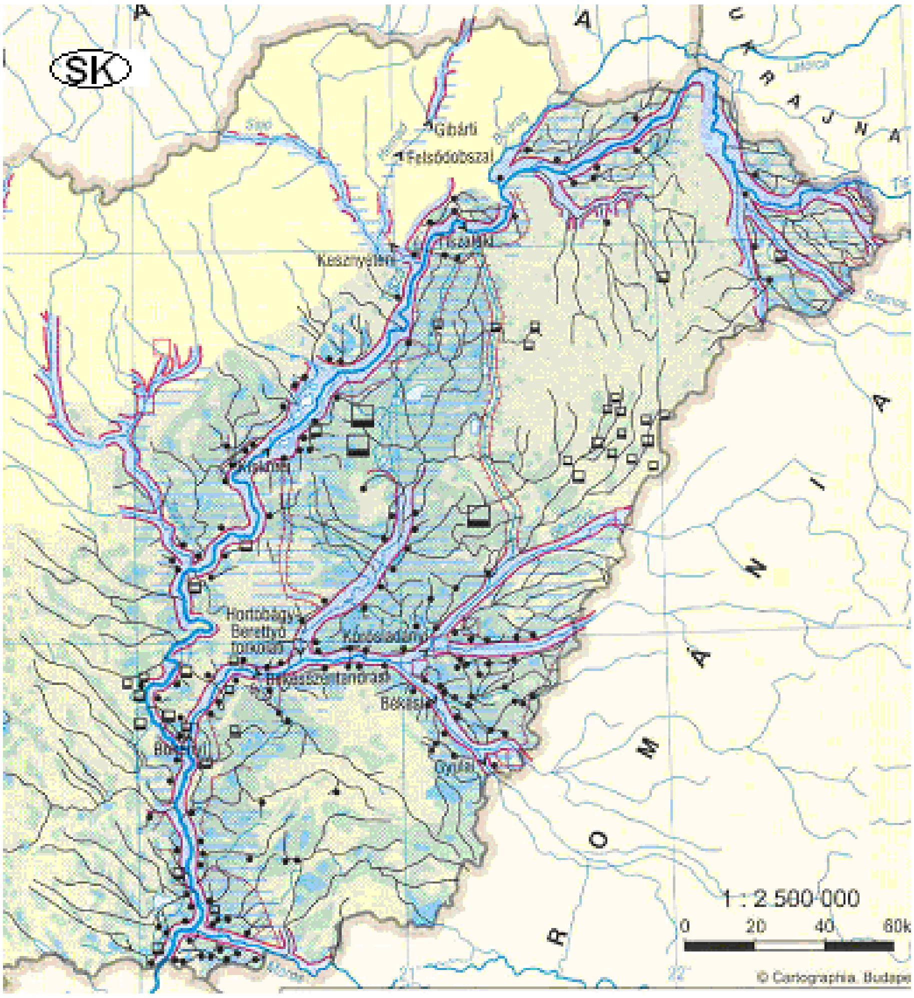

Figure 3.2 River network and flood defences in the Tisza Valley in Hungary

From the mid XIX[th] century more than one devastating flood occurred, such as that of 1879, leading to the catastrophic inundation of the town Szeged. There is relatively exact information available about the „historical" floods of the Tisza. Before 1970, snowmelt used to be very intensive, which, superposed by a great amount of liquid precipitation, triggered the flood of March 1888, that of April 1932 (resulting in particularly high water stages along the river stretch between Szolnok and Szeged), as well as the flood wave registered in December 1947 in the Trans-Carpathian part of the catchment, leading to various levee ruptures along the Upper Tisza.

The complexity of the hydrological processes taking place in the river system of the Tisza is evidenced also by the fact that the so far highest water stages on the various stretches of the river were caused by different flood waves depending on the magnitude of the discharges of the tributaries and/or the manner of their coincidence.

Prior to the flood wave of November 1998, the highest water levels (H_{max}) on the uppermost Tisza River stretch between Tiszabecs and Vásárosnamény had been observed during the flood of 1970. On the lower reach between Vásárosnamény and Tokaj, the highest stages were registered during the flood of March 1888, along most part of the reach between Tokaj and Szolnok in February 1979, while between Szolnok and Szeged again the flood of 1970 had caused the highest stages. Finally, along the lowest stretch of the Tisza, near to its mouth into the Danube, the so far highest water stages, due to the impounding effect of a great Danubian flood wave, had been measured in 1965.

As it is resulting from the above information, the H_{max} values registered before 1998 used to be the highest peak water stages observed during more than one century. Due to a caprice of Nature's forces - and partly/sporadically also as a consequence of anthropogenic effects - these secular record values were surpassed (at some places significantly and not only once) almost along the whole Hungarian Tisza reach during the subsequent three and a half years, as it is shown in Table 3.1, displaying both the water level values observed before November 1998 and those measured since then, surpassing all former values, showing in bold printing the presently valid critical values. The Table also shows, that at present, the record values are those of 2001 upstream Záhony, those of 2000 between Záhony and Szolnok and those of 2006 on the lowest stretch of the Tisza River. The degree of surpassing the former maxima is particularly great — more than 1 metre — on the Central Tisza between Kisköre and Szolnok, while at Szolnok the record water stage significantly increased (by almost 0.7 m), even during this relatively short period, subsequently at two events!

Table 3.1 Highest observed flood crests (H_{max}) before and after 1998

Gauge	Highest observed flood crestS (H_{max}) [cm]					
	before 1998	Nov 1998	Mar 1999	Apr 2000	Mar 2001	Apr 2006
Tiszabecs	680	708			732	
Tivadar	865	958			1,014	
Vás.namény	912	923			941	
Záhony	751				752	
Tokaj	880		894	928		
Kisköre	908		978	1,030		
Szolnok	909		974	1,041		
Csongrád	935			994		1,033
Mindszent	982			1,000		1,062
Szeged	960					1,009

The four major floods of the turn of the century triggered a development of the Tisza flood protection. The concept of increasing flood safety against the increasing flood risks in the Tisza Valley in Hungary, the so called Update of the Vásárhelyi Plan (UVP) has determined the main goals below:

- heightening and reinforcement of the primary flood embankments where their parameters do not meet the present design standards (to provide protection against the 1 in 100 years floods);
- decreasing flood peaks/crests by:
- *the improvement of the flood conveyance capacity of the high water bed;*
- *partial reactivation of the flood plain with controlled inundation, e.g. creation of a system of flood retention basins in the protected floodplain to reduce flood volumes passing down the river.*

To improve the river capacity, regulation of the floodway – creation of a so called "hydraulic corridor" is planned in a width of 600 m, by

- relocation of embankments, especially at bottlenecks,
- relocation and partial or complete demolition of summer dikes in the corridor, including
- demolition of channel-bars in the corridor,
- thinning vegetation, changing land use by rehabilitation of pastures and mosaic-type woodland in the corridor,
- increasing the flow capacity of bridge sections
- hollowing out natural elevation or silted up terrain where necessary and appropriate are envisaged along the river section between Kisköre and the southern border of the country.

The aim concerning reduction of flood crests was to find a solution by creating an appropriate system of flood retention basins which is capable of lowering the flood crests of the 1 in 1,000 years floods by 1.0 m. In fact, such a solution would provide safety against the 1 in 1,000 years floods as well, taking into consideration the expectable impacts of climate change.

To reach the above aim, a preliminary study estimated the total volume of flood retention to be in the range of 1.5 billion m^3 and included an overall investigation of 30 potential locations of flood retention basins along the River Tisza (see Figure 3.3).

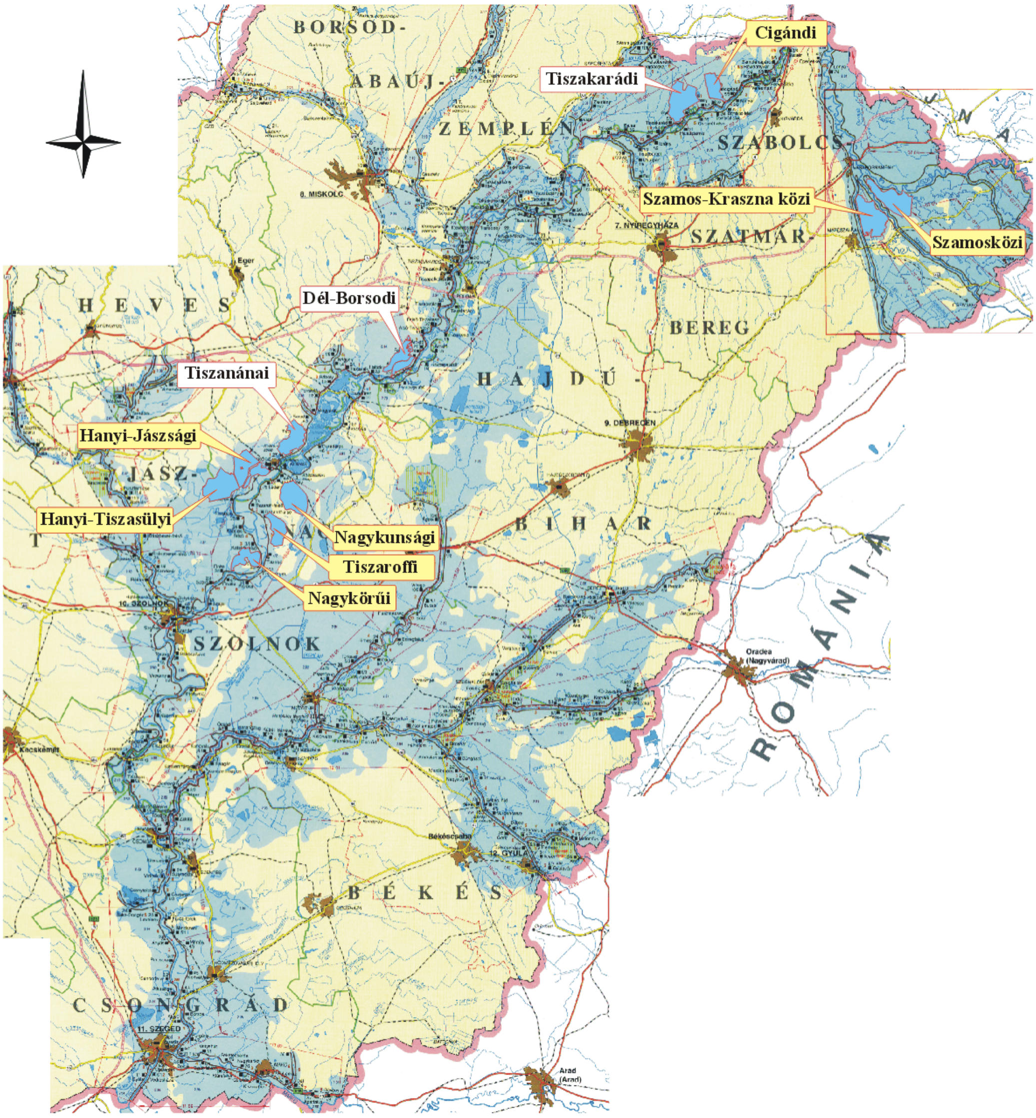

Figure 3.3 Selected flood retention basins along the River Tisza (version of 11 basins)

3.2 Objectives and approach

The Tisza pilot study was to apply and test the methods of flood risk management developed in the frame of FLOODsite project. As FLOODsite was carried out parallel to the "Update of the Vásárhelyi Plan" the research was harmonised with the Hungarian project and the results of FLOODsite were used to help improve the quality of the Hungarian project.

The objective of the Tisza Pilot was

- to develop a river basin based, precautionary and sustainable flood management strategies based on the investigation and analysis of previous floods, taking into consideration:
  - Analysis of catchment response and forecasting conditions
  - Factors of river capacity problems along the Middle-Tisza section
  - Effects of pollution due to flooding
  - Scenario analysis of intervention options to raise the flood conveyance capacity of the flood bed
  - Scenario analysis of partial floodplain reactivation with controlled inundation
- fostering international co-operation, especially in the fields of:
  - Review and evaluation of existing hydro-meteorological monitoring network, data exchange, methodology and dissemination of forecast and warning
  - Forecasting, data exchange, IT developments, virtual common flood management centre
- application of methods for determination of vulnerability developed in FLOODsite (sub-theme 1.3), in one of the flood cells to identify the effects of flood management strategies on flood risks.

Although Tisza pilot was a separate Task of its own the team contributed to other Tasks in FLOODsite such as "Identification and ex-post evaluation of existing measures" and "Emergency flood management".

3.3 Major findings

3.3.1 Inventory of pollution sources, fate of pollutants, need for further research

In early 2000, two major mining-related accidents occurred in the Maramureş County in Romania (See Figure 3.4) which caused the release of large amounts of cyanide and heavy metals into the rivers Szamos and Tisza (a major tributary of the Danube).

The Hungarian sections of the Tisza River and the Szamos River form the investigation area. The Tisza basin is the largest sub-basin (157,186 km^2) of the Danube basin (801,463 km^2). Samples of sediment and water were taken starting downstream of the eastern border to Romania at Csenger and ending at Szeged in the south of Hungary close to the Serbian border (See Figure 5-5).

The Tisza and three of its tributaries (Szamos, Körös, Maros) were investigated. The Szamos and the Maros can be seen as its most polluted tributaries due to the influence of industrial and domestic sewage from towns at the end of the Carpathian Mountains. As a result the water quality decreased drastically (WWF, 2002).

Following a period of heavy rainfall (30 l/m^2) and snowmelt, a dam breach occurred on January 30, 2000 at the Aurul S. A. gold processing plant in Baia Mare (Maramureş County, Romania) releasing ca. 100,000 m^3 tailings waters. The water contained ca. 1,000 t cyanides and 1,000 t heavy metals. The polluted water flowed over small rivers from the dam into the Szamos, which enters the Tisza at Vásárosnamény in Hungary.

Shortly after the Baia Mare accident (March 10, 2000), another accidental spill occurred at the Novat tailing dam[1] near Baia Borsa (Maramureş County, Romania) again triggered by heavy rainfall (37 l/m^2) and snowmelt. Polluted water flowed through the Vaser River into the Upper Tisza. The total

[1] at the Preparation Enterprise for processing complex ores of Pb and Zn

load was estimated at 40,000 t[2] solid waste (containing heavy metals, e.g. Cu, Pb, Zn) and 100,000 m^3 water.

The high concentrations of cyanides killed almost immediately more than 1,000 t of fish on the Hungarian side. Cyanides pose a short-term threat to the environment due to their degradability. In contrast, heavy metals deposit in the river catchment area and can accumulate in the food web due to their lack of degradability, which results in a long-term threat to the ecosystem and to humans.

Figure 3.4 Location of the accidental spills (Baia Mare and Baia Borsa) in the catchment area of the Danube

To assess the contamination, sediments were sampled along Szamos and Tisza in Hungary (see Figure 3.5) from 2000 to 2005. Concentration of arsenic, cadmium, cobalt, copper, molybdenum, nickel, lead and zinc was investigated both in surface sediment and in vertical sediment profiles. The aqua-regia soluble element contents and the bonding forms of selected elements were analyzed in the grain size fraction < 20 µm.

Heavy metal concentrations in sediments were initially high at the Szamos (≤ 3,000 mg/kg Zn) and decreased with increasing distance from the mining accident (ca. 500 µg/g Zn in the middle section of the Tisza). In 2005, the trace element concentrations in the Szamos have decreased to a level slightly higher than in the Tisza. The concentration decline is probably caused by dilution with "uncontaminated" sediment, transport of contaminated substrate further downriver as well as transport out off the river onto the floodplains. Most of the sediment profiles do not reflect the mining accidents of the year 2000, which indicates a long history of heavy metal contamination in the Tisza catchment.
Cluster analysis discriminates three sections of the research area: (1) Szamos, (2) middle Tisza and (3) lower Tisza. This pattern is based on the contamination level ranking from high to low.

Although the decrease of the sedimentary heavy metal concentration gives a positive impression regarding the sediment quality, potential sinks of the contaminants should be determined. Therefore

[2] other sources: 20,000 t of mineral waste

further research is needed to assess the effect on floodplains, because they are due to their agricultural use integrated in the human food web.

Overall it can be concluded that the contamination level of the sediments in Tisza and Szamos has decreased. The concentrations of heavy metals and As declined significantly since the mining spills in early 2000. The decrease is especially pronounced at the extremely contaminated locations at the Szamos. But still most of the investigated elements exceed target values recommended for sediments and soils.

Figure 3.5 Map of the Tisza River and the sampling locations

Since heavy metals are not biodegradable other mechanisms must have caused the decrease. These could be the redistribution of contaminated sediment during subsequent floods, which is connected to an increase in the contaminant concentration in adjacent floodplains and sediments downriver. Mixing with non-contaminated sediment could also be responsible for some of the concentration decline since the spill. This material can be derived from tributaries of the Tisza from non-mineralised regions. Dissolution can also play a role in the contaminant decrease, although the data from the performed bonding form analysis do not give a consistent picture.

Based on the results of the sediment analyses, an estimation of the potential input of contaminants bound on sediments into floodplains and adjacent areas of the Tisza and Szamos was made. This first rough assessment showed that the soil element content increased strongly during repeated flooding; in a few cases the increase was extremely high. This first assessment of the risk potential of heavy metal contamination for soils in floodplains demonstrates their high contamination threat and the need for further research.

3.3.2 Scenario analysis of intervention options to raise the flood conveyance capacity of the flood bed

After a relatively long dry period unprecedented series of extreme floods hit the Upper- and Middle Tisza River between November 1998 and March 2001. During the 28 month period four extreme floods occurred, as a consequence of which the total duration of flood alerts reached 24 month. Within this, extraordinary alerts lasted 9 months. The November flood in 1998 as well as the March flood in 2001 brought new records in flood peaks along the Upper Tisza, the latter caused even dike breach there. However, these floods due to the attenuation of the single flood waves resulted in a high, but not extreme flood on the Middle-Tisza section which is subject of our investigation, being the selected pilot site downstream of Szolnok (see Figure 3.2).

Analysis of the time series of annual maximal, mean and minimal water stages of the past century at the Szolnok gauging station (Figure 3.6) shows a trend of increasing high water levels, slightly decreasing mean water levels and decreasing low water levels. The decrease in the mean and low water levels is the result of the deepening and narrowing of the mean river bed as it will be seen on the evaluation of the changes of the cross sections. The reason of the increasing maxima is also partly connectable to the above changes but is more complex and will be explained by the evaluation of the discharge measurements.

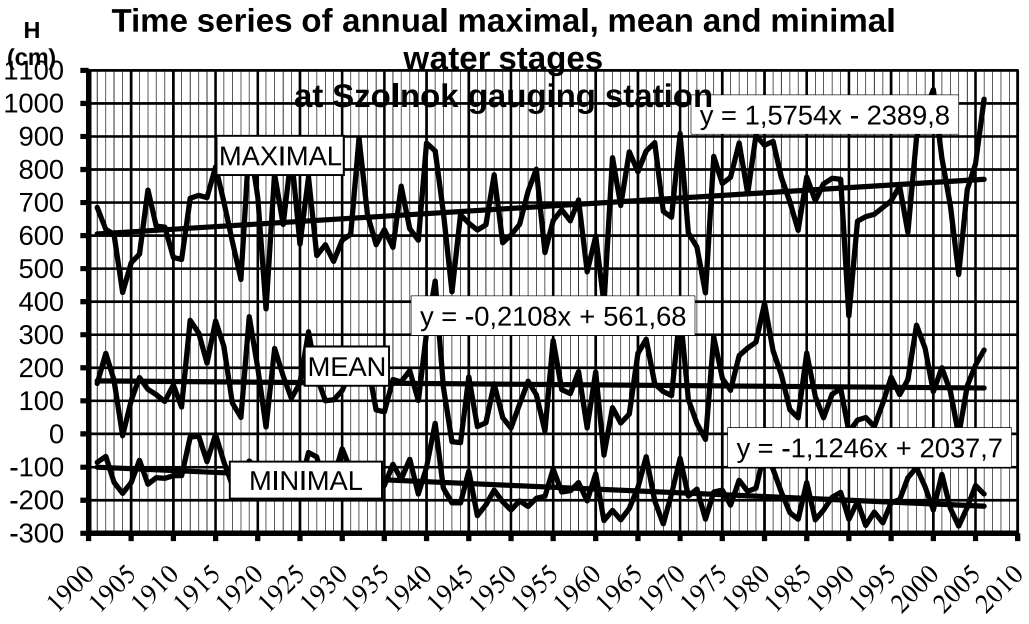

Figure 3.6 Trend in maximal, mean and minimal water stages

To discover the main causes of the problem data collection has been organised and performed including the analysis of sets of maps of the past 220 years (including the first military survey in 1782-85, the second military survey in 1826-66, a study on the changes of the river between 1830 and 1890 titled “The Tisza River long ago and now”, the Tisza Atlas made in 1930 and in 1976, finally ortophotos made in 2001). Data collection and analysis concentrated on the reduction of the area of the flood bed (floodway), on the artificial structures erected in the floodway, especially summer dikes, on the changes in the mean riverbed (Figure 3.7) and in the land use of the floodway with special regards to the floodplain forests.

Using the HEC-RAS 1D hydrodynamic model, after successful calibration and verification, analysis has been made on major intervention options to raise the flood conveyance capacity of the flood bed along the Middle-Tisza section, notably demolition of summer dikes, and creation of a ‘hydraulic corridor’ in the floodway cleaned from manmade obstacles of flow and from dense vegetation (rehabilitation of pastures and mosaic type floodplain forests in the floodway). Individual and integrated effects were also determined and proved to be very efficient in lowering flood crests (up to 40, 50 and 90 cm, respectively; Figure 3.8).

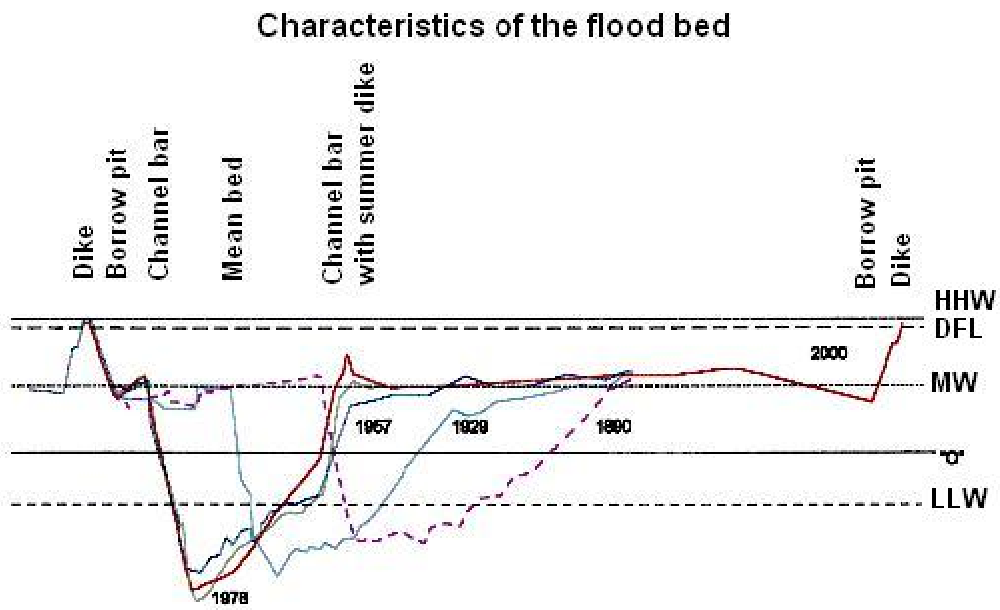

Figure 3.7 Characteristics of the flood bed

Analysing the results of model calculations accomplished along the Middle and Lower Tisza section it can be declared, that

- demolition of the summer dike sections crossing the designated hydraulic corridor has a water level decreasing effect varying between 5 to 42 cm along the river reach of 250-450 km sections between Csongrád and Tiszadorogma,
- as a result of dike relocations and land use change or changes in cultivation branches to create the 600 m wide hydraulic corridor a further decrease in water level of 5 to 48 cm can be reached in the section between Csongrád and Kisköre,
- the integrated effect may result in a reduction of 10 to 95 cm on the river section between Csongrád and Kisköre, at the same time the interventions may result in an increase of water level 10-15 cm on the section between Szeged and the southern border of the country; this effect also extends to the Serbian section of the river (Figure 3.8).

In case the floodway regulation is extended to the Lower Tisza as well, and the interventions are implemented section by section in a recommended sequence advancing from downstream to upstream, the negative effects observed in the previous case can be eliminated.

3.3.3 Analysis of the impact of extreme precipitation patterns on the flood peaks along the Tisza River

Following the almost three decades' time elapsing without any major event after the by now legendary great flood in the Tisza Valley of 1970, during the last ten years there were as many as five outstanding flood waves in the Tisza River system (in the years 1998, 1999, 2000, 2001 and 2006) resulting along a number of various shorter or longer river stretches of the system in water levels surpassing all the previously observed maxima.

On the basis of a detailed analysis of the hydro-meteorological scenarios leading to the various flood situations, one may conclude that – although these flood peaks in a number of places substantially surpassed the former maximum values – in most cases both the hydro-meteorological scenario preceding the flood and that following it, were far from being the potentially worst ones. This fact, of course, is involving the sinister perception that there is a realistic chance for the future occurrence of flood waves characterised by even more extreme hydrological parameters than those observed in the past.

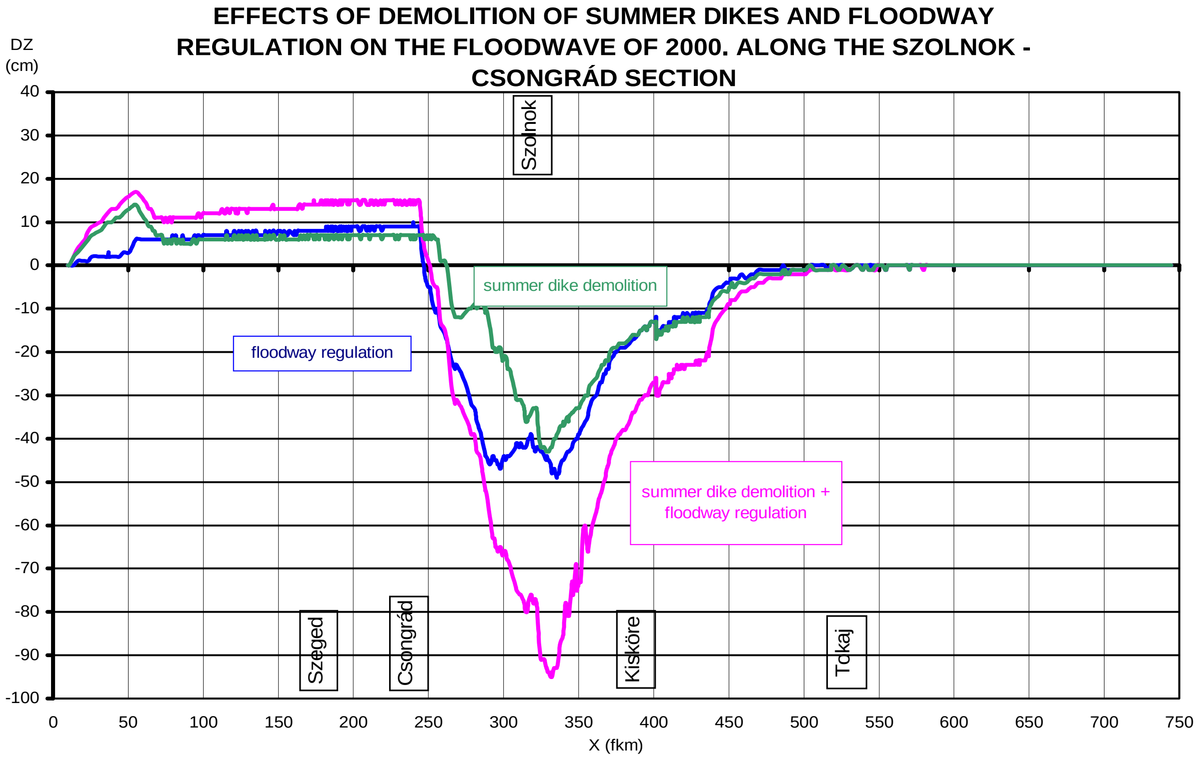

Figure 3.8 Effects of interventions in the floodway on the depression of flood crests

A detailed investigation on the effects of flood-triggering meteorological processes was started around 1970 by E. Bodolai-Jakus (BJE), identifying the types of weather patterns triggering floods, determining the frequencies of occurrence of these patterns and the role of each of them in creating the various types of flood waves. When classifying weather patterns, the investigation was based on the actually observed precipitation cycles producing flood waves. Thus the flood wave periods were not connected to the types of a pre-existing catalogue, but inversely: the types of weather patterns providing large amounts of precipitation were identified for the catchment area of the Danube and Tisza, in accordance with the hydrological goal of the investigation. To put it more concretely, the quasi stabile objects were identified, for the theoretically significant period of classification, for about 800 rainy days triggering flood waves in the area investigated, on the 500 hPa absolute and the 500/1,000 hPa relative topographic maps. The seven types of flood wave-triggering weather patterns (see 6 of them in Figure 3.9) were identified on the basis of the characteristic geographical positions of three objects: the near-to-surface centre of the cyclone, the depression- and the crest line of orographic maps.

The results of the meteorological investigations indicated that the frequency of weather scenarios leading to flood waves is changing with time and that there is an increasing tendency of their absolute frequencies within the range of all typical weather situations. It is also obvious that in the lowland part of an extended catchment area like that of the Tisza Basin with its strongly braided river system, flood waves propagate only very slowly, so that the genesis of the latter is predominantly determined by the weather conditions of longer periods, generally characterised by an accumulation of weather types. All the same, the attempts to maximise such weather type accumulations did not provide acceptable results: since their completion, even more disadvantageous weather combinations were observed over the catchment. Therefore the hydrological investigations carried out in the framework of the present work were aiming at the determination and analysis of the potential changes caused by certain modifications of the flood scenarios had already occurred in the past.

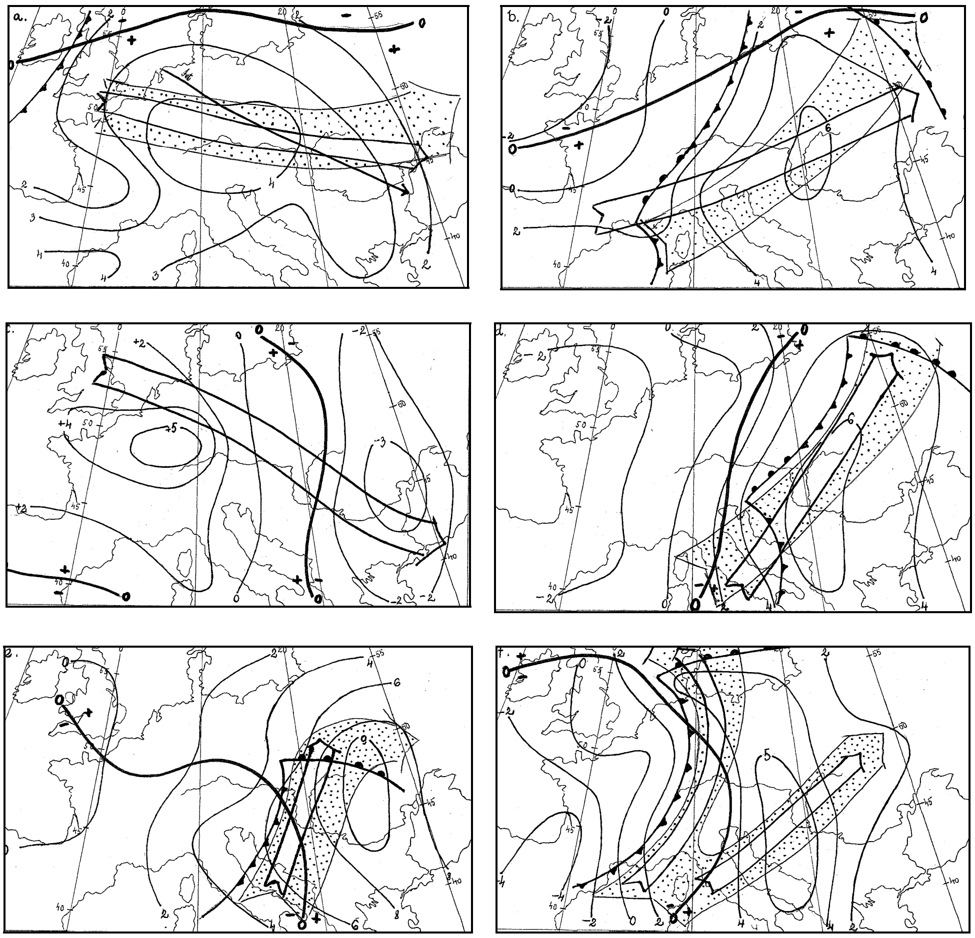

Figure 3.9 Flood inducing weather patterns:a - West (W); b - West with peripheric storm (W_p) c - Zonal (Z); d - Moving Mediterranean Cyclone (M);e - Central Type (C); f - Western Cyclone (C_W)

It was investigated, what would have been the effect exerted on the water levels of situations in which the meteorological and/or hydrological/flood defence conditions during and before the floods had been slightly more unfavourable than they were actually. Thus various hydro-meteorological scenarios were generated by modifying one or more selected parameters of any of the selected actual (observed) meteorological and/or hydrological/flood defence situations and then the effect of such a modification was determined. According to the type of the modified hydro-meteorological parameters, the scenarios generated may be classified into the following four types:

- On the upstream river stretches, the height of flood levees differs from the actual value, resulting in the non-occurrence of real dike failures (see Figure 3.10);
- Modification of the extension and the progress direction of the precipitation zone causing flood waves, i.e., of the areal distribution of precipitation as compared with the real one (meteorological scenario);
- Modification of the actual progress velocity of the flood-generating precipitation zone, leading to a modified timing of coincidence of flood waves of the various tributaries (meteorological scenario);
- Modification of the actual precipitation conditions of the various sub-basins of the river system (Figure 3.11)

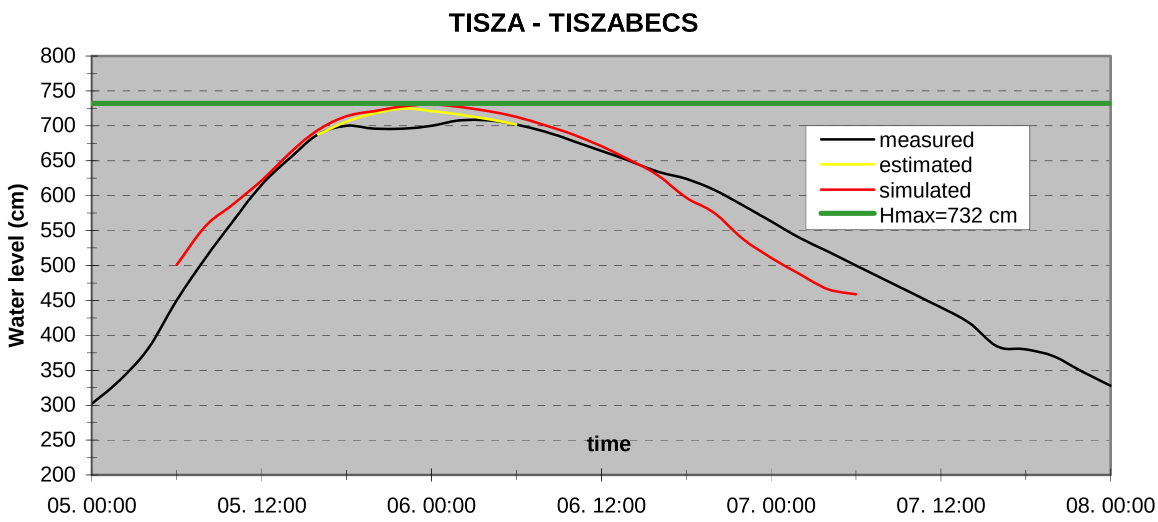

Figure 3.10 Observed, adjusted for dike failures and simulated hydrographs of the 1998 flood

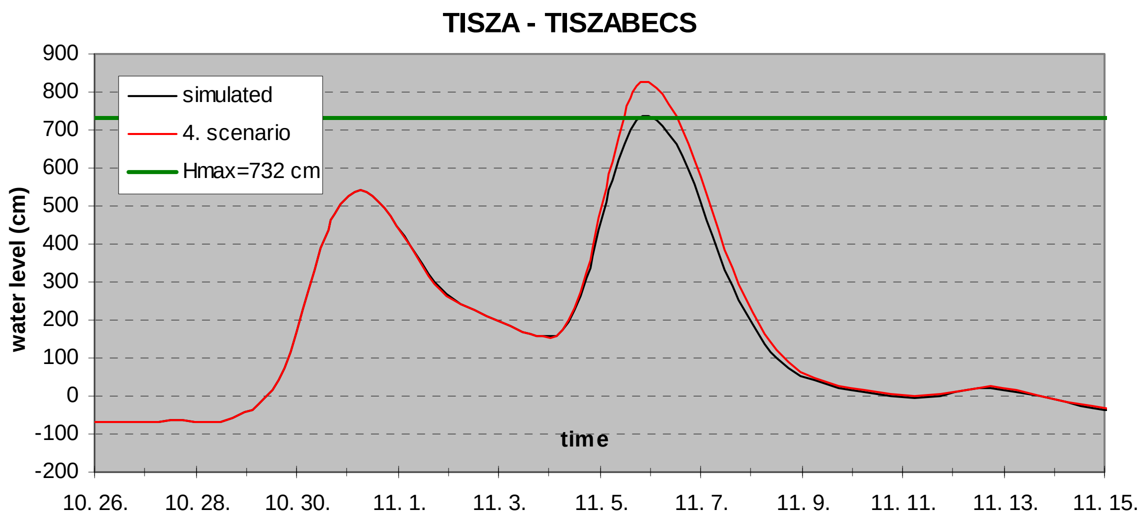

Figure 3.11 Stage hydrographs of the 1998 flood at Tiszabecs

The most important conclusions gained by the analysis of the processes, can be summed up as follows:

- The importance of the antecedent precipitation and the water content of the snow cover is higher than we have thought it previously,
- The run-off is very sensitive to the path of the frontal zones; minor deviation in geographical location of the precipitation field can produce extreme floods,
- The most dangerous situations for the lower Hungarian Tisza reach are the precipitation events on the Upper-Tisza followed by 8-10 days with a precipitation on the Körös-Maros catchment.

3.3.4 Scenario analysis of partial floodplain reactivation with controlled inundation

The concept of increasing flood safety against the increasing flood risks in the Tisza Valley in Hungary, the so called "Update of the Vásárhelyi Plan (UVP)" was explained before. To reach the target of 1 m reduction of the 1 in 1,000 year flood peak, a preliminary study estimated the total volume of flood retention to be in the range of 1.5 billion m^3 and included an overall investigation of 30 potential locations of flood retention basins along the River Tisza. Out of these potential locations 11 were selected for construction (see Figure 3.3).

Effect of partial floodplain reactivation on flood crest reduction has been investigated using the 1D HEC-RAS model. Results (see Figure 3.12) are in similar range than those of the improvement of river capacity (Section 3.2.2). The combined effects will result in the desired lowering of the flood crests in case of flood discharges equalling with that of in the year 2000 by min. 1.0 m.

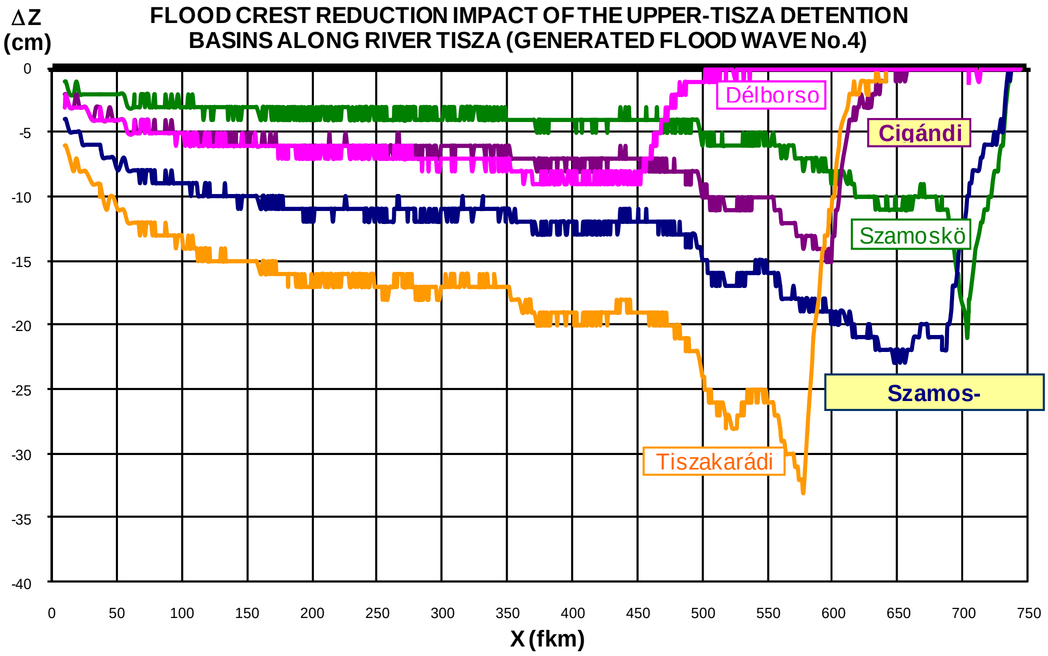

Figure 3.12 Individual effect on the reduction of flood crests of the Upper-Tisza detention basins

3.3.5 Development of a basin wide integrated system of monitoring, flood forecasting and warning

The basic aim of this action is to provide timely the necessary hydrological and meteorological information derived from monitoring networks together with the warnings and forecasts related to the future behaviour flood inducing processes and to transfer these data and information to those responsible for flood defence.

This part of research focused on three main topics:
- the inventory of existing monitoring systems (see Figure 3.13),
- the inventory of existing (in the Tisza Basin) flood forecasting systems and
- a proposal to create WEB based “virtual” forecasting centre (see Figure 3.14).

During the latest years many new, up-to-date, automated hydro-meteorological stations have been deployed in the Tisza Basin. They report to local forecasting centres. These centres are again connected to each other. The major advance in the co-operation of the Tisza Basin countries that some of the data collection centres are connected to each other across the state borders, thus the information can be easily transferred from one centre/country to the other. Though in many cases the data are collected hierarchically to a national centre and the international data transfer is initiated from there. Thus data transfer from country to another one can still be slow and during flooding situation the vital information might arrive late.

The range of hydrological forecasting models use in the Tisza Basin range from the simple correlation models, through linear routing routines and hydrodynamic modelling to grid based distributed parameter hydrological models. The more complex a model is the more data needed to run it.

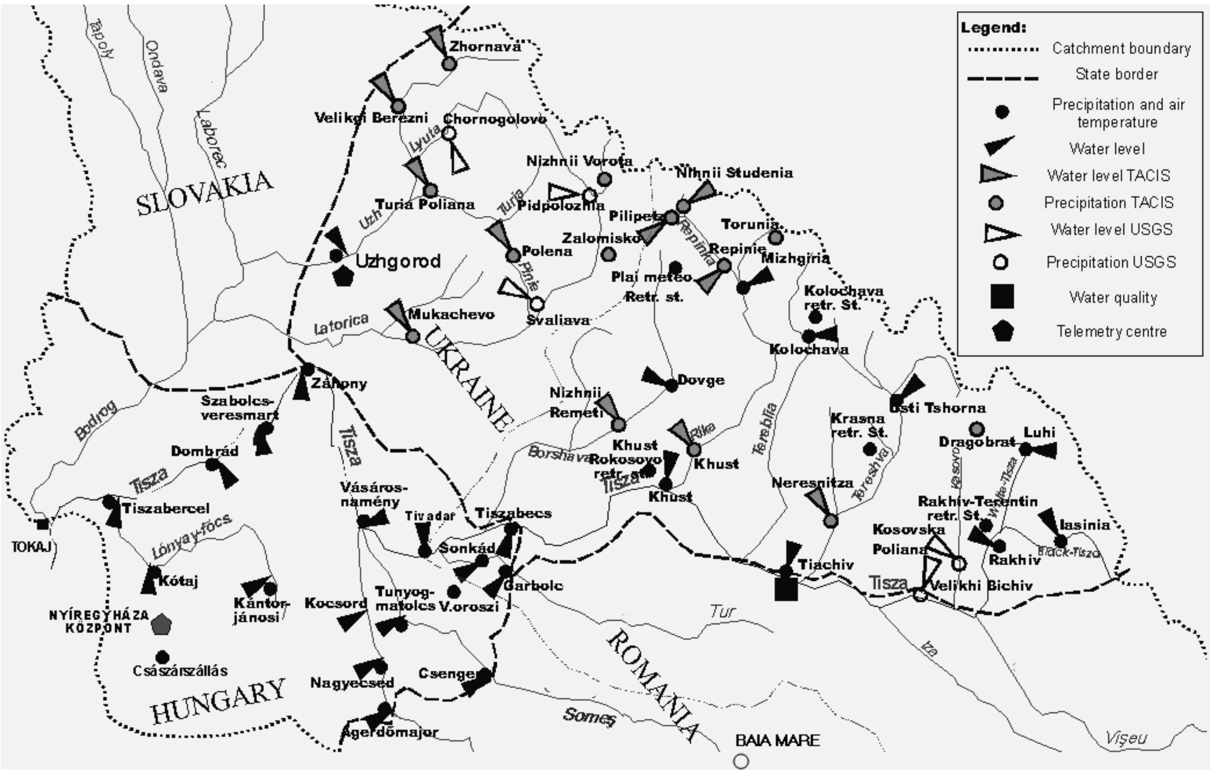

Figure 3.13 Joint Hungarian-Ukrainian Hydrological Telemetry System

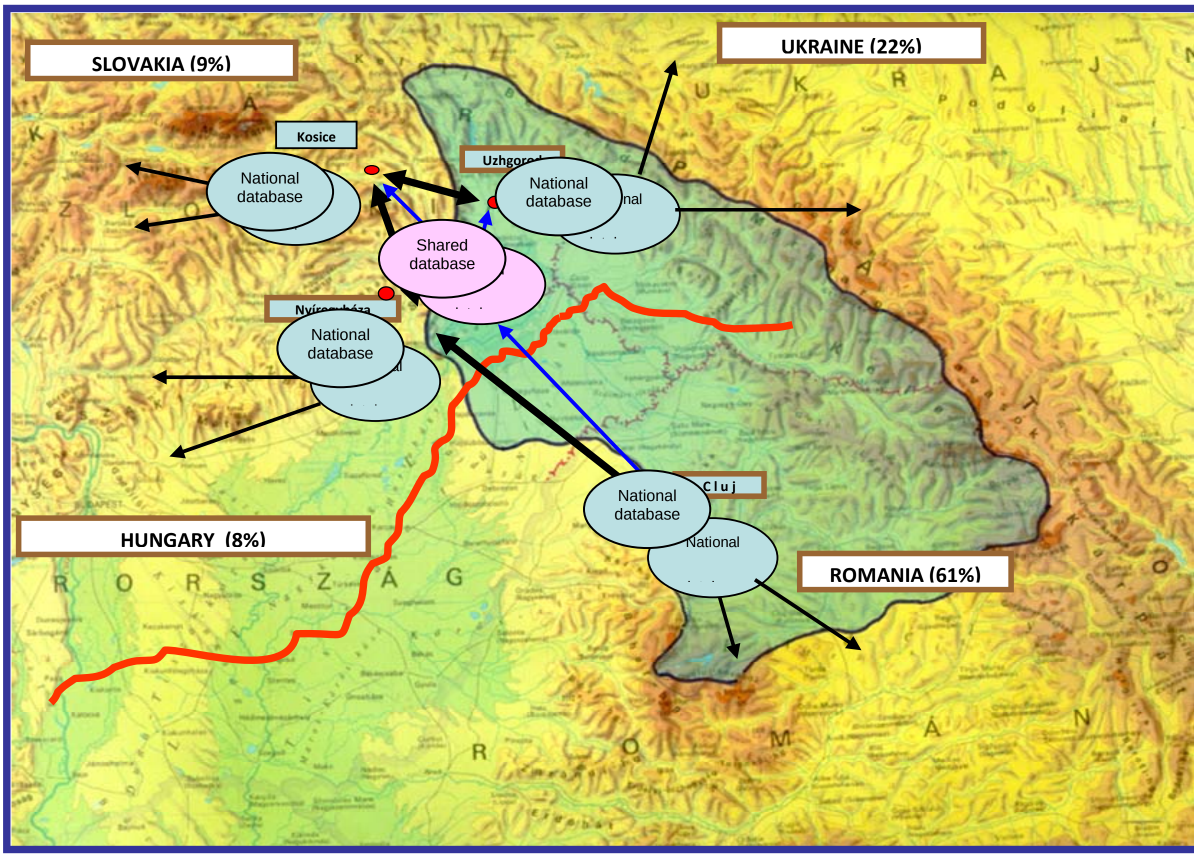

Figure 3.14 WEB based „virtual forecasting centre”

To meet the data requirements of the different models a central, "virtual" database is proposed. The NET based information centre can easily be accessed by each countries. The row data and the product (the forecasts) will be publicly available, while the private part serves for the communication of the national forecasting centres and for storage and exchange of internal data and information. A draft version of this "virtual" database has also been prepared.

3.3.6 Pilot study application of general vulnerability analysis to identify the effectiveness of flood management strategies

The objective of the pilot study was the application of a general vulnerability analysis techniques developed in FLOODsite sub-theme 1.3, in one of the flood cells to identify the effectiveness of flood management strategies. During the preparation for this analysis, to enable a realistic objective setting, first we had to review and evaluate data availability along the Tisza pilot site from Szolnok to Csongrád. The floodplain of this 88.4 km long river section consist of 6 separate flood area (floodplain basin) with a total extension of 563.42 km^2s accommodating some 110,000 inhabitants in 15 settlements, including Szolnok itself, an industrialised town.

In Hungary there are floodplain maps available produced in 1976-77 in scales of 1:50,000 and 1:100,000. (later in 1:500,000 as well) showing the extent of inundation of 1 in 100 as well as 1 in 1,000 year floods. However, these floodplain maps do not provide any information on elements of hazard like flood depth, duration or velocity. The maps are available in paper format only.

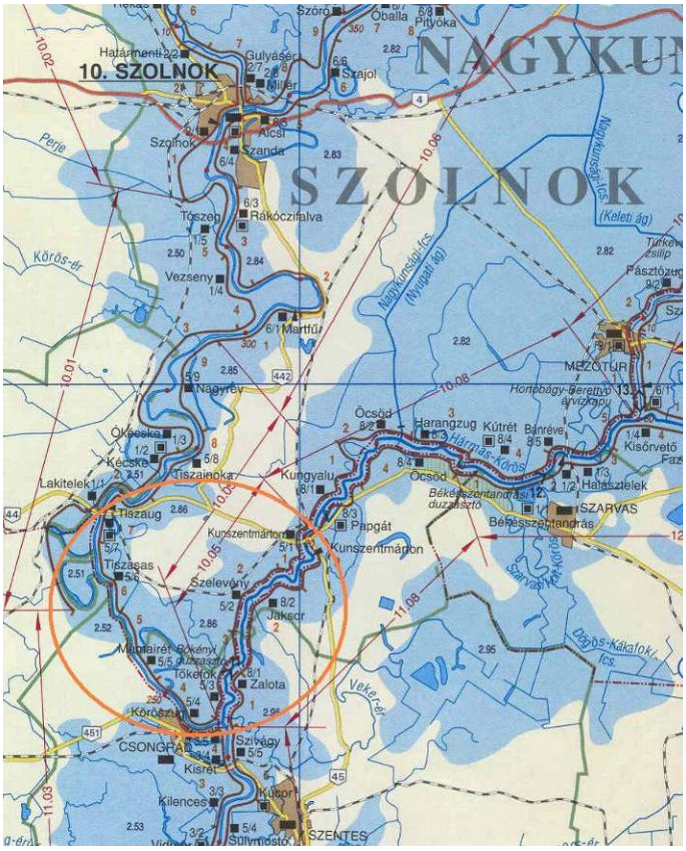

Figure 3.15 Location of the Körös corner flood area

Lack of data related to flood depth prevented us from undertaking the whole pilot area, therefore a smaller separate flood basin must be selected within it, for which DEM can be produced within the timeframe and budget conditions of this project. Further CORINE land use data were used while values of assets at risk were developed from Hungarian Statistical Yearbook, Regional and County Statistical Yearbooks, etc. Flood damage data of historical descriptions and records were also used, though no valid conclusion can be drawn for future measures from the existing unreliable and contradictory historical damage data.

The selected flood area (Figure 3.15 and Figure 3.16) is situated in a rural environment at the confluence of Tisza and Hármas-Körös rivers. It covers the inner area of four settlements (Tiszaug, Tiszasas, Csépa and Szelevény) and the outer area of Tiszainoka, Tiszakürt and Kunszentmárton. Population of the flood area is in the range of 5,000 capita while the endangered assets in the settlements are in the magnitude of 100 million Euros and in the agriculture 20 million Euros.

Land use patterns based on Corine Land Cover 1:50,000 (CLC 50) are shown in Figure 3.17. Prevailing land use category or type of activity at the lower elevations is agricultural, mainly arable land but there are also some complex cultivation patterns, orchards and pastures as well. Forests are rather rare in the protected flood area but are dominant in the floodway of the rivers. These forests are composed of broad-leaved trees with rather dense under vegetation. There are also some wetlands and lakes, mainly the oxbows of the River Tisza and Körös.

Industrial activity is restricted to the eastern edge of the flood area and is situated on rather higher elevation in the periphery of Kunszentmárton but still in the risk zone of potential inundation in case of failure of the defences. Commercial (retail, catering and hotel trade) units are placed on higher ground mainly in the inner area of the settlements. Hotel trade is developing in the area, mainly in Tiszaug, where not only guest houses but a three-star hotel with broad selection of leisure facilities and services is available.

The urban fabric of the settlements shows discontinuous rural character and is composed by detached houses with gardens. The average plot size is 655 m^2. Along the banks of the larger two oxbows recreation houses have been erected. These are also detached houses, sometimes bungalows. Several farm houses can also be found in the agricultural land.

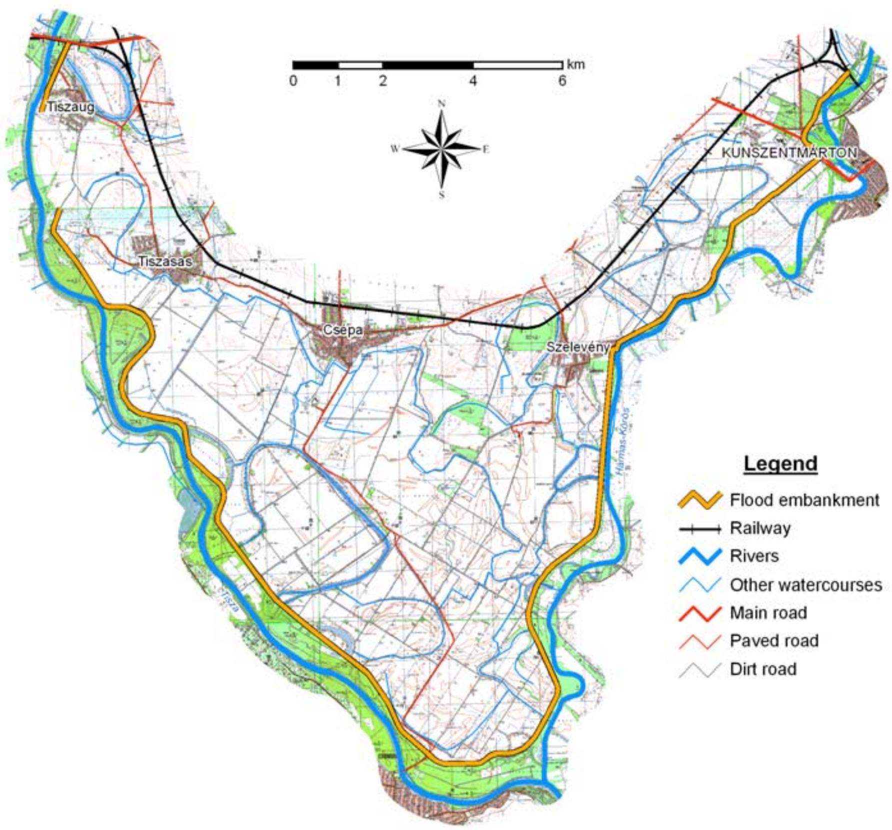

Figure 3.16 Topographical map of the Körös corner flood area

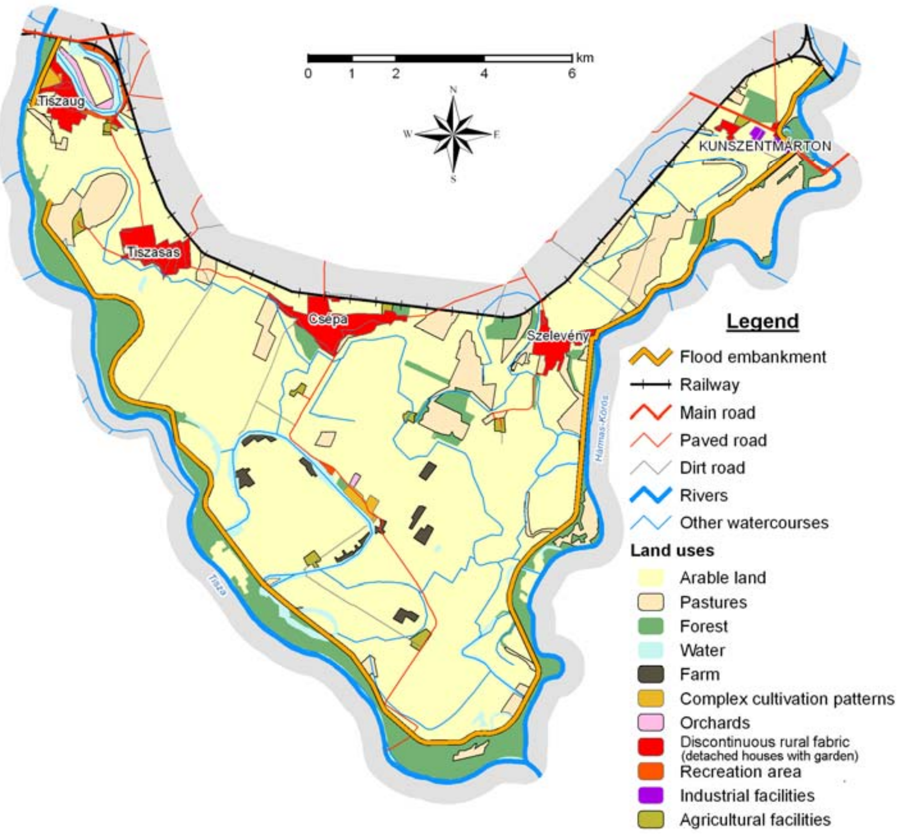

Figure 3.17 Land use map of the Körös corner flood area based on CLC 50 images

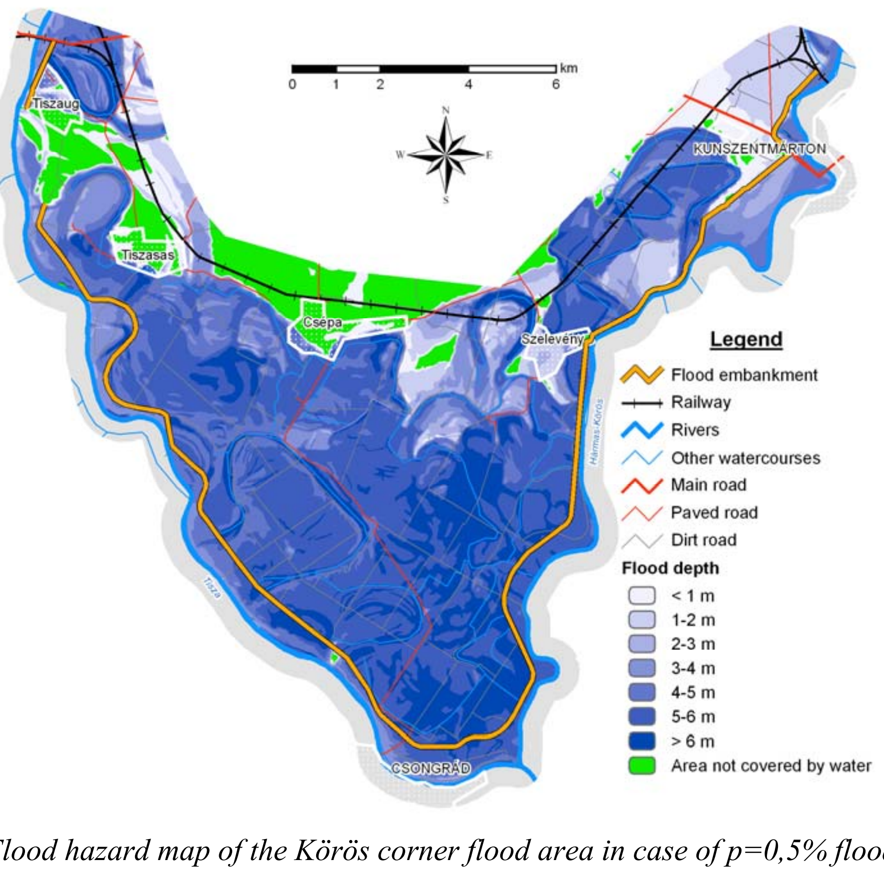

Figure 3.18 Flood hazard map of the Körös corner flood area in case of p=0,5% flood

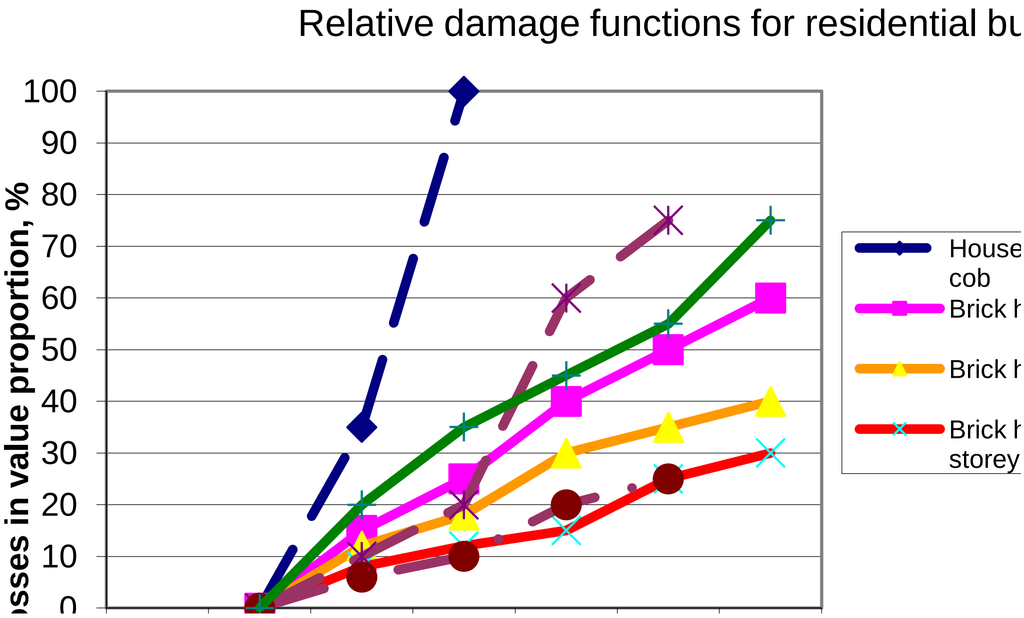

Figure 3.19 Relative damage functions for residential buildings

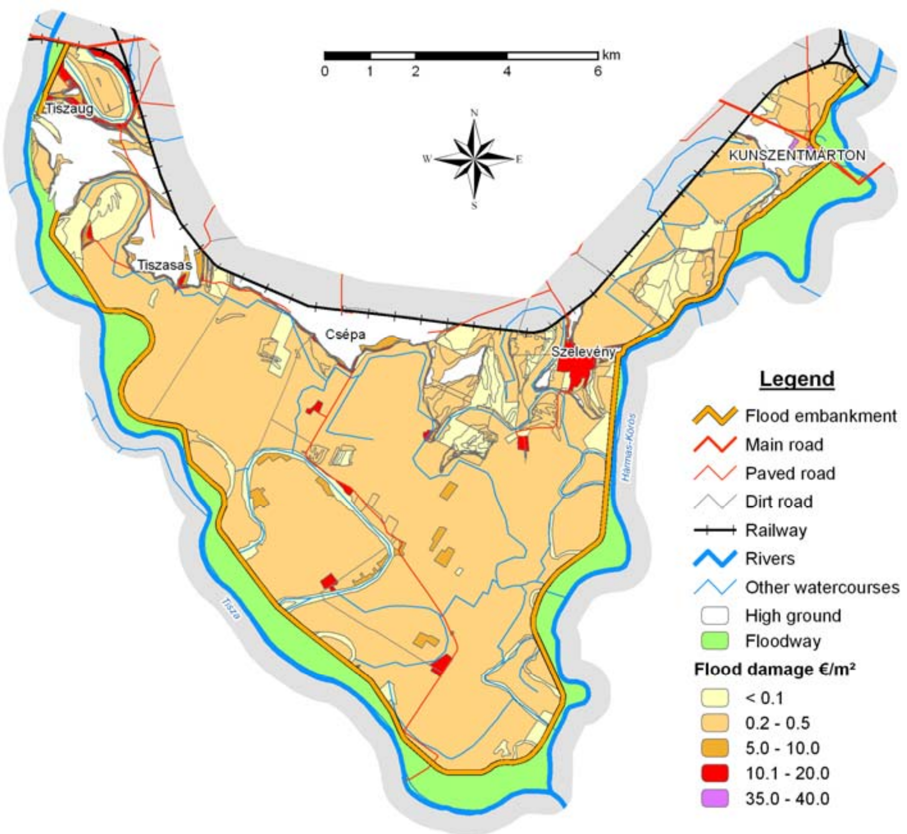

Figure 3.20 Damages for the 100-year flood event in the Körös corner flood area (mean estimation)

Inundation modelling has been performed by using the HEC-RAS model. Flood extent and distribution of flood depth is illustrated in Figure 3.18. It is clearly seen that properties in the fringes of municipalities Tiszaug, Tiszasas and Csépa will be covered in the range of < 1 m to max. 1-2 m, while Szelevény, which is intersected by the depressions of an ancient, silted up oxbow will suffer more serious inundation both in the share of inundated area and in flood depth. Industrial plant in the outer area of Kunszentmárton will be affected by ~1 m flood depth.

For the evaluation of the economic risk a macro scale approach was used since neither the available DEM, nor the rather coarse land use information and the level of economic data enabled us to apply a meso-scale method resulting in more detailed analysis.

To evaluate the damages relative damage functions were developed for residential buildings (Figure 3.19), for industrial, commercial and agricultural units.
Finally damages were calculated for different return period flood events (Figure 3.20).

Results of the work performed are demonstrated in the report,

- we developed the flood hazard map of the Körös corner flood area, indicating the distribution of flood depth,
- determined the extension of land use categories and the distribution of the value of assets at risk in the Körös corner flood area (mean estimation),
- developed relative damage functions,
- calculated and determined the distribution of flood event damages for three different scenarios, the floods of 200 year, 100 year and 50 year recurrence period (or 0.5% - 1.0% and 2.0% probability),
- calculated the annual average damage,
- documented the uncertainties.

3.4 Contribution to flood risk management practice

The key element of this research was to test the flood risk management methodologies developed in FLOODsite and to spread its use in the Hungarian practice. In the frame of the FLOODsite project the "FLOODsite methodology" was used to one of the flood basins of the Tisza River to develop a flood risk map of that region. The research focus on different aspects of the risk handling:

- the hydrology of floods,
- the spreading of pollutants on the floodplain,
- the improvement of the river channel conveyance,
- the use of flood retention reservoirs etc.

The results of the research will be (has been) incorporated into the "Update of Vásárhelyi Plan" (see Section 3.1). Later on it will be used in the future Duna flood protection development plan and in the flood risk management plan of Hungary.

The project pointed out some deficiencies of the Hungarian hydrological, geodetical, social and economic data collection. The quality of available data, the absence of digital elevation model etc. limited the scale and the accuracy of our pilot study in the application of the vulnerability analysis methodologies. In spite of the problem with the quality of data the methodology work perfectly well and we could develop the flood hazard and risk map of the "Körös corner".

The Hungarian water (flood) management has decided to adapt the "FLOODsite methodology" to the Hungarian conditions and use it for developing the flood hazard and risk maps required by the EU Floods Directive.

3.5 Conclusions and outlook

In the Tisza pilot project several elements of the flood risk and flood risk management have been investigated. Spreading of contaminants on the floodplain, improvement of river bed conveyance capacity, use of flood retention reservoirs, investigation of extreme meteorological conditions and their effects on the flood levels, use of "virtual forecasting centre" are mosaics of the complex research that contributed to the case study of the "Körös corner". The "Körös corner" is one of the many flood basins in Hungary. The vulnerability analysis developed in Task 1.3 was applied to this area. Flood hazard maps and flood risk maps were developed. In spite of the scarce and low quality data the results are very informative. Even a simple 1D analysis of the inundation (due to the financial constraints of the pilot study) showed enough details of flood risk to develop a proper flood risk management plan required by the EU Floods Directive.

The flood risk analysis methodology developed in the FLOODsite project was tested and successfully applied to one of the Tisza Basin flood cells. The “FLOODsite methodology” proved to be handy and useful in developing the flood hazard and risk maps.

3.6 References

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2. BODOLAI-JAKUS E (1983) *Árhullámok szinoptikai feltételei a Duna és a Tisza vízgyűjtő területén. (Synoptic conditions of floods on Danube and Tisza catchments),* Publications of the Hungarian Meteorological Service, Vol. 51, Az OMSZ Hivatalos Kiadványai LVI. K. Budapest.

4. Pilot site "European flash flood watersheds"

Marco Borga

4.1 Flood risks and previous mitigation efforts

4.1.1 Introduction

The term "flash flood" identifies a rapid hydrologic response, with water levels reaching a peak within less than one hour to a few hours after the onset of the generating rain event (Creutin & Borga, 2003; Collier, 2007; Younis *et al.*, 2008; Norbiato *et al.*, 2008). The time dimension of the flash flood response is linked, on the one hand, to the size of the concerned catchments, which is generally less than a few hundred square kilometres and, on the other to the activation of surface runoff that becomes the prevailing transfer process. Fast surface runoff mainly results from the combination of intense rainfall with steep slopes and/or saturated soils. It also results from anthropogenic forcing such as land use modification, urbanisation and fire-induced alteration of the natural drainage system.

The effects of a flash flood are potentially dramatic and can be measured both in terms of lost human lives and property damages totalling millions or even billions of Euros. In its 2000 policy statement, the AMS (AMS, 2000) acknowledges flash floods as one of nature's worst killers. Many recent examples underscore this claim. In a flash flood in Algeri on 9-10 November 2001, 740 people were killed and 0.5 billion Euro in property was destroyed in less than one day (e.g. Tripoli *et al.*, 2005). In another event occurred in Mala Svinka (Slovakia) on July 20, 1998 the death toll was forty-seven in less than one hour.

The examination of flash flood regimes across Europe shows that space and time scales of flash floods change systematically when moving from Continental to Mediterranean regions, while seasonality shifts accordingly from summer to autumn months (Gaume *et al.*, 2009). This has several hydrological implications, which need to be considered, for example, when examining potential effects of land use (urbanisation, deforestation, afforestation) and climate change on flash flood risk management.

The combination of large specific discharges and the short time left for warning, the occurrence at relatively small spatial scale, the local rarity, make the flash flood risk management particularly complex and challenging both in terms of long-term planning and in terms of flood event management. The physical factors which characterise flash floods shape the dimensions of the flash flood vulnerability. This is typically represented by dispersed urbanisation, transportation, tourism structures, as well as urbanised areas downstream of small basins (particularly along the Mediterranean coast).

Several important consequences arise for the risk management strategies from the characterisation of hazard and vulnerability of flash floods:

- Because the elements at risk are highly dispersed, the management of the flash flood risk by means of structural measures aiming to reduce flood volumes and peaks is difficult (and often unsustainable in ecological or economic terms). Region-wide river training measures and land-use planning have an important role in flash flood risk management, particularly when it is associated to erosion processes. Even in these cases, however, an often unquantified degree of residual risk will remain, which require 'acceptable' flood risk to be determined and mitigation solutions to be implemented.
- Flash flood forecasting, warning and emergency management are, by their nature, suitable to cope with the residual risk (Norbiato *et al.*, 2008). Advancements in precipitation, flash flood and debris flow forecasting are essential to improve emergency management. However, a focus on advances in forecasting alone will not be sufficient to reduce casualties and damages. A better understanding of the behaviour of people exposed to risk and of the organisation of warning and rescue services is also essential. This understanding includes perceptions of risk (both objective and subjective) and how such risk is communicated (Handmer, 2001).

- Specific preparedness strategies are necessary. The local characteristics and sudden nature of occurrence of flash floods are best managed by the local authorities with active and effective involvement of the people at risk and with effective coordination between local, regional and national level. The time available for communication is very limited and typically there is no time for learning as the flood develops. The preparedness strategies must capitalise on improvements in flash flood forecasting and warning and, at the same time, to adapt to the large uncertainties affecting these forecasts (Parker *et al.*, 2007).

Given the small space and time scales of occurrence, and the intensity of the runoff and erosion processes involved, the dynamics of flash flood events is poorly understood, in terms of both physical and social processes. This is mainly due to the difficulties arising in the observation and monitoring of these events. Improvement of flash flood risk management requires therefore the development of an observation and monitoring methodology capable to provide the essential observational elements to both advance the understanding of the hydrometeorological processes at work during flash floods, and to validate the effectiveness of the flash flood forecasting, warning and response systems. The network of European flash flood pilot basins, described in this chapter, has been developed to afford accurate monitoring of flash flood events, implementation of flash flood forecasting and warning systems, and evaluation of the social response. Specific emphasis is placed in this chapter to the examination of the current techniques for flash-flood monitoring and forecasting with reference to the requirements of the population at risk to evaluate the severity of the flood and anticipate its danger.

4.1.2 The network of the European flash flood watersheds

The network of the European flash flood pilot basins includes the following four pilots, all placed in regions of high flash flood potential:

- Catalunya (Spain) (Mediterranean region);
- Cevennes-Vivarais (France) (Mediterranean region);
- North-eastern Italy (Italy) (Alpine Mediterranean region);
- Ardennes (Transnational).

These pilots are characterised by a good density of hydrometeorological stations, by a reliable weather radar coverage, and incorporate considerable detailed information about flash floods observed in the last decade.

Due to the considerable richness in past hydrometeorological data, the pilot network affords to gain essential insight into flash flood hydroclimatology, i.e. to analyse these floods from the perspective of the temporal context of their history of development and variation and the spatial context of the local, regional and global atmospheric and hydrologic processes and circulation patterns from which flash floods develop. This approach is essential when considering the potential effect of future and on-going climate change on flash flood regimes and on flash flood risks.

Pilot area Cévennes-Vivarais Mediterranean

The Pilot initiative (http://www.lthe.hmg.inpg.fr/OHM-CV/index.html) started in 2000 and has received the label of "Environment Research Observatory" (ORE is the French acronym) from the Ministry of Research in 2002. The Cévennes-Vivarais Pilot area covers an area of 160 x 200 km^2 in the south-eastern part of the French Massif Central. The area includes several villages and many small to medium-sized towns. The main city, Nîmes, has a population of 200 thousand inhabitants.

The area is subject to particularly severe flash flood events. The topography of the area ranges from sea level in the south to a maximum height of 1699 m above sea level at Mount Lozère. The main Cévennes rivers (Cance, Doux, Eyrieux, Ardèche, Cèze, Gard and Vidourle) are right bank tributaries of the Rhône river with a typical Mediterranean hydrological regime (i.e. very low water levels during the summer with floods occurring mainly during the autumn). They are characterised by steep slopes in the head tributaries of the Cévennes Mountains.

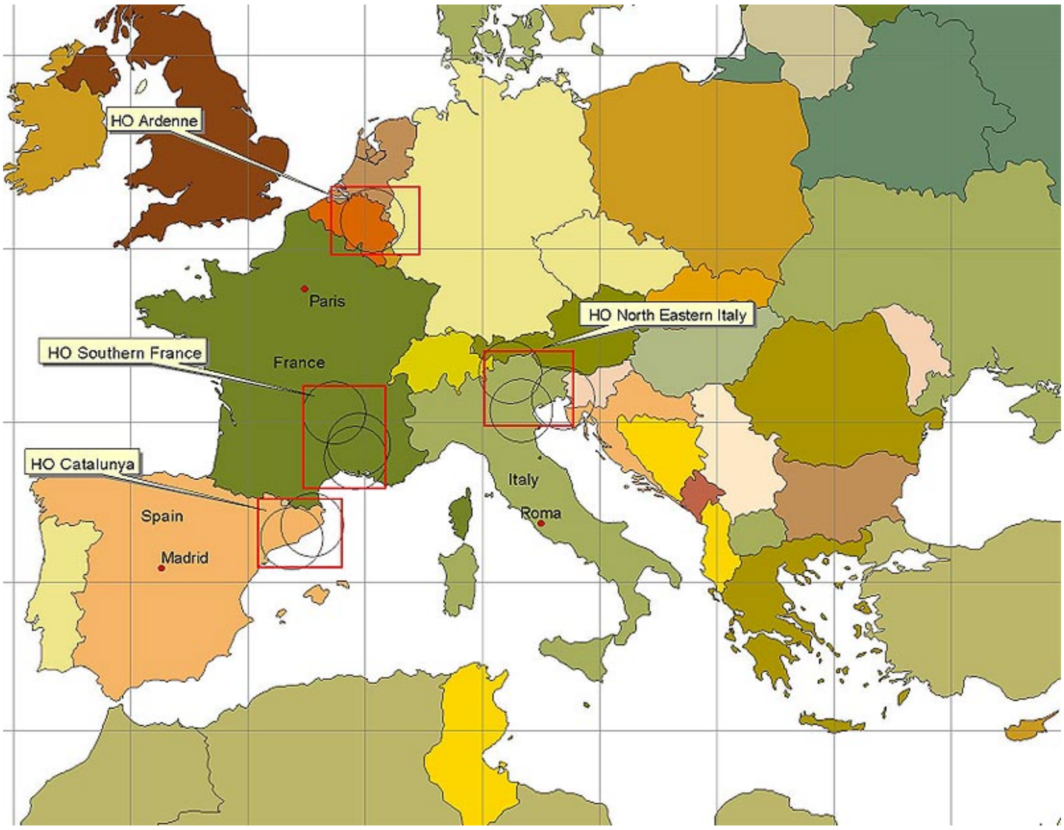

Figure 4.1 The network of flash flood pilot areas, reporting the radar coverage

Several historical major floods (Jacq, 1994; Deblaere & Fabry, 1997) can be mentioned. Among those occurred in the last two decades, the list includes: October 1988 (Nîmes), September 1992 (Ardèche area), September 2002 (Gard region), and December 2003 for all the right bank tributaries of the Rhône River. The punctual 10 year return period rainfall is greater or equal to 50 mm and 200 mm for the hourly and daily time steps, respectively, over most of the region (Bois *et al.*, 1997). Two Cévennes hydrological watersheds (Gardon d'Anduze River at Anduze 550 km^2 and the Ardèche river at Vogüé 635 km^2) were especially studied in the last three decades and may continue to be used as reference basins for detailed research projects. This region is already well instrumented with operational observation systems. Three weather radar sites are indicated in Figure 4.1 and the 40 km range indicators. The black circles and triangles give the locations of the hourly rain gauge network. Within the 160 x 200 km2 Cévennes-Vivarais window, the observation system is comprised at the moment of: (i) three weather radars of the Météo-France ARAMIS network located at Nîmes (S-band), Bollène (S-band) and Sembadel (C-band), (ii) two networks of about 400 daily rain gauges and 160 hourly rain gauges and (iii) a network of about 45 water level stations.

Pilot area Catalunya

The region of Catalunya (Spain) is located in the North-East of the Iberian Peninsula and covers an area of 32,000 km^2 showing a marked orography characterised by the increasing altitude of the terrain from the sea to the inner regions. Three major mountain chains can be distinguished. The first two are parallel to the coast (rising up to 500 and 1,700 m asl), and are located inside a strip of terrain at less than 40 km from the sea. These mountains act as a barrier that induces the convection of humid air coming from the sea, favouring the generation and growth of precipitation. The third mountain chain (the Pyrenees) is located at the North, and exhibits the highest elevations of the region (up to 3,400 m).

The mean annual rainfall over the region is about 600 mm. However, one third of the annual precipitation can usually fall in less than 48 hours. In average, two events exceeding 100 mm/day are recorded every year and the return period for events over 200 mm/day somewhere in Catalunya is two years.

This region is drained by a set of coastal rivers. Many of them cross densely urbanised and industrialised zones. Among them, the Besòs River and the Llobregat River pass north and south, respectively, of the conurbation of Barcelona (more than 3 millions of inhabitants). This area and its surroundings is the most vulnerable from the socio-economical point of view. It is also the best covered by the current radar network.

Of special interest is the Besòs watershed (1,020 km^2; Figure 4.1) which was affected in 1962 by a catastrophic flood event that caused about 800 casualties and exceptional economical damages. During last decades, the river bed has been degraded and canalised by means of big concrete protection structures. Considerable EU and Spanish investments have been devoted in recent years to rehabilitate this area into a modern urban sector and create a fluvial park.

The radar observation network allows a remarkable coverage of the Barcelona area and its main coastal rivers. The 1962 event made the Besòs watershed to be extensively instrumented and studied in recent years with exceptional hydrological time series compared to the Spanish standards. The creation of the fluvial park in Barcellona has motivated the development of a flood forecasting centre operated by CLABSA (the Sewer Management Company of Barcelona City). CLABSA has implemented new instruments (stage record stations) and control structures (inflated dams) along the park. Up to now this system relies on very simple hydrometeorological models, and the warning thresholds are based on conservative assumptions, but research efforts are made to improve this system. An on-line alert system based on hydro-meteorological data and hydrological models is being developed to monitor and forecast the combination of the flows coming from the semi-urbanised Besòs basin and the flows produced by the urban drainage network of the City.

Pilot area North-eastern Italy

The “north-eastern Italy Pilot area” started in 2000 with focus on the Adige river basin. During 2004, an agreement was reached with the OSMER of the Friuli-Venezia Giulia region to extend the research to the region covered by the Fossalon di Grado weather radar center (with main focus on the Tagliamento river basin). The main objective of LINE is to develop a methodology for flash flood risk management in an area characterised by the combination of heavy rainfall, flash flood, landslides and debris flows.

The Adige river is the second longest river of Italy, 360 km long, rising in the Tyrolean Alps, Northern Italy. It flows south, past Bolzano, Trento, and Verona, to the Po valley where it turns east to flow into the Adriatic Sea. The research is focused on the mountainous part of the basin (12,000 km^2), which includes two distinct administrative units: Provincia Autonoma di Bolzano (almost 7,000 km^2) and Provincia Autonoma di Trento (5,000 km^2). Altitudes range from 100 m a.s.l. up to 4,000 m asl. The region is located south of the inner alpine province: it ranges between a dry climate (600 mm/yr, due to the dual sheltering effect of the range to both the north and the south) and a wet climate (2,500 mm/yr) along the Venetian plains. The southern range experiences showery precipitation with thunderstorm and hail, particularly in summer and autumn.

The operational observation system for the Adige river basin includes a network of three weather radar systems.

The Tagliamento River (with an area of 2,871 km^2) is the dominant river system of the Friuli region in northeastern Italy. The steep environmental gradient from north to south which characterises this river system is associated with climatic differences, e.g., annual precipitation ranges from 3,100 to 1,000 mm per year and mean annual temperature from 5 to 14 °C. The southern fringe of the Carnian and Julian Alps frequently receives very intensive rainstorms, resulting in severe erosion, especially in the alpine area. Rainfall is concentrated mainly in heavy and erosive showers determining the torrential regime of the river. Furthermore, the mountain basin is seismically active and has a dense distribution of landslides, resulting in much bed load and a braided nature of the river downstream. The Tagliamento river basin is covered by the Fossalon di Grado weather radar, owned by ARPA Friuli Venezia Giulia (OSMER).

Pilot area Ardenne

The Ardennes is an undulating area of moderate relief (maximum elevation of approximately 700 m) and an important natural laboratory to study the hydrometeorology of mountainous catchments. The western part of the Ardennes (France, Belgium, Netherlands) mainly drains to the river Meuse, whereas the eastern part of the region (Luxemburg, Germany) mainly drains to the river Rhine (via the Mosel). Both the Meuse and the Rhine fulfil important functions in the water supply of The Netherlands. These rivers supply water for domestic, industrial and agricultural use and also fulfil important navigational, ecological and recreational functions. It is therefore of significant societal relevance to develop strategies to mitigate the impact of floods and droughts associated with the flow regimes of the rivers Meuse and Rhine. To achieve this objective, the hydrometeorology of the (mostly mountainous) upstream areas, such as the Ardennes, needs to be better understood. The aim of a recently established research collaboration between Wageningen University (WU), the Royal Meteorological Institute of Belgium (RMI) and the Hydrological Service of the Walloon Region of Belgium (MET-SETHY) is to investigate whether an improved assessment of the space-time structure of precipitation, as can be obtained with a newly installed weather radar in the Ardennes, in combination with an innovative approach towards modelling the rainfall-runoff process, will lead to an improved understanding of the hydrometeorology of Ardennes catchments.

4.2 Objectives and approach

Flash flood forecasting challenges traditional forecasting procedures because:

- the short lead time available, which implies both the integration of meteorological and hydrologic forecast, and the diagnosis of hydrological conditions most susceptible to flash flood triggering;
- the need to provide spatially distributed forecasts over river networks, rather than just at a few river sections; and
- the ungauged basin problem due to the fact that the small basins prone to flash flood are rarely gauged and must be modelled without calibration.

Recent research have focused on developing i) diagnostic methods, which aims to assess the potential for flash flood of catchments in a region, based on analysis of current soil moisture status (Norbiato *et al.*, 2008; Martina *et al.*, 2006), and ii) methodologies of application of distributed hydrologic models which are particularly suitable for flash flood forecasting and warning in ungauged basins. Research carried out within the framework of FLOODsite has significantly contributed to the improvements of these methodologies, with specific reference to the diagnostic methods.

Diagnostic methods generally provide critical rainfall thresholds, incorporating the influence of the initial soil moisture conditions. The use of rainfall thresholds is common in the context of landslides and debris flow hazard forecasting (Neary *et al.*, 1986; Borga *et al.*, 2002). In the context of flood forecasting/warning, rainfall thresholds have been generally used by meteorological organisations or by the Civil Protection Agencies to issue alerts. For instance, in Italy an alert is issued by the Civil Protection Agency if a storm event of more than 50 mm is forecast for the next 24 h over an area ranging from 2 to 50 km^2 (Martina *et al.*, 2006). Unfortunately, this type of rainfall threshold, which does not account for the actual soil saturation conditions at the onset of a storm event, tends to heavily increase the number of false alarms.

Methods for flash flood warning relying on rainfall thresholds and assessment of local soil moisture status are used by a number of National Services (such as the US National Weather Service). One of these procedures is the Flash Flood Guidance method (FFG). FFG is the depth of rain of a given duration, taken as uniform in space and time on a certain basin, necessary to cause minor flooding (e.g. 2-yr return time flow) at the outlet of the considered basin. This rainfall depth, which is computed by running in inverse mode a lumped continuous hydrological model (typically, a conceptual one), is compared to either real time-observed or forecasted rainfall of the same duration and on the same basin. If the nowcasted or forecasted rainfall depth is greater than the FFG, then flooding in the basin is considered likely. As such, the FFG is not a forecast quantity; rather, it is a diagnostic quantity.

Figure 6.2 shows an example of rainfall thresholds i.e. accumulated volume of rain versus time of rainfall accumulation.

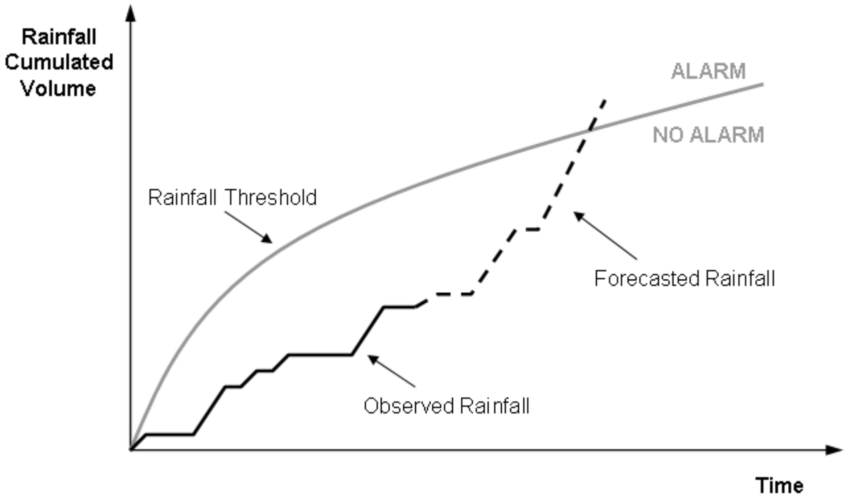

Figure 4.2 Example of a rainfall threshold and its use

The assessment of the susceptibility to flash flood, by taking initial soil moisture status into account, is a critical step to anticipate the locations of the river system which may be hit by the flood. Even though the occurrence, location and (or) timing of the flash flood is still uncertain, this information may provide enough lead time so that flash flood mitigation measures can be planned and managed in an anticipatory rather than responsive manner. Use of the FFG for the development of watches and warnings requires assessment of a present or imminent flash flood-inducing rainfall accumulation. The main objective with the FFG is the correct assessment of the flood threshold exceedance, while the correct timing forecast is left to the monitoring activity triggered by the flash flood alert (Norbiato *et al.*, 2009).

The key advantages of the FFG are that the method promotes close collaboration between hydrologists and meteorologists by simplifying communication about the hydrological status of basins and allows the forecaster to readily ingest local precipitation information and to update warnings without the need to run complex hydrometeorological forecasting chains. The limitations of the current operational methods stems from the need to operate a conceptual hydrological model at the small space scales of flash flood occurrence, where generally no flow data are available to calibrate the model. The performances of the method decrease sharply when applied to ungauged basins by using simple parameter transfer procedures, as reported by Norbiato *et al.* (2008) for an application to North eastern Italy and France. Degradation of performance in ungauged basins is generally due i) to the simulation bias which arise when the hydrological model parameter cannot be calibrated (Bloeschl, 2005), and ii) to the uncertainties in specifying the flow threshold leading to small flooding in the concerned basin (Ntelekos *et al.*, 2006).

The first objective in this study is to develop and test an alternative way for the application of the FFG to ungauged basins, which has the potential to inherently correct for simulation model biases and to filter out a portion of the hydrological model prediction uncertainty. Our approach requires running the lumped hydrological model to derive flood probability at the outlet of the ungauged basin under consideration, and then to compute the flow threshold based on model-derived simulations. This model-based threshold flow is subsequently used in the forecasting phase when running the model to compute the FFG. In this manner, the Flash Flood Guidance derived from the model-based flow threshold may account for the hydrologic model uncertainty and for biases originated by lack of model calibration on local conditions.

To effectively realise flash flood risk management, the improvements in flash flood forecasting and warning need to be adapted to the requirements of the population at risk. The current paradigm for flood hazard monitoring and forecasting relies on the relationship between the social response time and the catchment response time: when the social response time is shorter than the catchment response time, purely hydrological-hydraulic models may provide the forecast at the required lead time; on the contrary, when the social response time is larger than the catchment response time, the planning of the event management measures requires the use of forecasted rainfall fields such as from NWP (Numerical Weather Prediction) models (Siccardi *et al.*, 2005). Since the catchment response time gradually varies with the size of the catchment, both space and time considerations govern the appropriateness of the monitoring and forecasting strategies.

The second science question examined in this study is therefore to explore the structure of the social response to flash flood hazard and to identify how the current techniques available for flash-flood monitoring and forecasting can meet the needs of the population at risk to evaluate the flood severity and anticipate its danger. To this end, the study identifies the social response time for different social actions in the course of two well studied flash flood events which occurred in France and Italy. The study introduces a broad characterisation of the event management activities into three types according to their main objective (information, organisation and protection). The activities are also classified into three other types according to the scale and nature of the human group involved (individuals, communities and institutions). The conclusions reached relate to i) the characterisation of the social responses according to watershed scale and to the information available, and ii) to the appropriateness of the existing surveillance and forecasting tools to support the social responses.

4.3 Major findings

Major findings from the study relate to i) the improvement of the FFG methodology, and to ii) the analysis of the social and catchment response time to flash flood forcing.

4.3.1 Flash flood warning in ungauged basins by use of the Flash Flood Guidance

The objective of this study is to test the FFG method with model-based threshold flows under different conditions of data availability. More specifically, we evaluate the efficiency of the method both i) when data are available for model calibration and ii) when the model simulation parameters cannot be calibrated but must be transposed from either parent or nearby gauged basins to ungauged basins. The model used in this study to compute the FFG is a semi-distributed conceptual rainfall-runoff model, following the structure of the PDM (Probability Distributed Moisture) model (Moore, 1985; Norbiato *et al.*, 2008). We provide an assessment of this approach based on data from a number of catchments in the central-eastern Italian Alps, where both long-term data and data concerning specific flash flood events are available.

Three elements are included in the FFG method: i) the continuous soil moisture accounting model, ii) the computations of the FFG, and iii) the flood threshold conditions. These elements are described in the following.

Hydrological model

The continuous hydrological model used in this paper is a semi-distributed conceptual rainfall-runoff model. The model is described in detail in Norbiato *et al.* (2008); hence, only a summary description is reported here.

The model runs on a hourly time step and consists of a snow routine, a soil moisture routine and a flow routing routine. The snow routine represents snow accumulation and melt by using a distribution function approach based on a combined radiation index degree-day concept (Cazorzi & Dalla Fontana, 1986). Potential evapotranspiration is estimated by using the Hargreaves method (Hargreaves & Samani, 1982). The soil moisture routine uses a probability distribution function to describe the spatial variation of water storage capacity across a basin (Moore, 1985). Saturation excess runoff generated at any point in the basin is integrated over the basin to give the total direct runoff entering the fast response pathways to the basin outlet. Drainage from the soil enters slow response pathways. Storage representations of the fast and slow response pathways yield a fast and slow response at the basin outlet which, when summed, gives the total basin flow.

The model application requires specification of 14 parameters: three for the snow accumulation and melt module, 8 for the PDM module and three for the runoff propagation module.

FFG computation
Five rainfall durations are considered for computing the FFG: one, three, six, twelve and twenty four hours. The model is run continuously in time, and five values of FFG are computed each day (at 12:00) for each considered basin. Selection of the time during the day when the FFG is computed has been shown to have negligible impact on final results. For the considered day, the FFG values are compared with the maximum estimated areal precipitation over the corresponding five durations. The technique predicts the exceedance of the threshold flooding (i.e., a flash flood warning would be issued) when estimated precipitation exceeds the FFG for at least one precipitation duration.

Threshold flooding conditions
A number of alternatives are available in the literature to determine the threshold flooding conditions (Carpenter *et al.*, 1999). Generally, these are based on regional analysis of observed flow data. Carpenter *et al.* (1999) suggest that a 2-year flood is a reasonable threshold to use for flood warnings given that the flood flow associated with damage or hazard is often a little higher than bankfull flow.

In this paper, we use a methodology similar to that proposed by Reed *et al.* (2007), by computing the threshold flooding condition based on the flood frequency analysis of discharge values simulated by the model. This method requires the post-processing of the historical model simulations to convert flow to frequency. In this paper, we used a threshold frequency corresponding to a 2-year return period. A key assumption of the frequency-based approach is that the hydrologic model has skill in ranking events even if the simulated peak flows are biased relative to the observed data. If this is true, then forecasters can effectively use the model-based threshold flow to derive the FFG.

The skill and consistency of historical simulations in ranking events depends on the consistency of the model chain, and most importantly on the consistency of the rainfall input.

Use of this definition led to identification of 28 flood events exceeding the basin-specific thresholds, over the whole archive of stream flow data. However, use of this definition may give rise to sampling problems, due to the small number of local flood events. Owing to this reason, we used also a lower threshold, characterised by a return time around 0.5 year, corresponding to 94 flood events exceeding the threshold.

Study areas and assessment methodology
Data from six catchments located in the central-eastern Italian Alps are used for assessment of the method. Figure 4.3 shows the location of the basins, which are clustered into two river systems (upper Isarco river system and upper Brenta river system), together with the position of two weather radar stations used for rainfall estimation. Table 4.1 provides more detailed basin information, including information on the length period with hourly data available. Catchment drainage area ranges between 14.4 km^2 and 213.7 km^2. The topography is rather complex with altitudes ranging from 360 m asl (lowest altitude of Brenta at Borgo) to 3,600 m asl (highest elevation of the Ridanna basin). Measured runoff represents the natural runoff variability well, since management activities, such as artificial reservoirs and diversions, do not alter the river regime. However, the upper Brenta basins are heavily influences by the presence of natural lakes, which drains as much as 77 km^2.
Mean annual precipitation is lower for the upper Brenta basins (around 1,080 mm), due to the sheltering effect of the mountainous ranges to the southerly winds, and higher for the upper Isarco basins (around 1,270 mm) which are exposed to the stau effect. However, high intensity events are generally more frequent for the Brenta basins, owing to their position closer to the Adriatic Sea. At

Vipiteno, a raingauge station representative for the upper Isarco basins, 50-yr return time rainfall quantiles for 1 hour and 3 hours durations amount to 36.5 and 48.9 mm, respectively. At Levico, which can be considered representative for the upper Brenta basins, the quantiles increase to 47.8mm and 68mm, respectively (Borga *et al.*, 2005).

As a consequence of the moderate rainfall regime, peak discharges are relatively low. The largest recorded peak discharge at Vipiteno amounts to 158 m^3/s, whereas it is around 60 m^3/s for the Brenta at Borgo, due to combined effect of lakes and karst aquifer. Hence, the flash flood events in these areas are generally characterised by limited spatial extent.

We evaluate the efficiency of the method both when data are available for model calibration and when the model simulation parameters cannot be calibrated but must be transposed from either parent or nearby gauged basins to ungauged basins. The model is first calibrated on Ridanna at Vipiteno (for the upper Isarco river system) and on the Brenta at Borgo (for the upper Brenta river system), hence the model parameters are transferred to the other basins of the corresponding river system.

Table 4.1 Main characteristics of the study basins

Catchment Number	Station name (river system)	Area (km^2)	Elevation range (m asl)	Periods with hourly data available
1	Ridanna at Vipiteno (upper Isarco)	210.2	940-3,600	1/10/1992 - 1/10/2007
2	Racines (upper Isarco)	47.6	970-2,760	only flood event data
3	Rio Piana (upper Isarco)	14.4	2,165-3,420	only flood event data
4	Fleres (upper Isarco)	75.2	1,069-3,107	1/10/1992 - 1/10/2007
5	Brenta at Borgo (upper Brenta)	213.7	380-2,400	1/10/1994 - 1/10/2005
6	Brenta at Levico (upper Brenta)	113.0	435-2,000	1/10/1994 - 1/10/2005

Assessment of the hydrological model

With the long term assessment, the hydrological model was calibrated over Ridanna at Vipiteno (for the upper Isarco river system) and on the Brenta at Borgo (for the upper Brenta river system), with the objective of adjusting the model's parameters to decrease the difference between observed and simulated streamflow values. In this study, the Shuffled Complex Evolution-University of Arizona (SCE-UA, Duan *et al.*, 1992) global optimisation algorithm was used for calibration of the hydrological model parameters. The Nash and Sutcliffe (1970) coefficient of efficiency and the Relative Bias were used during the optimisation process for this study. A simple split sample test (Klemes, 1986) was considered for calibration and validation of the hydrological model. The test involves dividing the available data into two sets, one used for parameter estimation (calibration period) and the other for validation (validation period).

Results from the calibration and validation of the model are reported in Table 4.2, which reports both the coefficient of efficiency (E_{NS}) and the relative bias (RB) for the calibration and validation period, as well as for the whole data period. These results show on one hand the difficulties related with the application of the model to the Brenta river, where the poor model accuracy is due to the combined influence of lake storage and karstified aquifer, and a non-negligible bias remains even after calibration. On the other hand, validation results show that the model describes quite well the behaviour of the Ridanna at Vipiteno.

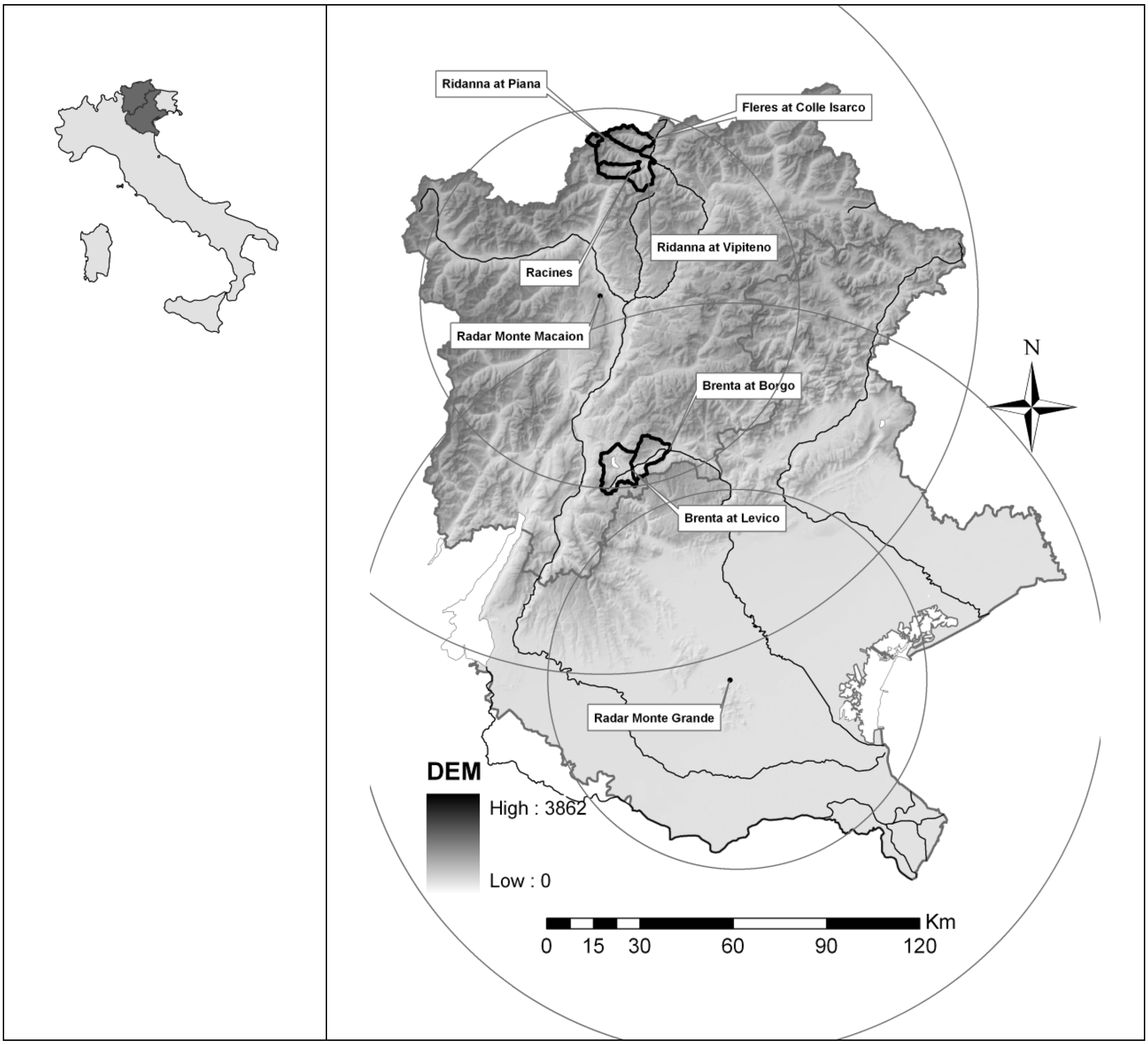

Figure 4.3 Study basins and their location in Italy

Table 4.2 Model validation and calibration results on Brenta and Ridanna

	Calibration period		Validation period		Whole simulation period	
	NS	BIAS (%)	NS	BIAS (%)	NS	BIAS (%)
Brenta at Borgo Calibration: 10.94-09.01 Validation: 10.01-09.05	0.71	2.6	0.5	8.7	0.64	5.0
Ridanna at Vipiteno Calibration: 10.92-09.97 Validation: 10.97-09.07	0.80	1.4	0.79	-2.6	0.79	3.4

Table 4.3 Overall score statistics: threshold runoff computed based on observed data

	POD	FAR	CSI
Model with calibrated parameters (basins 1 and 5)	0.90	0.45	0.52
Model with transposed parameters (basins 2 and 6)	0.95	0.65	0.34

Table 4.4 Overall score statistics: threshold runoff computed based on model simulations

	POD	FAR	CSI
Model with calibrated parameters (basins 1 and 5)	0.85	0.35	0.59
Model with transposed parameters (basins 2 and 6)	0.90	0.47	0.50

FFG assessment

Assessment of the quality of flash flood warnings based on FFG estimates is obtained by using contingency tables. Contingency tables are highly flexible methods that can be used to estimate the quality of a deterministic forecast system and, in their simplest form, indicate its ability to anticipate correctly the occurrence or non occurrence of predefined events. The POD (Probability of Detection), FAR (False Alarm Ratio) and CSI (Critical Success Index) are used to evaluate the quality of the results.

Due to the low number of events in the specific catchments, overall score statistics are computed by combining together all the events from selected catchments. Overall score statistics are computed over Ridanna at Vipiteno and Brenta at Borgo (by using the model locally calibrated) and over the Fleres and Brenta at Levico (by using the model with transposed parameters). In the first case the assessment describes the results over gauged basins, whereas the second case describes the results over ungauged basins. The assessment is carried out by using both observed and model-based threshold flow as a way to evaluate the capability of the method based on use of model-based flow threshold to account inherently for the bias in simulation (Table 4.3 and Table 4.4, respectively). We use here the 0.5-year return time discharge as a threshold to increase the number of flood events available for method analysis. Norbiato *et al.* (2008) has shown that results from the assessment exercise are only slightly affected by the choice of the threshold.

Comparison of results reported in Table 4.4 with those reported in Table 4.3 shows that the use of model-based threshold leads to improvements in both gauged and ungauged situations. In both cases, the remarkable decrease of FAR is associated to a slight degradation of POD values. This is explained by the general positive bias overestimation associated to the model simulations. This is in general emphasised over ungauged basins (results not reported here for the sake of brevity). Overall, CSI increases by 12% for gauged basins and by 31% for ungauged basins with use of a model-based threshold. As expected, the increase of CSI is more remarkable for ungauged basins, due to lack of local model calibration and the resulting greater likelihood of occurrence of a simulation bias in model application.

4.3.2 Catchment dynamics and social response during flash floods

This study examines how the current techniques available for flash-flood monitoring and forecasting can meet the needs of the population at risk to evaluate the flood severity and anticipate its danger. To this end, we identify the chronology of different social actions in the course of the events, and we employ well known space-time characteristics of catchment responses.

Data set used
The data set used combines the geophysical and human data that were collected in the framework of recent European research projects (such as HYDRATE) which contributed data to FLOODsite. These data are somewhat heterogeneous, mainly as a result of the various difficulties encountered when observing both geophysical and social processes during extreme events. In this section we outline our event selection procedure and the selected descriptive parameters employed.

Event selection
The selection procedure used is guided by two stages of screening. The first stage consists of identifying within Europe a number of "remarkable" flash flood events that caused casualties as well as damage. These events were then checked to ensure that they resulted from a storm that has, for some rainfall durations, a return period of 50 years or more. The second stage of screening is to ensure that the available social observations are precise enough to locate and describe the human actions and decisions during the event.

The above procedure led, at the first stage, to select a set of 20 notable events that were used for the basic understanding of flash-flood dynamics at a range of scales. At the second stage, two events were selected for which interviews have been conducted to document human and organisational response.

The first storm occurred in the Gard region in France in September 2002 (Delrieu *et al.* 2005). This event was one of the most violent observed in this region during the last few centuries (Huet *et al.* 2003). Rainfall accumulations of more than 500 mm in 36 hours covered significant area (ca. 5,000 km²) giving rise to multiple individual reactions of the tributaries of the rivers Vidourle, Gard and Cèze across a wide range of scales.

The second storm affected the watershed of the Fella River, in the Eastern Italian Alps, where on 29 August 2003 a Mesoscale Convective System (MCS) impacted a 1,500 km^2 wide area for almost 12 hours, causing loss of life and substantial disruption of the local economy, with damage valued at close to 1 billion Euros (Borga *et al.*, 2007). The storm total precipitation peak was up to 400 mm and the event rainfall maxima were characterised by return periods in the range of 500-1,000 years for 3 to 12-h durations (Norbiato *et al.*, 2007). The flood response in the upper Fella exceeded all the historical records, with unit peak discharges in the order of 20 $m^3(s^{-1}\ km^{-2})$ for catchment areas up to 10 km^2.

Geophysical parameters
The geophysical description of the selected flash-flood events is based on a small number of simple and verifiable hydrological parameters that characterise the time and space scales of the event.

It is now well known that flash flood events are difficult to observe reliably because they develop at space and time scales that conventional measurement networks of rainfall and river discharges are not able to sample effectively (Creutin & Borga, 2003). Rainfall accumulations for each event were carefully evaluated by using both raingauge and bucket data. More detailed rainfall estimates in space and time were obtained by adjusting radar observations to account for the physics of the radar sensing and incorporating the above rainfall accumulation data in the adjustment procedure (Borga *et al.*, 2002). Discharge data were obtained by combining streamgauge measurements when available and reliable, post-event surveys and model simulations to obtain indirect peak discharge estimates together with eyewitness accounts to estimate the timing of the peak discharges (see for example Borga *et al.*, 2007; De Marchi *et al.*, 2008).

Given these observations, we used the concept of lag time to characterise the dynamics of the basins of interest. In this study, we defined the lag time as the duration between the time of the centroid of the generating temporal rainfall sequence and the time of the discharge peak. Note that we used the centroid of rainfall amounts, instead of the more physically sound centroid of the excess rainfall (Morin *et al.*, 2002), due to the difficulty of reconstructing the excess rainfall sequence for each event.

Human organisation parameters
The human responses to the two flood events resulting after the second stage of selection are divided into a series of cases corresponding to the occurrence of a storm event on a particular watershed. For instance, we split the 2002 Gard event, into three distinct cases: the case of the Gard River itself that covers ca. 2,500 km², the case of the Vidourle River (an adjacent river of ca. 600 km²) and the case of the Valliguières River (a tributary of the Gard River of ca. 100 km²). This distinction was useful to examine the different types of documented human responses as a function of catchment area size. For the 2003 event that occurred in the Fella region (Italy), we considered only one case given the lesser scale of the storm.

Each case is associated with a documented sequence of human actions that are positioned in time and space and which are described in enough detail to be attributed to a type of activity and to the type of human group involved. The position of a given action in time is measured relative to the time of the flow peak in the concerned catchment. It can thus be considered an anticipation time with respect to the peak of danger if we assume, as a first guess, a direct linear relationship between the water flow and the danger. The position in space is measured by the size of the watershed assuming that watersheds of the same size will provide comparable conditions across the considered region.

Human data gathering included different but complementary strategies and techniques. For both events, we used existing data from secondary sources, such as municipal and provincial archives, logbooks from rescue brigades, as well as reports from experts.

To supplement this information we also used different types of interviews. For the Fella case fourteen semi-structured interviews were conducted with members of relevant institutions, such as local authorities, civil servants, community leaders, politicians, scientific and technical experts, members of the local fire brigade corps, etc. In addition, a semi-structured questionnaire survey of 100 residents was used which included some open-ended questions about residents' behaviours during the event (see De Marchi *et al.* 2007, for a description of the research design). For the Gard event, 8 months after the event we conducted thirty in depth field interviews asking people to explain how they experienced the event, with their own words and scale of time.

Rainfall field variability and catchment dynamics
We used a classical space versus time representation of the response time of a series of variously sized watersheds from the 20 flash flood events selected during the first stage of the study (see Orlanski, 1975 in meteorology and Blöschl & Sivapalan, 1995 in hydrology for examples of use of comparable graphs). Fig. 6.4 shows the lag time versus the watershed area for the set of flash-flood events, which occurred in Austria, France, Greece, Italia, Romania, Slovakia, Spain and the United Kingdom (Gaume *et al.*, 2008). This graph clearly shows a lower limit to watershed response time, which increases as a power function of the watershed size:

$$t = 0.1A^{0.55} \quad (1)$$

with the lag time t in hours and the watershed area A in km^2.

The line chosen to show this lag-time limit is close to that reported by previous studies (Sivapalan *et al.*, 2002; Berne *et al.* 2004) and has an exponent close to 0.5, which would be expected if the water velocity was constant over the considered range of scales. The dispersion of the points above this limit reflects the degree of resonance between the strength, size, duration and position of the generating storms and the size and position of the watersheds.

As far as the two events specifically selected for the social response study are concerned (Gard, 2002 and Fella, 2003), their position in Figure 4.4 shows that they are representative of the set of events, with some points being rather extreme in term of speed of response.

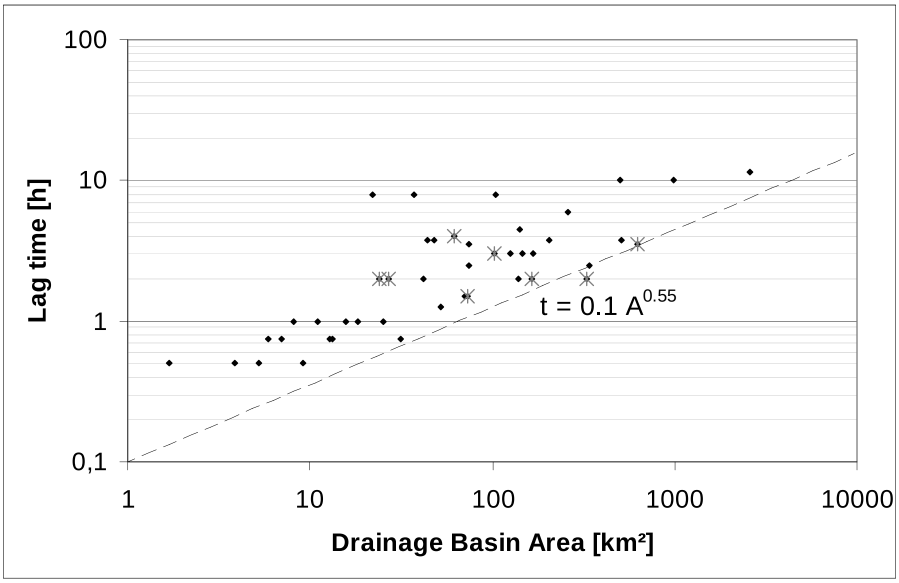

Figure 4.4 Lag time (in hours) versus drainage area (in km^2) for the selected events. The model representing the lower envelop is drawn in dashed line. Gard and Fella events are marked with stars.

Characteristics of the social response

Each reported action was qualified by the nature of the actors at the origin (initiator) and at the end (receptor), by the type of activity concerned (one of information, organisation or protection) and by the type of human group concerned (one of individual, communities or institutional).

In previous works, we observed that social actions for protecting goods or persons are preceded by a phase of assessment of the situation (Créton-Cazanave, 2009). We distinguish three types of actions: information, organisation and protection. They apply to all the actors, from forecasters to inhabitants and to all social group sizes. The information phase covers the collection of data and its crosschecking with other data or actors to assess its quality and relevance. It is the first activity of the warning cycle. Organisations synthesise and transform the above information before initiating a structured response such as mobilisation of human forces or the implementation of a pre-established defence plans. Chronological and logical organisation takes account of the available information and prepares the protection phase which ends the cycle. Protection involves efficient actions in terms of safety such as preventive evacuation of people or goods as well as rescue missions.

Human actions were also classified in three types according to the size of the groups concerned. We distinguish individuals, communities and institutions. 'Individual' concerns just one person and / or a small social entity (a family, for instance). 'Community' pertains to small groups of people which may be more or less organised to deal with emergencies. Neighbourhood groups, voluntary associations, but also the population of a school or a company as well as the population of small geographic entities like villages are included in this category. 'I[nstitution]' includes the public organisations such as police or civil protection as well as the national administration, its local representatives and technical operators like meteorological offices and water management departments.

Figure 4.5 displays the information contained in Table I according to the size of the relevant watershed and to the type of action (Figure 4.5a) as well as to the type of group of actors (Figure 4.5b). Examination of the different types of activities on Figure 4.5a supports the relevance of the logical cycle: information-organisation-protection. Even though the information gathering and analysis generally takes place among the first activities (except in one case), it is first noticeable that organisation and protection intervene at different stages in the sequences for the 4 cases. Different explanations can be given. An evolving flood situation generally demands successive waves of reaction cycles. Missing information in our dataset makes the documentation of these basic cycles incomplete. Nevertheless, we notice that complete cycles are present at all scales, confirming that this generic decomposition pertains to all sizes of human groups and is useful at all scales. It is also noticeable that no action is reported after the time of the peak. This is related, in a sense by definition, to the fact that we concentrated our selection of actions on risk prevention, rather than on risk relief. However, given the time needed for these different types of response to be effective, we must also realise that some cycles can potentially fail to work correctly when the reaction of the watersheds to rain comes before the full implementation of the social response.

Examining the social scale of the activities in Figure 4.5b assists in the analysis of the spatial dimension of the social response. Firstly, the characteristic reaction time of the different human groups decreases markedly with reducing size. The institutional reaction time develops around 30 hours to 36 hours before the flow peak. The community reaction appears to be organised in 7 hours whereas the individual reactions appear to be much shorter and starting a few hours before the peak.

Secondly, the size of the watersheds seems to be associated with the size of the reacting human groups. Most of the actions conducted by institutions apply mainly to the largest watersheds (Gard and Vidourle) while, on the smaller ones, communities and individuals take charge of the response. The dominance of institutional activities on large watersheds masks community and individual actions at those scales that are under-sampled in our dataset. For example, institutional actions certainly have effects on small scales through the broadcast of information but there was little indication in interviews of individuals and communities that they made use of such information. On the other hand, it is interesting to consider the cases where the individual response dominates. In the isolated locations that are not well covered by the institutional response, individuals have to protect themselves on their own. For example in the Fella river case study, some residents undertook an autonomous evacuation, saving their lives and those of their neighbours. This decision was made as a result of monitoring the level of the streams and possible points of obstruction. In this phase the village was almost isolated due to the obstructions of nearby roads caused by debris flows and institutional intervention was not possible.

A third point is that human groups have different abilities to anticipate flooding based on the nature of information they have access to. The information available at institutional scale comes mostly from meteorological and water services. In the cases studied here, even when the meteorological information is distributed early, at the smallest scales people appear to rely on their own monitoring of the water levels. In these cases, reliability of the sources of information plays a crucial role. In both the Italian and in the French case, the local voluntary fire brigades groups are considered the main safety agency by the residents, possibly due to their local attachment, their deep knowledge of the territory, and training in facing such emergencies. Besides, the hydrological evidence of the flood seems to be necessary for individuals and communities to react. As shown in a parallel study (Créton-Cazanave, 2009) the current meteorological information needs to be adapted at a smaller scale to be used directly by communities and individuals.

In summary, the social response is reasonably well described by a generic cycle: information-organisation-prevention across different group sizes. These groups have rather different characteristic temporal behaviours as regards both their anticipation and response.

Adequateness of monitoring and forecasting techniques at different scales: confronting with the social response time

Having defined, on one hand, the time and space characteristics of the hydrometeorological response (Figure 4.4) and, on the other, the characteristic times of different types of social responses (Figure 4.5), we can now combine these elements in order to appreciate the relevance of existing monitoring and forecasting tools.

a)

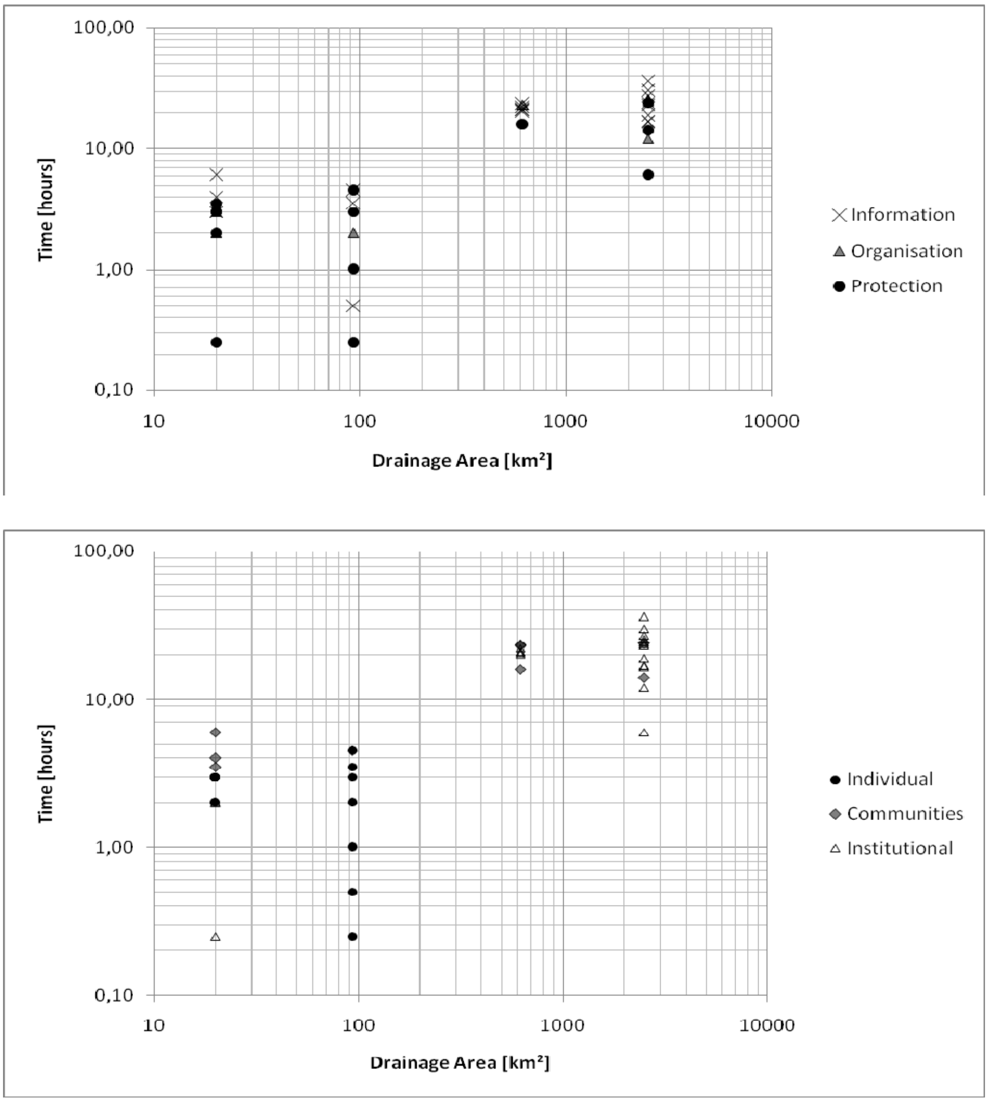

Figure 4.5 Representation of 43 elementary human actions in a logarithmic plot of their anticipation time (i.e. time of action before the flow peak) versus the area of the watershed where they occurred. Three types of actions (Figure 4.5a) as well as three types of sizes of human groups (Figure 4.5b) are distinguished by the shape of each point representing a elementary action.

Figure 4.6 combines, into the same space-time graph used for Figure 4.5, the lag time limit of Figure 4.4, indicating the relationship between the lower limit of catchment lag time and the corresponding catchment area ($t=0.1A^{0.55}$). In order to account, at least qualitatively, for the minimum duration of the rainfall event generating the catchment response, we have drawn the function $t=2(0.1A^{0.55})$. The shaded transition area obtained divides the time and space scale domain into two areas. Above the shaded area, the meteorological generation of the rain field is the dominant process. At such space scales and anticipation times, the risk precursors are meteorological factors. Below the transition area, runoff propagation is the dominant process and the relevant risk precursors are hydrological factors. The time scale of Figure 4.6 is an anticipation time with respect to the peak discharge. This figure can thus be used to examine the type of action according to the anticipation time and the catchment lag time.

The Figure 4.6 globally shows that the position of human responses with respect to the flood dynamics is rather homogeneous through a range of scales. Except for one case (93 km²) the distribution patterns of human actions relative to the flood dynamics are very similar. They cover a time range equal to 2 to 4 times the reaction time of the catchment and they rarely go beyond the rain peak (i.e. below the lag-time line). As a consequence, most part of the reported human actions develop at periods dominated by the meteorological processes. In that respect additional comments can be made.

The anticipation at the broader scales relies on the use of NWP models for rainfall forecasting and on the generation of relevant flooding scenarios that are summarised in the official broadcast of the meteorological services. It is noted that the largest spatial scale explored in this study is still relatively modest (2,500 km^2) compared to the typical areas targeted by NWP. At the smaller scales the anticipation time is much shorter (4 or 6 hours) and the question rises about the type of information used. Examination of the responses at a scale of less than 100 km^2 reveals that several organisation and protection actions occurred just before the peak time, and generally at anticipation times less than the catchment response. It is difficult to evaluate how these actions were triggered; however, as reported above, in general it was the raising of water levels in the neighbouring rivers, rather than the information received from outside, that triggered the individual and community actions. Of course, some of the evacuations were organised at these short anticipation times proving that the reactivity of communities and individuals is well adapted. Other actions, which are equally important, include the decision to stay home and to avoid moving. This implies that the information required at these time scales, and for these anticipation times, is a reliable and high-resolution description of the actual rainfall field and of its likely impact on the hydrologic response at very short times. For example, organising the evacuations requires knowledge of how the potential routes can be impacted by inundation in the next half hour or less.

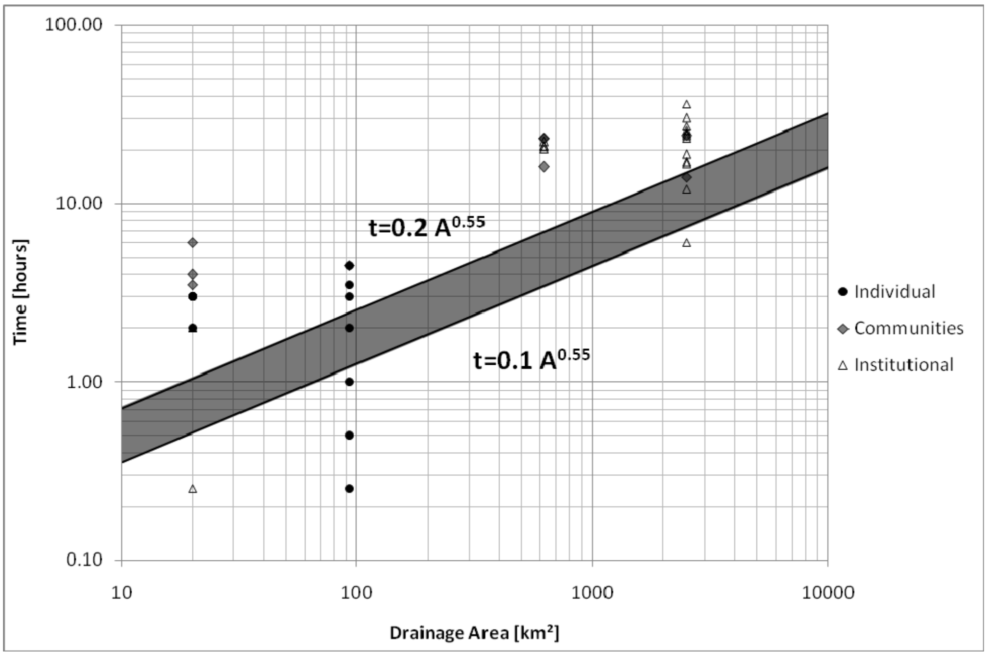

Figure 4.6 Representation of 43 elementary human actions in a logarithmic plot of their anticipation time versus the area of the watershed where they occurred. Three levels of organisation of the actors are distinguished by the different dot shapes. The bottom line of the shaded area represents the relationship between the catchment lag-time and its drainage area. The upper line is distant of Log 2 from the bottom line and qualitatively indicates the characteristic duration of the generating rain event.

Flash flood forecasting tools relying on accurate radar monitoring of the precipitation field and pre-established hydrological scenarios linked to the soil-moisture status of the soils, such as the Flash Flood Guidance method (Georgakakos, 2004, 2006; Martina *et al.*, 2006; Norbiato *et al.*, 2008), may provide enough information for warning at these space and time scales. Such real time analysis of radar rainfall accumulations allows forecast lead times that are at least equal to the response time of the watersheds and potentially allows handling of basin sizes that match the radar resolution. A key advantage of these methods is that they allow the forecaster to readily ingest local precipitation information and to update warnings without the need to run complex hydrometeorological forecasting chains (Norbiato *et al.*, 2008).

4.4 Contribution to flood risk management practice

Contributions to flood risk management practice are summaries in the following as guidelines for assessing adequateness and for improving flash flood forecasting and warning by means of diagnostic tools.

4.4.1 Guidelines to improve flash flood forecasting and warning in ungauged catchments

We propose using the Flash Flood Guidance (FFG) method and a method of model-based threshold runoff computation to improve the accuracy of flash flood forecasts at ungauged locations. Our approach requires running the lumped hydrological model to derive flood frequencies at the outlet of the ungauged basin under consideration, and then to derive the threshold runoff from these model-based discharges. This model-based threshold runoff is subsequently used in the forecasting phase when running the model to compute the FFG. The approach provides a pragmatic method to characterise flood severity at ungauged locations. The study examines the potential of this method to account for the hydrologic model uncertainty and for biases originated by lack of model calibration on local conditions.

Experiments to validate this approach involved the implementation of a semi-distributed continuous rainfall-runoff model and the operation of the FFG method over four basins located in the central-eastern Italian Alps and ranging in size from 75.2 km^2 to 213.7 km^2. Data were available for periods ranging from 11 to 13 years. The model was calibrated on two larger basins and the model parameters were transposed to the other two basins to simulate operations in ungauged basins. The FFG method was applied by using the 2-year discharge as the threshold runoff. The threshold runoff was derived both by using local discharge statistics and the model-based approach advocated here. Examination of the results obtained by this comparison shows that the use of model-based threshold leads to improvements in both gauged and ungauged situations. Overall, the Critical Success Index (CSI) increases by 12% for gauged basins and by 31% for ungauged basins by using the model-based threshold with respect to use of local data. As expected, the increase of CSI is more remarkable for ungauged basins, due to lack of local model calibration and the greater likelihood of occurrence of a simulation bias in model application over these basins. This shows that the method of threshold runoff computation provides an inherent bias correction to reduce systematic errors in model applications to ungauged (and gauged) basins.

The method was also applied to simulate FFG operations with three flash flood events and by using additional data from two further basins. This application showed that, even though reasonable results may be obtained by using the FFG to map susceptibility to flash flood across a region, the use of transposed model parameters from gauged to ungauged basins may limit the potential of the method. Improvements could be obtained in this case by using more reliable methods for model parameter regionalisation.

The promising results from these modelling experiments suggest that further work should be devoted to the analysis of the combination of FFG with model-based runoff threshold. In particular, future work should focus on the examination of the influence of spatial and temporal scales on the performances of the method and on the dependence of these scales on the type of rainfall information used to force the model. It is likely that different types of rainfall forcing will translate to different scale-dependence patterns.

Another area where further work is required is the development of more reliable methods for derivation of model parameters. Prior studies (Zhang *et al.*, 2008) have found that the correlations between stream flow characteristics and physical watershed characteristics are often significantly higher than between model parameters and watershed characteristics. Methods based on the regionalisation of stream flow characteristics could be tested to improve flash flood forecast in ungauged basins.

Conditio sine qua non for continuing this work in an effective way is the development of a flash flood occurrence database with long term data that would allow reliability analysis (Creutin & Borga, 2005; Gaume *et al.*, 2008). This is a pressing need in the area of flash flood risk management which should receive proper attention from both scientists and policy makers.

4.4.2 Adapting the monitoring and forecasting techniques to the societal needs

Our contributions and conclusions pertain to i) the characterisation of the social responses according to watershed scale and to the information available, and to ii) the appropriateness of the existing surveillance and forecasting tools to support the social responses identified in the previous sections.

We observed that the spatial scale seems to determine the size of the reacting human groups, and that there is a link between the spatial scale and the social response time. Most of the actions conducted by institutions apply to the largest watersheds while on the smaller ones communities and individuals are primarily in charge of the response. The institutional reactions develop as early as 30 hours before the event when community reactions appear to be concentrated in ca. 6 hours and individual reactions in even less. This suggests that representing the dynamics of the social response with just one number representing the average time for warning a population is an oversimplification. In practice the social response exhibits a parallel with the hydrological response time, by diminishing in time with decreasing the size of the considered watershed.

We observe secondly that human groups have different capabilities of anticipation apparently based on the nature of information they use. The information available at institutional scale comes mostly from meteorological services, whereas at smaller scales, even when the meteorological information is provided in a timely fashion, people act on other types of data, primarily monitoring of the level of water. This suggests that, even though at small scales actions are characterised by shorter response times than at larger scales, worthwhile decisions may be taken with considerable delay with respect to the onset of the precipitation.

These results were confirmed when comparing, on the same graph, watershed response times and social response times. This showed clearly that at scales less than 100 km^2, a number of actions were taken with response times comparable to the catchment response time. The implications for adapting the warning processes to social scales (individual or organisational scales) are considerable. At small scales and for the implied anticipation times, the reliable and high-resolution description of the actual rainfall field becomes the major source of information for decision-making processes e.g. initiating evacuations or advising to stay put.

Methods such as the Flash Flood Guidance (FFG) may provide enough information for warning at these space and time scales. Such real time analysis of radar rainfall accumulations allows forecast lead times that are least equal to the response time of the watersheds and potentially allows handling of basin sizes that match the radar resolution. Clearly, this leads to stress three major issues: i) the need to continue to keep improving the accuracy and quality control of real time radar rainfall data, especially during extreme flash flood generating storms; ii) the need to provide access to more and more accurate real time information about rainfall accumulations during the decision making process; and iii) the need to ensure widespread access to this information and to produce products which are readily understandable (such as the FFG) by people at risk.

There is clearly a need to confirm these results by means of further studies based on other events. The observation that a human society is to some extent structured in cascade, with space and time scales of response that are adapted to the disturbing atmospheric and hydrologic processes, may have a wide range of implications. One may deserve specific attention. The observation may provide a clearer view of the differences between social responses to natural hazards, distinguishing those hazards which are organised according to a natural spatial scale ordering (such as the flood hazard), from those hazards which are not (such as the wildfire hazard). The question of scales, so pervasive in the hydrological science, may be developed further by considering the social scales as well.

4.5 Conclusions and outlook

4.5.1 The flash flood observational system

Post event surveys

Traces left by water and sediments during flash floods provide an opportunity for developing spatially detailed post-event surveys of flash flood response along the stream network. Indirect methods such as slope-area, contracted opening, flow-over-dam, or flow-through-culvert are often used for this purpose. However, the important thing here is that the survey needs to capture not only the maxima of peak discharges: less intense responses within the impacted region are important as well. These can be contrasted with the corresponding generating rainfall intensities and depths obtained by weather radar re-analysis, thus permitting identification of the catchment properties controlling the rate-limiting processes. Collection of eyewitnesses' accounts and observations represents an integral part of the flash flood response survey.

It should be noted that these 'observations' may be currently collected as digital imagery from movies and pictures. These represent an extremely important information source to refine the assessment of flow type/depth, the estimates of flow velocity and discharge, and for the evaluation of flooding extent. For instance, digital imagery from movies may afford use of advanced techniques for discharge estimation, such as the Particle Image Velocimetry (PIV) technique. Interviews with eyewitnesses provide information and anecdotal evidence on the time sequence and dynamics of the flood, and as such they add a time dimension to the spatial patterns of flash flood response. It should be recognised that accuracy of the witnesses' accounts is limited (up to ±15 min, according to Borga *et al.*, 2007). Consequently, when these observations are used to estimate the timing of the flood peaks, their information content should be related to the catchment response time, and therefore with the catchment scale.

Integration of the survey observations by means of hydrological modelling

The utility of the individual observations gathered by means of the flash flood survey needs to be extended by use of hydrological models driven by the space-time estimates of rainfall obtained by means of radar re-analysis. The multiple simulations obtained in this way ensure closure of the water balance at the event scale and consistent dynamics of the rainfall-runoff sequence. The simulations may be compared with the spatially-detailed response observations with the objective of evaluating the consistency between the various sources of information within a framework for uncertainty analysis. It is likely that non-probabilistic approaches, including sensitivity-analyses, convey the most promising perspectives (Montanari, 2007) for this purpose.

Flash flood events are usually characterised by extensive flooding. More insight into the flash flood dynamics may be obtained by integrating hydrological models with 1D and 2D hydraulic models. The relevant simulations could be compared with the inundation maps made available for these events. Data concerning flooded bridges and damaged structures could also be exploited to evaluate the consistency of the hydraulic description of the events.

The final outcomes of the integrated survey methodology are represented by the data themselves, characterised by uncertainty assessment, and by the increased capability to examine the terms of the hydrological balance at the event scale. This affords examination of key hypotheses concerning the hydrology and hydraulics of catchment response under flash flood conditions. Examples include i) the role of antecedent soil moisture conditions on flood magnitude; ii) the role of land use and catchment properties on runoff generation; and iii) dependence of flood properties on basin scale by means of space-time scaling properties of rainfall.

Surveying flash flood response may therefore provide valuable insight; however, generalising the findings beyond the areas of interest may prove to be difficult. Each episode seems to have particularities that cannot be specified in full detail. Advancing understanding in the context of flash flood studies, which are by necessity opportunistic and event-based, requires the development of a parsimonious avenue to synthesis. This may be based on classification and similarity concepts which can be profitably used when the processes are not fully understood. Contrasting different case studies and learning from the similarities and dissimilarities may help to find an explanation or description of the underlying patterns.

Requirements for space-time rainfall observations

The literature on the significance of aggregation of rainfall for runoff estimation is complex and sometimes contradictory. Effects can be expected to vary depending on the characteristic of the rainfall, the nature of the catchment, and the spatial scale of the catchment and rainfall. The mountainous region on the north-eastern border of the Friuli region in Italy produces some of largest unit discharge peaks in the northern Mediterranean basin and is monitored with a dense network of weather radar and rain-gauge stations. This offered an opportunity to examine the impact of spatial aggregation of rainfall on extreme flood modelling.

Flood response to an extreme storm events, occurred on the Fella River basin, at various catchment scales ranging from 10 km^2 to 600 km^2, were reproduced by using high resolution radar rainfall estimates and a distributed hydrologic model, based on a Hortonian infiltration model and a network-based representation of hill slope and channel flow. Four input spatial resolutions were considered, with grid size equal to 1-, 4-, 8- and 16- km, for rainfall properties representation. A dimensionless parameter given by the ratio between input length aggregation and the square root of the watershed area (L_R/L_W) was used to describe the sensitivity of the runoff model. Given the focus on Hortonian runoff generation mechanism and surface runoff propagation through hill slopes and branched channel networks, we examined the role of runoff transport geometry in the coarsening of spatial rainfall representation and on simulated runoff volumes and peak discharges.

The rainfall spatial variability play an important role when rainfall fields are systematically structured across locations with equal flow distance coordinates, as it occurs in the case of orographic effect and when catchments are elongated in the direction perpendicular to the mountainous range. When heavy rainfall lies on a sufficiently narrow range of isochrones, the smoothing effect due to increasing the rainfall aggregation length may result in a significant distortion of the rainfall field geometry with respect to the river network. In these cases, the increase of the spatial rainfall aggregation length leads to a significant deformation of the flood shape, with an anticipation of the simulated flood peak when the precipitation is concentrated towards the periphery of the catchment, and a delay of the simulated flood peak when the precipitation is concentrated towards the outlet of the catchment. These effects are negligible at the small catchment scale and become significant with increasing the catchment size.

When infiltration is ‘switched off’ in the runoff model and all the variability arises due to runoff transport processes, the distortion of the rainfall field geometry with respect to river network may be an important control on peak discharge error, even at catchment scales less than 500 km^2. Obviously, this distortion has no impact on the runoff volume error, which is in this case completely determined by the rainfall volume error. This volume error arises when rainfall values pertaining to areas just outside the catchment enter the computation of the average rainfall over the basin by increasing the aggregation length. The rainfall volume error is controlled mainly by the ratio L_r/L_w and by the rainfall integral scale; it exerts a dominant impact on peak discharges at small catchment scales (75 km^2), and becomes less significant by increasing the catchment dimension.

Errors on both runoff volumes and peak discharges increase when infiltration is taken into account in the runoff model. This is expected, since the infiltration process injects further spatial variability, both random and structured, into the rainfall-runoff process. Effects are particularly remarkable when significant structured rainfall variability combines with relatively important infiltration rates due to dry initial conditions, as this emphasises the non linear character of the rainfall-runoff relationship. In general, these results confirm that the correct estimate of rainfall volume is not enough for the accurate reproduction of flash flood events characterised by large and structured rainfall spatial variability, even at catchment scales around 250 km^2. However, accurate rainfall volume estimation may suffice for less spatially variable flood events. The results show also that the rainfall volume errors generally magnify through the rainfall-runoff modelling, at least for the runoff model considered here.

This investigation has documented how input variability, as filtered by using different spatial aggregation lengths, feeds through to variability in modelled runoff response at the catchment scale. More extensive investigations would strengthen this understanding and provide additional guidance on the design of radar/rain gauge networks for flow forecasting and the spatial resolution requirements for rainfall and soil properties at different catchment scales. Further work might determine whether the results obtained in this investigation apply to other model formulations and may be generalised to other hydroclimatic environments. In this framework, future investigations should focus on the sensitivity of the averaging of space-time rainfall fields across locations with equal flow distance coordinates to the rainfall aggregation length and to river network geometry. As shown here, this is a significant and relatively unexplored feature of catchments where rain exhibits significant spatial variability and linear routing through branched channel networks plays a significant role.

4.5.2 Assessment of the FFG approach for flash flood forecasting and warning

In this section, we propose using the Flash Flood Guidance (FFG) method and a method of model-based threshold runoff computation to improve the accuracy of flash flood forecasts at ungauged locations. Our approach requires running the lumped hydrological model to derive flood frequencies at the outlet of the ungauged basin under consideration, and then to derive the threshold runoff from these model-based discharges. This model-based threshold runoff is subsequently used in the forecasting phase when running the model to compute the FFG. The approach provides a pragmatic method to characterise flood severity at ungauged locations. The study examines the potential of this method to account for the hydrologic model uncertainty and for biases originated by lack of model calibration on local conditions.

Experiments to validate this approach involved the implementation of a semi-distributed continuous rainfall-runoff model and the operation of the FFG method over four basins located in the central-eastern Italian Alps and ranging in size from 75.2 km^2 to 213.7 km^2. Data were available for periods ranging from 11 to 13 years. The model was calibrated on two larger basins and the model parameters were transposed to the other two basins to simulate operations in ungauged basins. The FFG method was applied by using the 2-yr discharge as the threshold runoff. The threshold runoff was derived both by using local discharge statistics and the model-based approach advocated here.

Examination of the results obtained by this comparison shows that the use of model-based threshold leads to improvements in both gauged and ungauged situations. Overall, the Critical Success Index (CSI) increases by 12% for gauged basins and by 31% for ungauged basins by using the model-based threshold with respect to use of local data. As expected, the increase of CSI is more remarkable for ungauged basins, due to lack of local model calibration and the greater likelihood of occurrence of a simulation bias in model application over these basins. This shows that the method of threshold runoff computation provides an inherent bias correction to reduce systematic errors in model applications to ungauged (and gauged) basins.

The method was also applied to simulate FFG operations with three flash flood events and by using additional data from two further basins. This application showed that, even though reasonable results may be obtained by using the FFG to map susceptibility to flash flood across a region, the use of transposed model parameters from gauged to ungauged basins may limit the potential of the method. Improvements could be obtained in this case by using more reliable methods for model parameter regionalisation.

The promising results from these modelling experiments suggest that further work should be devoted to the analysis of the combination of FFG with model-based runoff threshold. In particular, future work should focus on the examination of the influence of spatial and temporal scales on the performances of the method and on the dependence of these scales on the type of rainfall information used to force the model. It is likely that different types of rainfall forcing will translate to different scale-dependence patterns.

Another area where further work is required is the development of more reliable methods for derivation of model parameters. Prior studies (Zhang *et al.*, 2008) have found that the correlations between stream flow characteristics and physical watershed characteristics are often significantly higher than between model parameters and watershed characteristics. Methods based on the regionalization of stream flow characteristics could be tested to improve flash flood forecast in ungauged basins.

Condicio sine qua non for continuing this work in an effective way is the development of a flash flood occurrence database with long term data that would allow reliability analysis (Creutin &Borga, 2005; Gaume *et al.*, 2008). This is a pressing need in the area of flash flood risk management which should receive proper attention from both scientists and policy makers.

4.5.3 Catchment dynamics and social response during flash floods

This section aims to identify if the current means available for flash-flood monitoring and forecasting can meet the requirements of populations to evaluate the severity of the flood and anticipate its danger. To this end, we identify the social response time for different social actions for two well studied flash flood events in the course of the floods, and we compare these to the relevant catchment response time.

In the same manner as the response time of a watershed is linked to its size, we assumed that the characteristic time of the above defined warning procedure depends on the number of people concerned and on the level of information available about the hazardous phenomenon. We introduced a broad characterization of the event management activities into three types according to their main objective (information, organisation and protection). The activities were also characterised into three types according to the scale of human organisation dynamics (individuals, communities and institutions). The simplified schematisation of the human response was necessary because of the lack of structured observations. We provide so two main parameters to characterise the time schedule of social actions in regard to the storm and flood dynamics: the anticipation time and the reaction time.

Conclusion pertains to i) the characterisation of the social responses according to watershed scale and to the information available, and to ii) the appropriateness of the existing surveillance and forecasting tools to support the social responses identified above.

We observed that the spatial scale seems to determine the size of the reacting human groups, and that there is a link between the spatial scale and the social response time. Most part of the actions conducted by institutions applies mainly to the largest watersheds while on the smaller ones communities and individuals are in charge of the response. The institutional reactions develop in 30 hours when community reactions appear to be concentrated in ca. 6 hours and individual reactions in even less. This suggests that representing the dynamics of the social response with just one number representing the average time for warning a population is an oversimplification. Rather differently, the social response exhibits a parallel with the hydrological response time, by diminishing in time with decreasing the size of the considered watershed

The second result is that human groups have different capabilities of anticipation apparently based on the nature of information they use. The information available at institutional scale comes mostly from meteorological services, whereas at smaller scales, even when the meteorological information is provided early, people mobilise other types of data, monitoring of the level of water notably. This suggests that, even though at small scales actions are characterised by shorter response times than at larger scales, decisions may be taken with considerable delay with respect to the onset of the precipitation.

These results were confirmed when comparing, on the same graph, watershed response times and social response times. This showed clearly that at scales less than 100 km^2, a number of actions were taken with response times comparable to the catchment response time. The implications for adapting the warning processes to social scales (individual or organisational scales) are considerable. At small scales and for the implied anticipation times, the reliable and high-resolution description of the actual rainfall field becomes the major source of information for decision-making processes involving evacuations or advising to stay home.

Methods like the Flash Flood Guidance (FFG) may provide enough information for warning at these space and time scales. This real time analysis of radar rainfall accumulations allows forecasting lead times that are least equal to the response time of the watersheds and allows potentially dealing with basin sizes that match the radar resolution. Clearly, this leads to stress three major issues: i) the need to obstinately keep improving the accuracy and quality control of real time radar rainfall data, more particularly during extreme flash flood generating storms; ii) the need to introduce more and more accurate real time information about rainfall accumulations during the decision making process; iii) the need to ensure wide access to this information and to products quickly understandable (such as the FFG) among people at risk.

There is clearly a need to confirm these results by means of further studies developed on other events. The observation that a human society is to some extent structured in cascade, with space and time scales of response that are adapted to the disturbing atmospheric and hydrologic processes, may have a wide range of implications. One, among several, may deserve specific attention. The observation may provide a clearer view of the differences among social responses to natural hazards, distinguishing those hazards which are organised according to a natural spatial scale ordering (such as the flood hazard), with respect to those hazards which are not (such as the wildfire hazard). The question of scales, so pervasive in the hydrological science, may be developed further by considering the social scales as well.

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5. Pilot site "Thames River estuary"

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5.1 Overview of flood risk and the Thames Estuary

5.1.1 The importance of the floodplain

The Thames Estuary, located in the south-east of England, is an area of national importance. As host to London, the capital of England, there are over 1 million people living in the floodplain area. The area comprises extensive Central and Local Government institutions. For example, the Central Government district of Whitehall is wholly within the floodplain, as are the Houses of Parliament and the Greater London Authority's City Hall. As an indication, it has been estimated (EA, 2007) that if just the central London based civil-service staff lost one day of working to a flood event the cost in lost staff time is of the order of £10 million. London is the UK's largest centre of economic activity contributing around £250 billion annually to the UK economy. Significant portions of the business and financial service sectors are located within the floodplain at, for example, the "Docklands".

As well as the financial institutions there are a large number of buildings of historical and cultural significance within the floodplain (some are designated as World Heritage Sites). Examples include Westminster Abbey, Palace of Westminster and Parliament Square, Tate Gallery and Tate Modern, Lambeth Palace and Tower of London. The UK Environment Agency (EA) has estimated there are over 3,000 hectares of culturally significant sites within the floodplain area that are highly sensitive to flooding (EA, 2007). Whilst placing a value on these buildings is difficult, the EA note that London's "sense of place" is defined by its cultural assets and provide an illustrative indicator, in terms of the annual revenue from tourism, which is approximately £150 billion (EA, 2007). The Thames Estuary (in particular the outer estuary) is also home to a wide range of landscapes of high environmental value. These include national and international sites designated for protection such as saltmarsh, mudflats, freshwater grazing marsh and reed-beds. These areas support diverse species and provide habitats for wildfowl and waders, for example. The implications of flood risk reduction on these areas are a primary consideration for the development of future plans.

5.1.2 Historical and future flooding and defences

Flood risk origines on the Thames Estuary from a number of different sources: occurrences of high surges in the North Sea, fluvial flooding on the Thames and fluvial flooding on tributaries of the Thames. By far the greatest hazard arises from tidal surges and in 1953 an event caused widespread flooding and damage along the Thames floodplain. To counteract this threat the Thames Barrier and associated defences were constructed, becoming operational in 1982. As well as the Thames Barrier, nine other surge tidal excluding barriers have been constructed, downstream of the Thames Barrier, where tributaries join the Thames. Forecast and real time data on the tidal conditions in the North Sea are used to ensure these barriers and the Thames Barrier are closed simultaneously, prior to extreme tidal flood events in the Thames Estuary. There are approximately 280 km of raised flood defences on the Thames with approximately 200 km of tributary defences. These static defences vary in type, the most common are earth embankments, steel sheet piled vertical walls and concrete or brick structures. These defences may lie on the actual riverbank or some distance inland.

Historically, construction of these linear flood defences along the estuary has been carried out in a reactionary manner to flood events and as such many of the defences (in particular those in central London) show a 'stratigraphy' of raisings that often incorporates a variety of different materials. This means the defences are often composite in nature. Comprised within the linear static defences are a series of "frontager floodgates". These have been installed at locations where there is a purpose-made 'gap' in the tidal defence walls to allow access to wharfs, jettys and the foreshore for example. Downriver of the Thames Barrier these are significant in size and have various sealing devices (e.g. rubber flaps, eccentric hinges) and often a telemetry sensor to detect closure states. Upriver of the

Thames Barrier they are usually smaller, and some of the openings are closed by damboards. Closure of these gates is often the responsibility of the riparian owners who are notified of flood warnings. "Frontager floodgates" are an integral part of the system. The lack of closure or malfunction of one of them, particularly in the downriver locations, could allow extensive flooding. They are often in remote locations, and being on private frontages, can be susceptible to unreported damage.

5.1.3 How the flood system works

Protection against extreme high tides is provided by closing the Thames Barrier, tributary barriers, "frontager floodgates" and the tide flaps on drainage outfalls and fixed flood defences, downstream of the Thames Barrier. Protection against fluvial flooding on the Thames is provided by fixed defences upstream of the Thames Barrier, closure of the Thames Barrier at low tide to provide a storage volume upriver of the Barrier, thus minimising the possibility of 'backing-up' of fluvial flows by the tide and maintaining conveyance in the upper estuary reaches (west London). Similarly protection against fluvial flooding on tributaries with barriers is ensured by flood defences (which have a lower level than on the Thames) and closure of barriers at low tide. The River Roding (northern bank tributary of the Thames) has limited storage compared with the potential fluvial inflows. Protection against fluvial flooding on drainage channels is provided by tide flaps that exclude the tide and flood defence measures upriver of some outfalls including storage, pumping stations and fixed defences.

An extreme tide (present day return period of approximately 1,000 years), without operation of the Thames Barrier, ranges from 5 m above Ordnance Datum (AOD) at Southend to about 6.5 m AOD at Richmond. This is about one metre higher than the crest level of the defences upriver of the Thames Barrier. Operation of the Thames Barrier reduces this level to below 4 m AOD between the Barrier and Richmond, west London. Downriver of the Thames Barrier the fixed defences, with crest levels generally between 6 m and 7 m AOD, afford significant protection from flooding in the outer estuary. Extreme water levels arising as a result of extreme fluvial flows on the River Thames exceed flood defence levels upriver of Richmond with the Barrier operating. If the Barrier was not operated, the fluvial flood levels would be higher by about 0.5 to 1.0 m in the Teddington to Richmond area. The flood defences upriver of the Barrier generally have crest levels between 5 and 6 m AOD. These levels are required to avoid frequent closure of the Barrier during 'normal' high spring tides and small tidal surges. The interim defence raisings that were put in place whilst the Thames Barrier was being constructed also remain in some areas.

5.1.4 Future drivers of flood risk

Flood risk is a dynamic quantity and when developing a strategic flood risk management plan it is important to identify the future drivers of changing flood risk. Two of the primary drivers on the Thames Estuary are future floodplain development, increasing the number of people and property on the floodplain and climate change, that could see an increase in the frequency and severity of extreme events. With regard to the former, whilst there are difficulties in projecting future developments in the longer term, in the near term there are ongoing initiatives, for example, the Thames Gateway regeneration, that give an indication of the likely developments occurring over the near term (20-30 years).

The Thames Gateway comprises nearly 10,000 hectares (more than 35 square miles) of land, running along the River Thames, east from the Isle of Dogs to the edge of London. The area once served as the major centre of London's manufacturing industry and trading economy. It is now however, been identified as London's prime growth corridor. The next twenty years will see partners working together to build on the success of Canary Wharf, Crossrail, and the 2012 Olympic Games, in order to make the most of the area's extraordinary opportunities (London Mayor, 2002). The Mayor's vision is for:

> *"…exciting and varied places, that will draw people to London Thames Gateway; well connected places, linked by excellent public transport, improved cross river links, walking and cycling routes; green places, with great new buildings and public spaces,*

including three large new parks, integrated with the area's existing heritage; working places, which build on success, revitalise local economies, and integrate it with the rest of London and the south east, creating opportunities for new and existing residents; environmentally, socially and economically sustainable places, which help local people to access opportunities, which strengthen community cohesion and which become models of more environmentally responsible development and energy use."

The Mayor's London Plan suggests that London Thames Gateway should plan for a minimum of 120,000 homes before 2026, and could accommodate up to 200,000 more jobs over the same period. Much of the development that has been discussed will potentially be constructed in the floodplain area directly influencing flood risk.

Climate change can also influence future flood risk in a variety of ways, for example changes in: extreme sea level at high water (relative to land level, and including surge); extreme river flow; extreme rainfall (possibly for more than one duration); extreme wave conditions (deep water wave height and period); dependence between any relevant pairings of the above or mean sea level (relative to land level). The lowering of land level in London (isostatic effect) is also considered of significance for flood risk (UKCIP, 2002). Estimates of the rise in absolute mean sea level (ice melt and heat expansion effects) are provided, for different emissions scenarios in UKCIP (2002) and more recently, IPCC (2007). Whilst there is a significant amount of evidence to support the estimates of future sea level rise and other climate change related phenomena, there is still significant uncertainty associated with future projections. Methods to capture these uncertainties within the decision making process are discussed in more detail below.

5.1.5 Ongoing flood risk management studies

During the course of the FLOODsite Research Project, the UK Environment Agency (EA) has undertaken a project to develop a long term flood risk management plan for the estuary, the so-called TE2100 Project. The aims of the TE2100 Project are (EA, 2008) detailed below:

"Thames Estuary 2100 (TE2100) is an Environment Agency project to develop a tidal flood risk management plan for the Thames estuary through to the end of the century. The final plan will recommend what flood risk management measures will be required in the estuary, where they will be needed, and when over the coming century, based upon the climate changes and sea level rises we face. The plan will take into account the increasing flood risk due to: Climate change,; rising sea levels; natural ageing of flood defence infrastructure; changes in land levels and new development in the tidal flood plain."

Whilst there has been interaction between the TE2100 Project and the FLOODsite Research Project, it is important to note that the information provided below presents philosophies and results carried out under FLOODsite and does not in any way represent output from the TE2100 Project**.** The aims of the former work described here were to develop improved methods for managing flood risk and apply those methods to the Thames Estuary.

5.2 Objectives and approach

5.2.1 Objectives

The objectives for the Thames pilot study were to develop and apply a quantitative flood risk analysis model for the purposes of flood risk management. The model was developed to be consistent with the Source-Pathway-Receptor Framework and based upon the definition of flood risk provided by Gouldby & Samuels (2008). A range of flood risk mitigation measures are possible on the Thames and there are a range of drivers of flood risk. A specific objective was to utilise the model to quantify the risk reduction (benefit) achieved through implementation of the different interventions, whilst considering different potential flood risk scenarios. These scenarios comprised different socio-economic and climate change futures.

5.2.2 Flood risk analysis

A core activity for flood risk management is the quantification of flood risk. Having an appropriate risk analysis method or model enables the present day risk to be quantified, as well as the future risk which can vary as a result of climate change or floodplain development. Once established, the model can then be used to investigate how effective different interventions are in reducing risk. The method adopted for the Thames Estuary is a flood risk system based model that includes a probabilistic representation of the sources, pathways and receptors (see Chapter 1). The details of the method are described in Gouldby *et al.* (2008), an overview is provided here. The model components include: extreme value distributions of water levels, associated with each defence, along the length of the Thames Estuary and tributaries (*source*); fragility curves to represent the performance of the fixed defences as well as the active barriers and "frontage floodgates" (*pathway*); a hydraulic flood spreading model to represent the propagation of floodwater across the floodplain (*Pathway*) and the property data (*receptor)* allied to economic depth-damage functions (*consequence;* Penning-Rowsell *et al.,* 2005, to quantify the consequences of flooding).

Within the model domain, the study area floodplain is resolved into discrete flood areas. These areas are assumed to be hydraulically independent of one another, with boundaries typically formed from topographical features, high ground or river channels (ie tributaries), for example. The system of linear defences forms a boundary between the river channel and the floodplain area. The defence system comprises discrete lengths of defence sections that vary in type, embankments, sheet pile walls or "frontager floodgates" for example, condition or geometry, and therefore resistance to flood loading. The lengths of the defence sections are naturally limited to 600 m for soft defences (embankments) and 300 m for hard defences (sheet pile walls). Within any flood area, the likelihood of an extreme hydraulic load on the defence system is assumed to be dependent. The performance (structural integrity) of individual defences, in response to the hydraulic loading, is assumed to be independent.

The primary outputs from the model are the spatial distribution of flood risk, expressed as expected annual economic damage (EAD) over the floodplain area, the spatial distribution of the likelihood of flooding, typically expressed as the annual probability of exceeding 0 m flood depth, over the floodplain area and the defence specific contribution to residual flood risk. This latter output can be thought of as the reduction in risk that would arise if any given defence were "made" infinitely high and infinitely strong. It provides an indication of where defence based engineering interventions can be most effective at reducing flood risk. The results relating to the likelihood of inundation can be used to in subsequent analysis to determine the people to risk as well as damage to habitats. The model is flexible and can be used for a wide range of flood risk reduction activities such as the short term prioritisation of maintenance activities, as well as long term planning, the focus of this study. The drivers of flood risk, as well as flood risk reduction activities are reflected within the system model through modifications to the underlying databases (Table 5.1).

5.2.3 Model setup and data sources

The modelled area extends westward along the Thames Estuary from Southend in the east to Teddington (Figure 5.1). There are a number of tributaries included within the model that include Beverly Brook and the Rivers Lee and Roding. For the *source* element, the model requires inputs in the form of extreme value distributions of the loads (i.e. in-river water levels). To obtain extreme values of extreme water levels on the river Thames it was necessary to consider the likelihood of extreme North Sea surges occurring simultaneously with extreme fluvial flows on the Thames. Concurrent observations of Teddington flows and sea levels at Southend were analysed to determine the dependence between the variables. These data were then extrapolated to extreme values using the JOIN-SEA joint probability method (Hawkes *et al.* (2002).

Table 5.1 Drivers of change to the flooding system (adapted from de Bruijn et al., 2008; OST, 2004)

	Driver of change in flood risk	Factors the driver influences	Influence	Influences S, P, R or C?
Climate	1. Climate change due to emissions or natural processes	1.1 Temperature	None	S
		1.2 Precipitation	None	S, P
		1.3 Wind	None	S
Socio-economic	2. Population growth / decline	2.1 No. of people	None	R
		2.2 No. & location of houses	None	R
	3. Urbanisation I	3.1 No. & location of houses	None	R
	4. Public attitudes / preparedness	4.1 People exposure & vulnerability e.g. where live, insurance, awareness	Some	R, C
	5. Social status of a community	5.1 Risk to life i.e. conditional chance of death given context	Some	R, C
		5.2 Unpriced or 'intangible' losses e.g. stress, damage to health, quality of life	Some	R, C
		5.3 Social vulnerability	Some	R, C
		5.4 Risk of long-term loss of activities in an area	Some	R, C
	6. Market forces	6.1 Economic growth / decline	None	R, C
		6.2 Major developments	None	All
		6.3 Rise / decline in land value	None	R, C
Coastal / fluvial processes	7. Ground level movements	7.1 Morphology & sediment supply	Some	S, P
		7.2 Land subsidence	None	S, P
		7.3 Plate tectonics	None	S, P
	8. Sediment movement & veg. growth / changes	8.1 Conveyance capacity	Some	S, P
	9. Legislation / natural variability on environment, ecosystems & habitat	9.1 Change in land-use	Some	S, P
		9.2 Change in location & priority of protected sites	Some	S, P
		9.3 Change in river characteristics to meet habitat requirements	Some	S, P
Run-off	10. Rural land-use management	10.1 Agriculture activities: land-use	Some	S, P
		10.2 Agriculture activities: increased/decreased run-off	Some	S, P
	11. Urbanisation II	11.1 Land-use e.g. growing urban centres	None	S, P, R
		11.2 Increased run-off e.g. reduced permeability		S, P
Management / governance	12. Elected government	12.1 Views may influence policy e.g. promote environment	None	All
	13. Regulation / Development control	13.1 Where local / national housing infrastructure is developed	Some	R, C
	14. Institutional / Legislation	14.1 Land-use e.g. not permitted in floodplain	None	R, C
		14.2 Protection afforded to urban areas	None	P, R, C
	15. Insurance / risk compensation	15.1 Linked to 4.1	None	C
	16. Science, engineering & tech.	16.1 Vulnerability of people e.g. buildings, electronics, other	None	C
	17. Intervening priorities	17.1 Various e.g. less resource due to war; quarantined areas	None	All
	18. Defence deterioration (no FRM)	18.1 Lowered standard of protection	None	P

An Infoworks RS hydraulic model of the river channel was then used in conjunction with the joint probability method to derive extreme water levels (EA, 2007a). For modelling purposes, the required properties of the linear defences comprised the spatial location, crest level, type and condition grade.

These data were available from a number of different sources, with multiple potential sources available for any given parameter. These data sources varied in quality. A hierarchical system was therefore introduced that established the priority order for including data based upon quality. An example of the hierarchy for crest level is provided in Table 5.2.

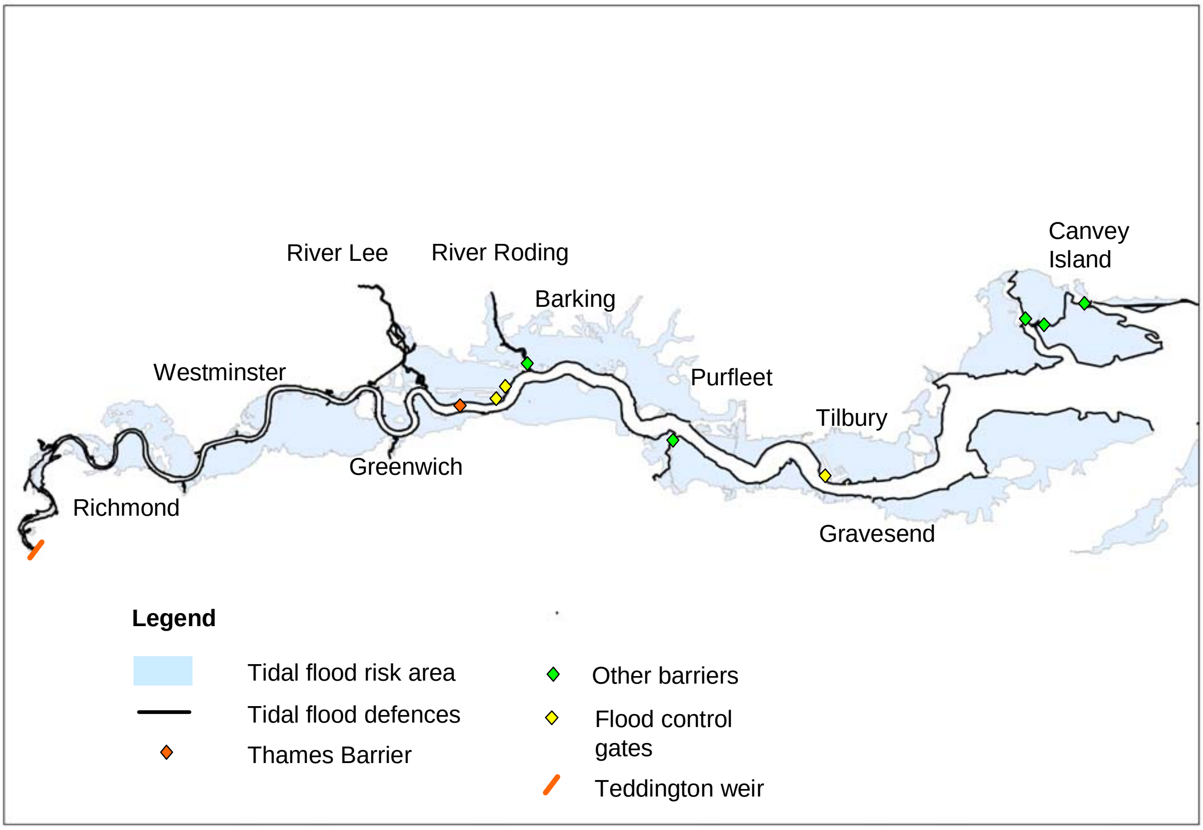

Figure 5.1 Extent of the modelled area

Table 5.2 Defence data prioritisation – crest level

	Source	**Spatial coverage**
1	GPS spot level data	Downstream of barrier
2	Low level (March 2005). Currently un-verified	Anglian and Southern
3	As constructed drawings (IA4). (Land Registry only)	All regions
4	Statutory defence levels	All regions
5	As constructed drawings (IA4)	All regions
6	IA3 Condition inspections	All regions
7	V1a model	All regions
8	Embayment strategy Volume III	Thames
9	Estimated crest level	All regions

This defence data is stored in a Performance Based Asset Management GIS System (PAMS) developed by HR Wallingford. The database is based on, and compatible with the UK Environment Agency's National Flood and Coastal Defence Database (NFCDD) but enables additional defence data and parameters, that are potentially useful for flood risk analysis, to be stored. Typical screenshot of the database is shown in Figure 5.2. It was also necessary to include information on the reliability of the various active structures, most notably the major barriers including the Thames, Dartford and Barking Barrier. Digital terrain data, for use in inundation modelling and establishing the elevation of properties, was obtained from a LIDAR survey, the horizontal resolution of which was 1-2 m. This was resampled to form a grid resolution of 50 m across the floodplain area. Spatial location and numbers of properties (residential and industrial) was provided in the form of the National Property

Database 2005. These data were combined with depth-damage information from Penning-Rowsell (2005) to translate flood depths into economic damages.

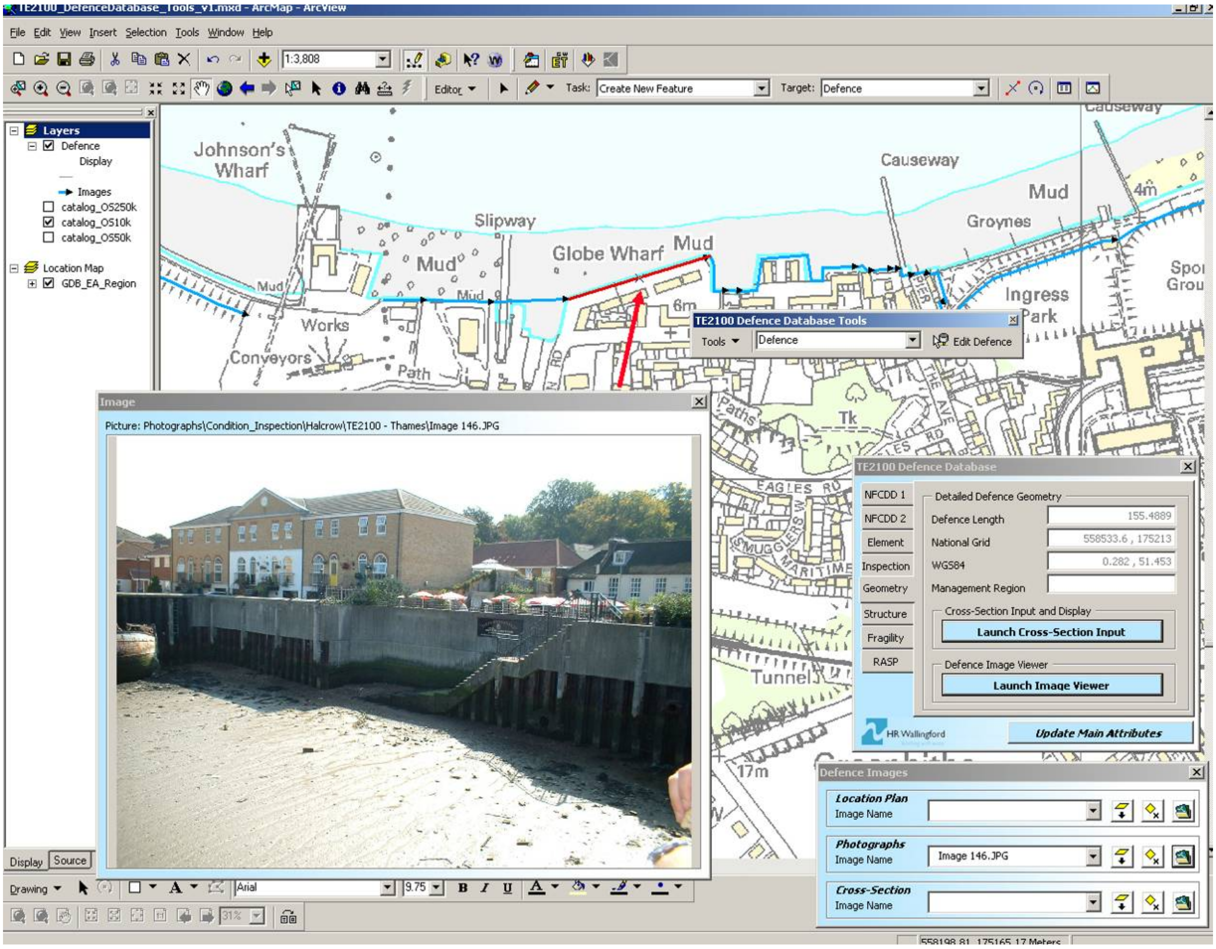

Figure 5.2 Screenshot of the flood defence asset management database

5.2.4 Composing scenarios for long term planning

An important aspect of developing a long term strategy that considers future changes to the drivers of flood risk is the development and quantification of a range of plausible future socioeconomic and climatic scenarios. These are also referred to as storylines. The storylines seek to capture the autonomous events over which flood risk management decision makers have little influence. Within the Thames study, the approach to storyline development has been based upon previous national scale analysis in the UK, the so-called Foresight study (Evans *et al.*, 2004). The Foresight futures based on the World Views Local Stewardship, World Markets, Global Sustainability and National Enterprise have been scaled down and implemented as appropriate.

The Thames region coincides with England's economically vibrant capital, which has had a Gross Domestic Product (GDP) growth which has been higher than the rest of the country for many years. This, together with the planned hosting of the 2012 Olympic Games in London and the Thames Gateway development (the largest regeneration project in Western Europe), indicates the likelihood of low future growth is low. In the interests of developing a wide scenario range not based on *a priori* assumptions, however, a Local Stewardship, that reflects relatively low economic growth has been analysed. The main drivers of change for the World Views in the context of the Thames pilot are summarised in Figure 5.3. These are classified in terms of governance/development, socioeconomic aspects, coastal and fluvial processes, climate change and run-off, and build upon the storylines adopted in Foresight (Evans *et al.,* 2004a & b).

Autonomy

National Enterprise

Governance/development: Weak, national closed. Continued extreme development pressure in Thames area. As objective is to maximise public or national interest, the preference is to achieve optimum FRM in terms of economic efficiency. Commercial activities are likely to be focused on bio- and nanotechnology activities with increases in susceptibility to flood damage. The industry will become specialist and concentrated, resulting in factories which may be single global producers of products with massive disruption to world stock.
Socio/economic: Population will redistribute, with more young people in Thames region. Individuals responsible for their personal flood risk - limited help from institutions and wider community. Property values will increase, and combined with increased spending on household durables, will increase susceptibility to damage.
Coastal & fluvial processes: There will be accelerated sediment transport and patterns of accretion and erosion. The lower Thames reaches and estuary mouth will, in particular, be subject to deposition. There will be increased water levels and reduced conveyance due to reduced environmental management requirements and regulation. This will also lead to concern for the intangible environmental benefits – as flood protection is prioritised. Operating authorities continue to explicitly recognise that the river has multiple users – with multiple needs – and an optimum solution is required for river management. This will be further promoted by the Water Framework Directive and Floods Directive.
Climate change: Medium-low growth with no action to limit emissions. Increasing and unregulated emissions from newly industrialised countries.
Run-off: Increased due to floodplain development, urbanisation & poor drainage solutions.

Local Stewardship

Governance/development: Strong, local, participative. The environment will be a constraint, limiting what actions can be done and environmental enhancements will be sought. Natural forms of flood management are favoured e.g. room for rivers, managed retreat, re-creation of wetlands. Strong land-use control policy to avoid flood prone land i.e. most of the Thames region. Power further devolved to local communities and small watersheds – making integrated water management a challenge. Limited reward for entrepreneurs leads to limited innovation.
Socio/economic: Emphasis on community and equity results in increased population to support development of community facilities e.g. shops, schools, healthcare. Little new floodplain development. Flood victims are viewed as 'sinners' as they are based in areas belonging to the river. This view is in conflict with the ethos of community solidarity & practicalities for supporting the high Thames region population. Real income increase relatively slowly. Expected life of consumption goods increases, as does cost, but these will be less susceptible to flood damage.
Coastal & fluvial processes: Local response to local problems means that problems are dealt with in a piecemeal fashion - reinforced by reduced public funding for public services. Lack of system-scale river management leads to progressively severe river responses. Environmental concerns are considered but conflict with individuals' perceived need for flood protection. The local emphasis leads to widespread variability in regulation - pending local enforcement.
Climate change: Low growth and low consumption, however, less effective internal action. Low innovation.
Run-off: Protection from floodplain development Sustainable storm water management. Increased urban density.

Consumerism ***Community***

World Markets

Governance/development: Weak and dispersed. Absence of land-use controls means development tends to take place where developers expect most profit e.g. planned Olympic village on the River Lee as well as the Thames Gateway which affects East London. As the Thames region is built-up, residence and government will provide improved community defences. Commercial activities are likely to be focused on bio- and nanotechnology activities with increases in susceptibility to flood damage. The industry will become specialist and concentrated, resulting in factories which may be single global producers of products with massive disruption to world stock.
Socio-economic: Population will redistribute, with more young people in Thames region. Human impacts of flooding are irrelevant. Individuals are entirely responsible for taking actions to reduce their own personal risk, resulting in the socially vulnerable becoming more vulnerable. Property values will increase, and combined with increased spending on household durables, will increase susceptibility to damage.
Coastal & fluvial processes: There will be accelerated sediment transport and patterns of accretion and erosion. The lower Thames reaches and estuary mouth will, in particular, be subject to deposition. There will be increased water levels and reduced conveyance due to reduced environmental management requirements and regulation. This will also lead to concern for the intangible environmental benefits, as flood protection is prioritised.
Climate change: Highest national and global growth. No action to limit emissions. Price of fossil fuels may drive the development of alternatives in the long term.
Run-off: Increased due to floodplain development, urbanisation & poor drainage solutions.

Global Sustainability

Governance/development: Strong, coordinated, consultative. Wide use of principles critical natural capital and constant natural assets. Compensatory actions for any negative environmental impacts. Preferred management strategy will be land-use control – including type of urban use. Regulators are more responsive to their perception of what stakeholders want. Emphasis on whole catchment management.
Socio-economic: The ethos of community solidarity in the face of natural disasters leads to the identification and help of the most vulnerable (defined by social terms not individual characteristics). Real income increases and spending on household durables. Real prices of household durables increase as regulations governing water and energy efficiency and recycling become increasingly rigorous.
Coastal & fluvial processes: Strong planning controls plus an emphasis on biodiversity mean a progressive retreat from river management i.e. return to natural state. Reduction in dredging to meet environment targets leads to increase deposition of sediment in the Thames mouth, reduced conveyance and greater water levels. Requirements for undertaking of compensatory actions for any negative environmental consequence will be focused on enhancement of functioning of the Thames catchment and coastal zone, rather than flood protection.
Climate change: Medium-high growth but low primary energy consumption. High emphasis on international action for environmental goals e.g. greenhouse gas emission control. Innovation of new and renewable energy sources.
Run-off: Little change to urban extent. Some increased density but with sustainable urban water management strategies. Planning control to prevent floodplain development.

Interdependence

Figure 5.3 Drivers of change

To quantify the flood risk under different futures, it is necessary to translate the coherent storylines into changes in the model parameters and variables. An important element of this translation is differentiating between global parameters such as climate change that have limited dependence on regional activities in the Thames Estuary, and more localised parameters such as socioeconomic change, which may be driven by regional influences, e.g. the Thames Gateway project. Thus, in developing the scenarios for the Thames Estuary, the local and global aspects are separated into two distinct categories. Climate change is represented in terms of discrete global emission scenarios that are characterised by a single parameter of sea level rise (the rate of sea level rise increases as carbon emissions increase) and associated other climate changes. Socioeconomic change represented in terms of regional growth that in turn is characterised by a single parameter of housing numbers and associated other changes (population, GDP, market forces etc.). On these axes, a 'plausible' future space can be obtained through identification of the extremes.

The evidence base for the range of climate emission scenarios was taken from three sources UKCIP (2002), Defra (2006) and EA (2008). The range of scenarios was qualified as 'High++', 'High+', 'Medium' (Defra, 2006) precautionary allowance and the UKCIP (2002) low emission scenarios. For the socioeconomic futures, a low, medium and high growth scenario was defined, based on historic trends and expected projections (e.g. housing, population, GDP, market forces). The socioeconomic growth is closely linked to the current and planned regional developments taking place in the Thames Estuary. There have been a number of detailed studies undertaken for the London Boroughs in the Thames Estuary, covering past trends and medium-term (30 years ahead) predictions of housing, employment and population growth, including the spatial resolution of these changes (e.g. Mc Fadden *et al.,* 2007). The approach involved adopting the predictions for housing growth (Mc Fadden *et al.,* 2007) through to 2030 and then developing three discrete growth scenarios – 'Low', 'Medium' and 'High' − based on no further growth ('Low'), direct extrapolation of the predicted curve ('Medium') and extrapolation of the prediction by a factor of two ('High'). The housing growth forecasts were combined with projections of the average house inhabitants to provide information on the population growth.

5.2.5 Strategic alternatives

Development of options

The option development philosophy developed within the FLOODsite Project (de Bruijn *et al.*, 2008) promotes the concept of resistant and resilient strategic alternatives, along with a reference case. The term resilience in the context of flood risk management can be defined as "*the ability of a system community society defence to react to and recover from the damaging effect of realised hazards*" (Gouldby & Samuels, 2005). This term is often closely associated with the use of non-structural measures that reduce flood risk. The use of non-structural flood risk reduction measures is increasingly being promoted. With emerging guidance such as the UK Government's Department for Environment, Food and Rural Affairs' (Defra) Making Space for Water initiative (Defra, 2007) and the EC Water Framework Directive (WFD), there has been a move towards less heavily engineered solutions for flood risk reduction and recognition that the floodplains are the natural areas for the transmission of flood flows − supporting the implementation of more non-structural measures. Table 5.3 provides a list of non-structural measures that have been considered for the Thames Estuary.

Whilst the use of non-structural measures has been considered in detail, in heavily engineered systems like the Thames, it is entirely appropriate to consider resistance based (i.e. heavily engineered) options as well. The range of options considered within the Thames Estuary therefore comprise: '*Do Nothing'* – the reference case, no active intervention; '*Resistant'* − involves improving the existing system through, for example, defence raising and maintenance, over-rotating the barrier (to give a higher crest level of the barrier) and introducing limited non-structural measures; '*Resilient'* − this involves small improvements to the existing system (e.g. limited defence raising, increased storage, managed realignment) as well as introducing non-structural measures; '*Highly Resilient'* − similar to the 'Resilient' alternative, however, many more non-structural measures are incorporated.

These options are based upon but not the same as the TE2100 high level options (HLO's) (Ramsbottom *et al.,* 2006). The 'Resistant' strategic alternative is detailed in Table 5.4 and Figure 5.4. Table 5.4 provides a summary of the risk reduction interventions and the timing of these. Figure 5.4 gives an overview of the spatial location of the structural changes. The 'Resilient' strategic alternative is detailed in Table 5.5 and Figure 5.5. Table 5.5 provides a summary of the risk reduction interventions and the timing of these. Figure 5.5 depicts the spatial location of the structural changes. The 'Highly Resilient' strategic alternative is detailed in Table 5.6 and Figure 5.5. Table 5.6 provides a summary of the risk reduction interventions and the timing of these. Figure 5.5 shows the spatial location of the structural changes.

Table 5.3 Summary of non-structural options and their assumed effectiveness ,and uptake, and model representation

Non-structural option	**Effectiveness**	**Uptake**	**Change reflected in model**		
			RD	CD	VP
Pre-event planning					
Public awareness raising e.g. flood risk maps, education of inhabitants, Radio/Television information channel	50% Limited in well defended areas where risk perception is low e.g. Thames	40%	3		2%
2. Flood Forecasting and warning	80% Improved effectiveness due to on-line systems.	50% Take-up in TE will be low due to perceived low risk.	1.05 (depths > 1m) [Ref: PAG3]		5% [Ref: PAG3]
3. Emergency planning including evacuation to high ground, crisis management	70%	30% Take-up in TE will be low due to perceived low risk.			3%
4. Development layout to facilitate safe evacuation e.g. high level access routes, reduced risk to people	75%	40% Take-up in TE will be low due to perceived low risk.			3%
5. Business contingency planning including flood recovery	70%	50%		8	
6. Land use zoning/planning e.g. development set back from defences, PPG25 sequential test	80%	50% Uptake likely to improve with e.g. PPG25	4	4	2%
7. Land use zoning/planning e.g. discourage new development in floodplain	80%	50% Uptake likely to improve with e.g. PPG25			3%
8. Flood resilient building design to minimise flood risk e.g. resilient design, multi-storeys with floodable bottom floors	80 %	50 % Uptake likely to improve	6 (depths < 2.5 m)	6 (depths < 2.5 m)	
9. Long-term planned relocation	70 % Requires detailed B:C analysis to assess effectiveness.	20 % Complex process - anticipated low up-take.			
10. Flood response planning (Local Authorities)			Captured in during event actions		
11. Subsidies for flood proofing or other measures			Captured in during event actions		

12. Insurances e.g. private or Government Bellwin Scheme					
13. Wetlands conservation/rehabilitation					
14. Coastal wetland protection					
15. Regulations on storage of toxics/chemicals	Not relevant for the Thames Estuary				
16. Adaptation of recreation functions	Limited opportunity in the Thames Estuary				
17. Adaptation of agricultural practices	Not relevant for the Thames Estuary				
18. Health and safety measures e.g. reduce impacts from flooding					
During event measures					
19. Flood fighting e.g. making breaches in secondary defences to lower levels, use of temporary demountable defences, informal defence walls, pumping water out of basements, emergency diversion of flood waters	90 % Very effective. Benefits far outweigh costs.	80 % Higher uptake as authorities involved	6 (depths < 1.5 m)	6 (depths < 1.5 m)	3 %
20. Damage avoidance actions – *collective* e.g. removal of assets, erecting temporary defences, opening rest centres, operating help lines, traffic management, turning power off to areas most badly affected etc.	90 % Very effective. Benefits far outweigh costs.	70 % Reasonably high uptake as authorities involved	4 (depths < 1 m)		2 %
21. Damage avoidance actions – *individual* e.g. moving valuables, installing temporary defences, installing sandbags, moving cars, avoiding travel through the flooded areas	75 % Potentially very effective. Cost of installation pays for itself within 1 flood;	60 % Uptake still fairly low.	3 (depths < 1 m)		
Post event measures					
22. Governmental relief funds					
23. Damage compensation					
24. Fines for damage increasing behaviour					

Evaluating the performance of strategic alternatives

The evaluation of the performance of the different strategic alternatives is undertaken through consideration of a range of performance measures, benefit-cost analysis, people at risk and habitat damage more specifically. Within this study the benefit-cost analysis is based upon traditional UK economic analysis methods (Defra, 2006), whereby the benefit is calculated as the reduction in risk achieved under the strategic alternative when compared to the reference case ('Do Nothing'). All benefits are discounted to the present day assuming a specified discount rate, to provide a present value (PV), which is then compared with the discounted cost of the strategic alternative. The difference here, when compared to the traditional approaches, is the consideration of different future climate change and socio economic scenarios.

The benefits of the strategic options have been evaluated over a range of possible future socio economic and climate change scenarios, a two dimensional surface thus describes the benefit. An example PV surface is shown in Figure 5.6 for the 'Resistant' strategic alternative. The issue then, for determining the preference ordering of the strategic alternative, is to determine how to account for the uncertainty in different future scenarios? A number of approaches can be considered here.

Table 5.4 'Resistant' strategic alternative

Epoch	SPR	Description of intervention (Defence raising … resistant)
2040	*Source*	Re-profile channel navigation channel (West London), reduces defence loads. Managed retreat, in the Outer Estuary, reduces upstream loads.
	Pathway	Defences raised by 0.3 m
	Receptor	Flood forecasting and warning
2070	*Source*	Managed retreat in the Outer Estuary, reduces upstream loads. Over-rotate the Thames Barrier, reduces upstream loads
	Pathway	Defences raised by 0.5 m; Some new defences
	Receptor	Flood forecasting and warning
2085	*Source*	
	Pathway	Restore interim defences upstream of the Thames Barrier
	Receptor	Flood forecasting and warning

NB: These are introduced under a baseline assumption of P3 (routine maintenance, refurbishment of defences and barriers operating to rule)

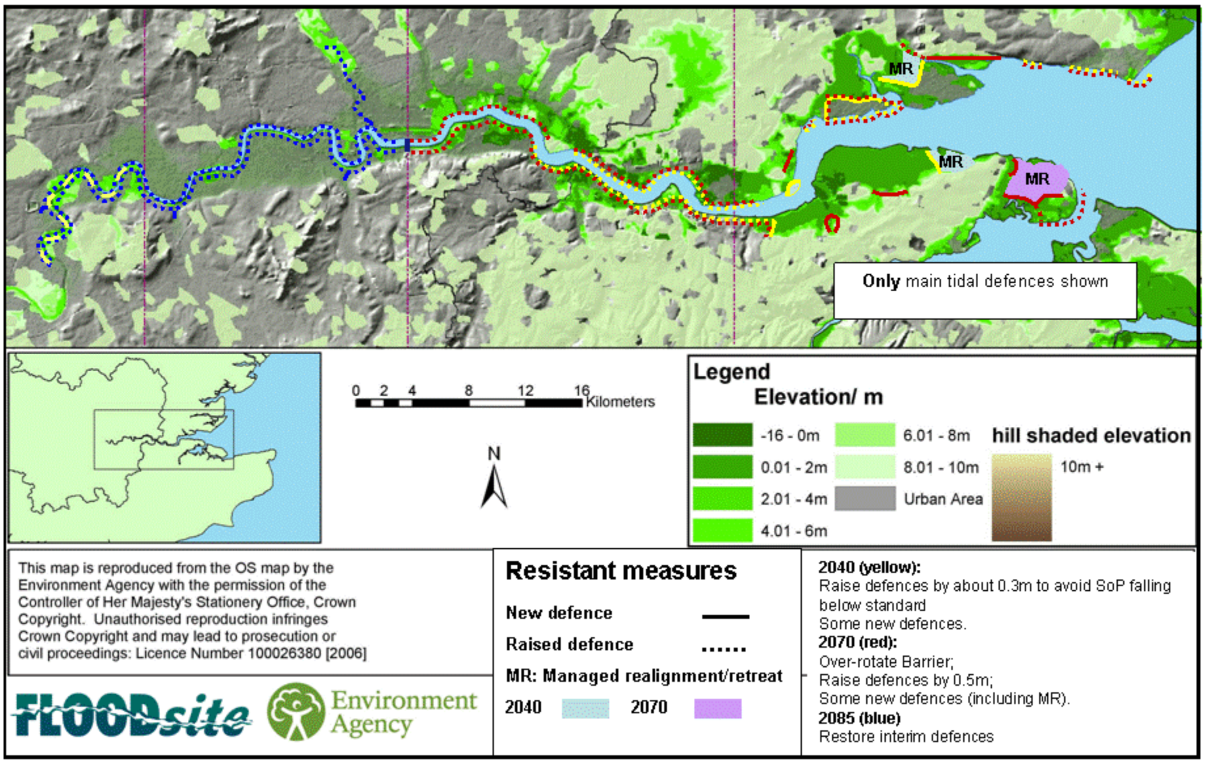

Figure 5.4 The "Resistant" strategic alternative

Classical decision theory (e.g. French, 1988), discusses two widely considered approaches. One based upon Laplace's Principle of Indifference or Insufficient Reason that involves assigning an equal probability to uncertain quantities, and is therefore fundamentally probabilistic. The other is Wald's Maximin model, which makes the assumption the worst case of the uncertain quantity will always arise and seeks to choose the alternative that maximises the reward given this assumption, the approach does therefore not involve assigning any likelihood to uncertain quantities.

Table 5.5 'Resilient' strategic alternative

Epoch	SPR	Description of intervention (Storage … Resilient)
2040	*Source*	Re-profile channel navigation channel (West London), reduces defence loads. Managed retreat, in the Outer Estuary, reduces upstream loads.
	Pathway	Defences raised by 0.3 m
	Receptor	Non-structural measures: 1 Public awareness raising, 2 flood forecasting and warning, 3 emergency planning, 5 Business Contingency Planning, 6 & 7 Land-use planning/zoning.
2070	*Source*	Managed retreat in the Outer Estuary, reduces upstream loads; Flood storage areas, reduce upstream loads Over-rotate the Thames Barrier, reduces upstream loads
	Pathway	Defences raised by 0.3 m Some new defences, including managed retreat
	Receptor	As for 2040 − maintain
2085	*Source*	
	Pathway	Restore interim defences upstream of the Thames Barrier
	Receptor	As for 2040 − maintain

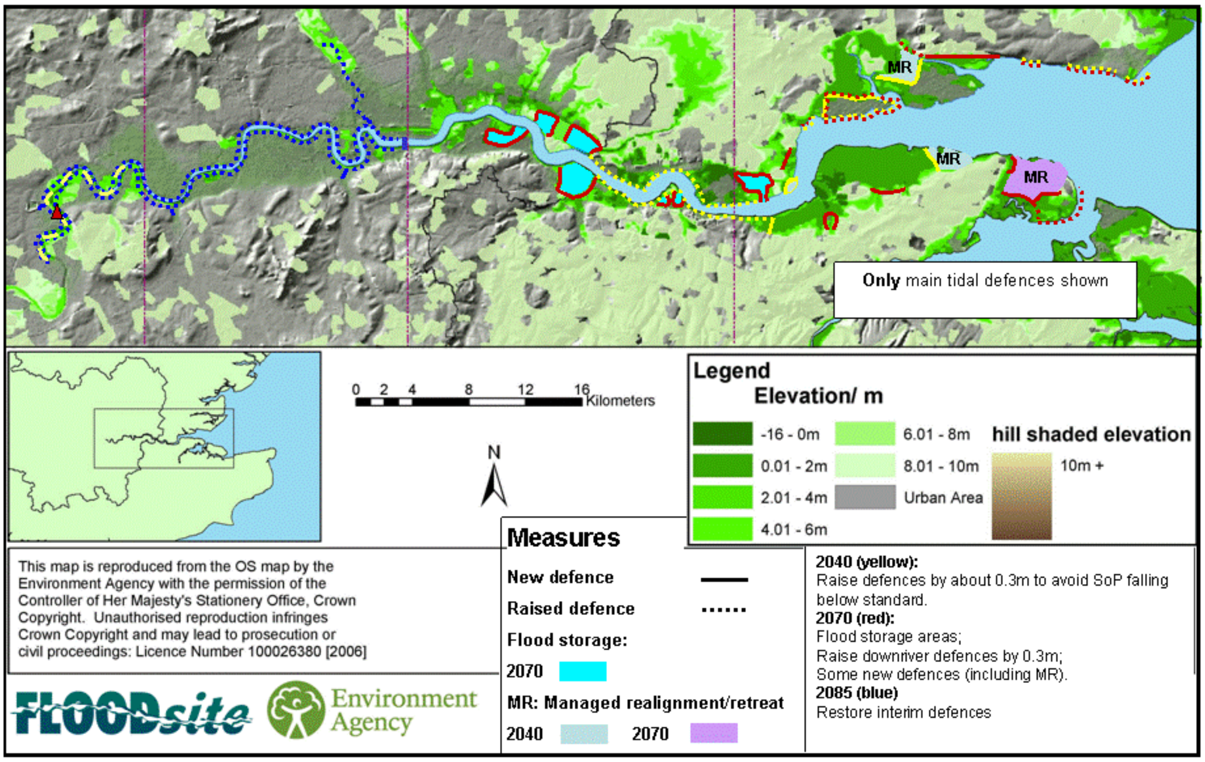

Figure 5.5 The "Resilient and Highly Resilient" strategic alternative

More recently Info-Gap approaches, that purport to be non probabilistic in nature, developed by Ben-Haim (2006) have been applied in the context of flood risk management by Hall & Harvey (2009). Sniedovich (2007) is critical of info-gap approaches suggesting the approach is based upon analysis in the neighbourhood on a point estimate of the system state (the uncertain phenomena) and the output of the analysis is sensitive to this decision. The method makes the assumption that the future system states become increasingly unlikely as they diverge from the point estimate (Hall, 2009). The method assumes that the most likely future system state is known *a priori*. Given that the system state is subject to severe uncertainty, an approach that relies on this assumption as its basis appears paradoxical and this is strongly questioned by Sniedovich (2007).

Table 5.6 'Highly Resilient' strategic alternative

Epoch	SPR	Description of intervention (Storage … Resilient)
2040	*Source*	Re-profile channel navigation channel (West London), reduces defence loads. Managed retreat, in the Outer Estuary, reduces upstream loads.
	Pathway	Defences raised by 0.3 m
	Receptor	Numerous non-structural measures: Pre-event measures 1 – 11 and all during event measures 19-21 i.e. flood fighting individual, collective, authorities etc.
2070	*Source*	Managed retreat in the Outer Estuary, reduces upstream loads; Flood storage areas, reduce upstream loads Over-rotate the Thames Barrier, reduces upstream loads
	Pathway	Defences raised by 0.3 m Some new defences, including managed retreat
	Receptor	As for 2040 - maintain
2085	*Source*	
	Pathway	Restore interim defences upstream of the Thames Barrier
	Receptor	As for 2040 − maintain

NB: These are introduced under a baseline assumption of P3 (routine maintenance and refurbishment of defences, barriers operating to rule)

A more traditional method that involves Bayesian type probabilistic weighting according to the decision makers strength of belief about the system states, is proposed by McGahey *et al.* (2008). In practice however, it is only necessary to apply these methods for the purpose of determining the preferred option when the preference ordering, based on benefits and costs, of the strategic alternative varies when the future scenarios are considered in isolation. In this study, the preference ordering of the options did not change under the different future scenarios, any method involving probabilistic weighting or Maximin analysis applied to the future scenarios would yield the same preference ordering. No further analysis was therefore required to determine the preferred alternative. The costs of the strategic interventions have been based on ongoing TE2100 work but modified for this analysis, these are detailed in de Bruin *et al.* (2008) and summarised in Table 5.7.

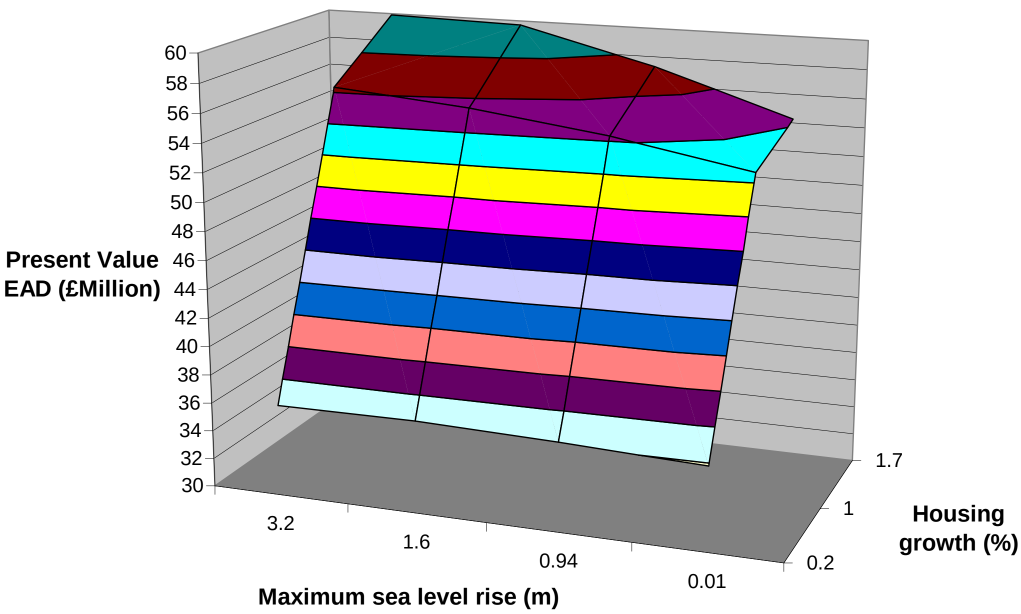

Figure 5.6 Two dimensional PV benefit surface – "Resistant" alternative

There is clearly significant uncertainty associated with both the benefits and costs described in this analysis and whilst a method for propagating epistemic uncertainties through the risk model has been developed (Gouldby & Kingston, 2007), this has not been implemented but is recommended for implementation within future research. In principle this method could be used to obtain a distribution of benefits and uncertain cost estimates could also be derived. This is discussed further in McGahey *et al.* (2008).

Table 5.7 Costs of the strategic options

Thames Estuary Cost Information	**£/metre**	**Capital costs**	**Annual main-tenance costs**	**Annual run-ning costs**	**Periodic refur-bishment (annual)**	**Periodic costs for 100yr period**
Defences (Personal communication D Ramsbottom on Royal Haskoning work)						
Upstream smaller defences						
Replacement costs per metre	£10,000					
Raising per metre	£5,000					
Downstream Larger defences						
Replacement costs per metre	£20,000					
Raising per metre	£5,000					
Barriers (Atkins 2006)						
Thames Barrier			£2,500,000	£3,700,000	£1,400,000	
Over-rotation		£890,000				
Replace FRGs		£13,300,000				
Raise piers		£3,750,000				
Decommisioning		£417,000,000				
King George V Dock Flood Gate replacement		£24,000,000	£148,000	£228,000	£200,000	
Gallions Reach Flood Defence Gates		£300,000	£27,000	£48,000	£71,000	
Royal Docks Pumping Station		£600,000	£15,000	£0	£2,500	
Barking Barrier		£2,150,000	£355,000	£545,000	£200,000	
Dartford Barrier (existing)			£355,000	£545,000	£200,000	
Dartford Barrier (new)		£1,500,000	£180,000	£275,000	£100,000	
Tilbury Flood Defence Gate (existing)			£148,000	£228,000	£200,000	
Tilbury Flood Defence Gate (new)		£30,000,000	£185,000	£285,000	£250,000	
East Haven Barrier		£150,000	£275,000	£180,000	£100,000	
Benfleet Barrier		£300,000	£275,000	£180,000	£100,000	
Pumping Stations (Atkins 2006)						
Small (<50l/s)		£195,000	£6,000	£3,400		£345,000
Medium (50-200l/s)		£277,000	£7,000	£4,000		£552,000
Large (>200l/s)		£410,000	£8,000	£5,000		£877,000
Extra Large (10cumecs/s)		£5,800,000	£94,000	£80,100		£2,235,000
Frontage gates (Atkins 2006)						
Small (3*1.25)		£24,000	£500	£750		£76,000
Medium (7*2.1)		£71,000	£800	£750		£220,000
Large (12*2.5)		£169,000	£2,500	£750		£529,000
Outfalls (Atkins 2006)						
Small (1000mm diameter)		£59,000	£500	£100		£118,000
Medium (2000mm diameter)		£80,000	£500	£100		£180,000
Large (2*1500mm diameter)		£108,000	£1,000	£200		£248,000
New Sluices (Atkins 2006)						
Flood Storage Area		£2,123,000	£2,500	£400		£226,900
Non-structural measures (JBA 2005)						
Public awareness raising (estimate - no source)				£100,000		
Flood Forecasting and warning (EA FWIS for Thames Estuary)				£1,500,000		
Flood Forecasting and warning (EA tidal defences & flood training exercises)				£528,000		
Emergency planning - evacuation to high ground (estimate - no source)				£500,000		
Development layout to facilitate safe evacuation (estimate - no source)				£500,000		
Business contingency planning including flood recovery (estimate - no source)				£200,000		
Land use zoning/planning e.g. dev set back from defences, PPG25				£50,000		
Land use zoning/planning e.g.discourage new development				£50,000		
Flood resilient building design to minimise flood risk				£1,000,000		
Flood fighting e.g. emergency diversion of flood waters (assumes 2.5 events/yr)				£5,000,000		
Damage avoidance actions – *collective* (assumes 2.5 events/yr; 50000 houses)		£751,250,000		£100,000		
Damage avoidance actions – *individual*		£0	£0	£0		

The risk to people has been quantified using the following definitions: 'Mild' − number of people exposed to frequent flooding (defined as the number of people in an area with an annual probability of inundation of 1:75 of exceeding 0 m depth); 'Serious' − Expected annual deaths and serious injuries (defined as annual probability of inundation of exceeding 1 m depth multiplied by the number of people at that location). Ecological damage can also be quantified using the model. This has been quantified in terms of area of habitat with an annual probability of inundation of 1:75 of exceeding 0.5 m depth.

These output risk metrics form the basis of the multi-criteria analysis that is detailed below. The approach to multi-criteria analysis involves combining the results of the different performance measures within an overall scoring framework. This framework can be visualised in the form of a diagram (see Figure 5.7). Invariably, within this type of multi-criteria approach, it is necessary to weight the difference performance measures. This can be a subjective process and in practice sensitivity analysis involving the weights is recommended. The application of this type of approach is discussed further in McGahey *et al.* (2008).

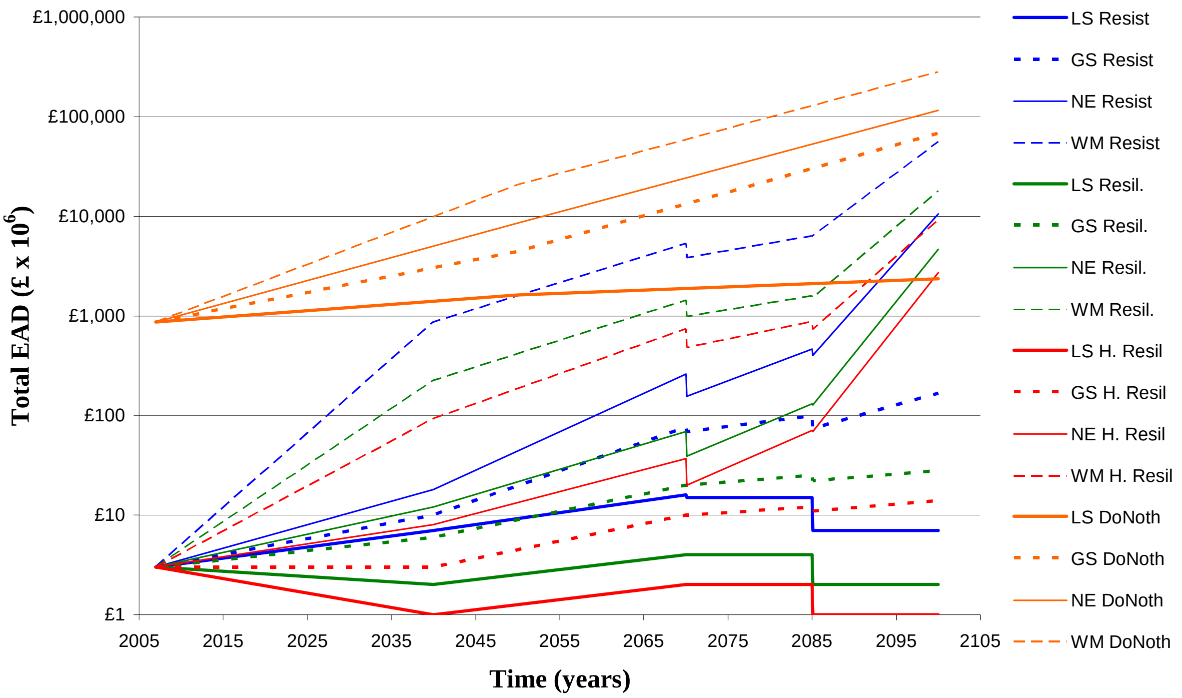

Figure 5.7 Change in EAD through time for all scenarios and alternatives

5.3 Major findings

5.3.1 Modelling results

The risk analysis model was run for each of the strategic alternatives over a range of future socio economic and climate change scenarios. The model runs are summarised in Table 5.8. The risk, expressed as EAD, over the whole study area for each model run was calculated. These results are illustrated in Table 5.8. It is apparent the risk increases significantly over the study area for all scenarios. These values were used to form the basis of the present value benefit estimates. For each strategic alternative, the present value benefit was calculated by subtracting the risk realised under the strategic intervention from the reference, 'Do Nothing', case and applying the UK standard discount rates (Defra, 2006). In the years between model runs, linear interpolation was used to compute the annual risk.

Table 5.8 Summary of the model runs

Strategic Alternatives	Present day	Future Scenarios			
		World Markets	National Enterprise	Local Stewardship	Global Sustainability
Do nothing - P1 policy	2007	2050 2100	2050 2100	2050 2100	2050 2100
Resistant		6* runs	6* runs	6* runs	6* runs
Resilient		6* runs	6* runs	6* runs	6* runs
Highly Resilient		6* runs	6* runs	6* runs	6* runs
No. of model runs:	2	20	20	20	20
Total Runs:					82

*includes 2040, 2070 before intervention, 2070 after intervention, 2085 before intervention, 2085 after intervention, 2100

The results of this analysis, together with the strategic alternative costs are presented in Table 5.9. The benefit-cost analysis shows the 'Resilient' alternative to be preferable over all scenarios. In this particular study, where the preference ordering of the alternatives is insensitive to the weighting or relative likelihood of the future scenario, there is no need for any additional analysis. The people at risk analysis for all scenarios are presented in Table 5.10 and in Table 5.11.

Table 5.9 Summary of the present values (PV) and benefit-cost ratios (BCR)

	PV Benefit	PV Cost Lower Bound	PV Cost	PV Cost Upper Bound	B:C Lower	B:C	B:C Upper	Uncertainty Band on B:C	Inremental B:C
Local Stewardship									
Resistant	£39,911	£3,031	£3,631	£4,231	9.4	11.0	13.2	3.7	2.3
Resilient	£40,016	£2,986	£3,586	£4,186	9.6	11.2	13.4	3.8	
Highly Resilient	£40,035	£3,335	£3,935	£4,535	8.8	10.2	12.0	3.2	-0.1
Global Sustainability									
Resistant	£271,714	£3,031	£3,631	£4,231	64.2	74.8	89.6	25.4	8.7
Resilient	£272,107	£2,986	£3,586	£4,186	65.0	75.9	91.1	26.1	
Highly Resilient	£272,188	£3,335	£3,935	£4,535	60.0	69.2	81.6	21.6	-0.2
National Enterprise									
Resistant	£451,339	£3,031	£3,631	£4,231	106.7	124.3	148.9	42.2	84.7
Resilient	£455,152	£2,986	£3,586	£4,186	108.7	126.9	152.4	43.7	
Highly Resilient	£456,287	£3,335	£3,935	£4,535	100.6	115.9	136.8	36.2	-3.2
World Markets									
Resistant	£1,029,228	£3,031	£3,631	£4,231	243.3	283.5	339.6	96.3	981.4
Resilient	£1,073,404	£2,986	£3,586	£4,186	256.4	299.3	359.5	103.1	
Highly Resilient	£1,082,133	£3,335	£3,935	£4,535	238.6	275.0	324.4	85.8	-25.0

Table 5.10 Summary of the people at risk results (mild)

	GS	WM	NE	LS	Year
Existing Policy	659,438	659,438	659,438	659,438	2007
	2,620,806	5,695,616	2,926,352	659,323	2100
Resistant	863	863	863	863	2007
	5,817	128,570	9,180	9,053	2040
	85,046	4,404,114	1,210,516	1,267	2100
Resilient	863	863	863	863	2007
	5,838	91,501	15,015	1,225	2040
	42,424	3,947,645	963,658	779	2100
Highly Resilient	863	863	863	863	2007
	5,838	105,332	15,013	1,225	2040
	42,513	3,949,878	962,932	12,464	2100

Table 5.11 Summary of the people at risk results (serious)

	GS	WM	NE	LS	Year
Existing Policy	25,347	25,347	25,347	25,347	2007
	886,994	3,919,997	1,576,508	25,396	2100
Resistant	69	69	69	69	2007
	244	14,238	365	355	2040
	1,574	409,831	115,781	42	2100
Resilient	69	69	69	69	2007
	244	8,588	551	81	2040
	995	579,376	190,264	39	2100
Highly Resilient	69	69	69	69	2007
	245	13,757	551	82	2040
	995	579,879	189,723	213	2100

It is apparent from Table 5.8, the 'Do Nothing' option provides a substantially higher damage estimate than the three strategic alternatives and all three alternatives far exceed a benefit-cost ratio (BCR) of unity and can therefore be considered economically viable. The preference ordering of the alternatives is the same over all socio-economic and climate-change scenarios with the 'Resilient' alternative having the highest rank. In UK practice, the 'Resistant' alternative would also be considered due to the high incremental BCR. Table 5.10 and Table 5.11 provide the outputs for people risk.

For all cases, the number of people exposed to frequent flooding increases by many orders of magnitude in 2100, with up to ~4 million at risk for three strategic alternatives in the World Market scenarios and just under 6 million at risk for the 'Do Nothing' alternative. The 'Resilient' alternatives generally show less people at risk of frequent flooding than the 'Resistant' alternative, in the near future. This is due to the non-structural measures such as flood warning and evacuation planning reducing the floodplain population exposed during events, which are less prominent in the 'Resistant' alternative. It is of note however, that the 'Resistant' alternative does provide improved performance towards the latter part of the century under 3 of the 4 scenarios.

To establish the overall preference order for the different alternatives it is necessary to consider the range of performance measures within a structured multi-criteria framework. Invariably these frameworks involve some kind of weighting of the various criteria, this is in general a subjective procedure and often driven by the specific values or beliefs of individuals or groups. A specific form of multi-criteria analysis, known as infraction analysis, is outlined in McGahey *et al.* (2008). Other approaches involve the moneterisation of all output measures and then undertaking a benefit-cost analysis. Here the weighting is applied through assigning a monetary value to each of the performance measures. This approach can be controversial in that there is often a reluctance to assign a value to life for example.

Based on the results presented here it is apparent that both the 'Resistant' and 'Resilient' options offer significant benefits. Within the context of developing a full strategy for the Thames Estuary given the timescales involved, it seems prudent to provide provision for introducing significant interventions in the future but a decision can be potentially delayed until the latter part of the century. A potential approach for capturing uncertainties within the future and costing for future provision and including this within a formal framework is described in Shwartz and Trigeorgis (2001). Consideration of this type of analysis could prove beneficial in terms of flood risk management decision making.

5.3.2 Discussion

The Thames flood risk system is complex, comprising hydraulic loading from different sources, a range of static and active defence structures and high value assets located on specific parts of the floodplain. A sophisticated flood risk analysis model, capable of handling this complexity has been developed and tested to assess the risk associated with a range of strategic alternatives. The model can reflect changes that arise within the flood risk system as a result of, for example, climate change, different defence maintenance and capital refurbishment strategies and floodplain development scenarios. The model has been used to analyse flood risks associated with economic damage to property, the risk to life and habitat damage. The reduction in economic damage to property (economic risk) that arises for any specific strategic option, when compared against a 'Do Nothing' scenario, has been compared with the cost of the strategic intervention within a benefit-cost analysis. The risks to people have been analysed at a number of future epochs.

These preliminary results indicate that no one alternative is favourable under all future scenarios and that there is merit in considering both the 'Resilient' and 'Resistant' alternative. To develop a comprehensive strategic flood risk management plan it is necessary to evaluate the risks arising under the different performance measures within the context of a multi-criteria analysis. An option that outlines one approach for this is described in an accompanying report (McGahey *et al.,* 2008).

5.4 Conclusions and outlook

There are many sources of uncertainty present within the type of analysis described above, whilst methods have been developed associated with propagating uncertainty through the flood risk analysis, there remains a requirement to fully implement uncertainty analysis within the context of the decision making process and in particular the multi-criteria analysis, this is a challenge and recommended for future research. In practice, based upon this preliminary analysis, it seems appropriate to adopt a flexible strategy with provisions being made, where necessary, for future flood risk management measures should the future risks, as identified within the scenarios be realised. The philosophy and approach of Real Options can potentially provide a more coherent framework for this than the current approach applied in England and Wales and future research in this area could prove beneficial.

It is also of note that the analysis described here is restricted to considering flooding from fluvial and coastal sources. More recently, following serious flooding in the UK from pluvial and sub-surface systems and the Floods Directive, there has been focus on integrated flood risk management that considers multiple sources (Pitt, 2008). Given the complex and extensive nature of the Thames urban drainage system and heavily urbanised environment, the Thames environment would provide a challenge for emerging flood risk analysis method that consider multiple sources of flooding.

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6. Pilot site "Scheldt River estuary"

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6.1 Flood risks and previous mitigation efforts

6.1.1 Introduction to the Scheldt River estuary

The trans-national Scheldt estuary (Figure 6.1) extends from the upper reaches near Gent in Belgium to the lower reaches and the mouth at Vlissingen in The Netherlands. The Dutch part of the estuary, called the "Westerscheldt", is characterised by meandering multiple channels, with intertidal islands and areas on the inner side of channel bends. The Belgian part, called the "Zeescheldt", is characterised by a single meandering channel, with intertidal areas along the channel margins. Throughout the estuary the higher intertidal areas host fauna and flora-rich salt-, brackish- and freshwater marshes. The lower intertidal flats are important feeding grounds for birds and resting areas for the increasing population of seals.

The study area is home to around 300,000 people in the Netherlands and less than 1 million people in Belgium (Zeescheldt area). This includes the city of Antwerp with a population of around 450,000 (2003). The estuary is of economic importance as a major shipping artery, hosting the harbour of Antwerp, as well as providing an access route to the harbour of Rotterdam via the Rhine-Scheldt canal. In 1999 to 2001, breaking with a 300 year tradition of conflict over the Scheldt, the Dutch and Flemish developed a joint long term vision for the Scheldt estuary (Zanting *et al.* 2002). In this broad policy document (LTV 2001) the triple functions of shipping, safety from flooding and the ecosystem are emphasised. Since then many policy-related activities have been undertaken under the auspices of a joint Dutch-Flemish project bureau tasked with the implementation of the measures necessary to achieve this long term vision.

Figure 6.1 Map of the Scheldt Estuary

A history of floods

Throughout the ages the province of Zeeland has experienced many disastrous floods, which made it the most vulnerable place to live in the flood-prone Netherlands. There is archaeological evidence that 117 villages have been destroyed through floods in the last 600 years (Van Dierendonck *et al.*, 2004). In 1953 the Dutch part of the Delta area experienced a disastrous flood, which inundated about 136,500 ha of land and caused a total of 1836 casualties. Tens of thousands livestock perished and approximately 100,000 people had to be evacuated. The damage to buildings, dikes and other infrastructure was enormous (Gerritsen, 2005). The majority of the flood defence structures that failed were not high enough to withstand the extreme water level and waves at the time. The overtopping of the dikes caused damage first to the inner slope and sliding and erosion of the inner slope subsequently led to a complete dike breach (Figure 6.2).

Figure 6.2 Dike breach during the 1953 disaster

The 1953 flood disaster provided the impetus for the development and implementation of a new flood defence system in the Netherlands. This was developed by the Delta Commission which was inaugurated only 17 days after the disaster. Interestingly, much of the necessary knowledge existed long before the flood, but disagreements between civil engineers, the outbreak of the war in 1940 and the priority of rebuilding infrastructure after 1945, prevented these plans from being implemented at an earlier date (Gerritsen, 2005). Key elements of the Deltaplan included:

- Provision of a very high level of safety through flood prevention (dikes and barriers);
- Diversification of safety standards based on a (relatively simple) cost-benefit analysis;
- Shortening of the dike system length by closing off tidal inlets;
- Revision and improvement of the institutional responsibilities with respect to design standards, maintenance and crisis management (supervising role of Rijkswaterstaat, reorganisation of water boards).

At that time, these measures were highly innovative. For instance, the protection level was no longer defined as the highest recorded water level plus 1 meter, but as design water levels based on recurrence times (Parmet, 2003). Also the notion that the safety standards could be defined according to the potential damage from flooding was quite new. Therefore, the highly populated and economically most valued parts of the Netherlands (the so-called Randstad, with Rotterdam, The Hague, Amsterdam and Utrecht as main cities) were given a high safety level of 1:10,000 per year, whereas less densely populated regions in the north of the Netherlands and in the Delta area received a protection of 1:4000 per year. For the dykes along the rivers Rhine and Meuse, a lower standard of 1:1250 per year was selected, because river floods were considered to be less hazardous (longer warning times, fresh water instead of salt water etc.).

Highlights of the Deltaplan included the construction of storm surge barriers in the Oosterscheldt (1986) (Figure 6.3) and the Nieuwe Waterweg (1997). The Westerscheldt estuary was not protected by a storm surge barrier because this would have compromised the navigation to and from Antwerp harbour. Instead, the dykes along the estuary were strengthened and heightened according to the safety standards prescribed by the Delta Law of 1958 (i.e. to withstand sea conditions with a probability of 1: 4000 per year).

Figure 6.3 Storm Surge Barrier in the Oosterscheldt estuary

A flood occurred in the Belgian part of the estuary in 1976. A North-western storm pushed water into the Scheldt estuary leading to dike breaches at several locations along the river. An area of more than 800 ha along the Zeescheldt was inundated. The municipality of Ruisbroek was particularly heavily affected (900 houses under water). This prompted the Flemish government to adopt the Sigmaplan. This plan aimed to achieve as high a safety against flooding as was envisaged by the Dutch Deltaplan. Recently (in 2006), the Flanders Parliament ratified an updated version of this Sigma Plan. It includes a combination of dyke strengthening and managed realignment along parts of the Zeescheldt.

6.1.2 Current flood risk management and new challenges

Safety on the agenda again

High river floods in the Netherlands in 1993 and 1995 triggered renewed political attention for the risk of flooding. Scenarios of accelerated sea level rise and increased peak river discharges induced by climate change led to questions regarding the robustness of the current flood safety system. In the discussion the following issues emerged:

- Is the current safety philosophy (primarily based on flood protection) still adequate or do we need to include measures that reduce the consequences of floods?
- Economic development since the 1950's has resulted in a significant increase in the potential damage from a flood, raising questions regarding the appropriateness of the current safety levels;
- The current safety levels are based on a design water level derived from studies of recurrence intervals. The probability of dike failure is not taken into account;

- The safety system is as strong as its weakest link: the probability of flooding should take into account the entire dike ring, including engineering structures such as sluices and pumps;
- Including flood risk in spatial planning could result in a less vulnerable situation, i.e. keep most dangerous areas free from residential and industrial developments.

For instance, an in-depth study of the flood risk of the dike ring of Zeeuws-Vlaanderen (at the southern border of the Westerscheldt estuary), showed that the probability of a dike breach is much higher than the safety level of 1:4,000 per year, which can be explained by potential failure of the weakest sections before the external sea conditions reach the design safety level (Rijkswaterstaat, 2005). New flood control concepts are currently being investigated, such as the 'Brede Waterkering' (Broad Dike), that tolerate more overtopping than traditional dikes before they breach.

Interestingly, the Belgium Sigma Plan adopted a flood risk management philosophy based on spatially differentiated flood risks. These were translated into a combination of both protection measures and water level reduction measures in the form of controlled flooding of the lowest areas along the river. The Sigma Plan was initially designed to provide a safety level of 1:10,000. Later this was downscaled to a much lower level based on an explicit risk approach using risk maps. After full implementation (in the year 2030) the New Sigma Plan will provide differentiated safety levels varying between 1:1000 to 1:2500.

Why are high waters rising in the Scheldt estuary?
Tidal characteristics in the Scheldt estuary have changed markedly in the 100 years up to 1990. The tide propagates more rapidly than it did in 1888, the high water levels are higher and the range is greater (Vroon, 1998). In the period 1888 to 1990, within the Scheldt upstream of Vlissingen, the height of the maximum high water level in the Westerscheldt has increased by approximately 0.7m (see Figure 6.4) and its position moved upstream by 33 Km. The tidal range has increased by almost one metre and the position of maximum range has moved upstream by 44 km. The speed of propagation of the tide has increased by 18% from 6.55 m per second to 8 m per second. These observed changes in tidal characteristics are consistent with what can be expected when the morphological development of the system is constrained and the intertidal volume reduced by land reclamation (Peters *et al.*, 2000). Nevertheless, how the historical changes have influenced the tidal propagation and the relative importance of each of the factors (land reclamation, dredging and autonomous sea level rise) is still unknown. Although it was announced in 1993 that this would be a topic for further study (Pieters, 1993), no definitive answer has been found as yet (Ledden *et al.* 2006).

Strategic alternatives for flood risk management
There are different ways to manage future flood risks. In the discussion on safety around the Scheldt estuary the following alternatives have been mentioned (e.g. (Löffler *et al.* 2001): i) continuation of dike improvements, ii) managed realignment and buffer zones, iii) construction of a storm surge barrier, iv) spatial planning and risk differentiation.

Dyke strengthening remains technically possible till 2030. Maintaining the present safety level for the Westerscheldt until 2030 implies an elevation of the dyke crest in the order of 1 to 1.5 m[3]. Even a 2 m increase is technically feasible, although it would require more space (in the order of 6 m per meter of crest elevation). At some locations, e.g. in urban areas, this could cause friction with other societal functions (Heijer & Calle, 2000).

Managed realignment has been under fierce discussion for a long time, not in the least because of confusion about designs, purposes, supposed impacts and legal obligations. Furthermore, this discussion should be seen in the wider historical and psychological context of the people who now live in the polders that they reclaimed from the sea at considerable sacrifice. The benefits of realignment in terms of safety against flooding are disputed as they are both site specific and time dependent.

[3] This would account for sea level rise, a twofold increase of storminess, deepening of the navigation channel and a twofold increase of population to be protected.

However, there are two mechanisms that could potentially enhance the safety of the land from flooding following managed realignment: i) a reduction of the high water levels during storm conditions because of an increase in tidal basin and ii) a reduction of the wave attack of the realigned dyke due to the energy dissipation on the foreland (Jeuken *et al.*, 2007). However, there are no quantitative indications at hand to substantiate the effect of these mechanisms.

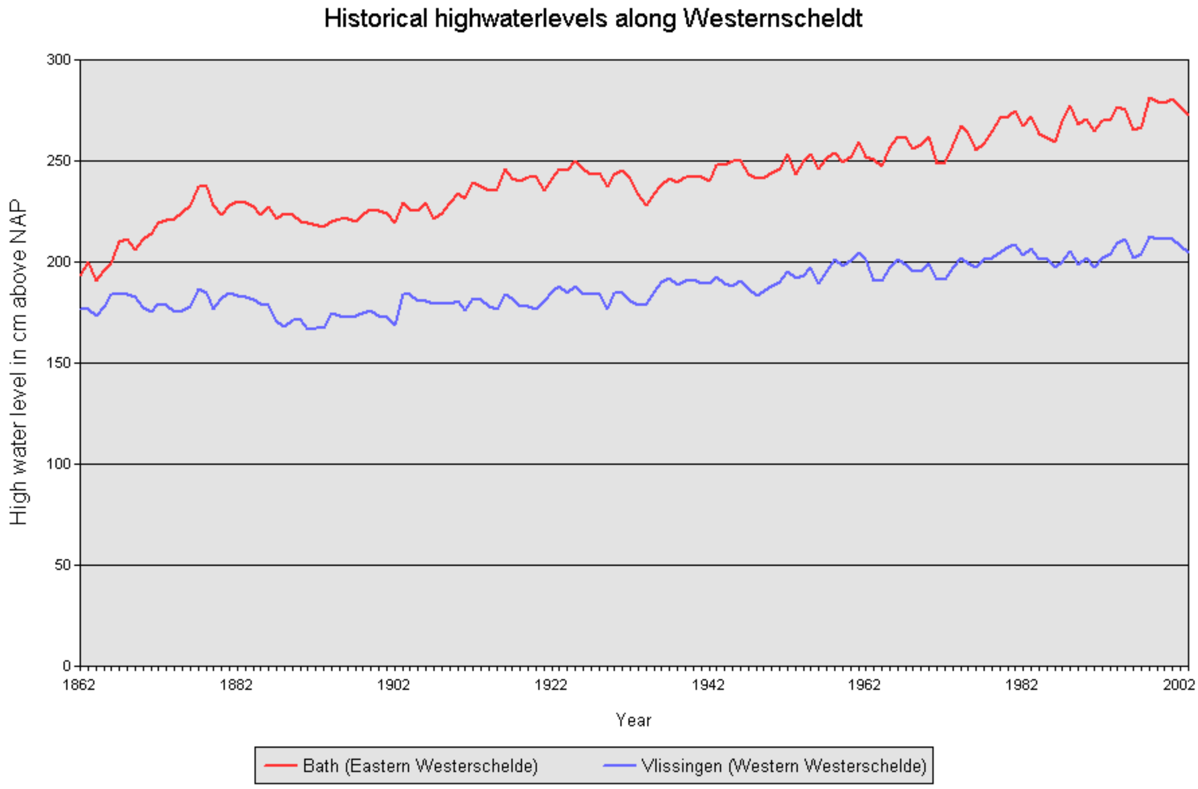

Figure 6.4 Historical water levels at Vlissingen (western part) and Bath (eastern part of estuary) (Source: RWS online database)

A *storm surge barrier* at Oosterweel has been considered in the early versions of the Belgium Sigmaplan to protect Antwerp against flooding. It was later discarded as the costs were much higher than the perceived benefits (VITO, 2004). In the FLOODsite research a barrier near Vlissingen at the mouth of the estuary was considered as a hypothetical option only (see Section 6.3.1).

Spatial planning and risk differentiation in the Dutch part of the Scheldt area have not been seriously considered as alternatives for the present policy. In Belgium, however, it is already part of the new Sigma Plan, the design of which was supported with risk maps for the entire Scheldt basin.

6.2 Objectives and approach

6.2.1 Objectives

The rationale for the Scheldt pilot study was to apply and test the approach to flood risk management developed in the FLOODsite project. This approach consists of three main elements (Gouldby & Samuels, 2005; FLOODsite, 2008):

- Flood risk analysis, to determine risk objectively by analysing and combining probabilities and negative consequences of floods;
- Flood risk assessment, to understand perception of risk, to assist societal weighing of costs and benefits of risk and to support decisions; and
- Design and implementation of physical measures and policy instruments for flood risk management.

Our pilot study focused on the first two elements, i.e. flood risk analysis and flood risk assessment. Design and implementation of measures was not included in the study as such. However, both in the analysis and assessment parts, a wide range of potential measures and instruments was taken into account.

Linked to flood risk analysis, the first objective was *to study the future vulnerability of the society along the Scheldt Estuary to flooding, taking into account changing hydraulic conditions and demographic and economic developments*. As part of a flood risk assessment the second objective was *to evaluate sustainable flood management strategies in association with stakeholders*, thereby acknowledging the importance of the process dimension as part of strategies for flood risk management (Hutter, 2006).

6.2.2 Study approach: linking science with policy and public perspectives

The FLOODsite project adopted a multidisciplinary approach to studying the vulnerability of the region bordering the Scheldt estuary. Our approach combined insights deriving from engineering and the natural and social sciences. Research activities were planned so that they complemented other ongoing or recent flood risk studies[4] in the region. As shown in Figure 6.5 and Table 6.1 most of the components of flood risk and flood management measures have been subject to some form of research. Components that still only receive marginal or no attention are measures such as flood resistant buildings[5], insurances, relief and reconstruction funds.

Figure 6.5 shows the complexity of flood risk management in full. Insight in the sources, pathways, receptors and impacts of a flood is required as well as in the feasibility of a wide range of potential measures. In deciding on a preferred risk management strategy all combinations need to be analysed in principle. The various ongoing projects, studies and research activities lead to a respectable body of knowledge, albeit in a rather fragmented and partially integrated way. But even more problematic for a sound risk assessment is that these activities take place almost exclusively in (applied) science and policy, largely ignoring the public. This prompted us to focus on the role of local citizens and stakeholders within the flood risk management process.

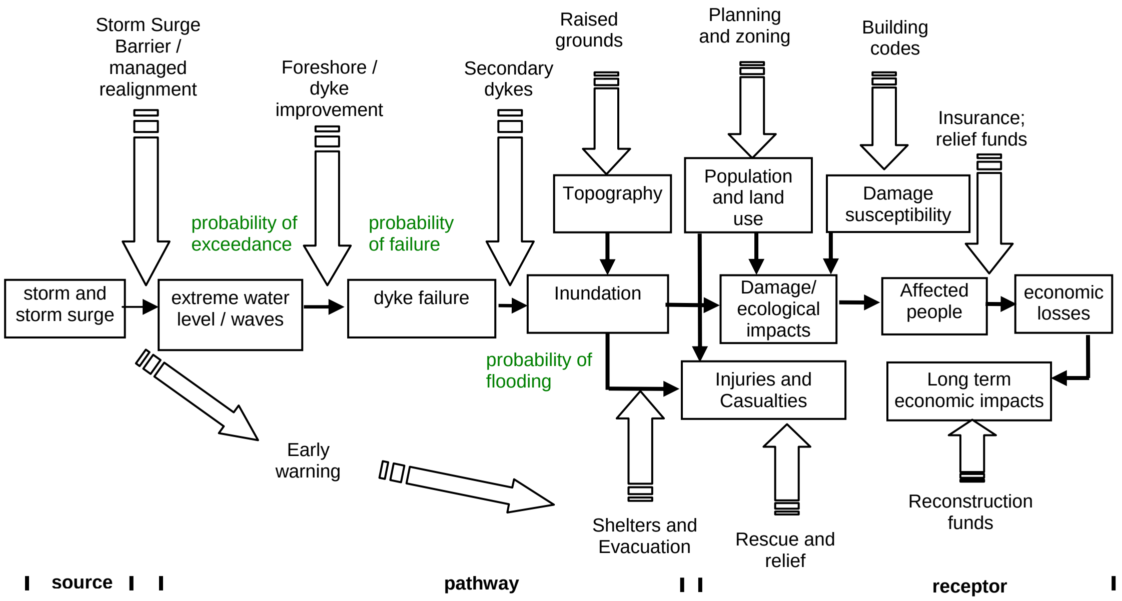

Figure 6.5 Schematic representation of the flood risk components along the Scheldt estuary

[4] especially projects such as: Long Term Vision for the Scheldt (LTV, 2001), Veiligheid Nederland in Kaart (VNK) (Rijkswaterstaat 2005), SIGMAPLAN, COMRISK, ProMo and FLIWAS.
[5] However, in the Netherlands (but not in the Scheldt area) innovative building concepts are being developed.

Table 6.1 Overview of research activities in the Scheldt Estuary region

Component	FLOODsite research	other on-going projects*
Storm and storm surge / extreme water levels	Scenario and strategy analysis (Task 14/18)	HR / SIGMAPLAN
dyke failure	Reliability analysis (Task 7)	VNK / SBW
inundation	Inundation modelling (Task 9)	
damages and casualties	Scenario and strategy analysis (Task 14/18)	VNK
managed realignment		SIGMAPLAN
Foreshore / dyke improvement		LTV COMRISK
Secondary dykes, planning and zoning	Scenario and strategy analysis (Task 14/18)	
Early warning, shelters and evacuation	Evacuation modelling and DSS (Tasks 17/19)	HIS / FLIWAS
Risk perception	Questionnaire (Task 25)	ProMo
Risk assessment	Interviews and workshops (Task 25)	

*: HR = Hydraulic boundaries research; SBW = Research into strengths and forces on embankments; HIS = High water Information System; LTV = Long Term Outlook for the Scheldt estuary; VNK = Mapping the Safety of the Netherlands; SIGMAPLAN = Safety Plan for the Belgian Scheldt river; COMRISK = INTERRREG IIIb project Common strategies to reduce the risk of storm floods in coastal lowlands; FLIWAS = Flood Information and Warning System.

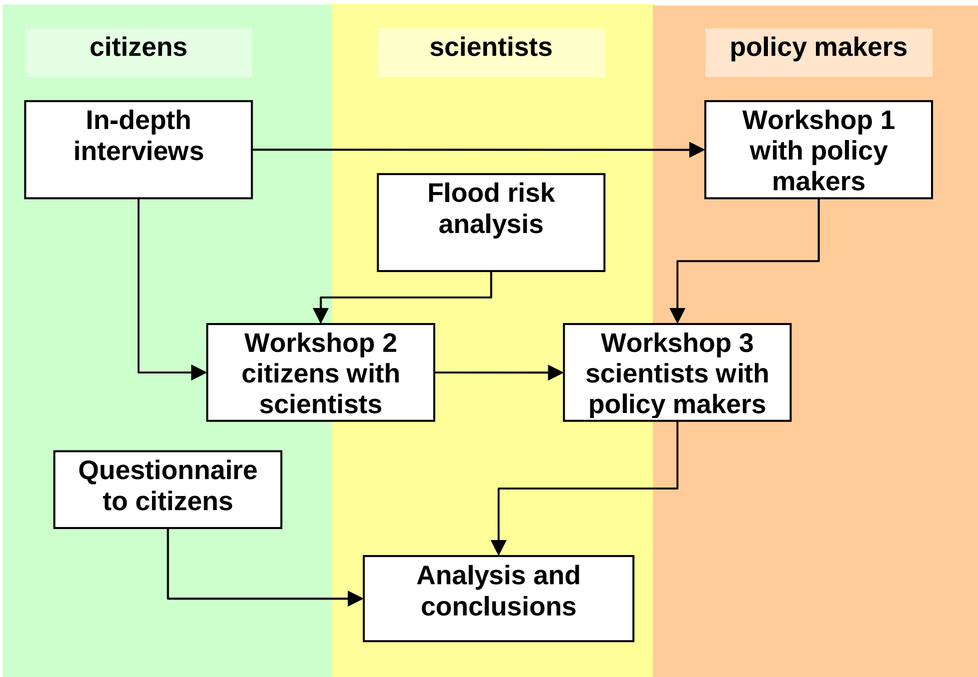

Figure 6.6 Sequence of workshops and interviews used in the pilot study

A major aim of the Scheldt Pilot was therefore to evaluate sustainable flood risk management strategies in association with stakeholders. We therefore chose to engage with scientists, policy makers and the local public (citizens). Instead of assuming that only improved scientific assessment (e.g. via hydrodynamic model simulations and flood hazard mapping communicated directly to policy makers via reports) can accomplish this, we hypothesised that active involvement of citizens can contribute to knowledge development for a flood risk assessment. We used modelling and scenario analysis, semi-structured interviews, workshops and questionnaires in our study (see Figure 6.6).

The idea behind this set up was to gain insight into the perception of local citizens with respect to flood risk through the interviews and questionnaire, as well as into the effect of communication between people of different backgrounds on their opinions. Detailed descriptions of the individual research activities of the Scheldt pilot are provided by De Bruijn *et al.* (2008b); Slinger *et al.* (2008) and Krywkow *et al.* (2008). This chapter presents the overall findings of the pilot study and places them within the wider flood risk management context. The results and conclusions pertain to three different questions:

- How will flood risk along the Scheldt Estuary evolve in view of future climate change and socio-economic developments?
- How do the local citizens along the Scheldt Estuary perceive flood risk and what are their policy preferences?
- What lessons have been learned in regard to public participation in flood risk management?

6.2.3 Flood risk analysis: the science perspective

The assessment of current and future flood risks for the Scheldt River estuary was prepared using an approach developed as part of the FLOODsite project (De Bruijn *et al.*, 2008a, 2008b; Figure 6.7). Central to the method is the definition of flood risk in terms of a probability of flooding times its consequences. The method consists of four steps:

1. Description of the current system and potential developments:
In this step the system and its boundaries are described and different plausible future development scenarios are formulated. These scenarios depict how the future might look like if the current flood risk management policy is continued or if alternatives would be implemented.

2. Analysis and preliminary risk assessment of the current flood risk management strategy:
The current flood risk is analysed by studying flood probabilities and flood impacts. When the flood risks are known, they can be compared to other risks or to costs of preventive measures to judge whether the risk is a concern. This is done for both the current situation as well as for the future.

3. Analysis and preliminary risk assessment of strategic alternatives
If flood risks are not acceptable now or in the future, different strategic alternatives may be developed. They are analysed and assessed across different future scenarios in a similar way as the current flood risk management strategy.

4. Full assessment of the strategic alternatives in view of uncertain futures
Finally, the functioning of the future flood risk system in different future scenarios is assessed. This full assessment not only includes an assessment of flood risks, but also of the functioning of the system in which the alternative is implemented. The functioning is scored over a range of criteria which reflect the sustainability of the region. This means that both the effects of the changed flood risk and the effects of the measures itself on social, economic and ecological functions of the system are addressed.

This approach is of course a simplification of a planning process that is usually dynamic and complex. In reality alternatives may be changed when unfavourable results are obtained or extra scenarios may be added half way through the whole process. Also other iterative links are possible. In order to calculate the flood risk both a hydrodynamic and a damage model were used. To cope with the potentially infinite number of combinations of events and their consequences, a representative set of storm conditions and river discharges was defined. These events were combined with assumptions on breach locations and breach growth and were then simulated with the SOBEK computational software for 1 and 2 dimensional hydrodynamics to generate water depth maps (see Figure 6.8). These maps were subsequently used as input for the Standard Dutch Damage Module (Kok *et al.,* 2006) to assess the corresponding flood damages. This damage module calculates direct and indirect damage, but does not include damage related to water quality, cleaning, evacuation and rescue. The number of affected people (persons who live in the flooded area) and the number of casualties (killed persons) were also calculated using the same damage module (Kok *et al.*, 2006). The number of casualties and affected persons was estimated based on the simulated water depths. No information on flow velocities, water level rise and other factors was used. The results should thus be considered as an indication.

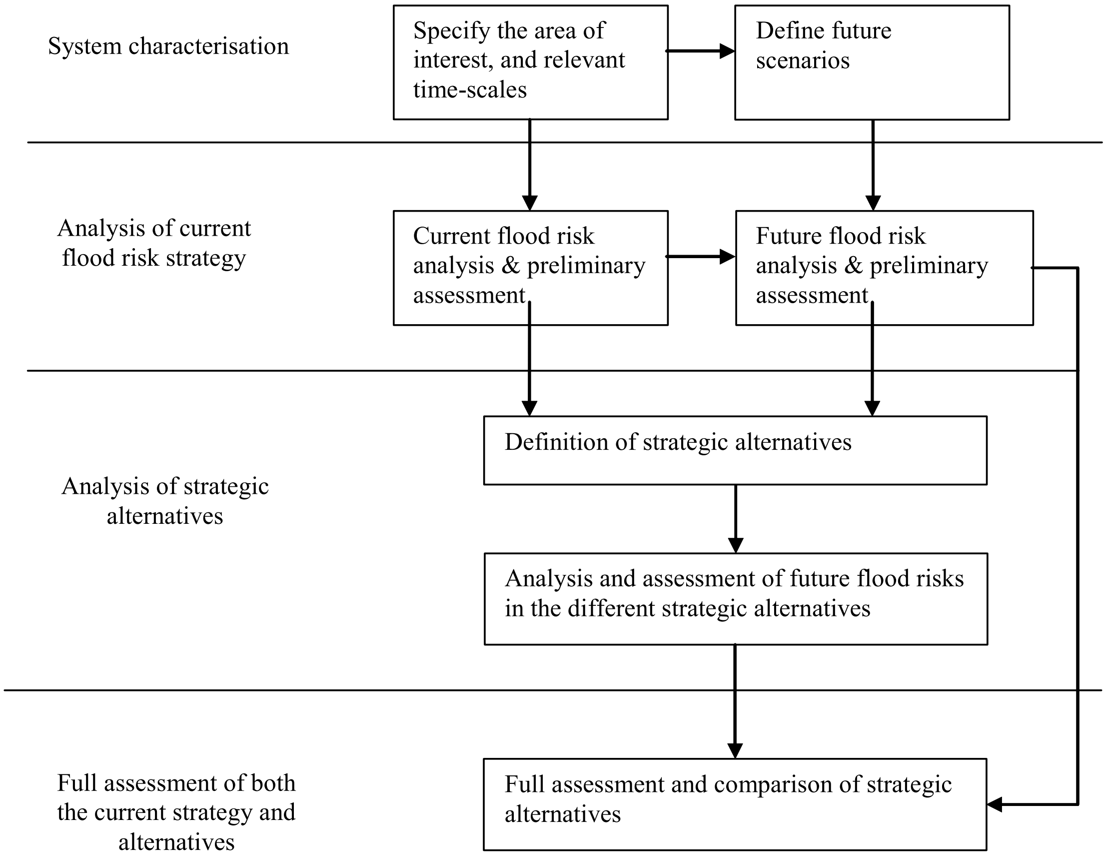

Figure 6.7 Schematic overview of the method for developing long-term flood risk management strategies in view of uncertain futures (de Bruijn et al., 2008a)

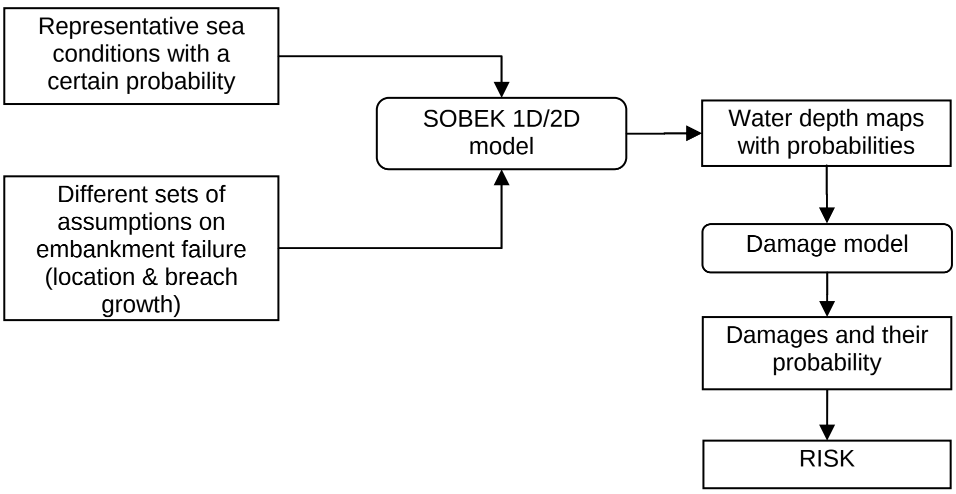

Figure 6.8 Risk analysis approach at the pilot site Scheldt River

Future changes in flood risk have been explored through a scenario approach. Scenarios were formulated for three different developments:

- climate change (i.e. sea level rise);
- developments in regional economy; and
- regional demographic changes.

6.2.4 Semi-structured interviews and workshops

Selection of participants

Seventeen citizens living in the vicinity of the Scheldt Estuary, who normally do not participate in research or policy processes dealing with flood risk management, were selected for participation in this study via a snowballing process. First we generated a list of preferred stakeholders on the basis of their professional or recreational activities and their rural and urban living environments. In addition we strove for equal numbers of Dutch and Flemish participants with sufficient variation in age, gender and nativeness to the area. Then, starting with a few general information sources, namely websites (e.g. recreational fishing in the Delta), the Yellow Pages and a representative on the municipal council of a town in the province of Zeeuws-Vlaanderen, we initiated email or telephone contact with the people suggested to us via these sources. Often via yet another contact person, we were able to track down the respondents listed in Table 6.2.

Interviews with citizens

Semi-structured, in-depth interviews with each of the respondents listed as interviewees in Table 6.2 were then held in the period September to November 2005. The interviews lasted approximately 1,5 hours or longer and were conducted either at the homes of the respondents or at their places of work. Family members were often present during the interview. The respondents were questioned on their relationship with the area, their affinity with water, whether (and what) they thought about flooding and the risk of flooding, their or their family's experience of flooding (if any), their knowledge of evacuation plans, their ideas regarding evacuation and the recovery process after a flood.

The respondents were also asked specifically what they knew of measures to prevent or ameliorate flooding and factors they considered important in determining the efficacy of these measures. The respondents were encouraged to answer based on their life experience and provide their opinions, not those representing any particular group of people. The recorded interviews were subsequently written up and sent to the respondents for correction and comment.

Selection of scientists and interviews

The scientists interviewed (Table 6.2) were selected on the basis of their involvement in the broader FLOODsite project and the relevance of their fields of expertise to improved flood hazard estimation. They were interviewed in late October and November 2005. The interviews followed the same format as those of the local inhabitants, with the scientists answering an additional question regarding their bond with their field of study before specifying their bond with the Scheldt Estuary in particular.

Workshop with policy makers

A consultative workshop with five policy makers and advisors (2 Dutch, 3 Belgian) on the Scheldt Estuary and environs was held on 5 December 2005 in Lillo (B). Communication of the findings from the interviews with local inhabitants occurred. Comments from the policy makers and advisors on the findings of the study were requested and recorded for comparison with those of the respondents and scientists. This information was subsequently analysed and prepared for presentation back to study participants.

Workshop with citizens and scientists

A workshop for study participants was convened on 26 January 2007 at Emmadorp alongside the Scheldt Estuary. Seven of the original interviewees were present as well as 4 of their partners, relatives or friends. Only one of the scientists previously interviewed was present. Additionally, three other scientists involved in flood modelling tasks within FLOODsite participated in the workshop.

Table 6.2 Categorization of respondents and workshop attendees

Occupation	Inter-viewee	Attended workshop	Nationality	Age	Sex	Native
Farmer A	Yes	Yes	Dutch	40 – 50	Male	Yes
Farmer B	Yes	Yes	Dutch	40 – 50	Female	Yes
Farmer C (partner of farmer B)	No	Yes	Dutch	40 – 50	Male	Yes
Farmer D (friend of farmer B)	No	Yes	Dutch	30 – 40	Male	Yes
Farmer E	Yes	No	Flemish	50 – 60	Male	Yes
Fisherman	Yes	No	Dutch	40 – 50	Male	Yes
Recreational Fisherman	Yes	No	Flemish	20 – 30	Male	Yes
Recreational Fisherman	Yes	No	Dutch	20 – 30	Male	Yes
Hotelier	Yes	No	Flemish	40 – 50	Female	Yes
Camping Manager	Yes	Yes	Dutch	50 – 60	Male	No
Camping Employee (son of manager)	No	Yes	Dutch	30 – 40	Male	No
Environmentalist	Yes	Yes	Flemish	40 – 50	Female	Yes
Environmentalist	Yes	No	Dutch	30 – 40	Male	Yes
Pastor	Yes	Yes	Dutch	60+	Male	No
Housewife (wife of pastor)	No	Yes	Dutch	60+	Female	No
Priest	Yes	No	Flemish	60+	Male	No
Wheelman	Yes	Yes	Dutch	60+	Male	No
Wheelman	Yes	No	Flemish	50 – 60	Male	Yes
Young person	Yes	No	Dutch	20 – 30	Male	Yes
Safety scientist	Yes	No	Dutch	30 – 40	Male	No
Civil Engineer	Yes	Yes	Dutch	30 – 40	Female	No
Ecologist	No	Yes	Dutch	50 – 60	Male	No

The categorization of the workshop participants is presented in Table 6.2. Upon arrival at the workshop and prior to its official opening, participants were required to fill in a questionnaire regarding the priorities that they would like policy makers to have regarding management measures for flood risk management of the Scheldt Estuary. This a-priori measurement of their opinions was necessary to be able to establish the effect of the exchange of information and ideas between participants and between scientists and participants in the workshop itself. The management measures are categorised as i) Flood Prevention Measures, ii) Flood Defence Measures Designed to Ameliorate the Consequences During an Event and iii) Management Measures for the Recovery Period, as well as a category of iv) Overarching Management Measures. The results derived from the initial interviews and the reactions of the policy makers to these findings (Slinger *et al.* 2007) were presented to the workshop participants and discussed. Participants responded with interest to the summarised views of their fellow respondents and the positive interest of the policy makers. The discussion focused on gaining a common understanding of the findings, rather than disputing these. Thereafter, the preliminary results from the flood modelling study were presented by the scientists involved in the FLOODsite project. They communicated their understanding of the flooding risk in the vicinity of the Scheldt Estuary, now and in the future (see Section 6.2.3).

Participants were most intrigued by the choice of dike breaching locations, which had been chosen semi-randomly by the scientists involved. They were also interested to see the effects of secondary dikes in containing the flood. In addition, participants expressed interest in the implications of the flood modelling studies for evacuation options. Next, posters for each of the flood risk management measures listed in the initial questionnaire were placed around the room. The workshop participants then came up with the advantages and disadvantages for each of these measures in a brainstorm session. These were then discussed so that differences in opinion could be made apparent rather than hidden. Finally, the participants were requested to once again allocate priorities to the management measures. This was undertaken by placing stickers on the posters of each management measure.

Workshop with scientists and policy makers
This workshop was held on January 24, 2008 in Lillo (B) along the banks of the Zeescheldt. Of the total of 17 participants (14 Dutch and 4 Belgian) there were 8 policy makers and 9 scientists. A central question of the workshop was to which extent a new flood risk approach is deemed necessary and feasible for the Scheldt estuary. The policy makers were confronted with the results of the flood risk analysis and the results of the interviews and previous workshops. Both before and after the official workshop the policy makers were requested to fill in a questionnaire regarding their opinions towards the need of a new flood risk approach. During the workshop participants were asked to formulate arguments in favour and against a safety policy based on a differentiated risk approach.

6.2.5 Questionnaire on risk perception

In addition to the interviews and workshops a questionnaire was sent out to 3000 inhabitants living along the embankments of the Scheldt estuary in the Dutch province of Zeeland, with the objective of obtaining insight in the level of risk perception and the representative nature of the workshops and interview results. Also an online version of the questionnaire was provided for respondents. After disseminating the letters on the 22nd of February 2008 a press release was sent to a regional daily newspaper in order to generate a positive attitude towards the questionnaire among the public in Zeeland, and to increase the response. The regional TV station reacted to the press release immediately and requested an interview, which was broadcast the next day.

The central issue of the questionnaire was risk perception. This has been approached by using the *psychometric paradigm* through which individuals rate judgements about risk characteristics on an ordinal scale (Slovic, 1987). Risk perception is described by three elements: Worry, Awareness and Preparedness, each of them being dependent on each other as depicted in the figure below:

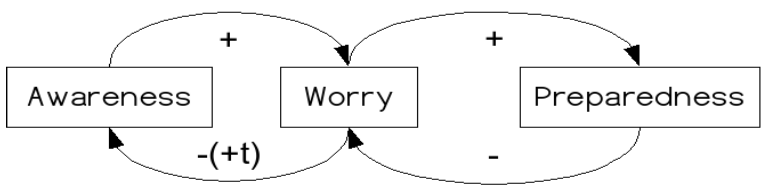

Figure 6.9 Relationship between flood risk characteristics (Raaijmakers et al., 2008)

The fear for natural hazards is indicated by Worry, the knowledge of the risk is defined as Awareness and the control over the risk as Preparedness (Slovic *et al.*, 1984). Awareness may lead to higher levels of worry, and as a consequence of that, higher preparedness. A better prepared society will worry less about the risk it is prepared for. Over a longer time scale (+*t*) reduced worry may lead to a decline in awareness of the risk, as individuals tend to forget risks to which they or their communities have not been exposed to for a long time. However, it should be noted that awareness will not necessarily lead to worry, and worry not necessarily to preparedness.

Voluntariness is a determining characteristic within the psychometric paradigm. When an individual voluntarily decides to expose him or herself to a risk, the individual is assumed to have the option of avoiding this risk. However, voluntariness is limited in the case of Dutch polders, and an individual risk-benefit trade-off cannot be made. The dykes that protect the polders against flooding are subject to a collaborative decision, whether or not this decision is made by a responsible (water management) authority. In other words, stakeholders and lay people have no direct influence on the decision what measures are appropriate for flood protection in their region, and have thus limited voluntariness. For this reason the performance of the responsible authorities is a vital part of the survey.

The questionnaire encompassed six different groups of questions: (1) individual data including education, age, profession, experience with inundation and related damage, (2) risk perception (worry), (3) damage on assets and willingness to pay, (4) measures for flood protection, (5) evacuation and early warning systems, and (6) The role of the responsible authorities. The questionnaire included multiple-choice questions, Likert-Scale questions (from strongly agree to strongly disagree) as well as open-ended questions to give the respondents the possibility of expressing their opinions in their own words.

The findings from the in-depth interviews led us to expect that the most respondents would feel safe behind the dikes and that they would hold the belief that it is the primary responsibility of the government to protect the citizens from flooding. We also expected that they would be uninvolved in flood management policy making and would have a high preference for technical measures. In particular we expected that the citizens would be strongly against any form of 'depoldering'. In addition, we expected that those citizens with an experience of flooding would feel less safe than citizens with no such experience, but that most people would still have some sort of personal evacuation plan. Finally, we expected that because citizens believe it is the responsibility of the government to protect them from flooding, they would not be concerned with having a high level of influence in the flood management policy making. We tested the latter expectation by setting two questions related to the present and the desired level of influence of citizens in flood risk management policy making and the degree of cynicism they evince in relation to those responsible for these policies. This included all levels of policy makers from grassroots organizations to local and national governmental bodies.

By the end of April 2008 535 valid replies were sent back to us. This response from 3000 disseminated letters implies a 17.8% response rate. The age structure of the respondents is skewed towards a higher age: the average age of the respondents is 55.3 years, with a standard deviation of 15, and 60% of the respondents are 50 years old or older. The average age of the population of Zeeland is 51 years. The majority of the respondents (81%) have higher education, of which one quarter have an academic degree.

6.2.6 Evacuation modelling

In the Netherlands the view is taken that an evacuation should preferably be preventive. The high-water in the Rhine in January 1995 provoked a large-scale preventive evacuation in the polder areas along the Rhine branches in the province of Gelderland. About 175,000 people were evacuated from these areas. This was the first time since 1953 that a major inundation was imminent and that an evacuation had to be considered seriously, and finally realised. The large-scale preventive evacuation during the 1995 flood emergency made the Dutch authorities improve the collection and dissemination of information during a flood emergency and streamline the cooperation between the many partners involved. Several activities were initiated.

To provide the parties concerned with timely and reliable information the Rijkswaterstaat agency, part of the Ministry of Transport, Public Works and Water Management, started the development of the automated Highwater Information System (HIS). This includes an evacuation model called the Evacuation Calculator (EC). This model was tested together with two other evacuation models (ESCAPE and INDY) for a potential flooding of the northern part of the Scheldt Pilot area (Walcheren and Zuid-Beveland). ESCAPE and INDY have been developed by Netherlands Organisation for Applied Scientific Research (TNO) and others. INDY has been used previously to estimate evacuation times for other areas than Zeeland. ESCAPE was jointly developed by authorities of the North Sea regions of the Netherlands, Belgium and the United Kingdom. It has been applied to parts of Zeeland. A detailed description of the models can be found in Lumbroso *et al.* (2008).

Also a prototype support system for evacuation planning (Evacuation Support System, ESS) was developed and applied on the Scheldt flood prone area of Walcheren and Zuid-Beveland. The ESS development for the Scheldt area followed a methodological framework that was based on a review of decision support systems in Europe (Mens *et al.,* 2008). The ESS tool links different breach locations to a database with simulation results of flood events. Moreover, it provides detailed information needed to derive evacuation plans, such as places with potential building collapse and places where the water can rise fast to dangerous depths. By linking this knowledge to a road network and traffic model results, evacuation procedures can be tested. It was presented to the end users after which conclusions were drawn and recommendations made.

6.3 Major findings

6.3.1 Flood risk analysis: economic developments dominate future risk

Using the *Foresight study* in the UK as reference (Office of Science & Technology, 2004; Evans *et al.,* 2004a, b), four different future scenarios have been formulated that proved to be sufficiently consistent, contrasting and feasible:

- *World Market:* An internationally oriented world that focuses on liberalism with a minimal role for policy;
- *National Enterprise:* A nationally oriented and individualistic world that has a state-centred policy;
- *'Global Sustainability':* An internationally oriented world that has strong social and environmental goals with strong governance;
- *'Local Stewardship':* A co-operative world that focuses on local solutions with a strong and local governance.

Table 6.3 Overview of combined socio-economic and climate change scenarios

Indicator		World Market	National Enterprise	Global Sustainability	Local Stewardship	2000
2050	GDP growth per year (%)	2.5	1.5	1.9	0.7	3
	Population (million people)	0.43	0.40	0.35	0.32	0.37
	Sea level rise (cm)	35	20	25	15	-
2100	GDP growth per year (%)	2.5	1.5	1.9	0.7	3
	Population (million people)	0.49	0.49	0.33	0.22	0.37
	Sea level rise (cm)	85	40	60	35	-

These scenarios concern the socio-economic development of the Netherlands and were scaled down to the Scheldt estuary region with respect to economy and demography. Sea level rise projections were based upon the latest IPCC reports and Dutch climate studies (KNMI, 2006). These scenarios were combined with these socio-economic scenarios in a way that a wide range of possible future flood risks is created (Table 6.3).

The increase in economic risk and expected casualties under the current flood risk management policy[6] depends on which scenario becomes reality, although the differences are limited until around 2050 (see Figure 6.10). Beyond this time horizon differences tend to become substantial: in the scenario of ‘Local Stewardship’ the flood risk increases from 0.53 M€/year in 2000 to 1.5 M€/year in 2100, whereas in the ‘World Market’ scenario an almost 30-fold increase could be expected (14 M€/year in 2100). Because the current flood risk management policy includes a gradual increase in embankment height to account for sea level rise, the large differences between the scenarios are almost entirely due to the assumed pace of economic development. In contrast to the big differences in economic risk between the scenarios, calculations show only a twofold difference between the highest and lowest expected annual number of casualties (EANC) in 2100. The societal risk expressed by the EANC currently is 0.08 to 0.2 casualties per year and increases to about 0.23 to 0.55 casualties per year in 2100.

The question that arises is how to interpret these outlook results. Do these increases in flood risk necessitate a change in risk management? Not according to the current risk policy, which only demands that the embankments need to be able to withstand extreme conditions with a frequency of 1:4,000. And as we have seen, an increase of crest height with 2m is still technically feasible, which could cope with sea level rise at least till 2030 (Heijer & Calle, 2000). Figure 6.10 shows that up to 2030 the risk levels under the different scenarios do not deviate from each other very much. Hence, it is tempting to postpone a decision for a changed flood risk policy for another 25 years.

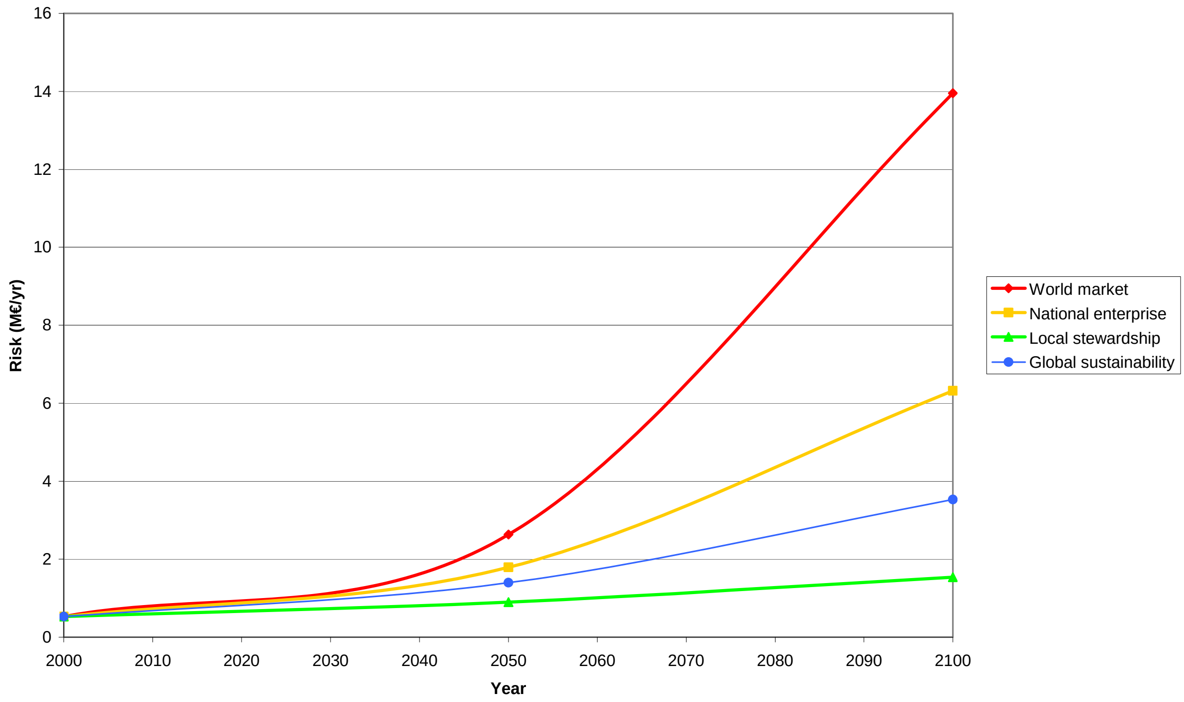

Figure 6.10 Increase in expected annual damage from 2000 to 2100 for the different scenarios (De Bruijn et al., 2008a)

However, it can be argued that an increase in the economic assets to be safeguarded requires reconsideration of the safety level. After all, this was determined 50 years ago when the region was far

[6] The Dutch flood management policy consists of maintenance and adaptation of embankment levels to sea level rise such that a flood probability remains 1/4,000 a year

less developed. Furthermore, as recent studies indicate, the probability of *flooding* could be (much) higher than the probability of the extreme *water level* when taking into account the reliability of the protection system (Rijkswaterstaat, 2005). In this study different failure mechanisms have been identified for the entire dike ring. Several weak spots of the dike could lead to damage and erosion and also a construction failure of a hydraulic structure in the dike ring was shown to have a much higher probability than that of the design water level. When these spots not considered, a probability of flooding of 1:2000 per year is calculated (Van Gelder, 2006). This has led to renewed discussions about the preferred or required safety level and how to achieve this level. In addition to the raising and strengthening of the dikes, community preparedness and spatial planning are considered relevant options in the debate. Accordingly, three alternative flood risk strategies were analysed: a *Storm Surge Barrier* at the mouth of the estuary and two combinations of differentiation of protection levels and (future) land use planning: *Risk Approach* and *Spatial Planning.* Table 6.4 describes the alternatives together with the current policy (the 'zero-alternative') in terms of their guiding principles and their elaboration.

When comparing the expected annual damage for the year 2050 under the different strategies (Figure 6.11), we can observe that i) a Storm Surge Barrier would provide the highest safety, albeit with the highest investment (very roughly estimated at 3.8 billion €), ii) the Spatial Planning alternative produces risks quite similar to those associated with the Current Policy and iii) the Risk Approach alternative will result in considerably higher economic risks than the other alternative strategies, especially in the World Market scenario (De Bruijn *et al.*, 2008a).

Table 6.4 Overview of the strategic alternatives for the Scheldt Estuary

	Name	Guiding principles	Description
0	Current policy	Resistance along long lines	Maintaining the once in 4,000 years protection level by raising embankments
1	Storm Surge Barrier at Vlissingen	Resistance concentrated at one location	Providing a once in 10,000 years protection level by a barrier
2	Risk approach	Increase of resilience Spatial developments occur autonomously, flood protection levels follow	Flood protection level differentiation based on flood consequences, spatial developments occur autonomously
3	Spatial planning	Increase of resilience Flood patterns control spatial developments;	Protection level differentiation and spatial planning are combined in order to lower flood risks.

The differences in the results of the Risk Approach and Spatial Planning alternatives can be explained by their different management approaches towards land use planning. Under the Risk Approach land use developments are considered to occur autonomously and flood protection standards *follow* these developments, but only when the costs of raising embankments are equal to, or lower than, the expected risk reduction that could be obtained by this measure. In this way the urban areas have the highest protection level and extreme events are expected to flood mainly rural areas.

Under the Spatial Planning alternative, spatially differentiated flood protection standards determine land use development. The strategy consists of a combination of safety differentiation, embankment strengthening and land use planning. Embankments of currently vulnerable areas are made higher while those of the rural areas remain lower. Thus the current land use determines which sub-areas receive the highest protection. Typical examples of such locations are the cities of Middelburg, Terneuzen and Breskens. Future land use developments are also directed towards these highly protected areas. In the remaining coastal areas economic investments are only allowed in such a way that flood impacts do not increase. Through this strict spatial policy the overall flood risk remains lower than under the Risk Approach without spatial planning.

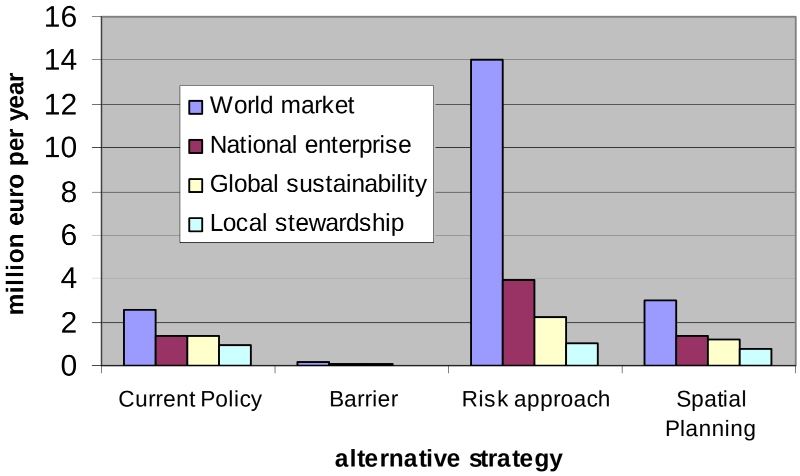

Figure 6.11 Expected Annual Damage for each alternative strategy under different scenarios (year 2050)

In terms of group risk, the Storm Surge Barrier provides the highest safety (Figure 6.12), whereas the Risk Approach strategy has the lowest safety. The Storm Surge Barrier lowers potential casualties far below those under the Current Strategy. Not shown in this bar chart is the distribution of safety, which is an important aspect in terms of equity: the Storm Surge Barrier and Current Strategies score highest in this respect as there is no spatial differentiation of flood risk. In contrast the other two strategies are less successful in this respect: Some people will be better protected than others and some will have more opportunities for economic growth than others. The rich or highly educated people may have more opportunities than the less privileged with little education and less opportunity to leave the less favourable parts of the area.

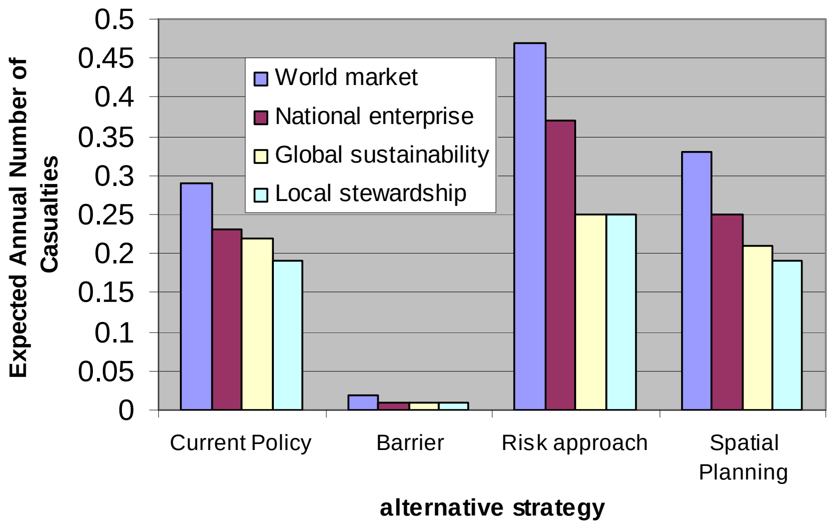

Figure 6.12 Expected Annual Number of Casualties for each alternative strategy under different scenarios (year 2050)

In economic terms the alternative strategies can be compared by dividing the present value of the reduced risk (the 'benefit' compared to a 'do nothing' situation) with that of the present value of the costs. As can be seen in Figure 6.13, the effect of the scenarios is dominating the picture: almost all strategies have a Benefit Cost Ratio above 1 under the World Market scenario. The Spatial Planning strategy scores above 1 also under the National enterprise scenario, whereas the other strategies score lower. Because of the very high investment costs of the Storm Surge Barrier, this strategy falls short in economic terms under all scenario futures.

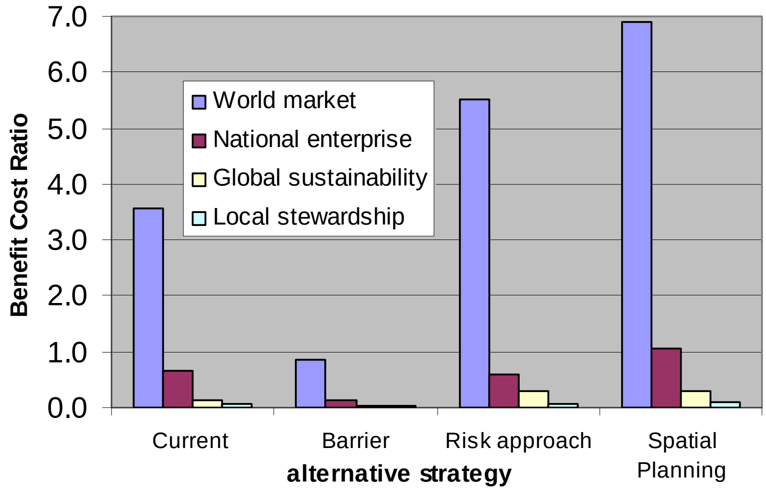

Figure 6.13 A comparison of Benefit/Cost ratios for each alternative strategy under different scenarios

8.3.2. Flood risk assessment: is a change in policy needed?

In the previous section a quantitative analysis of possible futures has been presented. The question remains: can we choose one strategy above another? Or, in other words, do the analysis results warrant a change in current safety policy or not? A Storm Surge Barrier could indeed be preferred in terms of maximising safety *if* society is willing to invest heavily. If not, both the Current Policy and Spatial Planning strategy are more rational choices than the Risk Approach Strategy, because the latter results in a larger residual risk in terms of damage and casualties and has a lower benefit/cost ratio.

Table 6.5 Score table for the alternative strategies (summarised) (de Bruijn et al., 2008a)

criterion	Current policy	Storm Surge Barrier	Risk Approach	Spatial Planning
casualty risk	++	++	- / --	0 / +
potentially affected persons	++	++	- / --	-
equity*	+ /++	+ / ++	0 / -	- / --
nature*	0/-	--	0/+	++
landscape quality*	- / --	- / --	- / +	0 / ++
costs	-	--	++	+
economic risk	+ / -	++	-- / -	- / +
economic opportunity*	0 / +	+ / 0	0	0
robustness*	- / 0	- / 0	- / 0	0 / +
flexibility*	0	--	+	++

*: Scoring of these qualitative criteria was done using the Delphi approach. A group of experts discussed the alternatives and criteria and then scored the strategic alternatives. The scores were discussed and the experts were asked to reconsider their scores. NB: variation in scores originates from differences in performance of each strategy under different scenarios.

This still leaves the choice between continuing with the current policy or introducing a new risk based approach with risk averse spatial planning. The scientific approach of the flood risk analysis does not provide enough arguments to choose for either option. In their report (De Bruijn *et al.*, 2008a), the scientists stressed that many more aspects should be taken into account to enable an integrated assessment based on all relevant criteria, including less tangible elements such as social and environmental side effects. Therefore, a Delphi method was used to assess in a rather qualitative way the effects on equity, nature and landscape, economic opportunities, and the robustness and flexibility of each strategy (Table 6.5). Furthermore, the relative importance of these criteria ('weighing factors') will no doubt prove to be decisive on the outcome of the decision. Here the limits of a scientific flood risk assessment are clearly reached, as the weighing of criteria is normative and depends on public opinion and politics.

Because the Spatial Planning alternative seems a promising strategy, but implies a fundamental shift in the Dutch safety policy, the approach and consequences have been discussed during the workshops. The stakeholder consultations provided much relevant additional information that complements the scientific analysis of the preceding section.

6.3.2 Citizens: aware of risk, yet confident in the current safety policy

The presentation of the results from the flood risk analysis during the second workshop brought about slight changes in participants' preferences regarding future flood risk measures. Worry about future flood risk and an urge to do things differently was not provoked. The questionnaire responses showed a similar picture: only 71 individuals (13.3%) of the respondents are worried about the possibility of a severe inundation.

Most opinions expressed during the workshop as well as in the preceding interviews revealed that citizens had confidence in the current flood risk policy based on strong and high primary embankments. Among the various flood risk management measures presented in the workshop, the strengthening of primary embankments (sea dikes) received the highest positive score. This confidence was also reflected in the questionnaire results, since a high percentage (77.2%) or 413 respondents think that technical measures, such as dikes, should be given high or the highest priority (Figure 6.14).

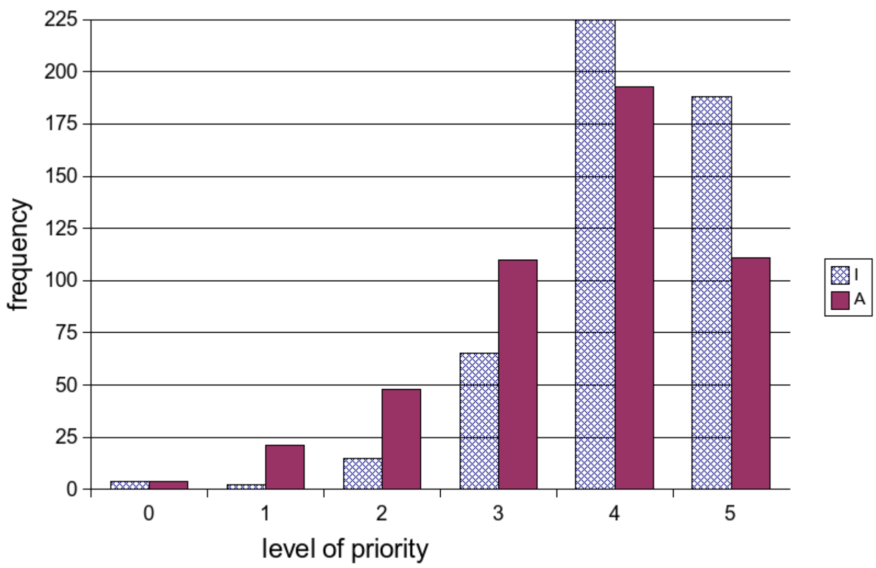

Figure 6.14 Questionnaire results: preference for technical measures (I = priority according to the respondent's own point of view, A = what the respondent believes is currently prioritised by the authorities, Priority level: 0 = no priority, 5 = highest priority)

Nevertheless, the discussions and information exchange caused participants to shift their attention more evenly over the different flood risk management phases. They indicated that policy makers should do more to mitigate the impacts during and after a flooding event, yet still pay attention to primary defence. Again, this tendency was corroborated by the questionnaire results.

The creation of safe havens and inspection of the dikes were the most favoured flood amelioration measures during the workshop. This reflects a growing understanding on the part of the participants that evacuation out of the area would not be possible for all citizens, and that a safe haven located relatively nearby was likely to offer more safety in the short term and make rescue at a later date possible. Dike inspection was viewed as necessary because those individuals who are most threatened could then be evacuated first and others warned to go to the safe havens. Participants expressed a need to know which buildings or dikes were highest in their area. Farmers indicated that they know, but the other participants were unsure.

Alternative strategies were initially not considered to be highly relevant or viewed to be not without serious shortcomings. Following the presentations and discussions, a more nuanced picture emerged. For instance the Storm Surge Barrier initially received mixed, relatively neutral reactions. However, following the discussions it received slightly more positive reactions. Doubts were expressed about prohibiting or limiting the development of low-lying land as proposed in the Spatial Planning strategy. Moreover, this measure received even more negative than positive votes after the discussions. Also the use of secondary dikes to create compartments (one of the measures in both the Spatial Planning and Risk Approach alternatives) was less favoured after the discussions, in which the risk of deeper inundations at particular locations was mentioned.

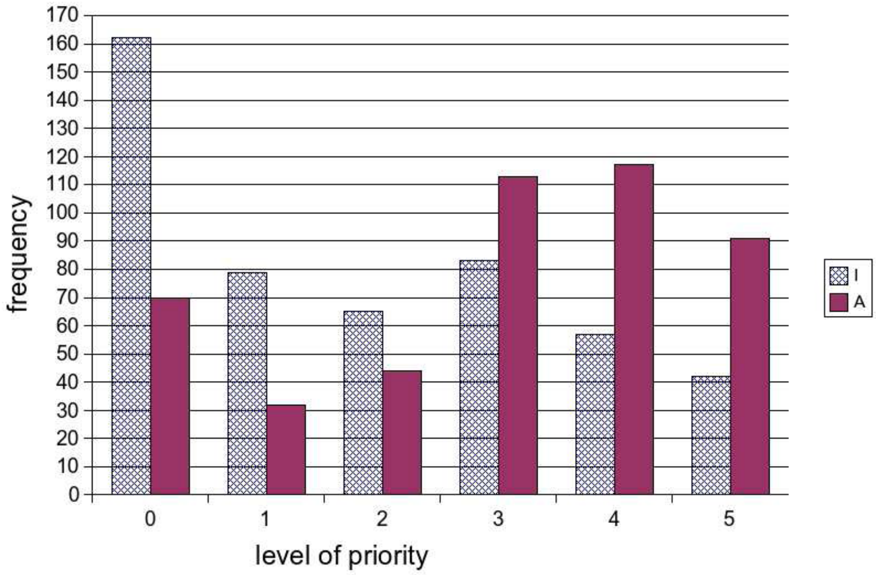

Figure 6.15 Questionnaire results: preference for spatial measures (I = priority according to the respondent's own point of view, A = what the respondent believes is currently prioritised by the authorities, Priority level: 0 = no priority, 5 = highest priority)

The questionnaire results tend to confirm the relatively low preference for spatial measures, and show a discrepancy between the respondents' preferences and the preferences that respondents believe the authorities have in this regard (Figure 6.15). However, this could also be attributable to the interpretation of the 'spatial measures' concept as being identical to managed realignment of the coastline. This 'depoldering' (i.e. giving previously reclaimed land back to the sea) has given rise to a furious debate in the province of Zeeland that was also clearly noticeable during the workshop discussions.

The stakeholder consultation also brought out elements that were hitherto not acknowledged in the flood risk analysis. For instance, the importance of safety from flooding in ensuring (foreign) investment and the risk that after a flood these companies would not return is something that has received little or no attention. Also it was interesting to note that instead of having their say in selecting and weighing criteria for a risk assessment, participants stressed their worry about the whole procedure of decision making. For example, when it comes to the expropriation of farming land for nature development or to protect the city of Antwerp from flooding, some participants view this as necessary, but would like to see the procedure managed expeditiously. Such concerns are presently not considered explicitly in a policy process because the public are not involved in the design of the process itself.

6.3.3 Policy makers: confused about how to organise the discussion

The workshop with policymakers focused on the advantages and disadvantages of a new flood risk policy enabling a differentiation of safety standards based on costs and benefits. This approach, of which the Risk Approach and Spatial Planning strategies are examples, was considered to have economic advantages and to enable practical combinations with spatial planning policy. It would also make people more aware of the flood risk than under the current policy. However, the participants also identified a number of problems, such as:

- Lack of knowledge;
- Implementation hurdles;
- Communication difficulties;
- Resistance of citizens;
- Institutional complexity.

One of the main problems of this risk approach is that it allows flooding to occur more often than it is currently the case, e.g. in an area with low economic value and low population density. This signifies a leap in thinking about flood risk management in the Netherlands, where protection against flooding was – and still is – the cornerstone of Dutch safety policy. A spatial differentiation in safety levels is difficult to implement because it requires a decision process in which many government levels need to be involved as well as the public and stakeholders. This necessitates a transparent and objective communication of flood risk, which implies that somehow the differences in risk perception between stakeholders, policy makers and scientists need to be bridged.

The new risk approach has been studied and discussed for a long period of time. However, there seems to be little progress in terms of decision-making. Guidance and vision seem to be lacking, which leads to more studies and postponement of decision making. Some workshop participants voiced the concern that the subject is too difficult for public debate and others regarded the discussion to be a hype in the wake of recent media coverage of disasters (such as hurricane Katrina in 2005) and climate change related issues.

However, the workshops and interviews with citizens proved that it is possible to discuss these issues in a sensible and constructive way with those directly involved without the debate becoming emotional or irrational.

6.3.4 Evacuation: to leave or not to leave, that is the question

Authorities face a difficult decision when flooding is imminent. An evacuation that proves to have been unnecessary results in a waste of money and time, it may cause stress and panic and it will spoil the image of the government. Besides, it may influence the response of the inhabitants to the next evacuation call. But issuing the call too late will lead to chaos on the roads and high risk of casualties. Can evacuation models support the end users who voiced this dilemma during the pilot study? In order to answer this question, we will first examine what happens when waters rise.

If the predicted water level at Vlissingen exceeds 3.10 m above mean seal level then “Alarm State 3” is reached. Alarm State 3 is part of an alarm system with 5 levels which describe the imminent chance of a disaster. For each state certain actions are required. In Alarm State 3 the mayors of the municipalities are responsible for the emergency response. Alarm State 4 is reached when the expected water level exceeds 4.10 m above mean seal level. In alarm state 4 the governor of the province takes overall responsibility. The Province of Zeeland, in which the pilot area is situated, has prepared an emergency plan for all the municipalities with respect to flooding. In these plans transportation means are available for schools, hospitals and nursing homes. Other people are expected to evacuate themselves. When the Governor of the Province decides that evacuation is necessary this is communicated to the relevant authorities. The public is informed by radio and television broadcasts. The police are responsible for traffic management during evacuation.

The three evacuation models EC, ESCAPE and INDY (see Section 6.2.6) predict that it will take at least 22 hours to evacuate the whole study area, when the evacuation is managed well and no unexpected events (like accidents) happen and people leave very efficiently. While this is probably an underestimation of the actual evacuation time, it is still too long to complete the evacuation within the lead time of the event-forecast, which is usually 6 hours in this region.

By coupling the evacuation model to a flooding scenario a strategy can be analysed in which the entire flood risk area is not completely evacuated, but only those areas that are expected to flood in the case of a dyke breach. A significant reduction in evacuation time can be achieved. The use of local shelters and nearby elevated areas can help to reduce the pressure on the road system. But a preliminary inventory for the areas of Walcheren and Zuid-Beveland estimated that these safe havens only have a capacity for about 5% of the people at risk.

Although the current evacuation models can be helpful in evacuation planning, none of them have been validated against a historic event in the Westerscheldt area. None of the models take into account the congestion due to crossing traffic flows at intersections. All models assume that people are at home and respond in an orderly manner to the evacuation call. In reality, however, an evacuation on Monday morning will probably lead to a different response and traffic patterns than one on Sunday afternoon.

It is advisable before using these models for planning purposes to undertake a sensitivity analysis to establish their reliability. Ideally, such models should have an appropriate and accurate representation of all kinds of local conditions and situations (such as elevated areas, potential bottlenecks in roads and information on people requiring special assistance). This is exactly the type of local knowledge that is available with the local authorities and local citizens. During the interviews and workshops participants placed priority on early warning and indicated strong interest in safe havens and evacuation as a means of ameliorating the effects of floods. Hence, a more active involvement of local stakeholders and citizens in the further development of such models seems both justified and feasible.

6.4 Contribution to flood risk management practice

6.4.1 Future flood risk along the Scheldt River estuary

There is little doubt that flood risk along the Scheldt will increase in the future. If sea level rise does accelerate, this will result in more frequent extreme high water levels, whereas autonomous economic development and population growth result in an increase in potential damage and casualties. The current flood protection policy consisting of strong embankments that can withstand storm surges with a 1:4,000 y^{-1} probability is able to offset the impact of sea level rise for at least the next 25 years (Heijer & Calle, 2000). Depending on economic development, the future flood risk could nevertheless increase significantly, especially in the longer term.

The strategy analysis clearly shows that a significant reduction of flood risk can be reached by investing in a storm surge barrier. After the 1953 flood disaster the Delta Commission explicitly decided not to opt for this measure for the Westerscheldt: maintaining free navigation for Antwerp was (and still is) essential. Despite an increase in flood risk over the past 50 years (because of economic development), it is questionable if present or near future conditions would result in a different trade-off. Although technical improvements could nowadays provide a solution that combines safety and navigation demands, the financial and environmental consequences are still excessive.

The Risk Approach and Spatial Planning strategies tend to entail similar or higher risks compared with the current policy. Thus a choice for either of these strategies cannot be motivated primarily from the desire for a reduced flood risk. Other arguments that play a role in the discussion include: costs and benefits, the desire for a more resilient strategy, environmental motives, etc. Since the societal implications of such a change in current flood risk thinking are profound, discussions cannot be limited to the scientific domain.

6.4.2 Public perceptions and preferences: a realistic view on flood risk

Local citizens were realistic and knowledgeable with respect to a possible failure of the flood control system. Even in the Dutch case where relatively high safety standards are present, people have diverse and explicit opinions and knowledge about what to do when things go wrong. Probably, this can be attributed to the fact that the 1953 flood is still present in the awareness of the residents alongside the Scheldt estuary. Nevertheless, the shift exhibited by participants at the workshop to spread attention more evenly over the flood risk management phases represents learning by the citizens about the value of redundancy in combating a natural hazard. Participants also expressed this after the workshop, by indicating a desire for information on potential safe buildings in their area. This indicates a potential change in behaviour from trying to evacuate along a busy, low-lying road to seeking a refuge in the area should a flood occur.

Interestingly, there was a marked difference between local citizens from both countries with respect to the role of the government after the occurrence of a major flood. The Flemish residents were convinced that the state would do as much as it could to help the recovery and were relatively secure in this trust. The Dutch respondents were less convinced. They thought that the Dutch government would do its best, but this would be insufficient and the recovery would have to come from the people themselves.

6.5 Conclusions and outlook

6.5.1 Lessons for public participation in flood risk management

The Scheldt pilot opened three windows of knowledge: the scientific domain where probabilities, models and uncertainties dominate; the local citizens' perception and experience of flood risk, that largely remains unused in decision making; and the policy and management institutions, where innovative approaches compete with vested interests, procedures and legislation. Lessons can be learned with respect to: the importance of trust, the use of local knowledge and mutual learning in the communication process.

The importance of trust

Appropriate communication implies an open exchange of information based on recognition of equality and mutual trust. However, the questionnaire results showed a low level of satisfaction of respondents with the response of the authorities upon their requests, opinions and commitment. Despite the fact that people trust the authorities in general, more public communication and improved responsiveness of the authorities is expected. Most individuals seem not satisfied with the way in which authorities interact with the public. A lack of trust between stakeholders was also illustrated in the discussions on managed realignment along the Westerscheldt. Over the past 15 years this item of 'de-poldering' appeared on the political agenda several times, but with different arguments. Safety reasons and nature compensation were alternately put forward and thus made people sceptical about the real reasons. Scientific evidence plays a minor role here, not in the least because there is not yet enough knowledge about long-term hydro-morphodynamic consequences of 'de-poldering' as a measure (Jeuken *et al.*, 2007).

Relevant local knowledge

Prior to the study we were concerned as to whether we would even be able to identify relevant local knowledge regarding flooding and the danger of flooding amongst the citizens selected for the study. But we found a depth of understanding of their living environment amongst the people of the Scheldt that astonished us. Especially those persons with professions providing them with primary contact with the water (e.g. a fisherman), showed an understanding of flooding comparable with that of the scientists. However, local knowledge of the consequences of flooding and the post-flood recovery went deeper than scientific understanding. Also their comments regarding the (lack of) utility of some of the planned policy measures to promote safety from flooding were confirmed as valid by policy makers. In fact, the policy advisors were also surprised by the high quality of the information derived from the study and felt challenged by the request for precautionary post-flood planning measures.

Social learning process
The Scheldt pilot has demonstrated the value and feasibility of involving citizens, scientists and policy makers in framing a future flood risk management strategy. Clearly, this process of strategy formulation does not and should not follow a strict sequential number of steps such as *risk analysis* → *risk assessment* → *measures*. Our experiences support the statement of Hutter (2006) that ‘strategy processes do not always follow a simple step-by-step logic to solve complex and dynamic problems’ (Hutter, 2006, p.235). Instead, this process requires iteration in which frequent and open discussions among the different groups exchange ideas and facts. Indeed, it is in a social learning process where participants acquire new knowledge from others and create new knowledge (cf. Siebenhuner & Barth, 2005; Pahl-Wostl *et al.*, 2008).

To reduce the observed obstacles in communication requires a continuous effort from the representatives of all three domains. Decision support tools, such as the Evacuation Support System, can play a role here, as they make scientific knowledge embedded in flood risk models available to non-scientists. Effective use of these tools, however, often remains mostly limited to government end users (and even then with mixed results). In addition, there are still significant gaps in knowledge (especially with regard to embankment failure and long term changes in the hydro-morphological boundary conditions) that make it difficult to produce tools that can be tested against generally agreed validity criteria.

Validity of knowledge also plays a role in the international dimension of the Scheldt. Because of the highly dynamic nature of the estuary, embedded in an age old history of human interference of land reclamation, dredging and civil engineering, the understanding of its past and future behaviour is rather poor. As the two nations have to manage the Scheldt together, it is important that they share a common knowledge base and agree on models that support future decision making on safety, accessibility and nature compensation.

6.5.2 Concluding remarks

Our experiences from this study offer insights on the benefits of using science and engineering in a participative approach to flood risk management. Yet we have to be careful in deriving general conclusions from these experiences. There are two reasons for this. In the first place it must be acknowledged that the discussions between the different groups of people were held in a research context instead of a real policy making process. Had decisions actually to be made, it is likely that elements of a political or tactical nature would have interfered with the content of the discussions. This could then affect level of trust and the success of social learning. To our opinion, however, this only underlines the importance of providing criteria for the participatory planning process. In this respect, it is illustrative that the respondents in our study provided criteria for the planning process itself rather than for the detailed measures therein. This indicates that it is public involvement in its design that could potentially lead to improvements in the quality of the planning process and its subsequent results.

Secondly, the results of *this* case study are not necessarily applicable to other flood prone areas and situations. The observed differences in risk perceptions and preferences between the Dutch and Belgium part of the Scheldt estuary show how important geographic and cultural characteristics are. Indeed, in Europe there is a great diversity in flood hazard, risk, awareness and preparedness. It is our conviction that it is through a participatory approach that this diversity can be taken into account in flood risk management. A willingness to exchange scientific insights and local knowledge on the part of scientists, citizens and policy makers and so learn from each other provides the best chances for this approach.

Acknowledgements
We are grateful to the respondents for their willingness to share with us their concerns and their experience of living and working on, or near, the Scheldt Estuary. The work described in this presentation was supported by the European Community's Sixth Framework Programme through the grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420.

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7. Pilot site "Ebro River delta coast"

José A. Jiménez, Dagoberto Alvarado-Aguilar, H. Coop, Joerg Krywkow, Magnus Larson, G. van Geest, Ruud Raaijmakers, Augustin Sánchez-Arcilla

7.1 Flood risks and previous mitigation efforts

The Ebro delta is located on the Spanish Mediterranean coast about 200 km southward of Barcelona. It has an approximate subaerial surface of 320 km^2 and a coastline length of about 50 km (Figure 7.1). It is an ecologically rich environment and it includes a Natural Park of 7,800 ha giving administrative protection to the areas of highest environmental value, including habitats like freshwater, brackish and saline lagoons, salt marshes and coastal and small dune sandy areas.

Figure 7.1 The Ebro delta. Red polygons indicate most vulnerable areas to storm impacts

At the same time, the delta is actively exploited by means of agriculture, mainly for rice production (about 66% of the total subaerial surface is devoted to rice production and between 10% and 15% to other crops) and provides support for a significant percentage of the fishing and aquaculture activities in Catalonia. The population is about 50,000 inhabitants, including people living in the delta itself and people with a direct economic dependence on it

The extensive damming in the Ebro catchment basin has reduced the overall sedimentary supply to the deltaic system during the second half of the 20th century. As a result of this, the delta has evolved from accretion to stability in terms of subaerial surface, although experiencing strong reshaping processes (e.g. Jiménez and Sánchez-Arcilla, 1993; Jiménez *et al.* 1997; Guillén and Palanques, 1997). Moreover, this sediment supply cut-off should produce a decrease in the relative land elevation due to the inexistence of river floods able to distribute sediments along the deltaic plain to compensate relative sea level rise in the area.

Although many studies have been done in the Ebro delta related to coastal evolution from different standpoints, none of them specifically deals with the impact of flood events. Taking into account that about the 50% of the subaerial deltaic surface is comprised between the mean sea level and the height +0.5 m above MWL, it seems clear that the area should be extremely vulnerable to this forcing. Coastal floods in the Ebro delta can be mainly originated by two main agents: RSLR and the impact of storms. The first one is a long-term process in which the difference between projected sea level and deltaic elevation will drive the inundation of low-lying areas in a more or less permanent manner. The second one is a transient process integrating the result of beach and dune erosion and overwash. A first estimation of the vulnerability to these processes was done by Sánchez-Arcilla *et al.* (1998; 2007) who identified main areas along the coast to be affected and also made a first estimation of the expected physical impacts. However, they did not quantitatively estimated storms-induced flood hazards and, their study did not directly consider environmental and/or societal impacts.

Figure 7.2 Overwash deposits in rice pads along the Marquesa beach after the impact of a storm on November 2001.

Storm impacts on the Ebro delta coast usually occur under the coexistence of surged water levels due to the passage of low pressure systems off the delta coast and eastern wave storms (e.g. Jiménez *et al.* 1997). Although the entire deltaic coast is subjected to the action of these events, most vulnerable stretches are those subjected to relatively large long-term erosion rates, resulting in a beach configuration given by a narrow emerged and low beach which are fronted by a “low-crested” bar or bar system. These most sensitive areas are (Figure 7.1): (i) Illa de Buda at the central lobe; (ii) Trabucador beach at the Southern hemidelta and (iii) Marquesa beach at the Northern hemidelta. These areas have been identified taking into account the magnitude of their morphodynamic response

(Jiménez *et al.* 2005) and the frequency of reported damages due to storm impacts during the last decade (Generalitat de Catalunya, 2004).

The induced "coastal damages" were situations characterised by (i) affectation of agriculture lands by inundation (local owners being the receptor of the damage), (ii) affectation of natural values due to storm impacts – wave exposure or inundation – (Natural Park being the receptor of the damage), (iii) impulsive coastal erosion of very large magnitude. Figure 2 illustrates the potential affectation of agriculture lands after the impact of extreme storms, when overwash deposits are observed in the rice pads closest to the shoreline.

7.2 Objectives and approach

Taking into account the above mentioned expected physical vulnerability of the Ebro delta to floods and the existence of high natural values and the high human pressure exerted on the system, it seems clear the need to assess the impact of coastal floods on the Ebro delta coast taking into account not only physical terms but also environmental and socio-economic ones. Thus, the main objective of this work is to examine vulnerability, risk and defence needs against flooding of marine origin at the Ebro delta coast.

General approach
To achieve the objectives of this work, the general methodology developed within the FLOOD*site* project was adapted to specific characteristic of the study area. Figure 7.3 shows the FLOOD*site* source-pathway-receptor approach applied to delineation of flood hazard areas in coastal sedimentary environments due to the impact of extreme events.

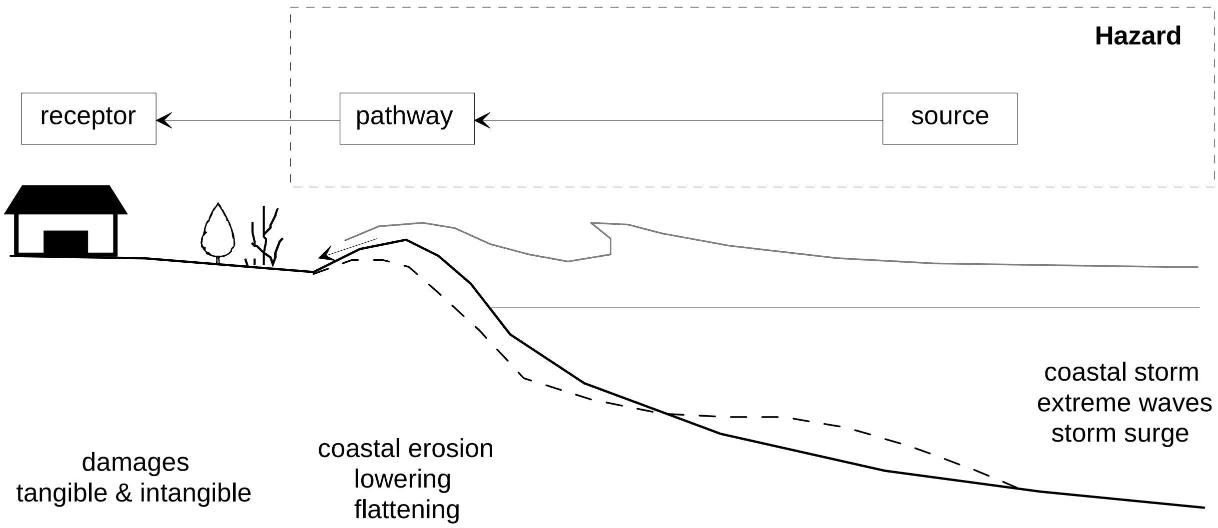

Figure 7.3 Source-Pathway-Receptor model for coastal flood hazard mapping (Jiménez et al. 2008).

Sources refer to marine forcing inducing the flood event. In this work we have selected two flood risk sources, one associated to long-term processes which is given by RSLR and, other one associated to episodic/extreme events which is given by storm impacts.

Pathways refer to processes leading to coastal flooding induced by the agents mentioned before. Since the Ebro delta coast is a dynamic sedimentary environment, here we consider two processes: inundation and erosion.

The characterization of the *Receptor* refers to estimation of the induced effect of flooding in the territory. Due to the high natural values of the Ebro delta we have specifically included the assessment of the ecological impact of coastal floods. In addition to this, the local perception of stakeholders to flood risks was also investigated.

In what follows the main methodological aspects used in the different parts of this study are outlined.

Flooding due to RSLR

At the long-term scale, flood hazard areas in the Ebro delta induced by RSLR have been delineated by estimating the deltaic surface lying below a given projected water level with a direct connection to the sea. Although theoretically, deltaic environments are able to cope to SLR this will only occur for deltaic plains able to vertically accrete mainly due to river sediment supplies (see e.g. Day *et al.,* 1997). However, this is not the case of the Ebro delta since the entire plain is occupied by humans (settlements and economic activities such as agriculture) and, this forces water policy to fully prevent inundation by regulating river flows.

Due to this, the delta is assumed to behave as a passive floodplain separated from the sea by a fringe which is active along the outer coast (which is formed by sand and able to attain a long-term equilibrium profile) and passive along the inner coast in the bays (where is composed by fine materials and sands sheltered from wave action).

The topography of the entire Ebro delta used in this work consists of a DEM derived from LIDAR data obtained by the Institut Cartogràfic de Catalunya. The original DEM has a resolution of 1 m x 1m and it was re-sampled to a grid of 5 m x 5 m.

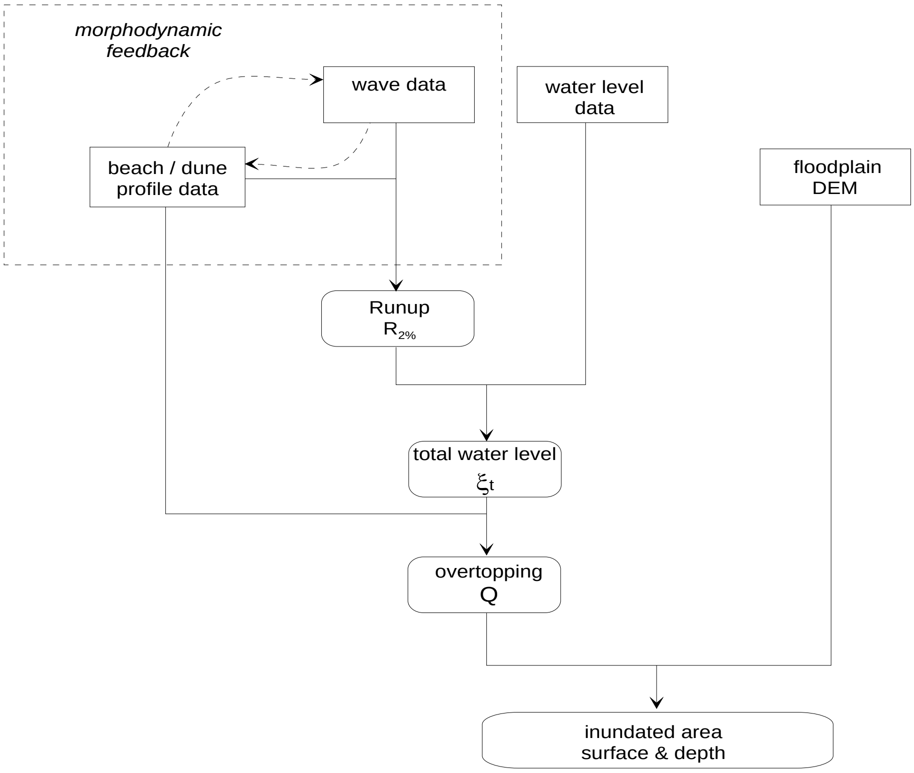

Figure 7.4 Methodology to generate a coastal flood hazard map for sandy coasts.

To delineate the floodplain areas to be inundated we took into account the different behaviour of outer and inner coastlines. Passive inner coastlines will maintain their absolute elevation and, thus, sites with an original elevation lower than the RSLR scenario will be inundated. On the other hand, active outer coastlines will maintain their relative elevation because we assume they will react to RSLR as predicted by Bruun's rule, i.e. maintaining constant their elevation with respect to sea level. Along these coastlines we also take into account the possibility to be temporarily connected to the sea due to the impact of extreme events. This is done by estimating the long-term distribution of beach erosion and overwash events in different stretches along the deltaic coast by using a dune erosion-overwash analytical model (Larson *et al.*, 2009).

The RSLR scenario used in this work was +0.50 m which should include the contribution of the climate-change eustatic component and a local component due to subsidence (see e.g. Sánchez-Arcilla *et al.* 2008).

Flooding due to storm events
At the episodic scale, flood hazard areas in the Ebro delta induced by the impact of coastal storms were delineated by estimating the deltaic surface to be temporarily affected by overwash landward flows over the beach during the storm. To do this, a specific methodology to map flood hazard coastal areas taking into account their morphodynamic response to storm action was developed (see Alvarado & Jiménez, 2008) which is outlined in Figure 7.4.

The first step consists in the estimation of a total water level at the shoreline. This is done by using the response-method approach, which is based directly on measured or simulated water levels and waves as they occurred in nature and, the water level of interest (associated to a given probability or return period) being directly calculated from a probability distribution of total water levels (see e.g. Divoky & McDougal, 2006). In this analysis the model proposed by Stockdon *et al.* (2006) is used to estimate the wave-induced runup in beaches. The obtained values are then added to simultaneous water level data (ζ_m) to build the total water level time series (ζ_t) which is then fitted to an extreme distribution to estimate water levels associated to given probabilities or return periods.

Once estimated the total water level, the following step is to calculate overtopping rates (Q) for those cases where water level exceeds the beach/barrier crest. This will determine the volume of floodwater penetrating the hinterland and, in consequence, determining the extension of the flood hazard area. The overtopping volume has been calculated following the method used by FEMA (2003) to estimate the inundation in low-lying coasts.

A critical issue of mapping coastal areas prone to be inundated during storms is the inclusion of beach morphodynamics. Beach configuration controls the magnitude of the run-up (via beach slope) and overtopping (via beach/dune crest height). Because beaches are continuously reacting to coastal dynamics, especially during storm impacts, to properly map coastal flood hazard areas beach dynamics have to be incorporated to the analysis (see e.g. Alvarado & Jiménez, 2008).

This is here included by simulating the beach profile response during the storm action by using the SBEACH model (Larson & Kraus, 1989; Wise *et al.*, 1996) which has successfully been used to simulate the dune lowering before the inundation of the hinterland during the impact of extreme storms (see e.g. Cañizares & Irish, 2008). Once the beach profile evolution during the vent is calculated, intermediate configurations from the pre-storm situation to the post-storm one are used to update the wave-induced run-up and overtopping rates according to the time-dependent beach slope and crest height.

Finally, once water levels and beach configurations are known, the last step is to determine which part of the coastal plain is flooded. This is done by using the LISFLOOD-FP inundation model (see model description in Bates *et al.*, 2005). The model predicts water depths in each grid cell at each time step, and hence can simulate the dynamic propagation of flood waves over fluvial, coastal and estuarine floodplains.

In our analysis we specify the data input as a time series of water flow at the shoreline bordering the deltaic plain (calculated through the overtopping rates).

In this work, we analyze the deltaic flooding due to the impact of an extreme storm with a return period of about 100 years. This storm impacted the coast in November 2001, and it was fully recorded by a wave buoy off the delta, being the most energetic storm ever recorded at the Ebro delta coast. It was a double peak storm from the E with *Hs* values of 5.6 and 5.95 m at the two peaks and durations (above a *Hs* threshold of 2 m) of 63 and 38 hours and with *Tp* values of 13.3 and 11.1 s. Due to this, in this work we used the real wave and water level data recorded during the storm to illustrate episodic flood risks.

Ecological impact
To determine the effects of sea flooding on vegetation composition in wetlands of the Ebro Delta, the following steps have been carried out (see details in Coops *et al.*, 2007):

- Selection of representative areas in the Ebro Delta.
- Selection of relevant habitat types and species.
- Determination of dose-effect chain: environmental variables - vegetation type.
- Assessment of habitat changes.

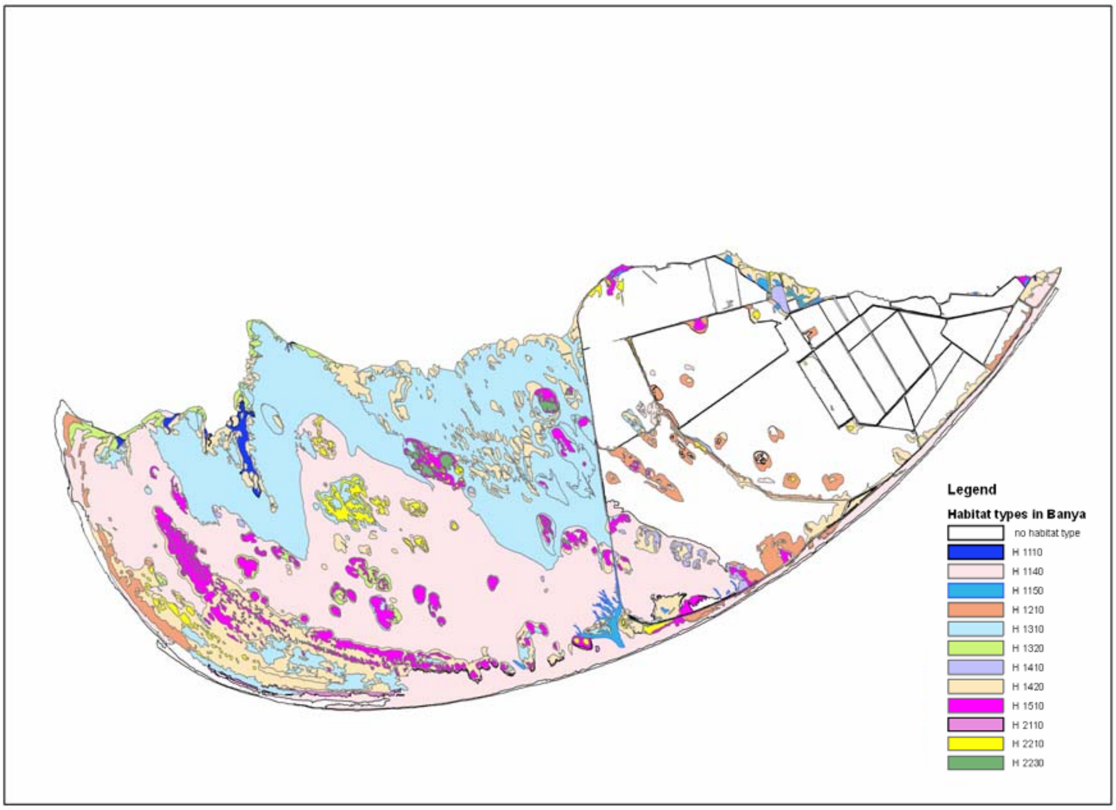

Figure 7.5 Map of Natura 2000 habitat types at Banya - H1110 Sandbanks permanent covered by sea water; H1140 Mudflats and sandflats intertidal; H1150 Coastal lagoons; H1210 Annual vegetation drift lines; H1310 Salicornia and other annuals; H1320 Spartina swards; H1410 Juncus maritimus salt meadows; H1420 Halophilous scrub (Sarcocornetea); H1510 Salt steppes (Limonietalia); H2110 Embryonic shifting dunes; H2210 Crucianellion maritimae dunes; H2230 Malcolmietalia dune grasslands.

In this study, two areas have been selected to analyse the effects of coastal flooding on natural values of the Ebro delta: Illa de Buda and Punta de la Banya (see Figure 7.1). These areas were chosen because of their expected differences in response to storm floods and sea level rise, respectively and, because they can be considered representative of the main biotopes along the Ebro delta coast. On Illa de Buda, a large coastal lagoon is present, which is bordered by low lying dunes at the sea side. Consequently, this area is sensitive for an increased occurrence of storm floods. These floods will result in episodic inflow of sea water, which may disrupt the spatial gradient of salinity in the lagoon. In addition, a progressive erosion of the coastal line is taking place at Illa de Buda, which makes this area particularly vulnerable for breaches during storms. La Banya consists of an extensive low-lying salt marsh system. The most southern tip of this area has no embankments, and is also in the absence of storms regularly flooded by the sea. Because of the low soil elevation of La Banya (60% of the area is lower than 0.2 m above sea level) and the absence of levees at the most southern tip, this area is highly sensitive to the effects of sea level rise.

The Ebro Delta has a large number of habitat types and species according to the Habitat and Bird Directive (Natura 2000) for which certain goals have to be met according to the Natura 2000 EU Directive. Therefore, we have focussed on the effects of sea level rise and storm floods for Natura 2000 habitat types which occur in the selected areas in the Ebro Delta (existing habitat types in Illa de Buda and La Banya can be found in Coops *et al.*, 2007). As an example, Figure 7.5 shows the distribution of habitats in La Banya spit.

The effects of environmental variables on vegetation composition can be visualised in a 'dose-effect chain'. A dose-effect chain describes the relationships between conditional variables, operational variables and their influence on plant distribution patterns. According to this information, predictions can be made how increased flooding frequency and global sea level rise will change the distributions of habitat and/or vegetation types. For wetlands of the Ebro Delta, separate dose-effect chains are available for:

terrestrial plants of salt marshes and dunes;
(semi-)aquatic plants in coastal lagoons.

Alvarez-Rogel *et al.* (2006) presented relationships between plant species dominance and gradients in soil salinity and hydrological conditions for salt marshes and dune systems along the SE Spanish Mediterranean coast. The identified main factors controlling the environment for plant growth were the depth of the groundwater table and salinity. A shallow water table will result in anaerobic conditions in the root zone that, in combination with extreme salinities, creates an inhospitable environment for plant growth. Furthermore, differences in flooding frequency will play a role, as salinity levels may rise because of increased flooding by the sea. Additionally, the vegetation composition may be affected by salt spray (Barbour, 1978) and sand movement (Morenocasasola, 1986), especially at sites close to the sea. The preferential zoning of each habitat type was derived separately for Buda Island and La Banya, because the response of vegetation composition to soil elevation differed significantly between these areas. The 'preference' for salinity was based on literature data (Alvarez-Rogel *et al.*, 2006; Phleger, 1971; Haines & Dunn, 1976).

For coastal lagoons, the conceptual framework for macrophyte, phytoplankton, and macro-algae occurrence developed by Menendez *et al.* (2002) for the Buda lagoon was used. In this study, the spatial distribution of phytoplankton, filamentous macro-algae, and macrophyte species were related to (variations in) salinity and nitrogen content. The two extremes of the salinity gradient were represented by the aquatic macrophyte species *P. pectinatus* (6 – 15 ppt) and *Z. noltii* (12 – 26 ppt), while *R. cirrhosa* grew optimal at intermediate values (range: 10 – 26 ppt). For vegetation stands of *Phragmites australis* (reed beds), soil elevation was derived from overlaying the habitat map and elevation map, while preference for salinity was derived from literature (Mauchamp & Mesléard, 2001).

Risk assessment

Risk assessment can be defined as the understanding, evaluating and interpreting the perceptions of risk and societal tolerances of risk to inform decisions and actions in the flood management process (Samuels & Gouldby, 2007). In this work, the used methodology for flood risk assessment combines three different methods: the quantifiable conventional approach to risk, the taxonomic analysis of perceived risk and the analytical framework of a spatial multi-criteria analysis (see Raaijmakers *et al.* 2008).

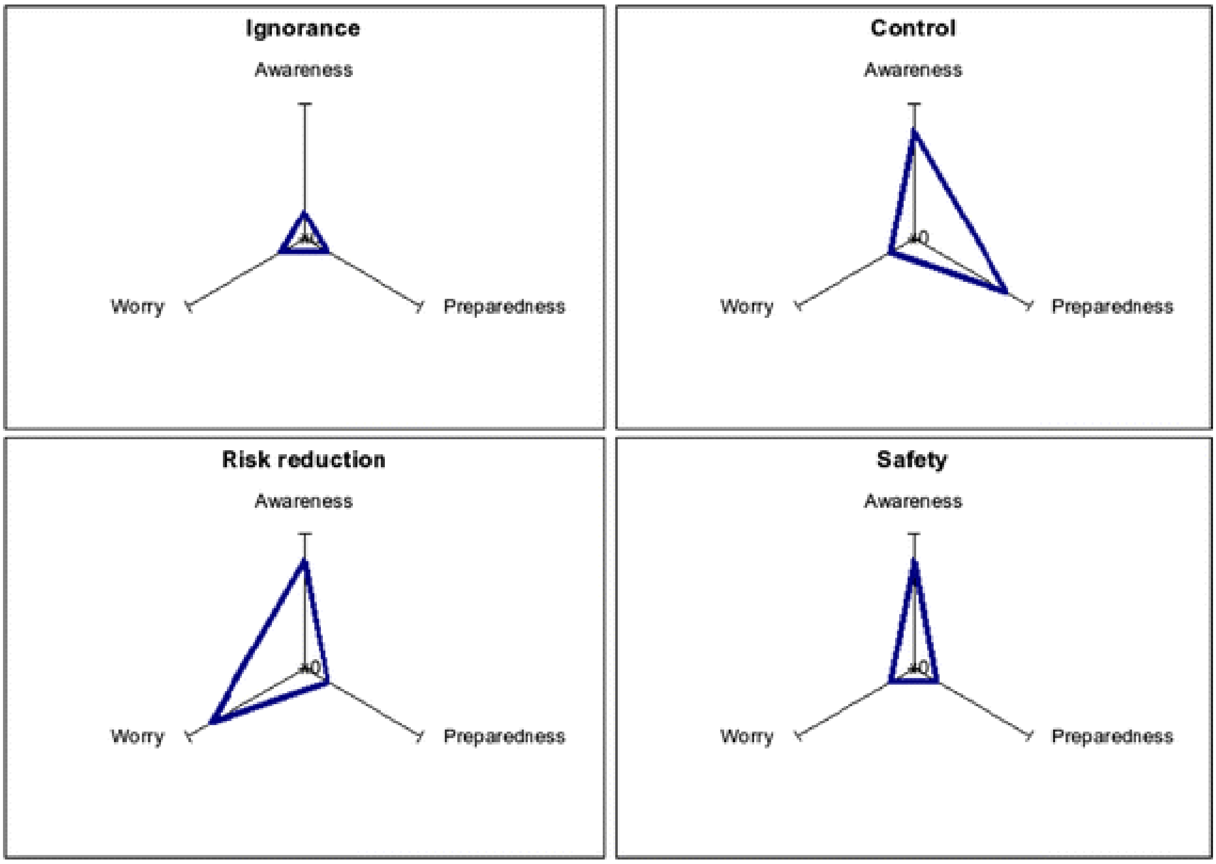

Figure 7.6 Typologies of risk characteristics (Raaijmakers et al., 2008).

First, a typology for flood hazards was developed based on individual and/or stakeholders' judgements. Awareness, worry and preparedness are the three characteristics that typify a community to reflect various levels of ignorance, perceived security, perceived control or desired risk reduction. Applying 'worry' as the central characteristic, a trade-off is hypothesised between Worry and the benefits groups in society receive from a risky situation. The four types of risk characteristics are depicted in Figure 6. Second, this trade-off was applied in Spatial Multi-Criteria Analysis (SMCA) where risk perception-scores were used as weights in a standard MCA procedure. Finally, local risk perception in the Ebro delta was characterised by an on-site survey to stakeholders who were selected to represent the main economic activities and functions in the delta. Seven individuals representing the following groups of stakeholders have been interviewed:

- The rice producers *Agrupation* (RP), a co-operative of rice farmers established in 1985 with about 2000 associates.
- The water distribution co-operative *Communidad Regantes* (WD) is responsible for the fair distribution of fresh water of the river Ebro to rice farmers. The organization is responsible for local water policy and water planning.
- The salt manufacturer (SM) who extracts salt on the Trinidad Salt pans on the La Banya spit. This salt extraction is vital for the pink flamingo population in the wildlife park. The extracted salt is transported by lorries along the Trabucador barrier, which is vulnerable to breaching during storm events.
- The restaurant at the Marquesa beach (RM). During the last years, the building is frequently damaged by the impact of storms.
- The local tourism organisation (TO) is prevailingly aimed at eco-tourists attracted by the Ebro delta Natural Park and beaches.
- The town council of Sant Jaume d'Enveja (TC), one of the coastal communities in the delta, being one of the centres of fishery and aquaculture in the region.
- The Department of Coasts (CE) of the Ministry of Environment which is responsible for coastal zone management.

7.3 Major findings

Deltaic inundation due to RSLR

Figure 7.7 shows the flood hazard deltaic area to a RSLR of +0.50 m. The calculated hazard surface was about 13,000 ha, which corresponds to approximately 44% of the deltaic surface. Figure 7.7 also classified the delineated hazard areas in different levels taking into account their "connectivity" to the sea.

Risk level 1 refers to areas with a direct connection to the sea and fronted by a passive coast, i.e. a coastal fringe not able to respond to RSLR (mainly the coastal fringe along the N and S bays). The consequence of this static behavior is that they will be ''instantaneously'' inundated.

Risk level 2 corresponds to areas presently protected by an active beach (able to respond to RSLR and, in consequence, maintaining their relative height with respect to MWL) but fronted by a coastal stretch subject to erosive processes and having suffered significant overwash events during the last decade. This is illustrated in Figure 7.8 where the calculated empirical long-term distribution function for the overwash volume in the Marquesa beach (Northern hemidelta coast) is presented. Results show that due to low dune elevation at the back of the beach, frequent overwash was calculated to occur at this site. For the analyzed long-term wave climate (1957-2001), calculations identified the November 2001 storm as the most erosive event, leading to an erosion of more than 90% of beach volume and producing a significant beach breaching.

Risk level 3 areas are "isolated" from the other ones by the barrier effects of structures such as levees and roads. They could be efficient in the short term (e.g. temporary floods) but their role in controlling inundation will not be efficient in the long-term (e.g. climate change induced) unless protected areas are converted to polders.

One of the implications of the obtained hazard areas is that, most of the "official" highly valued natural areas will be affected by this long-term scale inundation. This is due to the fact that the Natural Park extends along the entire deltaic coast (including both semi-enclosed bays) and, in consequence, one of the most affected values will be the natural one. Thus, it is expected that the 90% of the wetland surface will potentially be affected by RSLR. In a next section, the ecological impact will be detailed assessed for two representative areas.

Deltaic inundation due to the impact of coastal storms

Figure 7.9 shows the flood hazard area delineated for the impact of the target storm along the Northern part of the Ebro delta. This area is selected because is where rice pads are closest to the shoreline resulting in narrow beaches backed by the (rigid) contour of rice pads. As it can be seen, the inundated area is not continuous along the coast but it concentrates along the narrowest parts of the beach. In these areas, the impact of this storm led to significant beach and dune erosion resulting in massive local overwash events (Figure 7.2) driving floodwaters towards the hinterland. The shape of the hazard areas is controlled by the existing network of channels and dikes delimiting rice pads which will distribute the floodwater across the plain. Here we have not considered the possibility to close channels to avoid inundation which certainly may reduce its extension.

The estimated total extension of the flood hazard area is 252 ha from which a non negligible part will be inundated by a very small volume of floodwater resulting in a few cm water level. The inclusion of the beach evolution during the event resulted in a significant increase of overtopping rates with respect to the case of representing the coastal fringe by a static beach. Alvarado & Jiménez (2008) estimated an increase in overtopping rates up to 70% when compared to the ones calculated for the beach characterised by the minimum recorded elevation. This means that even when selecting the worst scenario for static-oriented (minimum elevation) flood hazard analysis in low-lying coasts, the volume of floodwater entering the coastal plain would be significantly underestimated.

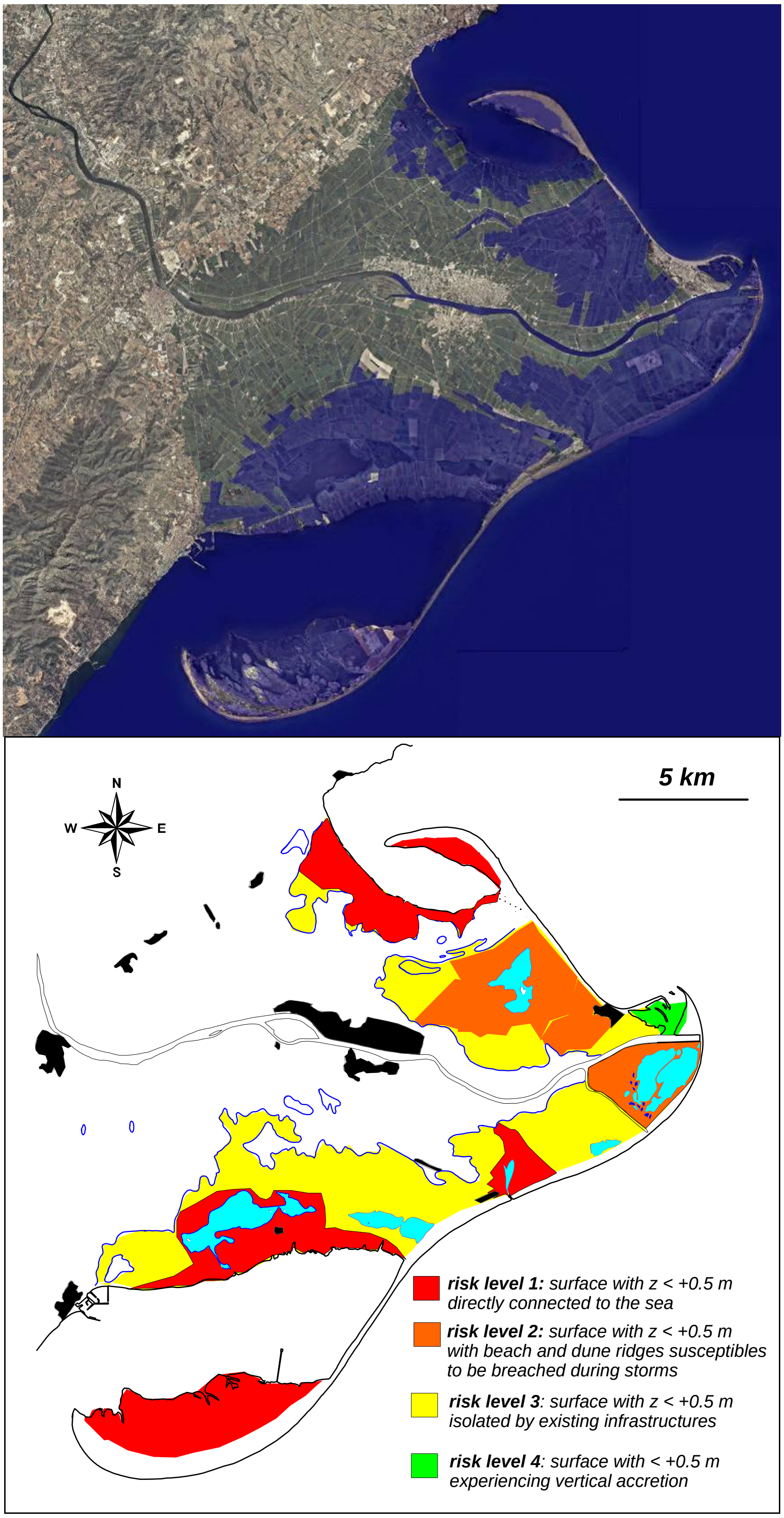

Figure 7.7 Top: Flood hazard map of the Ebro delta for a RSLR of +0.50 m (blue areas within the delta). Bottom: Classification of hazard areas in function of their connectivity.

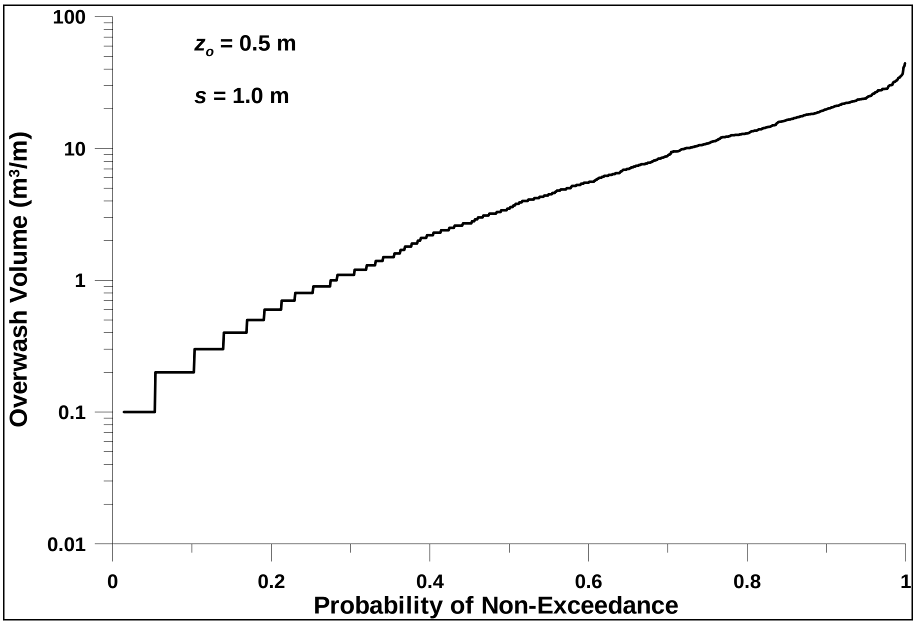

Figure 7.8 Empirical distribution function describing the probability of non-exceedance for a specific overwash volume during a storm event attacking La Marquesa beach.

Figure 7.9 Flood hazard map for 100 years return period storm in the northern part of the Ebro delta (blue areas within the delta).

As it can be seen in Figure 7.9, main value to be potentially affected by this temporary inundation is economic, since hazard areas consist of agriculture lands. In spite of this, it has to be considered that most of extreme storm impacts in the Ebro delta have been recorded in late autumn, later than the end of the collection of the crop. In consequence, the direct affectation of crops by floodwaters is not likely to occur. However, the impact of earlier extreme storms could affect the area during the last stages of crop collection (September) and, under those conditions the economic damage could be very high.

Ecological impact
Both two flooding scenarios were analyzed to assess the induced ecological impact in the identified hazard deltaic areas. This was done by using information extracted from existing maps of vegetation types in Illa de Buda and La Banya areas to derive a vegetation-elevation model which was used to predict spatial distribution of the vegetation under new (flooded) conditions.

Table 7.1 Qualitative changes in surface area of elevation height classes and corresponding Natura2000 habitat types (inclusive aquatic reed beds) as a result of 0.50 m SLR.

		zone	La Banya	Buda	Ebro Delta (national Park)
H1110	Sandbanks perm. covered by sea water	-0.2 – 0	--	+	0
H1140	Mudflats and sandflats intertidal	-0.2 – 0.2	--		-
H1150	Coastal lagoons	< -0.2	0	-	-
H1210	Annual vegetation drift lines	0 – 0.2	-		-
H1310	*Salicornia* and other annuals	0 – 0.2	--		--
H1320	*Spartina* swards	0.2 – 0.5	--	--	--
H1410	*Juncus maritimus* salt meadows	0.5 – 0.7	--	--	--
H1420	Halophilous scrub (Sarcocornetea)	0.2 – 0.5	--	--	--
H1510	Salt steppes (Limonietalia)	0.5 – 0.7	--	-	--
H2110	Embryonic shifting dunes	> 0.5	-	0	--
H2210	Crucianellion maritimae dunes	> 0.5	--		--
H2230	Malcolmietalia dune grasslands	> 0.7	--		--
H92D0	Riparian galleries and thickets	--			0
53.111	aquatic reed beds	-0.2 – 0.2		--	--

+ increase, 0 stable (± 10%), - decline (10-50%), -- strong decline (> 50%)

From the two analyzed scales, the long-term one RSLR will have the strongest impact on ecosystems in the Ebro Delta. A sea-level rise of 50 cm will lead to the "drowning" of most low-elevation habitats and a further salinisation of freshwater- and brackish habitats, resulting in a strong increase of unvegetated, shallowly flooded areas.

In addition, the increased frequency of flooding by the sea may also affect vegetation composition, especially if this results in increased salinity levels of the soil. Vegetation in coastal lagoons and freshwater inland wetlands will be primarily influenced by increased frequency of flooding by the sea (due to higher salinity levels, Valdemoro *et al.* 2007). Of the submerged lagoon vegetations, freshwater types may disappear and the brackish (*Ruppia*-dominated) vegetation type may expand in cover (Menendez *et al.*, 2002). Reedbeds may further decline when inundation with saltwater becomes more frequent. Increase in sea water level will probably not affect average water level in wetlands when there is active water management (pumping in and out of water). If not managed actively, water depth will increase at the expense of submerged and emergent vegetation density.

The changes in vegetation pattern due to sea-level rise imply severe habitat loss for many characteristic bird species of salt marshes and freshwater habitats, because many of these species are highly depend on habitat types at low elevations. Table 7.1 shows an example of estimated habitat changes due to sea level rise in the delta.

Temporary inundation due to the impact of storms will have a minor impact on deltaic ecosystems since coastal habitats are usually able to cope with these pulsing events. The only exception could be if the probability of occurrence of these flood events significantly increases in the near future in such a way that the volume of (sea) floodwater entering coastal lagoons significantly increase leading to a change in water salinity.

Flood risk perception

Figure 7.10 shows the flood risk perception of the different stakeholders in the Ebro delta. From the interviews one of the main differences detected between public and private stakeholders is their level of worry. In general, private stakeholders are generally more worried than public ones. From the interviews was concluded that lay people were unaware about what to do in case of a flooding. On the other hand, individuals of the authorities who were mostly involved in the development of land use plans were highly aware of the risk. To find an expression for the awareness of flood risk, the respondents were questioned about their current knowledge of the November 2001 flood event and to judge the current hazard of flooding for the coastal zone. Answers to both questions indicated no difference in comparison to the expert awareness of flooding. For preparedness, a similar approach was taken and, again, only public authorities declared to be prepared.

Figure 7.11 shows the average score of all stakeholders on risk characteristics in the Ebro delta. This served as an input into the MCA computations. Non-governmental stakeholders indicated a strong demand for risk reduction expressed in high levels of worry and awareness concerning the threat of flooding. This is reflected in the difference in the level of worry between the expert (CE) and the local policy maker (TC) (score 0.5 and 0.75, respectively) on the one hand, and lay people on the other one (score 1) (Figure 7.10).

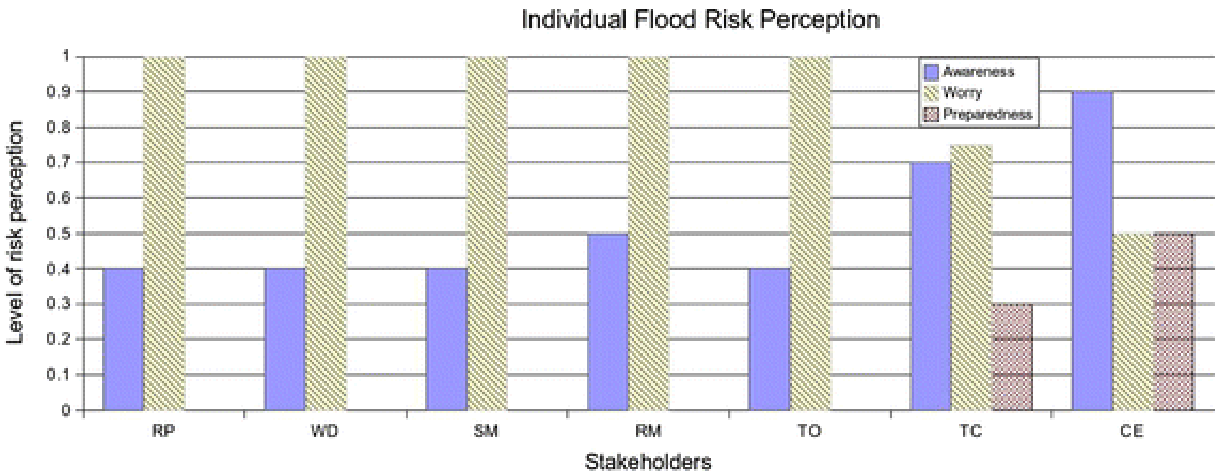

Figure 7.10 Individual scores on risk perception of stakeholders in the Ebro delta. Stakeholders corresponding to acronyms are described in the methodology section.

This methodology was apply to two land use scenarios for the Ebro Delta and compared with the base year. The two alternatives are the Business As Usual scenario and the Natural Development scenario. This last scenario is built by assuming that a strip of about 500 m wide along the coast is "re-naturalised" by abandoning the agriculture lands closest to the coastal fringe which are the presently affected by temporary floods. The combination of different methods of standardizing (maximum and interval) and weighting (risk perception and pairwise comparison) with ranking by weighted summation leads to the conclusion that the natural development scenario is the most favorable as sustainable flood risk management alternative (see Raaijmakers *et al.*, 2008).

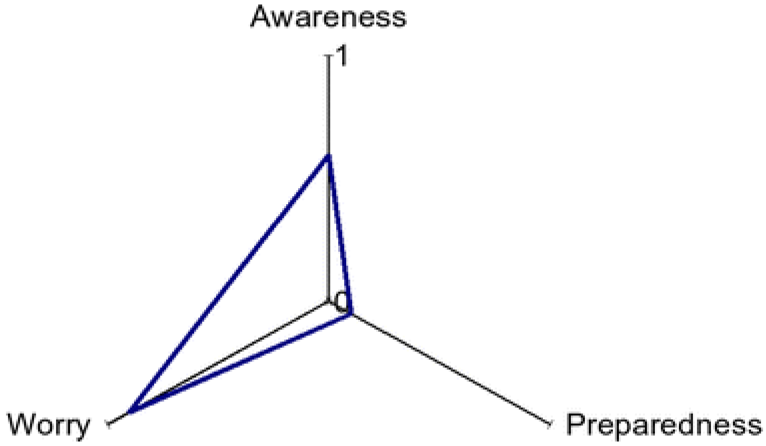

Figure 7.11 Average risk characteristics in the Ebro delta.

7.4 Contribution to flood risk management practice

The obtained results in the Ebro delta have a series of implications for the future management of the territory. The first implication is that short-term flood hazards are limited to some locations along the coast where narrow beaches are present due to the proximity of agriculture lands to the shoreline. Because these areas are also subjected to long-term erosion, it is expected that the frequency of events producing temporary floods will increase without considering any climate-induced change due to the decrease of beach widths. Their ecological impact can be considered as negligible since existing coastal ecosystems are able to withstand these pulsating events. However, if the frequency of these events significantly increases, freshwater and brackish wetlands could be affected by a salinity increase due to an increase in the volume of floodwater. In such a case, a habitat succession should be expected towards species more resistant/adapted to higher salinity values.

Main value to be affected by these episodic flood events is the agriculture. Thus, rice pads located in the areas closest to the coastal fringe in those zones subjected to overwash during extreme storms will be temporarily inundated. The time lag between the most probable occurrence of extreme storms and cultivation of rice pads makes the direct economic damages to crops to be relatively low. In spite of this, private stakeholders strongly demand for flood risk reduction which was detected in their high levels of worry and awareness concerning the threat of flooding.

Taking into account this perception and the relatively small spatial scale of the problem, an adaptation strategy to inundation is being considered by coastal managers. This consists of creating a 500 m wide buffer area shoreward of the actual beach along the Northern hemidelta to permit the inundation of the area during storms without affecting agriculture. This fringe will be bought to rice producers and incorporated to the public coastal domain. In addition to this, the innermost boundary of this fringe will be adapted to act as a barrier for inundation of the hinterland by constructing a dune and or bank. This strategy is also consistent with the expected impact of long-term flood scenario in the Ebro delta since the storm affected area will be also affected by RSLR. Thus, specific investments in harder measurements to prevent local floods under extreme events could become ineffective in the long-term.

In the long-term, flood hazards in the Ebro delta potentially affects to about the 40% of the deltaic surface. In this case, both natural an economic values should be affected. First estimations of the impact of inundation in the Ebro Delta due to RSLR predict "catastrophic effects" on coastal wetlands with about the 90% of their surface to be directly affected by a RSLR of +0.5 m. These catastrophic effects must be understood as a change or shift in the existing habitats along the Ebro delta coast that, consequently, will have to be managed in a different way. Parts of the delta where floodwater can be discharged actively may be protected from drowning as long as the incidence of floods (through levee breaching or overflow) remains within limits. However, the levees (sand ridges) along the delta are low, so that even a modest increase in sea level may lead to frequent overwash.

This flooding scenario is also indicating that to maintain the cultivation function in the Ebro delta in the long-term scale, it is necessary to have a proactive policy to compensate for the sea-level rise effects, or accept a move to polders. Otherwise this activity will eventually become economically unfeasible due to increased salt water intrusion, and sinking of much of the delta plain below sea level. In addition to this, and regarding the economic implications, it would be also necessary to consider, in a long-term analysis, the maintenance of subsidies which artificially keep the benefits of rice production at present levels. Also, the role of rice fields to supply food for bird living or hibernating in the delta has to be considered to analyse the full implications of this potential affectation.

7.5 Conclusions and outlook

At the core of this work lies the challenge of assessing flood risks at different scales in a low-lying coast of high natural values which also supports an intensive use by humans. The modification of the system characteristics due to this use is largely responsible of its very high vulnerability to flood hazards and its low resilience to cope with floods, especially in the long-term scale.

In spite of the fact that flood induced natural and economic damages can be calculated for different scenarios, one of the remaining problems to be solved is how to compare/integrate them in a “fair” manner. Although stakeholders’ perception can be used to determine weights for such integration and also to show preferences for a given management option, the included here can be biased due to the profile of selected stakeholders. This can be improved by carefully selecting (formal) representative stakeholders and/or launching an extensive questionnaire in the affected population. In addition to this, another option will be to valuing the ecosystem good and services provided by habitats to be affected by flood scenarios.

The analyzed Ebro Delta pilot site demonstrates that there is a difference between the demand for risk reduction on the one hand, and living with the risk while striving for benefits on the other. In a world with increasing flood risk decision makers have to cope with that paradox if they want to implement effective land use policy in flood prone areas.

Finally, to put the obtained results in the proper context, it has to be considered that some of the tools used in this assessment are being improved to more realistically deal with the analyzed problems. Thus, although morphodynamic changes and storm water levels have been coupled, some responses such as breaching are not sufficiently covered. Moreover, the influence of the morphodynamic response in the long-term scale is roughly considered. In addition to this, uncertainty in the morphodynamic response should be formalised in a similar manner to a fault tree for the beach and included in the analysis. The methodology developed to assess flood hazard taking into account the social perception has to be “refined”. Moreover, no data to build a damage curve due to inundation exist in the Ebro delta. It is necessary to derive such curve to make a meaningful damage analysis. This can be extended to other part of the analysis such as the ecological impact because some parameters involved in different parts of the methodology have been adjusted or selected by using a limited amount of information.

Acknowledgements
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8. Pilot site "German Bight coast"

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8.1 Flood risks and previous mitigation efforts

Along the German North Sea coast approximately 9,000 km² low-lying areas (< +5 m MSL) are at risk of being flooded by recurring storm surges. These storm surges are generated by winds coming from the west and northwest, causing a water level much higher (up to 4.10 m) than mean high tide. Furthermore, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change made evident that an ongoing global climate change will cause increased storminess and sea level rise (Meehl *et al.*, 2007). There is little doubt that the North Sea will be affected by an accelerating rise of the sea-level, an increase in extreme weather events and a greater tidal range as well, which could cause an increase in storm-surge frequency and severity. For the German Bight the current assumption is that mean high tide levels might rise by 0.65 cm/y during the 21st century (Sterr, 2008). In order to be prepared for future conditions, measures have to be improved and methodologies to be further developed to assess and manage upcoming risks.

As coastal areas have been at risk ever since, coastal defence has a long history in the German North Sea region. When two great storm floods in 1362 and 1634 caused up to 100,000 deaths and led to significant changes of the coastline, people have started to protect themselves from flooding, storm surges, and land loss. The building of dikes and land reclamation during the last centuries led to a division of the North Sea coastline into flood units, so-called "Koege". This typical marshland of the North Sea coast arises through deposition of marine sediments. Thus, except for the glacial "Geest", a great part of the region lies only a few meters above or even under mean high tide level.

Today coastal defence at the German North Sea coast aims at protecting the land from present and future flooding, erosion, and land loss. Most parts of the coast are protected by dikes and various structural defence measures. In the German Federal Land Schleswig-Holstein the primary and main dikes are built and maintained by the Coastal Division of the State Ministry, while secondary dikes are in the responsibility of the Waterboards. The State Water Act of Schleswig-Holstein is the legal document prescribing the duty to design the state dikes to withstand all storm floods. The main dikes are designed deterministically by superposition of tidal water level, storm surge, wave run-up and a safety level.

Schleswig-Holstein follows the concept of integrated coastal defence management, a continuous and dynamic planning process, where coastal defence is implemented as a spatial planning task. Risk management is becoming an increasingly important part in coastal defence planning and thus the knowledge of risk and its spatial distribution is needed. This need has fostered research on risk analysis and risk management issues as described in Section 8.2. To support coastal defence planning and risk management efforts at the German North Sea coast a pilot study was conducted for the community of St. Peter-Ording (FLOODsite, Task 27), named as pilot site "German Bight coast" hereafter.

St. Peter-Ording is one of the largest communities at the German North Sea coast with 7,278 inhabitants, whereof 4,022 are permanent residents; the others have a temporary home or summer residence. The local economy relies heavily on tourism with over 100,000 guests each year. Furthermore, the municipality has an important regional and national function as health centre with various hospitals and other health facilities. The community is very exposed to the North Sea on the west coast of Eiderstedt peninsula (Figure 8.1).

The coastal landscape of this area is dominated by dunes, which at least in the north of the town are high enough to serve as a natural coastal protection structure. The size of the study area is approximately 6,000 ha of which about 4,000 ha are considered to be flood-prone due to the respective elevation distribution. Hence, a flooding of the municipality could spread far into the hinterland of Schleswig-Holstein.

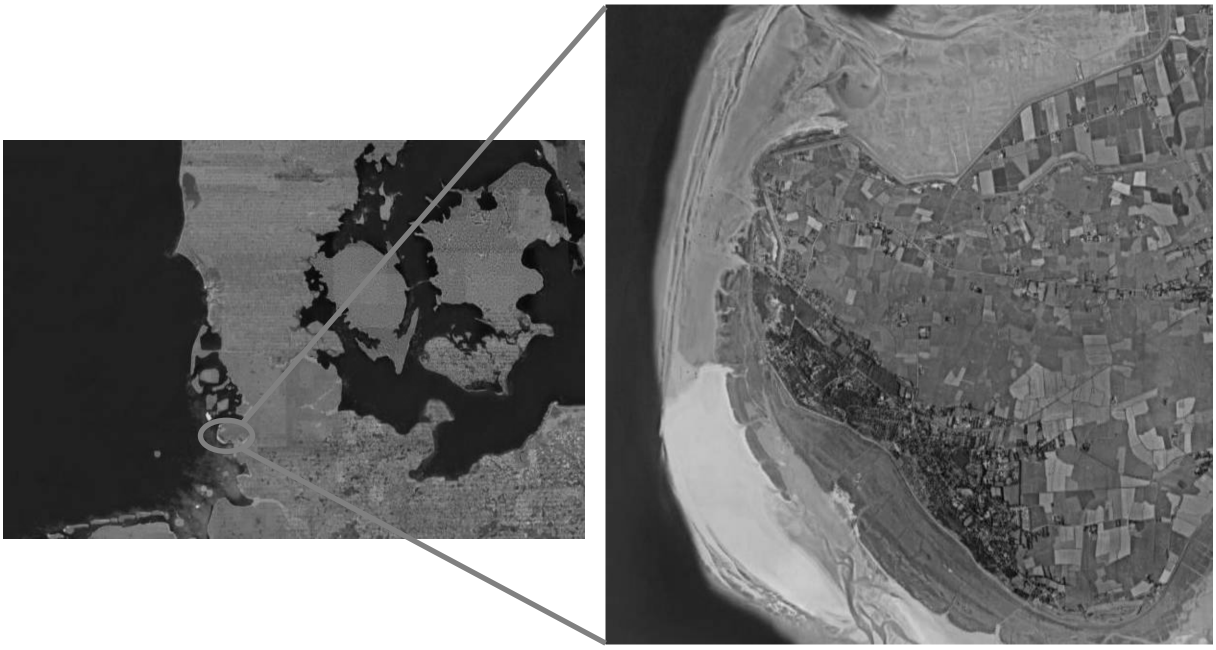


Figure 8.1 Location of the pilot site German Bight coast (left) and the community of St. Peter-Ording (right) (Google Earth, 21.09.2008)

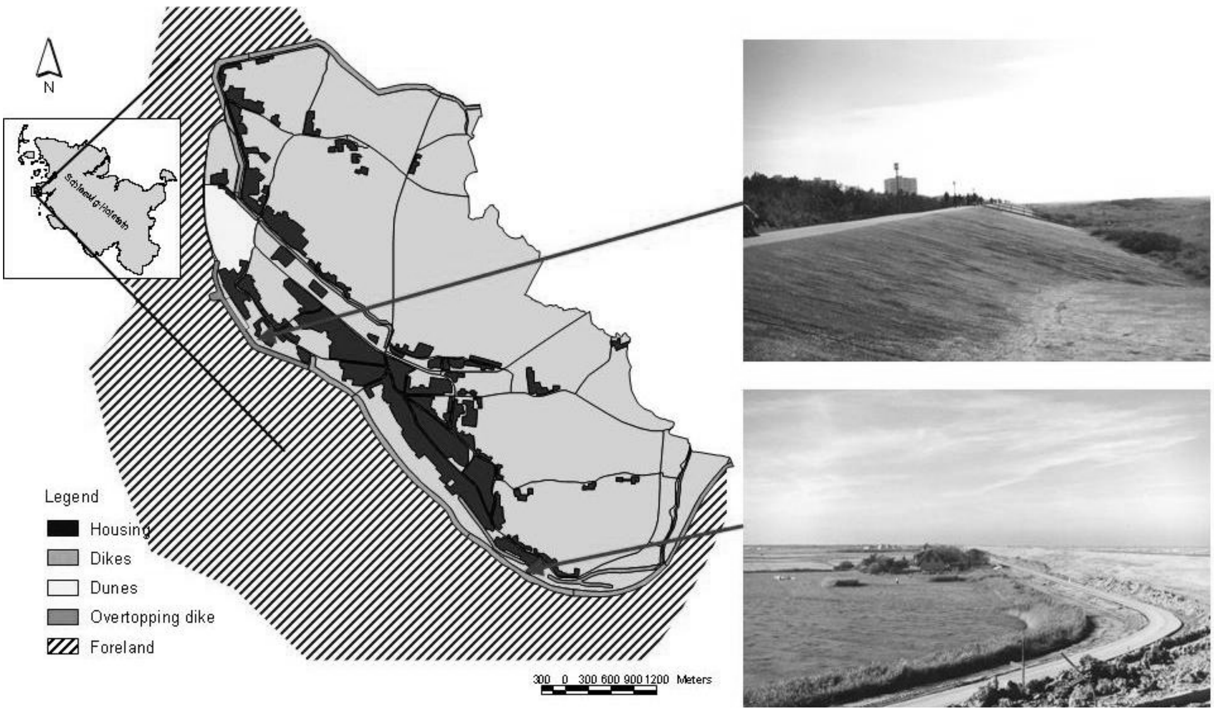


Figure 8.2 Coastal defence structures at pilot site German Bight coast

Strong storm surges, which may occur several times a year, pose a serious threat to the community. Severe storm surges have occurred in 1962 (water level in Husum: NN+5.21 m) and 1976 (water level in Husum NN+5.61 m). The former caused heavy damage in the German North Sea region while during the latter the highest storm surge water levels ever were recorded with a water level up to 4.8 m above mean sea level. In reaction to the 1962 flood, the protective measures were increased along the North Sea coast and the dikes were significantly heightened in St. Peter-Ording, resulting in only minor damage in 1976. Three other storm surges in 1962, 1981, and 1999 did pass the 4.0 m mark proving that a general increase of storm surge frequency and severity over the last decades has happened.

The community is protected against storm floods by a complex coastal defence system (Figure 8.2). It is divided into a foreland, dune structures (>2.5 km length, between ~10 and 18 m high), a major dike line and a second dike line. The major dike line is 12.5 km long and about 8.0 m high, although not constant over its entire length. Furthermore, there is a 2 km long so called overtopping dike. This type of dike is designed to withstand wave overtopping and wave overflow. It is therefore considerably lower than standard dikes and is protected by a very solid asphalt cover layer. Without coastal management and defence measures, the people of St. Peter-Ording would be exposed to an intolerable level of risk. To maintain present safety standards despite increasing natural and socio-economic pressures, long-term investments are mandatory to be prepared for future climate conditions.

8.2 Objectives and approach

A significant amount of investigations on coastal vulnerability and risk has been carried out for the German coasts in the last decade. These investigations focussed either on macro-, meso- or micro-scale (Table 8.1) in order to analyse the vulnerability of the region towards climate change and to build a basis for adequate coastal defence planning.

The Common Methodology, a macro-scale procedure to determine the vulnerability of coastal zones due to sea-level rise was adopted for the German coastal zone, focussing on the appraisal of socio-economic impacts of climate change to coastal regions (Sterr, 2008). To assess the socio-economic consequences on a regional level a meso-scale valuation method was applied by Hamann & Klug (1998, Valuation Study S-H) for the Schleswig-Holstein region. They estimated the socio-economic damage potential on the basis of official statistics and indicators. It turned out that the macro- and meso-scale approaches were not able to deliver data detailed enough for risk management. Finally, a micro-scale assessment was conducted by Reese *et al.* (2001; MERK study) estimating damages on an object-based level for six communities in Schleswig-Holstein (including St. Peter-Ording).

Table 8.1 Vulnerability assessment studies at the German North Sea coast

Assessment level	Macro-scale	Meso-scale	Micro-scale
Regarding level	(Inter)-national	Regional	Local
Decision level	(Inter)-national policy	Flood defence schemes	Defence measures
Investigation level	German Coast	Coast of S-H	Selected areas
Case studies	IPCC	Valuation study S-H	MERK, FLOOD*site*

In addition to the mentioned German macro-scale coastal vulnerability analyses mentioned above, different interdisciplinary interconnected projects were carried out in the framework of the research programme “Climate Change & Coast”. To cite just two examples, the project network “KLIMU (Klimaänderung und Unterweserregion; cp. Elsner & Knogge, 2001) and the case study „Island of Sylt“ (Daschkeit & Schottes, 2002; Hartje *et al.*, 2002) were engaged with the vulnerability of coastal areas. While in the „KLIMU-project“ the socio-economic impacts in the event of a dike breaching on a meso-scale were determined, the “Sylt study “ chose a micro-scale approach to estimate the possible consequences of climate change.

In comparison, these studies have shown that results based on macro- and meso-scale levels are in some respects inaccurate. With the increasing size of the investigation areas, the expenditure and accordingly the precision of the vulnerability assessment decreases, since methods on the meso- and macro-scale are generally based on aggregated data. However with regard to specific coastal defence measures and risk management, detailed and small-scale information is inevitable in order to enable the detailed calculation of vulnerability respectively the probability of harmful consequences due to a storm surge occurrence (Figure 8.3).

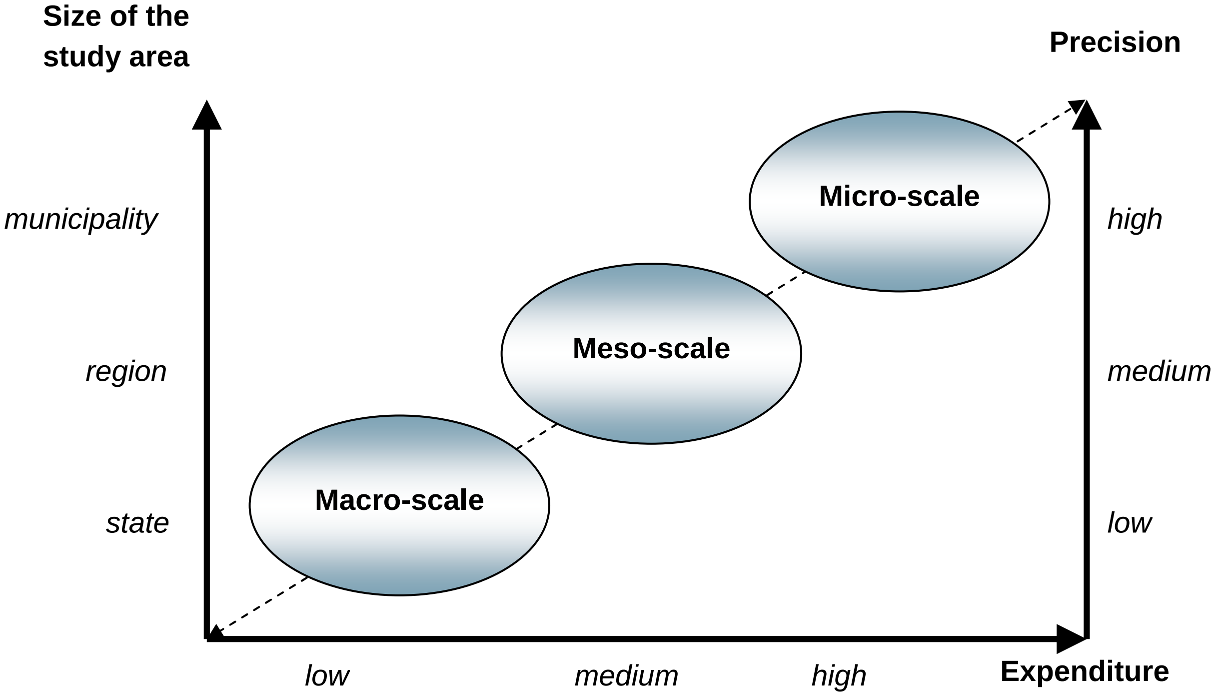


Figure 8.3 The spatial dimension of vulnerability assessments (Reese, 2003)

Micro-scale methods can achieve this high level of precision, as it is possible to identify the actual existing conditions in the areas at risk on an object orientated level. As the effort and the dependency on data quality and availability of detailed vulnerability assessment studies is problematic, new concepts and methods have to be developed to simplify and standardise methods for vulnerability assessment and make them more transferable and applicable in practice.

Furthermore, the link to probabilistic hazard assessment in the existing risk analysis studies was either based on assumptions or on deterministic estimations without quantifying the probability.

Thus the overall aim of the pilot study German Bight coast was to develop a micro-scale risk analysis methodology by combining a probabilistic hazard analysis with a micro-scale vulnerability assessment in order to elaborate key parameters of flood risk and to gain quantitative, spatial information about the flood risk on a local level. Hereby methodologies developed in FLOODsite were tested and applied for a coastal site.

The general methodology in this study is depicted in Figure 8.4, where risk is defined as probability of (negative) consequences (Gouldby *et al.*, 2009; see Chapter 1). This definition includes first the probability of flooding of the flood prone area, determined by the sources and pathways with the probability of coastal defence failure. Secondly, it comprises all kinds of receptors and consequences of flooding depending on the vulnerability of the flood prone area.

A full probabilistic approach in determining the flooding of the hinterland together with a micro-scale vulnerability analysis is assumed to be the most efficient way to quantify the magnitude of the flood risk and hence form a sound basis for any risk management activities performed in the area.

Thus the key elements of the analysis are a probabilistic hazard analysis, the determination of flooding scenarios based on the hazard analysis and a micro-scale vulnerability analysis. The vulnerability analysis follows an integrated approach and comprises economic, social and ecological vulnerability criteria. It is divided into damage potential analyses for St. Peter-Ording carried out with a standardised methodology and damage estimations for different flooding scenarios.

Finally, the methodology includes a GIS-based approach merging the various levels of the economic, social, and ecological vulnerability with scenario-based probabilities of flooding on a micro-scale level using a multi-criteria risk assessment approach. This was then planned to be used to map different zones of flood risks in the area.

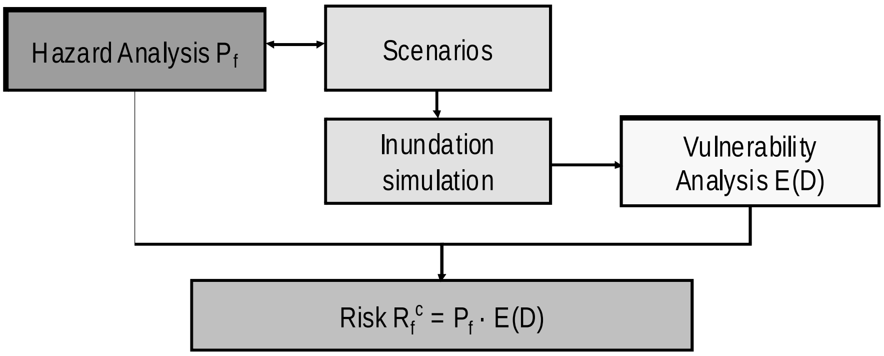


Figure 8.4 Methodological approach of the pilot site German Bight coast

8.3 Major findings

In this section the outcomes of the probabilistic micro-scale risk analysis for the community of St. Peter-Ording are subdivided into a scenario-based hazard analysis, a vulnerability analysis and an estimation and mapping of risk.

8.3.1 Hazard analysis

The hazard analysis describes the approach to derive the overall probability of failure for all flood defences in the area. This comprises

- a description of the flood prone area and the flood defence structures,
- the methodology to obtain geometrical parameters from laser scan measurements of the defence line,
- the development of an algorithm how the defence line can be split into different sections which can be treated independently,
- and the calculation of the failure probability for each section of the flood defence line.

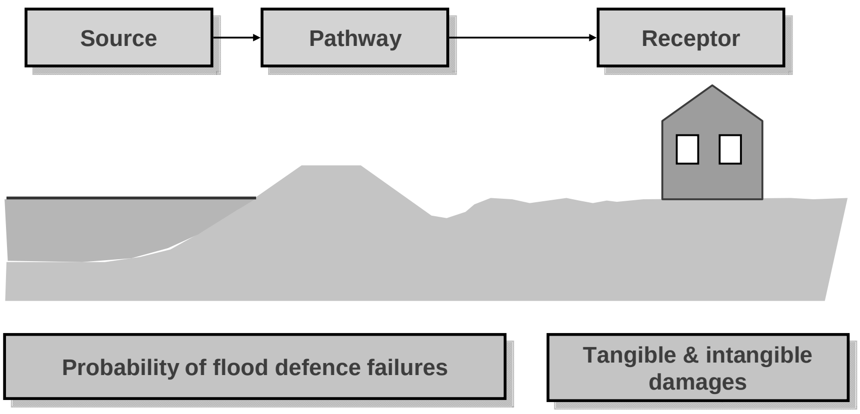


Figure 8.5 Source-Pathway-Receptor concept applied to the pilot site German Bight coast

The methodology applied here is following the source-pathway-receptor model used in FLOODsite and shown in Figure 5. The result of assessing the risk sources and the risk pathways is the probability of the flood defence failure, as highlighted in this figure.

Risk sources at the German Bight coast are resulting from storm surges in the North Sea associated with high water levels and storm waves at the flood defences. Typically, storm surges last no longer than 12 to 24 hours but may increase the water level considerably (up to 3.5 m in the North Sea). The interaction of normal tides (water level differences in the range of 1-2 m are normal in the North Sea region), storm surges, and waves is crucial for the determination of the water level at the coast. In addition, the foreshore topography plays a major role when determining the waves at the flood defence structure. In case of the German Bight coast the limited water depths over a high foreland will cause the waves to break and will therefore limit the maximum wave heights which reach the flood defence structures. However, the probabilistic hazard analysis has only considered single probability distributions for each of the governing variables such as water level, wave height and wave period. No joint or conditional probability density functions were considered.

As for risk pathways in the German Bight coast pilot site, flood defences comprise more than 12 km of dikes (grass and asphalt dike) and a dune area of about 2.5 km length. The probabilistic hazard analysis has however focussed on the dikes as the key flood defence structure since the dune belt is extraordinary high and wide and is regarded as significantly safer than the dike protection.

Table 8.2 gives an overview of coastal defence structures used in St. Peter-Ording. The various sections are defined by their number and a corresponding name. Additionally, the start and the end of the section, the resulting length of the section and its mean height is given.

Table 8.2 Coastal protection at the pilot site German Bight coast (taken from MLR, 2001)

Section No.	Name	Start (km)	End (km)	Length (km)	Crest height 2000 (NN+ m)
36.01	Ording Nord (to Nackhörn)	127.603	130.440	2.837	8.6
36.02	Ording Süd (to St. Peter)	130.440	132.352	1.912	8.0
37.01	St. Peter Nord (Dune)	132.352	133.195	0.843	max. 16.0
37.02	St. Peter Süd (Overtopping dike)	133.195	135.156	1.961	6.5
38.01	Boehl Nord (Asphalt dike)	135.156	138.176	3.020	7.5
38.02	Boehl Mitte (to Süderhöft)	138.176	139.771	1.595	7.6
38.03	Boehl Süd (to Ehstenkoog)	139.771	141.070	1.299	8.3
39.00	Ehstenkoog	141.070	142.605	1.535	7.8

Before starting the probabilistic analysis the dike geometry and laser scan data have been used to determine the exact height of the flood defence line in more detail (Figure 8.6) and to define different 'homogeneous' sections of the flood defences. Criteria for distinction of homogeneous sections were the type of flood defence, its height, its orientation, the key sea state parameters like water level, wave height, and wave period, respectively, and geotechnical parameters. Different from sections in Table 8.2, thirteen sections have been identified (Figure 8.7) using these criteria (cp. Kortenhaus & Lambrecht, 2006). Each of these sections is assumed to be identical over its entire length and hence will result in the same probability of failure.

The main geometrical parameters derived from the laser scans for the defined sections are shown in Table 8.3. For the section with dunes (Section 7) only average values are given here due to their geometrical complexity.

Potential failure modes of a standard sea dike in Germany have been described by Kortenhaus (2003). In this study, 25 failure modes for a sea dike have been described and limit state functions have been derived for all of them. Figure 8.8 provides an overview of these failure modes and where they occur.

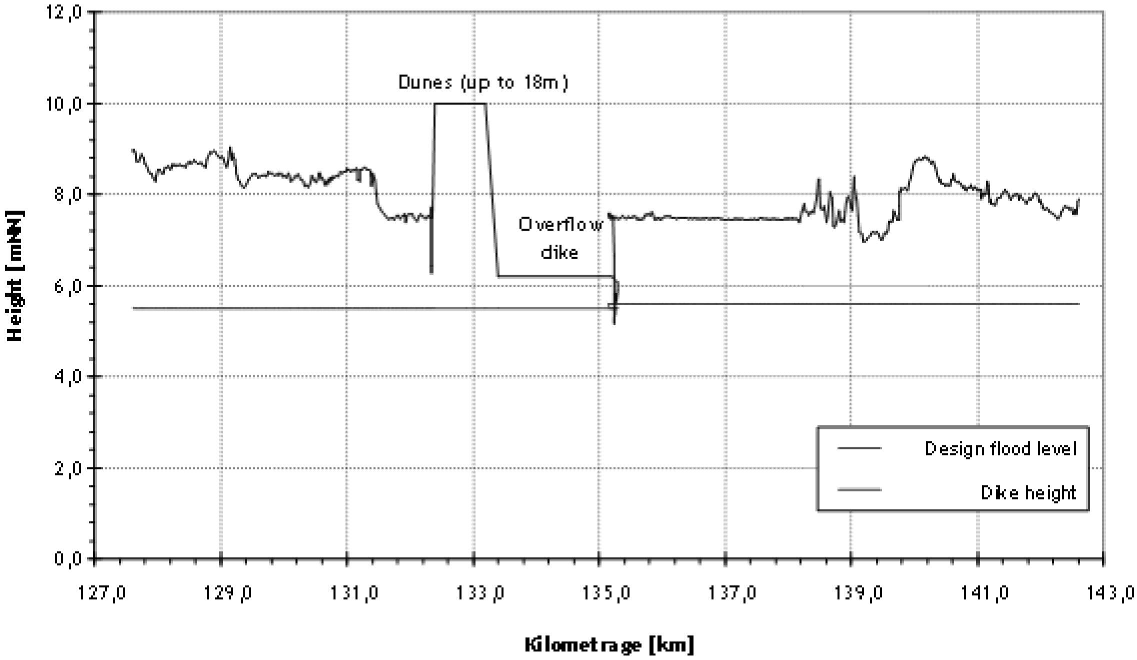


Figure 8.6 Height of costal defence structures at pilot site German Bight coast

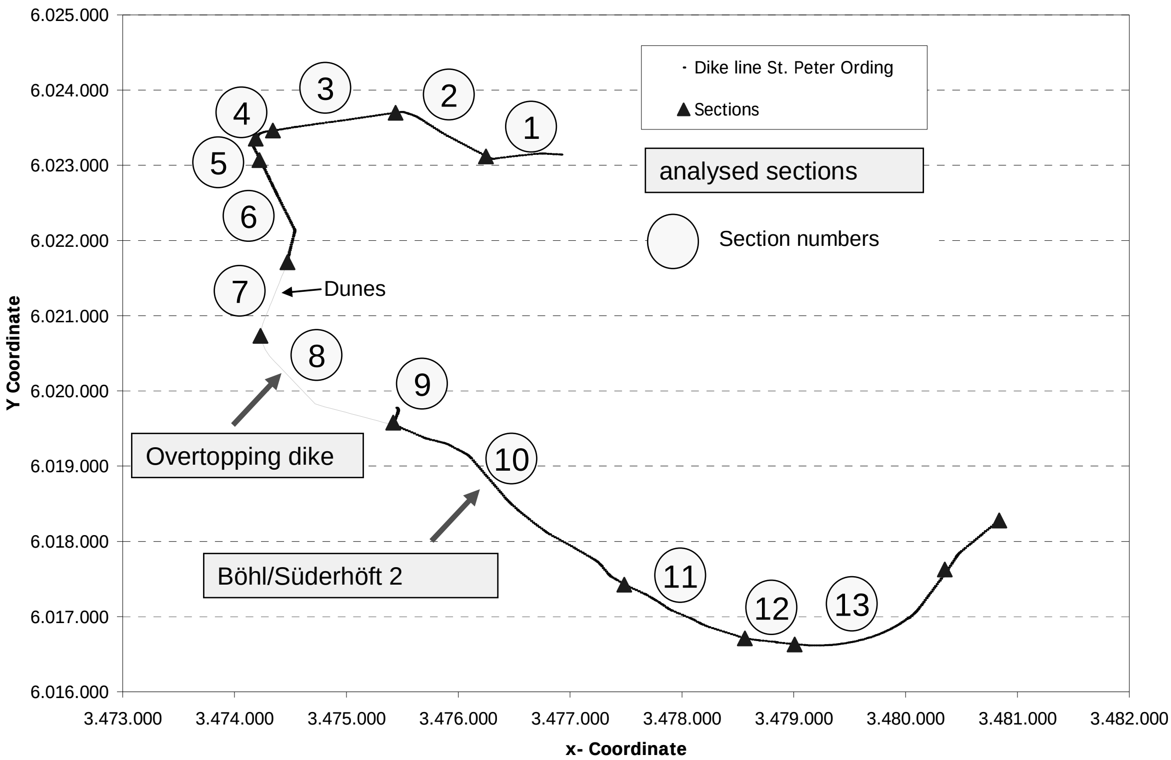


Figure 8.7 Defined sections for the coastal protection system at the pilot site German Bight coast

The hazard analysis has used a full probabilistic approach starting from the input parameters at the toe of the dike and applying early versions of these failure modes and fault trees which have been developed under FLOODsite, Task 4 and Task 7, for the specific type of flood defences. Time dependencies of limit state equations have been considered. Figure 8.9 shows a simplified version of the fault tree used for one of the sections at the pilot site German Bight coast for a typical sea dike. Most of the required input parameters for the failure modes are of stochastic nature, which means that not only mean or design parameters but also a statistical distribution of this parameter describing the uncertainty is provided. The result of this analysis is an annual probability of flooding of the hinterland for each dike section which has been selected. These flooding probabilities were typically found to range from a probability of 10-4 to 10-6 which means a return period of flooding in the range of 10,000 or 1,000,000 years. The overall flooding probability using a fault tree approach for all sections resulted in Pf = 4·10-3.

Table 8.3 Main geometrical parameters for the defined sections (Figure 8.7)

Section	Height of crest h_k [m NN]	Width of crest B_k [m]	Outer slope m [-]	Inner slope n [-]
1	8.28	1.00	3.00	6.00
2	8.35	1.50	3.00	6.40
3	8.19	1.50	3.00	6.50
4	8.43	0.90	2.80	4.50
5	8.30	0.00	3.20	4.30
6	7.00	1.50	3.00	4.10
7	15.00	2.20	10.00	4.00
8	6.22	1.70	3.00	4.00
9	5.99	2.00	7.00	4.00
10	7.18	2.20	4.50	5.50
11	6.98	3.50	4.80	8.00
12	7.05	1.80	4.50	7.00
13	8.00	1.00	2.90	5.20

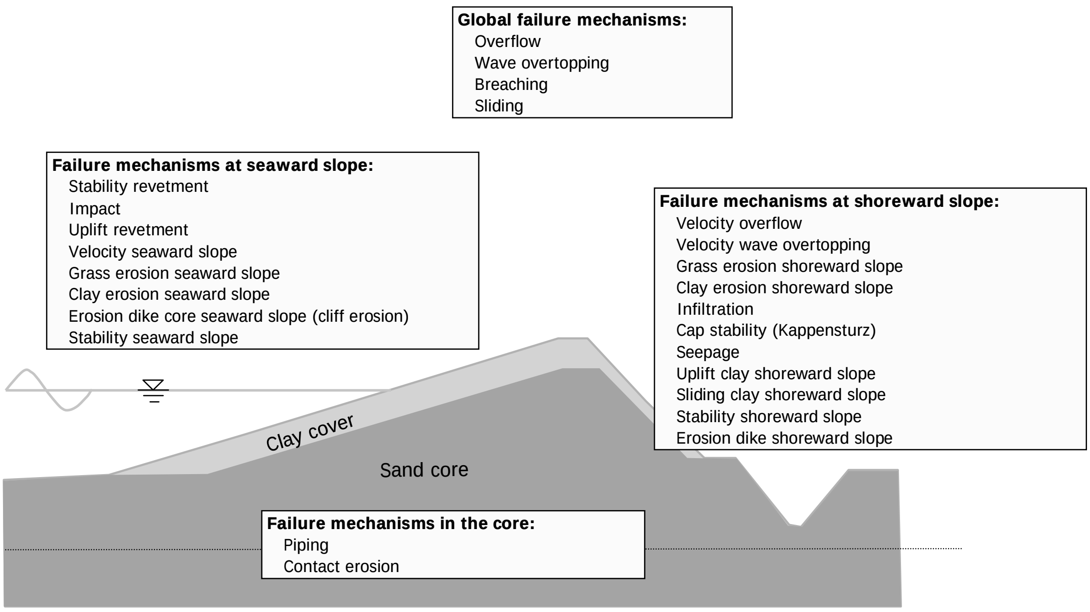


Figure 8.8 Key failure modes for sea dikes (Kortenhaus, 2003)

Overall, the results of all 13 sections in the pilot site German Bight coast have shown probabilities which were found reasonably low and comparable to earlier studies of similar flood defences, although those have been based on different fault trees and failure modes (cp. e.g. De Ronde & De Leeuw, 2001; Van Noortwijk *et al.,* 1999; Hussaarts *et al.*, 1999).

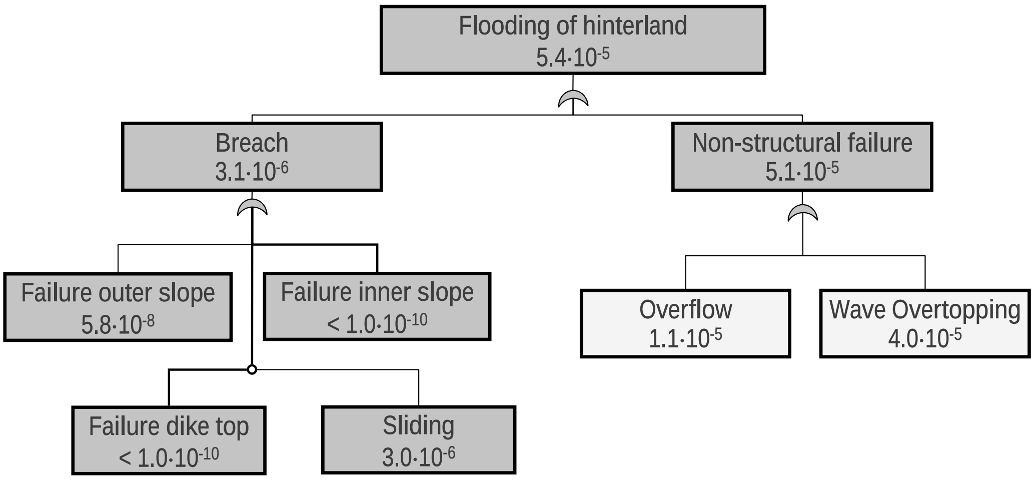


Figure 8.9 Typical simplified fault tree for dike section 2 at the pilot site German Bight coast

Key parameters steering those results were found to be the water level in front of the dike, the dike height, and the wave parameters (wave height and wave period, respectively). It should be noted again that no joint probabilities of input parameters have been used in this study, nor have been interactions of failure modes within the fault tree been considered. Time aspects for time-relevant failure modes have been considered though, although further improvements will be achieved if the deterioration would be considered as well.

When individual failure modes are considered in more detail, the velocity of uprushing water on the outer slope seems to have a rather high failure probability indicating that these velocities might get critical with respect to the erosion of the grass on the outward slope. Generally, wave overtopping and overflow may be considered crucial for the pilot site German Bight coast. This is due to too low sea dikes on the one hand, which allows for considerable wave overtopping even when the water level is not exceedingly high. On the other hand, many sections of the sea dikes are covered by asphalt so that many failure mechanisms cannot be considered relevant. This eases the calculations but also gives high relevance for the remaining failure mechanisms such as wave overtopping and overflow. It should be noted that probabilistic hazard analyses generally allow quantifying the importance of individual failure modes and individual input parameters but still this is very site and case specific so that results for one range of flood defences cannot easily be transferred to other areas with other sea dikes.

In bringing these results together to achieve an overall flooding probability of the area, a simple fault tree approach has been used. This assumes independent individual flooding probabilities for each section, which is known to be a first assumption only. It will be required to consider length effects between the various sections and to account for existing correlations of the sections which are present due to the same waves in front of the defence line only. Hence, the resulting flooding probability has to be considered slightly conservative.

The following lessons have been learned from performing the hazard analysis for the German Bight coast pilot site:

- The given results should only be used carefully since results depend on variations of parameter settings.
- A limit state equation for dunes is still missing and needs to be implemented.
- The wide foreland at the case study area will induce heavy wave breaking under design conditions (and also for lower water levels of course). Results might therefore be dependent on

morphodynamic processes and changes of these forelands. Breaker criteria should always be used when waves approaching the structure.
- A wide range of input parameters is not directly available and had to be estimated. Therefore, sensitivity analyses of the influences of parameters are needed to estimate the variability of the flooding probabilities for the 13 sections.
- Criteria for splitting the defence line into various sections need to be automatically derived in the model. Up to now, this is done semi-automatically (with some manual checks of the section at the end). Any change in key parameters of a dike section is therefore not directly leading to a re-calculation of the distinction of all the sections.
- Distinction between different sections was based on the assumption that the sections can be treated independently when calculating the overall failure probability of the system. This still needs verification or improved methods considering the length effect between sections.
- Dependencies between failure mechanisms or scenarios have not been considered yet. A first simple step to consider dependencies might be sensitivity calculations for different degrees of dependencies resulting in a range of possible failure probabilities. However, since the overall failure probability seems mostly dependent on section 8 (overtopping dike) the inclusion of dependencies at this stage will not influence the result significantly.

8.3.2 Flood scenarios and inundation simulation

The calculated flooding probabilities were used to derive flooding scenarios which up to now have been based on experience and expert knowledge. The section with the highest probability of failure for breaching of the dike was taken as the section where a breach location was assumed. Still, this assumption has to be discussed, the exact location of the dike breach has to be determined, and a probability of failure needs to be assigned to this scenario of dike breach.

Preliminary versions of breach models developed under FLOODsite (Task 6) were used to calculate the breach dimensions resulting from an analysis of the breach development and the final breach width. These parameters were then used to feed into the flood inundation model. Details of this procedure will be discussed in the following.

The previously described hazard analysis of the flood defences has led to an assumption of dike breaching at a specific location in the south of the area. The detailed location of the breach was defined after visual inspection of the relevant section and consultation with the local authorities. Additional analysis of other sections of the flood defence line has shown that the lowest part of the dikes (Figure 8.10) is overtopped for already relatively low storm surge water levels. Hence, a first flooding scenario was assumed which includes a water level of 5.30 mNN (design water level for this area), a breach location in the south of the area as described above and initiated by wave overtopping, and wave overtopping at a low asphalt dike near the village of Ording (Figure 8.10). This scenario was used as the standard flooding scenario for estimating the damages, too (see Section 8.3.3).

The probability of this flooding scenario is different from what was determined in Section 3.1 since the water level for any flood inundation simulation is fixed. Hence, the peak water level has to be taken as deterministic in the probabilistic calculations and the flooding probability has to be re-calculated based on this assumption. Furthermore, the occurrence probability of the water level d = 5.30 mNN has to be determined. These calculations led to a flooding probability of = 9.6·10-8 which is different from the results obtained by the hazard analysis due to the assumption of a fixed water level.

The numerical non-linear shallow water (NLSW) model SOBEK was used to perform the flood inundation simulation. SOBEK is one of the models used and evaluated in FLOODsite, Task 8. It is a user-friendly model, which was developed for river flooding and hence typical input for the model is a water level (but no waves) and breach location and growth developed for breaching of river embankments. Wave overtopping is not part of the model. The input for the model was therefore tentatively adapted from coastal characteristics to the equivalent river characteristics so that it could be used with SOBEK.

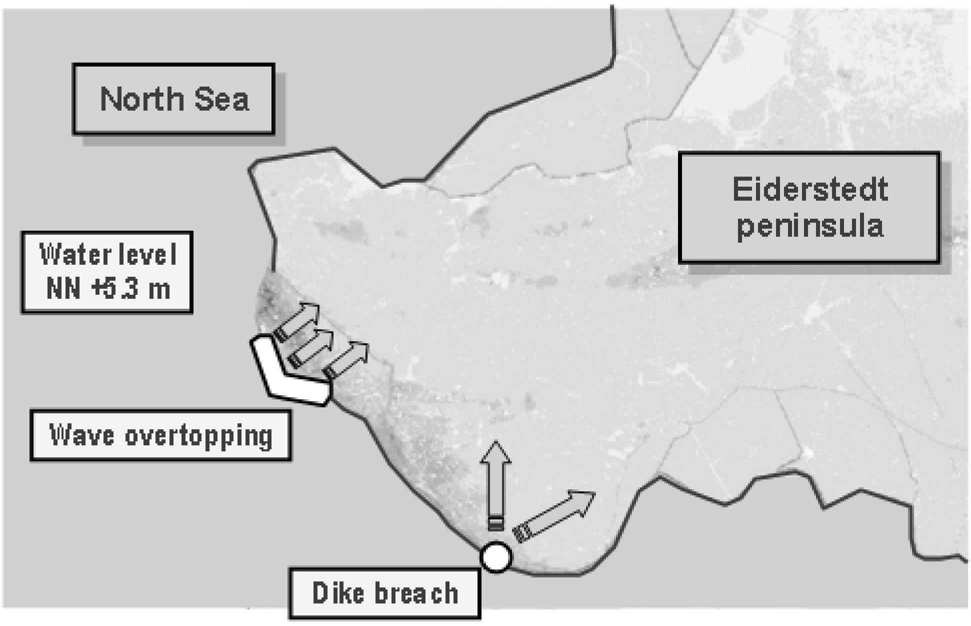


Figure 8.10 Flood inundation scenario for the German Bight Coast comprising wave overtopping over the lowest dike section in the West and a dike breach in the South

Ditches and channels were simulated using the 1D flow module of SOBEK and were found to be relevant for distributing the flood wave into the area. Boundary conditions were the time series of the storm surge water level on the one hand and the mean overtopping rates over the lowest part of the defence line on the other hand (Figure 8.10).

In Figure 8.11, the flood inundation is shown for a storm surge (peak) level of 5.30 m, wave overtopping of the sea dike in the western part of the Eiderstedt peninsula and a dike breach in the south (standard scenario). The inundated area resulting from these conditions is indicated in blue after one tide. It can be seen that there is a lot of water flowing into the area directly behind the overtopped dike and into a basin in front of the second dike line. The second dike line seems to stop the water from flowing any further but on the other hand will contribute to larger inundation depths in front of this dike. The dike breach results in a larger area to be flooded but the inundation depths are not as large as those resulting from the overtopping dike.

Figure 8.11 also shows two additional lines indicating the minimum and maximum range of inundation. These lines were achieved when identical simulations regarding the boundary conditions were run but roughness parameters (Manning's n) for the area and breach width were modified as follows:

- min. range: n = 0.060; breach width = 50 m
- max. range: n = 0.015; breach width = 200 m

Manning's roughness parameter is used to describe the overall 'roughness' of the inundated area. With this parameter, the roughness within one grid cell (12.5 x 12.5 m in this case) has to be described by a single parameter. Very few information is available on how these parameters have to be chosen so that sensitivity analyses were performed to determine its influence (see above).

Further parameters, which were varied throughout this study, are the peak sea water level and the breach characteristics (breach location, final breach width, and breach development).

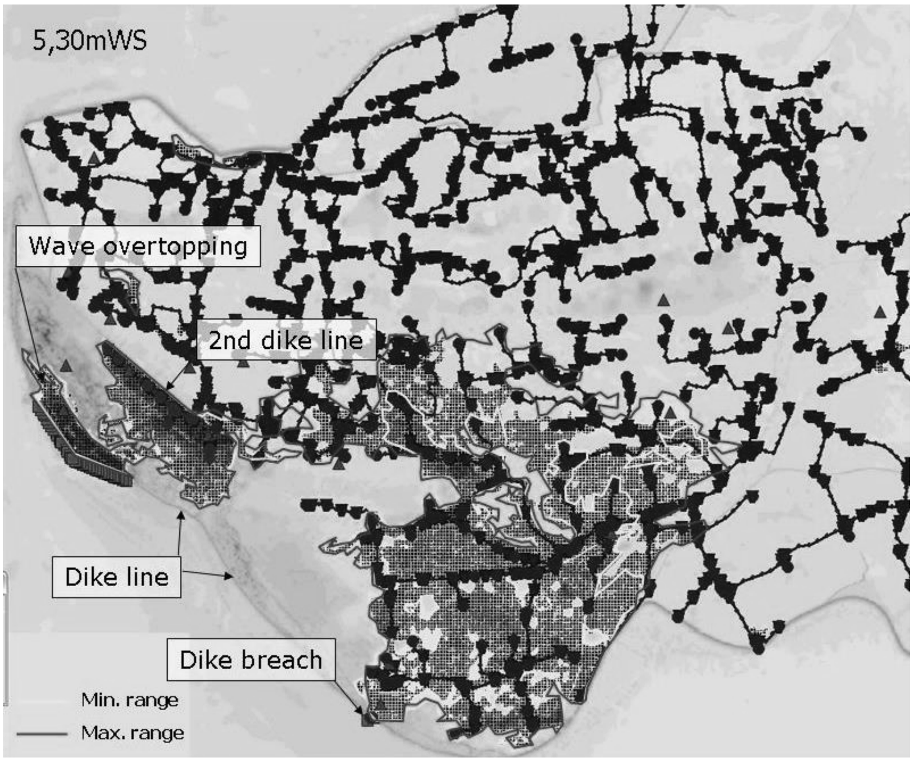


Figure 8.11 Simulated flooding for a flood inundation scenario as described in Figure 8.8

It could be seen that these variations have led to different outlines of the flooded area for different peak water levels. However, variations are not significant when the flooded area after one tide is compared. It has to be noted however, that the velocity of the water is much higher for the case with a lower roughness parameter so that the flood wave progresses much faster than in the case with higher roughnesses. Furthermore, these results are rather site-specific and cannot be transferred directly to any other site.

8.3.3 Vulnerability analysis

To quantify flood risk, the estimation of the expected damage and its spatial distribution is crucial besides the hazard analysis. The total flood damage of a specific flood event depends on the vulnerability of the socio-economic and the ecological system. Hence, a detailed vulnerability analysis was conducted for St. Peter-Ording focussing on two major deficits of former vulnerability assessment studies:

1. There is still a deficit of integrated, quantitative assessment methods that consider the full range of impacts from coastal flooding. Thus, up to now, vulnerability assessments at the German North Sea coast were designed according to economic criteria, which can be described in monetary terms, whereas intangible values, social characteristics and ecological values have been widely neglected. However, flood risk is determined by more than economic losses, rather it comprehends all kinds of consequences of flooding. Non-monetary risk categories, such as social structures or environmental characteristics can substantially influence vulnerability. Thus it is one of the great challenges for present and future vulnerability assessment to effectively integrate economic, social and ecological vulnerability factors and to merge and structure them so that they are not fragmented and incomprehensible when transferred into practice.
2. The scale of vulnerability assessments is substantial as it is directly linked to the application of the results in practice. At the pilot site German Bight coast former vulnerability assessment studies on macro-, meso- and micro-scale made evident that with regard to risk management, detailed and small-scale information is inevitable as only in that way it is possible to identify the actual existing conditions in the areas at risk on an object orientated level. This approach, however, is costly in

terms of time and money. Thus, a simplification of micro-scale approaches towards a quick economic feasible instrument is necessary.

The methodological framework presented in this chapter tries to provide solutions for these two problems.

Multi-criteria vulnerability assessment
To address the first issue, a quantitative approach was chosen to investigate the spatial distribution of economic, social, and ecological vulnerability at the pilot site.

Numerous vulnerability criteria or indicators exist in disaster, climate change or global change research (i.e. Brooks *et al.*, 2005; Boruff *et al.*, 2005; Cutter *et al.*, 2003). Not all of them are suitable to be applied to floods on micro scale, or at the pilot site German Bight coast as a specific area. As this investigation aims at designing a tool which is applicable in practical risk management the vulnerability criteria were chosen along five selection criteria:

- Completeness
- Coverage of all dimensions of vulnerability
- Availability at a reasonable cost-benefit ratio,
- Comparability at different times and places,
- Measurability, i.e. statistically sound, and minimal in order to be easily applied

To assess the overall vulnerability, including tangible and intangible damage categories, the following vulnerability criteria were assessed in St. Peter-Ording:

- Economic: - Building characteristics and values
  - Private inventory
  - Stock value
  - Gross value added

- Social: - Population at risk (& risk to life)
  - People with special vulnerability
  - Social hotspots

- Ecological - Coastal biotopes

The methodology to assess these criteria on a micro-sale level is described in the following sections.

Economic vulnerability
Economic vulnerability relies primarily on the description and quantification of the economic damage potential in the flood prone area and a scenario-based damage estimation in relation to the flood depth. The crucial point in estimating the damage potential is the selection of damage categories included in the value assessment. Flood damages can be categorised into direct and indirect flood losses, which are further subdivided into primary and secondary damages. Direct primary damages include all physical damages to buildings and infrastructure, while secondary damages describe the hidden costs of total restoration. Indirect, primary damages are the disruption of production, traffic and trade. Indirect, secondary damages result from a long-term reduced spending power in the affected area (Figure 8.12).

The choice of the damage categories relies on scale and purpose of the investigation, which here was the evaluation of damage potentials on an object level, i.e. single valuables of one damage category. The economic vulnerability assessment was divided into (1) the selection of damage categories, (2) the assessment of the monetary values and (3) the subsequent damage estimation by means of depth-damage functions, which represent the damage-to-total-value ratios in relation to the specific flood depth. In this context damage potential is not defined as damages or possible damages, but as the sum of existing monetary and non-monetary values/objects, which could suffer damages in case of a flood event.

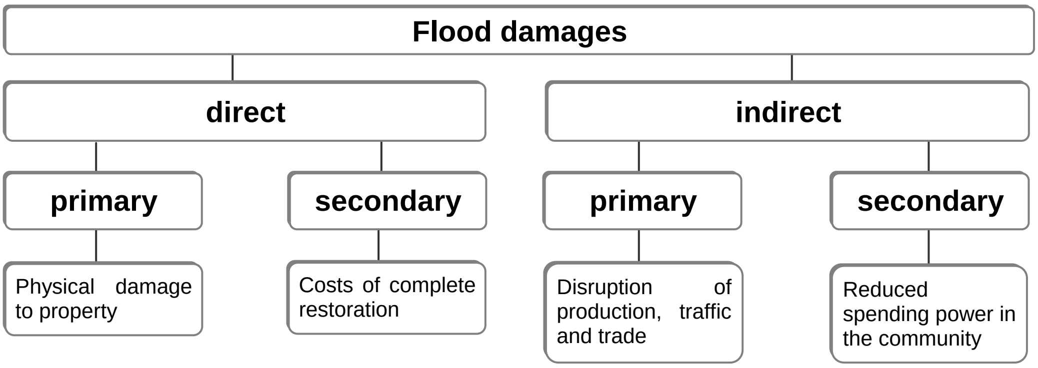


Figure 8.12 Economic flood damage categories (Smith & Ward, 1998, changed)

For the damage potential analysis the MERK database (Reese *et al.*, 2001) was used as it includes all damage categories and their values on an object-based level for six differently structured communities in Schleswig-Holstein (including St. Peter-Ording). This database was built by detailed site surveys, expert interviews and statistics. It includes i.e. building characteristics such as age, construction design, type of usage, and values.

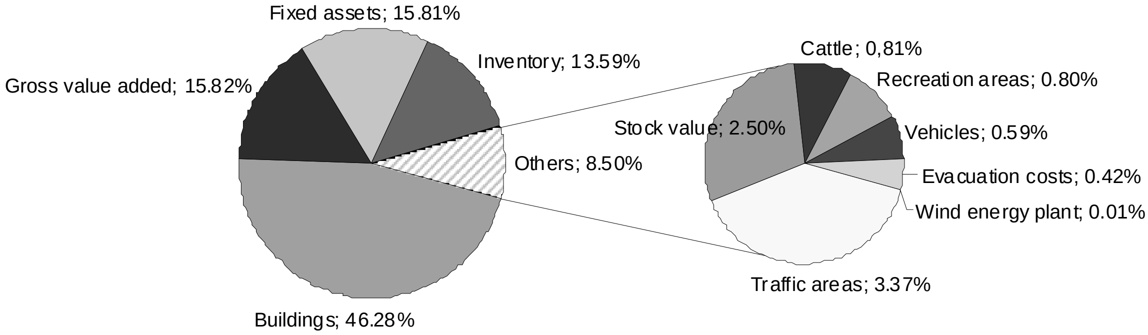


Figure 8.13 Damage categories for St. Peter-Ording (% of flood damage in €)

(1) Selection of damage categories
By analysing the outcomes of the MERK database it became obvious that out of the 15 damage categories present in St. Peter-Ording only four categories made up more than 90% of the monetary damage potential. These categories are buildings, inventory, fixed assets and gross value added. Other categories such as vehicle assets or life stock are negligible compared to the overall damages (Figure 8.13). This could also be approved for the other five communities in the MERK data base. Thus, these damage categories are assumed to be the key parameters of economic risk in coastal communities in Schleswig-Holstein. Assessing only those parameters allows reducing the effort, but still keeping the detail of micro-scale investigations. Thus in our case study the damage potential was calculated for the four relevant damage categories, neglecting the 10% of other categories in order to essentially simplify the valuation assessment and make it more applicable by reducing the effort of the assessment.

(2) Assessment of the monetary values
To assess the value of the four damage categories a standardised methodology developed by Reese (2003) was applied as follows:

Buildings
In the MERK project all buildings in St. Peter-Ording were assessed according to the "Valuation Guidelines and Manufacturing Costs 1995" (Kleiber, 2000) as well as by extensive field mapping. To simplify the assessment methodology for the pilot site application the Formula 8.1 (Reese, 2003) was used:

$$\textit{Value of building} = \textit{base area} * \textit{value of building/m}^2 * \textit{standardised number of storeys} \quad (8.1)$$

For the analysis the base area has been derived from the ALK (German digital cadastral map). To calculate the values of the buildings/m² the area of investigation has been classified according to the housing density and further descriptive parameters, as the values of the buildings correlate with the structure of the area of investigation (Table 8.4). The buildings/m² base areas for every storey could then be derived from the specific building parameters, i.e. number of storeys, base surface and the value of the building.

As the number of storeys cannot be gained from the ALK, a regression analysis was performed resulting in Formula 8.2:

$$Sstand = 1.394 + 0.0049 \cdot E - 0.0014 \cdot E^2 + (0.000014 \cdot E^3 \quad (8.2)$$

* Sstand = standardised number of storeys
* E = Pi (population index) / Hi (housing index)
* Pi = population density in the area (area of investigation/number of inhabitants),
* Hi = total area of storeys/ estate area

The standardised number of storeys for St. Peter-Ording is 1,673 (E: 4,1926). Eventually the value of every building could be calculated using Formula 8.1.

Table 8.4 Structuring of the investigation area (Reese, 2003)

Structure of area	Value of building/m² Area of floors	Classification features			
		housing density	% high quality infrastructure	% industrial area	% rural areas
Centre	1,100 €	> 10%	very high	very high	very low
Centre transition area	1,050 €	5-10%	high	high	low
Aggregation area	980 €	2-5%	medium	medium	medium
Peripheral transition area	840 €	1-2%	low	low	high
Periphery	560 €	< 1%	very low	very low	very high

* Housing density = total area of storeys/estate area

Private inventory
The values of the private inventory were calculated using Formula 8.3 (Reese, 2003).

$$\textit{Private inventory} = \textit{base areas of the building} \cdot \textit{number of storeys} \cdot \textit{inventory/m}^2 \quad (8.3)$$

Again, the base area could be easily gained from the ALK. To derive the inventory/m² the use of every building had to be considered, as a different use of a building leads to different values of the private inventory. In the area, there are four types of usage: (1) living, (2) mixed use, (3) hotels < 9 beds, and (4) adjoining buildings.

Mean values of the private inventory/storey for the parameters: number of storeys, base area, use, and value of inventory were then derived from the MERK database, where the determination of the inventory assets was conducted according to the rating of household insurances (Table 8.5). According to the different use and structure, mean values for the number of storeys could be derived from the database (Table 8.5). The inventory assets of business enterprises were determined separately in the framework of the valuation of the fixed assets.

Table 8.5 Inventory/m² storey area in areas of different structure (left), number of storeys (right) (Reese, 2003)

Structure of area	Living	Mixed use	Accommodation service	Adjoining buildings	Use	Inventory/m² storey area
Centre	3.1	4.3	2.0	1.2	Living	500 €
Centre transition area	1.95	2.95	1.5	1.05	Mixed use	240€
Aggregation area	1.8	2.95	1.5	1.04	hotels < 9 beds	340 €
Peripheral transition area	1.75	1.65	1.7	1.03	Adjoining buildings	70 €
Periphery	1.6	1.6	1.7	1.03		

Gross value added

In national economic terms the gross value added (GVA) is defined as the manufactured goods and performed work given. In the national accounting the added value is taken as the difference between output value and intermediate inputs (Schreiber, 2000, 504). The GVA can serve as a size for the possible losses of production in case of flooding. It is indicated for a full financial year.

For the GVA the limited micro-scale data availability allowed only a rough estimation of the potential values at risk in the study area. The economic sector and the size of industrial firms have been determined on the basis of the ALK. Statistics delivered information concerning the GVA/employee according to the economic sector. Depending on the economic category, an average GVA could be assigned to the employees of each business of St. Peter-Ording. Additionally mean values from the MERK database could be derived for the employees/m² floor area for every economic sector.
By combining this information the GVA for industrial firms could be calculated by means of the employees.

Fixed assets

According to Schreiber (2000, 26) the fixed assets comprise all the assets designed for permanent or perennial use. Thereby material, immaterial and financial fixed assets are distinguished. It is assumed that financial assets and parts of the immaterial fixed assets are normally not vulnerable to flooding. Hence, in the context of this study only the material fixed assets of the local businesses were determined and could consequently be defined as the equipment assets. In the scope of the valuation analysis, all non-privately used buildings were considered.

It turned out that the ALK does not include any information concerning fixed assets. Even statistical data were not available. Thus interviews conducted in the MERK project concerning the fixed assets of enterprises were used to derive mean values for each economic sector and were applied in this study.

The overall damage potential for all four damage categories in St. Peter-Ording is given in Table 8.6 and Figure 8.14.

Table 8.6 Overall damage potential for St. Peter-Ording

Assets at risk	Damage potential
Buildings	1,124,108,382 €
Inventory	240,947,924 €
Fixed assets	151,207,989 €
Gross value added (GVA)	140,543,548 €
Total	1,656,807,843 €

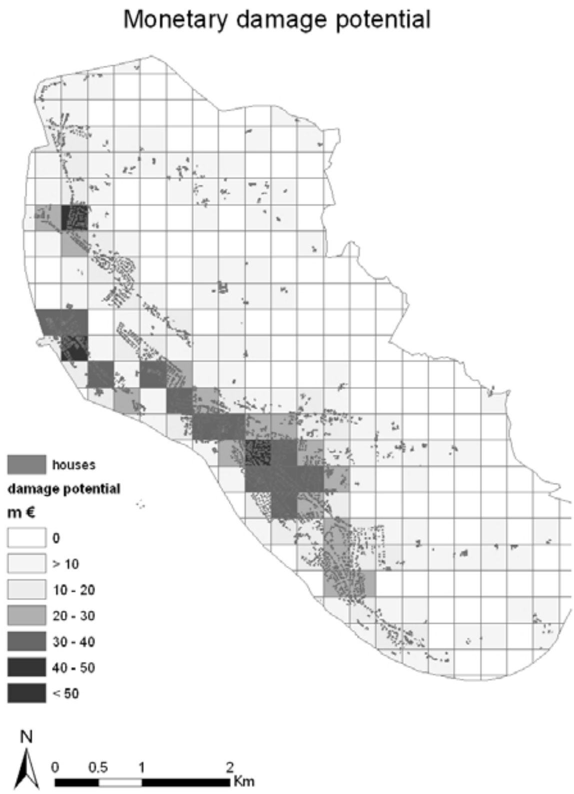


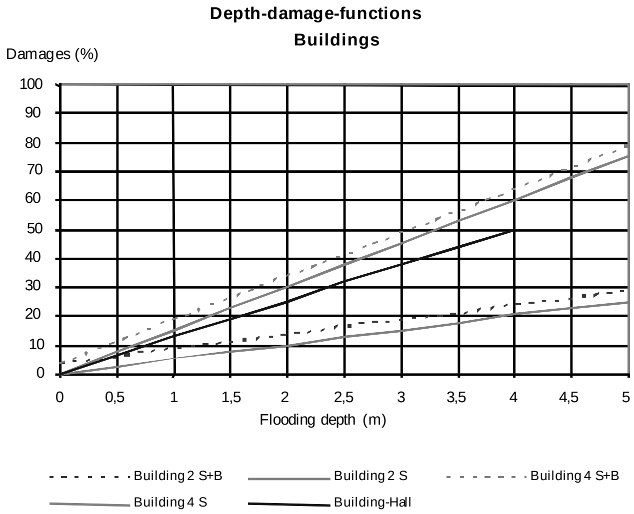
Figure 8.14 Monetary damage potential at the pilot site German Bight coast in a 300 x 300 m grid

(3) Damage estimation – methodology
On the basis of the different flooding scenarios described in Section 8.3.2 and the calculated damage potential the vulnerability could be subsequently assessed by means of an estimation of the possible damages.

The majority of the damage categories could be assessed via empirical models. The calculation of possible damages is mainly based upon so-called depth-damage functions. Thereby it is assumed that standardised functions describe a dependency between the flood inundation depth at the individual objects and the expected damage. The functions are based on data of past flood events and describe either the monetary damage or the percentage of the total value of the object (Niekamp, 2001).

A transfer of depth-damage functions derived from fresh-water damages to the coast is considered as problematic because of the different hydrologic and hydraulic conditions as well as the different water ingredients (i.e. salt). Since damage data of past storm surge events is extremely rare, expert interviews were necessary to ensure the applicability to coastal storm surges or the development of new inundation depth-damage functions. To estimate the damage according to different flood scenarios relative damage functions (adapted to coastal floods; Reese *et al.*, 2001) were applied for each damage category leading to a spatial distribution of the expected damage in the area. Figure 8.15 shows the depth-damage function and curve for buildings as well as the functions applied for private inventory and fixed assets.

The GVA is not defined by the flood depths. Here, specific other parameters such as the flood duration determine the damage expectation. From the expert survey, an evaluation model was derived and transferred into a GIS (Reese *et al.*, 2001). In consideration of the various damaging processes (flood depths, duration, and mechanical damage within the high impact wave zone), the value of the individual objects, the evacuation rates, and the damages of the different categories for the specific scenarios were evaluated.



Storey heights			
Occupancy	First floor	Basement	Hall
Service,Trade, Admin	3.00 m	2.20 m	4.00 m
Prod. industries	3.00 m	2.20 m	4.00 m
Residential building	2.50 m	2.20 m	-

Functions	
Building 2 S	Y = 5 X
Building 2 S+B	Y = 3 + 5 X
Building 4 S	Y = 3 X
Building hall type	Y = 12,5 X
Priv. inventory - first floor	Y = 60 v X
Priv. inventory B	Y = 68 v X - 6
Fixed assets Ser/ Tra/ Adm - first floor	Y = 57 v X + 5
Fixed assets Ser/ Tra/ Adm - B	Y = 68 v X - 6
Fixed assets production industries – first floor	Y = 20 X
Fixed assets production industries – B	Y = 28 X
Fixed assets production industries – hall Y	Y = 15 X

X = Flooding depth (m), Y = Damage (%), S = Storey, B = Basement, Ser = Services, Tra = Trade, P = Production industries, Adm = Administration

Figure 8.15 Depth-damage-functions for buildings applied to the pilot site German Bight Coast (Reese et al., 2003)

Social vulnerability

Vulnerability to floods is to a great part determined by economic aspects, but it can be assumed that the economical characteristics alone cannot explain why some regions or groups are more vulnerable and more at risk than others. “Social vulnerability can be defined as ‘… the exposure of groups or individuals to stresses both from exogenous risks and from their social and economic situation …’ (Adger, 1996, 3).

Social vulnerability is a complex set of characteristics that includes, according to Cannon *et al.* (2003), a person’s initial well-being (physical and mental health), livelihood and resilience (assets and capital, income, qualifications), self-protection (safe buildings, use of safe sites), social protection (preparedness), and social and political networks and institutions (social capital). Hence, it becomes clear that vulnerability is socially differentiated and that certain social characteristics influence vulnerability. For example, a lack of human resources can limit the ability of some weak groups such as children, elderly, uneducated, or handicapped people to respond to floods adequately. Social networks of individuals or of communities play a crucial role in coping with hazards and thus are a factor influencing vulnerability.

The spectrum of indicators of social vulnerability to coastal flooding is very wide and strongly depending on the location. They range from demographic vulnerability criteria (i.e. age, gender, people at risk), health (i.e. population with special needs, invalid persons), education, political structures in a community, personal risk awareness and preparedness up to personal welfare (i.e. income, insurance).

The choice of the social vulnerability criteria was done according to five selection criteria mentioned in Section 8.3.1. Though a focus was given their comparability in different times and places, their measurability, and the possibility to assess and apply them easily.

To determine the chosen social vulnerability criteria people at risk (& risk to life), vulnerable people, and social hotspots rather simple, statistical data were used. These indicators are far from being complete; they have been restricted due to the limited additional time and effort made available for the project.

The number of people at risk was taken from the statistics, including seasonal differences due to tourism. People with a special vulnerability include invalid persons, people older than 70 years and children younger than 8 years as they are assumed to be more vulnerable than others in case of a flood disaster. Social hotspots in St. Peter-Ording are schools, kindergartens, a nursing home, a youth recreation homes, and clinics. In Figure 8.16, the different social vulnerability criteria are displayed for the assumed standard flooding scenario.

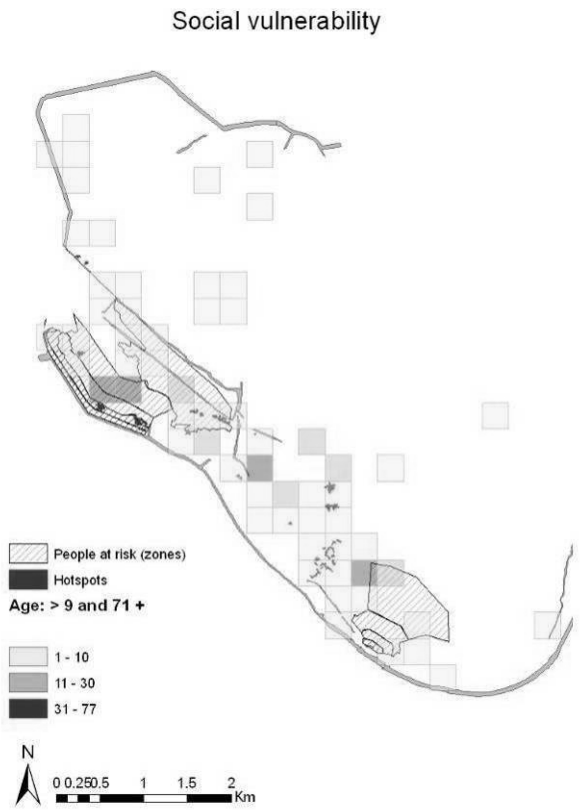


Figure 8.16 Spatial distribution of people at risk and social hot spots in St. Peter-Ording

A risk to life model was developed for river floods in Continental Europe by FLOODsite Task 10. The model builds on a previously existing model by Penning-Rowsell *et al.* (2005). This model was validated on several river floods and only in the UK. For Continental European floods, the model needed some adaptations and revisions, because of variant flooding types and geographical conditions. It comprises a threshold model based on hazard parameters and decides which factors primarily lead to fatalities. Including mitigation parameter in the risk to life model, evacuation results in different risk zones and principal management procedures are suggested. No estimate of the numbers of injuries and fatalities is included.

An application of the model to the pilot site results in a small zone of high vulnerability and all other zones of low vulnerability of the exposed people to floods. The major factors for fatalities are building collapse and flood hazard related in the first 250 m inland from the dike. The risk zones are rated “extreme” for the first 50 m inland from the dike, then “moderate” and “low” follow behind with 50-500 m and 500-1,000 m inland, respectively.

A direct transferability of the model to a potential flooding event on the coast is questionable. For example, due to the combination of different parameters the results for the pilot site show that a zone with 2.5 m water depth on average is only rated "moderate" in risk, with a risk to people only existing for people outside of their houses.

Also, the previous model by Penning-Rowsell *et al.* (2005), which includes precise estimates of fatalities, was tested. The resulting numbers for the pilot site German Bight coast are 286 injuries and 23 fatalities for the standard flood scenario. These numbers are the total potential risk to people and do not include any mitigation measures.

Ecological vulnerability
Ecological vulnerability describes the susceptibility of ecological values, protected areas, or biotopes towards adverse impacts. Coastal biotopes like dunes or wetlands have not only a high ecological value, they also provide ecosystem services, i.e. a buffer and protection function. At the same time, they are highly sensible to disturbances or changes by e.g. inundation, saltwater intrusion, or wave impact, which may lead to a loss of their function.

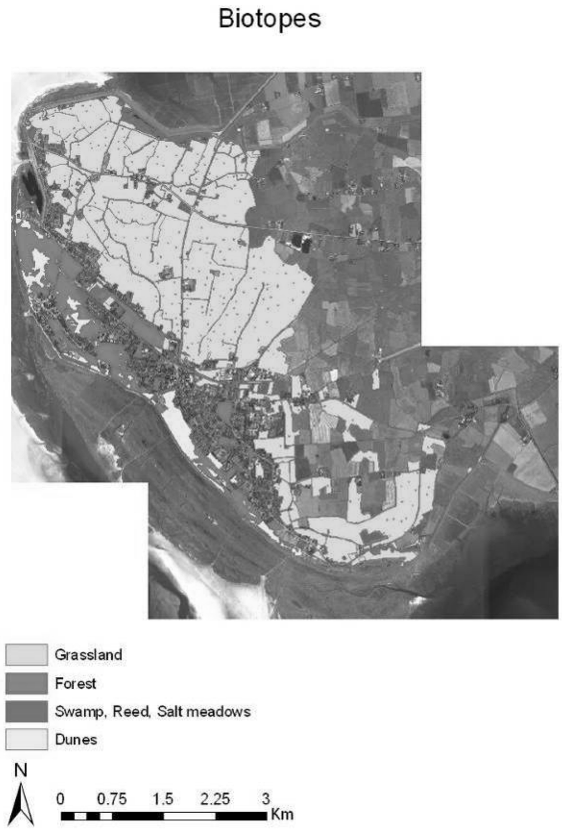


Figure 8.17 Spatial distribution of coastal biotopes at the pilot site German Bight coast

As the assessment of ecological vulnerability was not a main focus in this study, just the exposure of coastal biotopes was assessed rather simply by mapping the size and extension of coastal biotopes at the pilot site. Land use categories and biotopes were mapped, and classified in beach area (e.g. salt marshes, dunes, cliffs, outlets, tidal flats), natural habitats (e.g. reed belts, bog forest), semi-natural habitats (e.g. coniferous forest, mixed forest), grassland and acres, recreational areas, traffic areas and settlement areas.

From these classes, dunes, wetlands (swamp, reed, salt meadows), forests and grassland are within the flood prone areas and make up a large part of it. The size of the coastal biotopes has been determined in km² as a quantitative measurement was foreseen in this approach. Ecosystem dynamics which may be affected by flood impacts are not considered. From the selected classes, grassland covers the largest areas followed by forest, dunes and wetlands (Figure 8.17). However the size alone does not describe the degree of ecological vulnerability, as smaller areas like the dune belts are more sensible ecosystems. Hence, a weighting of the different coastal biotopes had to be done in a next step (cp. Section 8.3.4).

8.3.4 Risk analysis

The flooding scenarios together with the related probabilities provided the basis for combining the hazard and the vulnerability analyses. Different scenarios were calculated taking into consideration the various locations where breaching or severe overtopping may occur. These scenarios were linked to the damage potential in the risk zone to estimate the specific damage. From the inundation depth and the duration the expected damage could be calculated.

Table 8.7 shows the damage in the flood prone area with a storm surge scenario of 5.30 mNN (standard scenario). The economic assets have been assessed in monetary terms, and, for the four key damage categories, could be added up to 57 million €. Social and ecological vulnerability criteria were quantified in numbers to make them measurable. The results are the number of people at risk in different hazard zones, the amount of vulnerable people, and the number of social hotspots, which are primarily schools and hospitals and finally the size of coastal biotopes. More qualitative vulnerability criteria as i.e. the health condition of single person or the risk awareness, which essentially influence vulnerability, could not be considered in the framework of this study.

According to the risk formula mentioned in the beginning, risk = probability • consequence (Gouldby *et al.,* 2009), the risk has been calculated and mapped. In order to define risk zones it is required to quantify the flood risk as exactly as possible. This can be easily done for damages to assets, which can be measured in monetary terms. However, since vulnerability encompasses also non-monetary damage classes an approach is required, which incorporates all risk categories without measuring them on a monetary scale.

For the pilot site German Bight coast, this was done by a multi-criteria risk assessment coming up with a comparable risk rating approach including economic, social and ecological categories of adverse flood impacts. A GIS-based map output allows a ranking of risk zones. Therefore the area map of St. Peter-Ording is divided into a raster with a cell size of 300 x 300 m and all rating is based on individual raster cells.

At first, a so-called disjunctive approach (Meyer *et al.*, 2009) was tested. Here a threshold is defined for each criterion, which is supposed to identify the level of risk in each criterion, which is no more acceptable to the decision maker. Following the socio-economic guidelines in FLOODsite, Task 9 and 10, the following four criteria (with thresholds) were used:

- Economic risk: > 500,000 €
- Population at risk: > 50 people
- Social hot spots: > 1
- Environmental risk: > 50,000 m²

If one or more of the thresholds are exceeded in a raster cell the risk is increased by one for each. Thus risk zones 0 (no risk) to 4 (risk exceeds threshold in all criteria) can be distinguished. Figure 8.18, shows the highest risk, with a probability of 1:10.4 Mill. years for the standard scenario in the north of St.Peter-Ording, where three risk criteria were exceeded. A disadvantage of this method is the relatively arbitrary definition of the thresholds. If, for example, 49 people at risk are in one raster cell and 51 in the other, the discrepancy in risk rating is vast (zero or one).

Another, more robust approach is the Multi-Attribute Utility Theory (MAUT) approach (Meyer *et al.,* 2009, Malczewski, 2006) which was also tested for the pilot site. MAUT is used as an evaluation scheme for decision support, for example in product evaluation. With this scheme all criteria can be aggregated to a single scalar factor, thus it is possible to literally compare apples and oranges. A complex weighting system guarantees that the decision maker's interest is considered. Two weighting approaches have been tried, a simple ranking and a swing weight approach. The latter was more convincing; it is based on a decision of the importance of each criterion in relation to the others. Three categories have been used each with several criteria:

- Economic: Buildings, Private inventory, Stock value, Gross value added
- Social: People at risk, Vulnerable people, Hotspots
- Environmental: Dunes, Forest, Wetland, Grassland

Table 8.7 Results of the vulnerability analysis for the pilot site German Bight coast (standard flood scenario)

Risk category	Risk criteria	Damage (Standard scenario, 5.30m)	Measure
Economic	Buildings	12,740,624	EUR
	Inventory	20,062,292	EUR
	Fixed assets	24,779,280	EUR
	Gross value added	52,973	EUR
	Total	63,398,686	EUR
Social	People at risk	2065 + tourists 513p/day* Hazard zone inhabitants tourists 0-50 m 0 0 50-100 m 151 37 100-250 m 448 112 250-500 m 755 188 500-1,000 m 711 176	Number
	Vulnerable groups	> 70 years: 639 people < 8 years: 181 people Invalid persons: 1,231 beds in clinics**	Number
	Social hot spots	6 schools and kindergartens 4 clinics 5 children's clinics / homes 1 youth recreation home 1 boarding school 1 nursing home	Number
Ecological	Coastal biotopes	44,903 km² Dunes 487,772 km² Forest 171,572 km² Wetlands 5,019,493 km² Grassland	km²

* December, tourists assumed to be distributed equally over SPO
** Utilisation differs over year, between 573 in December and full utilisation in summer

Each criterion is given a value from 0 to 10, depending on its value in a raster cell. Then, using the swing weight approach, a weighting and normalisation within each category is carried out. Thus each category again can have a value from 0 to 10.

Depending on the stakeholders' interest, the different categories can now be weighted differently. In Figure 8.19, each category is weighted as one third. Of the possible 10 risk categories only the 6th is reached in the example. If, for example, more importance is attached to the social components a weighting of 70 % social, 15% economic and 15% environmental is possible. Figure 8.19 shows the six risk zones for the standard scenario and a probability of this scenario of 1:10.4 million years.

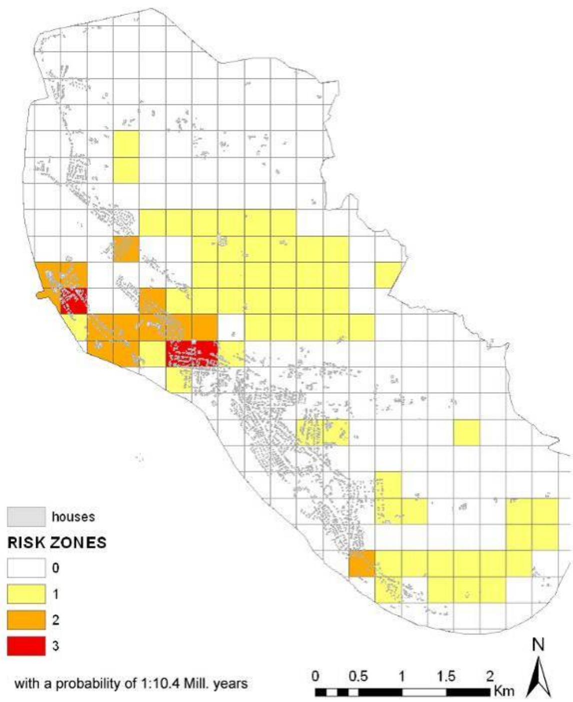


Figure 8.18 Risk zones with risk categories based on disjunctive approach as tested in the pilot site German Bight coast

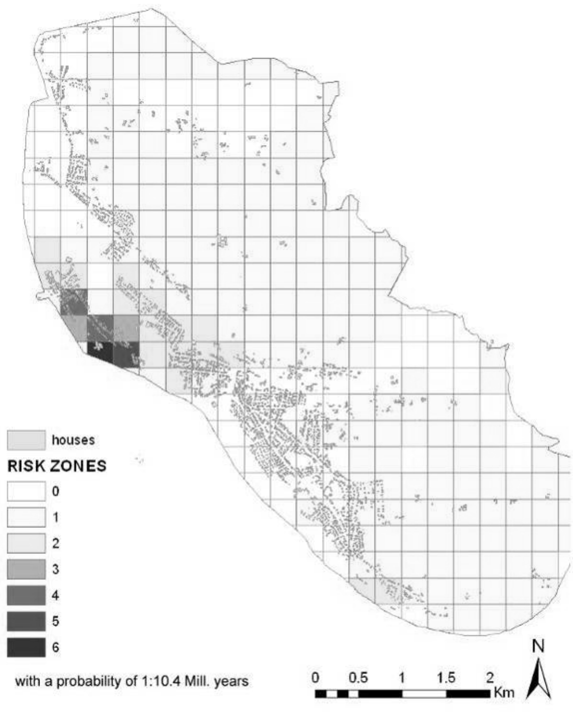


Figure 8.19 Risk zones with risk categories based on the MAUT approach (weighting each risk category 1/3) applied to the pilot site German Bight coast

Based on the analysis described in the previous sections a micro-scale risk analysis tool was developed (Figure 8.20), which includes:

- a combination of hazard probability, flood scenarios and micro-scale vulnerability assessment,
- an integrated and transferable approach to assess economic, social and ecological risk criteria,
- and a multi-layer GIS output as an appropriate tool for the spatial analysis of flood risk.

The developed risk analysis tool serves as a framework for further utilisation in research and practice. It consists of a summary of all parameters and criteria that should be used for the risk assessment, which have been described in detail above. The tool provides a substructure that can be applied in a decision support system for management purposes in the future.

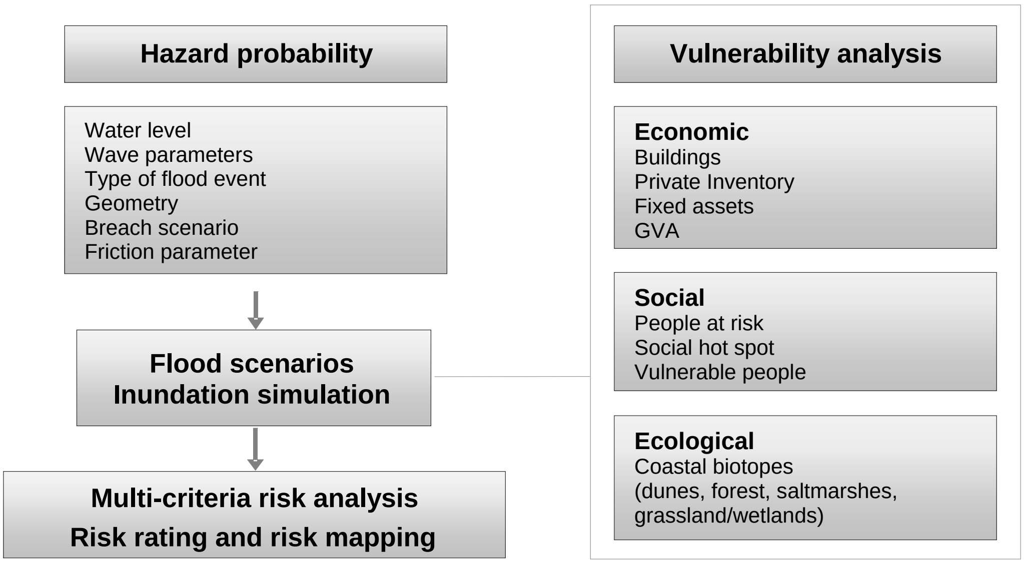


Figure 8.20 Risk analysis tool for coastal floods at the pilot site German Bight coast

8.4 Contribution to flood risk management practice

A key interest of this study is the relevance of the developed and tested methods to practitioners and end-users as the European Flood Directive asks for flood hazard maps, flood risk maps, and risk management plans to be developed within the coming years. Work at the German Bight coast pilot site has focussed on further development of risk analysis tools together with risk mapping including tangible and intangible damages. Hence, the eventually developed risk zone maps may serve as an output required under the Flood Directive although further developments and refinements might be needed.

The pilot site German Bight coast has focussed on developing risk analysis tools and adaptation of methods to typical coastal sites protected by flood defences. Many methods were taken from other Tasks of FLOODsite, others were directly developed within the case study. However, FLOODsite has led to more approaches on flood risk management, which have not yet been applied to any coastal site. Since these methods also comprise mitigation measures to reduce the risk, these are very relevant for any practical use. Therefore, there is an urgent requirement to adopt the developed risk management strategies to the coastal sites and provide them for practical use.

Within the case study, a GIS based risk analysis tool (Figure 8.20) has been developed. Despite limited time and resources to finally develop and implement this tool, first steps have been undertaken to not only include a probabilistic hazard analysis to provide a flooding probability but also include key intangible damages (loss of life, hotspots, etc.) for the estimation of the flood consequences. Both parts were then brought together by means of a risk rating method so that flood risk zones can be provided. This tool can be easily enhanced due to its modular structure and may be transferable to other coastal areas where sufficient data is available.

8.5 Conclusions and outlook

A detailed flood risk analysis has been performed at the pilot site German Bight coast. The study comprises a full probabilistic analysis of the flood defences protecting the hinterland close to the village of St. Peter-Ording on the Eiderstedt peninsula and a micro-scale vulnerability analysis, including economic, ecological, and social aspects of the vulnerability.

Previous studies in the area such as PRODEICH (Kortenhaus & Oumeraci, 2002) and MERK (Reese *et al.*, 2001) have generated sufficient data (flood defence system, water levels, socio-economic database etc.) to perform flood risk analysis studies. In this chapter, details are given for the determination of the failure probability of the flood defences as well as the related consequences, including economic, ecological, and social consequences.

With respect to the hazard analysis, the results have shown that even though some input parameters were not directly available and had to be estimated the results were believed to be very reliable (Pf in the range of Pf = 10-4 to 10-6). Sensitivity analyses have been performed accounting for the uncertainties of the input parameters. Additionally, results have shown that length effects and dependencies between sections and the dependencies between failure mechanisms or scenarios will have to be considered in the future.

The results of the vulnerability analysis have shown that the integration of economic, social, and ecological vulnerability criteria is feasible as it gives a more complete picture of the overall susceptibility towards flood risk. In order to assess the values at risk on a micro-scale level, which turned out to deliver the appropriate data needed for risk handling, a simplification and standardisation of the micro-scale assessment methodology was performed by defining key economic damage categories and selecting vulnerability criteria, which can easily be gained and quantified. With these data the spatial distribution of flood risk could be mapped.

The vulnerability criteria and the simplified assessment method chosen in this investigation are assumed to be more easily transferable to other coastal areas. However, the method has to be tested in other sites to validate the transferability. An improvement of the vulnerability analysis is desirable. For example, indirect damages like market disturbance, traffic disruption, or loss of tourists are not included yet. The latter might be significant for a community relying on tourism like St. Peter-Ording. Also further social criteria, like increased vulnerability and health problems, can be included.

Ecological vulnerability has only been considered very briefly in this study, as the main focus was on the assessment of the monetary economic damages. Additionally to the mapping of the size and the relevance of the coastal biotopes the impacts of flooding in these areas should be investigated in the future, i.e. consequences of salt water intrusion or impacts of waves and water on coastal forests and dunes. Furthermore the recovery potential of coastal biotopes should be included in vulnerability assessment as well as the capacity of the socio-economic system to cope with flooding.

The proposed risk analysis methodology does not include flood risk management approaches. As a next step, also to meet further objectives of the EU Flood Directive, the tool needs to be extended for risk management purposes. This includes all alleviative parameters like an early warning system, risk awareness of the people or evacuation procedures. More, the methodology serves as a framework for further utilisation in research and practice as it contains all parameters and criteria that should be used for the risk assessment. The framework provides a structure that can be applied in a decision support system for management purposes in the future.

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9. Lessons learned and further challenges for research and practice

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Overall conclusions of the research on integrated methodologies in the European pilot sites depend on the boundary conditions of the respective investigations. This especially means that it has to be considered that the case study approach focuses the individual flood risk management issues at the sites instead of being a comparative approach. As consequence, lessons learnt are mainly additive than representative for all cases.

Presentation of major findings is structured in scientific advances and contributions to flood risk management practice. Hereby the scientific advances are differentiated according to the tasks of flood risk management as it has been introduced in Chapter 2. In contrast the explanation of the practical outcomes follow the main chapters of the Floods Directive (see Chapter 1).

9.1 Innovations in science

9.1.1 Thematic innovations

Hazard, vulnerability and risk analysis

In general research results confirm a principle feasibility of simulating large scale flood risk systems of rivers, estuaries and coasts applying integrated methodologies. Differences of the flood types require different approaches mainly for the calculation of sources and pathways of risk. Nevertheless the SPRC concept turned out to be a generic means of indicating relevant processes for all flood types which provides a basis for the selection and coupling of models and tools.

The results of the risk analyses depend on the involved methods but also on the database with its spatiotemporal resolution. Approaches and conditions in the pilot site significantely vary in this respect why a number of solutions can be proposed from testing the methodologies. Systematic investigations on the influence of methods and data on the results were carried out as basic research of FLOODsite. Thus they need not to be treated with by a comparsion of the pilot sites. However, in some of the cases details of the hazard and vulnerability analysis are critically discussed.

The risk-based approach proved to deliver significant more information than a pure hazard analysis. This allows for a more comprehensive evidence base for decision making on risk reduction interventions. Hereby modelling the flood hazards is already well-advanced why respective innovations of the presented research refer to specific aspects such as failures modes and flood forecasting in ungauged mountainous flash flood watersheds. In contrast, the calculation of the vulnerability appeared to be still in its infancy. Approaches in the pilots range from land-use classification according to Corine Land Cover 1:50,000 to the detection of individual buildings with combined remote sensing and field investigations. In previous studies emphasis has been put on the calculation of direct economic losses. Research of FLOODsite beyond led to the development of approaches that also address other areas of vulnerability such as loss of life and impacts on soils and ecosystems of flood plains due to toxicological matters.

As one challenge the future alteration of the flood risk system is considered. The design of comprehensive and consistent scenarios on climate and societal change as well as the ex-ante analysis of strategic alternatives for risk reduction against these scenarios is not only manageable with the proposed methods. It also assists in understanding uncertainties more explicitely.

As follows innovations for hazard, vulnerability and risk analysis are described more specifically.

Hazard analysis

According to the SPRC concept the hazard analysis comprises a source and a pathway module. For a river flood this can be a rainfall-runoff model together with a hydrodynamic model (e.g. pilot sites

Elbe River basin, Tisza River basin) or a hydrodynamic model coupled with a dike breach model (e.g. pilot sites Thames River estuary, Scheldt River estuary). Significant uncertainties are associated with the path of the frontal zones, like the Tizsa River pilot sites indicates. Minor deviations in the location of rainfall can have a significant impact on the magnitude of a flood even on the scale of a large river. Moreover uncertainties are inherent to the prediction of embankment failure and hydro-morphological change in estuaries, as the study at the Thames River estuary figured out. Hence coupled models for estimating the flood hazard have been developed and tested at the Thames River estuary comprising the following: (i) probability of defence failure for all defences including barriers, (ii) deterioration of the defences, (iii) breach formation and development, (iv) a rapid flood spreading method that permits fast run times and the evaluation of a range of scenarios, and (v) a method for assessing uncertainty. The methodology is data intensive but can be used with simplified data sets in order to identify priorities for future data collection.

It is noteworthy that appropriate detailing of such a methodology is a relevant question for practicability. From this point of view it can be particularly important to adopt the simplest available method for the flood hazard analysis that is capable of achieving the required results. Therefore the identification and involvement of all critical factors of flood risk generation seem to be one key preparatory step before undertaking a full flood hazard analysis. In the case of the German Bight, sea water level, dike crest level and wave height are seen as critical, as wave overtopping and breaching of embankments are the most important flood mechanisms.

Inclusion of morphological changes in modelling the coast during a storm event already leads to an additional complication. These changes can increase flood levels as it has been shown for the Scheldt River estuary where land reclamation causes increases in tidal water levels further upriver. In the case of the Ebro River delta coast beach and dune evolution during a storm event has a significant impact on overwash and therefore the amount of flooding. Hereby is has to be considered that the impact of successive storms on coastal flooding can be greater than expected because there is not enough time for the natural recovery process to take place following erosion during the first storm (see pilot sites Ebro River delta coast, German Bight coast). The Ebro delta furthermore has suffered from a loss of fluvial sediment inflow over the years because of the construction of dams in the catchment. Accretion from fluvial sediments helps to mitigate the impacts of sea level rise. However the loss of sediment means that local flood risk has increased and will continue to increase as the sea level rises.

The use of a ‘static’ representation of the coast in the modelling would result in an underestimation of overwash and flooding. However, respective methods need only to be included if they have a significant influence on the flood hazard as demonstrated on the Ebro delta.

Simplification should not affect the accuracy of data, like for instance the height of the flood defence crest level. For that reason most recent data sources were successfully tested in the Thames River and Ebro River delta coast pilot sites such as LIDAR data for the derivation of digital elevation models.

To deal with the probable influence of climate change on the flood hazards, projections of regional climate models were coupled with rainfall-runoff and hydrodyanamic models (e.g. Elbe River basin, Thames River estuary). The analysis of data on the Upper Mulde catchment indicates an increase in extreme flood flows over the next 90 years. Research on the Tisza River shows that the frequency of weather conditions with a potential of triggering floods is increasing. Care is needed when selecting records for analysis because of the natural variability in the climate. On the Thames, long term records show an overall decrease in flood flows with time whereas short term records show an increase.

Whilet coastal storms can cause flooding by overtopping and breaching of defences, a serious long term threat to low-lying unprotected coastal areas is sea level rise. For the Ebro River delta, sea level rise of 0.5m (within current predictions of sea level rise by 2100) could lead to permanent submergence of 40% of the delta unless management measures are implemented.

Vulnerability analysis
Basic research under FLOODsite provides an overview of methods for analysing the flood vulnerability (Messner *et al.*, 2006). In line with that testing in the pilot sites focused on selected approaches. For example, for the Tisza River pilot site vulnerability was determined based on the CORINE Land Cover (1:50,000) classification. Moreover field surveys on the toxicological vulnerability of soils against heavy metals and other substances were carried out. In the Thames River estuary, the Scheldt River estuary and the Germain Bight potential economic losses of buildings have been dealt with. The former additionally encompassed the number of people affected and the vulnerability of habitats.

In the pilot site Ebro River delta coast vulnerability is tackled with regard to agriculture and biodiversity. For the Elbe River pilot site methods have been developed to determine the social, economic and ecological vulnerability. The social vulnerability covers the people affected by floods, a spatial analysis of the critical social infrastructure and an extensive qualitative field survey on the vulnerability of the people living in flood-prone areas to also reflect the intagibles. As economic vulnerability furthermore the damage potential of flood polders for agricultural use is considered.

All in all most case studies were committed to broaden the scope of vulnerability analysis and thus to avoid restrictiond by narrowing the consequences of flooding to the damage to assests. Instead all areas of sustainability are covered. Indirect effects of flooding were considered in the Scheldt River estuary and the German Bight pilot sites.

Risk analysis
Depending on the size of the pilot sites risk analysis methodologies focus a micro or a macro scale approach. A micro-scale approach is needed to provide sufficiently accurate results together with a fully probabilistic approach to determine flooding. An accordingy risk analysis tool has been developed in the pilot site German Bight coast. Data collection for this approach is time consuming and expensive. Thus a macro scale approach can be valuable for screening the risk more generally. Though, the quality of a flood risk analysis is affected by the quality of data. Where data quality is poor, uncertainty increases rapidly.

Based on the range of vulnerability indicators multi-criteria methods are suggested to be included in the risk analysis (e.g. pilot sites Thames River estuary, Elbe River basin). These methods can be an appropriate means of aggregating risks particularly in maps. However, normalising the risk from a number of indicators leads to a loss of information which makes it different to interpret risk curves and to derive the expected annual consequences.

As an additional outcome it became obvious that not only the day of the week (e.g. Sunday vs. working day) but also the season of flooding has a major impact on risk in some areas. This was particularly identified for agricultural and tourist areas.

Risk evaluation
Evaluating of risks and strategic alternatives of risk reduction is traditionally based on the criteria ‘effectiveness’ and ‘efficiency’. The comprehensive view on flood risk management together with the consideration of uncertain futures of the flood risk systems lead to a particular meaning of additional criteria. One the one hand the case studies resulted in the recommendation of the criterion ‘sustainability’ which judges a system’s state based upon social, economic and ecological indicators. It has been successfully tested in the Thames River estuary. On the other hand the criterion ‘robustness’ and also the criterion ‘flexibility’ provide the prerequisite to reflect the performance of interventions in the flood riks system under a certain scope of future scenarios. In this way robustness was tested in the pilot sites Elbe River basin and Thames River estuary.

For instance, the ‘do nothing’ risk reduction alternative for the Elbe River channel results only in a minor disadvantage compared to the other alternatives if only the scenario B is considered. In contrast, the look on all scenarios underlines that this alternative is rather unpreferable because of the low performance especially under scenario A (see Section 2.3.4).

Risk reduction

Understanding flood damage as a function of the state of a complex flood risk system not only broadens the scope of the risk analysis. It also enhances the options of reducing the flood impacts. In line with that the full range of physical measures and legal, planning, financial and other policy instruments for flood prevention and protection as well as vulnerability mitigation were investigated in the piliot sites. Nevertheless there was no explicet aim of comparing measures and instruments or structural and non-strucul measures respectively.

Controllable flood polders that are allowed to flood during large river floods showed a significant reduction of the peak discharges and therefore of flood levels and the flood risk on large lowland rivers with defended floodplains. This was demonstrated by modelling of the lowland Elbe River and the River Tisza. On the Elbe a single large storage area reduced peak flood levels by about 0.2 m, and on the Tisza eleven storage areas reduced peak flood levels by at least 1.0 m. The analysis did not assess the costs or benefits of this approach

Reservoirs proved to contribute to flood reduction in some circumstances. On the Horni Stropnice River, a Czech Elbe headwater, reservoirs reduce the discharge for frequent events but not large events. This result supports findings from previous work where storing water in existing reservoirs have been considered for reducing flood risk. The main factors in the effectiveness of reservoirs include the available storage volume compared with the overall flood volume, and the way in which the outlet flow from the reservoir is controlled.

Changing land use, for example introducing more forest, can theoretically reduce flood risk. On the Upper Mulde River, this effect is limited to frequent events. Moreover it is rather site-specific and depends on the kind and proportion of the land-use change.

Defences can fail at lower water levels than the design level, thus lowering the level of protection. On the Scheldt River the concept of a broad dike is being investigated, which can tolerate more overtopping than traditional dikes before they breach.

The probability of failure of flood defences forms an important component of the potential flood hazard in areas with flood defences. The concept of flood defence ‘fragility’ has been incorporated in models for assessing flood risk. One difficulty with this approach is the degree of uncertainty in the assessment of failure probability. The impact that this and other uncertainties have on flood risk estimates are dealt with by an uncertainty analysis. An according reliability analysis of flood defences at the Thames and Scheldt River estuary pilot sites provided improved methods of estimating the probability of flooding. Knowledge on failure modes suggest to cover both hazard-related structural measures and vulnerability related non-structural measures.

Long-term planning

The scenario planning approach has been further elaborated for the purpose of long-term flood risk management. This especially refers to proposed procedures on how to combine scenarios with strategic alternatives. Both the discriminant-axes methods and the world views from cultural theory appeared to be applicable for developing a scenarios funnel and deriving sufficiently parameterised assumptions for coupled model calculations. Testing happened at the Thames and Scheldt River estuaries and in the Elbe River basin.

To ensure transparency of the results and to facilitate the exploration of futures situations by decison makers, both the scenarios with the strategic alternatives and the coupled models have been integrated in decision support tools. The addressees of these tools range from experts to the interested public which is particularly reflected in the GUI.

Forecasting and warning
In parallel to the long-term perspective, investigations in the pilot areas of the flash flood waterscheds and at the Tisza River basin pilot site were dedicated to improve the forecasting an warning capacity. Among others, this led to the proposal of a Flash Flood Guidance method combined with a method of model-based threshold runoff computation to improve the accuracy of flash flood forecasts at ungauged locations (Chapter 4). Examination of the results obtained shows that the use of model-based threshold leads to improvements in both gauged and ungauged situations.

In addition a decision support tool has been developed with an emphasis of forecasting and evacuation. The tool was successfully tested in the pilot area of the Scheldt River estuary.

Flood risk management process
Based upon FLOODsite basic research on strategy formulation and implementation, involvement of actors of flood riks management − and in a few cases even the people − has been investigated in a number of pilot areas applying alternatives approaches. Results show that the experts got easily in touch with explorative approach of long-term planning and appreciated the opportunity of tool-based learning about the flood risk systems's behaviour. In comparison the people either had different perception of the flood risk issue (pilot site Elbe River basin) or rather similar perception (pilot site Scheldt River estuary).

More generally it became obvious, particularly from the pilot sites Elbe River basin and Scheldt River estuary, that flood risk of course is the major content. However perception, awareness and decisions are clearly influenced by the internal and external context of the actors and people as well as the process of planning and deciding.

9.1.2 Research demands

Related to the overall innovations from the pilot sites the following selected requirements for future research can be derived: In principal modelling results require an independent validation to see whether they are suitable. Particularly with the coupled models and methods but also for the assessment of non-economic risk being developed there is a risk that gross errors could occur. Furthermore modelling for the Ebro delta was based on models developed for riverine floods. A specific coastal inundation model is needed. This should take account of evolution of the coast during a storm. This problem also occurred in the German Bight pilot, where the model used does not include wave overtopping or coastal processes such as breaching.

In terms of the reliability analysis some further development is needed, for example to take account of the fact that some failures do not result in a flood (e.g. a slip surface failure following a very high tide) or are caused by local features not identified in a reliability analysis.

Knowledge on flash floods remains still rather limited. Thus post flash flood studies should be undertaken and shared in order to improve the understanding of this flood type. Studies should cover hydrology, hydro-meteorology, geomorphology, social and economic aspects. The promising results from modelling experiments in Chapter 4 suggest that further work should be devoted to the analysis of the combination of FFG with model-based runoff threshold. In particular, future work should focus on the examination of the influence of spatial and temporal scales on the performances of the method and on the dependence of these scales on the type of rainfall information used to force the model. It is likely that different types of rainfall forcing will translate to different scale-dependence patterns.

In addition knowledge on the course of decision making in flood risk management also considering participation of the people need to be improved to better understand how issue of flooding are treated compared to other societal tasks. Knowledge on the influence of the internal and external context and the process of planning and learning can be expected to be key factors for an effective management.

9.2 Advancements for flood risk management practice

9.2.1 Contributions to the implementation of the Floods Directive

FLOODsite has been worked on in parallel to planning and enacting the Floods Directive. Nevertheless the scope of the project and especially the site-specific testing allow for some contributions to the implementation of the directive. These contributions are briefly presented in accordance to the main chapters of the legal instrument (see Chapter 0).

Preliminary flood risk assessment
Methods for the macro scale risk analysis which have been tested in all pilot sites can be used for the the preliminary assessment.

Flood hazard maps and flood risk maps
Methods for the spatiotemporal analysis of hazards and risk maps were already available. FLOODsite advances particularly refert to failure modes and certain aspects of vulnerability analysis such as e.g. loss of life (Thames), ecological impacts (Tisza, Elbe, Thames) and spatial multi-criteria risk analysis involving social, economic and ecological aspects (Elbe, Lower Mulde River). The pilot sites have demonstrated several approaches to estimating flood hazard and flood risk. Whilst these follow similar processes including data collection and modelling, there are differences in the methods and techniques applied (cp. Elbe, Tisza, Thames, Ebro, German Bight).

There is a need to integrate the calculation of social, economic, and ecological impacts of flooding to ensure comprehensive flood risk maps.

Flood risk management plans
'Micro-scale' approaches to risk are normally adopted for flood risk assessment but these are unlikely to be practical for the large areas covered by Flood Risk Management Plans. It may therefore be necessary to simplify these methods so that they can be applied over large areas. It may also be advisable to apply different methods depending on the degree of flood risk, to avoid expending a large amount of effort in areas where the flood risk is small.

The scenario technique as it has ben successfully tested is ready for use to explore scenarios and calculate the performance of risk reduction alternatives.

Public involvement appeared to be a relevant topic: people need to receive appropriate information and experts need to include local knowledge. Results could not only improve acceptance of the planning but also its quality. Hereby the planning system and culture as well as the previous flood experience should be taken into account.

Selection and evaluation of interventions in the flood risk system should reflect all potential physical measures and policy instruments beyond traditional flood defence.

9.2.2 Outlook

To facilitate the uptake of the integrated methodologies guidance on the most appropriate methods for estimating flood hazard and flood risk, and developing Flood Risk Management Plans is prepared based on the FLOOD*site* pilot studies and other relevant work. This should take account of different scales, different levels of flood risk, data requirements and potential resource requirements.

The way in which stakeholders are involved in decision making requires consideration by Member States. The FLOOD*site* pilot studies provide examples of methods and benefits of stakeholder engagement, and also identified some of the pitfalls. Stakeholder participation is essential when considering measures that require actions by stakeholders including the public.

9.3 Overall conclusions

FLOODsite European pilot sites have proved the possibility of applying integrated approaches to deal with a comprehensive understanding of flood risk management as introduced in Chapter 2. The pilots do not provide new information on every aspect of flood risk management since knowledge is already well advanced. However the integrated view and according methodologies are now available.

9.4 References

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Abbreviations

1D/2D	One dimensional/ two dimensional
AOD	Above Ordnance Datum
B	Benefits
BCR	Benefit-cost analysis
C	Costs
CLC	Corine Land Cover
CSI	Critical Success Index
d	Day
DEM	Digital Elevation Model
DSS	Decision support system
EAD	Expected average damage
EANC	Expected annual number of casualties
EC	European Commission
ESS	Evacuation Support System
EU	European Union
FAR	False alarm ratio
FFG	Flash Flood Guidance
GDP	Gross Domestic Growth
GUI	Graphical User Interface
h	Hour
IPCC	International Panel of Climate Change
km	Kilometres
m	Metres
MAUT	Multi-Attribute Utility Theory
MCA	Multi-criteria analysis
MWL	Mean water level
NWP	Numerical weather prediction
P	Precipitation
POD	Probability of detection
PV	Present value
s	Second
SPRC	Source-pathway-receptor-consequence
T	Temperature
yrs	Years
WDF	Water Framework Directive

Note: Model abbreviations are not listed here.

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