Flood risk analysis : impact of uncertainty in hazard modelling and vulnerability assessments on damage estimations

Julian Eleutério

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BY JULIAN **ELEUTÉRIO**

Flood risk analysis:
impact of uncertainty in hazard modelling and vulnerability assessments on damage estimations

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at the National School of Water and Environmental Engineering of Strasbourg, France.

Supervisors:	Anne ROZAN	Professor, ENGEES, France.
	Robert MOSÉ	Professor, ENGEES, Director, IMFS, France.
Referees:	Bruno TASSIN	Professor, Research Director, Ecole des Ponts, France
	Nilo de O. NASCIMENTO	Professor, EHR/UFMG, Brazil
Examiners:	Roland NUSSBAUM	Director, Mission Risques Naturels, France
	Sandrine SPAETER	Professor, UdS, France

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Jury invited members: Sylvain PAYRAUDEAU, Associate Professor, ENGEES, France.
Charles BERTHET, Professor, Université Paris-Dauphine, Ex-president, Fondation MAIF, France.

...àqueles que mesmo de longe, sempre estiveram próximos me incentivando a persistir, a imaginar, a criar, a me esforçar, a alcançar meus objetivos e a ser feliz;

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Abstract

Floods are the most damaging natural hazard in the world. Better understanding on the flood hazard phenomenon and its potential consequences in our society is crucial for the development of flood control policies, risk reduction projects and other types of flood management strategies. Basic knowledge for apprehending the flood risk concerns the frequency and intensity of floods, the exposition of humans and assets to flooding, their sensitivity to floodwater and their susceptibility to suffer damage. In order to produce this knowledge, flood risk analysis embraces different states of knowledge including civil engineering, hydro-geo-socio sciences and economics. The multi-disciplinary aspect of the flood risk and the multi-modelling characteristic of flood risk evaluations lead to a complex methodological organization involving several sources of uncertainty. The accuracy of potential flood damage estimations depends on both, the modelling of the flooding natural phenomenon and the assessment of the vulnerability of the human systems exposed to floods. The understanding of epistemic uncertainty behind the different modules of the evaluation is essential to optimise the efforts in reducing the evaluation global uncertainty, in order to improve management decision-making processes. The aim of this thesis is to improve the global understanding about the different sources of uncertainty related to the economic analysis of flood risks. It focuses on how different strategies used to model flood hazards and assess the vulnerability of a territory may affect the estimations of potential flood damage.

The first part of this thesis introduces flood risk analysis concepts and principles. We realize a general state of the art of the research topic, we explore the research question and present the global research framework. In the second part of this thesis, we individually analysed the sensitivity of damage estimations to the different modules of the evaluation process. Several tests based on two French case studies were performed. We measured the variability of damage estimations as a function of different considerations on datasets, methods and models used to: analyse the probability of floods (hydrology); model and map flood hazard (hydraulics); and assess the vulnerability and susceptibility of buildings to floods (civil engineering, geography and environmental economics). The results of these tests highlight that the level of epistemic uncertainty linked to these evaluations is considerably high. The selection of models and methods used as well as the scales of analysis considered when estimating potential flood damage must be the object of consistent pre-studies. Further, we used parallel-modelling approaches to quantify the relative impact of different sources of uncertainty on the potential damage estimations. The results show that the relative contribution of the different modules to global uncertainty depends on several aspects of the evaluation, including site specificities and the distribution of flood probabilities. In despite that the use of complex methodological approaches to quantify global uncertainties is nowadays unrealistic for practical evaluations; the method developed here and its results should bring support for practitioners in the investigation of uncertainties, determination of evaluation priorities and optimisation of the distribution of resources between the different modules of the evaluation process. Finally, the third and last part of this work goes beyond the thesis main objective, in order to explore a second level of complexity concerning flood risk evaluations. We developed a method in order to analyse the systemic damage and dysfunction potentials of networks infrastructure in relation with the resilience of a territory to floods. This concern is barely deeply considered in flood damage evaluations, and it represents an important source of uncertainties. The methodology developed should provide more detail in the estimates of flood damage bringing the possibility to improve indirect damage estimations.

A general synopsis of this thesis is available in French language: Eleutério J., Mosé R. et Rozan A., Evaluation des dommages potentiels liés aux inondations : impact des stratégies utilisées pour modéliser l'aléa inondation et caractériser la vulnérabilité des enjeux sur les résultats des évaluations de dommages potentiels liés aux inondations, research project final report ENGEES/Fondation MAIF, 36pp., 2012.

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Résumé

L’inondation constitue le risque naturel le plus dommageable dans le monde. Une meilleure compréhension sur les inondations et les conséquences diverses qu’elles peuvent causer à notre société est un élément fondamental pour guider le développement de politiques de gestion et réduction du risque inondation. Les connaissances de base pour appréhender le risque inondation concernent la fréquence et l’intensité des inondations, l’exposition des enjeux aux inondations, leur vulnérabilité et susceptibilité à subir des dommages. L’analyse du risque inondation comprend différents états de connaissance comme les sciences de l’ingénieur, de l’eau, de la terre, sociales et économiques. L’aspect multidisciplinaire du risque inondation ainsi que les divers modèles nécessaires à l’évaluation du risque sont à l’origine d’une complexité organisationnelle contenant plusieurs sources d’incertitude. La précision des évaluations de dommages liés aux inondations dépend à la fois des modèles d’inondation et des modèles de vulnérabilité des enjeux. La compréhension des incertitudes épistémiques derrière les différents modules d’évaluation du risque est essentielle à l’optimisation des efforts de réduction d’incertitudes de l’évaluation, afin d’améliorer la prise de décision en matière de gestion du risque. L’objectif principal de ce travail est de contribuer à l’amélioration des connaissances concernant les différentes sources d’incertitude présentes dans l’évaluation économique du risque inondation. Il se concentre sur l’impact des différentes stratégies utilisées pour modéliser l’aléa inondation et la vulnérabilité d’un territoire sur les résultats de l’évaluation des dommages potentiels liés aux inondations.

La première partie de ce travail introduit les concepts et principes liés à l’analyse du risque inondation. Nous réalisons un état de l’art de la matière, en explorant la question de recherche et présentant le plan de recherche adopté. Dans la deuxième partie de la thèse nous mesurons les incertitudes liés aux évaluations de dommages. Nous analysons dans un premier temps la sensibilité des estimations de dommages aux différents modules de l’évaluation. Plusieurs tests ont été mis en œuvre sur deux études de cas en France. On a mesuré la variabilité des estimations en fonction des différentes bases de données, modèles et méthodes considérées pour : analyser la probabilité des inondations (hydrologie) ; modéliser et cartographier l’aléa inondation (hydraulique) ; et caractériser la vulnérabilité des bâtiments et leur susceptibilité à subir des dommages (génie civil, géographie et économie de l’environnement). Les résultats de ces tests révèlent l’importance des incertitudes épistémiques dans ce type d’évaluation. Le choix des modèles et méthodes à utiliser ainsi que les échelles d’analyse à considérer pendant l’évaluation doivent faire l’objet de pré-études consistantes. Ensuite, nous avons procédé à des « modélisation parallèles » pour quantifier l’impact relatif de différentes sources d’incertitude sur les estimations de dommages. Les résultats démontrent que la contribution relative des différents modules à l’incertitude globale dépend de plusieurs aspects de l’évaluation comme les particularités du site analysé et la distribution des probabilités d’inondation. Même si l’utilisation courante de méthodologies complexes pour quantifier les incertitudes globales dans ces évaluations demeure aujourd’hui irréaliste ; la méthodologie développée dans cette étude et ses résultats pourrons supporter le praticien dans l’analyse d’incertitudes, la détermination de priorités et l’optimisation de la distribution des ressources entre les différents modules de l’évaluation. Enfin, la dernière partie de ce travail explore un degré de complexité supplémentaire des évaluations du risque inondation. Nous développons une méthode d’analyse systémique du dysfonctionnement et endommagement potentiels des réseaux d’infrastructure en lien avec la résilience du territoire face aux inondations. Cet aspect n’est que rarement approfondi dans les évaluations de dommages potentiels, représentant une importante source d’incertitudes. La méthodologie développée devra permettre une analyse plus détaillée de cet aspect dans les évaluations, rendant possible l’amélioration des estimations de dommages indirects.

Une synthèse générale de la thèse est disponible en langue française : Eleutério J., Mosé R. et Rozan A., Evaluation des dommages potentiels liés aux inondations : impact des stratégies utilisées pour modéliser l'aléa inondation et caractériser la vulnérabilité des enjeux sur les résultats des évaluations de dommages potentiels liés aux inondations, rapport final de projet de recherche ENGEES/Fondation MAIF, 36pp., 2012.

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GENERAL INTRODUCTION

The evolution of human society always depended on the dynamics of water. For a long time men selected living places according to the availability of resources and climate conditions. First sedentary civilisations settled in riverine areas and their development was dependent on their capacity to control water resources and risks. Great civilisations developed near the rivers Euphrates, Tiger, Nil, Indus and Yellow constituting examples of settlements in constant relationship with river water issues. The knowledge of the hydrological cycle of rivers and the development of techniques of flood control were always essential to the development of the society. The best example of this was the case of Nil River where several hydraulic canals were used for irrigation, and several instruments were used for surveying the river dynamics (Viollet, 2004).

The great majority of further civilisations also settled near water bodies. The dynamics of water are interesting for agriculture, sanitation and energetic exploitation. The river waters were and are still an opportunity for man to produce, entertain and develop. Men always dealt with the water cycle trying to take the most of it. With this purpose, several works took place in the water bodies for adapting the environment to local societal demands. The floodplains are still attractive for several purposes, *e.g.* geomorphologic advantages for development of industrial facilities, river transportation capabilities, entertainment potential for living and tourism exploitation, well-being of living near water-bodies, resource availability, sanitation potential, etc. The growing of population contributed to the development of urban centres, historically and strategically located on floodplains. This scenario creates a strong occupation pressure over floodplains for residential, activity purposes and agricultural purposes.

The attractiveness of these areas generated great accumulation of values in floodplains, increasing the flood risk, *e.g.* in Netherlands where great percentage of the territory is located in flood zones, in France were major floodplains like Loire, Rhone and Rhine are densely occupied by commercial and industrial activities. On the one hand, the concentration of population on floodplains induces the modification of the cycle of water. It caused the growth of the flooding phenomenon due to the sealing of soils. Several techniques were developed to control water-bodies and to understand their functioning. They were used to modify the dynamics of water by constructing hydraulic structures like dams and dikes. On the other hand, a larger amount of goods and people became exposed to floodwater. Riverine society is nowadays threaded by several degrees of hazard with different intensities and probabilities of occurrence. Furthermore, these issues are in evolution and climate change could play an important role on the aggravation/attenuation of hazards and subsequently, risks.

Flood risk and flood consequences

Formerly, flood risk was mainly associated with hazard occurrence probability. However, flood risk is a concept in constant evolution. Nowadays, the flood risk is considered as the combination of the hazardous phenomenon of flooding and a vulnerable system susceptible to suffer loss. As inferred by White (1945), "Floods are acts of god, but flood losses are largely acts of man". The flood risk brings different aspects together, *e.g.* natural, human, social, economic and environmental. In some cases, floods can generate benefits, *e.g.* the case of the Nil floods and the fertilisation of floodplains, benefits of floods: flood in Seguenay in Quebec 1996, improving tourism in region, and the flood in "l'Aude" in France 1999 improving solidarity between towns (D4E, 2007). However, extreme events always caused several problems to our societies, *e.g.* the "deluge myth" that could represent the reflect of the fear of floods of ancient society, and the catastrophic floods occurred in the Yellow River floodplain during the last millenaries (Viollet, 2004). The flood risk is nowadays the more damaging natural hazard in the world. The catastrophes occurred during this last decade and their impacts on the society revealed that we are not yet prepared to deal with this problem. Damage caused by floods on human health is the most adverse consequence of flooding, *e.g.* psychological problems, injuries and loss of human life. However, the loss of goods and disruption of activities as well as environmental issues also gained the attention of experts all over the world.

Flood risk and potential flood damage assessments

The knowledge of the flood phenomenon and its consequences is crucial for the development of flood control, risk reduction, improvement of resilience and flood management in general. Besides understanding former phenomena, flood forecasting is essential for anticipating damage and preparing adequate alternatives to reduce them. Different states of knowledge are necessary to understand this phenomenon, *e.g.* the rain intensity and frequency (hydrology), how the river responds to the rain (hydraulics), what kinds of assets are inside the flood zone (geography), how sensitive theses assets are to floodwater, how they respond to the hazard (civil engineering) and how they are susceptible to suffer damage (environmental economics). The main purpose of risk analysis is to understand and measure the possible consequences associated with the occurrence of flooding in areas occupied by vulnerable systems. Scientists and practitioners all over the world brought great improvements to the state of the art of flood phenomenon and flood risk management over time (Merz et al., 2010b).

The analysis of potential flood damage is based on different aspects of the flood risk. The first aspect is the natural phenomenon, their magnitude and frequency. Flood maps are the base of flood risk analysis. Flood hazard maps can be used to regulate land-uses as well as to support project design to alleviate floods. The natural phenomenon is in a permanent evolution, which implies that these maps are just a "picture" of the situation in a specific moment. The knowledge of the flood risk goes far beyond the individual understanding of the flood natural phenomenon. The understanding of the human systems exposed to the flood hazard is also crucial to understand flood risks. The vulnerability of a specific system to the characteristics of the flood hazard is therefore the second aspect of the risk that must be understood in order to support flood management.

Flood risk management is extremely complex involving public and private interests, confronting social, economic, politics, environment, religion and nature. The stakeholders working on this field come from different fields of knowledge and have different interests. The economic evaluation of flood damage plays an important role in decision-making processes. Economic evaluations are being considered the standard approaches to guide flood management, *e.g.* cost-benefit analysis, multi criteria analysis considering the economic aspect of floods (MEDDE, 2012a; CEPRI, 2011). The EU Floods Directive 2007/60/EC (European Parliament Council, 2007) statements[1] are the reflex of this issue in the European context. The insurance system also plays an important role in this aspect once they are in the interface between private and public interests. Economic analyses of the flood risk are also crucial for budget determinations and insurance rates planning (NRC, 2009).

The implementation of economic damage analyses and associated uncertainties

Different stakeholders, with different purposes, can command food risk analyses. Furthermore, flood damage estimations bring together different pieces of knowledge of the flood risk. Several methods can be used to evaluate flood damage (Merz et al., 2010b). The different methods require production of knowledge about the flood phenomenon as well as knowledge about the vulnerability of the assets exposed to the risk (Messner et al., 2007). Hydrologic analyses are used to determine the probability and intensity of flood events. Hydraulic modelling is used to simulate floods and produce flood maps. Vulnerability assessments are realised in order to understand the exposure of a territory to floods and its vulnerability. Finally, susceptibility analyses serve to determine assets damage potential to floods.

The liability of potential flood damage estimations relies on both, knowledge on the flooding natural phenomenon and on the human system vulnerability to floods. Due to the multi-disciplinary aspect of these evaluations, their organization is a complex task. Uncertainty is part of the evaluation process. There are several variables in this process and several choices can be made when deciding on the different methods and approaches used to achieve these analyses. These choices concern the datasets, scales, hypothesis, methods and computer programs to use in the evaluation process. Understanding uncertainty behind these choices is crucial for reducing uncertainty efficiently (Green et al., 2011).

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[1] "In order to have available an effective tool for information, as well as a valuable basis for priority setting and further technical, financial and political decisions regarding flood risk management, it is necessary to provide for the establishing of flood hazard maps and flood risk maps showing the potential adverse consequences associated with different flood scenarios..." [L288/28, statement 12] and "Flood risk management plans shall take into account relevant aspects such as costs and benefits…" [L288/31, Chapter 4, article 7, statement 3].

Motivation

The contribution of the different aspects of risk estimations to the global uncertainty is not yet well understood. As suggested by Merz et al. (2010b) the relative contribution of the different elements of a flood risk analysis to the total uncertainty is a question which has been hardly explored. When implementing damage estimations, it is hard to make comprehensive choices on methods and models because of the current misunderstanding of their influence on the accuracy of the estimation. This misunderstanding compromises the optimisation of strategic choices when organizing damage evaluations. In practice, data availability is an important issue in these evaluations (Messner et al., 2007). As inferred by Green et al. (2011), "there is almost always a difference between the data that is necessary to make a decision and that which is available. Decisions therefore have to be made both with available data and in the knowledge that it is 'inadequate'; one definition of engineers is thus that they are people who have to take decisions using totally inadequate data" [page 69]. In order to guide decisions based on inadequate data or to decide on improving data, it is essential to understand the impact of data and methods used for evaluating flood damage on the results of the evaluation. Analysts tend to expend large proportions of scheme appraisal budgets in hazard modelling, giving less importance to the other aspects of the evaluation process, which can compromise damage estimations (Penning-Rowsell et al., 2005). A study allowing the comparison of methods and approaches used during the different steps of the evaluation process should bring guidelines for analysts when realising pre-studies concerning these evaluations. It should help to determine the evaluation priorities, supporting the selection of resources distribution for the evaluation process.

Objective of the thesis

The objective of this thesis is to contribute to the understanding of how different strategies used to model flood hazards and assess the vulnerability of a territory to floods can affect the results of potential flood damage evaluations.

The different strategies studied in this thesis concern (1) the realisation of flood hazard maps and (2) the assessment of assets vulnerability to floods. Different strategies are adopted to construct flood maps in relation to two aspects: the hydrological hypothesis considered when determining flood frequency and intensity, and the hydraulic approaches used to simulate flood events. Strategies concerning the assessment of the vulnerability of assets to floods are different in relation to the approaches used to make the inventory of assets, to identify their susceptibility to suffer damage, and to determine their damaging potential.

Thesis disciplines

This thesis focuses on the uncertainties linked to different aspects of flood risk assessments. In order to understand the influence of different states of knowledge on the evaluation of flood risk, this work embraces the following fields of knowledge: Civil engineering, Hydrology, Hydraulics, Geography and Environmental Economics.

Outline of this thesis

The present manuscript is organised in three parts. In the first part (PART I) we explain the context of the study introducing the concepts needed for the global understanding of this work and we develop the thesis question by making the state of the art of the question and by describing the methodology used in this thesis. The second part (PART II) is the core of the thesis. It is dedicated to the methods used to make the different tests and case-studies realised in order to respond to our objectives as well as the results of these tests. Finally, in the third part (PART III), we extend the objectives of this study to present a research on the evaluation of a second level of flood consequences. We develop a method to analyse damage and dysfunction of networks infrastructure in relation with the resilience of a urban system. A general synopsis of this thesis is available in French language[2].

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[2] Eleutério J., Mosé R. et Rozan A., Evaluation des dommages potentiels liés aux inondations : impact des stratégies utilisées pour modéliser l'aléa inondation et caractériser la vulnérabilité des enjeux sur les résultats des évaluations de dommages potentiels liés aux inondations, research project final report ENGEES/Fondation MAIF, 36pp., 2012.

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- PART I -

STATE OF THE ART

AND RESEARCH QUESTION

Flood risk management is still a big challenge in terms of scientific knowledge as well as in terms of socio-economic efficiency improvement. Flood risk analyses are essential tools to support territory organization, land-uses policies, flood management projects, recovery budget and insurance rates determination. Several types of analysis can be used with different purposes. The evaluation of potential flood damage is an important type of analysis that is gaining importance over time. These analyses allow us to quantify the risk, taking into account different criteria and approaches according to the objectives of the evaluation. In this thesis, we explore the evaluation of potential flood damage and its uncertainties associated to the datasets and methods used to map flood hazard and estimate the vulnerability of assets to floods. The first part of this dissertation is devoted to the development and explanation of the research focus and framework. This part of the document is organized in three chapters. In Chapter 1, we make a general literature review about flood management and risk assessments. In this chapter, we explain the context of the study introducing the main concepts required for the understanding of this work. Chapter 2 introduces the different sources of uncertainty linked to the evaluation process. We introduce, in this chapter, the thesis research question and describe how we proceed to answer it. Finally, in Chapter 3, we present the development of flood damage estimations based on a tool built to realize all the uncertainty tests used to achieve the objectives of this thesis.

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Chapter 1.

Concepts related to risk management and flood damage estimations

The objective of this chapter is to introduce the main concepts related to flood risk and damage estimations. Flood risk is the combination of flood hazard, the vulnerability of assets, flood consequences and probability. This complex phenomenon involves natural and human aspects, as well as private and public interests. The consequences of floods can be of several types. We can distinguish positive consequences of floods, *i.e.* benefits, from negative consequences, *i.e.* losses or damage. Losses caused by floods are of different natures, *e.g.* environmental, social, economic, human etc. Floods are the main natural hazard in the world, in terms of loss of life and monetary damage they cause. Flood risk management is a big challenge in our society. Different measures can be adopted to manage flood risks. Flood management schemes are used to reduce the actual vulnerability of assets to floods, to limit the increase of a territory vulnerability overtime, to control the flood hazard, to prepare for flood events, to improve the post-catastrophe recovery and resiliency, etc. The purpose of all kinds of measures is to reduce the damaging potential of floods. They all involve monetary costs, *e.g.* the construction of flood protection infrastructure like dams or dikes, the improvement of buildings fabric to resist to floodwater, the refund of damaged structures by insurance companies, etc. The evaluation of potential flood damage becomes an essential tool used to quantify the economic risk, and support portfolio organization, cost-benefit and multi-criteria analyses. Several methods can be used to evaluate potential flood damage. The deterministic approaches are the most frequently used with this purpose. They count on detailed description of the vulnerability of assets to floods and the flood hazard it-self. This method is herein described in details.

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1. Introduction

The flood risk represents the main natural hazard in the world in terms of damage it causes (Messner et al., 2007). In France, about 17 million people are exposed to the floods and the damage they caused are estimated from 250 million €/year in average[7] to 400 million €/year (MEDDE, 2011). Flood risk is a complex process that combines human and natural factors. The flood risk is characterized by the conjunction of the probability of floods to take place and the potential consequences associated to them. Floods only cause damage when flood zones are occupied by vulnerable human systems. The flood hazard is a physical phenomenon with its characteristics. The assets and their vulnerability to the flood hazard include their sensitivity to flood hydraulic parameters, *i.e.* flow velocity, water depth... and their exposure to the risk. The consequences of floods are from different natures, *e.g.* social, cultural, economic, human, environmental... These consequences can be negatives and/or positives, affecting different assets, *e.g.* material damage on buildings and contents, health damage on human being, environmental damage, financial losses and/or gains of different commercial/industrial activities.

All kinds of flood risk management processes expect the reduction of negative consequences of floods. We can reduce the risk by controlling the hazard and/or by reducing the vulnerability of the assets exposed to flood events. The evaluation of potential damage of floods allows us to compare different management solutions in economic terms. Therefore, potential flood damage assessments are essential tools to support flood management decisions, and they are gaining importance overtime. Cost-benefit and multi-criteria analyses are methods classically used to support management design (MEDDE, 2012a; Merz et al., 2010b). These methods are directly dependent on the results of these assessments. Damage potential evaluation is also an important tool to support insurance policy definition. Several methods and guidelines were developed and used all around the world to evaluate potential flood damage. These evaluations embrace several assumptions, models and variables inducing uncertainties on its results. The damage evaluation results reliability is an important issue when comparing flood risk reduction project scenarios or determining insurance rates, potentially influencing the management efficiency.

The objective of this chapter is to introduce the main concepts linked to flood risk and damage evaluation processes. Section 2 introduces the general concepts and notions concerning flood risk and damage potential. Section 3 presents flood risk management principles as well as the role of flood risk scientific knowledge in decision-making processes. In section 4, we present different flood damage evaluation methods available. Finally, in section 5 we present the deterministic evaluation of potential flood damage.

2. Flood risk

The term risk is commonly used to associate potential consequences, positive or negatives, linked to a specific decision, act, fact or hazard. In the case of floods, the risk has been and is still sometimes considered as a fatality, in which the ‘victims” or losses depend exclusively on the natural forces guiding the flood event. Therefore, the flood risk is largely used to designate the probability of floods to take place. Contrary to this use, scientific literature largely agreed that flooding is not a risk on its own: the concept of risk involves at least two aspects, a hazardous phenomenon and the vulnerable systems exposed to it (Merz et al., 2010b; Torterotot, 1993; White, 1945; Messner et al., 2007; Penning-Rowsell and Chatterton, 1977). The hazardous phenomenon is the presence of water and its characteristics in a specific place and time. The vulnerable systems are the assets, human beings, goods, environment and all kind of values exposed to the hazard. Therefore, the flooding phenomenon is a natural process that is considered as a risk only if human added values are potentially affected by floodwater. In order to understand the flood risk, we are constraint to understand the flooding phenomenon as well as the vulnerable systems potentially affected by the flood. The following subsections bring these essential concepts related to floods.

2.1. Floods – natural hazards?

The flood hazard is characterised by the presence of water in areas where water is not generally present (European Parliament Council, 2007). This general concept embraces all kinds of flood. We can distinguish some of them in Table 1.1.

A flood event is conditioned by several factors that promote the difference between events in different contexts. In the case of river flooding, extreme climate conditions lead to important concentration of rainwater that flows over the landscape and concentrate in the river channels. The concentration of water in riverbeds leads to the overflow of rivers that spread over the floodplain inundating areas that are not generally occupied by water. This type of event is the most damaging between the different types of floods described in Table 1.1 because of their frequency as well as the number of people and assets exposed to it. In the majority of types of floods, meteorological, hydrological and landscape parameters define the flooding phenomenon.

Humans had two options when developing a sedentary societal lifestyle: (1) they could adapt their inhabits according to the natural environment or (2) they could adapt the natural environment to their inhabits. By adopting the second option, several water-bodies were, all over the world, strongly modified over time, *e.g.* the Rhine River[3]. In addition, the natural floodplains were modified overtime

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[3] Internet site of the International Commission for the protection of the Rhine: http://www.iksr.org

in order to adapt the landscape for receiving the population and their activities. On the one hand, the modification of the water bodies helps society to protect goods from the natural phenomenon. On the other hand, new manmade hazards were created, *e.g.* dikes and dams break floods. These hazards can be associated or completely dissociated to natural climate and hydrological aspects. The flood hazard can be indeed independent of natural phenomena. In these contexts, flood risk is generally used to express the probability of occurrence of a flooding event, taking into account hydro-meteorological and technological aspects.

Table 1.1. Different types of flood phenomenon. Source: prim.net[4]

Type of flood	**Description of the flood phenomenon**
Floods by river water	The river flow slowly exceeds the riverbed capacity and flows out though the floodplain during a long period.
Groundwater inundation	During periods in which the soil is completely saturated with water, groundwater can be present in the soil surface. This phenomenon is slow.
Fast floods in torrential rivers	The intensity of rain and the forms of the watershed can contribute to high-speed concentration of rainwater in the river bodies. This water exceeds the capacity of the riverbed and generates fast floods.
Fast floods in peri-urban watersheds	The land-use characteristics of peri-urban areas reduce the soil infiltration capacity increasing the rainwater runoff. The flood water systems of cities can quickly became saturated generating overflow, and flooding in streets.
Technological floods	These floods can be generated by accidents occurred on hydraulic structures, *e.g.* a dam break can generate large amount of water flow in the downstream part of a river, a dike break generate a lateral vague quickly inundating the areas behind the dike.
Coastal flood	The sea level rises due to extreme climate conditions inundating coastal areas, *e.g.* tsunami, storms.

2.2. Human systems vulnerability – exposure and susceptibility to suffer damage

The organization of human society was always linked to the cycle of water. One of the consequences of this is that the majority of civilisations settled near water-bodies. The first aspect of the vulnerability of assets to floods is their potential to be reached by floodwater, *i.e.* exposure. Unfortunately, great percentage of city areas is still located inside flood zones, increasing the exposure of people and goods to floods, *e.g.* Netherlands, Bangladesh. The concept of vulnerability is complex and controversial, and goes far beyond the simple concept of exposition of assets to floods. The vulnerability also represents the susceptibility of the assets to suffer consequences due to this exposition (Barroca et al., 2006; Green et al., 1994; Messner and Meyer, 2006). Furthermore, the impacts of the exposition of values to floodwater depend on the characteristics of both, the assets and the hazard. Even though each asset or system has its own characteristics, we can consider that the

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[4] "Portail de la Prévention des Risques Majeurs" web site : http://www.prim.net

vulnerability concept is also intrinsically linked to the hazard characteristics. The terms of direct, material or physical vulnerability are used to define the probability or likelihood of assets to suffer consequences linked to the immediate contact with the hazardous phenomenon. Indirect and functional vulnerability are used to determine the likelihood of assets to be indirectly affected by a hazard or to induce other impacts. Both terms contain hazard and vulnerability characteristics. In this context, the flood risk is considered as the combination of hazard and vulnerability (Figure 1.1).

Figure 1.1. Flood risk as the conjunction of hazard and vulnerability. Source: prim.net[5].

2.3. Flood effects, consequences and damage

Floods generate several effects in the environment reached by them, in a direct or indirect way. Torterotot (1993) introduced an interesting differentiation between flood effects, impacts and damage. Some of the effects of floods are "perceived" by men, others are not. In the same way, some effects are "felt" and others do not. The meaning of the words "perceive", *i.e.* became aware or conscious of, and "feel", *i.e.* be affected by, express the basic difference between "effect", "impact" and "damage". The effects of foods are defined as all objective changes generated by floods, on natural, human and economical systems. Impacts are the effects perceived by society, or effects that society attaches some importance. Damage is impacts with anthropogenic added values, in a monetary or subjective way. The following scheme represents these concepts (Figure 1.2).

Flooding is considered the first damaging natural hazard in the world (Messner et al., 2007). Damaging floods are floods that have adverse impacts on the social system, the natural system or the

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[5] "Portail de la Prévention des Risques Majeurs" web site : http://www.prim.net

built environment (Merz et al., 2010a). Floods can also have positive consequences, like the fertilization of floodplains in non-controlled rural areas, the increase or maintenance of biodiversity in natural areas, the reinforcement of social links between affected people in urban or rural context, etc. The aggregation of values to consequences of floods includes a lot of subjectivity, especially when making the difference between positive and negative consequences of floods. They can be considered negative and positive at the same time, depending on the point of view. For example; dwelling structure material loss caused by a flood event is felt by the dwelling owner as a negative consequence of the flood once the owner will be supposed to expend monetary resources in order to repair or replace it; nevertheless, the civil engineering enterprise that will be in charge of the house repair or replacement works will perceive the consequence of flooding as a benefit once it will probably makes profit on it. Therefore, when using the term of flood damage, it is crucial to specify who suffer the damage and who pay for it.

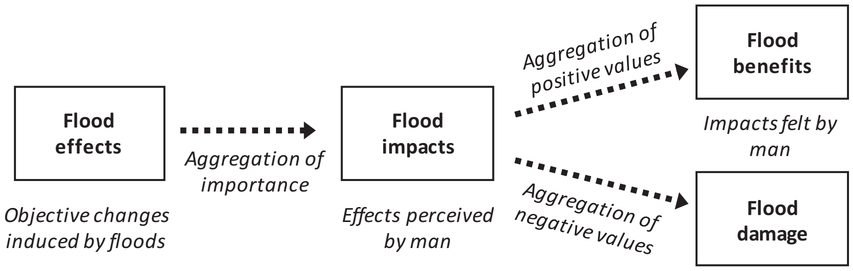

Figure 1.2. Effects, impacts and damage linked to floods.

2.3.2. Damaging processes and influencing factors

Assets exposed to floods can be damaged in three different ways (Green et al., 2011): (1) physical processes (*e.g.* mechanical damage as a result of impact); (2) chemical processes (*e.g.* corrosion) and (3) biological processes (*e.g.* mould). These processes depend on several characteristics of both, the flood hazard and the vulnerability of assets. In the context of flood analysis, several characteristics of floods can influence damage (Table 1.2). The characteristics of assets influencing damage in case of floods depend on the type of the asset exposed to the flood hazard. We present some examples in the following table (Table 1.3).

In addition to the three damaging processes elucidated, damage can occur on systems that are not directly exposed to floodwaters. This damage is therefore linked to the damage potential of structures touched by floodwater, their dysfunction and the degree of dependence on other elements to these structures (Narbonne, 2005).

Table 1.2. Inundation damage influencing factors. Source: Messner et al. (2007)

Inundation characteristics	**Relevance**
Area	Determines which elements at risk will be affected
Depth	Has perhaps the strongest influence on the amount of damage
Duration	Special influence on damage to building fabric
Velocity	Only high velocities will lead to increased damage; therefore mainly relevant in flash flood areas or areas near dike breaches
Rise rate	Influence on damage reducing effects of warnings and evacuation
Time of occurrence	Especially important for agricultural products
Contaminations	Contaminations and loads may increase damage significantly
Salt-/freshwater	Saltwater may increase damage; relevant in coastal areas

Table 1.3. Vulnerability damage influencing factors for different types of asset exposed to floods.

Asset	**Damage influencing characteristics**
Buildings fabric	Type of construction, materials, actual state of conservation of structure etc.
Buildings contents	Type of occupation, socio-economic characteristics, alert system efficiency, preparedness, context.
Human-beings	Age, health, preparedness, culture, level of instruction.
Networks	Type of network, level of dependency, etc.

2.3.3. Damage classification

Flood losses are commonly classified into four categories: direct tangible, indirect tangible, direct intangible and indirect intangible (Hubert and Ledoux, 1999; D4E, 2007; Penning-Rowsell and Chatterton, 1977; Merz et al., 2010b; Torterotot, 1993; Messner et al., 2007; DNRM , 2002). This classification is correlated to two aspects: the first one is the cause of the loss or “damaging way”, *i.e.* direct and indirect damage, and the second one is the possibility to associate a monetary value to the losses, *i.e.* tangible or intangible damage.

- Direct damage is due to all variety of effects caused by the immediate contact of floodwater with humans, goods or the environment. These impacts are easily felt by the society exposed by the event once it implies direct socio-economic losses.
- Indirect damage can have two different causes: (1) it is a consequence of direct damage that induced the dysfunction of systems, *e.g.* the interruption of gas or electricity delivery, traffic disruption etc; (2) it is linked to the measures adopted to reduce direct damage, *e.g.* rescue services. This damage cannot be felt and quantified immediately after the flood event.
- Tangible damage is losses “easily” expressed in monetary terms. It is therefore damage that the society is able to aggregate an economic value, *e.g.* the destruction of a building, the total loss of good, etc.
- Intangible damage is losses generated to non-marketable goods. This damage is hardly associated to a monetary value. The economic value of the loss is subjective and hard to evaluate. It is considered as a non-valuable cost, *e.g.* loss of life.

2.3.4. Typology of flood damage

Several types of damage can be caused by floods, *e.g.* “floods have the potential to cause fatalities, displacement of people and damage to environment, to severely compromise economic development and to undermine economic activities of the Community” [L 288/27, statement 1] (European Parliament Council, 2007). The impacts of floods are respectively those on human beings, on the socio-economic and natural environment (Hubert and Ledoux, 1999). The main damage types and categories are listed in Table 1.4:

Table 1.4. Types of flood damage. Source: Nascimento et al. (2007) and Hubert and Ledoux (1999)

Assets at risk	**Tangible damage**		**Intangible damage**	
	Direct	**Indirect**	**Direct**	**Indirect**
Residential dwellings	Degradation or destruction of goods	Cleaning, health care and housing facilities	Human life losses, corporal damage, loss of irreplaceable goods	Psychological effects, long-term health problems
Commercial and services activities	Degradation or destruction of goods, stocks, working material	Cleaning, technical unemployment, loss of exploitation and databases	Human life losses, corporal damage	Psychological effects, long-term health problems
Industrial and artisanal activities	Degradation or destruction of goods, stocks, machinery	Cleaning, technical unemployment, loss of exploitation and databases	Human life losses, corporal damage	Psychological effects, long-term health problems
Rural	Degradation or destruction of farms, cultures, animals and stocks	Cleaning, technical unemployment, loss of exploitation	Human life losses, corporal damage	Psychological effects, long-term health problems
Services and public buildings	Degradation or destruction of goods	Cleaning, rescue services, interruption of services	Human life losses, corporal damage	Psychological effects, long-term health problems, users inconvenient
Networks and infrastructure	Degradation or destruction of goods	Cleaning, interruption of services, crises management costs	-	Users inconvenient
Local development	-	Degradation of local finances, reduction of property prices, attractiveness	-	Citizens inconvenient
Cultural and historical heritage	Degradation or destruction of goods	Cleaning	Loss of irreplaceable goods	-
Environment	-	-	Diffuse pollution	Long term natural development

2.3.5. Intensity of economic damage

The number of human losses and the amount of material damage caused by floods represent a big socio-economic problem in modern society. Recent floods all over the world confirm this statement, *e.g.* Eastern Europe in August 2002, France in May 2008, Morocco in October 2008 and Brazil in

November and December 2008. The intensity of damage caused by floods is completely correlated to the context in which the flood takes place and the characteristics of the flood event. The works of (Barredo, 2007, 2009; Sanders et al., 2005) describe several damaging events in Europe. Table 1.5 summarizes some major events in Europe.

Table 1.5. Major damaging floods in Europe. Source: Sanders et al. (2005), RMS[6] and press data.

Date	Country	Type	Economic loss	Insured loss	Casualties
1362	Germany, Denmark	Coastal	-	-	100,000
1421 (Nov)	Netherlands	Coastal	-	-	10,000
1570	Netherlands, Belgium	Coastal	-	-	> 10,000
1717	Germany, Netherlands	Coastal	-	-	11,500
1755	Portugal, Spain	Tsunami	-	-	10,000
1910	France	Riverine	8.5bn	-	-
1928 (Jan)	United Kingdom	Coastal	-	-	14
1947	United Kingdom	Riverine	450m	-	0
1953	United Kingdom, Netherlands	Coastal	18bn	-	1,932
1962	Netherlands, Germany, Denmark	Coastal	4bn	-	350
1966	Italy	Riverine	10bn	-	39
1983	Spain	Riverine	2bn	-	40
1993	Germany, Netherlands, Belgium, France, Luxembourg	Riverine	1.4bn	620m	14
1994	Italy	Riverine	11bn	581m	64
1995	Germany, Netherlands, Belgium, France, Luxembourg	Riverine	2.7bn	581m	28
1997	Poland, Czech Republic	Riverine	3.8bn	581m	100
1998	United Kingdom	Riverine	-	215m	5
1998	Slovakia, Czech Republic	Riverine	-	-	63
2000	United Kingdom	Riverine	-	715m	-
2002	Austria, the Czech Republic and Germany	Riverine	15bn	2.25bn	110
2005	Romania, Switzeland, Austria and Germany	Riverine	2.3bn	1.25bn	42
2010	Poland, Austria, Czech Republic, Germany, Hungary, Slovakia, Serbia and Ukraine	Riverine	> 3bn	-	34

Damage caused by floods in urban areas is extremely high because of the amount and value of the stakes at risk. The intensity of damage varies among the different categories of assets impacted by floods. In general, buildings and contents represent the majority of damage in urban areas. Infrastructure and networks are also highly damaged by floods, increasing the cost of flood events (Hubert and Ledoux, 1999).

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[6] Risk Management Solutions (RMS) web site: http://www.rms.com/

In France, flood damage represents approximately 80% of the cost of damage due to natural hazards, 250 million €/year in average[7]. Insured damage caused by floods were estimated at 400 million €/year during the last 30 years, according to MEDDE (2011). Several damaging floods occurred in France all over its history (Champion, 1862). The following table summarizes some major damaging floods occurred in France during the last century (Table 1.6).

Table 1.6. Major recent damaging floods in France. Source: prim.net[7] and CCR database[8].

Date	Location	Monetary loss	Casualties
1910	Paris (Seine)	1,07 billion Euros	Less than 5
1930	Montauban and Moissac (Tarn-et-Garonne)	3,000 houses and 11 big bridges destroyed. Most damaging flood from twenties century in France.	More than 200
1940	Pyrénées-Orientales	Destructions	50
1987	Grand Bornand (Haute-Savoie)	-	23
1988	Nîmes (Gard)	500 million Euros	10
1992	Vaucluse (Vaison-la-Romaine), Ardèche and Drôme	More than 500 million Euros	47
1995	43 French "Départements" impacted (Basse-Normandie, Bretagne, Champagne-Ardennes, Pays de la Loire, Île-de-France)	610 million Euros	15
1999	Aude, Tarn, Pyrénées-Orientales and Aveyron	533 million Euros	36
2001	Somme, Oise and Eure (groundwater inundation)	In Somme "Département": 1,100 displaced inhabitants, more than 3,000 houses damaged; more than 150 million Euros	-
2002	Gard and near French "Départements"	1.2 billion Euros	23
2003	Rhône	More than 1 billion Euros	7
2008	Centre-west of France	160 million Euros	-
2010	Var French "Département"	560 million Euros	23
2010	Vendée and Charente-Maritime (Xynthia)	710 million Euros	47

2.4. Flood risk - conjunction of loss and probability

Finally, according to the EU Floods Directive 2007/60/EC (European Parliament Council, 2007), the risk is the conjunction of consequences of hazards on human systems and its probability of occurrence[9]. The determination of this risk in economic terms passes by the combination of hydrological knowledge about the frequency of flood events for different intensities, and the estimation of damage associated to these different flood frequencies of occurrence (probabilistic

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[7] "Portail de la Prévention des Risques Majeurs" web site : http://www.prim.net

[8] "Caisse Centrale de Réassurance" French reinsurance company web site : https://erisk.ccr.fr

[9] "flood risk' means the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event" [L288/19, chapter 1, article 2, statement 2].

approach of the risk). The risk is therefore represented by damage-probability curves (Figure 1.3). This widely accepted concept is used in this thesis.

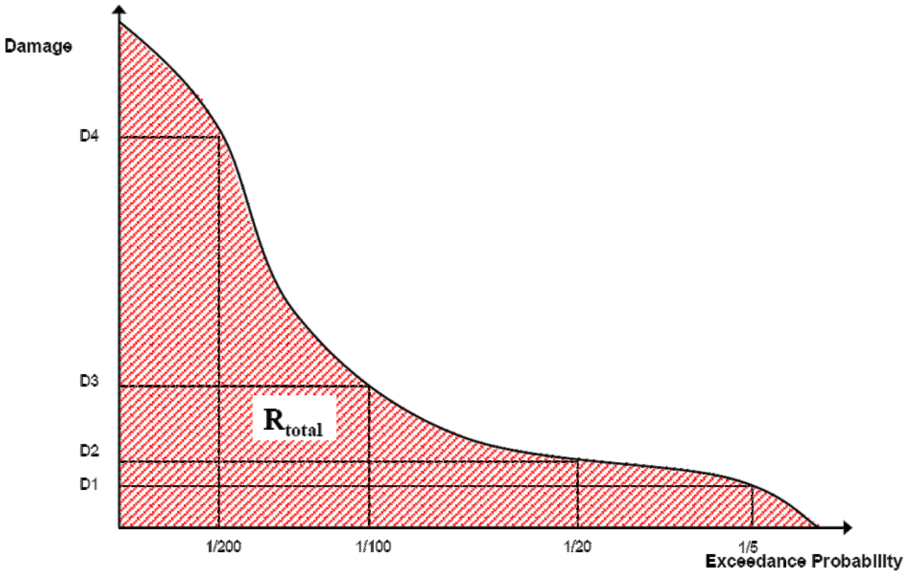

Figure 1.3. The risk as consequences vs. exceedance probability. Source: Messner et al. (2007).

2.5. Human systems resilience to floods

The term resilience is originally employed in physical science to describe the return of a material to its original form after a deformation. The use of this term in the context of natural hazards and flood risk management is recent, and it merits a special attention (Berkes, 2007; Turner II, 2010; Dauphiné and Provitolo, 2007; Klein et al., 2003; Adam, 2007; Fuchs, 2009). Greenberg et al. (2007) defined resilience as the adaptations within an economy that speed recovery from a shock and avoid some losses. Therefore, the resilience of a system to floods refers to the potential of this system to recover from perturbations caused by flood hazard events reducing the long-term negative consequences of them. The understanding of this aspect of the risk is proving to be essential for flood management purposes. The work of Kuhlicke et al. (2012) makes a description of several aspects of this concept related to natural hazards. In this purpose, the flood risk could also be considered as a combination of hazard, vulnerability and resilience. This concept of risk can be used to include functional aspects of the human system exposed to floods and is extremely useful for appreciating indirect consequences of floods.

3. Flood risk management

The main goal of flood management is to mitigate global damage caused by floods of different natures, *e.g.* human loss, social disruption and economic damage. For more details, refer to Plate (2002). Flood control systems were developed for a long time in our society, *e.g.* in the Nil River, lots of instruments and professionals were exclusively employed for observing and measuring the risk (Viollet, 2004; Nordon, 1991). Basically, two alternatives were used with this purpose: (1) the construction of hydraulic structures in order to reduce hazard, *e.g.* Dutch dams, Rhine dikes, and (2) the adaptation of the assets in order to resist floods, *e.g.* Amazonian riverside residents build their habitats elevated by pillars, so that they can live near the rivers without being vulnerable to floodwater. Even though the measures to reduce vulnerability are currently preferred, the control of hazard was and is still the measure more frequently adopted in flood risk alleviation projects. The term of flood control has progressed as well as the techniques employed to deal with floods. It is recent that we started to replace the "flood control" approaches by "flood risk management" approaches (Merz et al., 2010b).

3.1. Types of flood management measures

Several measures are used in flood management plans are used to reduce damage induced by floods. In order to reduce the flood risk, these measures objective to reduce the flood probability or to reduce the flood losses (Green et al., 2011). Different kinds of intervention strategies can take place with this purpose. As described by Torterotot (1993), we can make the difference between "structural" and "non-structural" measures. Basically, structural measures concern interventions on the physical world and non-structural measures focus on the behaviour of individuals. Different strategies can be found in the work of Bouwer et al. (2011). Furthermore, these measures can be used to reduce the risk adopting actions that can take place in three distinct temporal contexts: (1) to reduce the damage potential acting before the flood event, (2) to concentrate on the actions in order to reduce damage during the event and (3) to repair the damage after the event.

Preventive measures can be used to reduce immediately the actual risk and/or to reduce the risk in a long-term perspective. In this type of measure, the objective is to reduce the risk by mitigating hazard and/or the vulnerability of assets to suffer damage. The reduction of flood hazards is the more often used in management schemes (Kreis, 2004). These strategies are structural measures because they pass by the construction of infrastructure, *e.g.* deviation and rectification of water-bodies, dikes, dams, retention basins, etc. These measures imply transformations on the natural environment. Another solution in terms of risk reduction in a preventive way is the reduction of the vulnerability of assets exposed hazards. In this context, structural measures on the buildings and infrastructure can be adopted in order to reduce their susceptibility to suffer damage; and/or non-structural measures can be employed in order to modify the behaviour of the users of buildings, *e.g.* information, education and regulation, so that they become able to reduce their own vulnerability. The control of urbanisation is one of the key strategies for flood risk management in a long-term perspective. In France, the PPRi[10] (DDAF, 2006) is an example of this kind of strategy.

Crisis management serves to deal with the mitigation of damage through actions that take place just before, during and just after flood events. Rescue organization, evacuation plans and warning systems are the base of this management solution (Penning-Rowsell et al., 2000; Penning-Rowsell and Green, 2000b; Parker et al., 2007b; Kreibich and Merz, 2007; Parker et al., 2007a; Drobot and Parker, 2007).

Finally, curative measures may be used to deal with the recovery process from flooding consequences. Curative measures serve to repair damage caused by floods, allowing the recovery of the society after a flood. Insurance systems are the measure used in this case (Burby, 2001). In France, the CatNat[11] insurance system serves this purpose. GGGGGGGGFGDGFD

3.2. Stakeholders, risk knowledge and decision-making process

Different sectors are involved with the management of flood risks. The public sector is expected to ensure the security of the population as well as the stability of the economy. Therefore, the public sector is the first sector linked to flood management processes. Different scales of management can be adopted, from the national one, passing by the basin to the local scales (Merz et al., 2010b; Messner and Meyer, 2006; Messner et al., 2007; Büchele et al., 2006; de Moel et al., 2009; Merz et al., 2007). Once the management of the flood risk involves restrictions concerning the land-use occupation, different levels of public interests are confronted. Furthermore, public interests are confronted with private ones. On the one hand, local authorities are interested in developing the local economy, which sometimes is contradictory with land-use restrictions for flood risk management purposes. On the other hand, at the national scale we are interested to reduce the vulnerability of the territory in order to reduce the global risk. Insurance companies also play an important role on flood risk management, acting on the interface of public and private interests. The flood risk can also strongly impacts real estate/property market as well as regulation urbanisation, both affecting private interests (Shilling et al., 1989; Daniel et al., 2009).

The management of this complex phenomenon, which has both natural and human origins and confounds several levels of interests, constitutes a great challenge in contemporary society. The

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[10] The "Plan de Prévention des risques Inondation" (PPRi) is a French institutional instrument allowing to establish urbanization rules based on hazard and vulnerability analyses for flood risks.

[11] "CatNat" is the French national procedure that allows damaged individuals or institutions to be insured against important flood events. This procedure requires that the towns concerned by floods realize the inventory of damages though the declaration of damages. CatNat dossiers are prepared with this purpose.

understanding of the flood hazard, the knowledge about the vulnerability of the territory and the quantification of the risk are crucial to flood risk managers. “In order to have available an effective tool for information, as well as a valuable basis for priority setting and further technical, financial and political decisions regarding flood risk management, it is necessary to provide for the establishing of flood hazard maps and flood risk maps showing the potential adverse consequences associated with different flood scenarios” [L 288/28, statement 12] (European Parliament Council, 2007). Several scientific works and projects were developed during the last decades in order to better understand the flood risk for supporting flood managers (Begum et al., 2007; European Parliament Council, 2007; Handmer, 1987; Klein et al., 2003; Kreibich and Thieken, 2009; Kundzewicz et al., 2010; Merz et al., 2010a; NRC , 1995; Pender, 2006; Penning-Rowsell and Fordham, 1994; Plate, 2002; Schanze et al., 2006; Schumann, 2011).

The evaluations of flood consequences and reduction potential can be useful to improve budget allocation transparency, justifying public investments and demonstrating their appropriateness (Messner et al., 2007). These evaluations also make possible to compare and rank projects for budget allocation. As highlighted by the study of CEPRI (2008), requests of public funds for flood risk alleviation projects are increasing, which highlight that greater efforts should be done in order to prioritize the relevant ones. For a long time, flood alleviation projects in France have been built just after big catastrophes without considering solid economic evaluations for supporting flood management decision-making process (D4E, 2007). This scenario is still quite common, all over the world, however, this situation is changing, and cost-benefit analysis tends to be more frequently employed.

In Europe, cost-benefit analysis (CBA) and multi-criteria analysis (MCA) tend to become more frequent over time in flood management: according to the EU Floods Directive 2007/60/EC, “flood risk management plans shall take into account relevant aspects such as cost-benefit analysis” [L2 88/31 chapter IV, article 7, statement 3] (European Parliament Council, 2007). These economic analyses are used for a long time in the Anglo-Saxon context (D4E, 2007). The benefits of flood alleviation projects are measured in terms of avoided damage enhanced by the project. The work of Penning-Rowsell and Chatterton (1977) is one of the first references introducing this concept (Figure 1.4).

In France, this concept is gaining importance over time and CBA and MCA are becoming the standard methods to guide flood management (CEPRI, 2011; DREAL Rhône-Alpes, 2010; Erdlenbruch et al., 2007; Erdlenbruch et al., 2008; Grelot et al., 2009; MEDDE, 2012a, b).

Management alternatives are different in terms of used technologies and required investments. They are always associated to different monetary costs. The evaluation of potential damage related to floods, *i.e.* flood loss analysis, becomes a powerful vulnerability indicator. This make possible the analyzes of different flood management projects by investors in order to support decision-making processes (Jonkman et al., 2008). In flood risk management, the cost of flood is the difference between the damage they cause and the cost necessary to reduce them. The purpose of an economic analysis is to determine an optimum ratio between the cost of management alternatives and the damage reduction they generate, in order to reduce the global cost of floods (Figure 1.5).

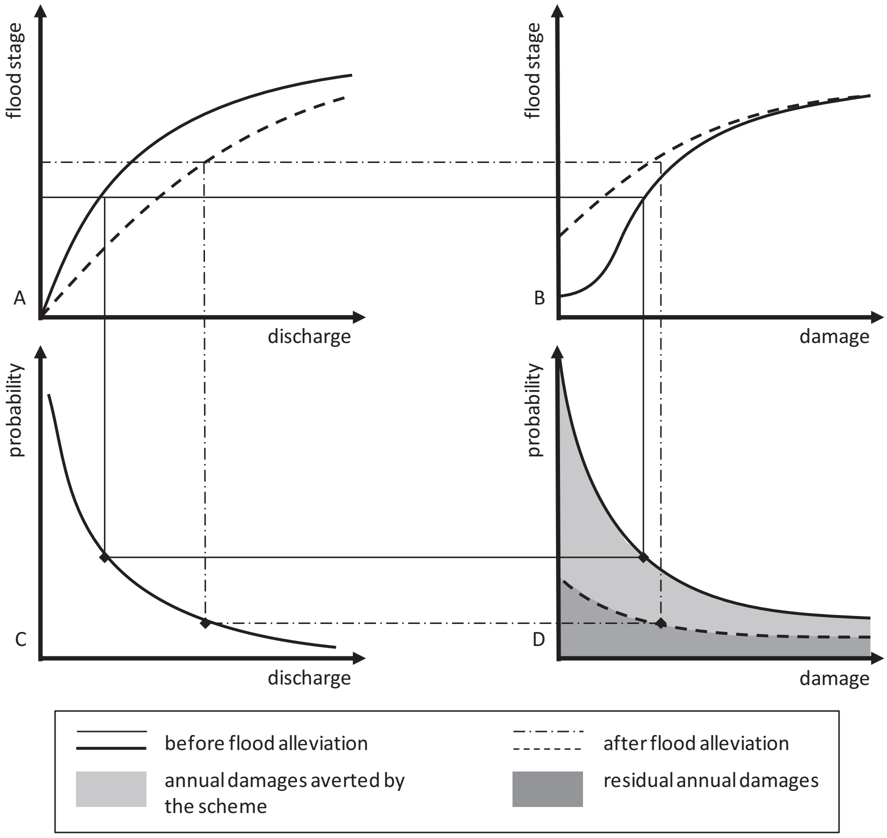

Figure 1.4. The classic 4-part diagram summarizing the calculation of annual average flood losses. Source: Penning-Rowsell and Chatterton (1977).

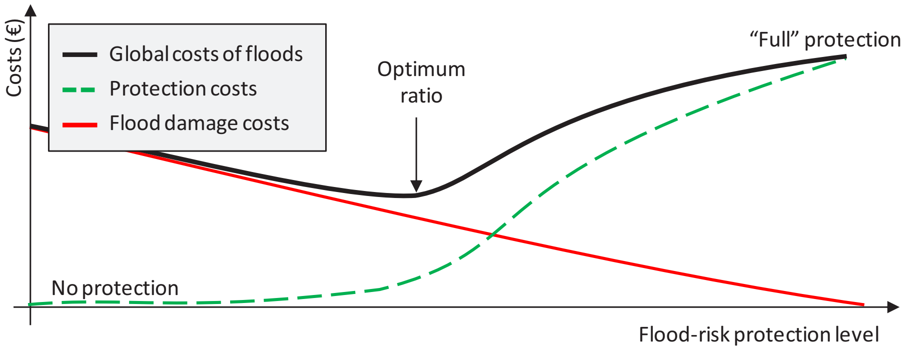

Figure 1.5. Typical approach to determine management alternative.

4. The assessment of potential flood damage

The assessment of potential flood damage is a fundamental key in flood management decision-making processes and insurance rates determination. These analyses also bring knowledge of different aspects of the risk, and facilitate budget prevision for crisis management (Kreibich and Thieken, 2008). Several European projects were developed in order to analyse flood and other natural hazards, *e.g.* EUROflood, FLOODsite[12], ConHAZ[13], and CapHAZ[14]. These projects contributed to the development of several methods to evaluate flood risk and damage potential. Messner et al. (2007) provide detailed guidelines on flood damage evaluation methods and Merz et al. (2010b) make an exhaustive state of the art of economic flood damage assessment. The works of Meyer and Messner (2005), D4E (2007) and Hubert and Ledoux (1999) synthesise several applications in France, United Kingdom, United States of America, Germany, Netherlands, the Czech Republic and Switzerland. CEPRI (2008) describe several applications in the French context. We describe in this following paragraphs important concepts and different methods used to estimate flood damage.

4.1. Actual and potential damage assessments

We differentiate "actual damage" from "potential damage". Actual damage corresponds to damage that really occurred in the past and potential damage is damage that could occur in future in the absence of any damage reduction measure (Merz et al., 2010b; Smith, 1981). Flood damage evaluations are used to assess both types of damage: *a posteriori* evaluations serve to estimate actual economic damage caused by one or many flooding events occurred in the past; and *a priori* or *ex ante* estimations are used to forecast the potential damage related to theoretical future flood scenarios, *i.e.* estimation of potential flood damage (Hubert and Ledoux, 1999).

4.2. Conceptual methods to estimate damage potential

Conceptual methods are one of the approaches that can be used to estimate potential flood damage. They are based on the capacity of the market to associate a monetary value to the flood risk. The fundamental hypothesis of this analysis is that the reduction of flood risk is expected by the society, which is ready to pay for it (Nascimento et al., 2007). In this context, hedonic-pricing and contingent valuation methods are used to estimate the cost that the society is ready to pay for reducing flood risks. These techniques used in environmental economics do not precisely describe impacts of floods and

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[12] Project: integrated Flood Risk Analysis and Management Methodologies, WEB site: http://www.floodsite.net
[13] Project: Cost of Natural Hazards, WEB site: http://conhaz.org
[14] Project: Social Capacity Building for Natural Hazards, WEB site: http://www.caphaz-net.org

damage, but they serve to evaluate all kinds of costs, including intangible ones (Hubert and Ledoux, 1999).

The hedonic-pricing method consists of identifying the likelihood of a society to pay for avoiding the risk throughout the real estate/property market. The method is based on the comparison of the prices of equivalent goods outside and inside flood areas (Shilling et al., 1989; Daniel et al., 2009; CEPRI, 2008; Erdlenbruch et al., 2008; D4E, 2007). It is based on hard hypothesis: the sellers and buyers have enough information concerning the risk and damage caused by floods, as well as concerning the reduction of risk obtained through flood management and control plans. The contingent evaluation method consists of identifying the willingness of a society to pay for protection or accept the risk refusing protection. This method is based on surveys and interviews to obtain this information. They must be carefully adapted to the context, and must be preceded by pedagogical documents in order to help on the understanding of the population about the risk. For more details refer to Venkatachalam (2004) and Carson et al. (2005). Some examples are given in CEPRI (2008).

4.3. Deterministic methods to estimate damage potential

The deterministic methods are based on a detailed estimation of the flood damage, passing by a precise description of the vulnerability of assets to suffer damage. These methods serve to evaluate direct and indirect damage, however, they generally concentrate on direct tangible damage due to the complexity linked to indirect damaging processes (Hubert and Ledoux, 1999; D4E, 2007). The estimation process counts on the description of three aspects of the flood risk: (1) the hazard and its characteristics; (2) the assets exposition and their vulnerability to floods; and (3) the assets susceptibility to suffer damage, based on damage functions establishing damage potential for assets as a function of vulnerability and hazard characteristics. This type of assessment is the current state of the art in terms of risk estimation (Merz et al., 2010b; MEDDE, 2012a), ant it is the centre of interest of this thesis. The deterministic method is therefore developed it in details in the following section.

5. The deterministic evaluation of potential flood damage

Several deterministic methodologies were developed all over the world for forecasting future flood damage. In the United States, first flood damage evaluations were developed at the beginning of the 50s (White, 1964, 1945) and were followed by the development of guidelines and several sets of damage functions by the US Army Corps of Engineers (Davis and Leigh Skaggs, 1992). In the United Kingdom, a first procedure was developed in the 70s (Penning-Rowsell and Chatterton, 1977). Since then, a sequence of guides were published improving the evaluation over time (Parker et al., 1987; Penning-Rowsell et al., 2005). In Australia, a national guide was developed together with the experience of the UK (Thompson et al., 1996; DNRM , 2002). In the French context, researchers started to study the evaluation of flood damage in the middle/end of the 90s (Hubert and Ledoux, 1999). Torterotot (1993) has contributed to this science with the development of several damage functions for damage estimations. The document developed by the CEPRI[15] makes a state of the art of the methods developed and used to evaluate flood damage in France from 1993 until 2008 (CEPRI, 2008). The works of Hubert and Ledoux (1999), Torterotot (1993) and D4E (2007) are the main French national references driving the evaluation to deterministic methods. Recent studies contributed to the development of standard national methods in France (DREAL Rhône-Alpes, 2010; MEDDE, 2012a; CEPRI, 2011).

A large number of methods to evaluate flood damage are available in literature all over the world. These methods are mainly different in relation to the scale of the evaluation, varying from elementary (unit/micro scale) to international scales, and to the level of details in which flood damage is evaluated. However, there is a common agreement on the use of deterministic evaluation of flood damage.

5.1. Economic evaluation principles

The objective of the evaluation is central in the organization of the evaluation process. “Economic evaluations of flood damage are purpose-related and therefore context-dependent. The rationales of economic evaluation are different in disaster relief programmes, for insurance contracts, or in public policy decisions. Disaster relief is assessed according to the individual need to recover after a flood, which has disturbed daily practices. Insurance compensation is assessed based on previously agreed contract terms, which promise different services from partial to fully functional repair of damaged goods. Public policy evaluations intend to support decisions such as flood risk zoning and cost-benefit analysis of structural flood defence” [pages 1699] (Merz et al., 2010b). In these evaluations, it is essential to determine what kind of damage shall be evaluated in the process and how damage shall be evaluated. The loss of goods can represent damage, but the evaluation of the value of damage is a complex task. In economy the value of a good is given by the individual, reflecting his or her subjective preference for that good (Penning-Rowsell et al., 2005).

The susceptibility of individuals and organizations to suffer damage can be irrelevant when analysing national economic damage. It is therefore crucial to make the difference between financial damage and economic damage: “Financial evaluations look at damage from a perspective of a single person or firm, neglecting public affairs and focussing on the actual financial burden. Economic evaluations have a broader perspective and want to assess the impact on national or regional welfare, including

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[15] European Centre of Flood Risk Prevention. WEB site http://www.cepri.net

impacts on intangible goods and services." [Page 11] (Messner et al., 2007). Table 1.7 gives an example of the difference between these approaches.

The assessment of one or another is strictly linked to the purpose of the analysis. In national evaluations, only economic damage should be accessed. The scale of the evaluation is another crucial aspect of the evaluation of flood damage once the damage in one area could be perceived as benefits in other areas, *e.g.* scale and transfer of damage/benefits (Pielke Jr., 2000).

Table 1.7. Financial and economic residential flood damage. Source: Penning-Rowsell et al. (2005).

Financial damage	**Economic damage**
Takes the standpoint of the individual household or organisation involved	Takes the standpoint of the nation as a whole – one person's loss can be another person's gain
Uses the actual money transfer involved to evaluate the loss or gain (*e.g.* if a household has a new-for-old insurance policy and they claim for a ten year old television, the loss is counted as the market price of a new television)	Corrects the actual money transfer in order to calculate the real opportunity cost (*e.g.* in the case of the ten year old television, the real loss to the country is a ten year old television; the depreciated value of that ten year old television is taken as the loss)
VAT is included as are other indirect taxes as they affect the individual household or organisation involved	VAT is excluded, as are other indirect taxes, because they are money transfers within the economy rather than real losses or gains

Another key principle of the evaluation concerns the estimation of the value of assets at risk, for considering damage potential. When evaluating damage potential to market goods, one should consider its actual value, *i.e.* depreciated value, instead of full replacement values. Furthermore, this value should not include pecuniary effects due to inflationary pressure (Messner et al., 2007; Merz et al., 2010b). This could cause overestimation of economic damage. Another aspect that could cause overestimation of economic damage is the double-counting of damage, *e.g.* sum of stocks and flow values for the same element at risk (Merz et al., 2010b). For more details on these economic aspects of the evaluation, see Messner et al. (2007), Merz et al. (2010b) and Green et al. (2011).

5.2. Flood damage evaluation process

Potential flood damage evaluations are essentially based on three aspects related to different fields of knowledge: flood hazards (hydrometeorology, hydraulics and engineering), the vulnerability of assets (geography, sociology and engineering) and assets susceptibility (economics and engineering). In flood damage estimations, hazards are represented by different types of flood maps for different probabilities of occurrence, *e.g.* inundation extent, water depth, duration of submersion and flow velocity distributions. The vulnerability of assets is represented by several types of asset maps and characteristics description, *e.g.* land-uses, assets location, structural and functional characteristics. Assets susceptibilities are expressed in terms of mathematical equations linking damaging potential with different relationships between flood hydraulic parameters and assets characteristics, *i.e.* damage functions.

A classic method to assess flood damage is composed of three main steps (Figure 1.6). These steps are presented in details in the following paragraphs according to Hubert and Ledoux (1999) and Merz et al. (2010b). The first step consists of characterizing and classifying the socio-economic assets in the study area according to land-uses and assets disorder potential in case of floods. Prior to start the evaluation process, it is necessary to determine the scale of the analysis as well as the types of assets and damage to consider. It is also necessary to determine the available damage functions for the study. These choices and the availability of data determine the typology of assets to be identified. Two methods can be used to evaluate flood damage: "unit damage evaluations", which is a property-by-property assessment methodology, and "homogeneous areas evaluation" which considers areas with similar characteristics in the calculation process (D4E, 2007). Therefore, the classification of assets can be realised by considering individual elements and their disorder potential in a building per building approach or by considering assets that are pooled into classes and associated to land-uses types with similar disorder potential to floods, *e.g.* housing buildings area, industrial areas, rural areas, etc. This step is completely dependent on the assets data availability prior to the evaluation process, to the objectives of the evaluation and to the resources available for possibly assessing data during the evaluation process.

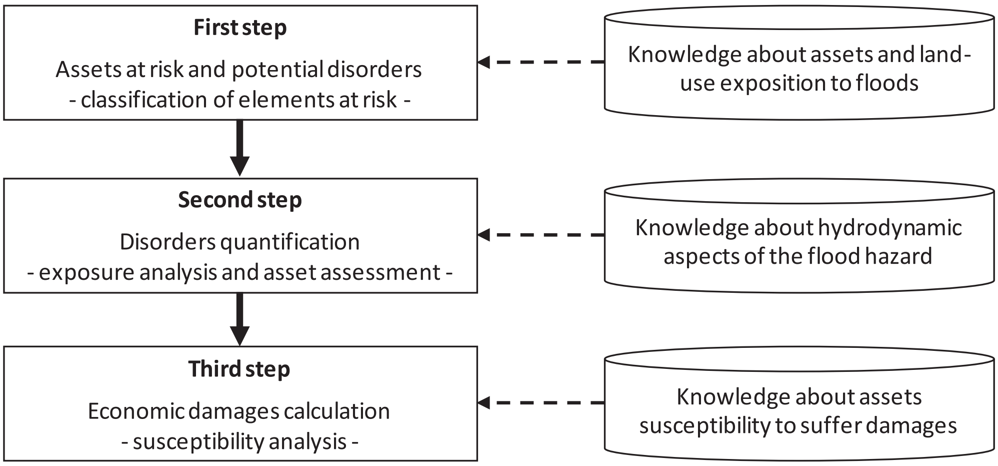

Figure 1.6. Classic method to evaluate flood damage. Source: Hubert and Ledoux (1999).

The second step consists of quantifying the potential disorders for the assets exposed to a certain flood scenario. The disorder potential of assets depends on the characteristics of the flood event itself and the value exposed to this event. “In order to achieve quantitative estimates of the exposed value (or value at risk), asset values have to be estimated for all flood-affected objects. Asset values depend on the type of the elements at risk, but also vary in time and space.” (Merz et al., 2010b). Data concerning the flood hazard event is also necessary to quantify the disorders potential of assets. This step of the damage evaluation process is an operational step in which Geographic Information Systems (GIS) are largely used for combining assets data, land-use information and hazard maps (Figure 1.7). This combination leads us to understand the different relationships between floodwater and the assets at risk.

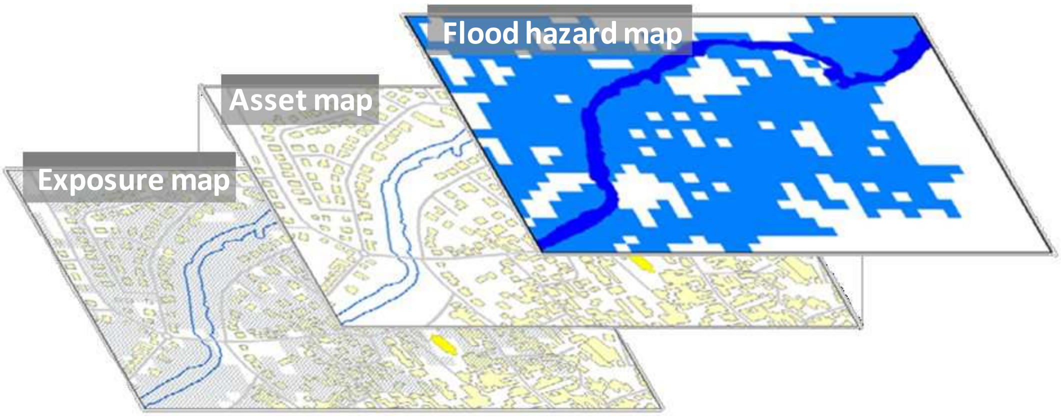

Figure 1.7. Combination of hazard with vulnerability data using GIS layers in an exposure analysis.

The third step of the evaluation process consists of associating damage potential for the different assets potentially impacted by floods. Damage is estimated as a function of the disorder potential of assets and the characteristics of the flood events. Direct damage to buildings and contents is generally obtained thanks to the use of damage functions, recognized as the standard method (Merz et al., 2010b; Smith, 1994; Penning-Rowsell and Chatterton, 1977). The estimation of indirect damage can be much more complex and may involve e certain level of detail hardly explored in these estimations. Damage and disorders caused by the disruption of lifelines and other networks, for example, may require extensive data collections and expert judgment. Indirect damage like disruption of activities can be in some cases calculated by damage functions (DREAL Rhône-Alpes, 2010) or by considering indirect damage as a percentage of direct damage (DNRM, 2002). Intangible damage is rarely considered in these types of evaluation because of the level of difficulty of expressing this damage in monetary terms, *e.g.* loss of life, induced stress, and historic/cultural heritage. However, some efforts were made to monetize this damage (Landefeld and Seskin, 1982; Lekuthai and Vongvisessomjai, 2001). This consideration is not yet common sense on damage assessment estimations.

5.3. Results of flood damage evaluations

Once these estimations are based on more or less precise data on vulnerability and hazard, the first result of damage estimation processes is the set of different databases gathered or produced during the evaluation process. These datasets may be used for different purposes related to flood risk management actions. Knowledge about the vulnerability of assets is needed for the appreciation of appropriate risk reduction measures like development of emergency plans and the realisation of emergency exercises (Merz et al., 2010b). They can be also used to support land-use management and other risk management processes. Flood maps are an essential tool for the development of land-use regulation procedures or for insurance studies (de Moel et al., 2009). However, the main results of the evaluation process are the quantification of the damage potential of specific flood scenarios and the construction of risk curves relating damage potential probability (Figure 1.3).

On the one hand, the evaluation of flood damage for a specific flood scenario makes possible to distinguish the intensity of damage associated with different types of assets, *e.g.* damage to dwelling, commercial buildings, infrastructure. This kind of evaluation also makes possible to understand the spatial distribution of damage related to specific flood events, supporting management actions delineation. On the other hand, the aggregation of damage for different probabilities of occurrence is useful for improving the efficiency of flood management projects. The Expected Annual Damage (EAD) index is largely used for supporting decision-making processes on flood management comparative procedures (*cf.* Figure 1.4 and Figure 1.5). This index, also known as Average Annual Costs (AAC), is the result of the combination of potential flood damage for different exceedance probabilities (Stedinger, 1997; Beard, 1997; Torterotot, 1993). It is calculated by accounting the area above the graph determined by the relationship between damage potential and occurrence probability (exceedance probability) (Figure 1.3). It represents an annual average value of damage considering that the flood events in future will occur according to their probability of occurrence. Both results have spatial dimensions, which allow the production of damage and risk maps. This kind of map brings great support on flood risk management and land-use regulation in a long-term perspective. As an example, the EU Floods Directive states that risk maps should be produced in order to support flood management plans (European Parliament Council, 2007).

6. Chapter summary

In this chapter, we summarized the main concepts linked to flood risk, flood risk management and the assessment of flood damage. The flood risk is a complex concept that involves several fields of knowledge, gathering different stakeholders. Flood risk is considered as the conjunction of damage and their exceedance probabilities. The term "damage" is used to designate economic loss, *i.e.* monetary damage. Tangible damage can be “easily” expressed in monetary terms, (*e.g.* material losses). In the opposite, intangible losses are hardly expressed in monetary terms, *e.g.* psychological trauma, loss of life. Direct damage can occur when floodwater directly reaches goods or men. Indirect damage is correlated to any kind of disruption linked to direct or other indirect effects of floodwater. Flood risk management is a continuous process that involves private and public interests. Different stakeholders are concerned in this process, *e.g.* public sector, insurance companies, private sector. Projects and decision-making processes need different levels of knowledge concerning the flood risk.

Economic flood damage evaluations are powerful tools for producing knowledge concerning the flood risk. Several methods were developed all over the world for evaluating flood “potential damage”, *i.e.* damage that can occur in future. These methods vary according to the purpose of the evaluation and the scale of the analysis. A classical method used to evaluate potential flood damage is based on three steps: (1) classification of elements at risk, (2) exposure analysis and (3) asset assessment and susceptibility analysis. This analysis is based on the knowledge and forecast of three different systems: the flood hazard, the vulnerability of the assets exposed to floods and the economic susceptibility of these assets to suffer damage. Two aspects define flood hazard: the hydraulic characteristics of flood events, *i.e.* floodwater extent, flow velocity, length of submersion, pollution rate; and the frequency of these events, *i.e.* the exceedance probability or its return period. Two aspects define the vulnerability of human systems to floods: the exposition of assets to the flood hazard, *i.e.* localisation of assets and their structural characteristics that leads them to be in contact with flood water during a flood event; and the susceptibility of assets to suffer damage, *i.e.* likelihood of assets to be impacted by the flood event, suffering negative consequences. Damage functions are widely used to express damage potential as a function of hazard and asset vulnerability characteristics. The results of the evaluation include damage for a specific flood event, and damage per type of asset, flood risk maps and expected annual damage values, *i.e.* annual average cost of floods.

Chapter 2.

Uncertainty on the ‘foundation’ of potential flood damage estimations

The deterministic evaluation of potential flood damage is a powerful tool for supporting flood management actions. This evaluation concerns the description of flood hazards, of the vulnerability and exposition of assets to hazards, and assets susceptibility to suffer damage. Several models and methods can be used for obtaining necessary data for the evaluation. Uncertainty is part of the evaluation process and it is present in all the modelling and assessment processes behind these evaluations. The propagation of uncertainty from the different models and datasets of flood damage evaluations on its results is still not well understood. This fact makes difficult the selection of appropriate strategies used to evaluate flood damage in pre-study processes. The aim of this chapter is to present different sources of uncertainty on the evaluation of flood damage and to develop the thesis research framework to analyze the impact of different strategies used to evaluate urban flood damage on the accuracy of its results. The main modelling processes of the evaluation, *i.e.* ‘foundation’ of the evaluation process, are analysed in this chapter: (1) hydrological analyses and hydrodynamic simulation of flood events, (2) assessment of the vulnerability of assets to floods and susceptibility to suffer losses. The framework proposes to measure uncertainty, *i.e.* variability of the evaluation results according to the selection of models and methods, as a function of the level of complexity of the methods and models used to assess hazard and vulnerability. The objectives of this methodological framework are to better understand the whole flood damage evaluation process and to identify the weight of the different steps of the evaluation. We intend to explore the accuracy of these estimations and help stakeholders in the selection of evaluation strategies considering their results liability requirements and the availability of resources for the evaluation process. These could consider time and investments necessary to apply a method, taking into account uncertainty levels.

This chapter is based on Eleutério J., Rozan A. and Mosé R., Identifying how the strategies used to assess potential damage of future floods can affect the results of the evaluation, World Wide Workshop for Young Environmental Scientists, 10pp., 2010, oai:hal.archives-ouvertes.fr:hal-00521309.

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1. Introduction

The evaluation of flood risks is a complex process which involves dynamic systems (*i.e.* flood hydrological/hydraulic aspects and human systems) and several modelling requirements (Green et al., 1994). Several methods can be used to evaluate damage potential of future floods. Deterministic approaches pass by the description of assets exposed to flood hazards and their vulnerability, allowing detailed results in terms of damage types and spatial characteristics of assets. Practitioners and scientists consider these approaches as the more realistic ones, and their use is gaining importance overtime. A well-established method used to evaluate potential flood damage is the "unit damage model" (Merz et al., 2010b). This method describes damage potential in monetary terms by means of damage functions (*i.e.* equations that correlate different parameters of hazard and vulnerability, for estimating damage potential for assets at risk). Flood inundation maps and data on the vulnerability of assets are necessary to apply this method (*cf.* Chapter 1).

Each set of data required for the evaluation is issue of a different modelling process. Different scales of analyses may be considered to evaluate flood damage, strongly influencing the level of accuracy of the evaluation (Messner et al., 2007). In addition, different hydrological assumptions may be considered to estimate flood frequencies and intensities; several hydraulic models are available to simulate flooding characteristics and to produce flood maps; several datasets and approaches may be used when assessing the vulnerability of assets to floods; and different damage functions may be used to represent the susceptibility of assets to suffer damage. Each component of the evaluation process involves uncertainties. The level of uncertainty in damage estimates depends on the different strategies used during the evaluation process, *i.e.* variation in relation to the scale of the evaluation, the datasets and methods used in the assessment and of models and programs used to process data.

The contribution of individual uncertainty propagation for the overall uncertainty of damage estimates is not yet well understood (Merz et al., 2010b). The understanding of the correlation between evaluation strategic choices and uncertainty potential is a fundamental driver to the realisation of damage evaluation pre-studies in practical applications. This understanding is the core of this thesis. The main objective of this chapter is to present the development of the thesis research question and explain the framework used to answer it. In section 2, we explain in details the different modelling processes used in the estimation of flood risks describing the different sources of uncertainty present on each of them. Section 3 puts in evidence some lacks in terms of research. It presents the development of a series of questions in the context of a pre-study for damage estimations, in order to reveal research questions. Finally, we present in section 4 the research question and the framework proposed to answer it.

2. Modelling processes and uncertainties behind the evaluation

There are several requests in terms of objectives and datasets upstream any kind of evaluation process. The organization of the evaluation is therefore dependent on the evaluation results requirements and the data and resources available (Messner et al., 2007). Several modelling processes charged with uncertainty are necessary for achieving flood risk estimations. As inferred by Green et al. (2011), "there is never 'complete knowledge', and clearly, absence of information, or information that may be unobtainable, leads to uncertainty" [page 72]. Going deeply into this statement, we highlight that the risk is a stochastic concept[16] (Ferrier and Haque, 2003), and uncertainty is intrinsically present on it. Therefore, uncertainty is part of the evaluation process and its role in decision-making process is gaining attention in the research field (Aerts et al., 2008). In the following sub-sections, we describe the modelling processes behind flood damage evaluation process and the myriad of uncertainties correlated to them.

2.1. The "pillars" of flood damage assessments

The evaluation of flood damage involves several fields of knowledge. They are grouped into two big aspects of the estimation, called here 'pillars' of the evaluation: hazard and vulnerability (Figure 2.1).

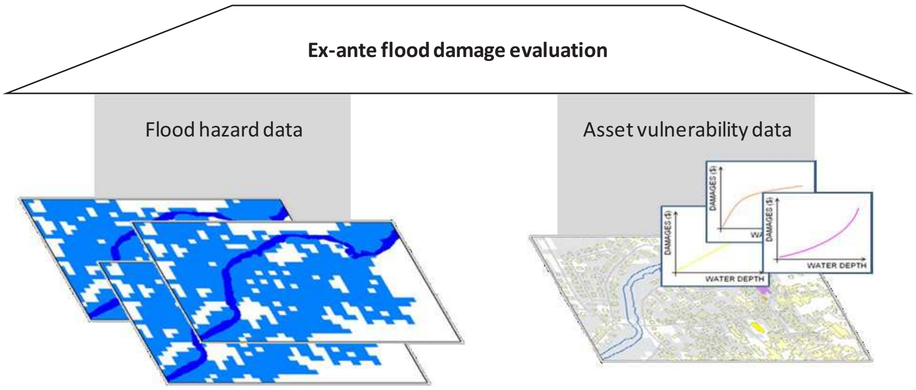

Figure 2.1. "Pillars" of flood damage estimation: flood hazard and vulnerability datasets.

Knowledge on the flood hazard is the first "pillar" of the evaluation. This knowledge concerns the flood intensities and probabilities of occurrence. The intensity of floods comprises its extent and

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[16] In Chinese, the word meaning "risk" is "wei-ji" that combines the senses of "opportunity/chance" and "danger" implying that there is always uncertainty involving gains and losses.

hydraulic characteristics, *e.g.* water depth and flow velocity. Flood hazard maps are to represent these characteristics (de Moel et al., 2009; Hagemeier-Klose and Wagner, 2009; Merz et al., 2007; NRC, 2009). The second 'pillar' of the evaluation concerns the knowledge about the vulnerability of systems potentially exposed to floods and their susceptibility to suffer damage. Vulnerability knowledge concerns their exposure and their susceptibility to suffer loss. Assets maps and damage functions are largely used to represent these characteristics. Data on these aspects are necessary to evaluate flood damage (*cf.* Chapter 1).

2.2. The "foundation" of the evaluation, source of uncertainties

The datasets, methodologies and modelling process necessary to support the "pillars" of the evaluation process are what we call here "foundation" of the evaluation process. It is composed of hydrological analysis, hydraulic modelling, assets and vulnerability assessments, all needed for assessing the necessary data behind the three steps of the evaluation processes. The operational process to evaluate potential flood damage includes many complex models, *e.g.* hydrologic, hydraulic and economic. Uncertainty exists all over the process: data uncertainty, data acquisition methods uncertainty and uncertainty on methods and assumptions made when building these models. In the following paragraphs, we detail the modelling processes behind flood damage evaluations and their uncertainties.

2.2.1. Flood hazard modelling and uncertainty

Flood hazard maps are the results of a process that includes hydrological, geospatial and hydrodynamic analyses. The hydrologic knowledge of the flood phenomenon is essential for the analysis of flood hazard. They serve to correlate the flow rate of rivers with frequencies of occurrence. The second essential aspect of floods is their hydraulic characteristics, *i.e.* flood extents, water depth spatial distribution, velocity spatial distribution and water pollution parameters (Merz et al., 2007). Hydrodynamic modelling processes are used to propagate flow rates and determine the hydraulic characteristics of flood events. Uncertainty is issue of these different elements and of the interaction between them (Merwade et al., 2008b). The following scheme (Figure 2.2) highlights the different aspects correlated to these analyses, leading to uncertainties on flood mapping processes. The availability of hydrological data, the resolution of Digital Elevation Model (DEM) and the type of hydraulic models (1D, 1D/2D, 2D) play an important role on the accuracy of results (Stelling and Verwey, 2005). DEM uncertainty plays a crucial role on the analysis accuracy (Casas et al., 2006; Werner, 2001; Wechsler, 2007). The work of Xu and Booij (2007) highlights the importance of the accuracy of flood frequency determination in the results of damage evaluation. Other uncertainty sources are also significant when producing flood maps, *e.g.* roughness coefficient determination. Several uncertainty-potential aspects are linked to the type of hydraulic model used to simulate flood events. Several operational models can be used to realize these simulations (NRC, 2009; Woodhead, 2007).

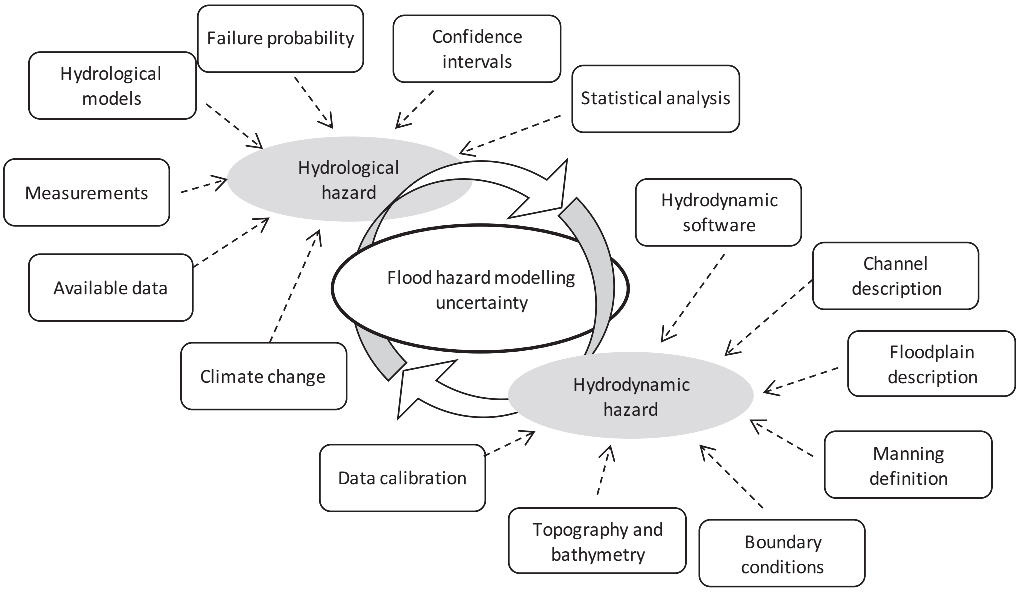

Figure 2.2. Uncertainty sources on the flood mapping process.

2.2.2. Vulnerability assessment and uncertainty

Vulnerability data refers specifically to information concerning the assets and their sensitivity to floodwater. The asset data acquisition process relies on the objectives of the risk analysis. It consists of classifying assets, and determining occupational characteristics, construction characteristics and human-behaviour characteristics. Different approaches, datasets and hypothesis may be considered for assessing the vulnerability of assets to floods (Simpson and Human, 2008; van der Veen and Logtmeijer, 2005; Dutta et al., 2003; D4E, 2007; CEPRI, 2008). Concerning the assets susceptibility to suffer damage, direct damage data is usually represented by damage functions, which establish relations between hazard and vulnerability parameters. Several studies were developed in order to produce these damage functions (White, 1964; Penning-Rowsell and Chatterton, 1977; Torterotot, 1993; Nascimento et al., 2007). Indirect vulnerability data is complex to analyse once the role of networks and their systemic functioning is much more difficult to apprehend (CERTU, 2002; Desgranges, 1999). The assessment of vulnerability to floods also counts on different aspects and sources of uncertainty (Figure 2.3). The quality of datasets and field surveys determines the accuracy of data, *e.g.* land-use uncertainties (Castilla and Hay, 2007). The work of Torterotot (1993) describes uncertainty on the construction of damage functions. The works of Penning-Rowsell and Green (2000b, a) and Apel et al. (2004) describe uncertainty in the overall process. Even though it is strongly recommended to generate damage functions in the site in study, that is not always possible because of data inexistence or time availability to realize the analysis. The use of damage functions created in other places is another source of uncertainty.

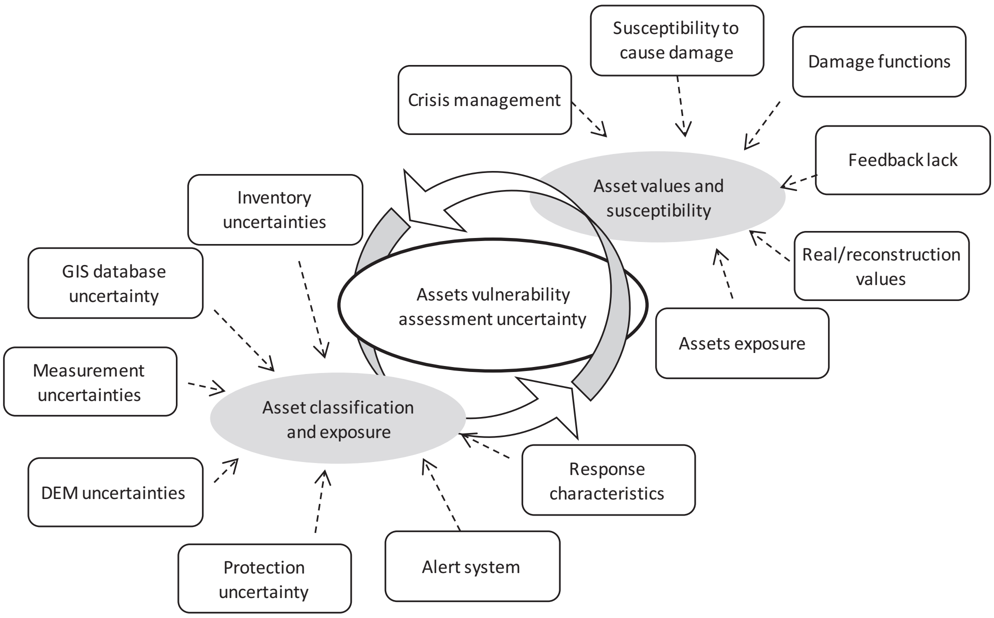

Figure 2.3. Uncertainty sources on vulnerability assessment process.

2.3. Role of uncertainty on the evaluation results

Individual uncertainty linked to the hazard modelling part of the evaluation (section 2.2.1) propagates in the results of the evaluation, as well as individual uncertainty linked to the vulnerability assessment step (section 2.2.2). The high level of uncertainty in flood damage assessment cannot be neglected (de Blois and Wind, 1995). Overall uncertainty on the evaluation process is complex to analyse due to this multi-modelling aspect of the evaluation. It is difficult to understand, identify, measure and represent uncertainty. Validation of *ex ante* flood damage evaluations are difficult to achieve. The only solution for using damage evaluation results to support decision-making processes is to understand the uncertainties and their propagation on the results of the evaluation. The presentation of these evaluation results to the decision-makers without related uncertainties may induce a misuse of these results. Damage evaluation results, when accompanied with uncertainty analyses, brings to the managers a richer comprehension of the dubious and variable nature of the flood risk.

2.3.1. Types of uncertainty

The different sources of uncertainty linked to the evaluation of damage evaluations described in section 2.2 can be classified into two types: (1) natural variability, aleatoric or stochastic uncertainty, related to the inherent variability of natural processes; (2) knowledge or epistemic uncertainty, due to incomplete knowledge. As defined by NRC (2000), "Natural variability is presumed to be an uncertainty of the world, a natural or inherent randomness. Knowledge uncertainty, in contrast, is presumed to be an uncertainty of the mind, a function of models and data" [page 42]. According to Merz and Thieken (2005), damage evaluation results should be accompanied by the analysis of these different types of uncertainty. The description of the global uncertainty behind damage evaluation results is an important element for decision-making processes. However, the understanding of knowledge or epistemic uncertainty should be the priority of research, once this type of uncertainty can be reduced at present, in opposition to natural variability, aleatoric or stochastic uncertainty (Schumann, 2011).

2.3.2. Uncertainty and sensitivity analyses

Uncertainty propagation analyses bring the uncertainties from data and methods together into the results of the damage evaluation. Other interesting analyses to complement the evaluation results are probability of uncertainty and sensitivity tests. The first one consists of aggregating probability ratios when defining the two previous scenarios. When applying this method, we can have more realistic information about the uncertainty aggregated to the results of the evaluation. Sensitivity tests serve to identify the sensitivity of the evaluation to different variables. The representation of uncertainty in terms of probabilities is the predominant technique used in engineering and economic analyses (Green et al., 2011), *e.g.* Monte Carlo analysis. However, different methods can be used to analyze uncertainty in environmental modelling processes. Five levels of treatment of uncertainties are presented by Paté-Cornell (1996): hazard detection and failure modes identification; 'worst-case' approach; quasi-worst cases and plausible upper bounds; best estimates and central values; probabilistic risk analysis; and multiple risk curves. The analysis type should be adequate to the specific purpose of the evaluation. The work of Refsgaard et al. (2007) analysed different methods currently used to analyse uncertainty, bringing guidelines for analysing uncertainties in environmental modelling processes.

2.3.3. Relative uncertainty

A myriad of studies were carried out in order to identify and quantify uncertainty on flood damage evaluations (Gaume et al., 2000; Al-Futaisi and Stedinger, 1999; Apel et al., 2008b; Beard, 1978; Merwade et al., 2008b; Merz and Thieken, 2009). However, rare are the studies which measured the relative contribution of the different elements of flood damage analysis to the total uncertainty (Merz et al., 2010b). Apel et al. (2008a) compared uncertainty linked to the type of hydraulic model with the damage model used to estimate flood damage. It highlights the significance of quantifying uncertainty linked to different models and the compensation of uncertainties. It also concluded that the selection of the flood loss model has a much larger impact on the final risk estimate than the selection of the hazard model (Apel et al., 2008a). In the study of Merz and Thieken (2009), hydrological uncertainties were also taken into account in the global estimation of uncertainty on the evaluation. The comparison of different sources of uncertainty linked to hydrological analyses, flood modelling and damage models leads to results different of those presented by Apel et al. (2008a). According to Merz and Thieken (2009), the contribution of the damage models to the global uncertainty is low in comparison with the other sources of uncertainty. A more recent study in France used a statistical approach in order to measure the influence of different modules of the estimation on cost-benefit analysis (Saint-Geours et al., 2011). It reveals that the role of one or another aspect of the evaluation is linked to the scale of evaluation.

2.4. Scales of evaluation and the liability of the evaluation

Damage evaluations can be realised for different areas, depending on the objectives of the analysis (Figure 2.4). In literature, different scales of damage evaluations are defined as a function of the level of details of the evaluation process (Schumann, 2011; Messner et al., 2007; Merz et al., 2010b):

- Micro-scale – in which single elements are considered during the evaluation process, *e.g.* building and punctual infrastructure. This scale is generally used for communal analyses.
- Meso-scale – in which spatial aggregations of assets are used, *e.g.* land use areas. This scale is generally adopted in inter-municipality or regional analyses, when the assessment of detailed datasets becomes harder.
- Macro-scale – based on large-scale spatial units, *e.g.* municipalities, regions, nations. This scale is generally adopted in national or international scales.

This classification is valid for the assessment of vulnerability as well as for the assessment of hazard, *e.g.* for the same level of details, the efforts necessary for analysing the area (A) is lower than for (B) and (C) (Figure 2.4). However, it is not strict once different combinations of analysis scales can be considered depending on the data and models availability, *e.g.* hazard maps produced using macro scale methods can be combined with micro scale vulnerability datasets in order to evaluate potential flood damage. We can observe different scales of evaluation and a mixture of them in literature (Meyer and Messner, 2005; CEPRI, 2008).

The liability of the evaluation process depends on strategies (*i.e.* choices concerning the methods, datasets and approaches) used to assess and produce the different datasets needed. Uncertainties on evaluation results can turn the evaluation inutile for decision-making processes (Green et al., 2011). The amount of data needed for simulating floods or representing the vulnerability of assets is proportional to the size of the area to analyse. Therefore, the greater the size of the area under investigation is, the harder it is to assess and forecast hazard and vulnerability data in order to evaluate flood damage with a specific level of precision (Figure 2.5). The selection of the different methods and models behind damage evaluations (*cf.* section 2.2) is therefore dependent on the scale of the evaluation.

Figure 2.4. Investigation area size.

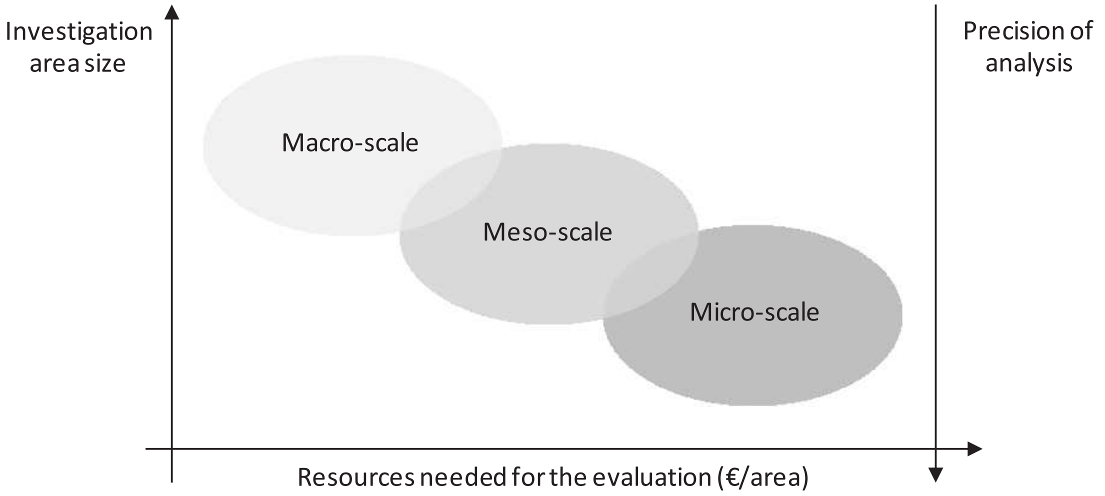

Figure 2.5. Evaluation scales, demands in terms of data and resources and accuracy of evaluation. Source: Messner et al. (2007).

3. Identification of the research question

Sophisticated methods are available and can be employed with the purpose of obtaining accurate data for evaluating flood damage. In despite that technological improvement allows great advances in modelling software and data acquisition material, the costs to pay for accuracy can turn out to be relatively high. The question of feasibility of the evaluation is an important factor in practical evaluations observed in Europe (Meyer and Messner, 2005) and it can be still more relevant in developing countries. The evaluation of flood damage are generally realised by local authorities, associations or by private companies. Even though lots of methods and guides exist to support flood damage evaluations, rare are the countries which adopted national standard methods (Dutta et al., 2001). Therefore, pre-studies are a fundamental step of flood damage evaluations. They are essential to the determination of time and evaluation efforts repartition. Several studies have evocated a list of questions that must be answered before starting the evaluation of flood damage. For example, the French state of the art CEPRI (2008) highlights a list of questions frequently asked by the modeller before applying the methods to evaluate flood damage. These questions concern data availability; the needs and expectative in terms of results of the evaluation; objectives of evaluation; scale of analysis; budget allocation; communication of results and method; how the evaluation contributes to the decision-making process; communication of final decision; etc. Based on the European experience in flood damage evaluation processes, the guide developed by Messner et al. (2007) also makes recommendations concerning the questions that should be asked and the data that must be assessed before evaluating flood damage. They proposed a four-step method for evaluating direct tangible flood damage, in which the first three steps concern the selection of methods used to obtain necessary data for evaluating flood damage. Guidelines are also provided by Flood Hazard Centre (Penning-Rowsell et al., 2005), in which we find more or less the same principles evocated before. It is proposed a ‘filtering method’ to determine appraisal priorities: “Careful consideration should be given as to when it is worthwhile appending appraisal resources quantifying losses or follow the simple alternative of just enumerating their relative status (*e.g.* rank of relative impact) in a qualitative statement in the project appraisal” (Penning-Rowsell et al., 2005).

3.1. Pre-study for flood damage evaluations

Independent of the method, potential flood damage evaluations are based on three main types of datasets in order to assess hazard and vulnerability: hazard parameters maps with associated intensity and frequency; vulnerability maps containing assets exposure and vulnerability characteristics; and damage functions expressing the susceptibility of assets to suffer damage. Based on pre-studies and feedback presents in literature (D4E, 2007; Penning-Rowsell et al., 2005; Messner et al., 2007;

CEPRI, 2008; Merz et al., 2010b), we propose a general pre-study method called 3C pre-study for assessing potential damage for future floods. This method defines a workflow around these three types of datasets, issues of the foundation of the evaluation process (*cf.* section 2.1). It is developed with the purpose of identifying research lacks on the foundation of damage-evaluation processes. The '3C method' refers to three circles of questions and decisions, which should be analysed before assessing data for evaluating flood damage (Figure 2.6).

The different choices behind evaluation processes depend on the objectives of the evaluation that must be clearly defined at the beginning of the evaluation process (Merz et al., 2010b). The internal circle of the method (Figure 2.6) is a general reflexion about the methodology to use when calculating flood damage in accordance with the objectives of the evaluation. It serves to determine three groups of characteristics of the evaluation process:

- (1) determine the types of damage to evaluate: direct/indirect, intangible/tangible.
- (2) determine the type(s) of flooding hazard(s) to analyse.
- (3) determine the different types of assets to consider in the evaluation (damage categories, and the spatial extent for the evaluation.

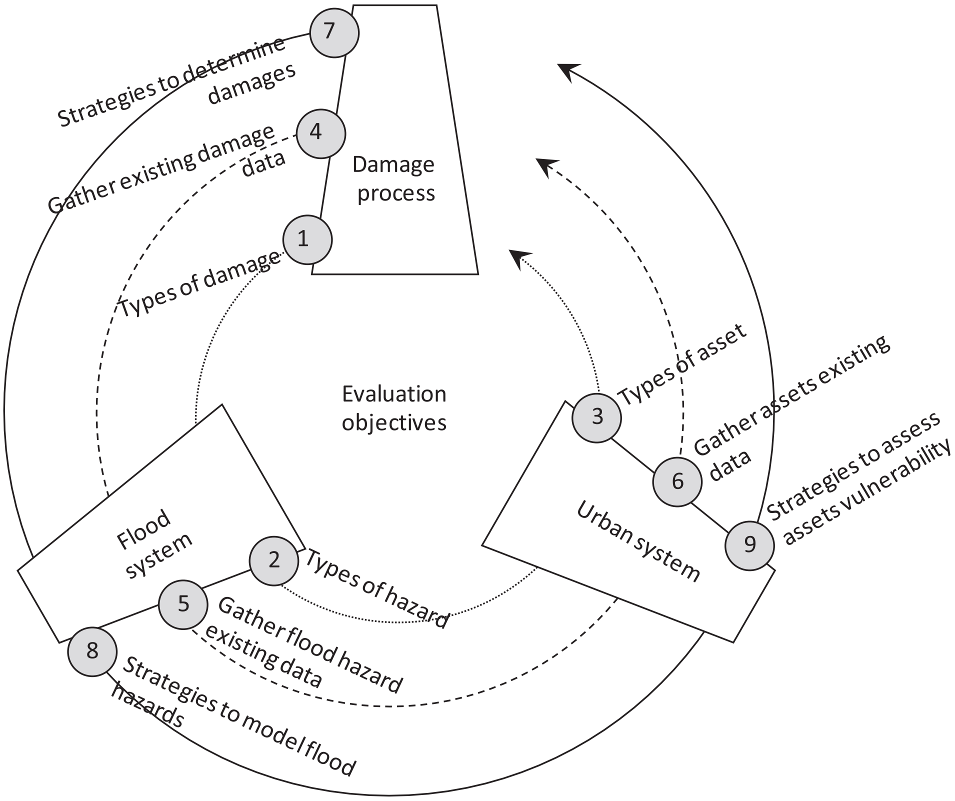

Figure 2.6. 3C pre-study to assess potential flood damage.

Two approaches can be used to obtain information: "developing its own protocol and methods and then collecting the data or use second source of information." (Green et al., 2011) [page 70]. It is natural and recommended to use existing data in order to reduce evaluation costs. It is therefore essential to assess existing datasets. The intermediary circle of the method (Figure 2.6) consists of three actions related to the gathering of all available data for the evaluation:

- (4) gather existing data concerning previous flood damage and existing damage functions. If no data exist in the site, regional and national data should be gathered.
- (5) gather available data concerning the flood phenomenon, *e.g.* historical flood maps, hydrological/meteorological data, topographic, bathymetric and digital elevation models (DEM), flood models, etc.
- (6) gather data concerning land-uses and characteristics of assets at risk, *e.g.* vulnerability maps, land-use maps, GIS databases, etc.

The last circle serves to determine all the strategies to use for assessing necessary data to evaluate flood damage.

- (7) In this step, we should analyse the applicability of available flood damage data and gather damage functions for all type of assets considered in the evaluation. An exhaustive analysis of the existing damage function, the actual land-use information and the types of damage adopted should be established. It serves to determine the damage functions and strategies used to apply them.
- (8) In this step, available data on hazard is to be analysed in order to organise the analysis. This step consists of determining the strategies to use when modelling hazard, *e.g.* determination of what kind of hydraulic model to use and how to obtain lacking data.
- (9) In this step, one should analyse the available vulnerability datasets in order to determine the strategies to adopt when assessing lacking data for vulnerability analysis purposes, *e.g.* land-uses, construction characteristics and exposure information.

3.2. The liability of the evaluation – a feasibility issue?

The selection of strategies, models and methods on the last circle of the pre study phase (Figure 2.6) should be determined by several factors, *e.g.* objectives of the analysis, existing datasets, size of area to analyse, type of analysis, time and resources availability, etc (Messner et al., 2007; Merz et al., 2010b). Time and resources availability for the evaluation process is a crucial element to be considered. It determines together with the objectives of the evaluation the scale of analysis (the accuracy of methods and datasets used) for the different steps of the evaluation process (Table 2.1).

Table 2.1. Characteristics of micro, meso and macro scale approaches of flood damage evaluation. Source: Messner et al. (2007).

Management level	Size of research area	Demands on precision	Amount of resources and data required per unit of area	Appropriate scale
Comprehensive flood mitigation policies	(inter)national	low	Low	Macro
Large-scale flood mitigation strategies	Regional	medium	Medium	Meso
Single protection measures	Local	high	High	Micro

The question evocated in Messner et al. (2007) "how much time and money is at hand to carry out the study?" [page 31] is therefore an important element for determining the evaluation strategies. (CEPRI, 2008) relates that in France the costs of the evaluation process are frequently a problem for the evaluation process. Another crucial element is the fact that existing datasets are issues of analyses with different levels of precision, *e.g.* macro scale flood maps may cover a region for which the accuracy of micro scale analysis is expected. It is essential to understand the level of uncertainty behind different strategies in order to make strategic choices according to the analysis objectives. The identification and quantification of these uncertainty sources in the evaluation is crucial for acting on the reduction of evaluations. Therefore, beyond the fact that evaluation pre-studies should take into account the overall cost of the evaluation process in order to guide the choices on strategies of the evaluation, uncertainty potential linked to strategic choices must be revealed by research in order to optimize evaluation investments. As Green et al. (2011) inferred by in relation to data collection process, "it could be very costly and time consuming to get this data. A key rule is to approach the gain in information by having a progressive refinement of critical parameters that need to be considered for further investigations. It is indeed important to first define how this data will improve the representativeness and the accuracy of the assessment" [page 71].

It is actually difficult to make choices (resources allocation) when determining which steps of the evaluation process should be deeply investigated. "Too often hydraulic or terrain modelling 'absorbs' large proportions of scheme appraisal budgets at the expense of thorough damage and benefit assessments. Thus appraisals data requirements may be 'squeezed' and the resultant Present Value of damage may become volatile or simply fallacious." (Penning-Rowsell et al., 2005). The strategies used for modelling hazard, assessing vulnerability and damaging potential differently affect the result of the evaluation process. The exhaustive flood damage evaluation review of Merz et al. (2010b) highlights that "an interesting question which has been hardly explored is the relative contribution of the different elements of a flood risk analysis to the total uncertainty" [page 1718].

4. Thesis question and research framework

On the one hand, “it is of importance to explore the boundaries of flood damage modelling and to try to find ways to move these boundaries” [page 491] (de Blois and Wind, 1995). To understand the limits of damage evaluation is crucial to support decision-making processes. On the other hand, it is crucial to understand the relevance of uncertainty sources on the total uncertainty (Merz et al., 2010b). Research has yet to be done in order to guide the selection of different strategies to model hazard, assess vulnerability and evaluate flood damage, taking into account the objectives of the evaluation, feasibility parameters, long-term perspectives, and results reliability. One question that should be more attentively studied in order to support flood damage evaluation process is where to act (expend more efforts and resources) for improving the results of the evaluation. The best way to answer this question is to understand how different strategic choices on the evaluation process affect its results. The present thesis is therefore devoted to answer the following question:

How different strategies used to model flood hazard and assess the vulnerability of a territory affect the results of *ex ante* flood damage evaluations?

Several aspects are considered in order to prepare the evaluation of flood damage: objectives of the evaluation, data and models availability, resources availability, etc (Penning-Rowsell et al., 2005). The understanding of uncertainty linked to the different methods and models used to evaluate flood damage is the core of this study. We focus our analysis in knowledge uncertainty associated with the simplifications induced by the selection of approaches (model uncertainty) and linked to the possible hypothesis and considerations made during the evaluation process (parameter uncertainty) (NRC, 2000) (*cf.* section 2.3.1). The selection of methods, models and data used in the analyses are called here strategies of evaluation. In order to measure the impact of strategies on flood damage evaluation results, we propose a general framework (Figure 2.7) based on the use of different strategies to evaluate potential flood damage. The application of this framework counts on three steps: (1) define the strategies used to model hazard and assess vulnerability; (2) propagate the uncertainties linked to the methods in the evaluation results; and (3) measure the variability of the evaluation results in comparison with other scenarios of analysis.

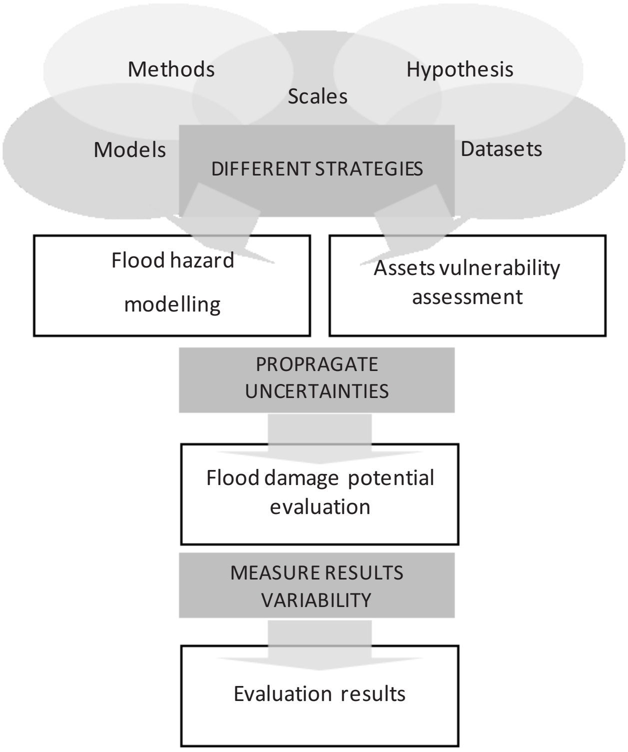

Figure 2.7. Research framework to identify how the strategies used to assess potential damage of future floods can affect the results of the evaluation.

4.1. Strategies of evaluation

The strategies studied in this thesis correspond to the decisions taken during the 'external circle' of the '3C pre-study', (steps 7, 8 and 9 in Figure 2.6) – they refer to the choices related to which data and methods to use during the different steps of the evaluation process. We notice that resources availability is a key issue in the evaluation process. On the one hand, models and data availability is essential in the determination of methods and models to assess vulnerability and model flood hazard. On the other hand, the difficultness for using a specific method or model is mainly correlated to data availability, the amount of supplementary data to gather and their demands in terms of technical knowledge. Resources availability and demands are completely dependent on the size of area for evaluation (*cf.* Figure 2.5 and Table 2.1). The fact that the scale of evaluation can strongly influence these methodological choices leads us to compare different strategies considering different scales of evaluation. The strategies we propose to analyse herein can be differentiated according to two criteria: (1) the types of model and approach used; and (2) the level of details described (scale of analysis). In relation to the first criterion, the models and approaches tested are chosen according to methodological characteristics. For the analysis scale, macro, meso and micro scale analyses (*cf.* section 2.4) are considered for the same size of analysis area. These different strategies concern different modules of the evaluation process, individually analysed in the second part of this thesis (*cf.* PART II):

- The hydrological analyses and considerations used for determining the discharge frequencies of floods (*cf.* Chapter 5);
- The types of hydrodynamic models as well as the considerations made when entering topographic and bathymetric data for simulating floods (*cf.* Chapter 6);
- The datasets and methods used for assessing buildings and contents vulnerability to floods (*cf.* Chapter 7);
- The damage functions used in the evaluation and their calibration based on the value of assets (*cf.* Chapter 8).

4.2. Propagation of uncertainty through the evaluation

In order to quantify the variability of damage evaluation results generated by different strategies used to assess hazard and vulnerability, we propagate the uncertainties linked to each strategy throughout the flood damage evaluation process (Figure 2.7).

4.2.1. Principles of potential flood damage evaluation

The general damage evaluation process analysed is based on the classic deterministic approach described by Merz et al. (2010b), Messner et al. (2007) and Hubert and Ledoux (1999). It consists of (1) the classification of assets at risk, (2) the quantification of potential disorders (risk estimation) and (3) the calculation of economic damage (*cf.* Chapter 1). The first step is part of the vulnerability assessment module, in which the assets in the study area are classified according to the damage functions used in the analysis, the assets data and the objectives of the evaluation. The second step of the evaluation consists of determining for each specific flood event, how the assets at risk are potentially affected by the hazard. Vulnerability and hazard datasets are combined at this stage in order to estimate flood risk and determine the exposure of the assets. The Flood hazard parameters, *e.g.* water depth and flow velocity, for floods with different probabilities of occurrence $\boldsymbol{T}$ are associated to the assets analysed for determining the probability of individual assets to be flooded. In the third step of the evaluation, flood damage is calculated for different flood probabilities. Direct material damage depends on hazard parameters and vulnerability characteristics of the asset at risk. For each asset at risk $\boldsymbol{i}$ we express direct damage $\boldsymbol{AD_{DIR}}$ as a function of hazard parameters $\boldsymbol{H_{PAR}}$, *e.g.* water depth and flow velocity, and the vulnerability of assets to floods $\boldsymbol{A_{VUL}}$, Equation (2.1). In order to avoid the complexity of domino effects and transfer of vulnerability[17] during the propagation of uncertainties, assets indirect damage $\boldsymbol{AD_{IND}}$ is estimated by using ratings $\boldsymbol{R}$ of direct damage,

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[17] A method to evaluate damages and dysfunctions of networks infrastructure is proposed in the PART III of this thesis in order to calculate indirect damages of floods in urban areas taken into account resiliency.

Equation (2.2). Total damage potential for a specific asset $\boldsymbol{AD_{TOT}}$ is calculated by summing up direct with indirect damage potential, Equation (2.3). Assets expected annual damage $\boldsymbol{A_{EAD}}$ is calculated by summing up the product of total damage related to floods with their frequency of occurrence $\boldsymbol{T}$, for all probabilities of occurrence (from 0 to 1), Equation (2.4).

$$\mathrm{AD_{DIR}}^{\mathrm{i}}(\mathrm{T}) = \mathrm{f}\,(\,\mathrm{H_{PAR}}(\mathrm{T}),\ \mathrm{A_{VUL}}^{\mathrm{i}}\,) \tag{2.1}$$

$$\mathrm{AD_{IND}}^{\mathrm{i}}(\mathrm{T}) = \mathrm{R}\ .\ \mathrm{AD_{DIR}}^{\mathrm{i}}(\mathrm{T}) \tag{2.2}$$

$$\mathrm{AD_{TOT}}^{\mathrm{i}}(\mathrm{T}) = \mathrm{AD_{DIR}}^{\mathrm{i}}(\mathrm{T}) + \mathrm{AD_{IND}}^{\mathrm{i}}(\mathrm{T}) \tag{2.3}$$

$$\mathrm{A_{EAD}}^{i} = \int_0^1 \mathrm{AD_{TOT}}^{\mathrm{i}}(\mathrm{T}) \times \partial T. \tag{2.4}$$

The sum of all the $\boldsymbol{n}$ assets at risk damage potentials represent the total damage potential caused by one specific flooding event with certain probability of occurrence $\boldsymbol{T}$ in the impacted area, Equation (2.5). The total expected annual damage for the area analysed is the sum of the expected annual damage for all the $\boldsymbol{n}$ assets impacted by the different flood events, Equation (2.6).

$$DAM(T) = \sum_1^n AD_{TOT}{}^{i}(T). \tag{2.5}$$

$$EAD = \sum_1^n A_{EAD}{}^{i}. \tag{2.6}$$

Once the different datasets used for the analyses have spatial distributions and characteristics, Geographic Information Systems (GIS) are indispensable tools in the evaluation process (D4E, 2007). We notice that great effort was expend in flood mapping, with the development of several computational programs to support the operation. Contrary to hazard modelling, few models are available to simulate vulnerability and to realise the overall evaluation of flood damage (Xu and Booij, 2007). Once the framework described in Figure 2.7 is based on multiple estimations of flood damage using different INPUT datasets in order to measure variability on the model OUTPUT, it is essential to have an appropriate GIS based tool. The damage evaluation process described herein is automated in a GIS-based method with this purpose (*cf.* Chapter 3).

4.2.2. Uncertainty bounds determination

Instead of using probabilistic methods to estimate uncertainties, we use a mixture of the 'worst-case' approach, the quasi-worst cases and plausible upper bounds, and best estimates and central values, proposed by Paté-Cornell (1996). The general framework proposed to analyse this uncertainty is composed of four steps: (1) determine the strategy to use for one specific part of the evaluation; (2) estimate the central, minimal and maximal values the different variables involved in the strategy can assume; (3) combine minimal and maximal values of different variables in order to minimize and maximize the results of the evaluation (this respecting the plausible bound criterion); and (4) calculate assets damage potential. The scheme in Figure 2.7 represents the evaluation flow, corresponding to how the uncertainties linked to different strategic choices propagate into the results of the evaluation of flood damage. Following the principle explained in section 4, we propose to change the strategies one at time for measuring the part of uncertainty liked to the different modules of the evaluation process.

4.3. Measure results variability

In order to measure the impact of strategies on flood damage evaluation results, we propose to realise damage estimations for one site considering different strategies to assess flood hazard and the vulnerability of assets (Figure 2.7). The principle of the framework is based on a repetitive method in which flood damage is evaluated several times using different strategies concerning the ‘foundation’ of the evaluation. This “parallel modelling” approach was also used by Merz and Thieken (2009) in the context of flood risk uncertainties estimation. In order to measure the relative importance of each aspect of the evaluation process, a sensitivity analysis principle is used: a unique parameter (or evaluation module) is changed conserving all the others unchanged (Refsgaard et al., 2007). Uncertainty propagation for each parameter is therefore measured in the results of the evaluation and we compare the impact of the different strategies in the global results of the evaluation.

4.4. Application of the framework

Buildings and contents inside flood areas are the main source of damage. Therefore, damage potential of buildings and contents has been the major focus of scientific research during these last decades. For example, in the French review CEPRI (2008) we observe a great majority of studies that concentrate their efforts in this type of damage. Buildings and contents damage potential is also of special interest because of the correlated social aspects, *e.g.* number of people concerned, social weigh in decision-making, and their relevance in flood management, *e.g.* cost-benefit analysis, insurance rates determination. We apply the research framework to determine the variability of buildings and contents flood damage evaluation results. We focus this study on residential buildings damage potential because of the great number of previous works, the availability of methods and data for the tests, and the homogeneity of the value of damage potential for this typology (in contrast with damage to industrial and commercial buildings). This research focus on damage linked to riverine flooding. Floodwater depth is considered the main damage-influencing factor for buildings and contents. The application of the framework implies the analysis of the variability of damage evaluation results in real case studies.

5. Chapter summary

The classical deterministic method is largely used to evaluate potential flood damage. Several datasets and different modelling processes are necessary to realise these estimations. Flood hazard and vulnerability datasets are the 'pillars' of the evaluation process. The modelling processes behind this data are what we called in this chapter the 'foundation' of flood damage evaluations. They include: (1) hydrological analyses, which are necessary to estimate flood flow rates and return-periods; (2) hydraulic modelling used to process this data together with other datasets to simulate floods and produce flood hazard maps; (3) assets investigation and classification methods used to estimate the exposition of assets to floods and their damage influencing characteristics; and (4) assets assessment methods and susceptibility analyses used to estimate assets damaging potential.

Uncertainty is part of the evaluation process. Several sources of uncertainty exist in the 'foundation' of the evaluation. We can distinguish stochastic uncertainty *i.e.* uncertainty linked to the natural variability of the phenomenon, from epistemic uncertainty *i.e.* uncertainty linked to the incomplete knowledge of the phenomenon. Several types of models, datasets and methods can be used to assess hazard and vulnerability data for flood damage evaluation processes. Inappropriate methodological approaches to evaluate flood damage can be an important source of epistemic uncertainty, over which we can act to improve the analysis, reducing global uncertainty. Indeed, it is crucial to understand and quantify this type of uncertainty. We notice that different criteria are considered in practice to determine the different approaches to evaluate flood damage. The difficulty of the methods (demands in terms of data, resources and time) is observed as an important criterion to consider. We also highlight the lack in literature for the understanding of the importance of the different modules of the evaluation process to its result, which turns difficult the optimisation of evaluation efforts. A recent study in France (MEDDE, 2012b) highlighted the needs for improvement of flood risk knowledge to reinforce management strategies in the national scale.

The present thesis focus on how different strategies used to model flood hazard and assess the vulnerability of a territory affect the results of *ex ante* flood damage evaluations. The selection of methods, models and datasets to use in the flood damage evaluation process is what we call here "strategies of the evaluation". In order to explore this question, we propose an uncertainty propagation framework in which sensitivity analysis principles and uncertainty high boundaries are analysed. The framework consists of measuring the relative contribution of the different ‘foundations’ of the evaluation to the global uncertainty of the evaluation. It is based on a deterministic framework in which different INPUT ‘strategies’ are tested in real case studies. Two case studies are proposed for analysis in this thesis. The role of the scale of the evaluation is an important parameter considered during the tests. The different tests and analyses are presented in the second part (PART II) of this thesis.

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Chapter 3.

Development of a GIS-based method to evaluate potential flood damage

Flood risk and damage analyses rely on qualitative and quantitative datasets with spatial distribution characteristics. They bring together environmental, engineering and socio-economic aspects of floods. Several hydrological and hydraulic computer models exist to analyse flood hazards, and to produce flood hazard maps. Several methods were also developed to evaluate flood risks. However, the absence of standard methods turns difficult the comparison and validation of results. Geographic Information System (GIS) is a powerful tool to analyse spatial data and they play a crucial role in flood risk evaluation processes. The development of computational models to evaluate future flood damage is an important step to harmonise methods. This chapter describes the role of GIS in flood risk assessments and it presents a general GIS-based method developed to estimate future flood damage. The description of the methodology details all the steps of the evaluation of flood damage in a way to support risk analyses. The method is based on the combination of flood hazard and vulnerability data to estimate potential flood damage. It was used to estimate damage to buildings, roads and agriculture in the low valley of the Bruche River, in eastern France. Flood risk maps produced by the method application are essential in flood management processes.

This chapter is based on Eleutério J., Martinez D., Rozan A., Developing a GIS tool to assess potential damage of future floods, Risk Analysis VII & Brownfields V, C.A. BREBBIA, Wessex Institute of Technology, UK and C.N. Brooks, Greenfield Environmental Trust Group, USA, 381-392, 2010, DOI: 10.2495/RISK100331.

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1. Introduction

Geographic Information Systems (GIS) modelling possibilities are crucial for natural hazard risk management and risk reduction (Zerger, 2002). In relation to flood hazard, several approaches and models are used for assessing related risks, depending on the context, existing datasets and objectives of the evaluation. The work of Merz et al. (2010b) resumes different methods and approaches used to assess potential flood damage worldwide. Despite that the role of GIS is central in flood risk and damage evaluation processes, commonly used GIS software does not offer specific tools for estimating economic damage for future floods. Only few flood damage assessment models are available (Dutta et al., 2003). The existence of several approaches to estimate potential flood damage as well as site-dependencies could explain this fact. The construction of GIS-based methodologies and models is an important step toward the standardisation of the whole evaluation process (Yi et al., 2010). For instance, only few countries developed national standard methods to evaluate flood damage (Dutta et al., 2003). The use of standard methods to assess and combine different datasets contributes to the improvement of the methodology, guarantees specific accuracy of results and enables the comparison of results in different contexts. As concluded by de Moel et al. (2009), a wide variety of methods exists to produce flood maps and a huge challenge includes the evaluation of flood damage in a uniform way.

The objective of this chapter is to describe the role of GIS in flood risk assessments and to present a general GIS-based method to evaluate potential flood damage and expected annual damage. In section 2, we present how GIS tools are currently used in flood risk analyses. In section 3, we describe the GIS-based method developed to evaluate flood risk and we explain its implementation in a GIS platform. Section 4 presents a French case study to illustrate the application of the model in which we estimate and visualise flood damage to buildings, roads and agriculture.

2. The role of GIS in flood risk assessments

The analysis of flood risks brings different aspects together, *e.g.* human, social, economic and environmental (Messner and Meyer, 2006). The general purpose of risk assessments is to understand and/or measure the possible consequences associated with the occurrence of flooding in areas occupied by vulnerable systems. The increase of flood damage in the world reflects the current need for improving management solutions. The evaluation of potential damage of future floods is an essential part of flood management project appraisals, getting more importance over time (Penning-Rowsell and Green, 2000b). In the European context, the EU Floods Directive 2007/60/EC (European

Parliament Council, 2007) determines on the one hand, that flood management projects must take into consideration cost-benefit analysis principles. On the other hand, it determines that hazard and risk maps should be produced for supporting the management of floods. There exist several types of flood maps, responding to different objectives (EXCIMAP, 2007; de Moel et al., 2009; van Alphen et al., 2009). Flood hazard and risk maps are essential for flood management: flood hazard maps contain information about the probability and/or magnitude of a flood event, *e.g.* flood extent and water depth distribution; whereas flood risk maps contain additional information about the potential consequences of floods, *e.g.* economic loss, human injuries and environmental impacts (de Moel et al., 2009).

Great amount of data and knowledge is needed to produce and use these maps (Merz et al., 2007; NRC, 2009). The spatial dimension provided by GIS-based analyses is crucial for mapping processes and natural hazard management issues (Zerger, 2002; Köhler et al., 2006). GIS-based tools are currently used for several risk-related purposes, *e.g.* risk communication (Hagemeier-Klose and Wagner, 2009; Müller et al., 2006), flood risk management analyses (Chen et al., 2009; Zerger and Wealands, 2004; Qi and Altinakar, 2011; Ramlal and Baban, 2008), flood real-time predictions (Dutta et al., 2003; Al-Sabhan et al., 2003), insurance analyses (de Moel et al., 2009; Chemitte, 2008). Advances in computational engineering and GIS also play an important role on the improvement of modelling and mapping processes. GIS tools are currently used all over flood risk assessments workflow, from the preparation of data for flooding simulations to the calculation of elements at risk damage potential. The following sections present the role of GIS in the different steps of flood risk assessments.

2.1. Representation of data in a GIS

GIS tools are largely used to represent and manage spatial data. The assessment of flood risk involves the knowledge of different aspects of the flood risk (Penning-Rowsell et al., 2005). The flood risk is a combination of flood hazard and the vulnerability of assets (Merz et al., 2010b). Both, hazard and vulnerability data have spatial characteristics and can be represented by spatial data and maps (Merz et al., 2007). Basic data concerns: (1) the natural phenomenon, *e.g.* flood extent, hydraulic parameters spatial distribution, exceedance probability; and (2) the territory vulnerability, *e.g.* assets exposure and susceptibility to suffer damage. In a GIS, flood hazard and the vulnerability of assets can be represented by points, lines and polygons (with characteristics described in tables associated to the different elementary shapes) or grids/raster (with information associated to grid cells), *cf.* Figure 3.1.

2.2. GIS in hazard modelling/mapping

Typical GIS applications include analyses of digital elevation models (DEM) over which several hydrological and hydraulic analyses are realised (Moglen and Maidment, 2005). Several tools/software were built on the basis of GIS in order to process DEM, and facilitate the construction of flood hazard maps. In relation to hydraulic modelling, specific tools have been developed to explore GIS spatial data processing functionalities for process different types of datasets, *e.g.* topographic and land-use data processing (Ames et al., 2009; Ackerman et al., 1999; Merwade et al., 2008a; Maidment and Djokic, 2000). Different software items are used to: prepare input data inside GIS platforms; export data according to requirements of hydrodynamic numerical models; and process hydrodynamic modelling results for generating flood hazard maps, *e.g.* HEC-GeoRAS tool (HEC, 2011). The use of these tools provides more efficiency for the analyst, reducing technical efforts and optimising the analysis in terms of technical possibilities. In resume, several hydrodynamic models and methods can be used in practice to simulate floods (Büchele et al., 2006), but by the end of the process, GIS software or integrated GIS based interfaces are necessary to represent and analyse the results of these models. Some hydrodynamic computational programs include integrated GIS functions in order to facilitate data processing and results analysis, *e.g.* RAS Mapper functions from HEC-RAS version 4.1 (HEC, 2010). Different studies were also carried out in order to link the hydraulic/hydrologic models to GIS (Renyi and Nan, 2002; Ren-yi and Nan, 2001; Nunes Correia et al., 1998). Other studies were developed to analyse flood hydrological aspects (Chubey and Hathout, 2004), and simulate different flood characteristics through numerical schemes inside GIS software (Dutta and Herath, 1998; Dutta et al., 2001, 2003; Tsanis and Boyle, 2001; Chen et al., 2009; Liu and De Smedt, 2005; Bates and De Roo, 2000). A great advantage of using GIS is the possibility to store flood maps in numerical formats, *e.g.* the FEMA's Map Modernisation Program (NRC , 2009).

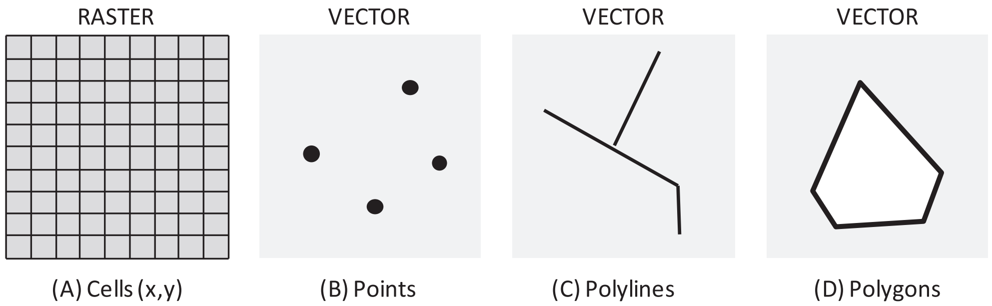

Figure 3.1. Representation of spatial information in GIS platforms.

2.3. GIS in vulnerability assessment/mapping

In the context of risk assessments, vulnerability can be expressed by the exposure of assets to floods and their susceptibility to suffer damage (Merz et al., 2010b). Exposure analyses identify "what can be affected by a flood" (de Moel et al., 2009) whereas susceptibility analyses describe "how will the affected elements be damaged" (Merz et al., 2007). Generally, stake vulnerability data for damage assessment purposes is explored in basis of land-use datasets with different levels of detail, varying from the description of units to large homogeneous areas (D4E, 2007). GIS technology is largely used to store, visualise and analyse stake data. Several land-use GIS datasets were developed in different scales for different purposes, *e.g.* European CORINE land cover data, BD TOPO® and BD CARTO from the French National Institute of Geography (IGN). Furthermore, it becomes common to observe the existence of GIS departments in city management utilities, which contribute to the construction of local vulnerability datasets. Other data crucial for vulnerability assessments includes aerial photos, DEM and field measurements/observations indicating physical and usage characteristics of assets, *e.g.* building ground floor height and occupation types. Comprehensive databases are the essential precondition for the formulation of vulnerability and risk assessments (Köhler et al., 2006). Vulnerability maps are used to represent the spatial distribution of assets as well as their vulnerability to floods (Merz et al., 2007). In addition to facilitate mapping procedures, GIS tools include the possibility to integrate several dimensions in vulnerability analyses (van der Veen and Logtmeijer, 2005). They enable the development of complex algorithms to correlate assets in systemic contexts in order to describe complex systems (Minciardi et al., 2006; Ge et al., 2010). The possibility of creating new information through the combination of different data and their updating are other advantages of using GIS for this purpose.

2.4. GIS in damage potential evaluation/mapping

Several methods were developed in different contexts for evaluating flood damage, *cf.* Merz et al. (2010b). The use of damage functions to represent assets damaging potential is widely accepted. Damage functions relate monetary damage potential with vulnerability and hazard characteristics (Kreibich et al., 2010). Their use implies the combination of hazard with vulnerability data. In addition to the fact that GIS plays an important role on the different analyses preceding damage evaluations, it is crucial for the spatial combination of hazard and vulnerability data. The data-combination process consists of overlaying flood hazard maps with vulnerability maps. Some GIS methods were developed to evaluate earthquake damage, *e.g.* Daniell (2011) and Chen et al. (1998). GIS-based methods were also developed for achieving flood risk analyses including the possibility of damage potential calculation (Chen et al., 2004; Betts, 2002; Guozhong et al., 2004; Jonkman et al., 2008; Luino et al., 2009; Ren-yi and Nan, 2001; Su et al., 2005; Yang and Tsai, 2000; Qi and Altinakar, 2011; Yi et al., 2010). However, commonly used GIS computer programs do not offer specific tools for estimating economic damage for future floods and the existing methods are not always compatible with other site particularities. In contradiction with the great amount of general hydraulic models available, only few flood damage assessment computational models are available, *cf.* Dutta et al. (2003) and Hardmeyer and Spencer (2007).

Few countries count on national standard methods to assess potential flood damage, *e.g.* Japan, Australia, US (Dutta et al., 2001). In the European context, it is concluded that the majority of studies concentrates on the analysis of the flood phenomenon. Flood damage maps exist and flood risk maps (probability and consequences) are rare (van Alphen et al., 2009). One of the challenges in flood mapping processes is the development of harmonised concepts or standards (Merz et al., 2007). These conclusions are also valid in national contexts. In the French context, we highlight the need for a standard method based on the conclusions of national studies revealing the variety of methods applied in France (CEPRI, 2008; D4E, 2007). GIS is essential in this kind of studies (D4E, 2007), however, no general models exist to estimate damage for future floods in France. Only tools restricted to a qualitative level of risk are available, *e.g.* the “Inondabilité” method for combining hazard with assets exposure characteristics (Gilard, 1999) and the French national WEB dispositive “Vigicrues” used to real-time visualisation of water-bodies hydrological measurements and communicate flood risk forecasting[18], none of them integrating the quantification of damage in monetary terms.

The development of methods and tools for achieving flood risk analysis and generate flood risk maps is still one of the challenges in research and practical fields (Zerger and Wealands, 2004; de Moel et al., 2009). The complexity of damage evaluations and their different uncertainties turn difficult their application. GIS is an adequate tool to model the complex relationships between assets in a systemic context as well as their flood damaging potential. The development of GIS-based models is a powerful instrument for homogenising evaluation procedures, reducing the evaluation technical efforts, allowing the realisation of uncertainty propagation tests and sensitivity analyses (Refsgaard et al., 2007), and fundamental for decision-making processes.

3. General GIS-based method principles

The method developed in this chapter places the elements or assets in the centre of the flood risk evaluation process. This assumption considers that our interest is to look for the damage potential of assets instead of looking for general damage potential for hazard events. Different scales of evaluation can be adopted according to the objectives of the analysis. The assets can be analysed individually in a property-by-property assessment following the principles of the “unit model method” or using large homogeneous areas in which average values can be estimated based on land-use classes (Messner et al., 2007; Merz et al., 2010b). The method is based on the combination of flood hazard and vulnerability data for estimating damage potential of floods thanks to the application of damage functions that associate damage potential to hazard and vulnerability correlations. It counts on different input data and it consists of three steps, displayed in the following schema (Figure 3.2).

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[18] Vigicrues WEB site: http://www.vigicrues.gouv.fr/

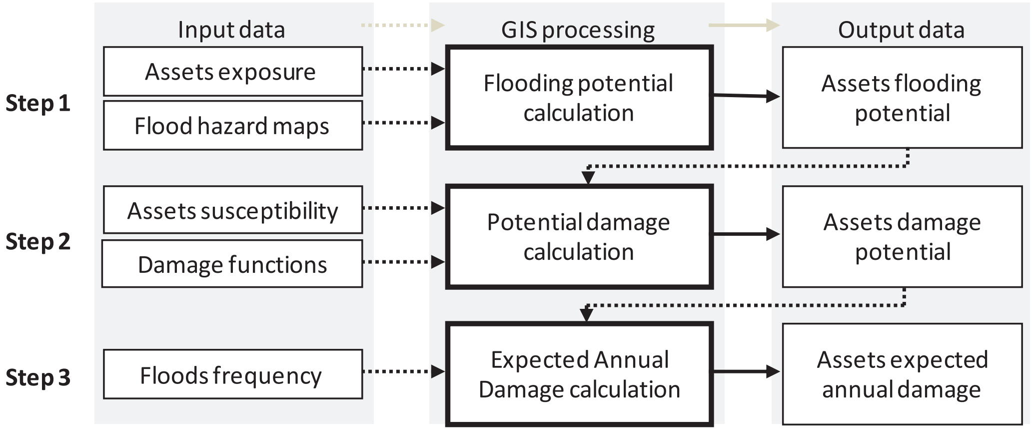


Figure 3.2. The three steps of the general flood risk assessment GIS-based method.

3.1. Step 1: assessing the assets flooding potential

The first step of the method determines the potential intensity of flood parameters, *i.e.* water depth, flow velocity etc, inside/over the assets, for different flood occurrence probabilities. Equation (3.1) is used to achieve this objective.

$$A_{FP}(i) = f\left(A_{EXP(x,y,z)}, F_{PAR(x,y)}(i)\right) \tag{3.1}$$

where A_{FP} is the assets flooding potential represented by the intensity of flood parameters inside/over each asset for hazards with specific annual exceedance probabilities ***(i)***; A_{EXP} is the exposure of the asset represented by its location ***(x, y, z)*** during the flood event; F_{PAR} is the maximum intensity of flood parameter(s) in the space ***(x,y)*** for given flood events with specific annual exceedance probabilities.

For solving Equation (3.1), flood hazard and assets exposure characteristics are combined (Figure 3.2). Basic data input requirement for determining assets flooding potential includes:

- vulnerability maps (vector data) including at least spatial localisation of assets - x and y coordinates if water depth is not taken into account in the analysis; and z coordinate if water depth is considered;
- flood hazard map(s) (grid/raster or vectors formats) including at least floodwater spatial distribution (x, y coordinates).

The combination process consists of overlaying vulnerability data and hazard maps through GIS functions for importing information from flood hazard layers to assets layer, taking into account the spatial localisation of the elements at risk and the characteristics of the assets described in the layer attribute table. The x and y coordinates of both hazard and assets are combined in order to determine the risk. In case water depth is used in the analysis, water depth inside/over the elements at risk is calculated by subtracting the flood map water depths from the asset elevation (z coordinate). The spatial combination of assets with floods depends on the types of geometry used to represent assets (Figure 3.1). Different hypothesis can be made in order to consider this aspect in the evaluation (Figure 3.3).

These hypothesis should be differently considered to take into account characteristics of the assets when calculating the potential flood parameters inside/over them, *e.g.* water depth inside buildings tends to be uniform all over the surface, in contrary, water depth on agriculture surfaces vary independent of the culture type (*cf.* opened surfaces approach in Figure 3.3). These approaches are also different in relation to the types of GIS layers used in the analysis:

- combination of surface assets with flood polygons - two approaches can be used for determining the values transmitted during the combination process. The first approach is the one used to combine opened surfaces with floodwater depth. The intersection between the two layers determines the water depth for the opened surface in a way several values are transmitted to the input surface. The other approach considers that only one value can be associated to each asset. In this approach, we can consider the minimum, average or maximum value of the different flood polygons affecting the asset surface.
- combination of punctual assets with flood polygons - two approaches can be used for determining the values transmitted during the combination process. The first approach can be used for determining a single value for the point according to its location in relation to the polygons (inside/outside). The second approach considers buffer areas around the point in order to determine the value of hazard. It is similar to the closed surface approach.
- combination of linear assets with flood polygons - one approach is used for determining the value of the length of asset intersected by polygons representing different water depth values.

Additional data such as other flood parameters, *e.g.* flow velocity, duration of submersion, or such vulnerability parameters influencing exposure, *e.g.* existence of flood protection structures, can be also incorporated into this analysis. Several flood events can be analysed simultaneously once the method is centred on the assets. Therefore, Equation (3.1) is solved several times for different hazard maps, with different occurrence probabilities and hydraulic parameters spatial distributions. This step estimates the risk of assets to be flooded by different events, associating the characteristics of the flood events analysed to each asset element. In GIS layers, these values are recorded in the assets attribute table.

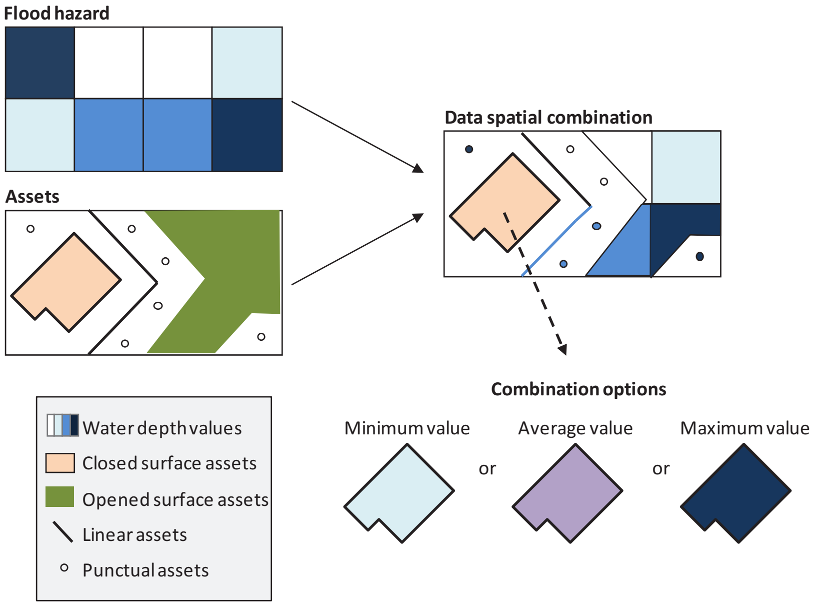


Figure 3.3. Direct spatial combination approaches using vector data in a GIS to analyse flood risks.

3.2. Step 2: calculation of assets damage potential

The calculation of assets damage potential is based on the application of damage functions expressing the relationship between flood parameters, the characteristics and vulnerability of assets, and potential flood damage. Equation (3.2) is used with this purpose.

$$A_{DP}(i) = f\,(\,A_{FP}(i),\, A_{SSD},\, A_{DmgP}\,) \qquad (3.2)$$

where $A_{DP}(i)$ is the asset damage potential related to a specific flood annual exceedance probability (i); A_{FP} is the assets flooding potential represented by the intensity of flood parameters inside/over each asset for hazards calculated with Equation (3.1); A_{SSD} is the asset susceptibility to suffer damage; A_{DmgP} is the asset monetary damaging potential represented by damage functions.

For solving the Equation (3.2), each asset element must be associated to an input damage function. In a GIS, this link can be made by using a common index that represents assets susceptibility to suffer damage corresponding to the identification of the damage function associated to the assets type. Different types of damage functions can used according to site characteristics (Merz et al., 2010b).

Assets damage is calculated using the flooding parameters inside/over the elements at risk provided by the first step of the method and vulnerability input data (Figure 3.2). Basic data input requirement for achieving this step includes:

- step 1 output - datasets on assets flooding/intensity potential for assets at risk (*cf.* section 3.1);
- the characteristics and vulnerability of assets including at least vulnerability index (expressing asset susceptibility to suffer damage);
- damage functions for the different vulnerability indexes;

Additional data such as other asset characteristics can be incorporated in the analysis, *e.g.* asset value, asset surface, existence of warning systems and damage reduction measures, intra- and interdependency indexes etc. It can therefore be used for taking into account complex systemic relationships between assets (Minciardi et al., 2006; Ge et al., 2010). These characteristics can represent an important part of the assets susceptibility to suffer damage, and they can play an important role on the evaluation of flood indirect and total damage.

3.3. Step 3: calculation of expected annual damage

This step calculates assets expected annual damage (EAD), which is an index commonly used to express the risk in terms of exceedance probabilities (Beard, 1997; CIEWR-HEC, 1989; Messner et al., 2007). Its calculation enables to define the average annual damage for the elements at risk based on the probability of damage caused by floods (Figure 3.4).

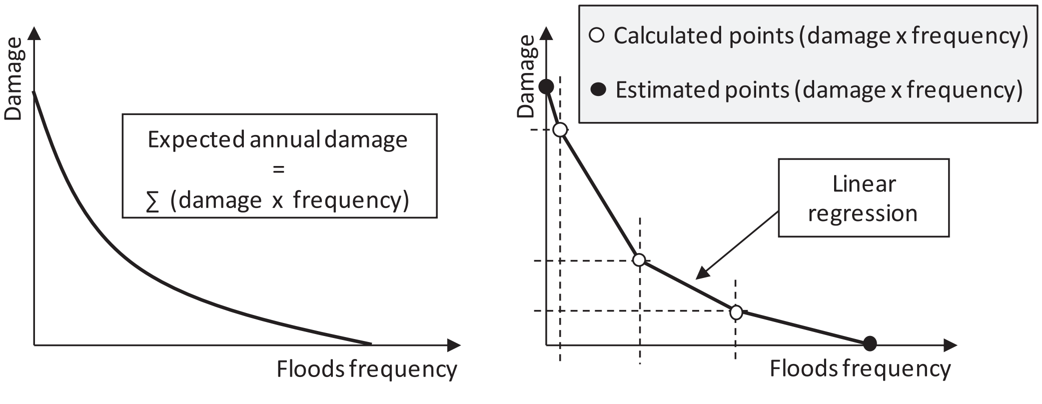


Figure 3.4. Calculation of expected annual damage using couple of values – flood frequency and damage potential.

Equation (3.3) is used to calculate the EAD for elements at risk.

$$A_{EAD} = \int_0^1 A_{DP}(i) \times i. \tag{3.3}$$

where A_{EAD} is the asset expected annual damage or average annual cost of damage caused by floods; $A_{DP}(i)$ is the asset damage potential related to a specific flood annual exceedance probability ***(i)*** calculated by Equation (3.2).

For solving Equation (3.3), this step uses data concerning the flood events return periods and the assets damage potential previously calculated in the second step of the method (Figure 3.2). Once it is not conceivable to estimate damage potential for the infinite event probabilities, we propose to use linear regression between the calculated and estimated couple of values (damage x frequency) for solving Equation (3.3), as represented in Figure 3.4. Basic data input requirement includes:

- step 2 output - datasets on assets damage potential for given event(s) (*cf.* section 3.2);
- information concerning the flood events return-periods, first damaging flood event return-period and damage values for low frequency flood events.

The minimum of three pairs of values (damage x frequency) are required for solving Equation (3.3). Two important values must be estimated: (1) first damaging event return period and (2) damage value for the null exceedance probability flood event, *i.e.* theoretical infinity return period event. The first value can be estimated in accordance with historical data (Figure 3.4). The second value can be estimated in relation to the higher flood damage estimated. Even though we can obtain the EAD index with these three values, we recommend to use a maximum of values, at least three calculated pairs of values (damage x frequency). It's also recommended to evaluate damage potential for frequent flood events once they can play a significant role on global damage evaluation (Merz et al., 2009).

3.4. Implementation of the method in a GIS platform

High level of professional skills and time are required to achieve the different steps of flood damage evaluation processes using basic functions of GIS. The automation of the method promotes easier comparison of different scenarios and facilitates sensitivity tests and uncertainty propagation analysis, important elements for decision-making processes (Zerger, 2002; Qi and Altinakar, 2011; Weichel et al., 2007). We developed a tool enhancing GIS classic applications with the purpose of realising flood risk analyses through the combination of data related to flood hazard, assets exposure and vulnerability according to the method developed in this chapter: the F.R.A.GIS tool extension (Eleutério et al., 2010). It is a combination of GIS functions and tools developed using Visual Basic computational language, ArcObjects and Visual Basic Applications (VBA) for use with ArcMap® GIS (ESRI) (Chang, 2007; Burke, 2003). This kind of GIS interfaces are commonly used for tool developing purposes, *e.g.* Morio et al. (2010). The tool is composed of two distinct parts: tool interface and tool calculation module (Figure 3.5). The tool interface is used for pre- and post-processing INPUT and OUTPUT data according to the model requirements and for defining the model run parameters. The graphical user interface (GUI) is a toolbar composed of different menus and shortcuts that allow the user to access windows for pre- and post-processing datasets, manage data inside the GIS environment, define the model parameters and RUN the model. The second part of the tool is the calculation module composed of three distinct modules, corresponding to the three steps of the method (Figure 3.2): Assets Flooding Potential Module (*cf.* section 3.1), Assets Damage Potential Module (*cf.* section 3.2) and Expected Annual Damage Module (*cf.* section 3.3). Each module has independent functions, relying on different input datasets and model parameters entered by the user.

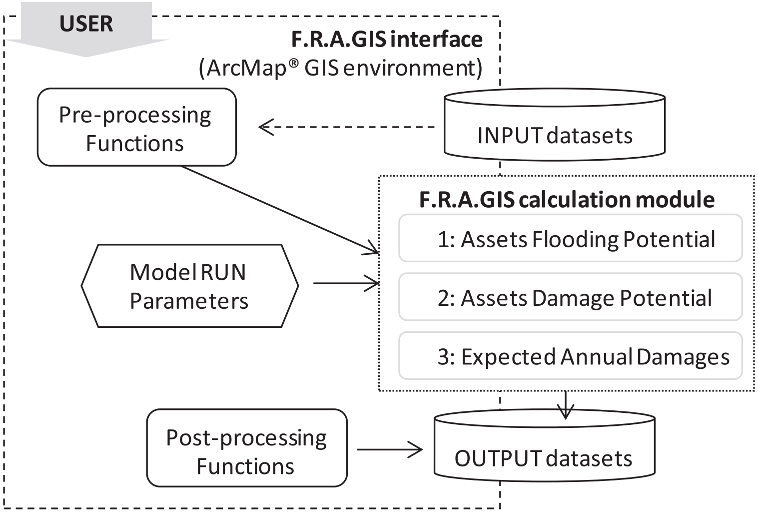


Figure 3.5. F.R.A.GIS tool structure.

4. Using the GIS-based method to estimate potential flood damage

The functionality of the GIS-based model and tool developed is illustrated throughout a case study. The model was used to calculate potential damage and expected annual damage to buildings, roads and agriculture in the city of Holtzheim, in eastern France. Figure 3.6 displays the different layers in ArcMap® GIS environment used to represent floods and vulnerability during the analysis. Vulnerability maps (vector layers) were generated using local datasets and field surveys. The building vulnerability map represented: building exposure by their geo-referenced contours and their ground floor height in relation to the natural terrain; building susceptibility to suffer damage by vulnerability indexes created as a function of building occupation type and construction characteristics; and building and contents damaging potential by adapting existing damage functions from Torterotot (1993) and DNRM (2002).

The roads vulnerability map represented: roads exposure by geo-referenced line shapes; susceptibility to suffer damage by vulnerability indexes based on the roads type; damage potential by existing damage functions (Erdlenbruch et al., 2007), using the impacted length of road for calculating damage. Agriculture vulnerability map represented exposure by geo-referenced polygons representing the spatial extent of the agricultural lands, susceptibility to suffer damage by vulnerability indexes representing the type of crops; damaging potential by existing damage functions (Erdlenbruch et al., 2007). All damage functions express damage as a function of water depth, flooded surface/length and vulnerability characteristics. Flooding water depth maps were generated through simulations by using the coupled 1D/2D hydrodynamic model Mike Flood, in 2007. Maps for floods with return-periods equal to 10, 30 and 100 were used in this study. The flood hazard maps were generated in a grid/raster format with 20 meters cell resolution.

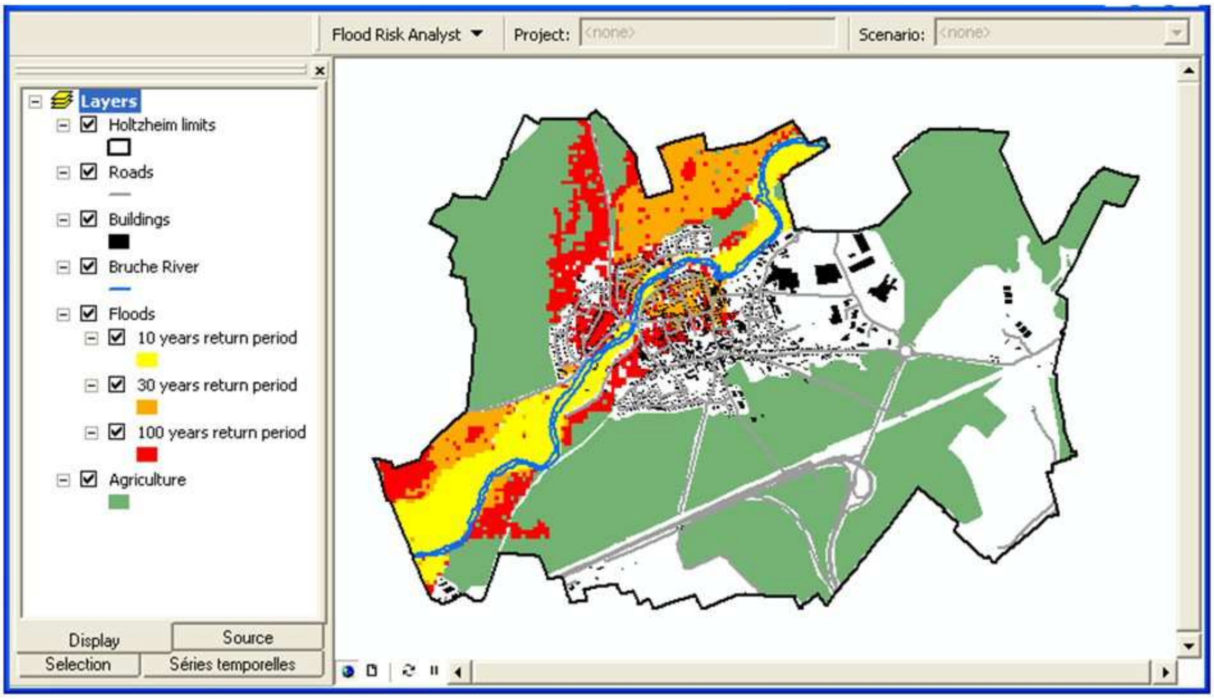


Figure 3.6. Overview of floods and vulnerability raw layers used in the case study. Data displayed in ArcMap® GIS environment.

4.2. Pre-processing functions

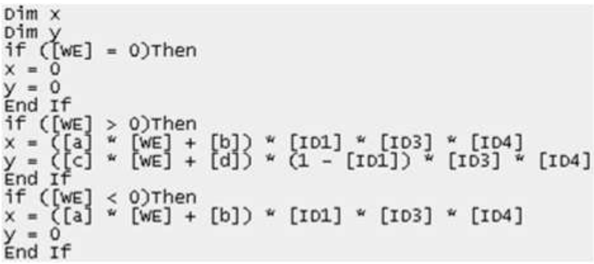
The tool pre-processing functions were developed to deal with existing datasets, *e.g.* flood hazard maps, assets maps and damage functions. They allow the user to easily process input data in order to respond to format requirements of the model. Another functionality of the pre-processing functions is that unit transformations and layer conversions can be realised without modifying the original data (new layers are generated for data processing). Some of the pre-processing functions are showed during the analysis of the case study.

4.2.1. Creation of a project, scenarios and data management

All the data used in the tool is recorded in a personal geo-database to facilitate data management. Each project created with F.R.A.GIS is associated with a geo-database in which specific tables are created for recording the project properties. Several scenarios can be created and analysed in one specific project. The pre-processing functions were developed for specifying following scenario characteristics:

- number of floods and the type of hydraulic parameter(s) analysed;
- calculation methods – it refers to the approaches used to calculate flood parameters inside/over assets and damaging potential for the different types of assets considered in the evaluation process. The user can choose standard calculation methods coded in the tool or use external text files (VBA routines);
- damage functions – the user must enter the values of damage according to the calculation methods chosen;
- return-periods of the different flood hazard analysed.

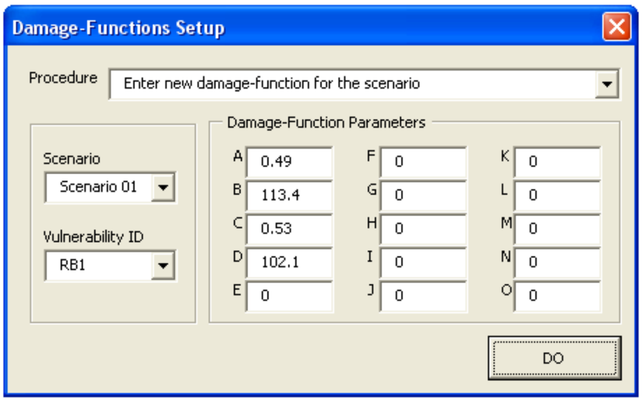
In the present case study, water depth spatial distribution of 3 flood events (return-periods equal to 10, 30-yr and 100-yr) were analysed (Figure 3.6). An internal coded function for water depth calculation was used for estimating buildings flooding potential. The method consists of calculating the difference between the buildings floor level height and the water depth inside the building. An external calculation method (text file containing VBA conditions) was used for calculating damage-potential, *e.g.* direct damage function used for estimating residential buildings damaging potential based on Torterotot (1993) (Figure 3.7).



```
Dim x
Dim y
if ([WE] = 0)Then
x = 0
y = 0
End If
if ([WE] > 0)Then
x = ([a] * [WE] + [b]) * [ID1] * [ID3] * [ID4]
y = ([c] * [WE] + [d]) * (1 - [ID1]) * [ID3] * [ID4]
End If
if ([WE] < 0)Then
x = ([a] * [WE] + [b]) * [ID1] * [ID3] * [ID4]
y = 0
End If
```

Figure 3.7. VBA text sample representing direct damage function for residential buildings.

In Figure 3.7, ***WE*** is the field where water-elevation is calculated by default; ***ID1*** corresponds to the percentage of buildings with basements in the study area; ***ID2*** is the height of building ground floors in relation to the natural landscape, ***ID3*** is the surface of the buildings; ***ID4*** is the percentage of building occupied by human activities; ***a***, ***b***, ***c*** and ***d*** are the values of damage related to the associated damage function, entered in the tool by means of the specific pre-processing functions (Figure 3.8).



Procedure: Enter new damage-function for the scenario

Scenario: Scenario 01

Vulnerability ID: RB1

A 0.49
B 113.4
C 0.53
D 102.1
E 0
F 0
G 0
H 0
I 0
J 0
K 0
L 0
M 0
N 0
O 0

Figure 3.8. F.R.A.GIS tool interface for processing damage functions.

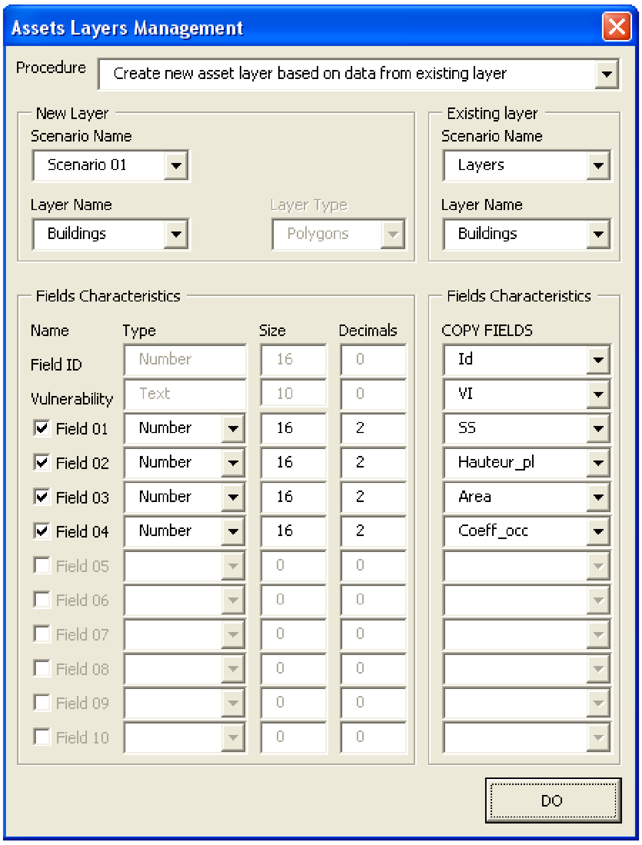
The ***Vulnerability ID*** for each damage function corresponds to one specific asset vulnerability index. In this case, the buildings with vulnerability index ***RB1*** (Residential buildings of type 1) are analysed using the damage function presented. Five other indexes were used for different types of buildings (5 vulnerability classes of non residential buildings) and specific functions were used for each of them, *cf.* DNRM (2002). The damage functions used for agriculture and roads were similarly processed.

4.2.2. Add of layers in the project

We used hazard pre-processing functions to transform the floodwater depth raster layers into vector layers inside the project geo-database. Vulnerability pre-processing functions were used to create new vulnerability layers inside the project geo-database (copying information contained in the raw layers and changing the name of fields in order to respond to the model input requirements). The following interface was used with this purpose (Figure 3.9).

By using the pre-processing functions we process the different layers analysed (Figure 3.7) to correlate the different variables for the application of the existing damage functions. For example, the information needed for application of the different damage functions correlated to the buildings layer (Figure 3.9) is: the ***Field ID*** to identify the different assets represented; the ***Vulnerability*** index field to specify the types buildings (residential, commercial, industrial...) and the damage functions to use for evaluating damage to the different assets; the ***Field 01*** index to explicit the existence of basements;

the ***Field 02*** to specify the height of building ground floors in relation to the natural landscape; the ***Field 03*** to specify the surface of the building and ***Field 04*** to specify the real occupation of the buildings. Different information was entered for agriculture and roads considering characteristics like types of crop, seasonal variables and roads construction characteristics, *cf.* Erdlenbruch et al. (2007).



Procedure: Create new asset layer based on data from existing layer

New Layer
Scenario Name: Scenario 01
Layer Name: Buildings
Layer Type: Polygons

Existing layer
Scenario Name: Layers
Layer Name: Buildings

Fields Characteristics

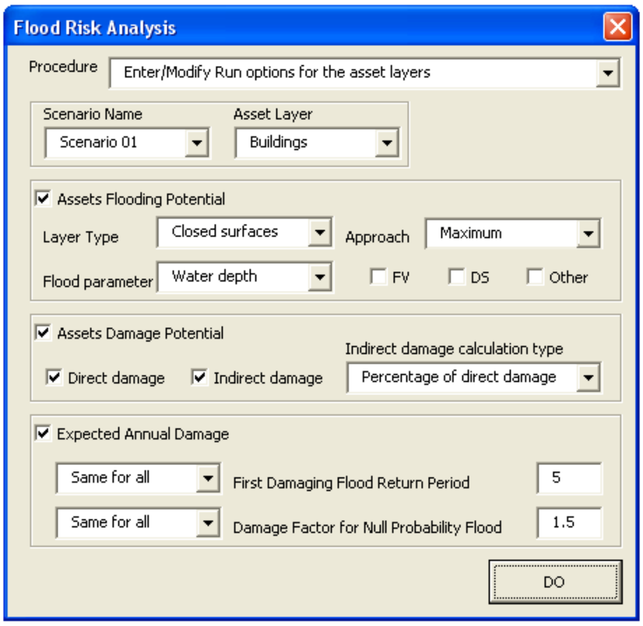
Name	Type	Size	Decimals	COPY FIELDS
Field ID	Number	16	0	Id
Vulnerability	Text	10	0	VI
☑ Field 01	Number	16	2	SS
☑ Field 02	Number	16	2	Hauteur_pl
☑ Field 03	Number	16	2	Area
☑ Field 04	Number	16	2	Coeff_occ
☐ Field 05		0	0	
☐ Field 06		0	0	
☐ Field 07		0	0	
☐ Field 08		0	0	
☐ Field 09		0	0	
☐ Field 10		0	0	

Figure 3.9. F.R.A.GIS tools assets layers management interface.

4.3. Model RUN parameters

When configuring the RUN parameters, the asset layers are individually parameterised. Different options are defined at this level to take into account the different approaches to use when combining hazard with vulnerability layers, when calculating assets damage function and expected annual damage. For example, we display in Figure 3.10 the module setup used for estimating the flood risk for dwellings.

In this example the three calculation modules (Figure 3.5) were selected and the different required parameters entered: the ***closed surfaces maximum combination approach*** was selected to estimate assets flooding potential to buildings (Figure 3.3); only flood water depth parameter should be used for calculating buildings flood potential and damage (the damage functions used depend exclusively on water depth values); we calculate direct damage using damage functions and indirect damage using percentage of direct damage values according to DNRM (2002); expected annual damage should be calculated (Figure 3.4) considering a 5-yr return period flood as first damaging flood event and asset damage for the null probability flood event was estimated 1.5 times flood damage caused by the 100-yr return period flood event.


Flood Risk Analysis

Procedure: Enter/Modify Run options for the asset layers

Scenario Name: Scenario 01
Asset Layer: Buildings

☑ Assets Flooding Potential
Layer Type: Closed surfaces
Approach: Maximum
Flood parameter: Water depth
☐ FV ☐ DS ☐ Other

☑ Assets Damage Potential
☑ Direct damage ☑ Indirect damage
Indirect damage calculation type: Percentage of direct damage

☑ Expected Annual Damage
Same for all — First Damaging Flood Return Period: 5
Same for all — Damage Factor for Null Probability Flood: 1.5

Figure 3.10. F.R.A.GIS tool RUN parameters interface.

4.4. Results

By running the tool, the three general equations (3.1), (3.2) and (3.3) were solved in order to respectively estimate the assets flooding potential, damage potential and expected annual damage. All data calculation is stored in the assets layers, which allows the user to generate risk maps by means of simple GIS functions. Display options can be changed by using post-processing functions. These functions were elaborated to provide quick overview of the results of the analysis. Figure 3.11, Figure 3.12, Figure 3.13 and Figure 3.14 display the results of the analysis processed with post-processing functions. Expected annual damage was calculated at 330 k€ per year for the assets analysed in the town of Holtzheim: 88.4% for residential buildings, 10.2% for non-residential buildings, 0.8% for roads and 0.6% for agriculture. The damage potential and risk maps (expected annual damage) produced are important elements for supporting decision-making processes. The spatial representation of assets brings the possibility to identify priorities in damage reduction programs. Several results can be explored *e.g.* number of buildings affected, distribution of damage per event return period, level of flooding water inside buildings. The global results of different scenarios can be easily compared in the context of uncertainty analysis, sensitivity tests and cost-benefit analysis.

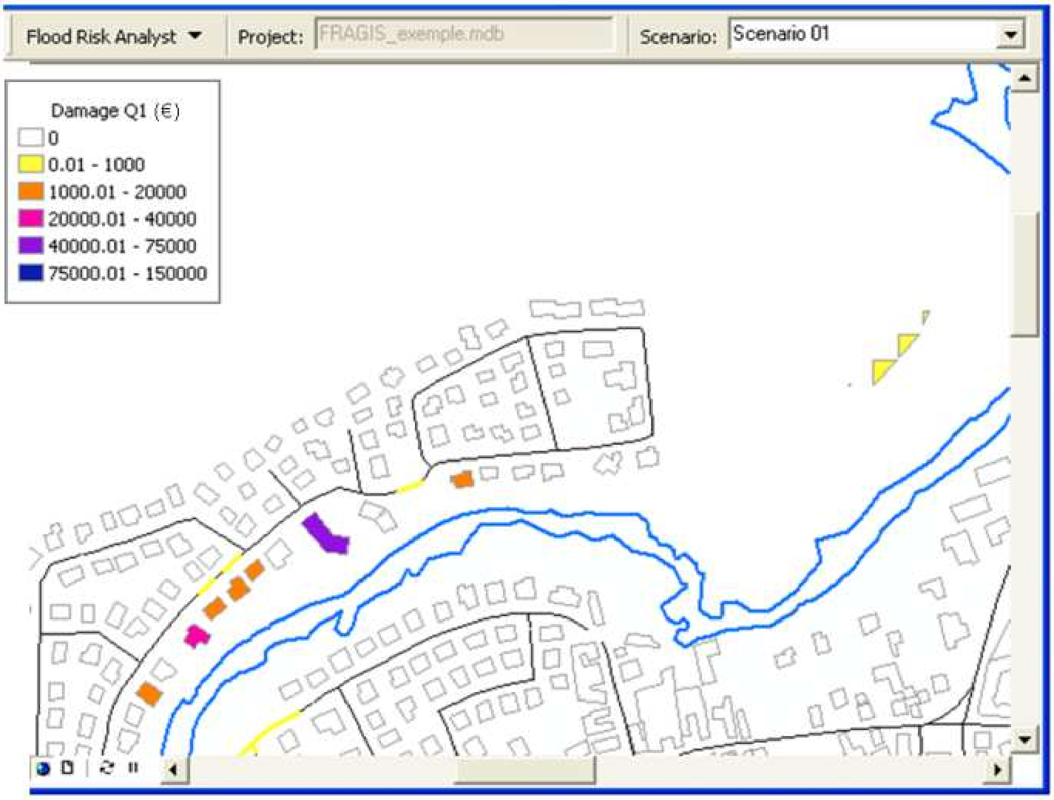


Figure 3.11. Asset potential damage map for a 10-yr return period flood.

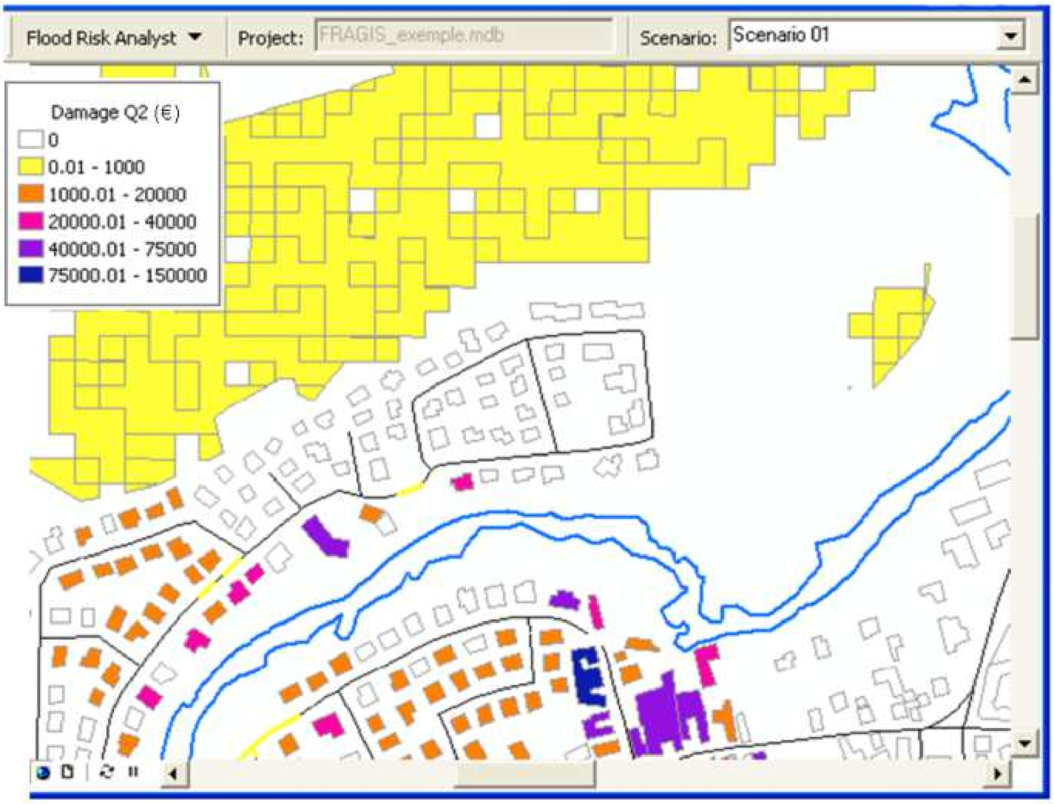
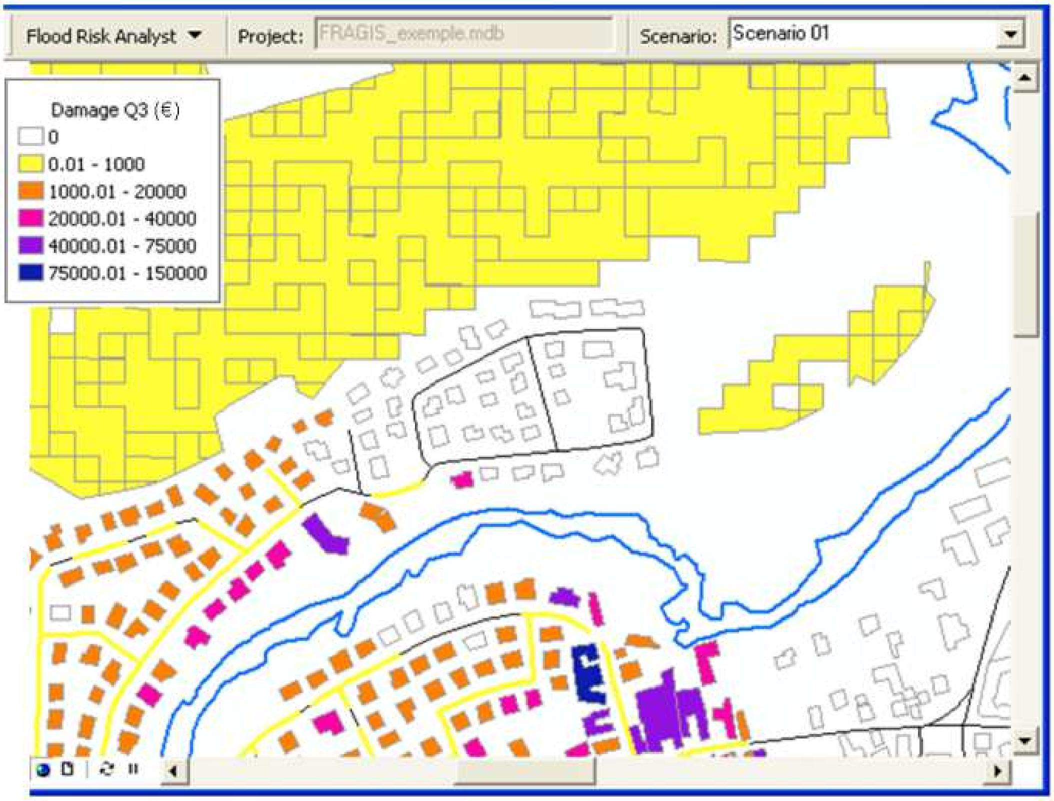
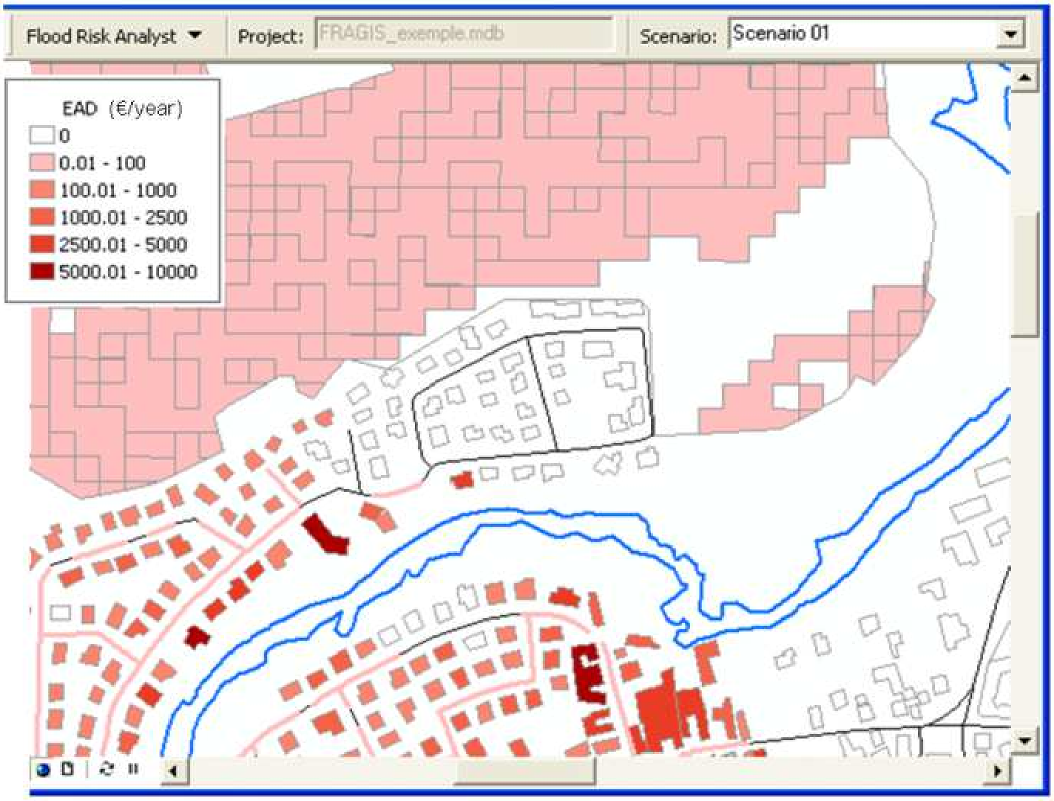


Figure 3.12. Asset potential damage map for a 30-yr return period flood.


Project: FRAGIS_exemple.mdb

Scenario: Scenario 01

Figure 3.13. Asset potential damage map for a 100-yr return period flood.


Project: FRAGIS_exemple.mdb

Scenario: Scenario 01

Figure 3.14. Asset expected annual damage map.

5. Conclusions and perspectives

GIS is used all over the different steps of flood damage evaluation processes. It is widely used in hazard modelling processes (*cf.* section 2.2) and vulnerability analyses (*cf.* section 2.3). Even though several methods are currently used to evaluate flood risks (*cf.* section 2.4), the construction of comprehensive databases and the harmonisation of methods in national and international contexts remains great challenges for researchers and practitioners (Merz et al., 2007; Köhler et al., 2006; European Parliament Council, 2007). The crucial role of GIS on spatial analyses and the needs for standard methods to evaluate potential flood damage incite the development of GIS-based methods to evaluate flood risks. This article presented a general GIS-based method to evaluate flood damage and its implementation in a GIS platform. The method developed is based on the combination of flood hazard and the vulnerability of assets spatial data, and it uses damage functions to estimate damage potential (Merz et al., 2010b). The assets can be analysed individually in a property-by-property assessment or using large homogeneous areas based on land-use classes. The GIS environment facilitates the production of different types of maps (van Alphen et al., 2009; de Moel et al., 2009). We explain in detail the principles of the model as well as its implementation in a GIS platform. The description of the methodology details all the steps of the evaluation of flood damage in a way to support model developers and practitioners. The brief case study presented here illustrated the functionalities of the model and tool developed. By running the GIS tool with appropriate input datasets, the analyst is able to: estimate intensity of flood parameters inside/over assets at risk for different flood events; estimate assets damage potential related to different flood events; calculate expected annual damage for the assets; realise and compare several scenarios of evaluation; produce flood risk maps; analyse damage and expected annual damage spatial distribution. The main gains enhanced by this model are: the standardisation of a general method to evaluate the potential damage of future floods; the generation of a friendly interface which allows the user to easily realise the analysis, without depending on a great GIS background; the possibility of comparing different scenarios of evaluation in project appraisal or uncertainty analysis contexts. The use of this kind of standard method promotes the comparison of results of evaluations in different contexts, which is one of the objectives of the EU Floods Directive 2007/60/EC (European Parliament Council, 2007). The utilisation of this model by stakeholders should bring great improvement to the evaluation process, and it could also provide feedback in order to improve the actual existing functionalities.

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- PART II -

VARIABILITY OF
POTENTIAL FLOOD DAMAGE ESTIMATIONS

Different types of datasets must be gathered for achieving flood damage evaluations. On the one hand, information about flood hazard is required for achieving these analyses. Several models can be used with different assumptions during the evaluation process. On the other hand, data on the vulnerability of assets to floods is necessary. This information is more or less available according to the context and scale of the evaluation. Several approaches and simplifications can also be considered when obtaining the necessary datasets related to the assets exposed to the flood hazard and their vulnerability to floods. Uncertainties are differently generated and propagated on both aspects of the evaluation process. It is essential to measure uncertainty propagation on the results of the evaluation in order to better understand the influence of the different methodological choices on their results. This, for supporting better investments in the evaluation process, and reduce uncertainty according to the objectives of the analysis. In this second part of the thesis, we applied the framework presented previously in two case studies, in order to explore the uncertainties linked to the different aspects of the damage estimation process. This part of the thesis is divided in six chapters. In Chapter 4 we present the two case studies analysed. In Chapter 5 and Chapter 6, we present the different tests and uncertainty propagation concerning the construction of flood hazard maps. In Chapter 7 and Chapter 8, we present the different tests realised in order to explore the uncertainties linked to the vulnerability aspect of the risk. Finally, in Chapter 9 we compare the levels of uncertainty generated by the different aspects of the risk evaluation process.

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Chapter 4.

Case studies: the towns of Holtzheim and Fislis

In this chapter, we present the two case studies analysed in this thesis: the town of Holtzheim, in the lower valley of the Bruche River and Fislis, in the upper valley of the Ill River. Both case studies are located in the west bank of the upper Rhine, in Alsace, France.

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1. Localization of case-studies

Two case studies were selected for analysis in the context of this thesis. These are the town of Holtzheim, crossed by the Bruche River and the town of Fislis, located in the confluence of Ill River and its tributary Limendenbach. Both case studies are located in the west bank of the upper Rhine (Figure 4.1).

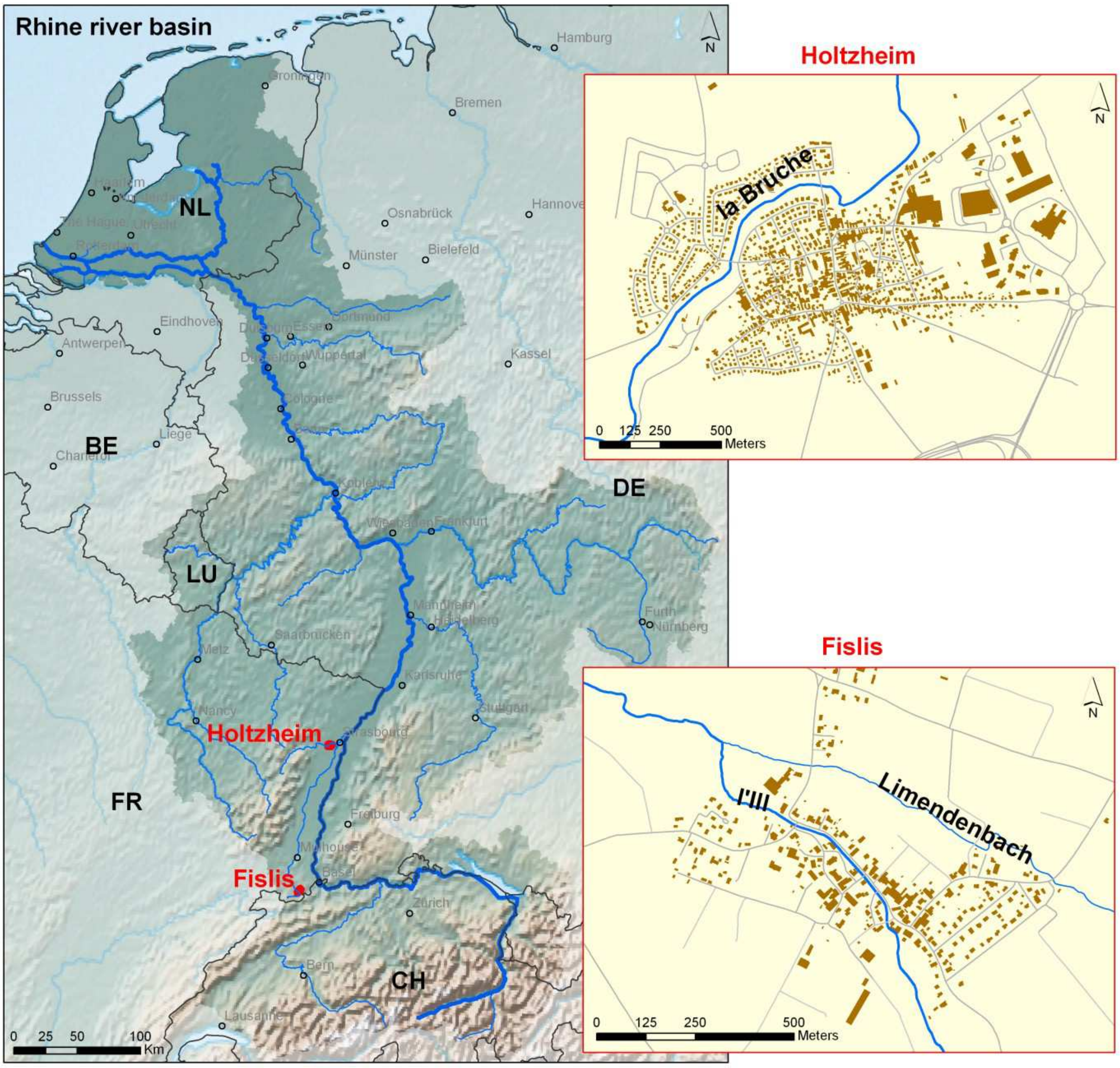

Figure 4.1. Localization of the case studies analysed in this thesis: the town of Holtzheim and the town of Fislis.

The complexity of big urban centres and their hydraulic and drainage systems considerably increase the need for detailed specific studies. In order to possibly generalize the conclusions of the tests realized in this thesis, we preferred to select less complex contexts for analysis. This choice was also strongly motivated by the great amount of tests realized and the complexity of the construction of the different strategies of evaluation introduced in Chapter 2. The selection of the case studies was realised according to the following criteria: (1) town characteristics – small or medium size towns in rural or peri-urban contexts; (2) potential flood risk – frequent or medium frequent damaging flood events; (3) typology of assets concerned by the flood risk – mainly residential buildings and contents; and (4) hazard characteristics – type of floods and complexity of the hydraulic system, (5) data availability for realisation of the different tests – existing hydraulic model, hydrological data, assets datasets.

2. Holtzheim in the Bruche lower valley

The town of Holtzheim counts on approximately 3,056 inhabitants[19]. It has a surface of 691 hectares in a flat area at the altitude level of 148m (IGN 69) in average. It is a peri-urban town, part of the Urban Community of Strasbourg in which development leads to the increase of demands in terms of urbanization[20]. However, the town is crossed by the Bruche River in the low valley of this river not far from its confluence with Ill River, and it is vulnerable to its different types of floods. The town counts on a PERI[21] since August 1991, which establish different rules for urbanization according to the flood risk (SNS, 1991). The regulation map based on a historical flood event is displayed in Figure 4.2. The Bruche River is long of 78km (from the Vosges mountains to its confluence with the Ill River in Strasbourg city, in the Alsatian flat valley), counting on a drainage basin of 727km^2 (DREAL Lorraine, 2012). The 2/3 of the Bruche River path is in mountainous regions, with torrential characteristics (from its source to the city of Molsheim). The city of Holtzheim is located in the lower valley of the Bruche River where the floods are slowly. The drainage basin upstream the case study has a surface of 688km^2. The inter-annual mean discharge of the river at this point is estimated in

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[19] Population in 2009. Internet site: http://www.annuaire-mairie.fr/ville-holtzheim.html (consulted in April 2012).

[20] Holtzheim population has increased of 2.11% per year since the end of the Second World War. Its actual population is almost 5 times greater than its population in the end of the XIII century - analyses based on data from the French national institute for statistics and economics studies (INSEE), http://www.insee.fr (consulted in April 2012).

[21] The "Plan d'Exposition au Risque Inondation" is the ancient name of the actual "Plan de Prévention des risques Inondation" (PPRi), which is a French institutional instrument allowing to establish urbanization rules based on hazard and vulnerability analyses for flood risks.

8.1m3/s[22]. The river maximum instantaneous discharge reaches approximately 196m^3/s for a 30-yr flood event and 260m3/s for a 100-yr return period. The river counts on few hydraulic structures in the point analyzed (bridges and hydraulic jumps) and it has no water retention hydraulic structures (SNS, 1991). The hydrological dynamics of the river is due to the inexistence of flood control systems in the Bruche River. Floodwater rises slowly and the propagation of the flood wave is quite slow which leads to slow flood events (SNS, 1991).

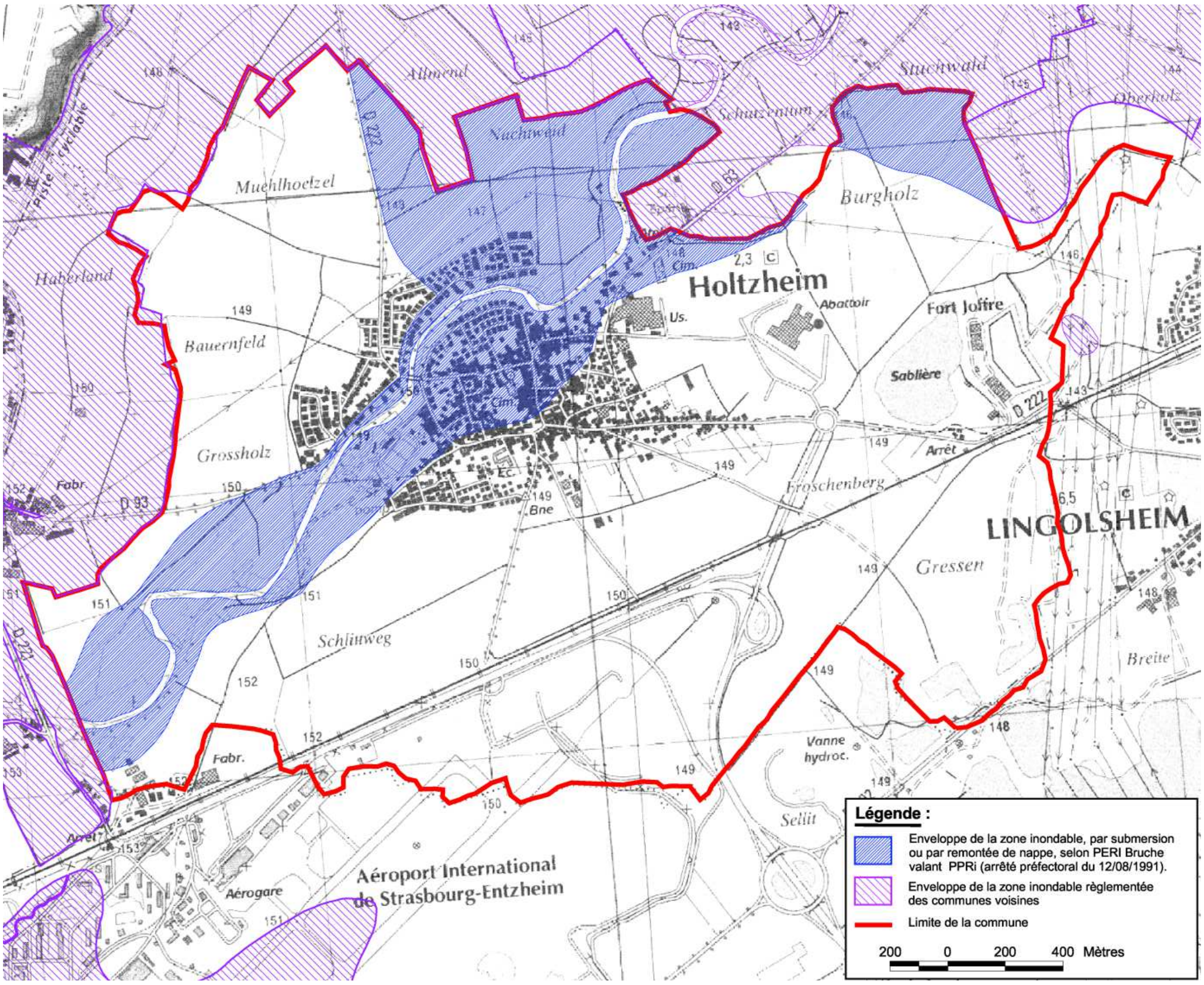

Figure 4.2. Map used in the context of the PERI of Holtzheim. Source: Internet WEB site[23].

Flood events are recurrent and the proximity of the population of this town to the river highly increases the flood risk. Buildings and contents represent the majority of damage in case of floods. A 100-years flood event reach almost the half of the town buildings (around constructed 25 ha) and

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[22] Hydrological data from 1965 to 2012. Internet site: "Banque hydro" http://www.hydro.eaufrance.fr (consulted in April 2012).

[23] Map available on-line in the Bas-Rhin prefecture WEB site: http://www.bas-rhin.pref.gouv.fr

around 40% of its population. In this type of flood, the water depth can reach the 1.25 m in areas with few assets and a maximum of 0.75 cm in residential and commercial areas (SNS, 1991). The river is of a pluvial-oceanic regime, flood events generally occur in Spring and Winter (DREAL Lorraine, 2012). Several damaging floods occur in the town in the last 30-yr (DREAL Lorraine, 2012): in 1983, two important flood events took place in April and May; the flood of February 1990[24] is the stronger event still present in the consciences of the population; other flood events of less impact took place in June 1996, December 1999, December 2001 and January 2004. Some of them (floods of 1983, 1990, 1996 and 1999)[25] were considered of national relevance and were declared as natural catastrophes for the town of Holtzheim and others, according to the CatNat procedure[26].

3. Fislis in the Ill upper valley

Fislis is a rural small town counting on a population of around 432 inhabitants[27]. The surface of the town is of 753 ha. Urbanisation in the city is restricted although we observe the recent increase of its population[28]. The town is crossed by the Ill River and its tributary, the Limendenbach. The Ill River is the main Alsatian tributary of the Rhine. It is 223 km long (from the Alsatian Jura to its confluence with the Rhine River downstream the city of Strasbourg) and it drains a 4,760 km^2 basin (DREAL Lorraine, 2012). From its source to the city of Mulhouse, the river slope is relatively high, which leads to flash floods. The case study is located in this area. Downstream Mulhouse, the Ill River crosses the Alsatian plain with lower altitudes and slopes, where the floods are slow (DDAF, 2006). The Ill river is also of pluvial-oceanic regime with flooding period in spring and winter seasons (DREAL Lorraine, 2012). Several strong flood events took place during the last century *e.g.* floods of 1910, 1919, 1947, 1955, 1983 and 1990. Damage caused by these flood events was important (DDAF, 2006). More recent important floods took place in January 2004 and august 2007 (for the upper Ill River) (DREAL Lorraine, 2012).

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[24] In Holtzheim, the Bruche River reached its maximum discharge in 1990 February 16 (185m^3/s) - “Banque hydro” http://www.hydro.eaufrance.fr (consulted in April 2012).

[25] Years of "Arrêtés d’état de catastrophe naturelle" for the following flood events: from 22/05/1983 to 27/05/1983, from 14/02/1990 to 19/02/1990, from 09/06/1996 to 09/06/1996 and from 25/12/1999 to 29/12/1999 - Internet site “Prévention de risques majeurs" http://macommune.prim.net (consulted in April 2012).

[26] The “CatNat” procedure is part of the French insurance system, which allows the population to require insurance funds for dealing with damage.

[27] Population in 2009. Internet site: http://www.annuaire-mairie.fr/mairie-fislis.html (consulted in April 2012.

[28] The population of Fislis is almost the same observed by the end of the XIII century. We notice that its population decreases until the end of the IX century and stayed stable until the end of the Second World War. Since 1946, the town’s population increases 0.73% per year - analyses based on data from the French national institute for statistics and economics studies (INSEE), http://www.insee.fr/ (consulted in April 2012).

The town of Fislis is located at the altimetry point of 455m high in IGN69 in average, in a mountainous region (altitude varying from 377 to 532 meters high in IGN69)[29]. The town is frequently affected by floods suffering damage[30]. Damage in the town is essentially to dwellings, their contents and agriculture. The town urbanisation is also regulated by a PPRI[31] (Figure 4.3), since December 2006 (DDAF, 2006).

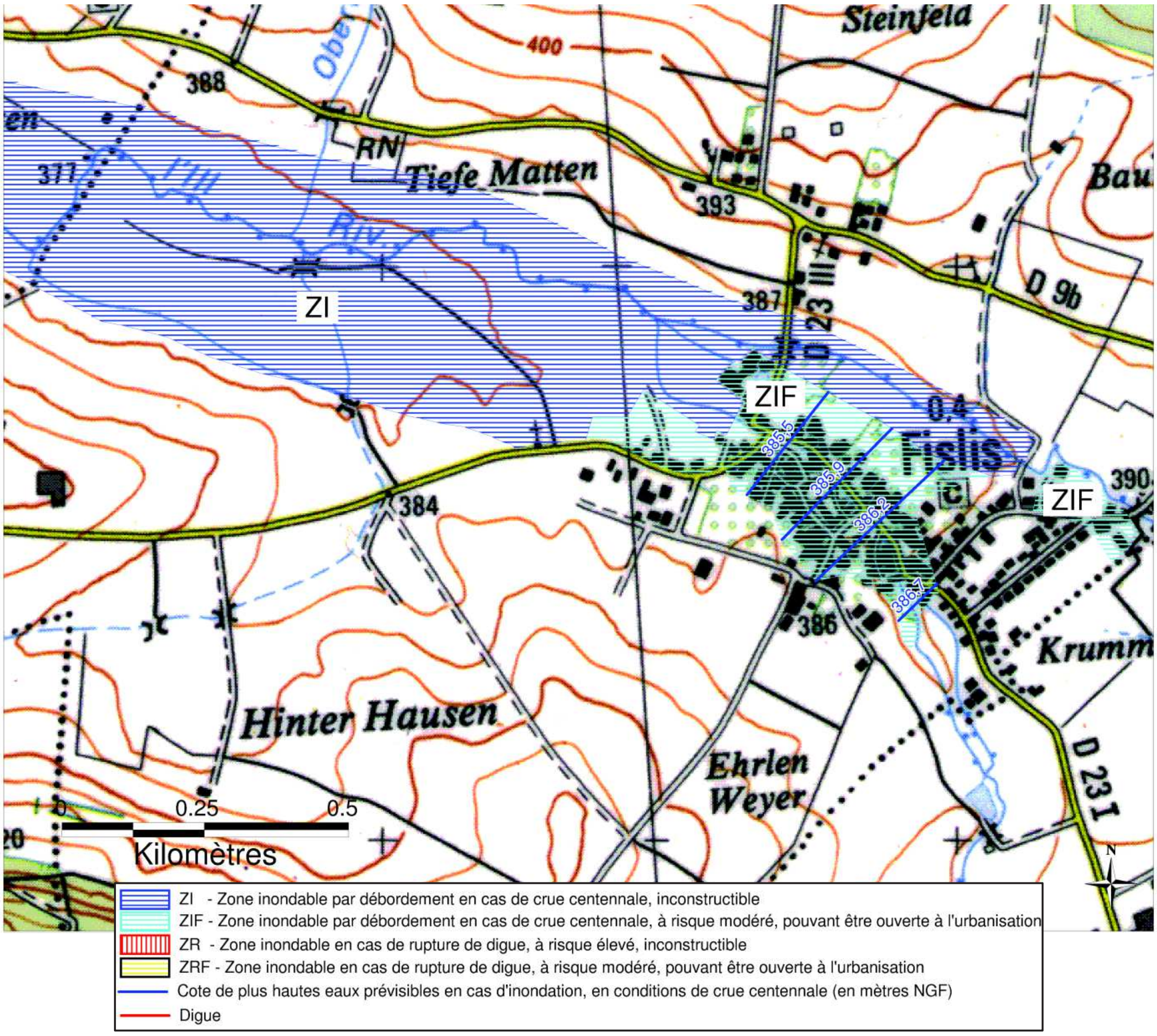

Figure 4.3. Map used in the context of the "Plan de Prevention du Risque Inondation" (PPRi) of Fislis. Source: Haut-Rhin French "Département" prefecture internet WEB site[32].

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[29] Data provided by the internet site: http://www.annuaire-mairie.fr/mairie-fislis.html (consulted in April 2012).

[30] Fislis town was flooded and considered to suffer natural catastrophe according to the CatNat procedure "Arrêtés de catastrophe naturelle" for the floods from 18/05/1994 to 20/05/1994, from 29/05/1995 to 01/06/1995, from 21/02/1999 to 22/02/1999, from 25/12/1999 to 29/12/1999 and from 08/08/2007 to 09/08/2007 - internet site "Prévention de risques majeurs" http://macommune.prim.net (consulted in April 2012).

[31] The "Plan de Prévention des risques Inondation" (PPRi) is a French institutional instrument allowing to establish urbanization rules in bases of hazard and vulnerability analyses for flood risks.

[32] Map available at the Haut-Rhin prefecture WEB site: http://www.haut-rhin.pref.gouv.fr

The Ill River at the point of its confluence with Limendenbach stream drains a small catchment of approximately 43km^2. Its affluent, Limendenbach, drains a 24km^2 surface catchment[33]. The inter-annual flow rate of the Ill River crossing the town of Fislis[34] is around 0,5m^3/s. We estimate that a 100-years return-period flood event can lead to a flow rate of around 30m^3/s for the Ill River and 13m^3/s for its tributary Limendenbach stream at the point of confluence of both of them. During the last damaging flood event in August 2007, the Ill River flow rate[35] reached 12.20m^3/s. For a 100-yr flood return period, more than half of the buildings of the town are impacted by the flood (DDAF, 2006).

4. Conclusions

The two case studies presented here were analysed for the different aspects of risk assessments. Different strategies used to achieve hydrological analyses, hydraulic modelling, vulnerability assessments and susceptibility analyses were developed on the basis of these case studies. The following chapters of this thesis present these analyses.

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[33] Topographic analyses realised in 2010.

[34] Hydrological data from 2006 to 2012 - internet site: “Banque hydro” http://www.hydro.eaufrance.fr (consulted in April 2012).

[35] Ill River discharge measured in Oltingue station around 1.5km upstream the town of Fislis, at 2:00 of 09/08/2007 - internet site: “Banque hydro” http://www.hydro.eaufrance.fr (consulted in April 2012).

Chapter 5.

Hydrological analyses of flood discharges and frequencies

This chapter presents how the confidence intervals considered when using distribution functions to analyze discharge series influence flood hazard and risk estimations. The Bruche River case study, in eastern France upper Rhine, was retained with this purpose. Hydrological uncertainty was propagated in the production of flood maps and further on the evaluation of flood damage, risk and risk maps. Firstly, we analyzed how discharge-frequency forecasts were affected by different statistical distribution analyses. Four functions frequently used in flood analyses were retained: GEV (Generalised extreme value), GUM (Gumbel), PE3 (Pearson type 3) and LN3 (Lognormal 3-parameter-type). Two confidence intervals frequently used in France were adopted to determine flood flow return periods, 70% and 90%. We realised uncertainty propagation tests linked to both, the selection of the statistical distribution and the confidence interval considered. 108 flood hazard maps produced using the different approaches were used to quantify potential flood damage and expected annual damage. The selection of statistical distributions slightly influenced the results of damage evaluations. The variability of results was considerably increased when taking into account distributions confidence intervals. These results highlight the need for standards in relation to the uncertainty acceptance level in flood frequency analyses, especially when those are used to produce flood maps and estimate flood risks.

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1. Introduction

On the one hand, the evaluation of potential flood damage serves to support project appraisals and flood management. These evaluations are largely used worldwide for different purposes (Merz et al., 2010b). Flood maps bring, on the other hand, the spatial dimension of floods and are crucial for projects appraisal. Different types of flood maps are currently used to support flood management (EXCIMAP, 2007; de Moel et al., 2009; van Alphen et al., 2009). The use of these different tools for flood management purposes is crucial and it has gained in importance overtime (Penning-Rowsell and Green, 2000b). For example, the EU Floods Directive 2007/60/EC (European Parliament Council, 2007) determines that flood risk management should be supported by the production of hazard and risk maps, and that cost-benefit analysis principles should be used in project appraisals. The role of uncertainty in the production of flood maps and flood damage assessment is highly significant and cannot be neglected (de Blois and Wind, 1995; Merz et al., 2010b). Both hazard and vulnerability uncertainty sources contributes to total uncertainty on flood risk analyses (Apel et al., 2008b). Many studies explored different sources of uncertainty on risk evaluations (NRC, 2000, 2009; Merz and Thieken, 2009; de Blois and Wind, 1995). They highlight the importance of hydrological uncertainty on the global uncertainty of flood damage estimations. Hydrological information is crucial to determine protection standards and for other flood management purposes (Plate, 2002; Plate, 2009; Schumann, 2011). Al-Futaisi and Stedinger (1999) argue the relevance of considering flood risk analysis uncertainty in order to minimise the impact on the design of flood risk management projects. It is therefore crucial to understand how uncertainty in flood frequency analyses propagates throughout flood risk estimations.

1.1. Flood frequency analyses and flood risk evaluation

Hydrological analyses are at the beginning of flood risk evaluation processes. Three hydrologic methods are generally used in flood mapping studies: flood frequency analysis, rainfall-runoff models and regional regression equations (NRC, 2009). Throughout these analyses, we estimate the flow of a river and its associated exceedance probability for further production of flood hazard, evaluation of potential flood damage and production of risk maps. Flood frequency analysis of stream gage records is the most reliable hydrological approach in flood risk evaluation process (NRC, 2009). The objective of flood frequency analysis is to provide the quantiles of maximum peak flow or daily discharge corresponding to a given return period (Chow et al., 1988). The use of frequency analyses for economic risk estimations was a subject of great controversy because of uncertainty (Gunasekara and Cunnane, 1991; Beard, 1960, 1978; NRC , 1995; Arnell, 1988; Stedinger, 1983a, b, 1997; Arnell, 1989; Beard, 1997). It is concluded that uncertainty is part of results of these analyses and must be considered and quantified in order to support decision-making processes (NRC, 2009, 2000).

Frequency analysis is a complex task once little information is generally available. In the French context for example, the installation of hydrometric equipment has started just after the Second World War (Lang and Lavabre, 2009). The gages record length plays an critical role on the liability of the quantiles of maximum peak flow corresponding to a given return period (Xu and Booij, 007; NRC, 2000). The statistical methods used and the considerations made when processing existing data can also strongly influence the determination of discharge for specific frequencies. The selection of distribution functions plays an important role on flood damage evaluations (Merz and Thieken, 2009). To provide effective and meaningful results for flood risk analyses, quantile estimations have to be complemented by uncertainty assessments. IACWD (1982) distinguished natural variability from knowledge uncertainty in flood-frequency calculations. It considers that discharge probability distribution describes natural variability, and the error bounds about the curve reflect knowledge uncertainty. Merz and Thieken (2005) showed the interest to distinguish stochastic and epistemic uncertainty during the flood frequency analysis. According to these authors, the occurrence of flood peak or maximum daily discharge is considered as a random process. All other steps of flood frequency and risk analyses are supposed to be associated with epistemic uncertainties. The sources of epistemic uncertainties during flood frequency analysis include assumptions of extreme value statistics, selection of sample, selection of distribution function, selection of parameter estimation method and statistical inference uncertainty (Merz and Thieken, 2005). The uncertainty in parameters of distribution functions and quantile estimation is usually accounted for by adding confidence intervals to point estimates (Serinaldi, 2009; Lang and Lavabre, 2009). Confidence intervals (CI) can be assessed by parametric, non-parametric and simulation techniques (Serinaldi, 2009; Chowdhury and Stedinger, 1991).

Therefore, as highlighted by Khaliq et al. (2006) it is unrealistic to expect summarize all uncertainty associated to a quantile estimates in a single value. Using the upper value of confidence intervals instead of quantile estimates strongly affects the inundation estimation and the damage estimation. Therefore, the choice of upper values directly affects the results of flood risk analyses. It is common to represent the theoretical 0.95 CI when estimating flood discharges (Xu and Booij, 2007). This value minimizes the risk of using an underestimated peak flow quantile value in the flood assessment process. However, the use of a high CI directly influences the cost of flood protection techniques, *e.g.* levees, bridges and detention ponds design, associated with the expected peak flow. Therefore, the choice of upper CI values can be determined, in practice, as a function of the vulnerability context. In France, a confidence interval of 70% and 90% of the peak discharge value is generally retained for rural areas and urban areas, respectively.

Hydrological uncertainties propagate throughout the whole chain of flood damage evaluation process. It passes by the production of flood maps and its associated hydraulic characteristics affecting the quantification of the risk (NRC, 2009). The propagation of hydrological uncertainty is aggravated into the damage evaluation results (Xu and Booij, 2007). Formal uncertainty analyses are the exception rather than the rule in flood risk assessments (Merz and Thieken, 2009). In practical applications, hydrological confidence intervals are not considered when producing flood hazard maps or evaluating potential flood damage once no standards exist to determine uncertainty acceptance levels in hydrological analyses for the production of flood hazard maps or damage evaluations.

1.2. Objective of this chapter

Despite that the choice of the confidence intervals is determinant to the results of hydrological analyzes, no studies were developed for quantifying the impact of this choice on flood hazard maps, damage estimations and risk mapping. The goal of this chapter is to take into account hydrological confidence intervals during flood hazard mapping and damage evaluation processes. In the first part of this chapter, we present the methodology used to propagate hydrological uncertainty throughout the flood risk estimation process (section 2). We investigate the influence of confidence intervals for different distribution functions, on the damage evaluation process. In the second part of it (section 3), we quantify the impact of flood frequency analysis uncertainty on the determination of hazard maps, damage potential estimations, expected annual damage and risk maps.

2. Uncertainty analysis method

The methodology used in this chapter focuses on the impact of statistical distributions confidence intervals determination on flood risk assessments. With this purpose, we measure this impact on the different modules of the evaluation process (Figure 5.1).

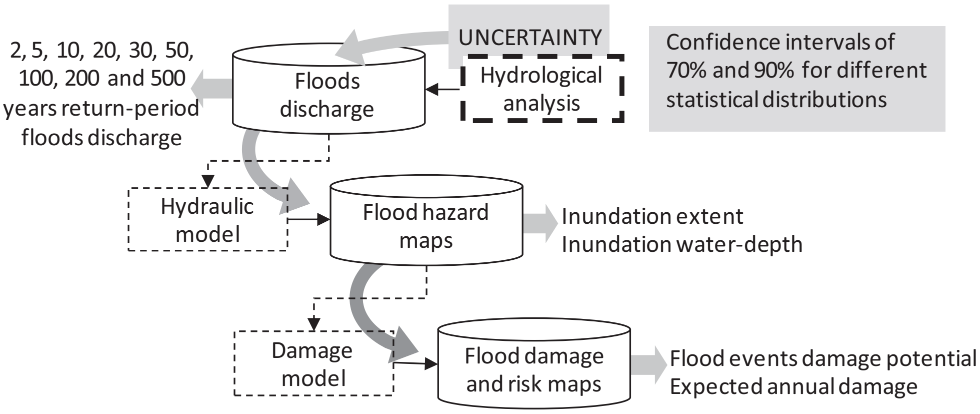

Figure 5.1. Synthetic scheme for the propagation of flood frequency uncertainty on flood risk analysis.

We propose to determine 0.7 and 0.9 confidence intervals for different statistical distribution functions (these values are frequently used in the French context). The hydrological discharges for different return period events are entered in a hydraulic model in order to simulate flood events and produce flood maps. These flood maps are therefore used to quantify damage potential using conventional stage-damage models (Merz et al., 2010b). Beyond flood damage calculation, we quantify the flood risk in terms of expected annual damage (EAD), *i.e.* flood risk is a combination of the flood events probabilities of occurrence and the associated consequences (European Parliament Council, 2007) and produce flood risk maps with the different values calculated. The propagation of uncertainty throughout the different modules represented in (Figure 5.1) is described in the following sections.

2.1. Flood frequency analysis

The hydrological analyses were performed on the maximum daily discharge series with the Hydrological Frequency Analysis (HYFRAN®) software[36]. The classical frequency analysis of hydro-meteorological variables is based on the assumptions of independence and stationarity of observations (Khaliq et al., 2006). The independence and stationarity of the maximum daily discharge series was tested applying the Wald-Wolfowitz and Kendall tests, respectively with a significant level of 5%. As highlighted by Merz and Thieken (2005), a large source of epistemic uncertainty of hydrological analysis is linked to the selection of the distribution function. Among the 15 distribution functions provided in the HYFRAN® software, six functions frequently used in flood analysis were tested (Xu and Booij, 2007; Merz and Thieken, 2005; Haktanir, 1992): GEV (Generalised extreme value), GP (Generalised Pareto), GUM (Gumbel), PE3 (Pearson type 3), LN3 (Lognormal 3-parameter-type) and EXP (Exponential). As pointed by Merz and Thieken (2005), it is common that hydrological available data is not sufficient to identify a 'correct' model and different distribution functions can be used simultaneously. Different statistical tests can be used to determine if a distribution function is adapted to fit the sample data (Lang and Lavabre, 2009; ÖnÖz and Bayazit, 1995). The Khi 2 test was applied to assess the capacity of the GEV, GUM and PE3 functions to fit the sample data. The Shapiro-Wilk test was retained to test the LN3 function owing to the sample size.

The parameters of these distributions can be estimated by different estimation methods: method of moments, L-moment and maximum of likelihood (Katz et al., 2002). The efficiency of the parameter estimation methods depends on the distributions functions and sample size (Martins and Stedinger, 2000). The Khi 2 test was used to select the more efficient parameter estimation methods for GEV, Gumbel and Pearson functions. The impacts of both the selection of parameter estimation method and the empirical probability methods, *e.g.* Hazen, Cunnane or Gringorten, are out of the scope of this

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[36] Software internet site: http://www1.ete.inrs.ca/activites/groupes/chaire_hydrol/chaire9.html (consulted in June 2012).

study. The computation of the confidence limits was performed using the HYFRAN® software using parametric bootstrap (Fortin et al., 1997).

2.2. Flood risk assessment

Flood damage evaluations are largely used to quantify flood risks (Dutta et al., 2003; Merz et al., 2010b; Penning-Rowsell and Chatterton, 1977). Damage models are used with this purpose to correlate flood hazard characteristics with the vulnerability of assets to estimate damage potential. In this chapter, we focus on unit damage evaluations based on depth-damage functions, *i.e.* correlation between damage potential, the vulnerability of assets and flood hazard parameters. This type of evaluation is widely accepted for forecasting flood direct damage potential. It considers that each asset in a flood area has a specific potential to suffer flood damage. The asset potential to suffer damage depends on its vulnerability to floodwater parameters, *e.g.* water depth, velocity or pollution rate, and the intensity of these parameters in case of floods. In order to estimate total damage potential correlated to a specific flood event probability, we sum-up the potential for all the assets impacted by the flood analysed. Therefore, flood events damage potential depends on the number of assets impacted (function of the extent of the flood), and their potential to suffer damage. Finally, in order to analyse the flood risk as a combination of flood probability (P) and its potential damage (D), expected annual damage (EAD) is calculated for the different potential damage estimations, *cf.* Equation (3.1)

$$\mathrm{EAD} = \int_{0}^{1} \mathrm{D(P)}\,.\,d(\mathrm{P}) \qquad (5.1)$$

This index is largely used as a flood design criterion to support flood management and it is particularly sensible to flood frequency analysis (Beard, 1997; Arnell, 1989; Stedinger, 1997; NRC , 2000).The understanding of the error of this index is crucial for planners (NRC, 1995). Flood hazard maps are the base for damage and EAD calculations. They represent the magnitude of flood events for different probabilities of occurrence, *e.g.* flood extent and water depth distribution for 100-yr return period events (de Moel et al., 2009). These flood maps are produced by means of hydraulic simulations (Bates and De Roo, 2000; Horritt and Bates, 2002; Stelling and Verwey, 2005; NRC , 2009). Several types of hydraulic models can be used to simulate flood events and to estimate the spatial distribution of flood parameters. These models require different datasets. On the one hand, data representing the physic aspect of the river, river geometry, the riverbed bathymetry, the floodplain topography, the hydraulic structures and roughness coefficients (Pappenberger et al., 2005; Cook and Merwade, 2009;

Horritt and Bates, 2001b). Uncertainty linked to this data is out of the scope of this chapter[37]. On the other hand, hydrological data is necessary for determining the flow of the river for different flood events. This chapter focus on the uncertainty linked to the determination of the discharge inputs used for producing hazard maps and further damage evaluations. Flood frequency analysis results using the different statistical functions and confidence intervals hypothesis are at the origin of the variability of discharge return periods. We propose to analyse a large number of flood events return periods, *i.e.* 2, 5, 10, 20, 30, 50, 100, 200 and 500-yr, in order to quantity the propagation of uncertainty for a large range of event from frequent to exceptional flood events. It is essential to analyse frequent floods once expected annual damage index is largely sensible to the determination of the first damaging flood event (Arnell, 1989; Penning-Rowsell and Green, 2000a).

We realise uncertainty propagation in accordance with the scheme in Figure 5.1, and its results can be measured following the Figure 5.2. The uncertainty framework proposed here generated different hydraulic simulation results and therefore different flood hazard maps for one specific flood event return-period. The hydrological uncertainty (Figure 5.2 A) impacts the flood hazard maps, *i.e.* uncertainty in flood extent and water depth distribution (Figure 5.2 B), which are spatially propagated to the damage potential estimation results (Figure 5.2 C). In order to appreciate the spatial dimension of flood risk uncertainty, we produce flood risk maps representing EAD for the different methods and assumptions analysed in this chapter.

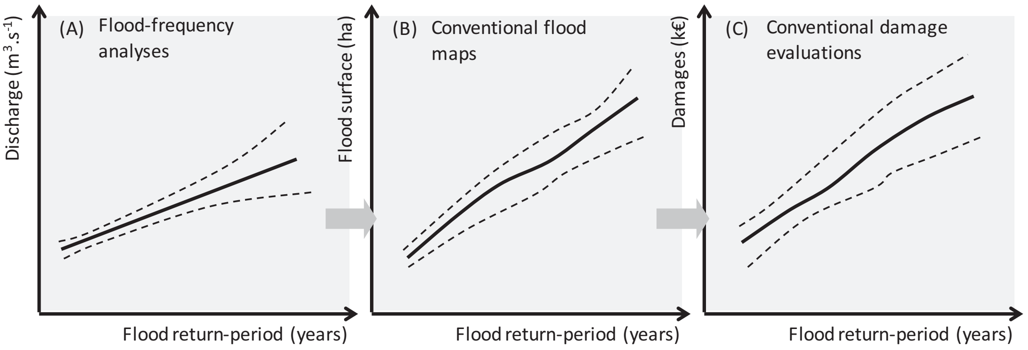

Figure 5.2. Uncertainty propagation scheme throughout flood maps and damage estimations.

2.3. Case study and datasets

The method presented here was applied in a case study in eastern France: the town of Holtzheim crossed by the river Bruche, located in the west bank of the upper Rhine (*cf.* Chapter 4 for more details). The hydrological analysis was performed on instantaneous discharge monitored during 39 years since 1973. One coupled 1D/2D hydraulic model constructed with Mike Flood® software was

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[37] Chapter 6 focuses on damage estimation uncertainties liked to hydraulic modelling processes.

used to simulate all flood events analysed in this chapter. Coupled 1D/2D models are used for simulating the main channel in 1D and the floodplain in 2D, which is a good compromise between data requirement and phenomena description, especially for urban areas. The model was constructed using a digital elevation model with 10 cm altimetry resolution and 4 points/m², issue of LIDAR[38] technology data acquisition. The model was calibrated for the 1990 historical flood event with discharge estimated to 185 m^3/s. The damage model used is based on land-use occupation data obtained through the analysis of available geographic information system (GIS) datasets and detailed field-surveys realised to determine the typology of buildings, their construction characteristics and their elevation (Eleutério et al., 2008)[39]. Damage functions for residential (Torterotot, 1993) and commercial (DNRM, 2002) buildings were used for evaluating buildings damage-potential. The damage functions used to evaluate damage establish damage potential as a function of the types of buildings, their surfaces and the water depth inside buildings[40]. Independent of the type of buildings, damage is proportional to floodwater depth. Floodwater depth is considered the most influencing factor leading to damage in urban areas (Merz et al., 2010b). The GIS-based model developed in Eleutério et al. (2012) was used to combine hazard with vulnerability data, calculate flood damage, produce flood risk maps and proceed the uncertainty propagation tests (*cf.* Chapter 3).

3. Results

The independence and stationarity of maximum annual daily discharge values of the Bruche River were checked according to the Wald-Wolfowitz and Kendall tests with a significant level of 5%. Among the six distribution functions tested, the GP was rejected with a significant level of 5%. The five other functions fitted the sample data with the significant level of 5%. Based on an expert judgment the EXP was rejected. According to the Khi 2 test results, the L-moment estimation method was retained to estimate the GEV and GUM function parameters. The Maximum likelihood method was used to estimate the parameters of the PE3 and LN3 functions. The Figure 5.3 illustrates the four retained distribution functions: GEV, GUM, LN3 and PE3. Table 5.1 summarizes the central values and the 0.7 and 0.9 upper bound confidence intervals.

The difference of central values between the four distribution functions ranged from 1.3% to 11.2%, depending on the considered return period values. The maximum deviation between the central values and maximal bounds of 0.7 confidence intervals ranged from 8% to 36%, respectively for 2-year

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[38] LIDAR is the acronym for Light Detection and Ranging, which designates a remote sensing or optical measurement technology based on analysing the properties of a laser light reflected back to its transmitter.

[39] Deep explanation on vulnerability assessment methods and their uncertainties are in Chapter 7.

[40] Further details on damage functions and correlated uncertainty are the scope of Chapter 8.

discharge and 500-year discharge. For the 0.9 confidence intervals, the maximum deviation between the central values and maximal bounds, ranged from 13% to 51%, respectively for 2-year discharge and 500-year discharge. Discharges considering 0.7 and 0.9 CI were respectively 12.1% (SD = 2.4) and 19.1% (SD = 3.7) higher in average than discharges calculated with central values (Table 5.1).

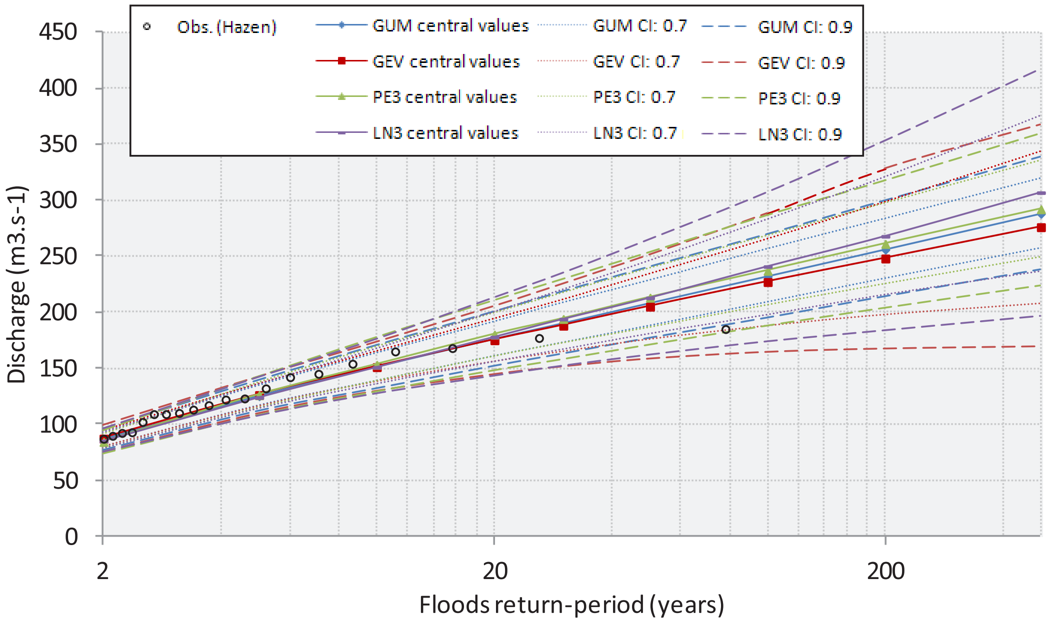

Figure 5.3. Comparison of the GUM, GEV, LN3 and PE3 fits for the annual maximum daily discharge values at Bruche River with associated 0.7 and 0.9 confidence intervals.

Table 5.1. Central values and maximum bounds of 0.7 and 0.9 confidence intervals for the annual maximum daily discharge at Bruche River.

	central value				**CI = 70% upper bound values**				**CI = 90% upper bound values**			
	GUM	**GEV**	**PE3**	**LN3**	**GUM**	**GEV**	**PE3**	**LN3**	**GUM**	**GEV**	**PE3**	**LN3**
T	**Annual maximum daily discharge at Bruche River upstream the town of Holtzheim (m3/s)**											
2	86	87	84	85	92	94	91	92	96	99	95	96
5	125	126	126	124	134	136	137	135	139	142	143	142
10	151	151	153	151	163	165	169	167	170	173	178	176
20	176	175	180	178	191	194	199	200	200	205	211	213
30	190	188	194	194	208	211	217	220	218	225	230	235
50	208	205	213	213	228	234	239	246	240	251	254	265
100	232	227	237	241	256	265	268	283	269	288	287	307
200	256	248	261	268	283	298	297	321	299	328	318	353
500	288	276	292	307	319	343	335	376	338	367	360	417

T - flood return period (years); CI - confidence interval considered for hydrological analyses

Based on a case study, our results supports the conclusion of Merz and Thieken (2005) on the difficulties to retain only one hydrological model to describe the extreme values of discharge. Therefore, four different models, *i.e.* statistical functions, were retained introducing a first source of epistemic uncertainty. As expected, using the upper value of confidence intervals, to summarize all uncertainty associated to a quantile, instead of quantile itself strongly impacts the peak flow values.

These quantiles of maximum peak flow and CI corresponding to the different return periods were used to produce hazard maps and evaluate flood damage (*cf.* section 2). The ensemble of results obtained throughout the application of the method presented here is shown in Figure 5.4 and Table 5.2. The following sections detail and discuss these results.

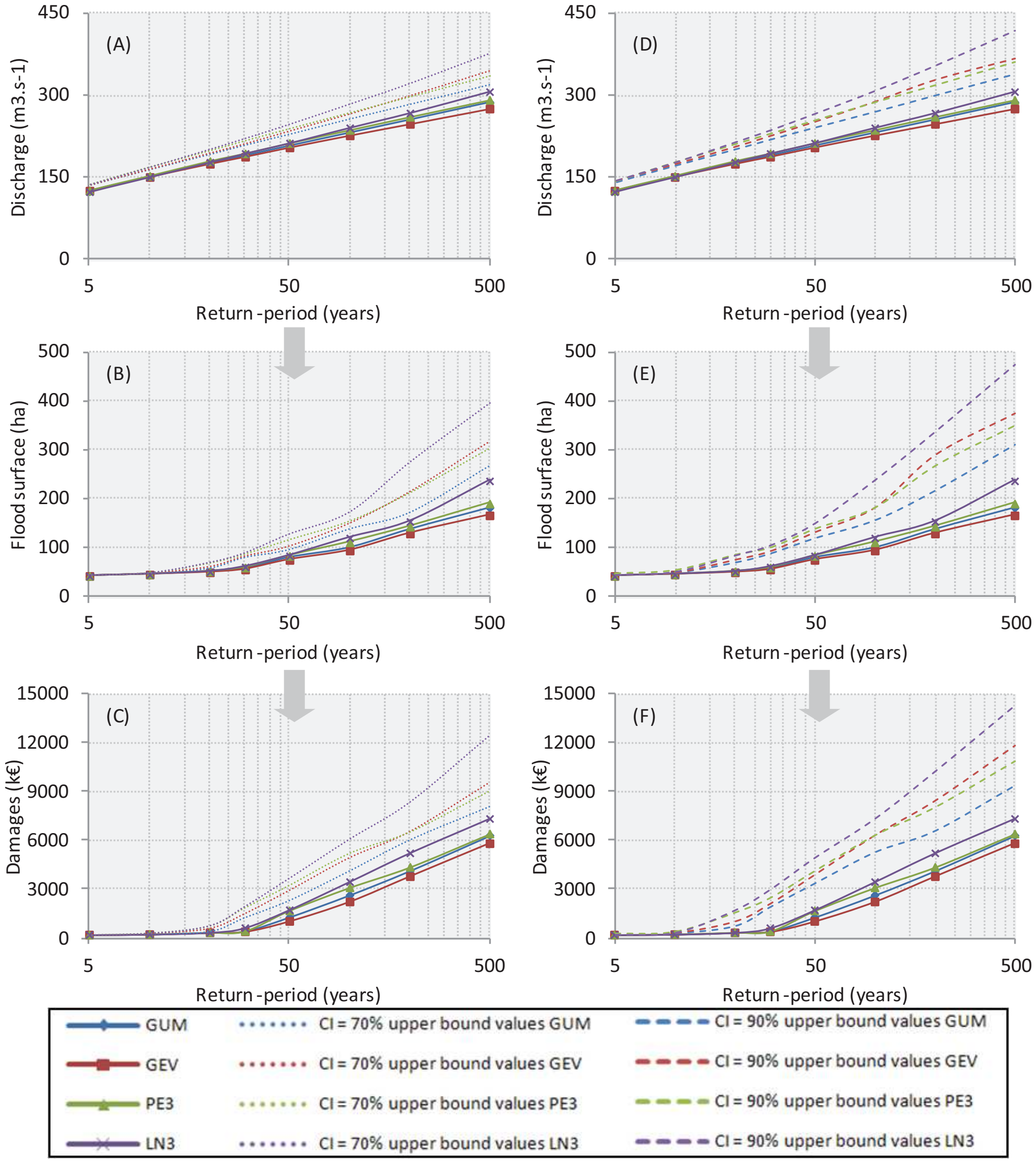

Figure 5.4. Propagation of flood frequency uncertainty on the estimation of flooded areas and potential flood damage.

Table 5.2. Propagation of hydrological uncertainty throughout flood risk evaluation results.

	central value				**CI = 70% upper bound values**				**CI = 90% upper bound values**			
	GUM	**GEV**	**PE3**	**LN3**	**GUM**	**GEV**	**PE3**	**LN3**	**GUM**	**GEV**	**PE3**	**LN3**
T	**Flooded areas calculated in the town of Holtzheim (ha)**											
5	42.8	43.0	43.0	42.7	43.8	44.0	44.1	44.0	44.2	44.5	44.6	44.5
10	45.9	45.9	46.2	45.9	47.7	48.3	48.6	48.4	48.8	49.4	51.5	50.8
20	50.8	50.4	52.2	51.5	58.1	61.4	68.5	69.8	69.6	75.7	82.7	84.0
30	57.2	56.2	60.2	61.4	80.2	82.7	87.1	89.4	88.0	93.4	97.8	104.7
50	80.2	75.7	83.9	84.0	96.3	103.1	116.4	127.6	118.8	131.9	135.8	149.3
100	100.6	95.0	111.7	120.7	138.5	149.6	154.4	172.6	155.3	182.7	179.5	237.4
200	138.4	129.8	143.7	154.3	172.5	213.8	212.2	274.3	215.4	290.3	264.9	335.7
500	182.7	166.9	191.2	237.4	268.0	315.6	303.0	394.4	308.2	375.4	347.3	471.9
T	**Number of buildings concerned**											
5	11	11	11	11	11	11	11	11	12	12	12	12
10	13	13	14	13	14	15	16	15	16	16	17	17
20	17	17	18	17	29	47	61	61	61	81	121	127
30	29	25	29	47	105	121	135	137	137	151	175	218
50	105	81	127	127	165	212	231	264	235	281	285	343
100	195	158	226	244	294	343	366	405	367	409	408	457
200	290	270	304	366	405	417	415	525	419	530	499	638
500	409	390	412	457	511	603	573	712	594	686	660	782
T	**Average values of water depth inside buildings (cm)**											
5	101	112	110	99	110	107	101	113	111	98	111	110
10	110	112	115	110	116	113	106	112	113	110	117	111
20	110	53	50	111	75	51	108	50	45	113	51	47
30	85	45	46	74	46	47	76	47	44	53	48	40
50	50	40	40	46	45	41	45	40	41	47	40	40
100	46	40	44	41	41	40	40	40	44	40	43	44
200	40	46	45	41	43	46	42	45	45	39	45	47
500	41	46	50	44	44	46	45	45	48	44	50	55
T	**Buildings and contents damage potential (k€)**											
5	203	205	205	202	213	215	216	214	218	222	223	222
10	232	232	244	232	304	313	327	320	328	332	343	339
20	339	338	349	343	427	626	766	779	776	1039	1522	1727
30	425	402	430	626	1282	1522	1869	1953	1940	2131	2429	2997
50	1282	1039	1684	1727	2335	2938	3238	3669	3364	3894	4080	4933
100	2644	2235	3100	3453	4158	4934	5191	6062	5255	6304	6270	7328
200	4142	3784	4360	5216	6061	6528	6488	8324	6555	8416	7997	10226
500	6304	5809	6401	7328	8111	9528	8990	12394	9300	11776	10822	14248

T - flood return period (years); CI - confidence interval considered for hydrological analyses

3.1. Impact of hydrological CI on hazard maps

We realised 108 flood simulations considering the nine return periods, the four distribution functions and the upper bounds, *i.e.* central value, CI 0.7 and 0.9 (Table 5.1). Floodwater in the floodplain was only observed from 5-yr return-period flood events. Flood hazard maps containing the floodwater depth distribution and the flood boundaries were constructed for all the flooding events analysed. Figure 5.5 shows the increase of the flood extension for the 30, 100 and 500-yr return-periods.

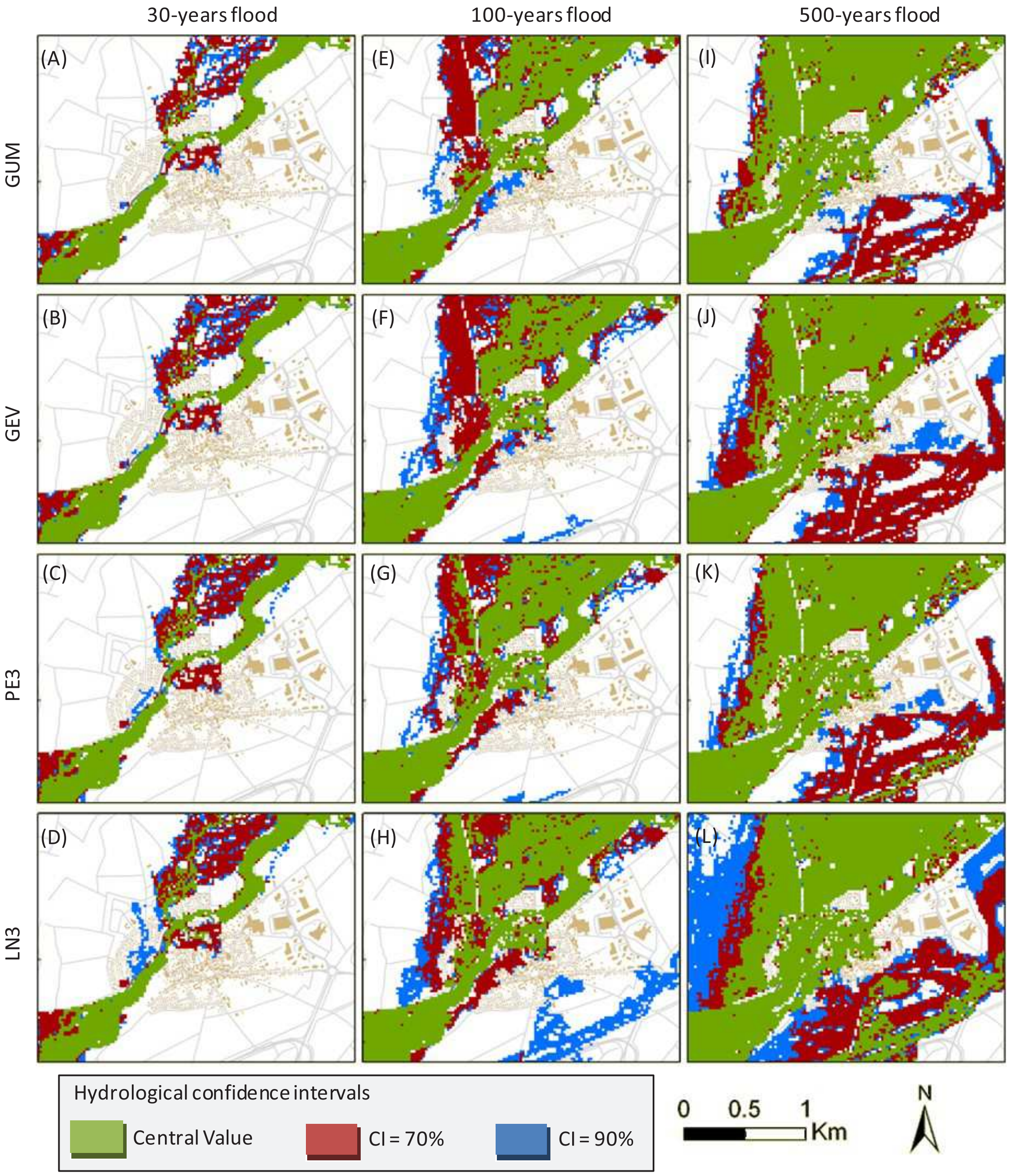

Figure 5.5. Flood hazard maps for 30-yr, 100-and 500-yr return-period flood events estimated with different distribution methods and confidence intervals.

The flood boundaries calculated for flood events of less than 50-yr return period were quite similar when comparing the central values for different distribution methods, *e.g.* the 30-yr flood event (green surface in Figure 5.5 A-D). The variability of flood areas generated by the choice of CI showed to be much more important, starting from frequent flood events. From 20-yr return-period floods, the modelled flood area started to significantly range for both CI 0.7 and 0.9. These differences were still more important from 100-yr flood events for CI 0.7 and from 50-yr flood events for CI 0.9 (Figure 5.4 B and E). For the 30-yr flood event, we observed that the town centre (centred in the maps) and the areas at the north of the town are potentially inundated only when considering 0.7 and 0.9 CI (respectively brown and blue surface in Figure 5.5 A-D).

We gave a special attention for the 100-years flood event, once it is the French flood minimum return-period standard for establishing PPRI[41] for land-use planning (Lang and Lavabre, 2009). The extent of the 100-years flood maps produced was highly different when considering the different hypothesis on flood frequency analysis. When we used the hydrological central values of the four distribution functions, the maximum 100-years flooded estimation was 27.1% higher than the minimum value (flooded areas in Table 5.2 and Figure 5.5 E-H). The LN3 function provided the largest flooded area for this return-period (Figure 5.5 H): the north-west area of the town was flooded when using central values, the contouring west area was flooded for CI 0.7 and a second flood area in the south of the town appeared for CI 0.9. For the rare 500-yr flood event, the differences are even greater between the four distribution functions (Figure 5.5 I-L).

Uncertainty on discharges estimations (Figure 5.4 A and D) is significantly aggravated when propagated to hazard maps areas from 20-yr return period flood events (Figure 5.4 B and E). In average, 10% of increase in peak flows generated 32% (SD = 6) of increase in flooded area estimations from 20-yr return period evens; 10% of increase in peak flows generated 35% (SD = 0.5), 37% (SD = 0.4) and 38% (SD = 0.3) for 30-yr, 100-yr and 500-yr return period events, respectively. The variation of flood area estimations was much more sensible to the confidence intervals considerations than to the selection of distribution functions. The deviation of surfaces calculated using the central values for the four distribution functions ranged from a maximum of 0.6 to 42.2%, depending on the flood return period (flooded areas in Table 5.2). The maximum deviation of surfaces from central to CI 0.7 values ranged from 3% to 89.1% depending on the return-periods. The maximum deviation of surfaces from central to CI 0.9 values ranged from 4.2% to 124.9% (Table 5.2). Flood surfaces calculated considering 0.7 and 0.9 CI were respectively 34.7% (SD = 8.1) and 57.3% (SD = 12.9) higher in average than flood surfaces calculated with central values (Table 5.2). These results highlight the high sensitivity of hazard assessment step to the CI associated to the peak values. This impact should be systematically considered when producing hazard maps.

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[41] The “Plan de Prévention des risques Inondation" (PPRi) is the French National regulation tool used to orient urbanization in the bases of hazard and vulnerability analyses of flood risks.

3.2. Impact of hydrological CI on assets exposition and damage

In the case study analysed here, we noticed that the increase of the peak flow used in the hydraulic model generated a progressive increase of simulated flood surfaces (Figure 5.4). In a unit damage evaluation, the number of assets impacted by the floodwater is determinant for the damaging potential of the flood event. As expected, in the study area, the number of buildings impacted by floodwater was proportional to the flood surface (Figure 5.6).

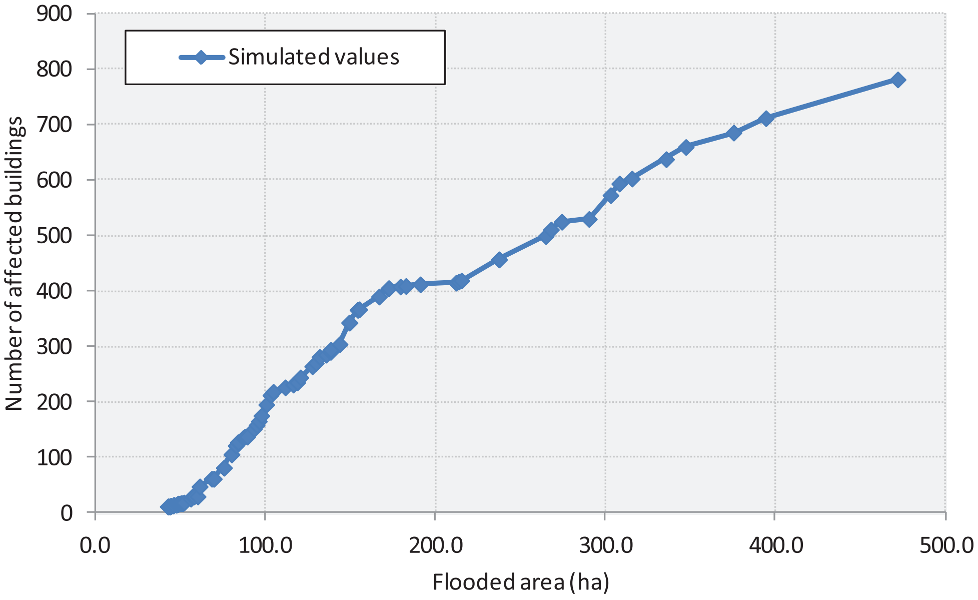
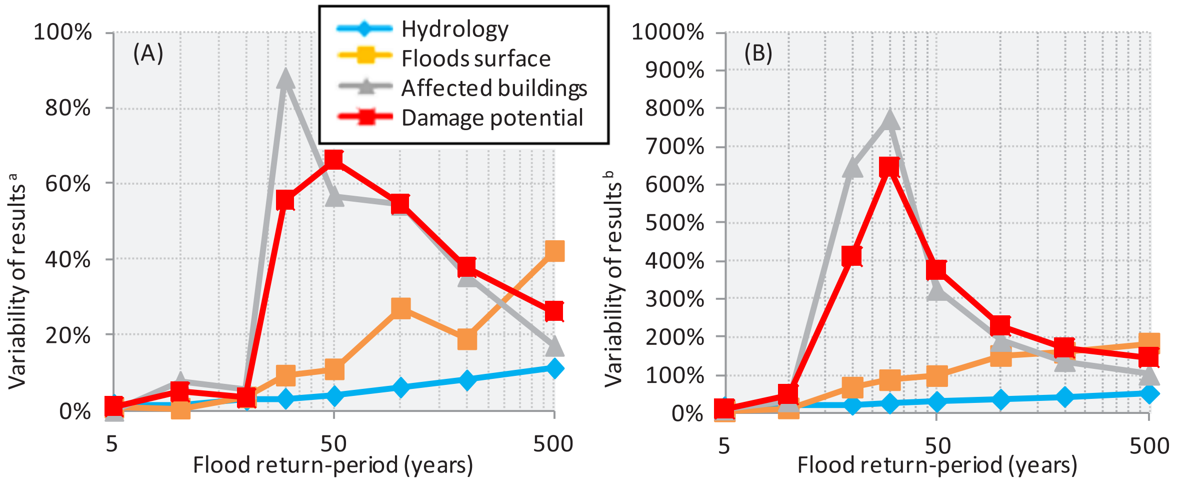


Figure 5.6. Relation between flood surface and number of buildings impacted by floods.

At the elementary scale, damage potential is proportional to water depth (Torterotot, 1993; DNRM, 2002). Water depth potential inside a specific building is also proportional to the intensity of the flood phenomenon, *i.e.* peak flow value, which explains that damage for flood events simulated that impacted the same number of buildings is different (Table 5.2). We noticed that for the ensemble of buildings impacted by flood events, the average value of floodwater depth inside buildings was lower for exceptional events than for frequent events (Table 5.2). This is explained by the fact that the number of buildings affected by low floodwater depths was much more important for exceptional events (Table 5.2), which decreases the average value. These results illustrated the limitation of the average value of floodwater depth inside buildings to be considered as the main indicator of the potential damage of a flood event.

In Figure 5.4 C and F, we can observe the difference between damage calculated using the different hypothesis for analysing flood frequency. When comparing the central values of the different distribution methods we noticed significant variations of damage estimations from 30-yr flood events (values ranged from 1.1% to 4.9%). When considering 0.7 CI and 0.9 CI significant variations of results were observed from 20-yr return-period flood events (average variation of 48.1%, SD = 15.9), in accordance with the differences observed in flood surfaces (Figure 5.7).



[a] report between the differences of max and min values in relation to min values calculated using the central values for different probability distributions.
[b] report between the differences of max and min values in relation to min values calculated using central, CI 0.7 and CI 0.9 values for the ensemble of probability distributions.

Figure 5.7. Variability of results in fonction of distribution methods and confidence intervals.

Damage potential increases with the return period in an almost linear way (Figure 5.4 C and F), differently from flood surfaces that present a more important increase from 100-yr return-periods (for 0.7 CI) (Figure 5.4 B) and 50 year return-period (for 0.9 CI) (Figure 5.4 E). This is explained by the relationship between flood area and number of buildings concerned (Figure 5.6). The impact of the use of confidence intervals on the evaluation of flood damage Figure 5.7 B showed to be much more relevant than the impact of the different discharge distribution functions Figure 5.7 A. We can observe in Figure 5.7 A that damage results ranged from 1.1% to 66.1% depending on flood return periods (values in Table 5.2). This variability is small for frequent floods and it increases drastically from 30-yr flood events, following the increase of the number of buildings affected. The same phenomenon is observed in the comparison between results obtained considering the differences between central values and 0.9 CI upper bounds Figure 5.7 B. However, damage values results ranged in this case from 10% to 645% depending on the frequency of floods, equivalent to almost 10 times the range caused by the different hydrological distribution functions alone. The maximum range was observed for 30-yr return period floods, were damage estimations varied from 402k€ (GEV central values) to

2997k€ (LN3 0.9 CI) (Table 5.2). These important ranges for this return period are explained by the fact that once the city centre is impacted by floodwater, a large number of buildings are suddenly concerned by the flood event (Figure 5.5). Damage values calculated considering 0.7 and 0.9 CI were respectively 86.3% (SD = 19.3) and 151% (SD = 27) higher in average than those calculated with central values (Table 5.2). In average, 10% of increase in peak flow generated 123% (SD = 67) of variation in damage estimations from 20-yr to 100-yr return-period evens. This proportionality was smaller for flood return-periods shorter than 20-yr and longer than 100-yr: 10% of increase in peak flow generated 27% (SD = 15) in average.

3.3. Impact of hydrological CI on flood EAD and risk maps

Expected annual damage (EAD) values were calculated using the pair of values damage/frequency in order to solve the Equation (3.1). The estimation results for the four discharge distribution functions analysed considering the central values and the 0.7 and 0.9 confidence intervals upper bounds were represented in Figure 5.8.

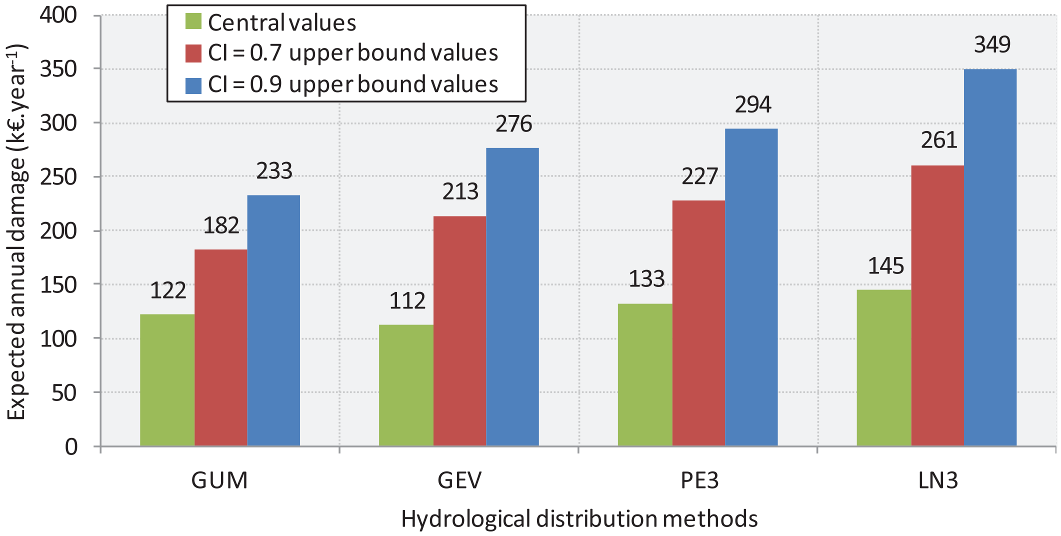


Figure 5.8. Buildings and contents expected annual damage as a function of hydrological distribution methods for different confidence intervals (CI).

When using the central values of the discharge distribution functions, GEV function presented the lower value, of 112k€/year, and LN3 the higher value, of 145 k€/year, with a maximum range of 29.5% between the four distribution methods. The total variability of EAD results generated by the methods considering the max 0.9 CI was of 211%, corresponding to the range between EAD calculated with GEV central values and LN3 0.9 CI values. The variability generated by the CI was different from one function to another. The impact of confidence intervals on the determination of EAD is much less important for GUM function then for the other distribution functions. For the GUM function, EAD values increased in relation to central values of 49.4% and 90.9% for 0.7 and 0.9 CI values, respectively. For 0.7 and 0.9 CI values, the EAD values increased 90.2% and 146%, 70.7% and 121%, 80% and 141%, respectively for GEV, PE3 and LN3. The different CI hypotheses for GEV represented the maximum variations in EAD results. EAD calculated considering 0.7 and 0.9 CI were 72.9% (SD = 17.5) and 125% (SD = 25.1) higher in average than EAD calculated with central values, respectively (Table 5.2). In resume, the maximum EAD estimation between the four distribution functions used was 28.8% higher than the minimum estimation value. When considering 0.7 and 0.9 confidence intervals, EAD was estimated respectively 1.33 and 2.11 times higher than when considering central values all functions together.

Risk maps constructed on the basis of the different discharge distribution functions represented the spatial distribution of the risk, expressed by expected annual damage (EAD), and confidence intervals analysed in this chapter (Figure 5.9). The main differences are observed in the borders of the river (in the town centre) and in the south of the town. The differences at the proximity of the rivers were mainly due to the variability of damage calculated from floods with return period longer than 20-yr return-period floods (Figure 5.7). Frequent damage strongly influenced EAD estimations once damage was multiplied by their probability of occurrence. The risk maps difference between the distribution methods (Figure 5.9 A-D) was minor in comparison with the differences between central values, 0.7 and 0.9 confidence interval values. When considering the CI upper bounds, floodwater reached the town centre for more frequent floods, and the flood flow contoured the town centre by the south for lower return-period floods, increasing the risk estimation in these areas (Figure 5.5). In Figure 5.9 E-H and I-L, we clearly noticed that the difference between flood risk maps in these areas (centre and south) was higher when considering different CI upper bound values.

3.4. Results general discussion

The impact of confidence intervals was differently propagated throughout the different modules of the risk evaluation process (Figure 5.4). In average, estimates considering 0.7 and 0.9 CI were higher in relation to central values: 12.1% (SD = 2.4) and 19.1% (SD = 3.7) for discharge values, 34.7% (SD = 8.1) and 57.3% (SD = 12.9) for flooded area estimations, and 86.3% (SD = 19.3) and 151% (SD = 27) for damage evaluations. Uncertainty was significantly increased when propagated throughout the risk evaluation process. In average, 10% of variation in river discharges generated a variation of 25% (SD = 14) and 75% (SD = 26), respectively for flooded area and potential damage evaluations. Variability of results revealed to follow completely different rules for the different flood probabilities and evaluation modules analysed (Figure 5.7).

The variability of flood discharge and flood surface increases together with the flood return-period. In contrast, the damage potential variability is low for very frequent floods, highly increases for frequent floods and decreases after, in accordance with the variability of the number of buildings affected by the flood surface.

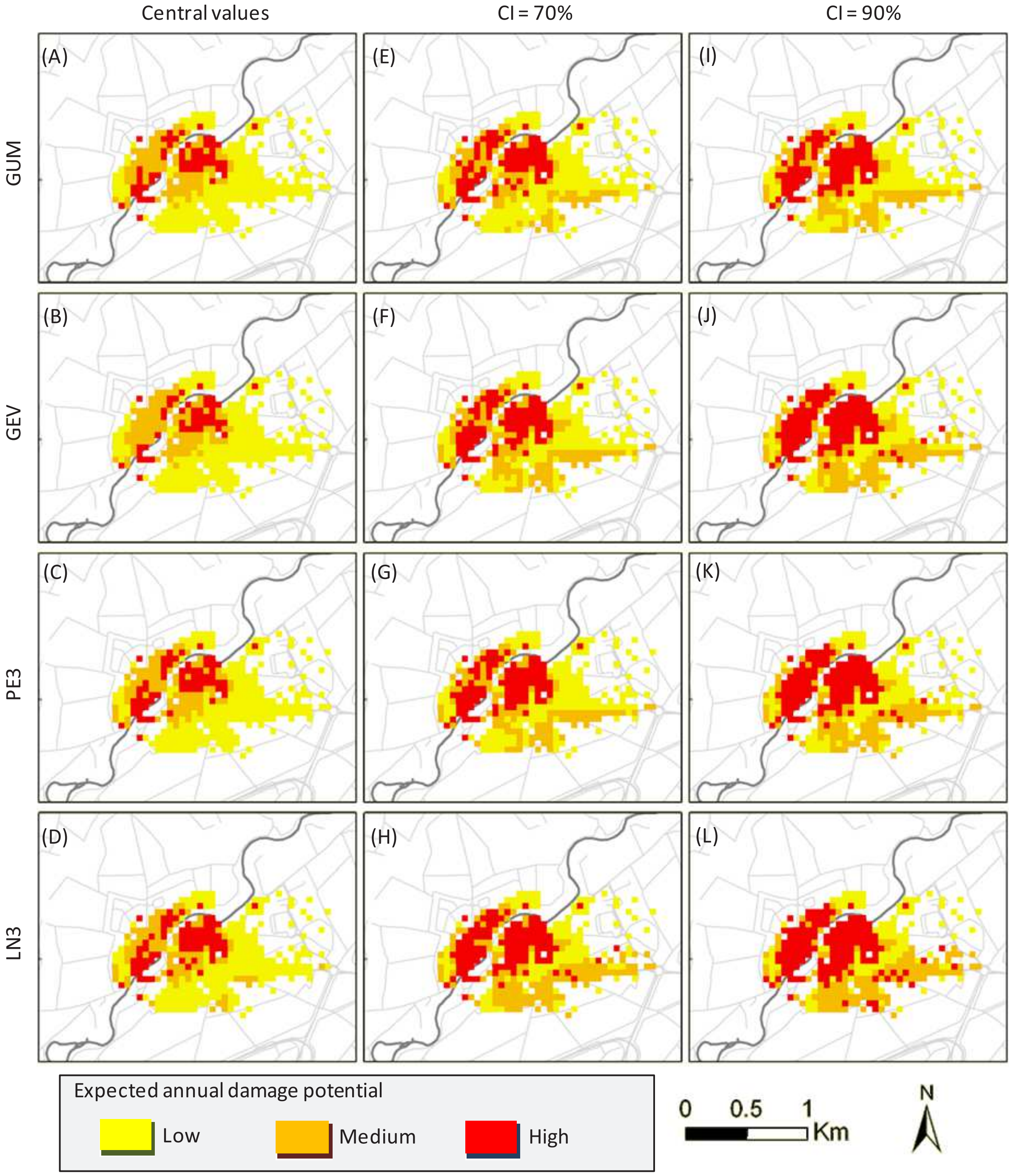


Figure 5.9. Flood risk maps expressing buildings and contents expected annual damage as a function of distribution methods with different confidence intervals (CI).

The impact of the selection of discharge distribution functions revealed to be much more significant on the flooded areas and damage estimations when taking into consideration confidence intervals (CI) during the evaluation process. When comparing the different distribution functions, the maximum expected annual damage (EAD) estimation was 28.8% higher than the minimum EAD estimation (Figure 5.8). EAD was estimated respectively 1.33 and 2.11 times higher than when considering central values all functions together, respectively for 0.7 and 0.9 confidence intervals. The risk map differences between the distribution functions were minor in comparison with the differences between central values, 0.7 and 0.9 confidence interval values (Figure 5.9). We also highlighted that the impact of confidence intervals was different from one distribution function to another. The GUM distribution function presented the smaller uncertainty range and GEV the highest. These types of result depend on the case study analysed, as observed by Xu and Booij (2007), Merz and Thieken (2009), Merz and Thieken (2005) and NRC (2009). Nevertheless, the benefit to integrate confidence intervals taking into account the uncertainty on the peak flows was clearly demonstrated. This chapter provided general framework to provide an assessment of the uncertainty in flood hazard assessment.

4. Conclusions

This chapter revealed that the variability of flood surfaces and damage potential estimations induced by the selection of hydrological distribution functions was highly increased when considering confidence intervals. It also revealed that the four distribution functions analysed are differently affected by confidence intervals considerations. This uncertainty is therefore differently propagated throughout the flood risk evaluation modules. The variability induced by confidence intervals for different distribution functions on flood hazard and risk maps, damage potential and risk estimations highlighted the importance of better characterizing, understanding and reducing uncertainties linked to the hydrological probabilistic aspect of the risk.

It is of evidence that the reduction of total uncertainty linked to flood frequency analysis is possible overtime by increasing the amount and quality of measured data (Xu and Booij, 2007; Apel et al., 2004). However, the selection of distribution functions to estimate flood frequency is not well established once several methods can fit data and be consistent in theory (Merz and Thieken, 2005). In relation to the confidence intervals for flood frequency analysis, no standards exist for considering uncertainty on the production of neither flood maps nor damage evaluations.

The choice of confidence interval values is a key point of all flood frequency analysis. The adopted values affect both, the risk of using an erroneous peak flow value and the cost of flood protection techniques associated to the expected peak flows. If a confidence interval is systematically associated to peak flow quantile in flood frequency analyses, its use by the stakeholders in the process of flood risk management remains limited.

Based on this study case, uncertainty acceptance levels for hydrological analysis should receive more attention when producing flood maps, especially when those maps are used for quantifying monetary damage potential of floods. We suggest that standards should be formally established in relation to the confidence intervals to use during flood frequency analysis. In addition to the use of different distribution functions in flood frequency analysis, confidence intervals should be systematically considered when producing flood maps and analysing flood risks.

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Chapter 6.

Hydraulic modelling and flood mapping

This chapter focuses on the impact of strategies used to model and map flood hazard in damage estimations. We consider different strategies to model the flood phenomenon, as a function of: (1) the type of hydraulic model used – 1D, hybrid 1D/2D or 2D software, *i.e.* model selection; and (2) the simplifications made by the modeller when representing the topography and bathymetry of the river system, *i.e.* parametric choices. With this purpose, different hazard models and damage estimations were realised in the town of Fislis, in eastern France. Hec-RAS, Mike 21 and Mike Flood hydraulic models were used in order to measure the selection of model effects. We considered different scale of analysis (level of details) when constructing the different modelling scenarios – density of cross-sections and hydraulic structures (1D models), and the digital elevation model cell resolution (2D models). Thirty-two models were built to simulate flood hazards. These models were used to simulate floods with different return-periods. 100-yr return-period flood maps were compared in terms of flood surface and water depth distribution. The 2D models tended to overestimate the flood surfaces and the 1D models tended to overestimate floodwater depths. The results of uncertainty propagation tests on damage estimations revealed that the choice of the scale of analysis was the mainly uncertainty influencing aspect of the evaluation. These parametric choices were responsible for 75% of global uncertainty, against 18% for model selection. Furthermore, we notice that the increase of the precision of hazard modelling has different impacts on flood maps and damage estimations, according to the type of model. For 1D models, the more detailed the models are (higher density of cross-sections), the higher damage estimation results are. For 2D models, the more the models are precise (small grid-cells) the lower damage estimates are. The results of damage estimations are strongly influenced by hydraulic modelling choices, therefore the production of flood maps for this purpose should be deeply analysed.

This chapter is based on Eleutério J. and Mosé R., Comparison of strategies used to map riverine flooding: the town of Fislis, in France, as a case study, 12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11-16 September 2011.

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1. Introduction

Flood hazard maps are the main base for flood control and flood management studies (NRC, 2009). Former flood hazard maps as well as hypothetical flood maps for different probabilities of occurrence and flood risk maps are powerful tools improving the understanding of the flood phenomenon and its related risks (de Moel et al., 2009). However, several uncertainty sources can influence the accuracy of flood maps (Bales and Wagner, 2009). As described by NRC (2000), uncertainty in flood maps can generate several losses in terms of flood management. Better understanding on the flood phenomenon and its related uncertainties is required to guide decision-making processes. This concern have induced different institutions to investigate the quality of flood mapping: the Federal Emergency Management Agency's Map Modernization Program in the U.S. (FEMA, 2006) and the EU Floods Directive 2007/60/EC (European Parliament Council, 2007) are examples which highlight the importance of this concern.

In practical applications, several criteria influence the strategic choices to model floods and produce hazard maps. The scale of the analysis is a fundamental criterion, as well as data and resources availability for the study. However, this choice is still vague (NRC, 2009). In the case of the EU Flood Directive (European Parliament Council, 2007), the national analysis of the flood risk is a difficult challenge once national and local scale models are to developed in order to map flood hazard as well as the flood risk. In spite that potential flood damage estimates becomes an important tool for flood management purposes, the impact of flood hazard mapping on flood damage evaluations are not yet deeply analysed in literature. Few studies propagate flood hazard uncertainties into damage estimations (Chen et al., 2004; Apel et al., 2008b; Merz and Thieken, 2009; Apel et al., 2008a). These studies revealed that this uncertainty might represent a big part of global uncertainty of flood damage estimates.

The main objective of the present work is to quantify the impact of hydraulic modelling choices on flood damage estimations. The selection of the hydrodynamic software and the scale-induced simplifications are the core of this work. Indeed, we compare several strategies used to map riverine flooding based on these aspects, and we measure the variability of damage estimates as a function of these different aspects. In this section, we present the general concepts related to flood modelling and we make a brief state of the art of flood hazard mapping. In the second part of this chapter (section 2), we present the case study and the methods, datasets and scale-considerations used in the construction of the different modelling scenarios. Finally, in section 3 we compare the results of the simulations in terms of hazard map components, *i.e.* flood surface and water depth distribution, and we measure the variability of damage estimates according to the different flood modelling strategies.

1.1. Flood maps

Flood maps are currently used for different purposes, *e.g.* land-use policies, flood alleviation project appraisals, economic evaluations, insurance rates determination, emergency planning, etc (de Moel et al., 2009; EXCIMAP, 2007; van Alphen et al., 2009; Ferrier and Haque, 2003; Fuchs et al., 2009; Sanders et al., 2005; Pender, 2006). The US Federal Emergency Management Agency's (FEMA) Map Modernization Program (NRC, 2009) and the EU Floods Directive 2007/60/EC (European Parliament Council, 2007) are examples of programs that highlight the needs for accurate flood maps in risk management contexts. In the European context, the EU directive decline that flood hazards and risks maps should be developed and may form the basis of future flood risk management plans. At this occasion, the work of de Moel et al. (2009) gives an overview of existing flood mapping practices in 29 countries in Europe and shows what maps are already available and how such maps are used. This work distinguishes several types of flood maps (Figure 6.1).

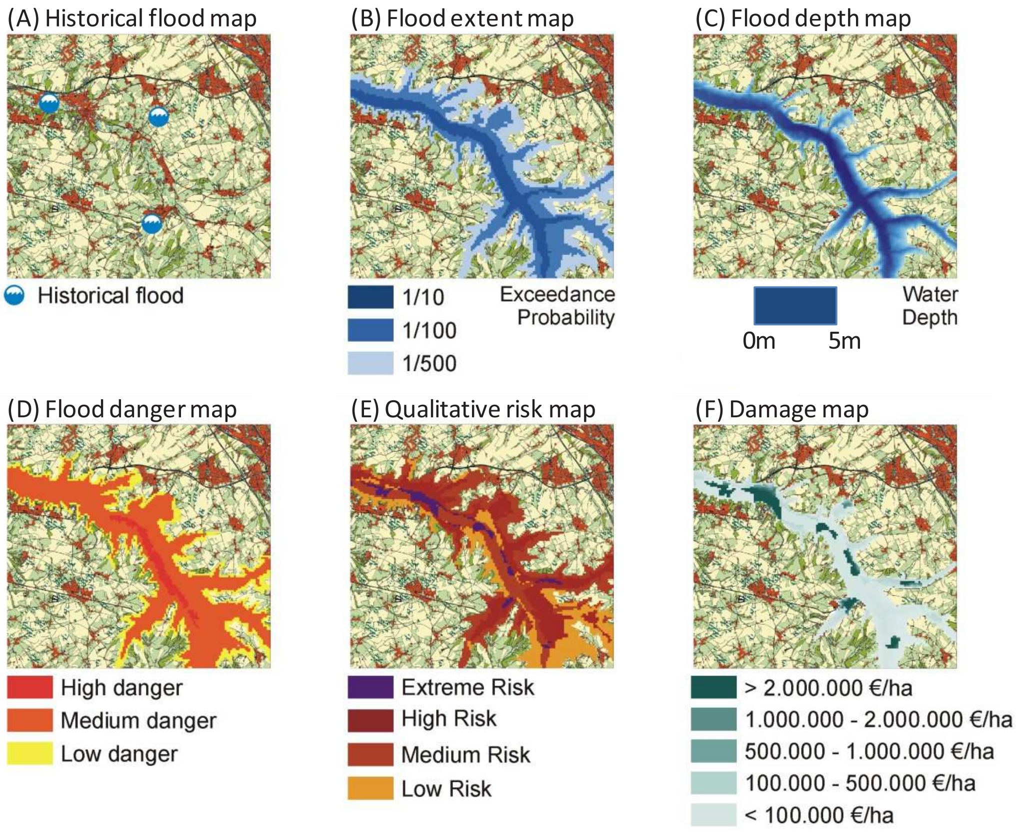

Figure 6.1. Illustrative examples for different types of flood map. Source: de Moel et al. (2009).

In summary, we can distinguish two groups of flood maps: flood hazard maps, *i.e.* maps describing the flood event natural characteristics (maps A, B, C and D in Figure 6.1) and flood risk maps, *i.e.* maps describing the potential consequences of floods on a specific territory (maps E and F in Figure 6.1).

The flood extent maps (map B in Figure 6.1), for both historical and hypothetical flood events, are the most common flood hazard maps. These maps display the inundated areas for historical specific events and hypothetical floods for different probabilities. These maps together with exposure maps are needed for the production of risk maps (Messner et al., 2007). Maps displaying the intensity of hypothetical floods by describing its hydraulic characteristics, *e.g.* flood duration, flood flow velocity and flood depth maps (map C in Figure 6.1), are essential for flood damage estimations. The construction of these maps is essentially based on hydraulic modelling processes.

1.2. Hydraulic modelling and hazard mapping

Hydraulic modelling is an essential step toward the construction of flood maps. The flood hazard modelling process calculates how the flow of water propagates throughout the river channel and floodplain during flood events (Chow, 1959; CETMEF, 2001). Several thousand years of history and great scientists contributed to the global comprehension of fluid mechanics and hydraulics, *e.g.* Newton, Descartes, Leibnitz, Bernoulli, Euler, Chézy, Borda, Darcy, Reynolds, Manning, Navier, Stokes, etc (Viollet, 2004). The physical understanding of the conservation of mass and momentum was essential for the understanding of river dynamics. The Saint-Venant shallow-water equations derived from the Navier-Stokes equations are the most often applied for river analysis purposes (Stelling and Verwey, 2005; Woodhead, 2007). The solution of these equations was and is still a challenge for scientists. (Stelling and Verwey, 2005), Horritt and Bates (2002) and Woodhead (2007) give comprehensive explanations and examples on numerical schemes available for solving the shallow equations and simulating floods.

1.2.1. Modelling approaches

In hydraulic modelling, the water dynamics is apprehended on the basis of the Saint-Venant equations, adapted according to the modelling approaches used (Kreis, 2004; Woodhead, 2007). Several approaches based on different simplifications were developed during the last decades for simulating floods (Table 6.1). Several studies compare different modelling techniques and software. (Horritt and Bates, 2002; Woodhead, 2007; Cook, 2008; Horritt and Bates, 2001a; Büchele et al., 2006; Di Baldassarre et al., 2009; Dutta et al., 2003; Finaud-Guyot, 2009).

The great majority of modelling processes are based on one-dimensional (1D) approaches (Kreis, 2004; Bales and Wagner, 2009). 1D-based models describe the river channel and floodplain as a series of discrete cross-sections perpendicular to the flow direction. It considers that the water flow propagates only in the river x-axis, and the water level and flow velocity are constant along each cross section. Its main disadvantage is that its simplifications account on bad representations of flow velocity and energy loss between the river main channel and the floodplain.

Table 6.1. Hydraulic approaches and models for flood simulation. Source: Woodhead (2007).

Method	Description	Application	Example Models	Inputs	Outputs	Computation time (as of 2006)
0D	No physical laws included in simulations.	Broad scale assessment of flood extents and flood depths.	ArcGIS Delta mapper	DEM Upstream water level Downstream water level	Inundation extent and water depth by intersecting planar water surface with DEM	Seconds
1D	Solution of the one-dimensional St Venant equations.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size.	Mike 11 HEC-RAS SOBEK-CF Infoworks RS (ISIS)	Surveyed cross sections of channel and floodplain Upstream discharge hydrographs Downstream stage hydrographs	Water depth and average velocity at each cross section Inundation extent by intersecting predicted water depths with DEM Downstream	Minutes
1D+	1D plus a storage cell approach to the simulation of floodplain flow.	Design scale modelling, which can be of the order of 10s to 100s of km depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data.	Mike 11 HEC-RAS Infoworks RS (ISIS)	As for 1D models	As for 1D models	Minutes to hours
2D-	2D minus the law of conservation of momentum for the floodplain flow.	Broad scale modelling or urban inundation depending on cell dimensions.	LISFLOOD-FP	DEM Upstream discharge hydrographs Downstream stage hydrographs	Inundation extent Water depths Downstream outflow hydrograph	Hours
2D	Solution of the two-dimensional shallow wave equations.	Design scale modelling of the order of 10s km. May have the potential for use in broad scale modelling if applied with very course grids.	TUFLOW Mike 21 TELEMAC SOBEK-OF Delft-FLS	DEM Upstream discharge hydrographs Downstream stage hydrographs	Inundation extent Water depths Depth-averaged velocities at each computational node Downstream outflow hydrograph	Hours to days
2D+	2D plus a solution for vertical velocities using continuity only.	Predominantly coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects.	TELEMAC 3D Delft-3D	DEM Upstream discharge hydrographs Inlet velocity distribution Downstream stage hydrographs Inundation extent	Water depths u, v and w velocities for each computational cell Downstream outflow hydrograph	Days
3D	3D solution of the three-dimensional Reynolds averaged Navier Stokes equations.	Local predictions of three-dimensional velocity fields in main channels and floodplains.	CFX FLUENT PHEONIX	DEM Upstream discharge hydrographs Inlet velocity and turbulent kinetic energy distribution Downstream stage hydrographs	Inundation extent Water depths u, v and w velocities and turbulent kinetic energy for each computational cell Downstream outflow hydrograph	Days

However, 1D models are simple to calibrate (dependent on cross-sections roughness coefficients), they count on low computation requirements, and they can perform good representations of the main channel hydraulic structures.

Residual uncertainties linked to the simplifications made in these models may be reduced overtime due to methodological evolutions on flood modelling (Bales and Wagner, 2009). Given the advances in data availability, numerical methods and computational power, it is noticed that 2D finite-difference and finite-element models have increasingly been developed and applied to overcome some of the limitations of 1D schemes (Tayefi et al., 2007; Stelling and Verwey, 2005). In two-dimensional (2D) approaches, the floodplain surface is discretized into a large number of small storage cells. The topologic and geometric description of models is based on digital terrain models (DTM) representing altimetry in space with x and y coordinates. They can be based on rectangular or triangular grid cells (with regular or irregular sizes). It considers flows in two dimensions, which imply that lateral flows are calculated. High requirement levels of data and computational efforts as well as the difficulty to calibrate these models are their major inconvenient. However, they can achieve high detailed simulations (Ernst et al., 2010). Hybrid 1D/2D approaches represent the in-channel flow with 1D-based methods and the floodplain flows with 2D methods. The use of this hybrid models is the current state of the art for flood control because of flexible schematization options, time for model development and use, numerical robustness and accuracy (Stelling and Verwey, 2005).

Other approaches used to simulate flow dynamics are the 3D and the “0D” approaches (Woodhead, 2007). On the one hand, detailed 3D approaches are complex, and are still barely used in fluvial hydraulic applications because of hard parameterization and computational limitations (Woodhead, 2007). They are generally used for punctual studies that need high levels of accuracy (Kreis, 2004). The “0D approach”, on the other hand, is a more simple method to analyze floods, without passing by the mathematical description of hydraulics. Flood maps are generated through interpolations of gauged water stages or water surface elevations predicted on the basis of flood frequency analysis, over digital elevation models (DEM), *e.g.* the French “Hydrogeomorphological approach” (METT and ME, 1996).

1.2.2. Hydraulic models and data requirements and flood mapping

Several numerical models based on these different approaches were developed during the last decades for simulating floods as shown in Table 6.1. Advances in computational engineering and the increased availability of detailed data for modelling purposes allowed great improvement on this science (Woodhead, 2007). Nowadays numerical techniques have matured, providing robustness and efficiency in model simulation (Stelling and Verwey, 2005; Crossley, 1999). Some frequently used models used to simulate floods are: Hec-RAS, Mike Flood, Sobek, ISIS of Wallingford software, Telemac 2D and Lisflood (Stelling and Verwey, 2005; Büchele et al., 2006; Di Baldassarre et al., 2009; Dutta et al., 2003; Finaud-Guyot, 2009; Horritt and Bates, 2002). A list of twenty-one 1D and four full 2D – hybrid 1D/2D models acceptable under current FEMA's Flood Hazard Mapping Program is available at the FEMA website[42]. Geographic information system (GIS) and raster-based models are also available for modelling floods (Bates and De Roo, 2000; Chen et al., 2009). Data requirements vary from one model to another, according to the approach used, scheme simplifications and model interface[43]. The basic data required by flood inundation models is composed of (Bales and Wagner, 2009; Mason et al., 2010): (1) topographic data for the hydraulic model computational grid and the inundation maps (DCPH / SH, 2000; Tate et al., 2002; Cobby et al., 2001; French, 2003; Marks and Bates, 2000; Casas et al., 2006); (2) boundary conditions at the downstream and upstream ends of the model domain (Pappenberger et al., 2006); (3) effective friction values (roughness coefficients) (Pappenberger et al., 2005; Wohl, 1998); and (4) model calibration/ validation data (Vidal et al., 2007).

The main results of hydraulic modelling processes are the floodwater surface elevations (flood stage data). Independent of the method used to obtain this data, the flood mapping process is a combination of this data with altimetric data (Figure 6.2). Geographic Information Systems become essential to produce flood maps and to support flood management projects (*cf.* Chapter 3).

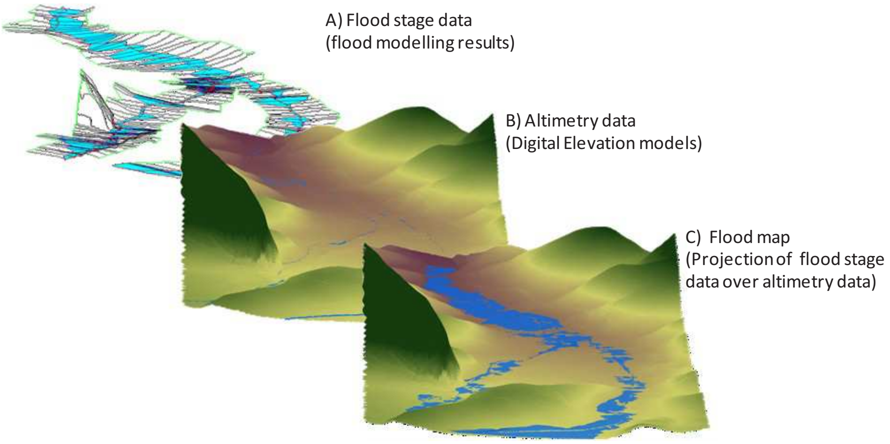

Figure 6.2. Combination of datasets in order to map flood hazards.

1.3. Uncertainty sources

Several sources of uncertainty can influence flood inundation mapping processes and compromise their accuracy (Bales and Wagner, 2009; de Moel et al., 2009; Horritt and Bates, 2002; NRC , 2009; Merwade et al., 2008b; Prinos, 2008). Some examples of uncertainty sources are: hydrologic data (*cf.* Chapter 5 for further details); topographic/bathymetric data (Casas et al., 2006; Hilldale and Raff,

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[42] Software web site: http://www.fema.gov/plan/prevent/fhm/en_hydra.shtm (consulted in October 2012).
[43] Data requirements are generally specified in software user's manuals.

2008; Vaze et al., 2010; Salomon, 2000); land-use data (Castilla and Hay, 2007) and roughness coefficient estimation (Bates P.D. et al., 2004; Aronica et al., 1998; Wohl, 1998; Aronica et al., 2002); models initial condition determination (Bates and Anderson, 1996); models calibration (Pappenberger et al., 2005; Pappenberger et al., 2007), etc.

Topography and hydrological errors are considered as the most important sources of uncertainty on flood hazard maps (Stelling and Verwey, 2005; Casas et al., 2006; NRC , 2009). Bales and Wagner (2009) considers that high-quality topographic data, along with the appropriate application of hydraulic modelling, are likely the most important factors required for accurate inundation maps. Indeed, the kind of hydraulic model that should be used for different purposes represent another important source of uncertainties (NRC, 2009). The most appropriate flood study method to be used for a particular map depends on the accuracy of the topographic data and the overall flood risk, including flood probability, defined vulnerabilities, and consequences (NRC , 2009; Kreis, 2004). The FEMA guidelines for flood hazard mapping (FEMA, 2003) highlights the limitations of several models but do little to help in the determination of which type of models are most appropriate for a given situation (NRC , 2009).

The construction of hydraulic models involves several choices in order to represent the rivers system. Different levels of details can be used during these analyses (Büchele et al., 2006), *e.g.* micro scale (Ernst et al., 2010) and large scale (Jonkman et al., 2008) hydraulic models. The major difference is the amount of information used in the study process (FEMA, 2006). The scale of the analysis plays an important role on the determination of the methods and levels of accuracy to consider. Uncertainty is linked to the amount of data used as well as how modellers process this data, *i.e.* human-factor behind modelling processes. Few studies analysed these aspects. Cook and Merwade (2009) measured how flood maps are influenced by the type of model used, and by the different topographic data and geometry simplifications made when building flood scenarios. Other studies analysed the effect of grid/mesh resolution on flood modelling (Golding, 2009; Horritt and Bates, 2001b; Yu and Lane, 2006; Werner, 2001). They highlight that these considerations can also considerably affect flood extent predictions.

2. Hydraulic uncertainty, flood maps and damage estimates

In this study, we explore the impact of the selection of hydraulic models and parametric uncertainties on damage estimations. In order to measure this uncertainty, we proceed as follows. Firstly, different strategies were used to model floods and produce flood hazard maps for one specific site. Secondly, the flood maps produced were used to estimate flood damage. Finally, we measure the variability of damage estimates induced by the different hydraulic modelling uncertainty sources. These steps are presented in the following sections, after a general overview of the dataset used to construct the different hydraulic modelling strategies.

2.1. Case study and datasets used for the simulations

The comparison of flood modelling strategies realised in this work is based on a real case study: the town of Fislis, in eastern France. The Fislis town is crossed by the Ill River and an affluent, Limendenbach stream (Figure 6.3). The river geometry, the hydraulic structures and the proximity of buildings to the river contribute to the recurrent flooding of dwellings (*cf.* Chapter 4 for more details).

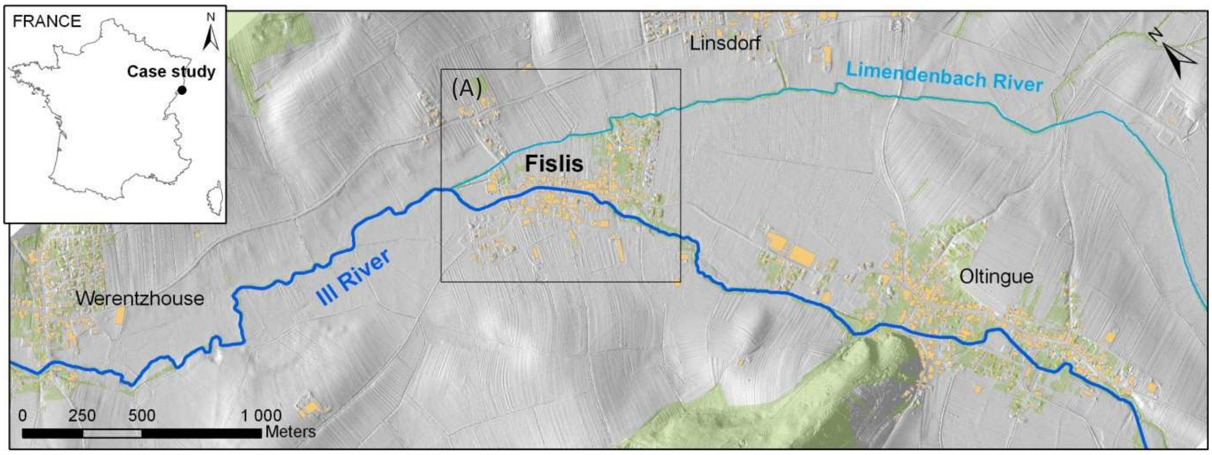

Figure 6.3. Study area: the town of Fislis, in Alsace, France.

A hydraulic model constructed by the French institution "Conseil Général du Haut Rhin" with HEC-RAS software was used as a starting point for the construction of the different flood modelling scenarios developed in this study. Topographic data used in this study was issue of a digital elevation model (DEM) produced with Light detection and Ranging (LIDAR) technology in 2008, with 0.2 vertical and 0.5 horizontal precision. Data relative to the rivers bathymetry, roughness coefficients and hydraulic structures (singularities) was obtained through field measurements realized in 2010. This data accounted 23 hydraulic structures for the 6.1 km of the Ill River in analysis and 5 hydraulic structures for the 4.1 km of the Limendenbach River. Hydrological analyses were realised with the Gumbel distribution method for a series of 30 years gauged data[44]. Regional regression based on the surface of the watershed was realised for obtaining the following discharge-frequency relationships (Figure 6.4). Finally, the satellite images-based land-use dataset named BD OCS [45]

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[44] Hydrological data from 1978 to 2008 in the hydrometric station of Altkirch (Ill river) - internet site: "Banque hydro" http://www.hydro.eaufrance.fr/ (consulted in April 2012).

[45] The BD OCS dataset distinguish 94 classes of land-uses on the scale of 1: 25000. This database covers the whole Alsace "French Région" area and it was established for the "Région Alsace" institution.

(Géoméditerranée, 2003) was used for the development of floodplain roughness-coefficient maps (Manning-Strickler values). These datasets were used for the different modelling scenarios developed hereafter.

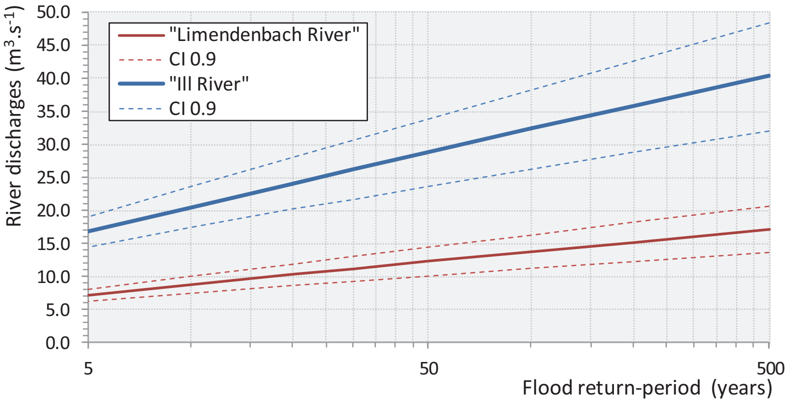

Figure 6.4. Estimated discharge/frequency values for the Ill River and its tributary Limendenbach at their confluence point.

2.2. Differences between modelling scenarios

The hazard modelling strategies developed here are different in relation to two aspects: (1) the type of hydrodynamic approach (1D, 1D/2D and 2D computational programs) used to simulate flood events, *i.e.* model selection; and (2) the density of data processed when representing the geometry, bathymetry and topography (cross-sections for 1D and 1D/2D models and grid resolution for 1D/2D and 2D models) of the studied system, *i.e.* model parametric choices.

2.2.1. Type of hydraulic model

In practical modelling processes, the selection of models is often based on the required engineering staff time for model development, overall consultancy time for product delivery, speed of computation, accuracy level of results, data requirements, numerical robustness, user-interface of the software, etc (Stelling and Verwey, 2005). Indeed, the cost of flood modelling and mapping can be consequent and then influence the selection of models and methods to use as well as the quality/quantity of data to use (NRC , 2009). Indeed some efforts were done to guide modeller on the selection of models (CETMEF, 2007; FEMA, 2003), this selection is still vague (NRC , 2009). In this study, three hydrodynamic models largely employed all over the world for flood analysis were used to build the different scenarios of flood simulations (Table 6.2). These models are based on different hypothesis and they offer different possibilities for the end-user to simulate floods.

Table 6.2. Description of the main characteristics of the models used to simulate floods.

Approach	Model	Physical laws	Numerical methods
1D	HEC-RAS software (v. 4.1) by the U.S. Army Corps of Engineers[a] (HEC, 2010).	Bernoulli energy equation (steady-state flow); Saint-Venant shallow water equations (unsteady-state flow)	Algebraic equation (steady-state flow); FDM (unsteady-state flow)
2D	Mike 21 software by DHI Group[b]	2D Saint-Venant shallow water equations (steady/unsteady state flow)	FVM (steady/unsteady state flow)
Hybrid 1D/2D	Mike Flood software developed by DHI Group[b]	1D and 2D Saint-Venant shallow water equations (steady/unsteady state flow)	FDM (steady/unsteady state flow)

[a] Hydrologic Engineering Center River Analysis System web site: http://www.hec.usace.army.mil/software/hec-ras

Water resources MIKE by DHI products web site: http://www.mikebydhi.com/Products/WaterResources

2.2.2. Geometric representation of the river systems

All three models require geometrical datasets, although they use them in different ways. The type of model and the scale of analysis play an important role on the model parametric choices. In 1D models, the amount of hydraulic structures and cross-sections to consider in the analysis is influenced by the size of the area due to resources constraints. For 2D models, the modeller is constraint to rescale topographic data in order to respond to model requirements. Even thought great improvement was done on the quality of topographic data, the models numerical limitations and simulation time requirements induce to downscaling methods. Therefore, the level of detail on the description of the floodplain topography (resolution of the grid/mesh cell) also depends on the size of the study area.

We constructed 32 flood models considering different geometric representation of the case study for the three hydraulic approaches used here (Table 6.3).

Table 6.3. Differences between the modelling scenarios built with different hydraulic models.

Approach	Nb. of scenarios	Differences between scenarios
1D	12	Number/position of cross-sections and number of hydraulic structures
2D	5	Size of the interpolated grid cells
Hybrid 1D/2D	15	1D part - Number of cross sections and hydraulic structures 2D part - Interpolated grid cell size

The density of cross-sections and hydraulic structures modelled in 1D models as well as the size of the interpolated grid cells in 2D models were both based on scale-based assumptions, making reference to the model expected level of detail (Messner et al., 2007). When using the 1D approach (HEC-RAS), we distinguished three scales of analysis: “micro”, “meso” and “macro”, from which the micro-scale is the more detail one. Four micro-scale (high-density data) scenarios were built considering different emplacements for cross-sections (scenarios A-D in Figure 6.5). The same consideration was made for constructing four meso-scale (medium-density data) scenarios (scenarios E-H in Figure 6.5) and four macro-scale (low-density data) scenarios (scenarios I-L in Figure 6.5).

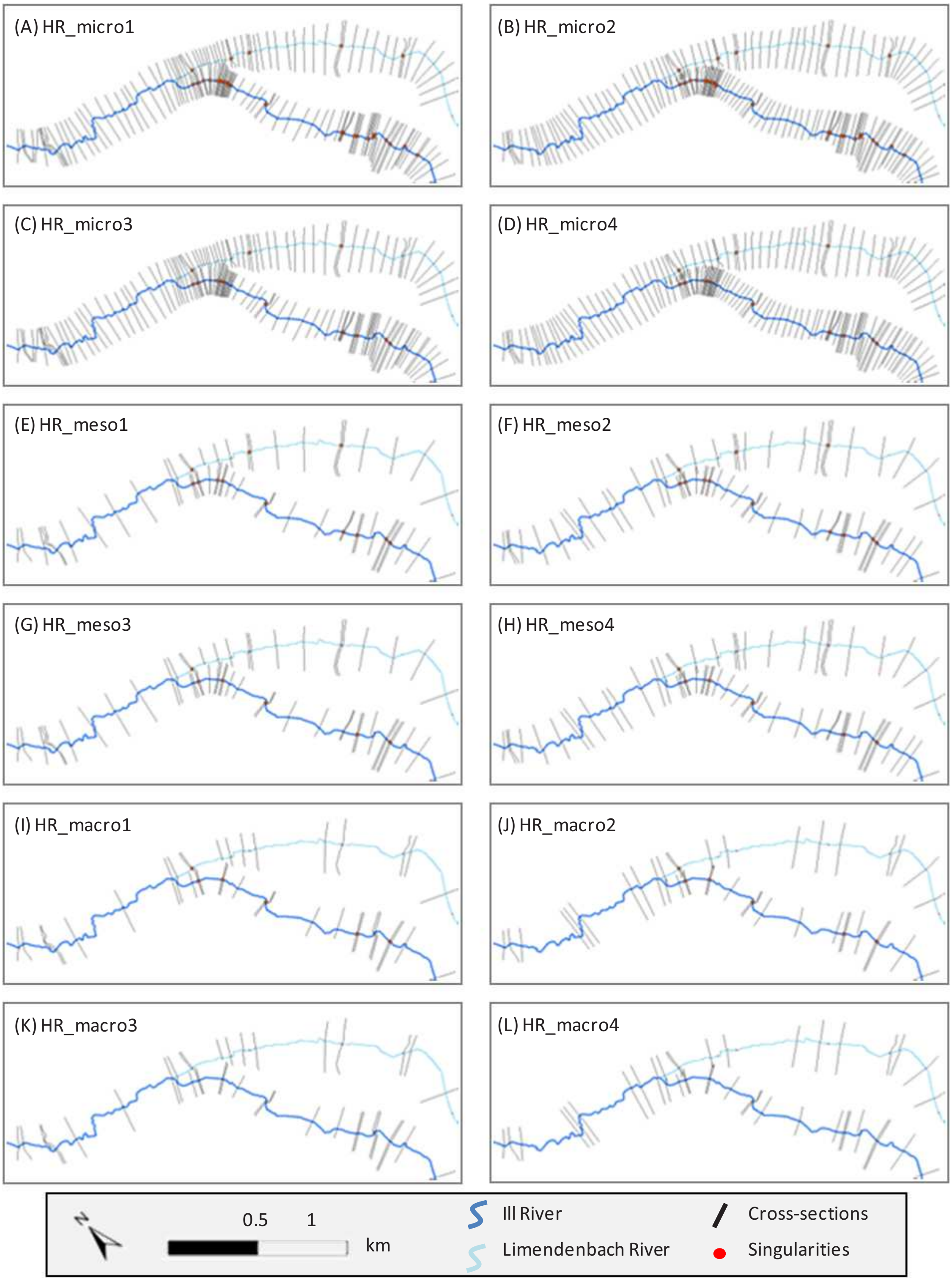

Figure 6.5. Topology of the 1D modelling scenarios built with HEC-RAS.

HEC-GeoRAS® v. 4.3 software[46] and the Geographic Information System (GIS) ArcGIS v. 9.2 by ESRI[47] were used to construct these different models (Ackerman et al., 1999; HEC, 2011).

The 2D modelling scenarios were based on the available digital elevation model (DEM). In order to improve the accuracy of bathymetric data for 2D simulations, the GIS-based method proposed by Merwade et al. (2005, 2006, 2008a) was used to interpolate the river main channel using field measurements. The DEM was processed using the ArcGIS v. 9.2 abd its Spatial and 3D Analyst extensions. All the 2D models constructed were based on regular rectangular grid cells representing the rivers bathymetry and the floodplain topography. The scale-considerations used to construct the 2D modelling scenarios concern the size of the interpolated grid cells used in the models. Five scenarios were built considering different levels of detail (grid cell sizes): the DEM was downscaled to 2m, 3m, 4m, 6m and 10m grid cell sizes – scenarios named M21_02, M21_03, M21_04, M21_06 and M21_10. For the construction of hybrid 1D/2D models we also considered three levels of detail (micro, meso and macro) for the 1D part of the model (river channels) (Figure 6.6).

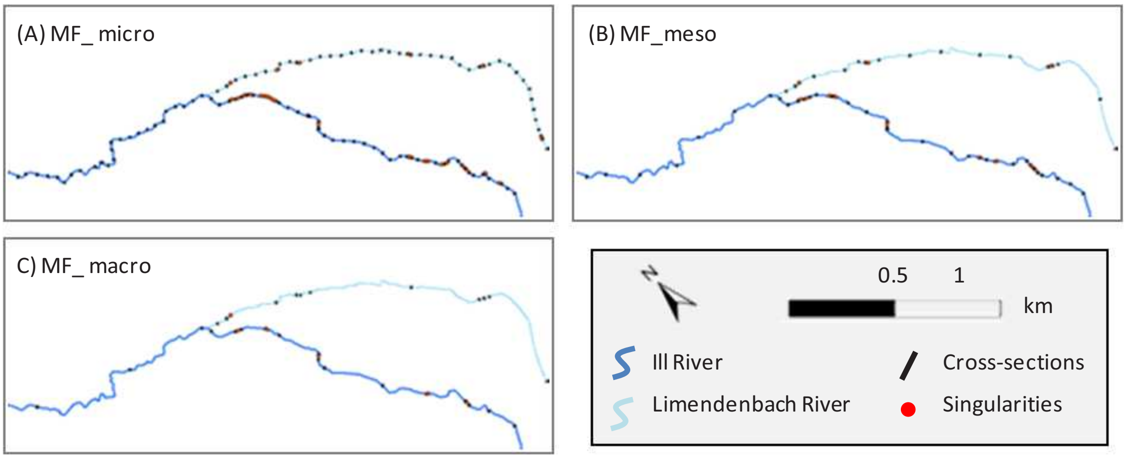

Figure 6.6. Geometry of the 1D part of the hybrid 1D/2D modelling scenarios.

Five scenarios were built for each of the different 1D scales of analysis used, using the Mike11 GIS[48] software (DHI, 2008). These scenarios were different in relation the size of the interpolated grid cell used for the 2D part of the model (floodplain). The five scenarios built considering the 1D micro-scale (high-density data) used the DEM downscaled to 3, 4, 6, 10 and 15 meters grid cell resolution (scenarios MF_micro03, MF_micro04, MF_micro10 and MF_micro15). The 1D meso-scale (medium-

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[46] HEC-geoRAS is set of ArcGIS tools specifically designed to process geospatial data for use with HEC-RAS software.

[47] ArcGIS software WEB site: www.esri.com/software/arcgis

[48] MIKE 11 GIS is an extension of ArcGIS developed by DHI Group. It provides a range of features for setting up network and cross section data for the MikeFlood 1D part (MIKE 11).

density data) used 4, 6, 10, 15 and 20 meters grid cells (scenarios MF_meso04, MF_meso06, MF_meso10, MF_meso15 and MF_meso20) and the five 1D macro-scale (low-density data) scenarios used 6, 10, 15, 20 and 25 meters resolution (scenarios MF_macro06, MF_macro10, MF_macro15, MF_macro20 and MF_macro25).

2.3. Flood modelling and hazard mapping

Discharge/water depth relationships were used as boundary conditions downstream and upstream the model (determined using the reference model). In order to avoid boundary condition influences, the section of the reach considered for the construction of the different modelling scenarios was much longer than the area of interest (area A in Figure 6.3). Once adequate calibration data is seldom available for inundation models, the different modelling scenarios here were calibrated by using measurements at a single point which is the normal practice (Horritt and Bates, 2002; Bales and Wagner, 2009). Finally, we performed, for each modelling scenario, steady-flow simulations for eight hypothetical flood events: 5, 10, 20, 30, 50, 100, 200 and 500-yr return-period flood events (Figure 6.4). The HEC-RAS Mapper Floodplain Delineation Capabilities (HEC, 2010) was used to construct flood hazard maps issues of the HEC-RAS 1D simulations. The available DEM was used for the interpolation of the calculated flood-stages (*cf.* Figure 6.2). We used ArcGIS 9.2 to process the results of the simulations performed with Mike 21 (2D) and Mike Flood (hybrid 1D/2D) software. All the flood maps were generated for the town of Fislis: the sub-area of 0.94 km^2 (area A in Figure 6.3) was used for all the comparisons presented in the results of this work.

2.4. Damage estimation

The damage estimation realized on this work concerns only buildings and contents direct damage potential to floods. The damage model used establishes damage potential as a function of the types of buildings, their surfaces and the water depth inside buildings. Seventeen damage functions for residential (Torterotot, 1993) and commercial (DNRM, 2002) buildings were used to evaluate buildings damage-potential[49]. Building vulnerability data was obtained through the analysis of available GIS datasets and detailed field-surveys. We analysed 231 buildings, classified according 17 vulnerability classes. The field surveys were realised at the elementary scale (building per building), in order to determine the typology of buildings, their construction characteristics and their ground floor elevation[50]. The GIS-based model presented in Chapter 3 was used to combine hazard with vulnerability data, calculate flood damage, produce flood risk maps (Eleutério et al., 2012).

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[49] Tests related to the selection of damage functions and associated uncertainties are presented in Chapter 8.

[50] Chapter 7 focuses on the description of different strategies used to assess the vulnerability of buildings.

3. Results

3.1. Impact of hydraulic modelling choices on hazard maps

In order to measure the effect of modelling uncertainties in flood maps, we compared the different maps produced here. Our analysis is done over 100-years flood maps once this frequency of floods is the most commonly used for flood management purposes, *e.g.* US FIRMS[51] (NRC , 2009) and French PPRi[52] (MATE/METL, 1999). The following maps represent flood-depths distributions calculated with the different models: 12 Hec-RAS models (Figure 6.7, HR scenarios), 15 Mike Flood models (maps A-O in Figure 6.8, MF scenarios) and 5 Mike 21 models (maps P-T in Figure 6.8, M21 scenarios).

The graphical analysis of the maps generated shows that the maps produced using the 1D software (Figure 6.7) overestimate water depths in relation the other scenarios (Figure 6.8). We also notice that the surfaces calculated with these 1D models and the hybrid 1D/2D models (Figure 6.8, MF scenarios) are quite similar, exception made to the right-upper corner of the study area. This difference was due to hypotheses on a bridge modelling, revealing that the micro 1D scenarios underestimated the bypass potential of this hydraulic structure for important flows. We also notice that the flood surfaces are largely overestimated when using low-resolution grid cells for 2D models and the 2D part of hybrid models (*e.g.* maps D, I, J, N and O in Figure 6.8, MF scenarios and maps R-T Figure 6.8, M21 scenarios).

In full 2D models, this overestimation can be explained by the difficulty to represent the exchanges between the main channel and the floodplains for these rivers using regular grid cells. Another explication is that the DEM downscaling methods may underestimate altimetry and levees. Contrary to the effect of the model selection, the effect of the parametric choices is more hardly perceived in the 1D models flood maps. These differences are more comprehensive when comparing the hybrid 1D/2D and full 2D flood maps (Figure 6.8, MF and M21 scenarios): we notice that the higher the scale is, the bigger the flood surface is, at least when considering the grid cell size variation (2D part of the hybrid models). The flood surfaces and water depths calculated for the different scenarios (Figure 6.9 A) reinforce the conclusions of the graphical analysis.

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[51] The US FEMA’s Flood Insurance Rate Maps (FIRMs) are used for setting flood insurance rates, regulating floodplain development, and communicating the 1 percent annual chance flood hazard to those who live in floodplains.

[52] The "Plan de Prévention du Risque Inondation" (PPRI) is the French floodplain development regulation tool. They are based hypothetical 100-yr flood maps or real flood events if those are less frequent than the 100-years flood.

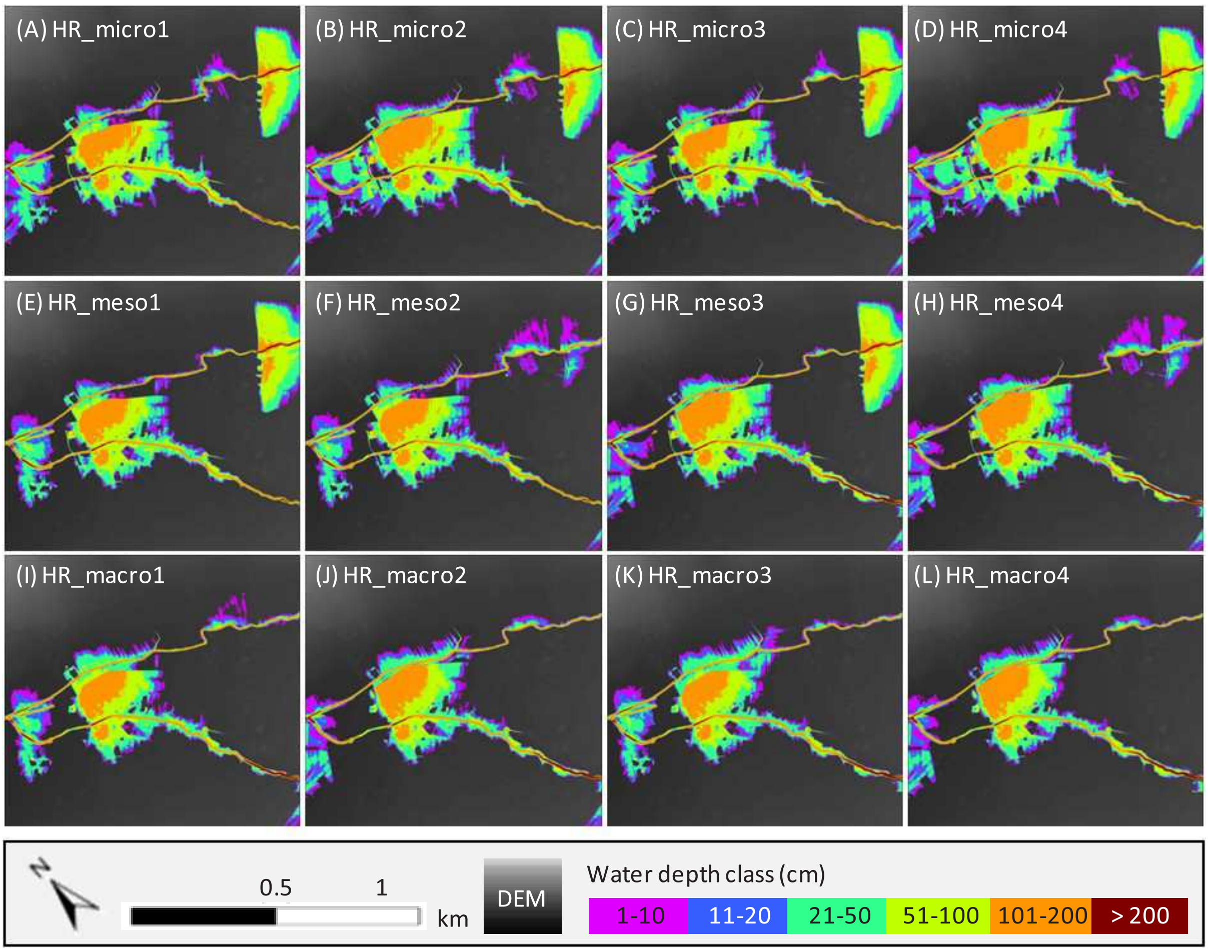

Figure 6.7. Flood extent and water depth maps for the 12 full 1D modelling scenarios.

When using the hybrid 1D/2D model, the predicted flood surfaces were strongly increased when we increased the grid cell size (reduction of DEM resolution) (Figure 6.9 A, Mike Flood scenarios). This influence is still more important for the full-2D models (Figure 6.9 A, M21 scenarios). In hybrid 1D/2D models, the influence of the number of cross-sections and hydraulic structures modelled showed to be less significant to the estimation of flood surfaces (*cf.* differences between Mike Flood micro, meso and macro in Figure 6.9 A). However, the choice of the number of cross-section showed to be more relevant for full 1D scenarios (*cf.* differences between Hec-RAS micro, meso and macro in Figure 6.9 A). In both, 1D and Hybrid 1D/2D models, the increase of the number of modelled cross-sections induced to the increase of predicted flood surfaces. The different choices concerning the position of the cross-sections revealed to have a slight influence on the estimation of flood surfaces. However, we noticed the choice of the emplacement of cross-section and of which structures to model leaded to concentrated differences on flood surfaces around specific structures (bridges) (*cf.* differences between HEC-RAS sc. numbers in Figure 6.9 A). These conclusions based on 1D models are similar to findings provided by Cook and Merwade (2009).

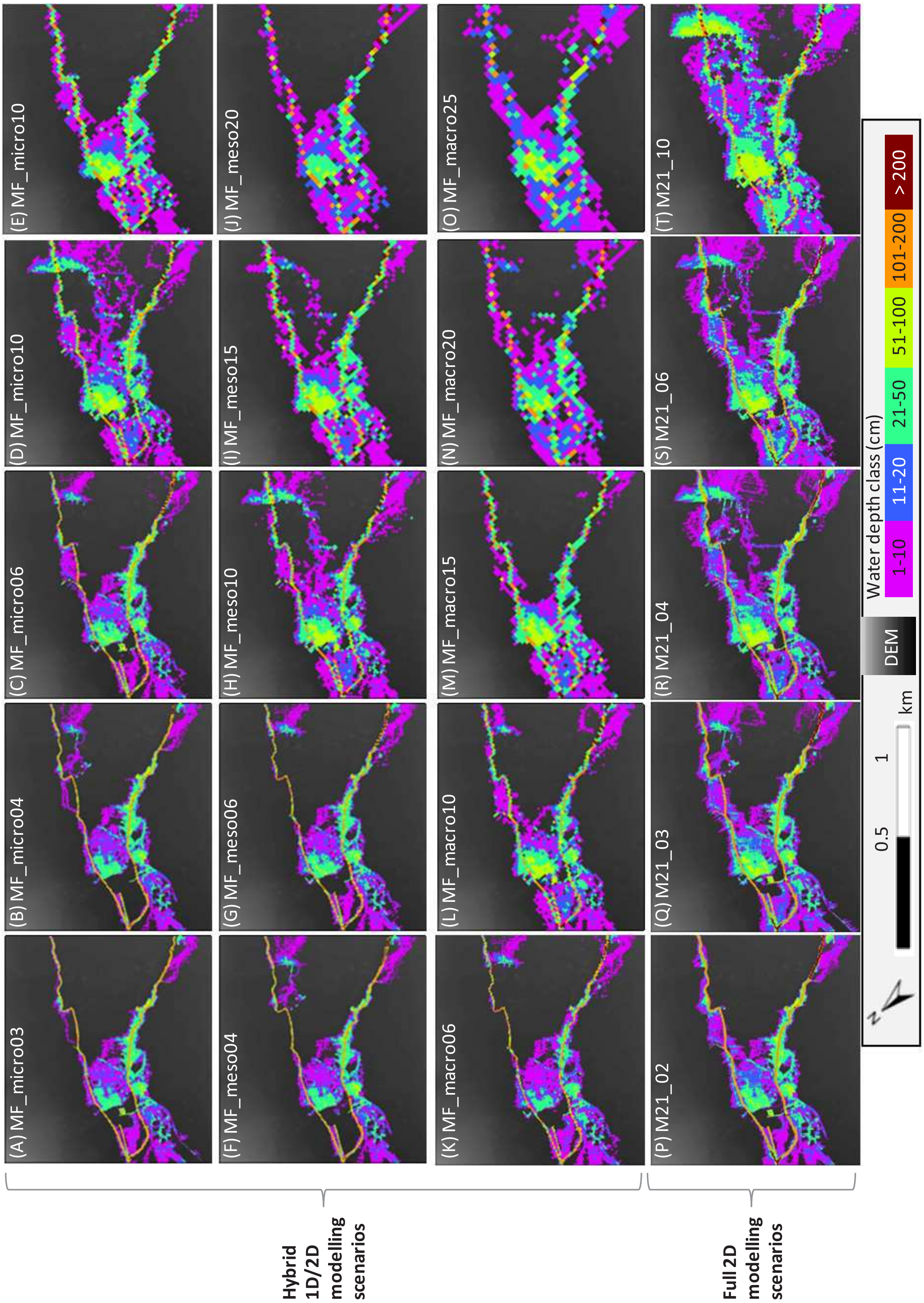

Figure 6.8. Flood extent and water depth maps for the 15 coupled 1D/2D modelling scenarios and the five full 2D modelling scenarios.

When analysing the water depth distributions (Figure 6.9 B), we noticed that the types of models is a predominant source of variability. The hybrid and 2D scenarios presented the same pattern of distribution (Figure 6.9 B, MF and M21 scenarios). Low water depths (0 to 20cm) are predominant for those scenarios (64% of flood surface in average). This can be explained by the fact that velocity is taken into account in both models resolution scheme, and the floodplain water depths are heterogeneous and influenced by roughness coefficients. The 1D scenarios present a completely different water depth distribution pattern (Figure 6.9 B, HR scenarios). Lower water depths represented only 28% of the flood surface in average. These simulations predicted considerably higher water depths values: water depths higher than 50cm represented 44% of the flood surface in average for 1D models against 13% in average for 2D and hybrid 1D/2D models. This can be explained by the fact that the water depth in this case is calculated by cross-section interpolation, without taking into account the differences between main channel and floodplain, and the topography of the case study promoted high water depth predictions.

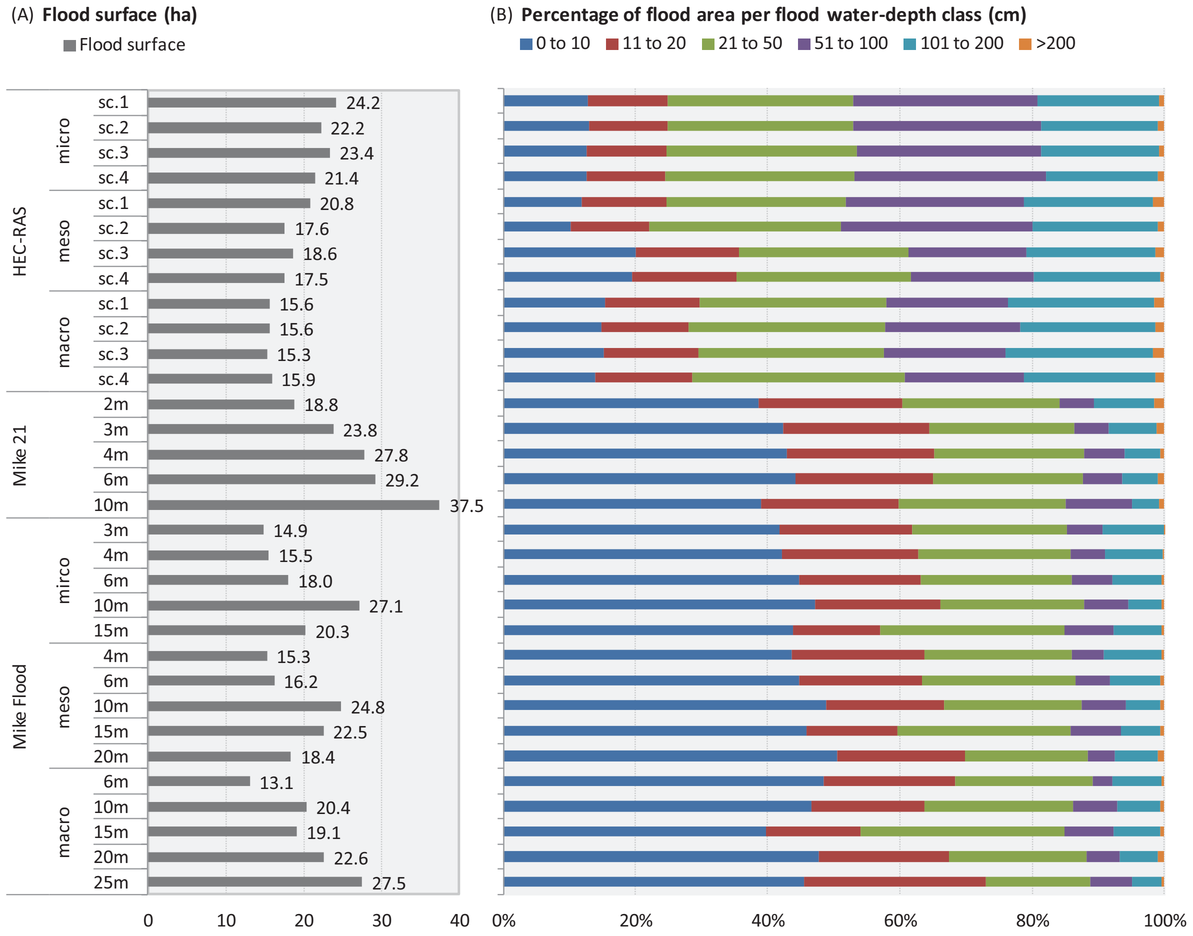

Figure 6.9. Statistical comparison between the flood hazard hydraulic components: (A) flood surface (ha) and (B) percentage of surface per class of floodwater depth (cm).

3.2. Impact of hydraulic modelling on damage estimates

We realised 256 damage estimations, one for each of the eight flood-return period considered by the thirty-two modelling scenarios analysed in this work. These estimates are represented in thirty-two risk-curves (damage potential estimate vs. probability of occurrence), one for each hazard modelling scenario (Figure 6.10). In this figure, we highlight the best estimates for each model approach (1D; full 2D and hybrid 1D/2D). These were considered best estimates in relation to the similarity of 10, 30 and 100-yr flood extent maps produced with these scenarios in relation to the reference model used in this work. The estimates using the best 2D modelling scenario were higher than the estimates obtained through 1D and hybrid 1D/2D models. When comparing 1D with 1D/2D estimates, we notice that the estimations using the 1D best method result on greater damage values for flood return-periods shorter than or equal to 30 years. However, these estimations were quite similar.

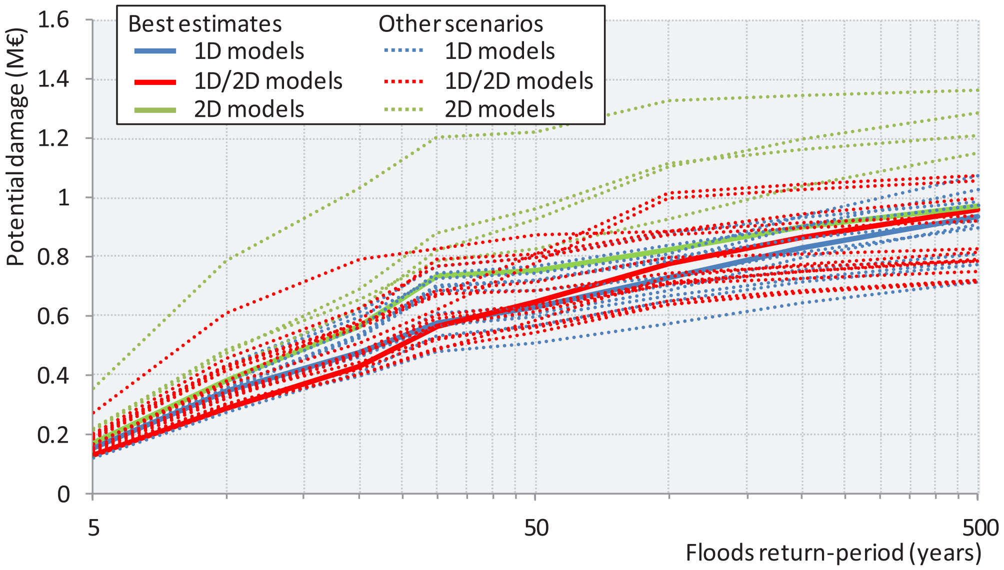

Figure 6.10. Risk curves (damage vs. probability) built using the different modelling scenarios.

The risk curves above revealed that the uncertainty generated by parametric choices generated higher variability of estimates than the uncertainty generated by the selection of the models. The variability of 2D models showed to tend to the overestimation of damage estimates. The same tendency is observed for hybrid 1D/2D models, for which we notice great overestimation, especially on frequent events (lower than 50-yr return-periods). The variability of 1D based estimations is more homogeneous in relation to the best estimates. In order to evaluate the global impact of different sources of uncertainty on the different evaluations we used these risk curves to calculate Expected Annual Damage (EAD) by summing up the "damage x frequency" values (*cf.* Chapter 3). These results are presented in the following graphs (Figure 6.11 and Figure 6.12).

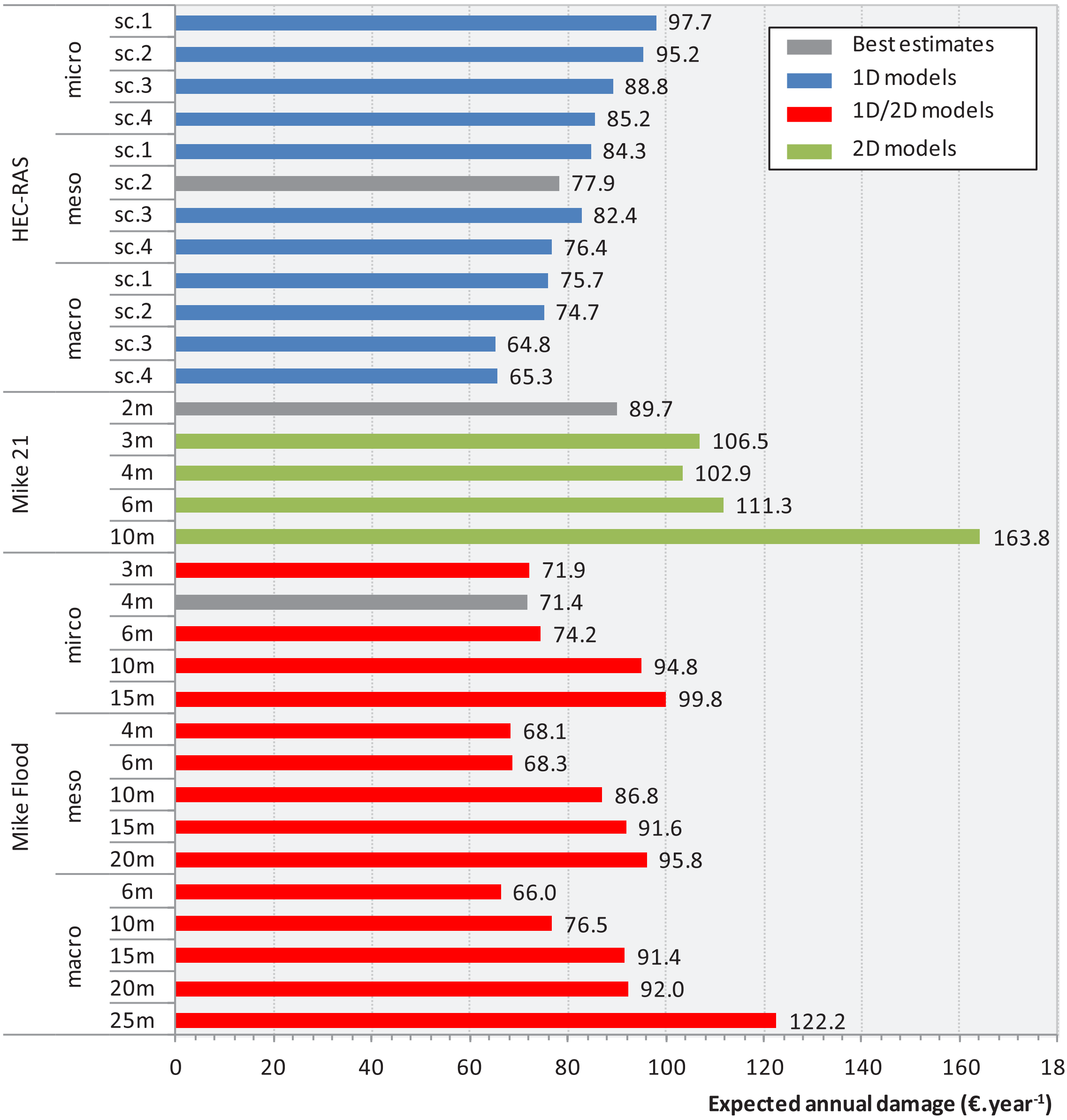

Figure 6.11. EAD calculated using the different hydraulic modelling strategies.

The scale-considerations in the HEC-RAS modelling scenarios revealed that damage estimates increased when we improved the level of details on the hydraulic modelling process (*cf.* differences between 1D micro, meso and macro scales in Figure 6.11). In "micro" scale analyses, we were able to better appreciate low points along the channel, inducing more frequent inundations on the floodplain (larger flood surfaces). EAD were estimated at respectively 70, 80, 92 k€.year^{-1} for respectively macro, meso and micro scenarios, in average. We can make the same conclusions when comparing the scale-considerations for the 1D part of the hybrid models, (*cf.* differences between Mike Flood micro, meso and macro scenarios considering the same grid cell sizes for the 2D part of the model Figure 6.11). For example, EAD calculated with the Mike Flood 10m grid resolution vary from 76.5 k€.year^{-1} (1D macro scale), 86.8 k€.year^{-1} (1D meso scale), and 94.8 k€.year^{-1} (1D micro scale).

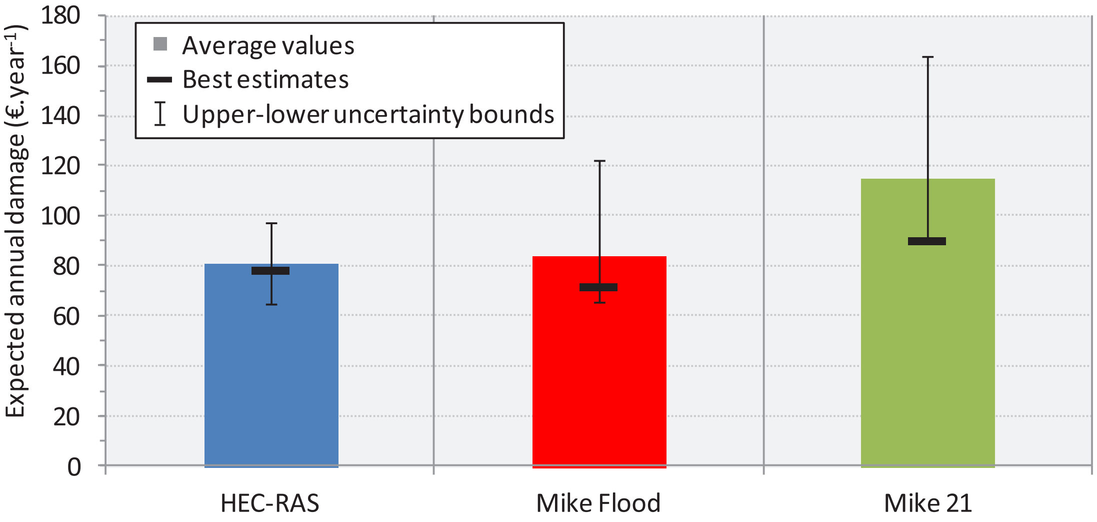

Figure 6.12. EAD estimated using the different modelling scenarios.

EAD best estimates (based on best surface estimations) were 71.4 k€.year^{-1} using Mike Flood, 77.9 k€.year^{-1} using Hec-RAS and 89.7 k€.year^{-1} using Mike 21. When considering total variability (scale effect) the minimum EAD value was estimated at 64.8 k€.year^{-1} and the maximum at 163.8 k€.year^{-1} (more than 2.5 times the minimum estimate. These results presented in Figure 6.11 highlight that scale considerations relative to the grid cell size strongly influenced the results of damage evaluations. The exaggerated estimate realised with the 2D model scenario based on 10m grid cell resolution reveals the limits of using this kind of models with simplified structure for large-scale damage studies. Once the river channel sections are thinner than 10m, large-scale 2D models considering regular grid cells were unable to represent the river flow in the main channel, even for frequent floods (*cf.* the upper bound risk curve in Figure 6.10).

The sources of uncertainty analysed here propagate differently from one model to another. When comparing these uncertainties in relation to the approaches used (1D, hybrid 1D/2D and full-2D), we notice that the tests realised generated large uncertainties in estimations based on 2D approaches (Figure 6.12). For both, full 2D and hybrid 1D/2D models the best estimates are placed in the lower limits of the uncertainty boundaries. The best 1D estimate is in the centre of the uncertainty boundary, near the average value.

3.3. Result discussions

The model selection uncertainty contributed to 18% of the global uncertainty of EAD estimates generated by the different flood modelling considerations. The parametric uncertainties had a much higher influence on these estimations: they contributed to 75% of the global uncertainty. This strong influence was due to scale considerations, and mainly due to those induced by grid-cell size considerations. On the 1D model (Hec-RAS), the uncertainty relative to the position of cross-sections contributed to only 10% of the 1D EAD estimates uncertainty. The uncertainty linked to scale considerations (density of cross-sections and hydraulic structures) contributed to 95% of EAD uncertainty. By increasing of the number of modelled cross-sections (from macro to micro scale), we induced the increase of predicted flood surfaces and flood damage. This influence was similarly identified for flood areas prediction in the tests realised by Cook and Merwade (2009).

The scale effects on the Hybrid 1D/2D models generated divergent uncertainties on the 1D and 2D parts of the models. On the one hand, the increase of details (from macro to micro scale) on the 1D-part of the models generated an increase of predicted inundated surfaces and damage estimates. The increase of details (from macro to micro scale) on the 2D-part of the models, on the other hand, decreased the surfaces and damage estimates. However, the uncertainty on the 1D-part of the model contributed to 19% of EAD estimate uncertainty against 64% of contribution from the 2D-part related uncertainty. For full-2D models, the scale effect is similar to the 2D-part of Hybrid models. Therefore, contrary to 1D models, the greater the scale of evaluation is, higher the EAD estimation results are.

4. Conclusions

The present analysis highlights that the different strategies used in modelling processes, *i.e.* type of hydraulic model and choices made by the modeller to represent geometry, topography and bathymetry, are determinant for flood maps and damage estimates accuracy. The comparison of thirty-two 100-years flood maps produced using different models and scale-considerations revealed that:

- the selection of the type of model is the most important factor when considering the variability of flood maps parameters (water depth distributions);
- the scale of analysis is the most important uncertainty source for the determination of the surface of flood maps;
- the choice of the DEM resolution strongly influenced the results of the modelling processes.

The propagation of uncertainty on damage estimates allowed us to explore some important aspects of the evaluation. We highlight that:

- uncertainty on estimations generated by the flood hazard modelling scale considerations revealed to be much higher than the uncertainty linked to the selection of model. Scale considerations contributed to 75% of expected annual damage (EAD) estimates against 18% for model selection;
- the increasing of the precision of hydraulic modelling has a different impact on damage estimations, according the type of hydraulic approach used. For 1D models, the more detailed the models are (higher density of cross-sections), the higher damage estimation results are. For 2D models, the more the models are precise (small grid-cells) the lower damage estimates are.
- the effect of scale-considerations on 2D-based damage estimates (variability of grid-cell size) is much higher than the effect of scale considerations on 1D-based damage estimates (density of simulated cross-sections);
- damage estimations based on hybrid models are much more influenced by the considerations on the grid-cell sizes than those relative to the number of modelled cross-sections.

The great influence of grid cells sizes revealed by this work is in accordance with literature that considers topography as the main source of uncertainties on flood hazard modelling. On the one hand, topographic reliability depends on the technologies and personal used to acquire the data, and on the methods used to analyze data. Uncertainty could be reduced by adopting the best available technology and by improving performance of the technical staff. On the other hand, this work revealed that it is essential to take necessary precautions when processing topographic data for flood hazard modelling and mapping processes. Hydraulic uncertainty is related to the capacity of the modelling software to represent the flood phenomenon and on the model construction. Several available models, *e.g.* FEMA guidelines list[53], are able to correctly represent different types of flood. Though, when accurate data is available, the selection of the appropriate model was less relevant for damage evaluations than the simplifications considered when using them, *i.e.* parametric uncertainty. To reduce uncertainty, the selection of the modelling software has to be in accordance with the characteristics of the site on study, and data availability. Further, the scale of the analysis should not compromise the performance

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[53] Document available at http://www.fema.gov/plan/prevent/fhm/en_hydra.shtm (consulted in October 2012)

of the selected software. The conclusions of this work are based on a case study and it only considers part of uncertainties related to flood mapping processes. Research is still to be done in order to clarify the global role of hydraulic uncertainty on flood damage evaluations and explore the different criteria that should be considered when realising flood maps for this specific purpose. However, this work highlight that special attention is to be given when using existing flood maps or producing simplified hydraulic analyses for damage estimation purposes. These considerations can strongly affect the results of the evaluation.

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Chapter 7.

Asset exposure and vulnerability assessments

Buildings and contents frequently represent the majority of damage in case of floods, which makes the assessment of their vulnerability an essential step in flood risk analyses. Even though research focused on these assessments during the last decades, their practical application is still charged with uncertainties. Quantifying and understand uncertainty is important for better decision-making processes. This chapter compares several methods to assess the vulnerability of buildings to floods in order to analyse how they influence flood damage assessments. These approaches are different in relation to two aspects: (1) the datasets and field surveys used to assess buildings and contents vulnerability to floods; and (2) the level of hypothesis that should be done in the representation of the vulnerability of buildings during the damage estimation process. The size of area to analyse is an important criterion for the selection of the assessment methods in risk analyses. The resources and amount of data needed to carry these assessments can play an important role on their accuracy. The methods tested herein are analyzed in terms of scale-feasibility and reliability criteria. The two aspects analysed are different from one method to another taking into account different scales. The town of Holtzheim in the Bruche River low valley is analysed with this purpose. The test realised revealed that damage estimates can be strongly influenced by scale considerations. Micro scale analyses revealed a greater building "resistance" to floods, aspect ignored by large-scale analyses. This leads to a tendency to overestimate damage in large-scale analyses. For concluding this chapter, we make some recommendations concerning the selection methods to assess the vulnerability of buildings to floods.

This chapter is based on Eleutério J., Payraudeau S., Rozan A. Sensibilité de l'évaluation des dommages associés aux inondations en fonction de la caractéristique de la vulnérabilité des bâtiments, Ingénieries EAT, n°55-56, pp.29-44, 2008; and Eleutério J., Flood loss analysis uncertainties: how to assess, process and analyse different data. 17th Annual Conference of the European Association of Environmental and Resource Economists, Amsterdam, Netherlands, 24-27 June 2009.

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1. Introduction

Material damage to buildings and their contents frequently represents the majority of direct damage in case of flooding (Hubert and Ledoux, 1999). Therefore, the most important category to investigate during the evaluation of flood damage is buildings and their inventories (Messner et al., 2007), followed by infrastructures and networks[54]. The potential of buildings to suffer flood damage depends on several characteristics of both, the hazardous phenomenon, *e.g.* floodwater depth, flow velocity, duration of submersion; and on the vulnerability of buildings to the specific phenomenon, *e.g.* fabric construction type, occupation type, level of protection, capacity of occupants to respond to an alert dispositive, etc. The use of damage functions to estimate flood damage is the current state of the art, largely applied all over the world (Merz et al., 2010b). When using these damage functions to estimate potential flood damage, both site-dependent characteristics incurring to damage (hazard intensity and the vulnerability of buildings) must be assessed. Therefore, flood hazard maps, and the different characteristics of the assets at risk in a territory are essential to achieve damage estimations.

On the one hand, research has mainly focused on the hazard aspect of the risk over the last decades. Great advances were made in hazard modelling processes in order to elaborate accurate flood maps and estimate hydraulic parameters distribution (Woodhead, 2007; Horritt and Bates, 2002; Stelling and Verwey, 2005). On the other hand, the knowledge of a territory and its vulnerability is crucial to the estimation of flood consequences (Green et al., 2011). Furthermore, the development of appropriate risk reduction measures is strongly correlated to the level of knowledge about vulnerability of elements at risk, *e.g.* development of emergency plans and the realisation of emergency exercises (Merz et al., 2010b). The vulnerability aspect of the damage estimation process was much less explored in literature and the understanding and reduction of related uncertainties is a great issue to be relieved. As concluded by Merz et al. (2007), one of the actual challenges in research is the development of comprehensive studies on vulnerability, in order to produce accurate data relative to flood consequences.

In practical applications, damage-estimations are essentially based on existing datasets, in order to reduce the costs of the evaluation process (Messner et al., 2007). Certain level of accuracy may be required according to the objectives of the analysis, which may determine the search for more refined information concerning the assets. However, the level of detail of asset assessments also depends strongly on the size of the study area and the available input data (Merz et al., 2010b). Detailed analysis of vulnerability may lead to important costs in terms of time and investments for the analysis

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[54] The vulnerability of network is out of the scope of this chapter. Potential damage and dysfunctions to network infrastructures are explored in Chapter 10.

(Green et al., 2011). In order to reduce uncertainty efficiently, it is essential to understand what the consequences of more or less accurate data on the results of the evaluation are.

This chapter focuses on the vulnerability aspect of the risk. We analyse the variability of damage evaluation results induced by the vulnerability assessment uncertainties. In order to achieve this objective we compare several scale-based approaches to assess the vulnerability of buildings to floods. These approaches are different in relation to the datasets and field surveys used and their level of accuracy. Flood hazard maps and damage functions are used to achieve damage estimates based on these different approaches. In this present section, we realise a brief state of the art on the assessment of vulnerability to floods. In section 2, we describe the different methods used to assess the vulnerability of buildings to floods and propagate uncertainties on damage estimations. Further, section 3 describes the results of the uncertainty tests realised. We finally achieve this work (section 4) by making recommendations concerning the selection of the appropriate approach to assess the vulnerability of buildings to floods.

1.1. Damage-influencing factors

In relation to hazard intensity, several characteristics of floods can induce damage, *e.g.* water flow velocity, water depth, submersion length, pollution rate (Messner et al., 2007; Thieken et al., 2005; Kreibich and Thieken, 2008). Floodwater depth is the damage-influencing factor more frequently used to assess damage potential to buildings and contents (Smith, 1994; Merz et al., 2010b). Uncertainty is still important on the determination of this parameter (*cf.* Chapter 6). In relation to buildings and contents, several building characteristics can influence damage. We can divide these characteristics in 3 major groups:

- group of construction characteristics: localization of construction, type of material used in the buildings fabric (wood, concrete, steel…), existence of basement, protection dispositive, existence of a supplementary floor for evacuation of goods, property floor height, age…
- group of occupation/functional characteristics: type of occupation (housing, commerce, industrial…), age of occupants, health state, disposition of occupation inside the building…
- group of external characteristics: existence of flood warning systems, flood protection measures, crisis management characteristics, accessibility of dwellings…

Damage functions establish different relationships between these damage-influencing factors in order to estimate potential flood damage. Vulnerability assessments may therefore require knowledge on the different physical, social and economic characteristics of the assets, and their susceptibility to flood hazards (Messner and Meyer, 2006). When estimating potential flood damage, the selection of damage functions determines what characteristics of buildings should be assessed in order to reveal their vulnerability to floods.

1.2. Assessment of the vulnerability assets

Building vulnerability data for damage evaluation purposes refers to the information concerning the assets and their sensitivity to floodwater required for the use of specific damage functions. Several methods allow characterizing the vulnerability of assets to floods (Green et al., 1994; Pottier et al., 2005). According to D4E (2007), we can distinguish two types of approaches to assess the vulnerability of assets: (1) we can assess vulnerability considering homogeneous areas, *e.g.* Simpson and Human (2008); van der Veen and Logtmeijer (2005) and Dutta et al. (2003); or (2) we can investigate the vulnerability of the different elements in a flood zone, *e.g.* individual buildings, element of networks, (Gilard, 1999; Oliveri and Santoro, 2000; Erdlenbruch et al., 2007).

1.2.1. Data collection

These evaluations are mainly based on existing datasets. The growing use of Geographic Information Systems (GIS) in public utilities highly increased the availability of datasets that may be explored in these assessments. However, supplementary data may be necessary for filling gaps in terms of amount or quality of existing data. Different strategies may be used to assess vulnerability data for damage assessment purposes:

- we can use existing data on land-uses and elements. Land-uses are generally represented by maps or geo-referenced GIS layers containing different homogeneous zones, which are associated to different land-use characteristics, *e.g.* CORINE Land Cover [55], statistical datasets... More detail datasets can represent different entities in a specific area, *e.g.* DBTOPO from the French National Geography Institute (IGN) [56]. This data represent the assets in a zone by geo-referenced features in GIS layers;
- we can collect data through field surveys. These field surveys can be organized according to different objectives. Therefore, we can assess assets' individual characteristics or groups' characteristics by homogeneous zones;
- we can collect data through interviews. The characteristics assessed by means of interview processes depend on the organization of the interview and on the statistical methods used to determine the sample. However, a great amount of data can be assessed by this approach.

The following table (Table 7.1) gives some examples of datasets currently used for assessing the vulnerability of assets to floods.

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[55] "Coordination of Information on the Environment" (CORINE) Land Cover data is issue of a project hold by the European Environment Agency. Information at the EEA WEB site http://www.eea.europa.eu/

[56] French National Geography Institute « Institut National de Géographie » internet WEB Site: www.ign.fr

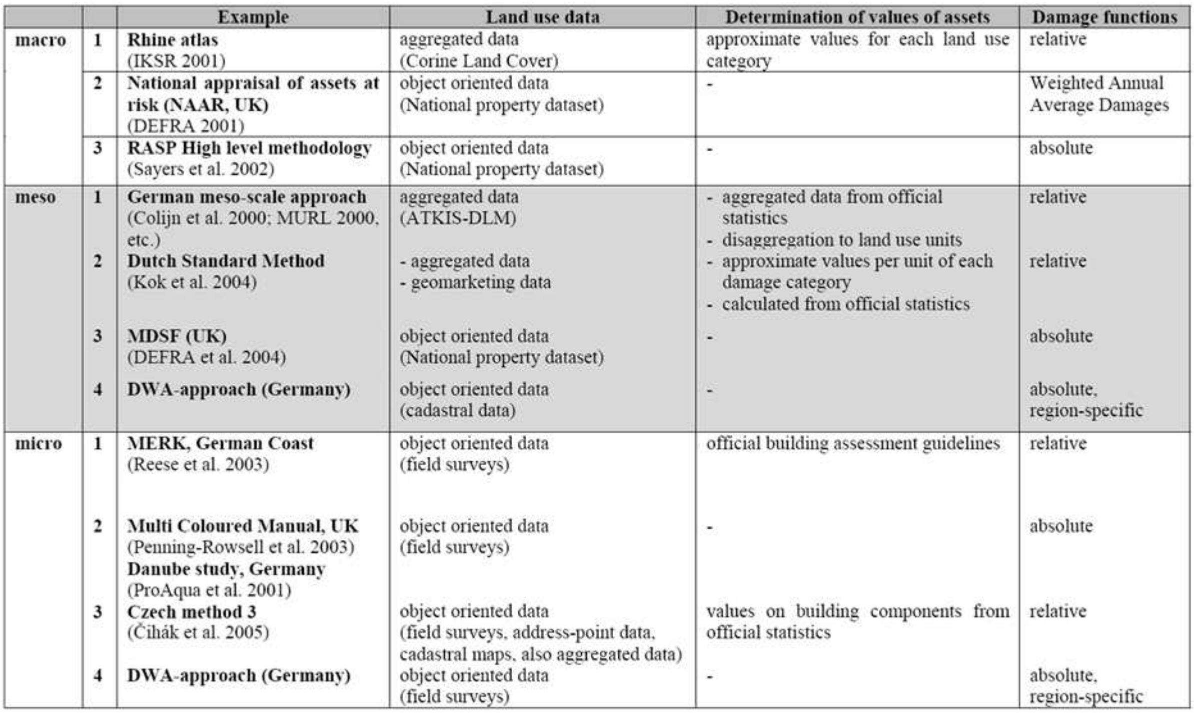
Table 7.1. Example of different land-use data types. Source: Messner et al. (2007).

Types & examples	Spatial resolution	Differentiation*
Field surveys	Object oriented: Single properties	> 100 different building types
Address-point data *E.g.* UK, National Property Dataset	Object oriented: Address-points	> 20 different building types
Cadastral maps Germany, ALK	Object oriented: Ground floor areas	> 2 different building types
Detailed aggregated data *E.g.* Germany, ATKIS Czech Republic, UPD NL, CBS	Aggregated: Blocks of similar use	> 10 different land use types
Low detailed aggregated data *E.g.* CORINE Land Cover	Aggregated: Areas > 25 ha	Ca. 6 different land use types
Geomarketing data *E.g.* NL, Bridgis Germany, Infas-Geodaten	Postcode areas, Election districts etc.	(Additional socio-economic information)

*Some of the data sources mentioned contain more categories, but not all of them are useful for the purpose of damage evaluation.

1.2.2. Scales of analysis

The data collection process depends on the purpose of the risk analysis and its requirements in terms of accuracy. In practical applications, it's an evidence that the detail of assessment strongly depends on the size of the study area, the available input data and the availability of resources for the analysis (Merz et al., 2010b). The scale of the analysis therefore is a determinant aspect when collecting and producing assets related data. Depending on the level of detail required and scale of evaluation, field surveys to collect data can quickly turn out very difficult to lead. The assessment of assets and their vulnerability is a complex task that is often simplified by aggregating or disaggregating existing information (Wünsch et al., 2009). As noted by Merz et al. (2010b), "depending on the spatial extent of the investigated inundation area and the chosen degree of detail of the damage assessment, a large number of elements at risk has to be considered. In general, it is not possible to assess the damage for each single object, because there is no information on the damage behaviour of each object and/or because such a detailed assessment would require a huge effort. Therefore, elements at risk are pooled into classes, and the damage assessment is performed for the different classes, whereas all elements within one class are treated in the same way. For example, in the assessment of flood damage to private households, all households of a certain type may be grouped in one class and may obtain the same asset value, *e.g.* related to the floor area. Similarly, the relative damage of all households in this class may be estimated by using the same susceptibility function" [page 1701]. Different classifications were done in order to simplify this aspect of the risk estimation process (Schanze et al., 2006; Penning-Rowsell et al., 2005; Machado, 2005; Kang et al., 2005; Su et al., 2009). Some examples of methods and datasets used to assess vulnerability in different damage estimation scales are shown in Figure 7.1.



		Example	Land use data	Determination of values of assets	Damage functions
macro	1	**Rhine atlas** (IKSR 2001)	aggregated data (Corine Land Cover)	approximate values for each land use category	relative
	2	**National appraisal of assets at risk (NAAR, UK)** (DEFRA 2001)	object oriented data (National property dataset)	-	Weighted Annual Average Damages
	3	**RASP High level methodology** (Sayers et al. 2002)	object oriented data (National property dataset)	-	absolute
meso	1	**German meso-scale approach** (Colijn et al. 2000; MURL 2000, etc.)	aggregated data (ATKIS-DLM)	- aggregated data from official statistics - disaggregation to land use units	relative
	2	**Dutch Standard Method** (Kok et al. 2004)	- aggregated data - geomarketing data	- approximate values per unit of each damage category - calculated from official statistics	relative
	3	**MDSF (UK)** (DEFRA et al. 2004)	object oriented data (National property dataset)	-	absolute
	4	**DWA-approach (Germany)**	object oriented data (cadastral data)	-	absolute, region-specific
micro	1	**MERK, German Coast** (Reese et al. 2003)	object oriented data (field surveys)	official building assessment guidelines	relative
	2	**Multi Coloured Manual, UK** (Penning-Rowsell et al. 2003) **Danube study, Germany** (ProAqua et al. 2001)	object oriented data (field surveys)	-	absolute
	3	**Czech method 3** (Čihák et al. 2005)	object oriented data (field surveys, address-point data, cadastral maps, also aggregated data)	values on building components from official statistics	relative
	4	**DWA-approach (Germany)**	object oriented data (field surveys)	-	absolute, region-specific

Figure 7.1. Examples of methods used to evaluate damage based on different scales of analysis.

Source: Messner et al. (2007).

1.3. Uncertainties linked to vulnerability assessments

In practical applications, the liability of a method depends on its ease of implementation, *i.e.* data availability, time and resource demands (Messner et al., 2007). Find the optimal ratio between reliability and ease of implementation is an additional challenge to the evaluation process. The aggregation of building vulnerability characteristics for damage evaluation purposes may lead to uncertainties in the evaluation. Each building in a territory has its own characteristics, which give to these uncertainties a spatial dimension. The uncertainty linked to the occupation and construction characteristics of buildings is related to the level of knowledge of them, depending only on the data assessment method used.

Uncertainty is also linked to the quality of existing datasets potentially used for damage estimation purposes, *e.g.* land-use data uncertainty (Castilla and Hay, 2007). An important source of uncertainty on the vulnerability of assets is the height of ground floors (NRC , 2000). Penning-Rowsell et al. (2005) states that the accuracy of the assessment of property thresholds and 'footprint' areas is fundamental to the accuracy of damage evaluations, and it depends on the techniques employed and the resources available. This uncertainty may be reduced by improving assessment techniques nut the costs could be consequent (NRC, 2009).

The sensibility of the evaluation to the selection of the method used to describe the vulnerability is rarely analysed. Apel et al. (2008a) compared different damage models that implied the use of different vulnerability assessment data. However, they do not focus on the vulnerability assessment method alone. Wünsch et al. (2009) also compared different damage models based on different scales for considerations related to the assets assessment method. The author concluded that it is important to invest in assets data in order to improve flood damage assessments.

2. Variability direct damage estimations to buildings

In order to quantify the impact of the vulnerability assessment methods on the results of flood damage estimations, we proceeded as follows:

- firstly, we used different strategies to assess the vulnerability of buildings to floods. These strategies are different in relation to the datasets used during the assessment;
- secondly, the results of these assessment approaches were individually used to calculate potential flood damage;
- finally, we compared the results of the damage evaluations and we measure the related uncertainty due to each of the methods used to assess the vulnerability of buildings to floods.

This method was applied in the town of Holtzheim. The town is crossed by the Bruche River, and it is vulnerable to its floods (*cf.* Chapter 4 for more details). The last important flood revealed that residential buildings and contents represents the biggest share of urban flood damage in the city. Residential buildings represented 90% of buildings total share[57].

2.1. Basis for damage estimations

The damage functions developed by Torterotot (1993) were used in this work to estimate damage to residential buildings. These damage functions are largely used in the French context (D4E, 2007; CEPRI, 2008). For non-residential buildings (*i.e.* industrial, commercial and public buildings), we used the damage functions developed by DNRM (2002) which were already used in the national context for evaluating flood damage (Erdlenbruch et al., 2007; Erdlenbruch et al., 2008). A set of two damage functions were used herein to estimate residential potential damage. Non-residential buildings damage-potential was represented by five groups of damage functions corresponding to five building

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[57] The last important flood event caused more than 2.3M Euros on the basis of the analysis of the 1990 flood event CatNat dossier in the municipality of Holtzheim (*cf.* Chapter 8 for further details).

vulnerability classes, *i.e.* pools of buildings with occupation types leading to similar damage in case of floods. This damage was calibrated in order to express damage in €.m^{-2} of the buildings impacted, as a function of the water level and the type of buildings. For using these damaging functions, we needed to obtain the following characteristics relative to the vulnerability of buildings and the flood hazard:

- type of buildings occupation of the ground floor of the building, *e.g.* housing, school, church, offices, hospital, etc.
- existence/absence of basement (for residential buildings)
- property floor height (in relation to natural terrain)
- flood water depth (in relation to natural terrain)
- buildings "footprint" surface
- percentage of the ground floor surface of building occupied

The type of buildings occupation and the existence/absence of basement for residential buildings are the criterion of selection of damage functions to use in the estimation of damage for a specific property. The property floor height and the floodwater depth makes possible to estimate the level of hazard affecting each building (difference between the floodwater calculated and the property floor height, both in relation to the natural terrain). Finally, the buildings "footprint" surface together with the percentage of ground floor surface of the building makes possible to determine the surface impacted by floods, for total damage calculations (*cf.* Chapter 3 for more details on the estimation of damage based on these different data). Both damage functions used take as reference the value of buildings construction per square meter. Several methods can be used to assess and disaggregate these values. However, we used only one approach in order to measure the effect of other parameters as follows.

A hybrid 1D/2D model using the hydraulic model Mike Flood® was used to simulate floods and produce hazard maps, based on a digital elevation model obtained with LIDAR[58] technology. Flood hazard maps for events with different return-periods (5, 10, 20, 30, 50, 100, 200 and 500-yr) were used for damage estimation purposes. These maps represent flood extent and water depth distribution for the different frequencies of analysis. All the other characteristics necessary for the application of the damage functions (vulnerability characteristics) were the object of tests realised in this work, and are presented in the next sections.

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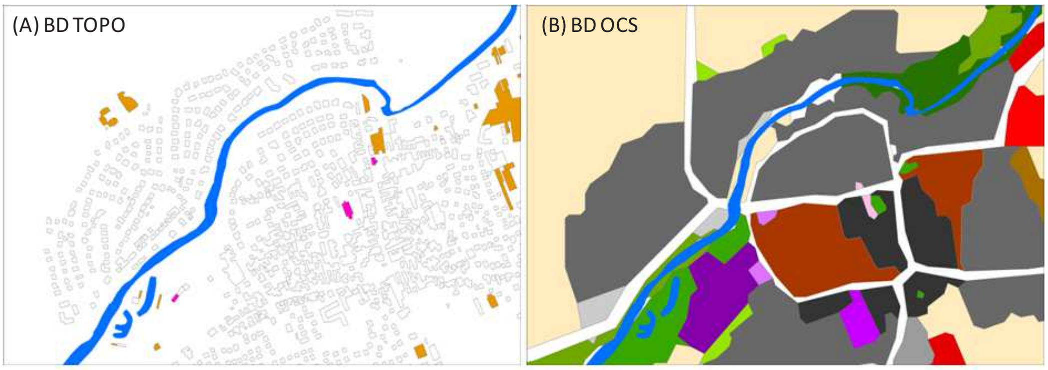
[58] LIDAR is the acronym for Light Detection and Ranging, which designates a remote sensing or optical measurement technology based on analysing the properties of a laser light reflected back to its transmitter.

2.2. Available datasets for vulnerability analyses

Three databases with different levels of precision were analysed in order to characterise these different aspects of the building vulnerability to floods (Figure 7.2). The BD TOPO® database built by the French National institute of Geography (IGN)[59], uses numerical information (geo-referenced data) on land use and morphology at a scale of 1 :25 000. The data available in the database includes a GIS "buildings" layer that contains the spatial representation of the contours of buildings and types of use. It differentiates residential buildings from other types of buildings, *e.g.* industrial, commercial, and rural (Figure 7.2 A). The BD OCS describes land use in homogenous areas according to 94 classes at a scale of 1:25 000. This database was built at the request of the Alsace Region (Géoméditerranée, 2003), it differentiate residential areas from, mixed areas, industrial, commercial, with different density scales (Figure 7.2 B). The GIS local databases are composed of geo-referenced points indicating the addresses of buildings. They were enhanced with information drawn from local databases (Local Chambers of Commerce/Industry and local municipalities) with reference to the types of activity of the buildings. This database identifies the registry of professional activities, linked to the addresses of the buildings (Figure 7.2 C).



Identification of different types of buildings.

Identification of different types of land-uses.

Identification of different types of buildings.

Figure 7.2. Example of information extracted from existing datasets for the case study.

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[59] French National Geography Institute « Institut National de Géographie » internet WEB Site: www.ign.fr

Among the datasets available in this case study, some of them are available in the national scale (BD TOPO® in the French context), others only in the regional (BD OCS in the Alsatian context) and local scales (BD CUS in the community scale). This scenario is common everywhere: the more the scale is big, the less detailed homogeneous data is available for all assets at risk. The following information cannot be determined by these three existing databases:

- the location of the activity inside the buildings, *e.g.* basement, ground floor or upper floors;
- presence/absence of basements;
- property floor height,
- occupation rates

Besides, it is not possible to estimate *a priori* the reliability of the only information available on these datasets, the “type of occupation”. In order to fill the gaps of this data, real estate expert interviews and field surveys were realised in 2010 and 2011. They are described in the following section.

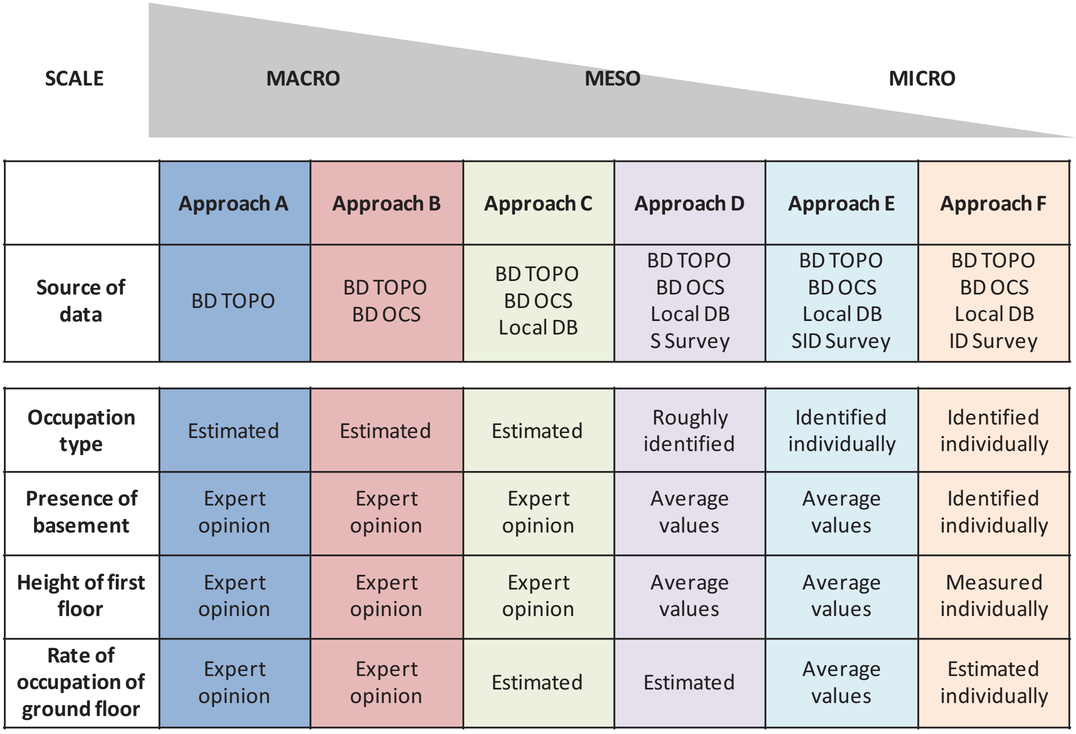
2.3. Interviews and field surveys

Complementary methods were implemented to make up for the limitations of the existing databases. It consisted of the realisation of interviews and field surveys. Firstly, interviews were conducted with two local real estate experts to determine buildings lacking construction and occupation characteristics, *i.e.* presence of basements, height of first floor and percentage of building ground floors occupied by non-residential buildings. When realising these interviews, we considered three different scales of analysis: (1) a large scale, in which we were interested in average values for the French Region of Alsace, *i.e.* macro scale; (2) a medium scale in which we focus on average values for the French Department Bas-Rhin where the case study is within, *i.e.* meso scale; and (3) a local scale in which we asked for average values for the specific town in study.

Secondly, three types of field survey were performed on the case study: (1) a superficial field survey, called “S Survey”, in order to identify the average characteristics of all the buildings of the municipality; (2) a semi-in-depth field survey called “SID Survey” in order to estimate the average characteristics of buildings by homogenous area of land use, pre-identified by map analyses; and (3) an in-depth survey called “ID Survey”, in order to identify and measure the characteristics building by building.

2.4. Different methods used to estimate the vulnerability of buildings to floods

Six approaches based on the different available datasets and the results of the interviews and field-surveys were used in order to test the sensitivity of damage estimations to this aspect of the evaluation (Figure 7.3). These approaches were also based on different scales of analysis: the level of precision of the strategies developed increased from Approach A ("macro" scale) to Approach F ("micro" scale). Expert opinion issue of the "macro", "meso" and "micro" strategies were respectively used for these respective scales when filling the gaps in existing datasets. The amount and quality of data used in this approaches increase from Approach A to Approach F. This last approach is therefore considered as the most accurate, once it is based on building oriented field surveys.



	Approach A	**Approach B**	**Approach C**	**Approach D**	**Approach E**	**Approach F**
Source of data	BD TOPO	BD TOPO BD OCS	BD TOPO BD OCS Local DB	BD TOPO BD OCS Local DB S Survey	BD TOPO BD OCS Local DB SID Survey	BD TOPO BD OCS Local DB ID Survey
Occupation type	Estimated	Estimated	Estimated	Roughly identified	Identified individually	Identified individually
Presence of basement	Expert opinion	Expert opinion	Expert opinion	Average values	Average values	Identified individually
Height of first floor	Expert opinion	Expert opinion	Expert opinion	Average values	Average values	Measured individually
Rate of occupation of ground floor	Expert opinion	Expert opinion	Estimated	Estimated	Average values	Estimated individually

Figure 7.3. Approaches used to assess the vulnerability of buildings to floods.

The following figures expose the spatial variability of these vulnerability assessments (Figure 7.4, Figure 7.5 and Figure 7.6). Figure 7.4 shows the great variability of the estimation of the height of the first floor elevations. We notice that Approaches A and B globally underestimate these values in relation to the other approaches (Figure 7.4 A and B). We also notice the great heterogeneity of this values for the Approach F with the exception of the buildings neat the water path, where the first-floor elevations got higher values (Figure 7.4 F).

In Figure 7.5 we can notice that the classification of the types of occupation of buildings were relatively similar for meso and micro approaches (Figure 7.5 C, D, E and F). Figure 7.6 highlight the great variability of the information relative to the presence/absence of basements. The macro scales underestimated the percentage of buildings with basements in relation to micro scales.

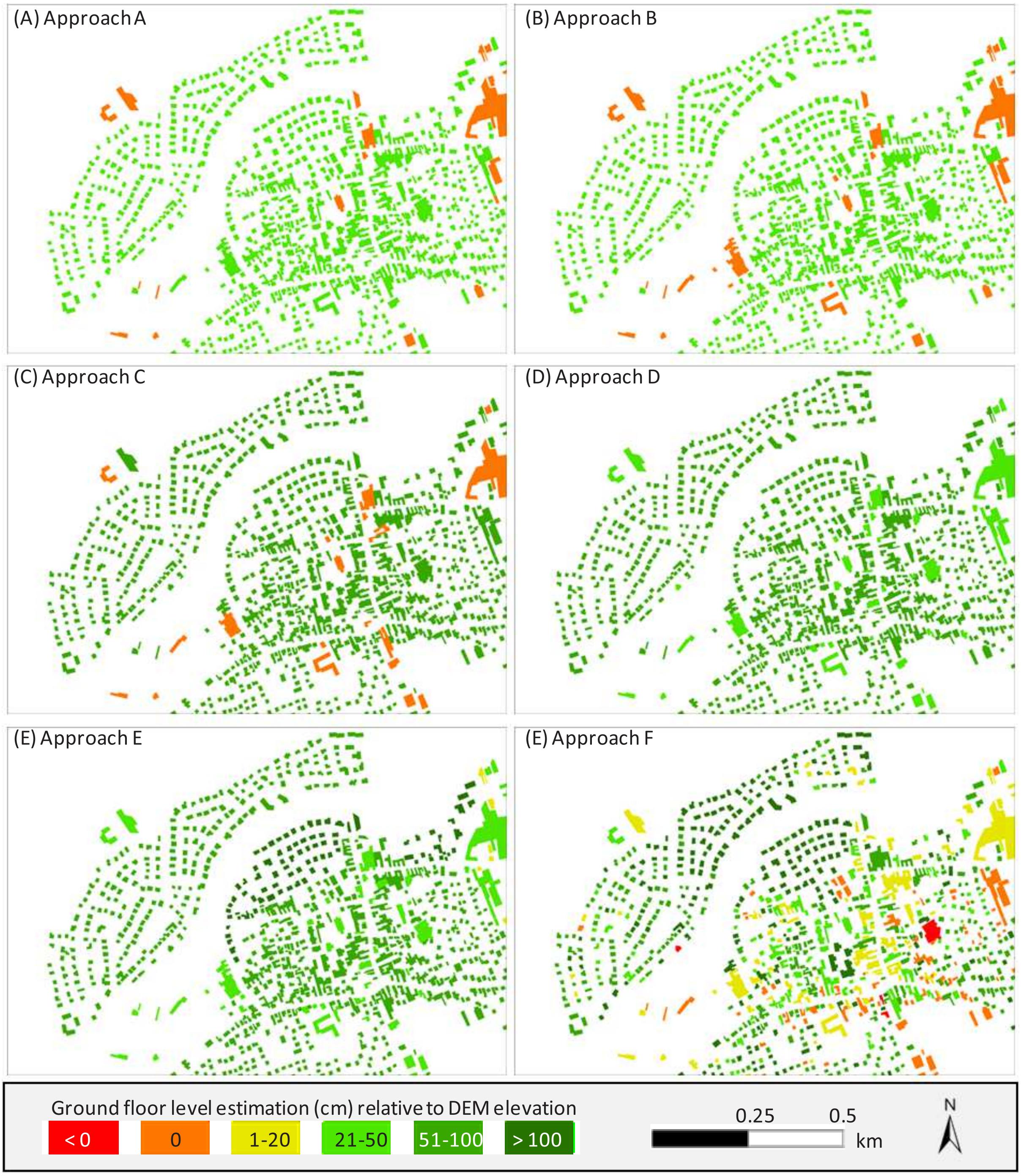


Figure 7.4. Building ground floor height according to the different assessment approaches.

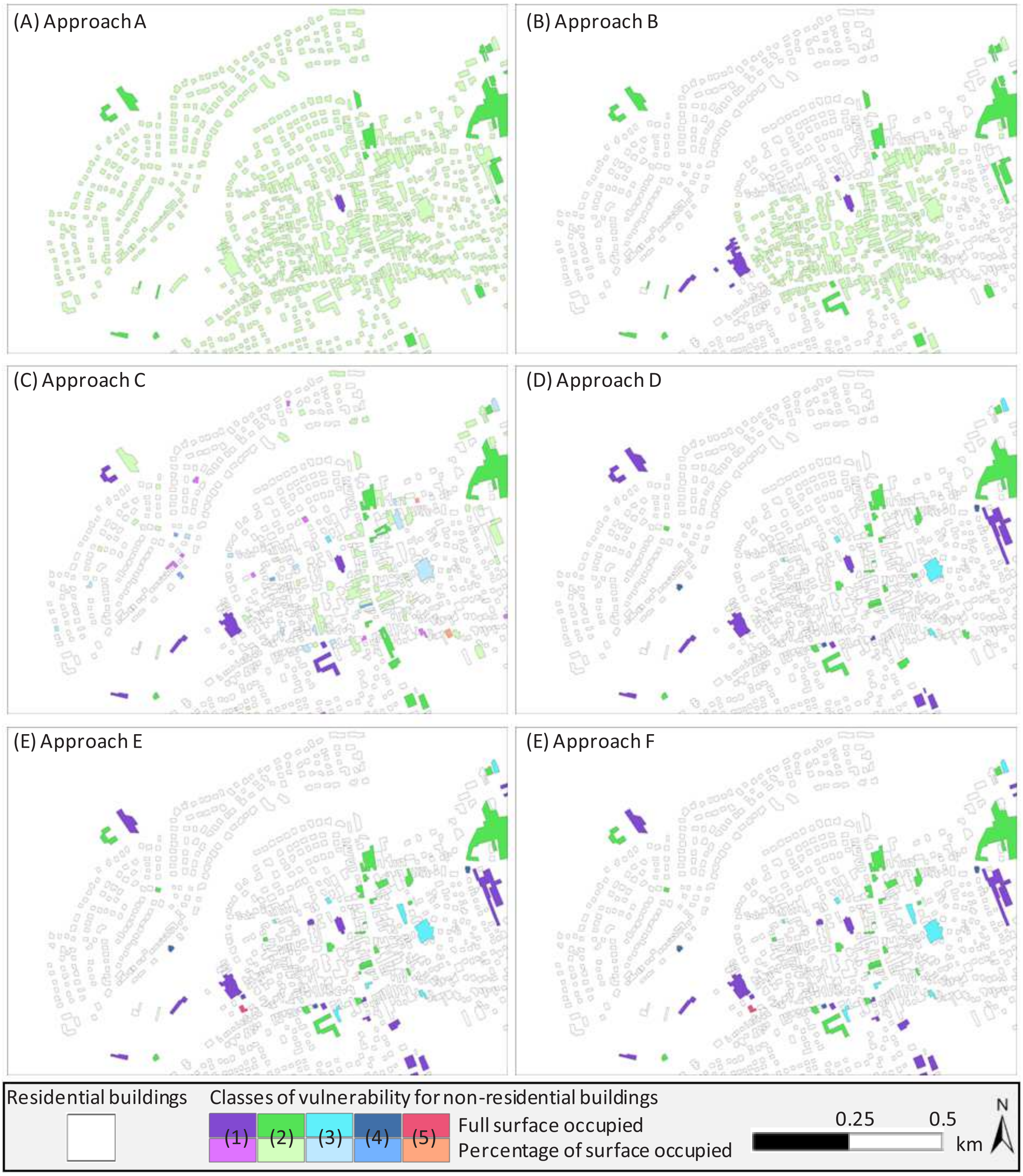


Figure 7.5. Buildings occupation type according to the different assessment approaches.

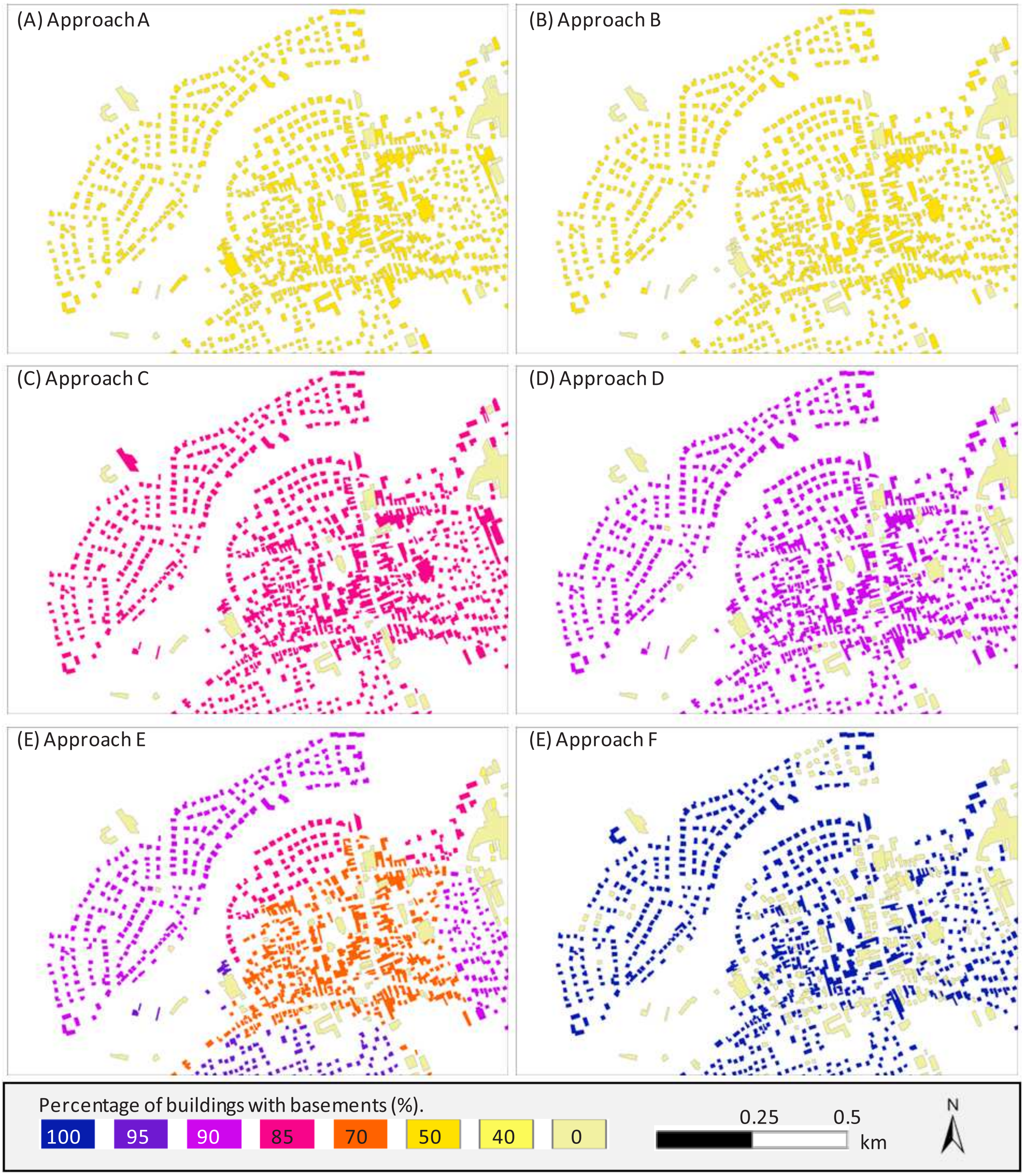


Figure 7.6. Part of buildings with/without basement according to the different assessment approaches.

Error estimates were performed for the different characteristics of buildings and their vulnerability according to the different approaches used (Table 7.2). On the one hand, these estimations were based on the variability of answers and the uncertainty bounds given by the state experts interviewed (for the characteristics revealed by those interviews). The measured variables during the field surveys were accompanied by uncertainty bounds linked to measurement potential errors.

Table 7.2. Error estimation using different approaches.

	Approach A	**Approach B**	**Approach C**	**Approach D**	**Approach E**	**Approach F**
Occupation type (OT)	no error estimation	no error estimation	no error estimation	no error estimation	no error estimation	no error estimation
Basement (BMT)	20-90%	20-90%	70-100%	-+10%	-+5%	no error expected
Ground floor height (GFH)	0-100 cm	0-100 cm	50-100 cm	-+ 20cm	-+15cm	-+10cm
Relative surface (RS)	0-10%	0-10%	5-10%	-+5%	-+5%	-+5%

2.5. Damage estimations

The different vulnerability assessment approaches analysed here were considered in order to produce flood damage estimates to buildings in the town of Holtzheim. We achieved damage estimations for flood events of different probabilities of occurrence (5, 10, 20, 30, 50, 100, 200 and 500-yr return-period floods). The F.R.A.GIS method developed in this thesis (*cf.* Chapter 3 for more details) was used to combine these different datasets and achieve damage estimations. The part of damage to non-residential buildings represented 10%, in average, of the total buildings-related damage, which is coherent with real damage feedback.

3. Results

The risk curves produced based on the six vulnerability approaches (approaches A, B, C, D, E and F) are displayed in the following graph together with the uncertainty boundaries calculating throughout the errors estimations (Figure 7.7). We notice that the damage estimates for the different flood return-periods were proportionally increased or reduced depending on the approach used. Indeed, the global shape of the flood risk curves was not affected by the vulnerability assessment considerations. However, the damage estimations were differently affected by the vulnerability assumptions, according to the flood intensity (or frequency). Damage estimations for flood return-periods shorter than 30 years ranged from 63% in average, considering the global uncertainty generated by the selection of methods and the hypothesis behind them. This range was more important for flood events with return-period equal or longer than 30 years; it is equal to 98% in average and reached 146% for

50-yr return-period floods. The propagation of these uncertainties on Expected Annual Damage (EAD) estimations is presented in Figure 7.8.

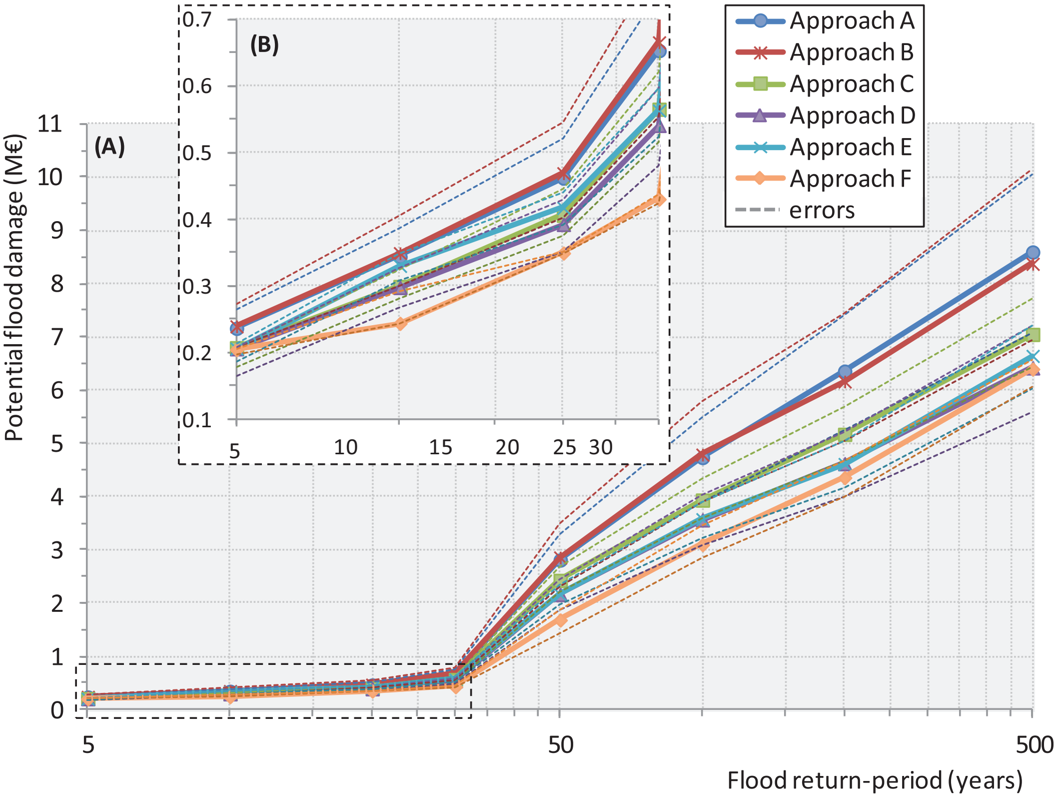


Figure 7.7. Variability of flood risk estimations and uncertainty boundaries as a function of the different approaches used to assess buildings and contents vulnerability to floods.

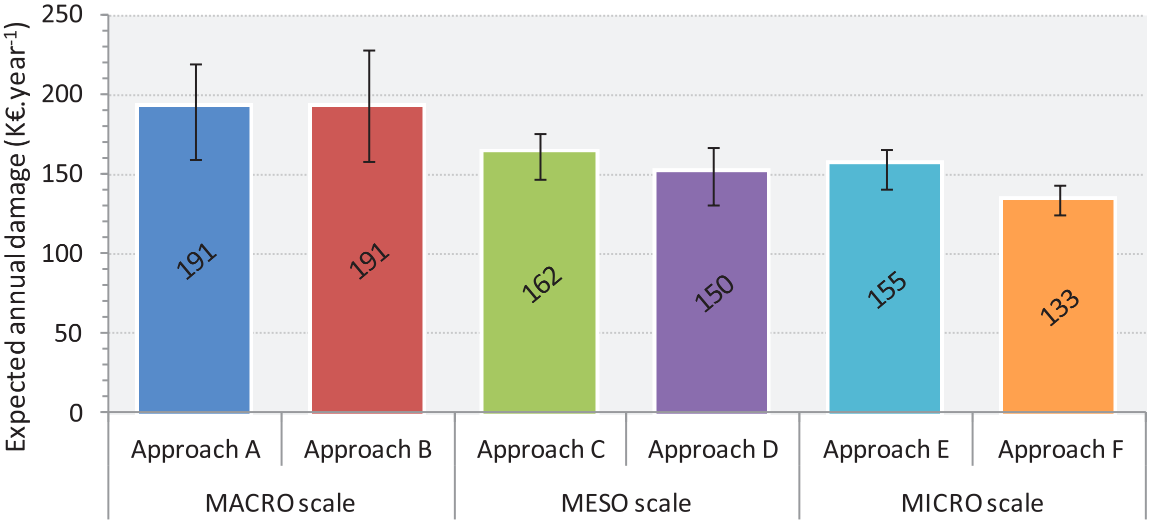


Figure 7.8. Expected annual damage estimations and uncertainty boundaries as a function of the different approaches used to assess buildings and contents vulnerability to floods.

These results show that the MACRO scale methods induced to large overestimations of damage estimates in relation to more precise scales of analysis (MESO and MICRO scales). The great level of uncertainties related to the “macro” scale is mainly linked to the accumulation of uncertainties linked to the height of ground floors and the existence/absence of basements (expert opinion). The important difference between the estimations performed with the Approach E and F were induced by the overestimation (of Approach E over Approach F) of the rate of buildings with basements in the area concerned by frequent floods. The results of the evaluation are quite similar for MESO and MICRO scales. Their uncertainty bounds are also quite similar and mainly influenced by the uncertainty linked to the property floor height. However, we noticed that all the approaches overestimate the amount of damage in relation to the more detailed approach (Approach F), revealing that the constructions of the case-study were designed in accordance with the local flood risk, which could not be revealed by larger scale assessments.

A particularity of these results is the similarity of EAD estimates based on the Approaches C, D and E. It is also interesting to notice that the Approach D leads to estimations closer to Approach F than the other micro Approach E. This is explained by the fact that the Approach E overestimates damage for frequent floods in relation to Approaches D and F (Figure 7.7 B). Even though Approach E estimations for less frequent floods are closer to Approach F (Figure 7.7 A) the EAD estimate differs. High frequency events have a stronger impact on EAD index. Depending on the extent of the flooding area and the number of buildings affected by floods with different return period, we suggest that field surveys focus to assess vulnerability of buildings at least in areas affected by frequent floods (return periods shorter than 30 years). This could significantly reduce global uncertainties in the results of EAD. We suggest that exhaustive field surveys should be used to assess vulnerability of buildings at least in areas affected by frequent floods (RP<30years). This could significantly reduce global uncertainties in the results of EAD without highly increasing the estimation technical requirements.

4. Results discussion and recommendations

Ideally, the Approach F based on detailed information of buildings and contents should be the best option for obtaining accurate damage estimations and support flood management actions. However, this approach requires great efforts of evaluation that may be incompatible with the reality of some flood management programs. On the basis of the results obtained, we propose guidelines for the selection of the appropriate approach to assess the vulnerability of residential buildings to floods for damage estimation purposes, according to the objectives of the damage estimation and the difficultness of the approach.

4.1. Prioritization of areas for investments

If the purpose of the damage estimation is to identify the main areas for flood management actions (prioritization of areas for investments), the selection of the approach should consider the scale of the management program. For national flood management programs, the realisation of field surveys is not feasible (Approaches D, E and F). Between the other approaches, only the Approaches A and B are based on datasets potentially available in national scale levels. Their use may induce to the overestimation of damage potential. This is mainly due to the selection of uniform values underestimating the building ground floor elevation (Figure 7.4). When considering large areas for analysis, this consideration disregards the adaptation of buildings in areas recurrently affected by floods. Therefore, there is a tendency to overestimate EAD estimations. For regional or River basin management programs, the use of local datasets and real estate experts may induce results that are more accurate. We recommend the use of the Approach C with this purpose and eventually the Approach D (for smaller areas). However, uncertainty relative to datasets and expert opinions produced by different institutions may lead to the under/overestimation of damage for specific areas, which can compromise the effectiveness of the assessment comparative objective. The approach D should avoid this disadvantage in relation to the elevation of ground floors and presence/absence of basements, which are important damage-influencing factor.

4.2. Selection of flood risk alleviation measures

The selection of appropriate risk alleviation measures should be based on the spatial aspect of the flood risk once both, hazard and vulnerability alleviation are intrinsically correlated to this aspect. Only the approaches D, E and F (based on field surveys) give accurate appreciations of the spatial distribution of damage. If the objective of the damage estimation is to identify areas for application of vulnerability reduction measures, it is essential to deeply understand the vulnerability of assets for the different areas at risk. Indeed, we recommend the use of the more accurate approach (Approach F). However, if the number of buildings analysed is important, the low feasibility of this method could lead to the impossibility to use it. In this case, the methods D or E should be used, depending on the assessment area. If the estimation aims at revealing benefits of flood hazard alleviation projects, the Approaches D and F should bring enough details. For large-scale alleviation measures, *e.g.* inter-municipalities, the approach C and D could represent the best compromises in terms of feasibility and accuracy of estimations. Especial attention must be accorded to expert opinion in this case.

4.3. Estimation of global costs of damage for budget organization

If the estimation of damage aims at determining global costs of damage for specific flood events, the macro approaches could provide good results once the compensation of uncertainties from one site to another could alleviate the impact of this uncertainty on the global value evaluates. These approaches could also be used in lower scale analyses, with the objective of giving drivers for further detailed analyses. In local analyses, these approaches could be used with a substantial help of local state experts.

5. Chapter conclusions

The first step toward flood risk management is the understanding of all aspects of the risk. An important aspect of the risk is the economic loss potential. Flood damage evaluation is nowadays an indispensable tool to help in management project decisions. In addition, this analysis brings necessary knowledge to help in crisis management forecast. However, the results of the evaluation are charged with uncertainty. These uncertainties take origin in different sources, *e.g.* the data assessment method, the data intrinsic uncertainty and the evaluation process hypothesis. Identifying and quantifying these uncertainties are important steps to increase reliability on damage evaluations. Associating uncertainty into the results of the damage evaluation is an indispensable measure to avoid misuse of these results.

The presented case study of the Bruche River, Bas-Rhin, France, exemplifies the sensitivity of damage evaluations to the vulnerability data assessment method used. In addition, the uncertainty propagation method used clarifies the importance to present results of damage evaluations accompanied by uncertainties limits. This work allowed measuring the sensitivity of damage estimations to different approaches used to assess the vulnerability of buildings to floods. It highlights the role of the scale of the evaluation and the data availability on the accuracy of estimates. As mentioned by (Green et al., 2011), “all data is more or less inaccurate, coarse or imprecise; any attempt to improve any of the characteristics costs money and takes time so a key question is whether it is worth doing so”. The results of the analyses realised in this work showed the weakness of different approaches and highlight some possibilities of improving them.

Uncertainty propagation methods and sensitivity tests are both analyses that can be used to identify and measure uncertainty on the evaluation. These analyses should always be used to complement damage evaluations results. Their application and principles, explained in this paper, enable the analyst to judge the pertinence of the evaluation. In addition, these analysis results enable to identify fragile elements in the evaluation, guiding the analyst in the decision in where to improve efforts in the evaluation. The results of loss evaluations accompanied by uncertainties bring to the decision-maker a supplementary decision tool. Further research should focus on the assessment the vulnerability of non-residential buildings to floods.

Chapter 8.

Asset value estimations and susceptibility models

The aim of this chapter is to analyse the influence of damage models uncertainty on the results of potential flood damage estimations. The variability of damage evaluation results induced by the selection of damage functions and the approach used to assess asset values are the core of this work. We applied two different sets of national damage functions to residential properties in order to measure the variability of results according to this choice. We also tested different strategies to estimate asset values, considering different scales of analysis. Both aspects of the evaluation directly affect the estimates. On the one hand, these tests revealed that the shape of flood risk curves is not affected by uncertainty on the damage-models. Uncertainty propagates in the same way independent of the flood return-period, which may lead to under/overestimation of the flood risk. On the other hand, we notice that the influence of the selection of damage functions or asset values estimations is site-dependent. Nonetheless, the selection of damage functions is determinant for the evaluation process. Data on former damage (damage declared in the city town in the context of the French National insurance tool CatNat) were analysed in order to validate the evaluation results. Despite CatNat data is charged with uncertainty, the results obtained were close to some estimation values. Uncertainty bounds are rarely determined for existing damage functions and their validation is not always possible because of lack of data. Therefore, we propose a theoretical approach in order to analyse these uncertainty sources on the final results of the evaluation.

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1. Introduction

The evaluation of flood damage relies on the combination of different models and methods used to assess and forecast flood hazards and the vulnerability of assets. Damaging potential is usually represented by damage functions that express damage for specific assets as a function of hazard parameters (Hubert and Ledoux, 1999; Messner et al., 2007; CEPRI, 2008; D4E, 2007; Merz et al., 2010b; Meyer and Messner, 2005). Damage models were also developed for apprehending damage potential linked to other natural hazards (Blong, 2003b, a). Two different strategies can be adopted in order to evaluate potential flood damage: damage functions can be developed based on local data, expert judgement and statistical analyses; or existing damage functions may be transposed to the study context in order to avoid the development of new damage models. It is largely recommended to construct damage functions in situ; however, it is rare that studies can afford the construction of such damage functions, because of time, lack of feedback and resources constraints. Generally, damage functions that express damage as a rate of asset values, *i.e.* relative damage functions, created in previous studies are used taking in consideration context differences (CEPRI, 2008; Merz et al., 2010b). Although the selection of damage functions and the assessment of the asset values are crucial for the estimation of damage little research was made to determine uncertainty linked to these aspects of the evaluation (Merz et al., 2010b; D4E, 2007).

The aim of this chapter is to analyse the variability of damage evaluation results induced by the selection of damage functions and the method used to assess asset values when applying these models. In the first part of this work, we present a brief state of the art of damage functions explaining how they are developed and applied to estimate potential flood damage. In section 2, we compare the results of damage potential estimations to buildings and contents for different damage functions and approaches used to calibrate them, *i.e.* asset value estimations. Former damage are analysed in order to analyse the impact of different approaches on the calibration of damage functions. Finally, we propose, in section 3, a theoretical analysis of uncertainty in order to consider damage functions uncertainties on damage estimations. We discuss in this section how this uncertainty is propagated to the results of the valuation.

1.1. Susceptibility analyses

A well established method to evaluate flood damage consists of describing the susceptibility of assets to suffer damage by damage functions, expressing damage potential in monetary terms as a function of flood parameters and the vulnerability of assets (Merz et al., 2010b). These are called damage functions, firstly introduced in the United States of America at the beginning of the 50s (White, 1964, 1945). They become the base for deterministic evaluations of potential flood damage and therefore the core of the evaluation process (Smith, 1994). Different approaches can be used to build damage functions (Messner et al., 2007; Smith, 1994). In short, we can build damage functions based on real flood damage data collected after flood events, *i.e.* empirical approach, and/or based on expert judgement in which damage data are estimated via what-if-questions, *i.e.* synthetic approach (Merz et al., 2010b; D4E, 2007). In any case, data has to be processed, and damage must be associated with hazard and vulnerability characteristics, through statistical analyses (Thieken et al., 2005). This analysis considers on the one hand, the vulnerability characteristics of assets, *i.e.* resistance parameter, that determine the characteristics of assets increasing or reducing potential flood damage. On the other hand, this analysis considers the flood hazard characteristics, *i.e.* impact parameter, that determines how the assets are vulnerable to floodwater. Water depth is the main hazard parameter that influences damage and it is the more commonly used hydraulic parameter used in the construction of damage functions (White, 1964; Messner and Meyer, 2006; Kreibich and Thieken, 2008). Other flood parameters can also play an important role on flood damage evaluations and are considered by some authors in order to enhance the estimation (Kreibich and Thieken, 2008).

Another difference between damage functions is linked to how they relate losses to damage-influencing factors. We can distinguish two types of damage functions (Messner et al., 2007; Merz et al., 2010b). The first one estimates damage potential as a relative function of the asset value, *i.e.* relative damage functions. This type of approach calculates damage for a specific element at risk as a function of hazard and vulnerability characteristics, as a percentage of the property value. The second type of damage function directly estimates damage without considering this aspect, *i.e.* absolute damage functions. These damage functions enable a direct estimation of damage amount for each property or unit of property without estimating the value of the property evaluated.

1.2. Damage models

Many studies all over the world established different relationships between flood parameters, assets characteristics and damage potential. The works of Merz et al. (2010b) and Bubeck and Kreibich (2011) summarize damage functions constructed all over the world. The works of D4E (2007), CEPRI (2008), Hubert and Ledoux (1999) summarize damage functions used in the French context. Buildings and contents are the most common typology of damage for which damage functions were developed, *e.g.* residential buildings (Schwarz and Maiwald, 2008; Thieken et al., 2008a; Nascimento et al., 2007; Torterotot, 1993; Kang et al., 2005; Davis and Leigh Skaggs, 1992) and commercial and industrial buildings (DREAL Rhône-Alpes, 2010; Su et al., 2009; Kreibich et al., 2010; Seifert et al., 2010). Several other models and damage assessment tools were developed and applied for flood risk assessments[60] (Klaus et al., 1994; Dutta et al., 2003; CRES, 1992). Some examples of damage models are described in the (Table 8.1).

1.3. Using existing damage functions

Each territory has its own characteristics in terms of land-uses, construction characteristics, defence systems and values, leading to the spatiotemporal dependency of damage functions to the context it has been developed. When using existing damage functions, the types of damage function used for different buildings must be in adequacy with the local characteristics of the site analysed. Furthermore, these damage functions must be updated and eventually transposed to fit the new study area. On the one hand, relative damage functions are better transferable in time and space since they are independent of the changes in market values of individual structures. However, they involve the estimation of the properties values, which might bring additional uncertainty into the evaluation (Merz et al., 2010b). On the other hand, absolute damage functions are easier to apply but they demand re-calibration for accounting context and temporal differences, also introducing uncertainties into the evaluation (D4E, 2007; Messner et al., 2007). The re-calibration of absolute damage functions are made by means of different indices, *e.g.* purchasing power, exchange rates, property prices, etc.

These different types of damage functions may be available for damage estimation studies. Generally, relative damage functions are more adequate for use in other contexts. These damage functions are the more commonly used in practice (Meyer and Messner, 2005; CEPRI, 2008; Hubert and Ledoux, 1999). When using relative damage functions, the values of assets must be estimated to calculate damage potential for the different types of assets analysed. Exposure analyses are generally used to delimitate the extent of the area in which the asset values will be estimated (Merz et al., 2010b). Different datasets can be used to realise exposure analyses and evaluate the value of assets. Messner et al. (2007) give an overview of typical and exemplary approaches used with this purpose.

1.4. Uncertainties

Three levels of uncertainty in potential flood damage evaluations can be correlated to damage functions. A first level of uncertainty is intrinsically linked to the construction of damage functions. On the one hand, empirical damage functions will never be enough exhaustive in order to represent damage potential for the different characteristics of hazards and types of assets in a territory, *e.g.* uncertainties are linked to the correlation between damage and flood parameters (Middelmann-Fernandes, 2010; Messner and Meyer, 2006) and to the efficiency of flood warnings (Penning-Rowsell and Green, 2000b; Penning-Rowsell et al., 2000; Torterotot, 1993).

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[60] List of models used to simulate floods: http://www.economics.nrcs.usda.gov/technical/models/flood

Table 8.1. Example of existing damage models. Source: Bubeck and Kreibich (2011).

	Country	Relative/ absolute approach	Empirical/ synthetic data	Economic sectors covered	Loss determining parameters	Validation	Data needs
Model of Multicoloured Manual (Penning-Rowsell et al., 2005)	UK	absolute	synthetic	Residential, and commercial properties, leisure and sport facilities, public buildings, infrastructure	water depth, flood duration, building/object type, building age, social class of the occupants, warning time	Yes (Penning-Rowsell and Green, 2000b)	Values of exposed assets, socioeconomic information, hazard characteristics
FLEMO models of GFZ (Büchele et al., 2006; Thieken et al., 2008b; Kreibich et al., 2010; Seifert et al., 2010; Elmer et al., 2010)	DE	relative	empirical	residential buildings, public and private services, producing industry, corporate services, trade	water depth, contamination, building type, quality of building, precaution, business sector, number of employees	Yes (at micro and meso-scale) (Elmer et al., 2010; Seifert et al., 2010; Thieken et al., 2008b)	values of exposed assets, residential building and company characteristic, hazard characteristics
Model of ICPR (ICPR, 2001)	DE	relative	empirical - synthetic	Residential, commercial, forestry, agriculture infrastructure	water depth, economic sector	n.a.	land use data, values of exposed assets, water depth
Anuflood (DNRM , 2002)	AU	absolute	empirical	Residential and commercial properties, infrastructure	water depth, object size, economic sector, object susceptibility	n.a.	Property characteristics, water depth
RAM (NRE, 2000)	AU	absolute	empirical - synthetic	Buildings, agricultural areas, infrastructure	object size, object value, lead time, flood experience	n.a.	Object charact., land use, warning times, flood experiences, season
Model of MURL (MURL, 2000)	DE	relative	empirical	Residential and commercial properties, infrastructure, agriculture forestry	water depth, economic sector	n.a.	land use data, values of exposed assets, water depth
Model of Hydrotec (Emschergenossenschaft and Hydrotec, 2004)	DE	relative	empirical	Residential buildings, commerce, vehicles, agriculture, forestry, infrastructure	water depth, business sector	n.a.	land use data, values of exposed assets, water depth
HAZUS-MH (Scawthorn et al., 2006b; FEMA, 2011)	US	relative	empirical - synthetic	Residential buildings, commerce, infrastructure, agriculture, vehicles	water depth, flow velocity, wave action object type, riverine or coastal flooding	n.a.	object type, land use data, hazard characteristics
MEDIS Model (Förster et al., 2008; Tapia-Silva et al., 2011)	DE	relative	empirical - synthetic	Agriculture (*e.g.* wheat, rye, barley, corn, oilseed plants, root crops, sugar beets and grass)	Flood duration, crop types, season,	Yes at meso-scale (Förster et al., 2008)	market prices of agricultural goods, planted crop types, flood characteristics
HIS-SSM (Kok et al., 2005)	NL	relative	synthetic	Residential and commercial properties, agriculture Infrastructure Nature Recreation Vehicles	Flood depth Flow velocity Economic sector	n.a.	values of exposed assets, socioeconomic data, land use, hazard charact.
Model of Schwarz and Maiwald (Maiwald and Schwarz, 2010)	DE	relative	empirical	Residential properties	Water depth, flow velocity structural characteristics,	Yes (Maiwald and Schwarz, 2010)	Information on building structure, land use data, hazard characteristics

Furthermore, these damage functions are generally based on poor quality data because of the lack of detailed damage surveys after flood events. On the other hand, synthetic damage functions are subjective, resulting in uncertain damage estimates (Merz et al., 2010b). Furthermore, mitigation actions are not taken into account in these analyses (Smith, 1994). The quantification of overall uncertainty linked to damage functions is extremely difficult because damage functions are rarely accompanied with uncertainty bounds or error estimates (NRC, 2000).

A second level of uncertainty is linked to the selection of the appropriate set of damage functions for a specific context of analysis. As highlighted by Green et al. (2011) and D4E (2007), the variability of damage function rates between countries deserves special attention. Few studies compared different damage models in a same case study (Apel et al., 2008a; Seifert et al., 2010; Merz and Thieken, 2009). By these analyses, we can conclude that the role of this selection is significant to the evaluation process.

Finally, a third level of uncertainty is related to the hypothesis made when using existing damage functions during evaluation processes. The re-calibration of absolute damage functions and the estimation of asset values when using relative damage functions are both sources of uncertainty not well explored in literature. The great majority of practical evaluations are to be based on existing damage functions, which highlights the interest to better understand this uncertainty. The estimation of asset values depends on the type of the elements at risk, varying in time and space. In a methodological guide was developed with this purpose (Cannon et al., 1995). Rare are the studies that explicitly explain approaches for the estimation of assets (Merz et al., 2010b). Some recent studies started to give attention to this kind of uncertainty, *e.g.* commercial and industrial values (Seifert et al., 2009), regionalisation of asset values for risk analyses (Thieken et al., 2006), disaggregation of asset values (Wünsch et al., 2009).

1.5. Validation of damage functions

The good estimation of real damage is essential for understanding flood damage processes (NRC, 1999). Even though databases concerning real damage in large scales are nowadays available, *e.g.* the Emergency Events Database EM-DAT[61] of the Centre of Research on Epidemiology of Disasters (CRED) in Brussels, it is not always possible to validate damage functions. The validation of damage functions is complex because the data detail needed for this is generally not available. Rare are the studies that can count on exhaustive real damage datasets for validating damage potential estimates

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[61] EM-DAT, The international Disaster Database WEB site: http://www.emdat.be

(Merz et al., 2004). In France, the "CatNat" procedure[62] leads to an appreciation of damage to insured structures just after flood events and may be used for validation purposes. Even though disaster loss data is generally full of uncertainties, it is relevant to compare estimates with real feedback in order to validate damage potential estimates (Downton and Pielke, 2005).

2. Influence of methods on damage potential estimates

The variability of residential buildings damage evaluation results induced by the selection of damage functions and the approach used to assess asset values are the core of this work. These aspects are explored in the following paragraphs of this work. The towns of Fislis and Holtzheim, in the French side of the Rhine basin, are explored with this purpose (*cf.* Chapter 4 for more details). The great majority of assets exposed to floods in both towns concerns residential buildings, typology of damage explored in this work.

2.1. Selection of damage functions

2.1.1. Residential buildings

Two sets of residential buildings damage functions were used in this work (Ledoux Consultants, 2010). Both sets of damage functions distinguish buildings with basement from buildings without basements. They are both relative damage functions correlating damage to the value of the asset and the level of floodwater reaching it (Figure 8.1). Those are the damage functions more frequently used in the national context (D4E, 2007; CEPRI, 2008).

The first set of damage functions used « Model 1 » was developed by Torterotot (1993). These damage functions are based on former damage on residential dwellings. More than 300 individual dwellings were interviewed in 1988 in different towns in France: Saintes (Charente), Béziers (Orb), Sérignan (Orb), Mâcon (Saône), Lagny sur Marne (Marne), Esbly and Conde Sainte Libiaire (Grand Morin), Poitiers (Clain), Châtellerault (Vienne). (Torterotot, 1993) developed a set of damage functions considering different criteria: construction characteristics (presence/absence of basement), public reaction aspects (presence/absence of alert dispositive and possibility to displace building contents before the flood event), hazard characteristics (speed of water rising during flood events). The "Model 1" damage functions displayed in (Figure 8.1) are average values distinguishing only

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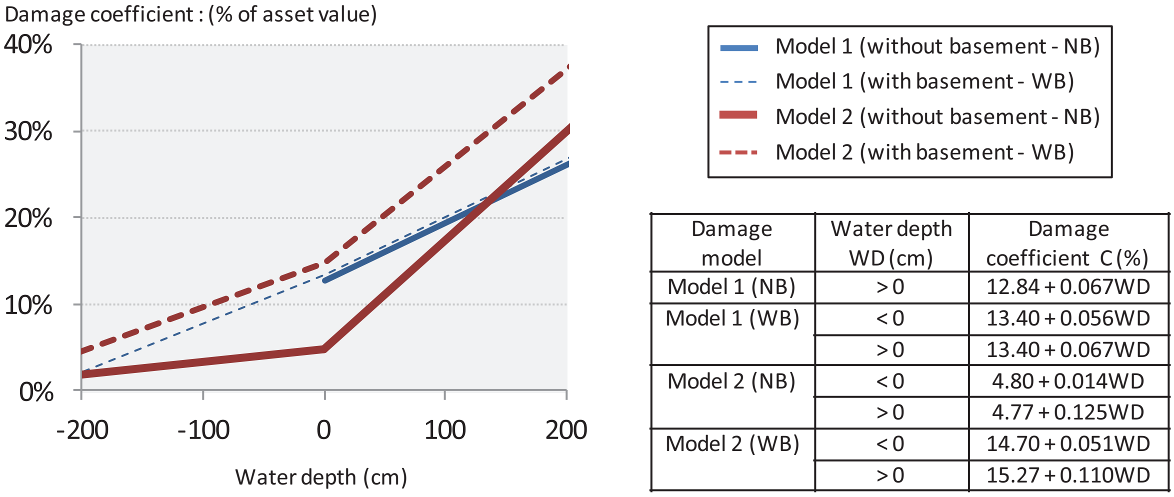
[62] "CatNat" is the French national procedure that allows damaged individuals or institutions to be insured against important flood events. This procedure requires that the towns concerned by floods realize the inventory of damages though the declaration of damages. CatNat dossiers are prepared with this purpose.

buildings with basement from buildings without basement. Low-speed flood event (water rising velocity slower than 10cm/h) damage functions were considered in this study. The second set of damage functions "Model 2" was developed on the basis of damage incurred in some towns in Ile-de-France (Seine) by the end of the 80s (D4E, 2007; Hubert and Ledoux, 1999). It was also used to develop the standard tool to perform cost-benefit analyses in the context of the "Plan Rhône" in 2010 (Ledoux Consultants, 2010). These damage functions also distinguish buildings with basement from buildings without basement (Model 2 in Figure 8.1).



Damage model	Water depth WD (cm)	Damage coefficient C (%)
Model 1 (NB)	> 0	12.84 + 0.067WD
Model 1 (WB)	< 0	13.40 + 0.056WD
	> 0	13.40 + 0.067WD
Model 2 (NB)	< 0	4.80 + 0.014WD
	> 0	4.77 + 0.125WD
Model 2 (WB)	< 0	14.70 + 0.051WD
	> 0	15.27 + 0.110WD

Figure 8.1. Damage-models used for residential buildings.

Both sets of damage functions are relative to the value of the asset exposed to floods ($€.m^{-2}$) and damage is proportional to the floodwater depth value inside the building. The estimation of potential damage to a building is made through the Equation (8.1). The estimation of the asset values is explained further on this work (section 2.2.1).

$$Di = Si * Vi * C\ f(i\ vulnerability,\ i\ hazard) \tag{8.1}$$

where "i" is the analysed building, "D" is the amount of damage potential (€), "S" is the building footprint (m^2), "V" is the value of the asset ($€.m^{-2}$), "C" is the damaging coefficient to use according to the building vulnerability criterion, *i.e.* presence/absence of basement, and the hazard parameter, *i.e.* water depth inside the building (Figure 8.1).

2.1.2. Commercial and public buildings

Once this work does not investigate the uncertainty linked to the evaluation of commercial and public damage, only one set of existing absolute damage functions was used here to estimate damage potential for commercial buildings (Smith, 1994). The set of damage functions was based on former flood events damage in the Australian context, during the ANUFLOOD program (CRES, 1992). They were also used in the Queensland guideline for flood damage evaluations (DNRM, 2002). Several types of buildings are considered in order to establish the different damage functions. Five vulnerability classes were adopted for distinguishing those buildings according to the type of commercial and public activities they are used for (Figure 8.2).

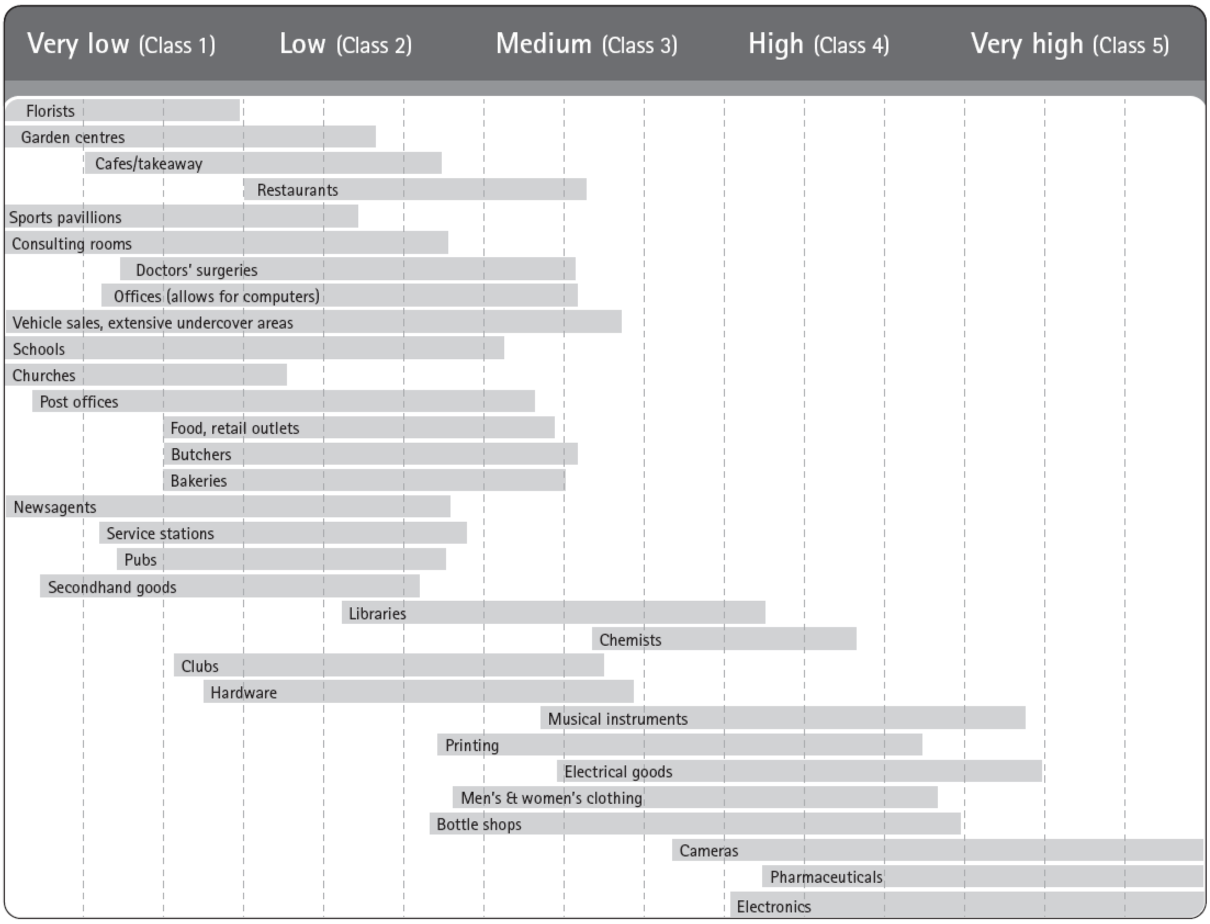


Figure 8.2. Classes of vulnerability according to building types of activity. Source: DNRM (2002).

The total of 15 damage functions were created as a function of the class of vulnerability of the buildings, the building footprint (land projected surface of building) and the flood water depth inside the building (Table 8.2). These values were transposed to the French context using three index values: the ratio between the Australian dollar value and the Euro value, the ratio between living costs in

France and Australia, and the ratio between the construction cost index ICC in 1992 (date of dollar values update) and 2010 (Erdlenbruch et al., 2008; Erdlenbruch et al., 2007).

Table 8.2. Damage functions used to calculate damage potential to commercial and public buildings Source: DNRM (2002).

	Small properties (< 186m²)	**Medium properties (> 186 et < 650m²)**	**Large properties (> 650m²)**
Class	Damage (€)	Damage (€)	Damage ($€.m^{-2}$)
1	$96{,}7.WD - 0{,}226.WD^2$	$298{,}9.WD - 0{,}693.WD^2$	$0{,}3784.WD + 0{,}002317.WD^2$
2	$193{,}5.WD - 0{,}453.WD^2$	$597{,}7.WD - 1{,}386.WD^2$	$0{,}7621.WD + 0{,}004604.WD^2$
3	$386{,}9.WD - 0{,}905.WD^2$	$1195{,}5.WD - 2{,}771.WD^2$	$1{,}532.WD + 0{,}009177.WD^2$
4	$773{,}9.WD - 1{,}810.WD^2$	$2391{,}3.WD - 5{,}544.WD^2$	$3{,}020.WD + 0{,}01857.WD^2$
5	$1547{,}8.WD - 3{,}620.WD^2$	$4782{,}0.WD - 11{,}085.WD^2$	$6{,}058.WD + 0{,}03707.WD^2$

*WD = water depth inside the building (cm)

Differently from the damage functions used to estimate damage potential to residential buildings, the application of these absolute damage functions does not require the calculation of asset values. The calculation of damage potential “D” (€) for a commercial or public building “i” is directly obtained by applying the damage function “DF” according to the building “i” vulnerability class (Figure 8.2), the building “i” footprint (m^2) (small, medium or large properties, *cf.* Figure 8.3), and the water depth “WD” inside the building, *cf.* Equation (8.2).

$$Di = DF\ f(i\ vulnerability, WD) \tag{8.2}$$

2.1.3. Application of damage functions

The evaluation of potential flood damage was based, on the one hand, on the characterization of buildings in both case studies through detailed field surveys used to identify the types of occupation of buildings, their relative surfaces, the presence/absence of basements and the ground floor high (*cf.* Chapter 7 for further details). The building surfaces were calculated with the national GIS database BD TOPO®, and the asset values were obtained through interviews with local experts (795 $€.m^{-2}$ in Holtzheim and 556 $€.m^{-2}$ in Fislis). More details on these estimations are presented further in this work (section 2.2). On the other hand, damage potential was evaluated for 8 flood hazard maps of each case study, corresponding to different flood event return-periods (5, 10, 20, 30, 50, 100, 200 and 500-yr return-periods) (*cf.* Chapter 6 for further details). These flood maps were produced with Mike Flood® software, representing the spatial distribution of maximal water depths reached in the study areas for each flood scenario (with a resolution of 10 meters for Holtzheim and 4 meters for Fislis case study). Total damage for the different flood events in both case studies are presented in the following graphs (Figure 8.3).

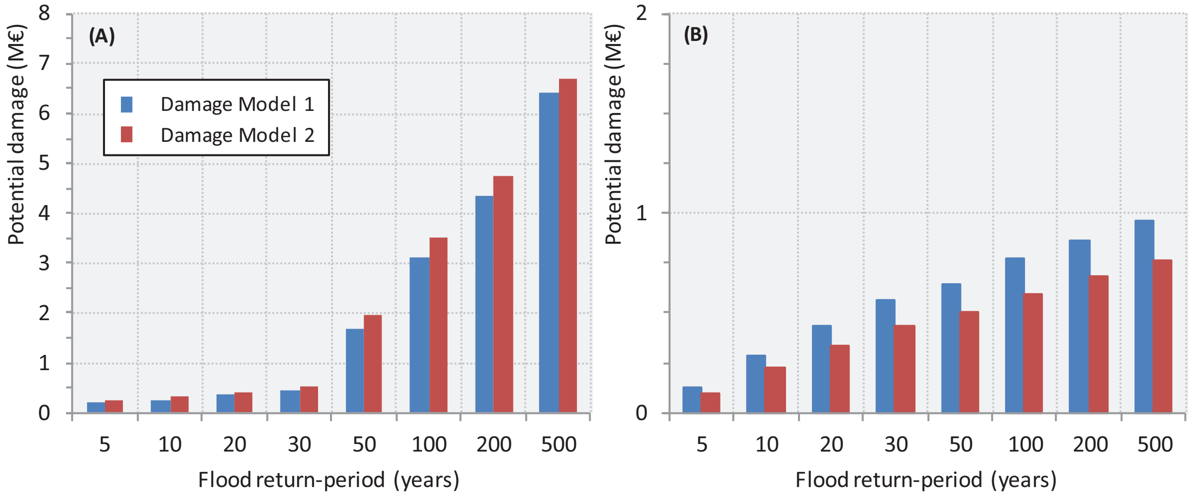


Figure 8.3. Difference between estimations using different damage functions (damage per flood return period).

These results highlight that the impact of the selection of damage functions is different from one case study to the other. The ratio between the deviation from the estimates using the different damage models and the average value is equal to 3.5% for Holtzheim case study and 6.2% for Fislis Case study, in average considering the different return-periods. The impact of the selection of damage functions revealed to be much more important to Fislis case study than to Holtzheim case study. Furthermore, we notice that "Model 1" estimates are lower than "Model 2" estimates in Holtzheim, in contrast with Fislis. Expected annual damage (EAD) was calculated, *cf.* Equation (8.3), for both case studies using the different values displayed in (Figure 8.3).

$$A_{EAD} = \int_0^1 A_{DP}(i) \times i.di \tag{8.3}$$

where A_{EAD} is the asset expected annual damage (or average annual cost) caused by floods; and $A_{DP}(i)$ is the asset damage potential related to a specific flood annual exceedance probability (i).

When using the “Model 1” to evaluate flood events damage potential in Holtzheim case study, EAD value was 14.2% lower than EAD calculated using “Model 2”. At the opposite, the EAD value calculated in Fislis with the “Model 1” was 28.6% higher than EAD value calculated using “Model 2”. These differences are explained by two site-dependent characteristics: (1) great majority of buildings in Holtzheim have basements (the Model 2 gives a higher value of damage for this type of buildings, *cf.* Figure 8.1) and the majority of buildings in Fislis do not (the Model 1 gives a higher value of damage for this type of buildings, *cf.* Figure 8.1); and (2) there is a bigger compensation of errors in Holtzheim induced by the larger number of buildings concerned by floods. The part of commercial and public buildings damage is minor in both case studies. In Holtzheim, 8.5% of EAD are due to commercial and public buildings. This value represents 7.1% of EAD in the case of Fislis.

2.2. Calibration of damage functions

Both sets of residential damage functions used in this work are relative to the value of the assets at risk (*cf.* section 2.1.1). Torterotot (1993) and Ledoux Consultants (2010) defined that this value is relative to the surface of the buildings concerned by floods, equivalent to the buildings land projection, *i.e.* footprint. The estimation of asset values comprises two characteristics of the assets, *cf.* Equation (8.1): buildings value (€.m^{-2}) and buildings footprint (m^2). On the one hand, the value of the assets to take into account for these estimations are independent of market prices variations, *i.e.* the value of the property exclusively represents the value of the construction and the goods in it (Torterotot, 1993; Ledoux Consultants, 2010). This hypothesis leads to a great deal of uncertainty linked to the difficulty to appreciate the “real” value of assets. On the other hand, the estimation of the properties “footprint” is another source of uncertainties directly influencing the estimation of the values of properties at risk.

2.2.1. Asset value assessment

The estimation of asset values is generally made on the basis of interviews, field surveys and expert judgement (Hubert and Ledoux, 1999). In order to measure the impact of the approach used to assess the value of assets at risk, we used different approaches to determine the value of buildings. These approaches were different in relation to the scale of analysis considered. Four scales of analysis were considered that we call here “approaches 1, 2, 3 and 4”. In “approach 1”, large scale areas (French “Régions”) average data was considered for the analysis of both case studies. In “approach 2”, medium scale areas (French “Départements”) average data was considered for the analysis of the case studies. In “approach 3”, smaller French statistical areas (groups of towns) average data was considered for the analysis of the case studies. Finally, in “approach 4” we considered estimations at the town scale for the analysis of the different case studies.

Data issue of the Franch civil-law notaries statistic analysis[63] was collected for three larger scales of analysis. These values were confronted to expert judgement through interviews. Four semi-structured interviews were realised with real estate local experts: two estate agents, a civil law notary and a real estate developer were interviewed in order to determine the average values of buildings (€.m^{-2}) of the different regions/scales analyzed, including the specific towns values. These estimations are presented in Table 8.3. The present values do not consider transaction commissions, taxes, and attempted to represent the real value of properties without considering market influences.

Table 8.3. Asset value estimations

Case study	**Holtzheim**				**Fislis**			
Approach	1	2	3	4	1	2	3	4
Scale of analysis	Alsace	Bas-Rhin	Strasbourg	Town	Alsace	Haut-Rhin	Altkirch	Town
Property surface (m^2)	121	136	105	130	121	125	120	120
Property value (€)	225000	233800	296700	310000	225000	195000	202000	200000
Property floor levels	3	3	3	3	3	3	3	3
Property value (€.m^{-2})	620	573	942	795	620	520	561	556

The different approaches used to determine the value of assets revealed large uncertainty of this estimation. The maximal estimate is 64% higher then the minimum estimates for the Holtzheim case study. The uncertainty range corresponds to a deviation of ± 25% in relation to the average value. For the town of Fislis, this difference was less important. Nevertheless, the maximal estimate is 19% higher then the minimum estimates corresponding to the deviation of ± 9% in relation to the average estimate. The interviews revealed the difficulty to establish average values once several variables are relevant to the determination of the value of properties. The experts consulted during the interviews highlight that great uncertainty is linked to these estimations and the difference of the values is partially explained by these several characteristics of properties, *e.g.* the type of construction, building fabric material, finishing and fitting characteristics, building services and equipments, the age of the construction, the conservation of the buildings. They also highlighted the limits of this estimation, which may be influenced by market variations because of the difficultness to separate this variable from the others during the analysis of average values of properties.

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[63] WEB site disposing statistical data relative to real estate market prices: www.immoprix.com

2.2.2. Assets "footprint" and damage estimation

The "footprints" of the residential and commercial buildings were calculated through the national dataset BD TOPO® from the French National Institute of Geography (IGN)[64]. We calculated the surface of each building of the case studies in GIS software. In order to measure the uncertainty correlated to this calculation, 155 buildings of the town of Holtzheim were deeply analyzed. We compared their BD TOPO® surfaces with the surfaces calculated from contours of buildings defined over orthophotos[65] at the scale of 1:1,000 (Eleutério, 2008). This comparison revealed that the surfaces evaluated with the BD TOPO® were 5% bigger in average than those realized on the basis of orthophotos.

2.2.3. Variability of damage estimations

The value of assets and the estimation of the "footprint" of buildings directly affect the estimations of damage potential evaluations for the different flood return-periods analyzed in this work. Therefore, this uncertainty affects the risk curves presented in (Figure 8.3) in a uniform manner (equal percentage variability of the total amount of damage for each flood event), and does not affect the shape of these curves. Expected annual damage (EAD) is also impacted according to the impact of the flood risk curves. The following graphs display the impact of the asset values estimations on the EAD (Figure 8.4).

The different approaches used to estimate the values of assets make the results of the evaluation range from 95 to 157 k€.year^{-1} (Model 1) and 109 to 179 k€.year^{-1} (Model 2) for the town of Holtzheim; 67 to 80 k€.year^{-1} (Model 1) and 52 to 62 k€.year^{-1} (Model 2) for the town of Fislis. In Holtzheim, the estimation of damage is mainly impacted by the approaches used to estimate asset values. Buildings EAD were estimated at 131 k€.year^{-1} ± 23% in average values. In contrary, Fislis damage estimates were mainly influenced by the selection of damage functions. Fislis buildings EAD were estimated at 64 k€.year^{-1} ±15% in average values. All these estimations are affected in the same way the considerations relative to the estimation of the buildings "footprint". The under/overestimation of buildings surface of a certain percentage induces the under/overestimation of the same percentage for residential buildings.

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[64] French National Institute of Geography WEB site: www.ign.fr

[65] Aerial photographs geometrically corrected so that real distances can be measured throughout geographic information systems.

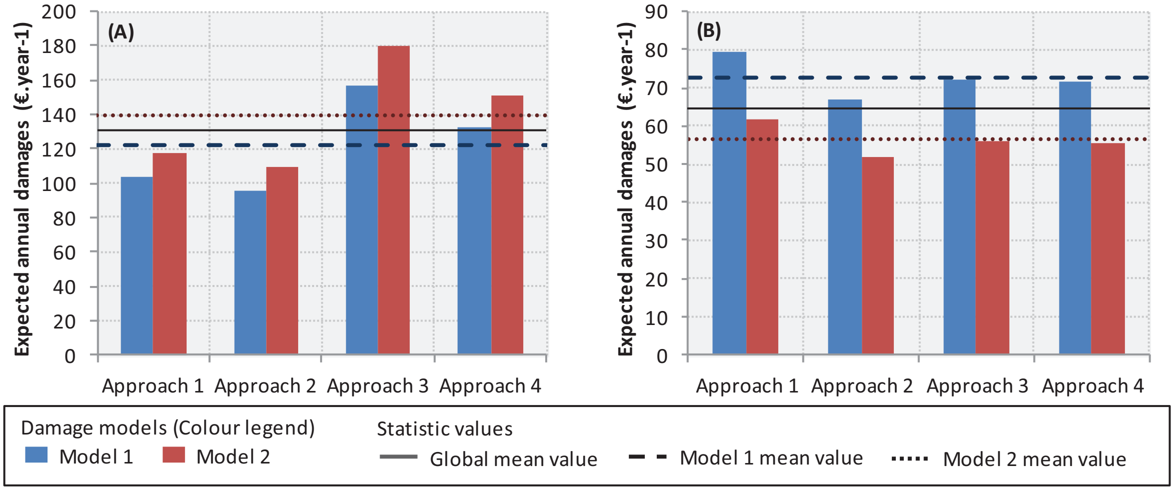

Figure 8.4. Expected annual damage estimations as a function of the damage models (sets of damage functions) and the different approaches used to assess asset values – The case of Holtzheim (A) and the case of Fislis (B).

2.3. Actual damage analysis

Real damage data was analysed in order to validate the damage functions used for residential buildings in this work. Former flood damage data was only exploitable for the case study of Holtzheim: the "CatNat dossier" produced at March 1990 after the February 1990 damaging flood event (~30-yr return-period flood event) was analyzed with this purpose. The document consulted in the city town has information relative to the repartition of the different types of damage incurred by the flood event (Table 8.4). The values presented were updated from Francs to Euros, taking into account the construction cost index (ICC) variation over time according to the French National Institute of Economics and Statistics (INSEE)[66]. Great majority of damage occurred to residential dwellings (73%) followed by commercial and public buildings (14%) and infrastructure (13%).

The consulted document also counts on the individual declarations of the costs related to the replacement of damaged goods. Great part of the cost descriptions were accompanied with sale quotes. Part of the declarations described the cost of damage and the characteristics of the flood event (generally the water level inside houses). These descriptions revealed that the great majority of damage to residential buildings occurred to basements inundated by floodwater.

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[66] Construction Cost index historical data available at the French National Institute of Economics and Statistics internet WEB site: http://www.insee.fr/fr/indicateurs/ind102/icc_m.pdf

Table 8.4. Repartition of the costs of damage declared in the “dossier CatNat” of the town of Holtzheim after the 1990 flood event.

Typology of damage	Number of buildings	Estimated damage (M€)	Percentage of damage
Residential dwellings	300	2,5	73 %
Commercial and industrial dwellings	9	0,2	7 %
Public dwellings	7	0,2	7 %
Infrastructure	7	0,4	13 %
Total	323	3,3	100 %

Through this data we attempted to correlate water depth inside buildings, buildings surface and flood damage (Figure 8.5). This correlation is only valid for buildings with a basement and for water depth values lower than the ground floor level, once the amount of data on other types of buildings and higher water levels were not sufficient for the analysis.

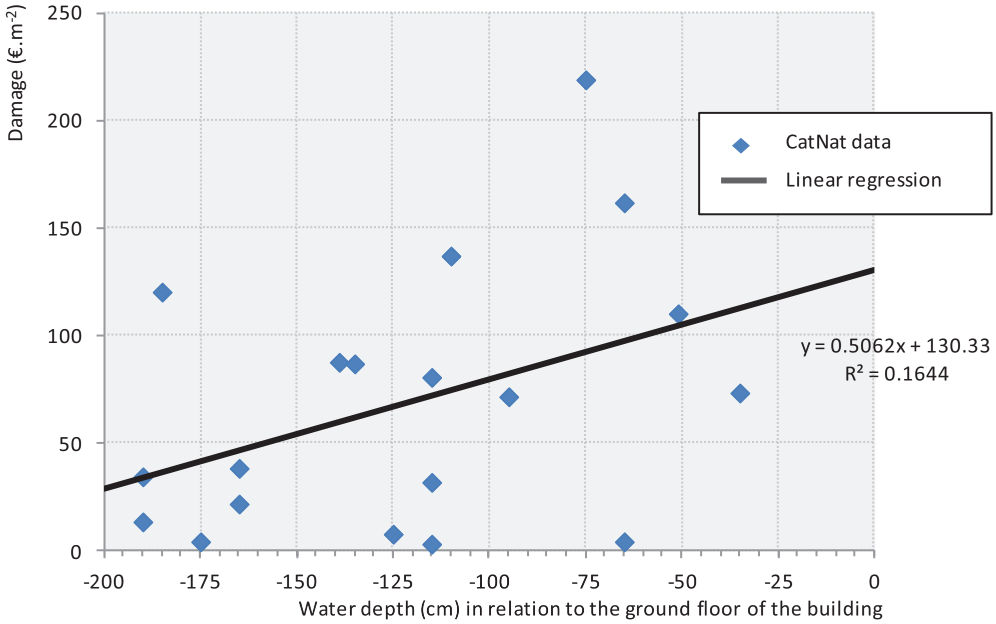

Figure 8.5. Correlation between building surface, water surface and monetary damage based on real damage data declared on the “dossier CatNat” constituted in March 1990 after the floods occurred at February 1990.

Beyond the uncertainty related to the small sample analysed, the uncertainties of these documents are relatively high (Hubert and Ledoux, 1999). The document is constituted of individual declaration of damage incurred by the flood. Part of declarations does not count on expert judgment of damage. On the one hand these values are generally relative to full replacement costs once the declaration are in majority based on invoices relative to the replacement of goods damaged and on repairing costs. On the other hand, these declarations are done just after the flood event, which completely ignore damage that is not perceptible in a short-term horizon. This rough estimate is not ideal for validation purposes because it is charged with uncertainties, however, it can be used as an order of magnitude indicating if the evaluation is in the ballpark. The following graph displays the impact of the different approaches used to assess the asset values for both damage functions tested in this work in comparison with the relationship between damage and water depth based on former damage (Figure 8.6).

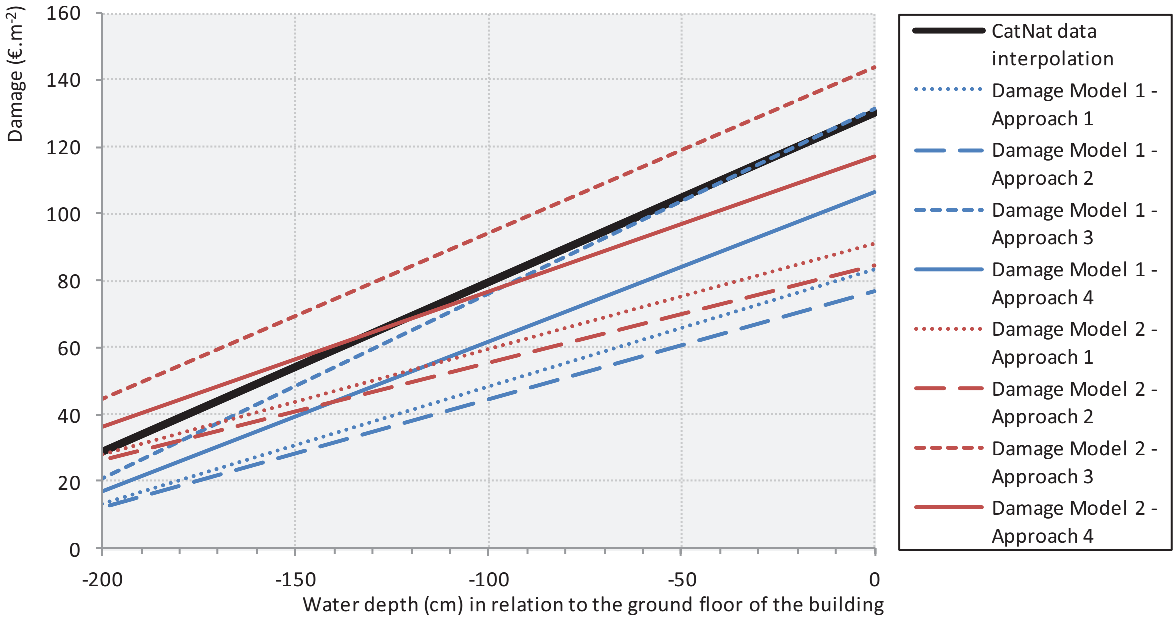

Figure 8.6. Comparison between CatNat data and the damage functions of buildings with basements of both damage models as a function of the different approaches used to calibrate them.

This comparison shows that the estimations realised here are coherent with observed damage. However, the approach used to determine the value of assets revealed to be crucial for the calibration of damage functions.

3. Cumulating uncertainty sources for uncertainty analyses

In addition to the uncertainties analysed in this chapter, those related to the construction of damage functions (*cf.* section 1.4) are to be considered on the damaging coefficients proposed in Figure 8.1. However, the majority of existing damage functions does not count on uncertainty bounds describing their associated uncertainties. We analyse here how these uncertainty is propagated to damage estimations. Uncertainty bounds of 10% and 30% (errors) are analysed (Figure 8.7).

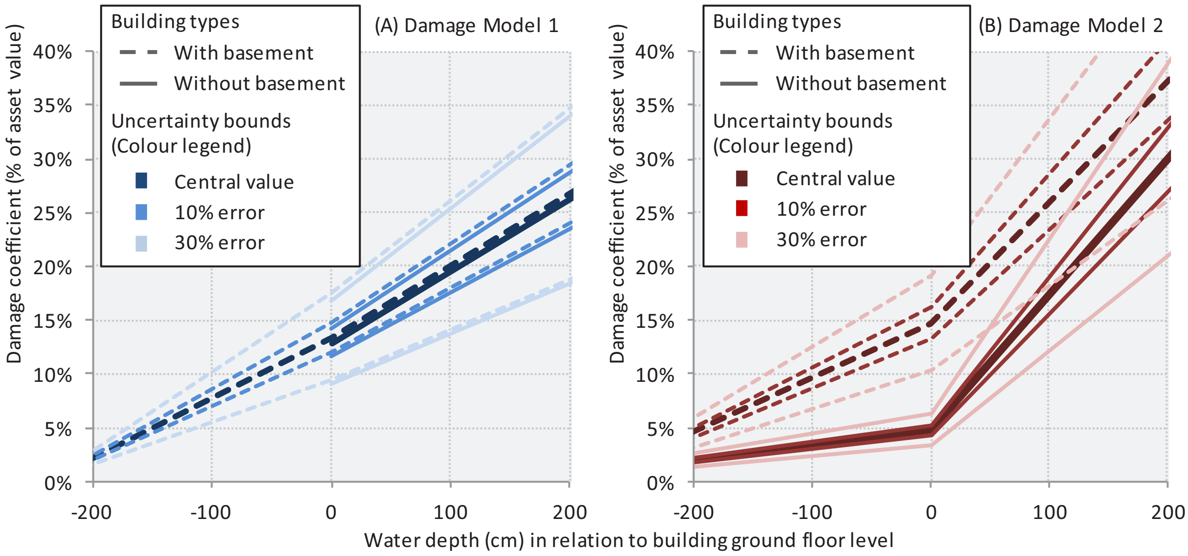

Figure 8.7. Uncertainty bounds of relative damage coefficients used for representing the global uncertainty of damage functions.

The propagation of this uncertainty on the results of damage evaluations is linear. Therefore, the under/overestimation of 10% and 30% of the damage coefficients leads to a variation of respectively 10% and 30% (under/overestimation) of the damage estimates. This influence is independent of the flood return-period and propagates to expected annual damage (EAD) in the same manner. The Equations (8.4) and (8.5) display how this uncertainty can be considered during the calculation of EAD.

$$A_{EAD} = \int_0^1 X \times A_{DP}(i) \times i.di \qquad (8.4)$$

$$A_{EAD} = X \times \int_0^1 A_{DP}(i) \times i.di \qquad (8.5)$$

where A_{EAD} is the asset expected annual damage (or average annual cost) caused by floods; $A_{DP}(i)$ is the asset damage potential related to a specific flood annual exceedance probability (i); and X is the uncertainty linked to the damage function.

Generally average asset values are considered for homogeneous areas when calculating potential flood damage. Therefore, the impact of uncertainties linked to the estimation of asset values can be also evaluated in this manner so that the damage function error “X” in Equations (8.4) and (8.5) can be considered as a function of the errors of damage functions and errors on asset values. These uncertainties can be cumulative or compensative in a specific context.

4. Chapter conclusions

The results of the case studies presented here showed that the influence of the selection of damage functions and the approaches used to estimate asset values are site-dependent. In one of the case studies the selection of damage functions was the main factor inducing uncertainty on the results of the evaluation once in the other, it was noticed the opposite. The selection of the damage functions and the method used to assess asset values and update/transpose damage functions are both aspects of the evaluation that directly influence the results of the damage-evaluations. However, the selection of damage functions is determinant to the evaluation process once the data needed to their application may lead to different methodological approaches and efforts and the uncertainty relative to this selection does not propagate linearly in the evaluation results, depending on the site hazard and vulnerability characteristics. Even though relative damage functions are easier to transpose to other contexts, they require the estimation of asset values. The evaluation of the value of assets is extremely complex and charged with uncertainty. Damage functions uncertainties directly propagate to damage estimates. We also highlight the fact that the uncertainties on a damage function used for a specific typology of damage can be compensated or cumulated with uncertainties of other damage functions used for different typologies of damage. The uncertainties in these aspects of the evaluation propagate throughout the evaluation independent of the frequency of the flood event. Even though the impact of this type of uncertainty is significant, we agree with Apel et al. (2004) who also concluded that it does not affect the shape of the flood risk curves. Once this influence does not depend on the frequency of flood events, the proposition of using uncertainty bounds for damage coefficients may be considered in damage estimations in order to represent uncertainties linked to damage models (both damage functions and asset assessments). The determination of the amplitude of the uncertainty bounds to test should take into account the level of uncertainties linked to the damage functions used in the evaluation and to the estimates of asset values. Monte-Carlo analyses could be used in order to better apprehend uncertainty compensation mechanisms.

An aspect not analysed here is that uncertainty linked to the estimation of the value of assets to large areas tends to be compensated, *e.g.* the values of assets may be underestimated for a town and overestimated for another town leading to underestimation of damage to the first town and overestimation for the second one. This aspect could lead to the compensation of the global value of damage potential of large areas. However, the uncertainty on damage distribution could be extremely relevant to decision-making processes and project appraisals, which strongly incites the deep analysis of these uncertainties.

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Chapter 9.

Cascade of uncertainties in flood damage estimations

This chapter makes use of all the aspects presented in the previous chapters of the thesis and proposes an analysis of all the uncertainties linked to the assessment of potential flood damage. On the one hand, we compare the impacts of uncertainties of four damage assessment modules: (1) hydrological analyses and considerations for determining discharges for different event probabilities; (2) the types of hydraulic model built and considerations when integrating topographical and bathymetric data; (3) the data and methods used to characterise the vulnerability of buildings to floods; and (4) the damage functions used and the errors related to characterising the value of the stakes. On the other hand, we quantify the impact of scales of analysis for mapping flood hazards and assessing the vulnerability of assets on the estimation of potential flood damage.

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1. Introduction

Several recent studies have focused on the analysis of uncertainties linked to flood damage estimations. However, few studies have dealt comparatively with the impact of all the assessment strategies on the global result of these estimations (Merz et al., 2010b). Apel et al. (2008a) compared the impact of the selection of hydraulic models and damage models (damage functions) used when carrying out risk assessments. The authors insisted on the importance of quantifying the uncertainties of the different flood risk assessment modules, in order to gain better understanding of the compensation of uncertainties. They noted the considerable importance of the damage model in the final uncertainty of damage estimations. Contrary to Apel et al. (2008a), Merz and Thieken (2009) reached a different conclusion, that is to say that the damage model contributes little to the global uncertainty of damage assessments in comparison to uncertainties linked to hydrological and hydraulic models. Other studies have concluded that hydrological uncertainties and damage models are major sources of uncertainty in this type of estimation (de Blois and Wind, 1995).

Obtaining better understanding and the reducing the uncertainties linked to damage assessments remain a real challenge for research (MEDDE, 2012b). Resources availability as well as the size of the area of study are all decisive factors regarding the tools to be implemented, and thus elements crucial for the precision of the analyses (Messner et al., 2007). To reduce the uncertainties of these assessments efficiently, it is essential to determine the importance of the different sources of uncertainties in the process (de Blois and Wind, 1995). As mentioned by Green et al. (2011), appreciating the gains regarding the accuracy of the results in essential for risk management.

The objective of this chapter is to compare the impact of the different sources of epistemic uncertainties in estimations of potential flood damage. In the first part of this work (section 2), we present the propagation of uncertainty method used to measure the part of the uncertainties related to different assessment modules. In the second part of this chapter (section 3), we analyse the impact of the different assessment modules on estimates of direct damage to buildings in two case studies in Alsace. An analysis of scales of assessment is carried out in view to quantifying the uncertainties linked to this aspect of the evaluation.

2. Method

This study focuses on the epistemic uncertainties existing in different models required to assess flood damage. Merz and Thieken (2009) suggested that using several methods for analysing the same problem introduces the notion of epistemic uncertainty. We adopt this notion, by distinguishing the uncertainties linked to models, methods and data, *i.e.* model uncertainties; and the uncertainties correlated with the hypotheses and choices to be introduced in the models, *i.e.* parametric uncertainties (NRC, 2000). The uncertainty analysis method proposed here considers damage assessment as a classical deterministic process that comprises two major groups of variables that must be combined to obtain results (*cf.* Chapter 2 for further details). We call these groups "parts" or "pillars" of damage assessment. The "hazard" part of the assessment includes the hydrological analysis and hydraulic models necessary to understand flood hazard. The "stakes" part includes the assessment of the vulnerability and susceptibility of assets to suffer damage. In order to measure the global uncertainty of the damage estimation, different data acquisition and modelling strategies are proposed for the four fundamental modules of the assessment (Figure 9.1).

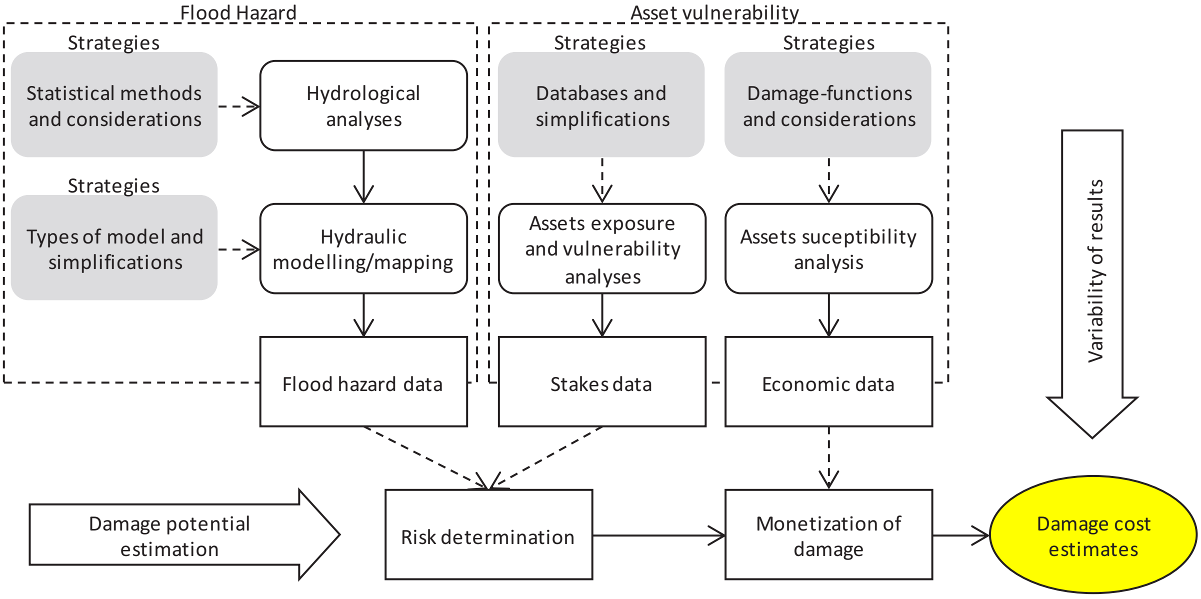

Figure 9.1. Diagram of the propagation of epistemic uncertainties of the different damage assessment modules.

The uncertainty analysis method proposed above (Figure 9.1) is composed of three steps: (1) the definition and implementation of several "strategies" for producing the different datasets required to assess potential damage (data related to flood hazard, the asset vulnerability and its susceptibility to damage); (2) the propagation of uncertainties linked to different strategies in the assessment results (sensitivity tests related to each assessment module); and (3) the quantification of the results variability generated by the different assessment scenarios and strategies. The method in question was applied to two case studies to better understand the influence of local characteristics on the mechanisms of uncertainties propagation linked to different damage assessment modules. The subjects of this study were the municipality of Holtzheim in the lower valley of the Bruche River and the municipality of Fislis in the upper valley of the Ill River. The two zones are located in the French part of the Rhine River basin (*cf.* Chapter 4 for more details).

2.1. Definition of evaluation strategies

The tests performed in this work were based on two strategic differentiation criteria concerning the assessment of potential flood damage: (1) the selection of models, methods, data and correlated uncertainties; and (2) the choice of assessment scales to model flood hazard and to assess the vulnerability of assets.

2.1.1. Models, methods and data

In the methodology described in (Figure 9.1), we determine a global configuration for the selection of models and hypotheses, taken as "reference". The "reference" assessment is composed of a single model and a set of hypotheses for each assessment module, *i.e.* a hydrological model, a hydraulic model, a vulnerability model, and a damage model. This assessment comprises the most detailed description of the "hydraulic" and "vulnerability" modules. The other scenarios proposed conserve both the reference structure for three of the assessment modules, whereas the fourth module is subject to different choices: on the one hand models, methods and data (which reveal the models uncertainties); and, on the other hand, considerations and simplifications in the parameterisation of the models (which reveal parametric uncertainties).

2.1.2. Scales of assessment

Different global approaches are taken regarding the analysis scales of the two sections of the flood damage assessment, *i.e.* vulnerability of the stakes and the flood hazard. Three levels of scale are considered in the definition of these assessment scenarios: "micro" scale, "meso" scale and "macro" scale (Table 9.1).

It has been demonstrated that different scales of analysis can be considered for different assessment modules (Messner et al., 2007). The methodology employed here considers this aspect by taking into account all the possible combinations of scale for assessing flood hazard and the vulnerability of assets described in Table 9.1. Two assessment modules are particularly dependent on the size of the study area. These are the "hydraulic" and "vulnerability" modules since their spatial nature makes the acquisition and processing of data more complex for a finer scale of analysis. In this study, only the strategies correlated with simplifications performed on these two modules are concerned by changes of scale. For each, a "micro", "meso" and "macro" scale-based strategy are described in what follows.

The reference "hydrology" and "damage" modules were left unchanged for the construction of the different risk assessment scenarios.

Table 9.1. Scales for assessing flood hazards and the vulnerability of assets.

Scale	Assets vulnerability	Flood hazard
MICRO	The characterisation of the assets is performed at the elementary scale (each building, infrastructure, object, etc.). Attention is given to the details of construction and occupation of each stake, for determining their material vulnerability.	Efficient hydrodynamic models are used with a detailed description of flows in river main channels and floodplains, by taking into account the particularities of existing hydraulic structures. Attention is given to the hydraulic characteristics of frequent and extreme floods.
MESO	The assets assessment is performed at the scale of homogenous blocks of land use (residential, industrial, commercial areas, etc.). Attention is given to the construction characteristics of stakes presenting a similar occupation. Aggregations of values are required.	Hydrodynamic models take into account rough description of flows in the river main channels with a relatively detailed description of the flood plain, without taking into account the detail of the analysis. Attention is given to events of all frequencies, with emphasis on the areas flooded by exceptional events.
MACRO	The assessment of assets is performed at the scale of administrative bodies (municipalities, departments, regions, nations, etc.). Attention is above all given to land use characteristics, omitting the characteristics of constructions.	The hydrodynamic modelling gives an approximate description of what occurs in the river main channel and floodplain, with attention mostly being given to the area flooded by exceptional events.

2.2. Implementation of the different assessment strategies

2.2.1. "Hydrological" module: determination of event frequencies

We used a series of measurements over 39 years for the case study of the municipality of Holtzheim, and a series of measurements of the river Ill over 30 years for the municipality of Fislis. This hydrological data is available in the national "Banque Hydro" [67] database of hydrological measurements. The hydrological analyses were performed on a series of maximal data on daily discharges using the "Hydrological Frequency Analysis" software (HYFRAN®)[68]. Six distribution functions often used to analyse flood frequencies were applied (Xu and Booij, 2007; Merz and Thieken, 2005; Haktanir, 1992): GEV (Generalised Extreme Value), GP (Generalised Pareto), GUM (Gumbel), PE3 (Pearson type 3), LN3 (Lognormal 3-parameter-type) and EXP (Exponential). The calculation of confidence intervals was performed with the HYFRAN® software using the "parametric bootstrap" method (Fortin et al., 1997). The four statistical distribution methods judged representative of a probable reality (GEV, GUM, PE3 and LN3) were tested in the two case studies, in order to reveal

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[67] WEB site of "Banque hydro" http://www.hydro.eaufrance.fr/ (consulted in June 2012).

[68] WEB site of the hydrological analysis software used in the framework of this study: "Hydrological Frequency Analysis" HYFRAN http://www1.ete.inrs.ca/activites/groupes/chaire_hydrol/chaire9.html (consulted in June 2012).

the model uncertainties. A confidence interval of 90% was used to take into account the parametric uncertainties of the models (*cf.* Chapter 5 for further details). The results of the hydrological analyses in terms of discharges for different probabilities of occurrence (return periods) are shown in the following graphs (Figure 9.2). The central, minimum and maximum values (CI = 90%) related to eight different return periods were used to perform the different sensitivity tests (5, 10, 20, 30, 50, 100, 200 and 500-yr).

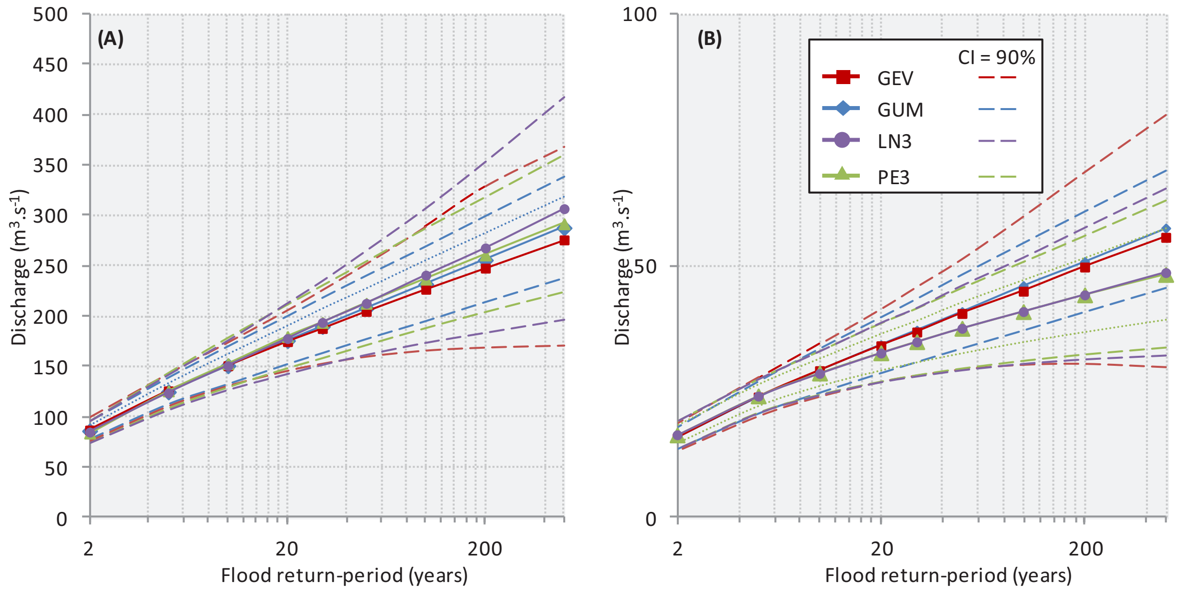

Figure 9.2. Results of hydrological analyses. The case of Holtzheim on the left (A) and Fislis on the right (B).

2.2.2. *"Hydraulic" module: flood simulation and mapping*

Several hydraulic models were developed in the framework of this study. For the municipality of Holtzheim, we used as basis: a hydraulic model designed by the engineering office DHI between 2005 and 2008 at the request of the Urban Community of Strasbourg, with the hybrid 1D/2D software (1D-2D) MIKE Flood®; and topographical data obtained using the LIDAR[69] technique with 1 point per m^2, with an altimetric precision of 10 cm. For the second case study, an existing model designed by the General Council of Haut Rhin (French institution) with the 1D HEC-RAS® software and a numerical model with a resolution similar to that of Holtzheim were used. These tools formed the foundations of the different models developed in the two case studies. The different modelling strategies adopted for

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[69] LIDAR is the acronym for Light Detection and Ranging, which designates a remote sensing or optical measurement technology based on analysing the properties of a laser light reflected back to its transmitter.

the "hydraulic" module were based on the type of hydraulic modelling software used (model uncertainty identification) and methodological simplifications/considerations adopted when building the topology of the models (parametric uncertainty identification). Other authors have also considered these aspects in a different way (Apel et al., 2008a; Merz and Thieken, 2009; Cook and Merwade, 2009). In this study, we used three hydraulic software applications and three different levels of detail were considered when building each model, with reference made to three scales of analysis (micro, meso and macro) (Table 9.1). The following table summarizes all the different strategies developed (Table 9.2).

Table 9.2. Differences between the strategies of the "hydraulic" module of the flood risk assessment with respect to the different types of hydraulic modelling software and simplifications performed.

Type of hydraulic modelling software (approach)	Methodological simplification/considerations
1D software HEC-RAS 4.1[a]. Representations of main river channels and floodplains by lines and cross-sections.	Number and position of cross sections; number of hydraulic singularities modelled.
2D software MIKE21[b]. Representation of main river channels and floodplains by a digital elevation model (DEM).	Size of 2D grid cells; number of hydraulic singularities modelled.
Hybrid 1D/2D software MIKE Flood[b]. Representation of the river main channel by lines and the floodplain by a DEM.	Number of cross-sections and singularities concerning the 1D part of the model. Size of grid cells concerning the 2D part of the model.

(a) Software developed by USACE (United States Army Corps of Engineers). Site WEB: www.hec.usace.army.mil/software/hec-ras/ (consulted in June 2012)
(b) Software developed by the engineering office DHI Group. Site WEB: www.mikebydhi.com/Products/WaterResources/ (consulted in June 2012)

The two-dimensional parts of the 2D and 1D-2D models were built with a grid of square rectangles of homogenous size. The method of bathymetric interpolation developed by Merwade et al. (2006) and Merwade et al. (2008) was used to complete the bathymetric information of the 1D models and supply better description of the main channel for 2D models. All the scenarios considered the main hydraulic obstructions as a function of the scale of analysis adopted (*cf.* Chapter 6 for further details). In all, 18 models were built and analysed in this study. We simulated and mapped floods with return periods of 5, 10, 20, 30, 50, 100, 200 and 500-yr.

2.2.3. "Vulnerability" module: classification and characterisation of assets

Two groups of building characteristics were needed to characterise building vulnerability: (1) construction characteristics, *i.e.* the height of the first floor, presence of a basement; and (2) occupation characteristics, *i.e.* type of occupation, type of activity, localisation of the activity in the building and the real rate of occupation. Several databases with different levels of precision can be used to identify these different aspects of the vulnerability of a territory. Three existing databases (DB) were used here to extract the building occupation characteristics for both study sites:

- the BD TOPO® database designed by the French National Institute of Geography (IGN), uses numerical information (geo-referenced data) on land use and morphology at a scale of 1 :25 000. The database includes a geographic information system (GIS) "buildings" layer that contains the spatial representation of the contours of buildings with tabular descriptions of types of use (residential, commercial, etc).
- the BD OCS database describes land use in homogenous areas according to 94 classes at a scale of 1:25 000. This database was built at the request of the Alsace Region (Géoméditerranée, 2003);
- local databases composed of GIS layers with geo-referenced points indicating the addresses of buildings were enhanced with information drawn from other local databases (Chambers of Commerce/Industry and local municipalities) with reference to the types of activity of the buildings. These databases were much more complete for the case of Holtzheim than for that of Fislis.

Complementary methods were implemented to make up for the limitations of these databases. First, interviews were conducted with local real estate experts to determine construction characteristics, *e.g.* presence of basements, height of first floor. Second, three types of field survey were performed on both case studies: (1) a superficial field survey, called "S Survey", in order to identify the average characteristics of all the buildings of the municipalities; (2) a semi-in-depth field survey called "SID Survey" in order to estimate the average characteristics of buildings by homogenous area of land-uses, pre-identified by map analyses; and (3) an in-depth survey called "ID Survey", in order to identify and measure the characteristics in an elementary scale, building by building. Six strategies concerning the "vulnerability" module, based on these different databases were used to characterise the vulnerability of buildings in the two case studies (Table 9.3). These strategies were also based on different scales of analysis: the level of precision of the strategies developed increased from Approach A ("macro" scale) to Approach F ("micro" scale).

The variability of risk assessment results induced by these approaches reveals model uncertainties in the estimations. To take into account the uncertainties linked to considerations on the data measured, estimated and determined by expert opinion, *i.e.* parametric uncertainties, we determined the MIN-MAX uncertainty boundaries according to the study by Paté-Cornell (1996). Two supplementary scenarios were considered for each approach: the MIN and MAX scenario, corresponding to the combination of uncertainties on data resulting in a minimum and maximum estimation of the vulnerability of buildings (*cf.* Chapter 7 for further details). Thus, 18 vulnerability assessment approaches were performed for each case study.

Table 9.3. The data and considerations taken into account in the different strategies concerning the "vulnerability" module, used to characterise the vulnerability of buildings.

	Approach A	Approach B	Approach C	Approach D	Approach E	Approach F
Source of data	BD TOPO	BD TOPO BD OCS	BD TOPO BD OCS Local DB	BD TOPO BD OCS Local DB S Survey	BD TOPO BD OCS Local DB SID Survey	BD TOPO BD OCS Local DB ID Survey
Presence of basement	Expert opinion	Expert opinion	Expert opinion	Average values	Average values	Identified individually
Height of first floor	Expert opinion	Expert opinion	Expert opinion	Average values	Average values	Measured individually
Rate of occupation of ground floor	Expert opinion	Expert opinion	Estimated	Estimated	Average values	Estimated individually

2.2.4. "Damage" module: damage functions and asset values

Two groups of damage functions frequently used in the French context to assess potential flood damage to residential buildings were used in this study (D4E, 2007; CEPRI, 2008). The first set of damage functions used "Model 1" was developed by Torterotot (1993) while the second set, "Model 2" was developed for several municipalities in the Ile-de-France Region (at the end of the 1980s) (D4E, 2007), and reused in the framework of the standard cost/benefit analysis tool for flood management purposes of the "Plan Rhone" in 2010 (Ledoux Consultants, 2010). These two sets of damage functions distinguish buildings with and without basements. They represent the potential damage index of residential buildings as a function of submersion height in relation to the first floor of buildings (water depth) (Figure 9.3).

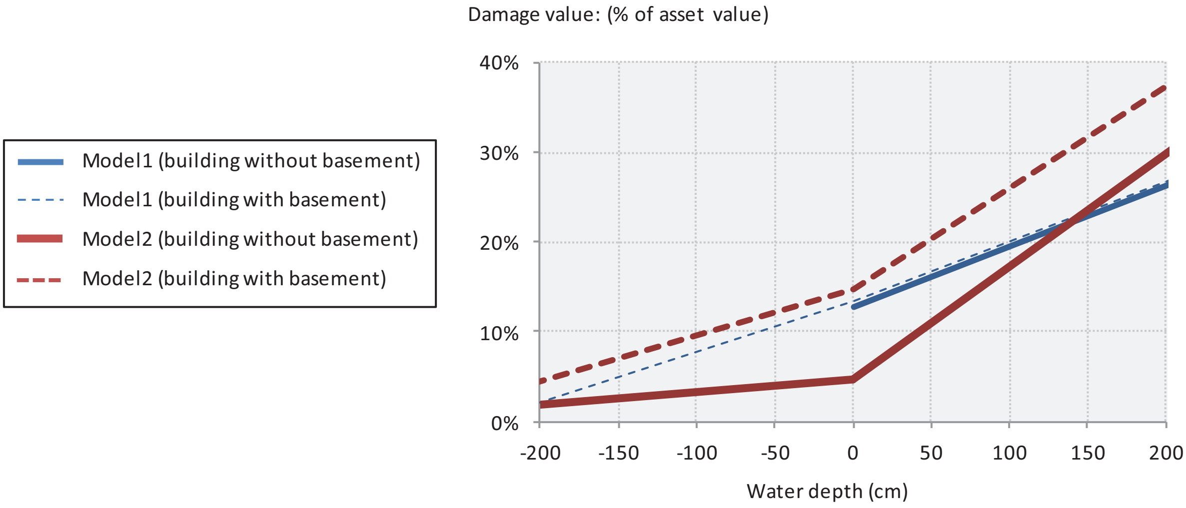

Figure 9.3. Different damage functions used in the sensitivity tests for the "damage" module.

In order to calibrate these damage functions, it is necessary to determine the average value of the dwelling by m^2 and the surface area of buildings exposed to floods. The total projected area of the buildings and their spatial localisation were identified in the same way for the different scenarios of analysis, using the BD TOPO® database. This method was also the source of diverse uncertainties. A comparison of the areas of 155 buildings in the zone of Holtzheim obtained from the BD TOPO® database with areas extracted from orthophotos highlighted that this database overestimated the areas of buildings by 5% (Eleutério, 2008). The construction value of the buildings was estimated using the opinion of real estate experts. A standard deviation of 25% of the value estimated in comparison to the average was observed between the minimum and maximum values estimated according to expert opinion. In addition to these uncertainties, the damage coefficients proposed above (Figure 9.3) are themselves marked by uncertainties (D4E, 2007). Damage functions associated with error margins and explanations concerning the existing level of uncertainty are rare, making this estimation difficult. All these cumulated uncertainties were considered in this study as sources of parametric uncertainties and assessed theoretically. We considered that the damage coefficients used in our tests could have an uncertainty of ± 30% (*cf.* Chapter 8 for further details).

The monetization of direct damage to economic activities was performed with existing damage functions (DNRM , 2002) for the different assessment scenarios. Given that this typology of building represents the minority of buildings in the municipalities analysed, these functions were not subjected to the uncertainty tests performed in our work.

2.3. Propagation of uncertainties

The combination of different data and the calculation of damage and average annual costs of damage, *i.e.* expected annual damage (EAD), were done using a GIS tool developed for this purpose (*cf.* Chapter 3 for further details). Each analysis strategy of the different modules gave rise to a risk estimation. The number of scenarios implemented to analyse the impact of each assessment module on the damage estimates are presented in Table 9.4.

Table 9.4. Number of damage assessment scenarios implemented for each case study to analyse the impact of epistemic uncertainties of each assessment module in risk estimations.

Assessment modules	Holtzheim	Fislis
Hydrology	12 scenarios	12 scenarios
Hydraulics	18 scenarios	18 scenarios
Vulnerability	18 scenarios	18 scenarios
Damage	8 scenarios	8 scenarios

In addition to these assessment scenarios, we considered nine others for each case study in order to take into account the impact of scales in the assessment results. The total of 65 damage assessment scenarios was implemented for each case study. Each scenario comprised damage assessments for eight floods, with return-periods equal to 5, 10, 20, 30, 50, 100, 200 and 500-yr, and the calculation of EAD. The quantification of the variability of these damage estimates is presented in the following section.

3. Results

3.1. Global uncertainty of assessments

The risk curves (damage/frequency) were obtained as a function of the strategic choices made for the different assessment modules, according to the combinatory method proposed (Figure 9.1). The minimum and maximum boundaries of these curves are shown in the following graphs (Figure 9.4).

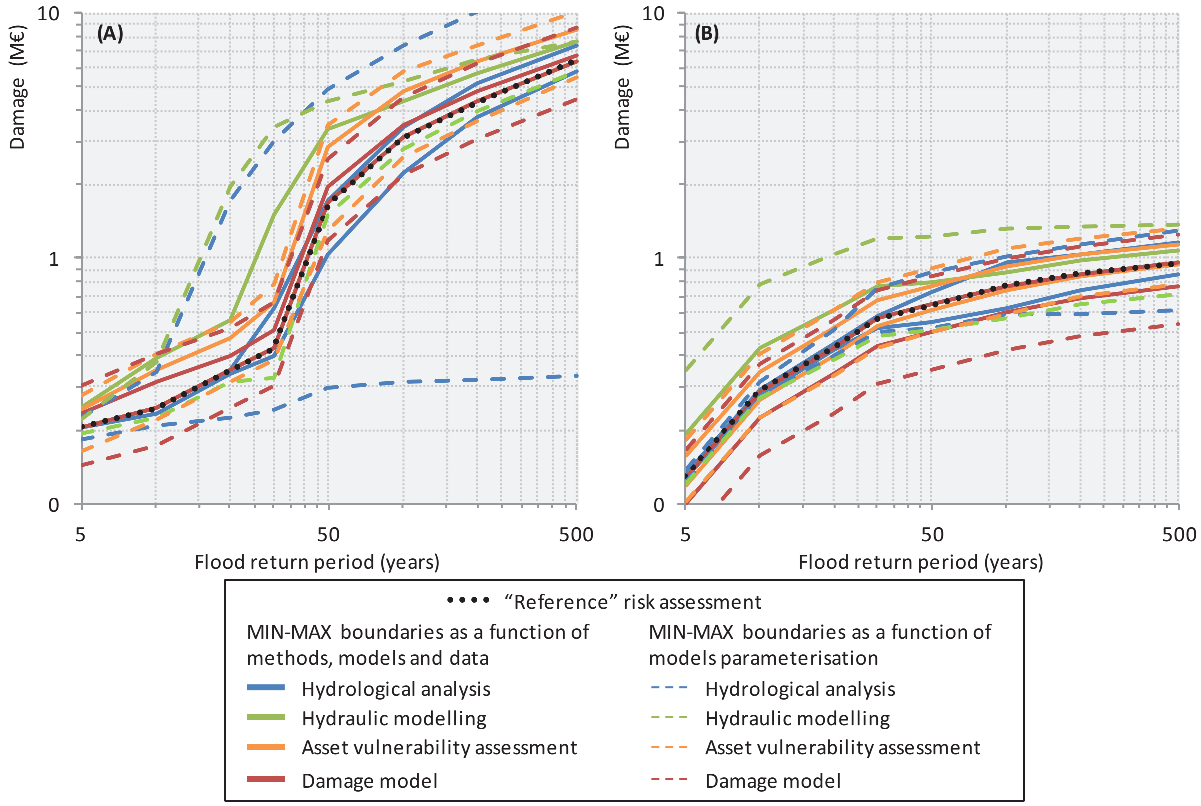

Figure 9.4. Damage potential for different flood return-periods as a function of the methods, models, data (model uncertainties) and parameterisation of the models (parametric uncertainties). The case of Holtzheim on the left (A) and that of Fislis on the right (B).

The flood risk proved to be very different for the two municipalities analysed. By analysing the "reference" scenario, we observed that the first flooding events were likely to cause damage of the same order of magnitude for the two study sites. Few stakes were exposed to flooding for small return-period flood events. However, for the municipality of Holtzheim, the progression of damage was relatively slow for events of high frequency since the town centre is protected against floods by a dike (return-periods less than around 30 years, shown in graph A of Figure 9.4). Whereas for the municipality of Fislis, the damage increased significantly for these high frequency events (graph B of Figure 9.4). We also observed that the variability of the results due to the selection of models, methods and data was less marked when adding the uncertainties linked to their parameterisation (parametric uncertainties). The following graphs allow clearer understanding of the results by highlighting the role of each assessment module in the variation of risk estimations. These graphs represent the minimum and maximum boundaries in comparison to the values obtained with the "reference" assessment as a function of the methods, models and data (Figure 9.5), and as a function of the parameterisation of the models (Figure 9.6).

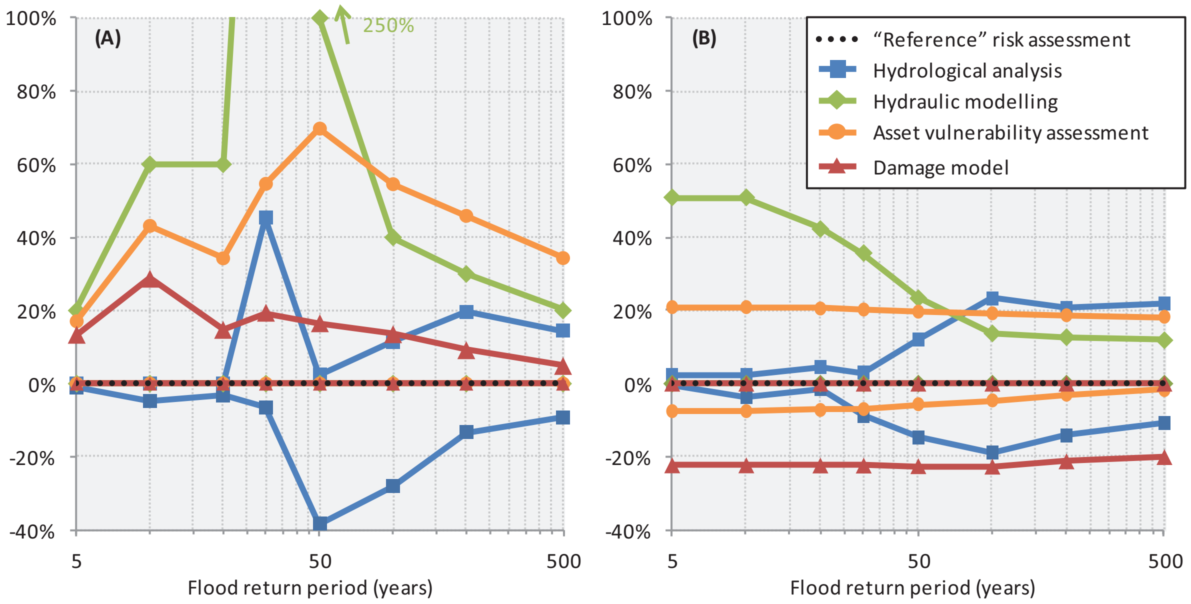

Figure 9.5. Variation of damage estimates in comparison to the results of the "reference" assessment – as a function of the methods, models and data. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

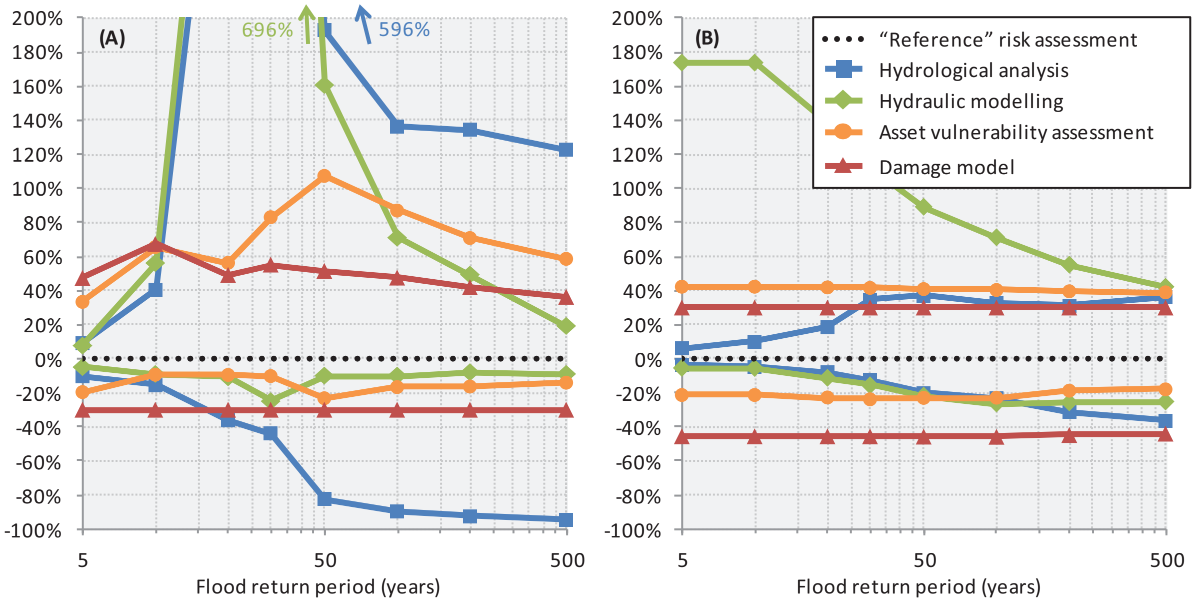

Figure 9.6. Variation of damage estimates in comparison to the results of the "reference" assessment - as a function of the parameterisation of the models. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

The peaks shown in the case of Holtzheim (graph A in Figure 9.5) highlight a particularity of this site due to the existence of a flood protection dike. The difficulty of certain modelling scenarios to represent this structure led to considerable variability in determining the return-period of failure of the structure. In the case of Fislis (graph B in Figure 9.5), hydraulic uncertainty was observed mainly for frequent floods, for which small overestimations of water heights and areas covered by the flood hazard played a very important role in quantifying potential flood damage.

Although the order of magnitude of the uncertainties was much greater for the parametric uncertainties (Figure 9.6), the similitude between these two figures (Figure 9.5 and Figure 9.6) reveals that the parametric uncertainties propagate in a very similar way to that of uncertainties linked to models, methods and data. However, we observed a huge difference concerning the hydrological module (graph A in Figure 9.6). The impact of taking into account the confidence intervals of 0.9 was very significant for the case of Holtzheim. This was also due to the hydraulic structure present on this study site.

The following graphs (Figure 9.7) represent the variations induced by these different sensitivity tests carried out in terms of expected annual damage (EAD).

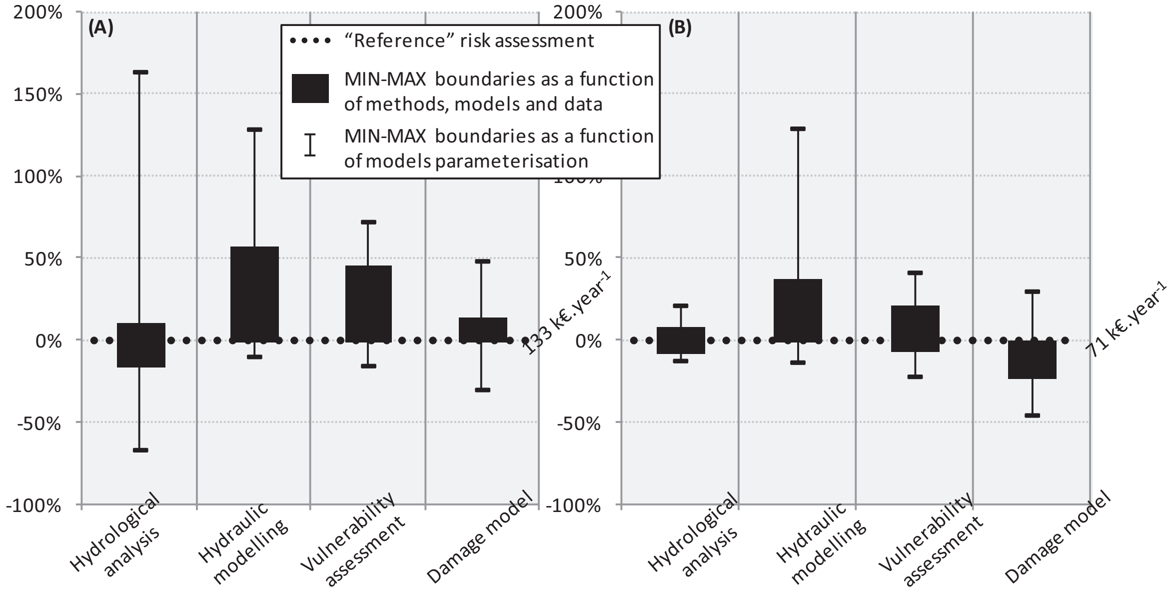

Figure 9.7. Expected annual damage and uncertainty bounds as a function of methods, models, data and parameterisation of the models. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

We observed that the variability of EAD due to the selection of methods, models and data (model uncertainties) was very similar for the two case studies. The hydraulic modelling was the most important factor in the variability of estimates, followed by the characterisation of the the vulnerability of assets. The amplitudes (MAX-MIN) of the uncertainty boundaries relating to the "hydraulic" module were 25% (Holtzheim) and 43% (Fislis) greater than those related to the "vulnerability" module. There was a difference regarding the roles of hydrology and the damage functions. In the case of Holtzheim (graph A in Figure 9.7), the selection of hydrological functions played a greater role than the selection of the damage model. The amplitudes induced by the "hydrology" and "damage" modules correspond to 56% and 31% respectively of the amplitude induced by the "vulnerability" module. In the case of Fislis, these amplitudes were relatively higher corresponding to 54% and 83% respectively (graph B in Figure 9.7). This can be explained by the fact that in the second case study buildings without basements predominated and that the heights of the water flooding the site for events of greater frequency were relatively low. In this case, the difference between the two damage models used (damage functions) is greatest (*cf.* Figure 9.3).

The major difference between the two case studies concerns the variability of the EAD due to simplifications/considerations taken into account during the analysis (parametric uncertainties). In the case of Holtzheim (graph A in Figure 9.7), we observed the strong influence of hydrological considerations (confidence intervals of 0.9) and the parameterisation of hydrological models. It is noteworthy that the sensitivity tests concerning parametric uncertainties performed on the "hydrology" module indicated strong potential for both under overestimating EAD. The MIN-MAX boundaries of these tests (graph A of Figure 9.4) demonstrate how the flood protection structure of Holtzheim influenced this module, *e.g.* the minimal assessment scenario was caused by the non-failure of the protection structure due to the underestimation of water stream height generated by hydrological considerations. At Fislis (graph B in Figure 9.7), we observed a very weak influence of hydrological considerations on the EAD. The uncertainty linked to the parameterisation of hydraulic models remained strong, though not as strong as that of the other case study. It appears that the uncertainties mostly generated overestimations of potential direct damage.

3.2. The role of the analysis scale

The risk curves (damage/frequency) calculated as a function of the scales used to model flood hazard and to assess the vulnerability of buildings are represented in the following graphs (Figure 9.8).

We observed that for the two case studies, the uncertainties were much more pronounced for the most frequent events (return-periods less than 50 years) than for rare ones. The maximum estimations of damage at Fislis were higher by 91% on average than the minimum estimations (for return-periods shorter than to 50 years), and on average 34% for return-periods longer than 50 years. This uncertainty is much higher in the case of the municipality of Holtzheim: the maximum estimates were higher by 446% and 82% on average than the minimum estimates for return-periods shorter and longer than 50 years respectively.

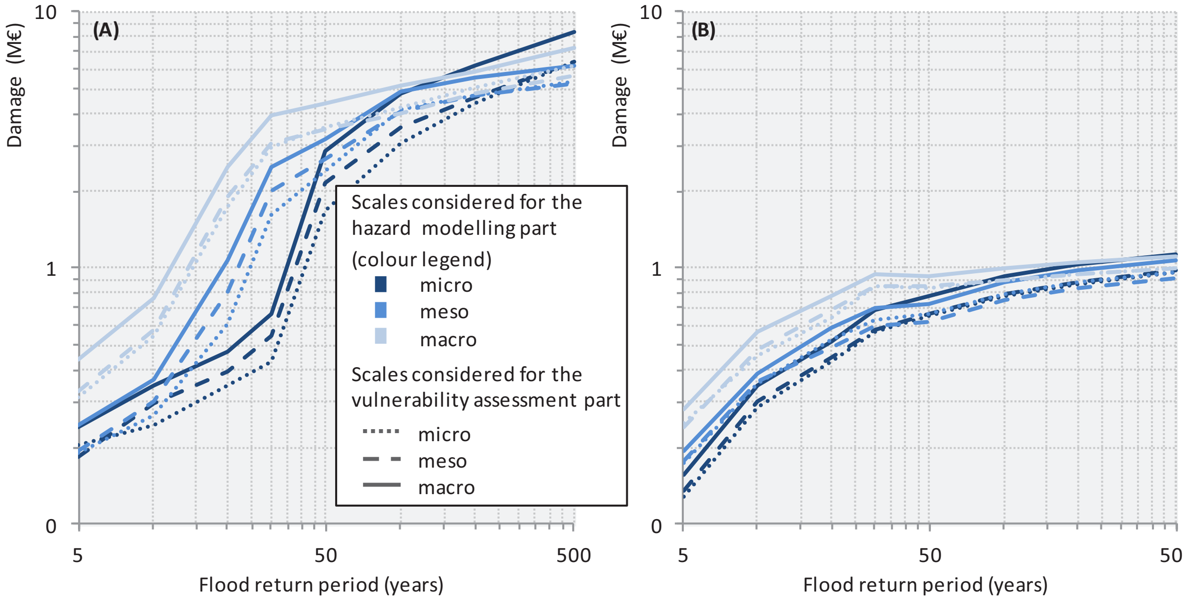

Figure 9.8. Potential damage for different return-periods as a function of scales of hazard and vulnerability assessments. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

3.2.2. Expected annual damage (EAD) estimates

EAD were calculated with the pairs of values (damage vs. probabilities of occurrence) estimated by the different assessment scenarios studied (Figure 9.9).

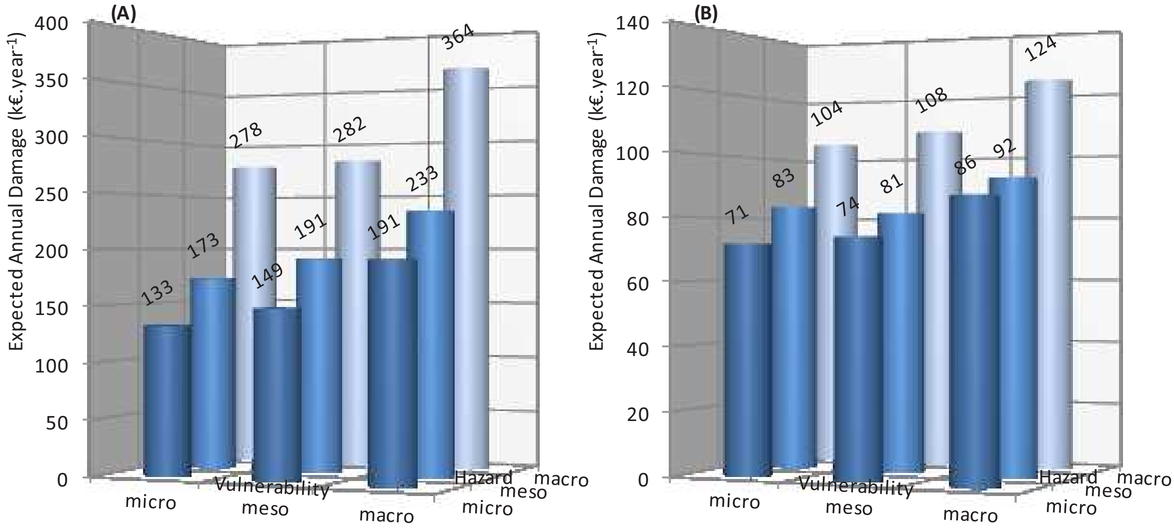

Figure 9.9. Expected annual damage as a function of scales of hazard and vulnerability assessments. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

For Holtzheim (graph A in Figure 9.9), the estimations of EAD based on hazard models at “macro” scales were on average 96% higher than those estimated with the “micro” scale. The estimations based on hazard models at “meso” scales were only 27% higher on average than those estimated at “micro” scales. This highlights that high uncertainty in the assessment is generated when passing from “meso” to “macro” scales regarding the hazard part of the risk estimation. Regarding the scales of analysis for assessing the vulnerability of buildings, they have less impact on EAD estimations. The estimations based on the “macro” scales of vulnerability were on average 28% higher than the estimations based on the “meso” scale, which were only 12% higher than those based on the “micro” scale. These percentages are lower for the case of Fislis (graph B in Figure 9.9), though the influence of the probability is nonetheless much lower. The influence of flood inundation models at “macro” scale on EAD estimations is also notable. The hazard “macro” scale-based estimations are on average 31% higher than estimations based on the “meso” scale, which are only 11% higher than the estimations based on the “micro” scale hazard model.

These results also show that the two assessment modules are influenced in the same way: the larger the scale, the more the estimation tends to overvalue expected annual damage (EAD). EAD estimates based on the hazard and vulnerability "macro" scales is higher by 175% (Holtzheim) and 73% (Fislis) than the estimation based on the hazard and vulnerability "micro" scale. We observe that the estimation of hazard-vulnerability "meso" scales is as high or closer to the estimation at "micro" scales than the estimation based on the hazard "micro" scale the vulnerability "meso" scale, for both case studies.

3.2.3. The share of the "hazard" and "vulnerability" parts of the evaluation

We observed that flood hazard modelling uncertainty generally plays a greater role in the variability of estimations than the characterisation of building vulnerability (see the variations of estimates for return-periods shorter than 50 years on graph A in Figure 9.8). This observation is also apparent in the estimations of EAD (Figure 9.9) discussed above. In order to explore how the uncertainties stemming from the scales of assessment affect one or the other assessment modules, we quantified the contribution of these modules on the global uncertainty of the estimations. The "parallel models" method proposed by Visser et al. (2000), which was reused by Merz and Thieken (2009) in the context of flood risk analysis was adapted to this end. The following approach was taken:

1) for each return-period (T), we calculated the maximum uncertainty range of estimates generated by the use of the 9 combinations of scales of analysis, *i.e.* the difference between the maximum and minimum boundaries of the uncertainties ($MUR_{total,T}$);
2) for each scale of analysis of the "hazard" part (micro, meso and macro), we determined the uncertainty range of the estimates generated by the different scales of analysis performed in the "vulnerability" part. This led to three estimations of uncertainties range for each return period: $UR_{haz\ (micro),\ T}$, $UR_{haz\ (meso),\ T}$ and $UR_{haz\ (macro),\ T}$. These ranges were caused by the variability of the methods used in the "vulnerability" part;
3) thus we determined the maximum uncertainty range generated by the "vulnerability" part for each return-period ($MUR_{vul,\ T}$), by calculating the average of the maximum ranges calculated previously;
4) the influence of the "vulnerability" part on the global uncertainty of the assessment for each return-period was defined as $I_{vul} = MUR_{vul,\ T} / UR_{total,\ T} \ .\ 100\%$;
5) we determined the influence of the "hazard" part by repeating steps 2, 3 and 4 and by determining the ranges caused by the variability of the methods used in the "hydraulic" part.

The following graphs (Figure 9.10) show the results of this analysis:

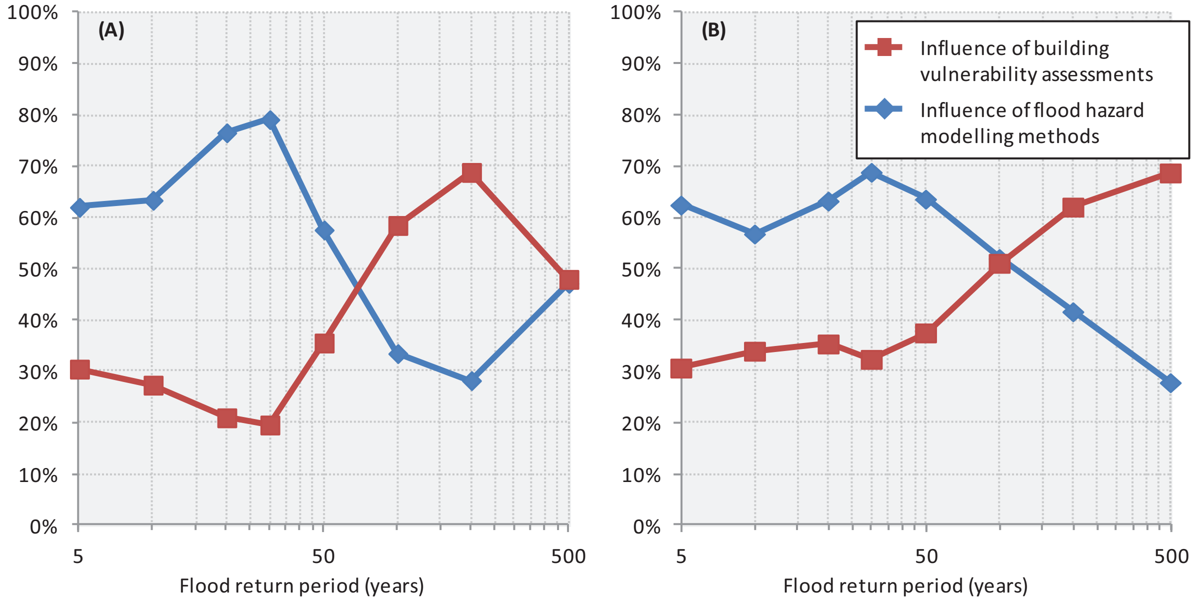

Figure 9.10. Contribution of both, "hazard" and "vulnerability" parts of the estimation to the global uncertainty of estimates with all scales considerations. The case of Holtzheim on the left (A) and that of Fislis on the right (B).

We observed that the influence of the different risk estimation parts on the variability of estimates was very similar for both case studies. In both the case of Holtzheim (graph A in Figure 9.10) and that of Fislis (graph B in Figure 9.10), the "hazard" part contributes the most to the global uncertainty of estimates for floods with return-periods shorter than 100-yr while the influence of the "vulnerability" part is greater for higher return-periods. The increase in the influence of the "hazard" part for extreme events in the case of Holtzheim (graph A in Figure 9.10) can be explained by the fact that an additional number of buildings is identified as being within the perimeter of floods due to the variability of the hydrological models.

By analysing EAD estimates in the same way (steps 1 to 5 of the parallel models method), we determined the global influence of the different parts of the estimation on flood EAD. The variability of the results induced by the scale variations when modelling flood hazard influenced in 65% the EAD value calculated for Holtzheim, whereas the influence of the approach to assess the vulnerability of buildings was 30%. For the second site, the influence of hazard was 67%, and that of vulnerability 28%. This was because the EAD index is more strongly influenced by frequent damage values (damage induced by high frequency floods).

3.3. Discussion on the results

All the tests performed revealed a general tendency of overestimating flood direct damage potential to buildings. The tests at different scales of analysis of hazard and vulnerability demonstrated the strong influence of these considerations on the assessment results by pointing out the precise role of one module or the other as a source of uncertainty. In the two case studies, the larger the scale of assessment, the higher the estimated damage values for both the hazard modelling and the method to assess the vulnerability of assets. The uncertainty compensation mechanism proved very complex to analyse. The variability of the results due to the selection of methods, models and data were very similar between the two case studies. Regarding the latter, hydraulic modelling was the most important factor in estimate variability, followed by the assets characterisation approaches. The uncertainties linked to flood models tended to under/overestimate risk through the generalised increase or reduction of water heights and flooded surfaces. On the contrary, the uncertainties linked to the characterisation of asset vulnerability were subjected to spatial variability, liable to be the source of a compensatory effect when summing up the overall potential flood damage, *e.g.* the underestimation of the first-floor height of a building can be offset by the overestimation of this characteristic for other buildings. The main differences between the results of the two case studies were observed when performing the tests relating to parametric uncertainties, *i.e.* uncertainties linked to different considerations and data introduced in the models. The determination of the hydrological confidence intervals and the uncertainties related to the processing of topographical and bathymetric data in the hydraulic models was crucially important for the first case study (Holtzheim). The flood protection dike at the site in question was the main source of these differences. On the one hand, the variation of the failure return-period of the structure was a very sensitive parameter for the assessment. On the other hand, certain hydraulic simplifications eliminated the detailed inclusion of this structure in the calculation, leading to an overestimation of the damage caused by floods of greater frequency. These particularities linked to the sites highlight the complexity of studying uncertainties in deterministic approaches.

4. Conclusions and outlook

The quantification of flood risk and its mapping involve several modelling steps each of which comprises uncertainties. The study in question shows, firstly, that the uncertainty of each module of the assessment (hydrology analysis, hydraulic modelling, vulnerability assessment and damage models) depends on several factors that are highly dependent on the characteristics of the sites studied. The role played by flood hazard modelling was preponderant in assessing flood risk to buildings, especially for the most frequent floods. This showed that great attention must be given when modelling frequent floods for damage assessment purposes. The results of this study showed that taking protection structures (dikes and dams) on a site into account is an important factor in decisions involving the accuracy of the probability analysis. This aspect proved to be a significant source of uncertainty in the damage assessment process. Furthermore, the study in question showed that scale-considerations played a non-negligible role in the risk assessments. Larger scales led to considerable overestimation of damage in comparison to smaller scales. These results show that in-depth consideration is required prior to using flood maps and vulnerability databases in view to assessing potential flood damage.

The degree of subsisting uncertainty in these assessments leads us to reflect on existing uncertainties at a second level of assessment (networks and their effects). Uncertainties linked to the identification of hazard still require integrating the risks of structure failure and climatic change (hydrological probability). The vulnerability of a territory also depends on networks, infrastructures and crisis management systems. The complexity of these aspects of risk leads to other still more complex levels of uncertainties when assessing indirect and intangible damage. The weight of existing uncertainties in quantifying risk calls into question the use of this sole criterion as a support for decision-making. Standardised methods that take into account uncertainties would be an efficient mean of using these tools in a comparative manner. In spite of the existence of different uncertainties, these assessments are extremely powerful tools for understanding flood risk. Consolidating these assessments remains a path for further research, as does flood risk management for which the scope of analysis should be widened to include the social and political dimensions of this risk.

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- PART III -

THE COMPLEXITY OF FLOOD INDIRECT DAMAGE AND RESILIENCY

The understanding of potential flood damage is essential for apprehending the risk in order to manage it. The great majority of studies concentrate in the evaluation of direct damage to buildings and contents, which represent the main source of damage in urban contexts. However, the understanding of the global damage potentiality of floods is dependent on the global understanding of the urban system. Networks play an essential role in urban centres. Their direct damage potential is the "start-up" of several dysfunctions in a society depending on the services offered by these networks. The indirect damage caused by network dysfunctions can be more relevant than flood direct damage. It becomes essential to understand the dysfunction potential of networks in risk contexts. In addition to support flood management decision-making processes, the understanding of networks damage potential to floods is essential for improving the resilience of urban centres. We expand the scope of the thesis objectives in order to reach a second level of potential flood damage estimations. This part of the thesis is dedicated to the evaluation of networks damaging and dysfunctions potential to floods, as a first step toward the improvement of the resilience of cities to floods. It is composed of one chapter (Chapter 10) in which we develop a method to evaluate network damage and dysfunctions potential in the case of floods.

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Chapter 10.

Estimation of potential damage and dysfunction to network infrastructures

Understanding network infrastructures and their functioning under exceptional circumstances is fundamental for dealing with flood risks and improving the resilience of a territory. This work presents a method for evaluating network infrastructure dysfunction and damage potentials in cases of flooding. In contrast to existing approaches, this method analyses network infrastructures in an elementary scale, considering networks as a grouping of elements with specific functions and individual vulnerabilities. Our analysis puts the assets in the centre of the evaluation process, resulting in the construction of damage-dysfunction matrices based on expert interviews. These matrices make it possible to summarise the different vulnerabilities of network infrastructures. They describe how the different components are linked to each other and how they are able to compromise the functioning of the network. They also identify the actions and resources needed for the system to recover from damage and dysfunctions, which is essential in working with the question of resilience. The method promotes multi-network analyses. A French case study is used to illustrate this method. Sixty network experts were interviewed during the analysis of the following networks: drinkable water supply, wastewater, public lighting, gas distribution and electricity supply.

This chapter is based on Eleutério J., Hattemer C. and Rozan A., A systemic method to evaluate potential impacts of floods on network infrastructures, submitted and accepted for publication at Natural Hazards and Earth System Sciences Journal.

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1. Introduction

Networks represent the main structural elements in an urban context supporting the exchange of different services and the transport of people and goods (Hubert and Ledoux, 1999). We generally differentiate two types of network: transport networks and technical networks. Transport network infrastructures support the transportation of people and goods, *e.g.* roads and railways. Technical network infrastructures support the production/processing and/or distribution/collection of services/resources, *e.g.* electricity, gas, information, water and wastewater. Network infrastructures are necessary for supporting the general objective of the network. They have the fundamental characteristics of systems, *i.e.* grouping of elements dynamically correlated to each other, organised according to an objective (Narbonne, 2005). This general objective can be categorized in specific missions (Petit, 2009) (Figure 10.1). For example, the extraction of water resource, water treatment, water transportation and delivery to the end-users are missions of the water network. Several infrastructures, *i.e.* components, are behind these missions. They are composed of different installations and technical apparatus, *i.e.* elements, which have specific functions inside the network itself, *e.g.* inside power networks, the tension transformers, electric cables and individual electric boxes have different functions. The understanding of the global structure of the network is essential for identifying the functions of the different network components and technical apparatus, as well as how they are connected to each other. These equipments together support the general objective of the network, *i.e.* to support the functioning of a society providing the resources and services permitting the socio-economic activities (Blancher, 1998).

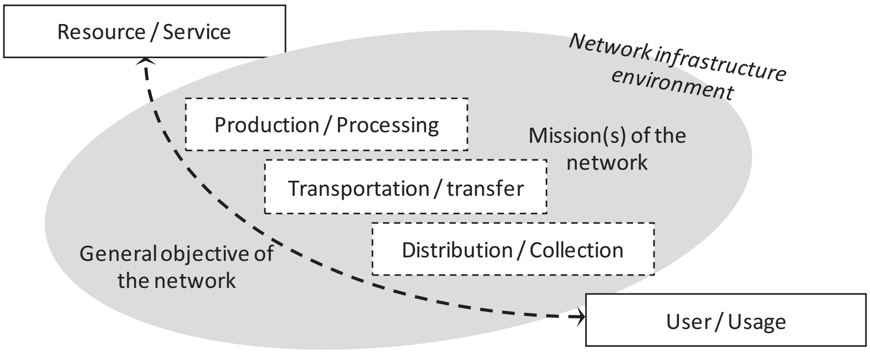

Figure 10.1. The different missions of network infrastructures.

Network infrastructures have received special attention in terms of security (Petit, 2009). The increasing dependence of people and economy on the services offered by network infrastructures puts them at the centre of the functioning of contemporary society. The good functioning of networks during crisis periods and their capacity to return to normal functioning is fundamental to the society depending on them. Several works highlight the need for a better understanding of the capacity of networks to ensure their functions (Bouchon, 2005; Røstum et al., 2008; Petit, 2009). The appearance of the concepts of critical infrastructures and lifelines, and their development during the last decades highlight the global interest for the resilience of networks regarding a large variety of risks, *e.g.* terrorism, financial risks and natural hazards (Adam, 2007; Popescu and Simion, 2011; Robert et al., 2003b; Utne et al., 2010).

1.2. Flood consequences evaluation

Floods are the most damaging natural hazard in the world and the damage they cause are increasing over time (Messner et al., 2007; Jonkman, 2005). The evaluation of potential flood damage is largely accepted for studying the vulnerability of systems helping on decision-making processes (Merz et al., 2010b; Smith, 1994; White, 1945, 1964). Flood damage is generally classified into four categories according to the damaging process, *i.e.* direct or indirect damage, and to whether or not it can be evaluated in monetary values, *i.e.* tangible or intangible damage (Merz et al., 2010b). In the context of network infrastructures, we expand this classification in order to distinguish internal from external damage. On the one hand, internal damage is the impact of floods on the network itself; including infrastructure direct damage and the indirect dysfunctions inside the network environment. For example, the damage of a power transformer station can lead to the disruption of several components of the power-supply network. External damage is, on the other hand, the indirect impacts of the disruption of networks on the environment that depends on the resources and services offered by them (Blancher, 1998; Robert et al., 2003b; Røstum et al., 2008; Petit, 2009). For example; during the Var floods of June 2010, in France, 200,000 houses suffered from the absence of electricity for about three days, due to the disruption of the network; during the same event, a railway between the cities of Nice and Toulon stopped working for four days, and several roads and bridges were destroyed[70].

The great majority of existing methods focuses on the evaluation of external indirect damage of networks. These include large-scale models dealing with indirect economic losses of natural hazards (Crowther et al., 2007; Hallegatte, 2008; Henriet et al., 2012), methods to evaluate damage induced by the disruption of transport, wastewater and electricity networks (Penning-Rowsell et al., 2005), damage induced by loss of accessibility to a territory (Demoraes, 2009; Demoraes and D'Ercole, 2009), by the disruption of the water system (Hardy, 2009), and by the interruption of gas distribution (Bouchon, 2009). In relation to internal direct and indirect damage to infrastructure, little data and no well-established models exist (Merz et al., 2010b). Penning-Rowsell et al. (2005) recommend using

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[70] French national press information.

the depth-damage approach for assessing direct damage of network infrastructures, however, no standard data is available. Though some mathematical models are used for evaluating networks direct and indirect damage (Dutta et al., 2001, 2003; Jonkman et al., 2008), they are designed for general use, and are applicable to all types of networks without taking into account high levels of detail. Very few methods were developed for forecasting flood damage to networks (Parker et al., 1987; Jonkman et al., 2008; Penning-Rowsell et al., 2005; Dawson et al., 2011). In addition, the few methods that exist generally adopt large-scale analyses ignoring the functional aspect of the networks themselves.

In France, the studies analysing damage to networks mainly focused on the investigation of former real damage (CEPRI, 2008). The majority of them evaluate damage to road infrastructures. Only a few studies analysed former damage regarding multiple networks (MEDD, 2005a; S.*I.E.*E., 2005; Ecodécision, 2006; MEDD, 2005b). Former flood events feedback shows that networks internal damage represent a large percentage of total direct damage caused by floods in France (Lefrou, 2000; Huet, 2003; MEDD, 2005b; Ecodécision, 2006; Vinet, 2003). These studies are also limited to the evaluation of damage in large scales, ignoring the complexity of networks' internal dysfunctions. Only the study developed by Desgranges (1999) takes into account the technical dysfunctions of networks in an *ex ante* approach, proposing flood scenarios for network managers for the Seine and Marne rivers. D4E (2007) a,d CEPRI (2008) highlight that networks are barely considered in flood damage evaluations in France.

Studies analysing the behaviour of networks under hazardous circumstances are useful for understanding network inter- and intra- connections, *e.g.* catastrophe feedback (Lau et al., 1995; Adachi and Ellingwood, 2008), systemic methods for evaluating network infrastructures vulnerability to earthquakes (Menoni et al., 2002), interdependencies between different networks (Rinaldi et al., 2001; Petit et al., 2004; Robert, 2002; Robert et al., 2003a; Robert et al., 2003b; Robert et al., 2003c; Chiaradonna et al., 2011; Ge et al., 2010; Johansson and Hassel, 2010; Ouyang et al., 2009).

1.3. Resilience and network infrastructures

The resilience of socio-economic systems to floods is intrinsically linked to the capacity of networks owners and operators to deal with flood damage and dysfunctions during and after floods (Pelling, 2003). The understanding of the vulnerability of network infrastructures and their functioning and dysfunction potential in the case of natural disaster is therefore the core of urban resilience against natural hazards. Knowledge concerning the vulnerability of network infrastructures is also the main step toward the construction of schemas for reducing flood-related risks. However, the complexity of network infrastructures, their technical components and the different links and dependencies between them is one of the primary factors in the current misunderstanding of their damage-dysfunction potential in case of flood. The complex organization of systems also contributes to the multitude of network infrastructure vulnerabilities (Narbonne, 2005; Petit, 2009). Flood consequences on network infrastructures depend upon the complexity of the overall structure of its components and their material, functional and structural vulnerabilities (Blancher, 1998; Ecodécision, 2001; CERTU, 2002; MEDD, 2005b; SOGREAH and ASCONIT, 2006; Petit, 2009). The following schema represents the different relationships between network components and how flood impacts propagate through them (Figure 10.2).

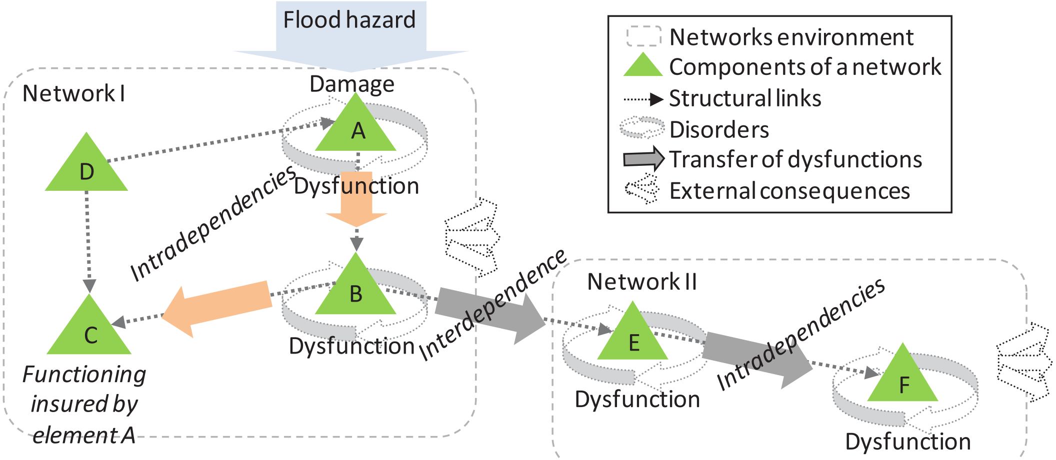

Figure 10.2. Relationships between network infrastructures in case of flood.

When a network component is reached by floodwater, its material vulnerability determines whether it may suffer damage. Similarly, its functional vulnerability determines its dysfunction potential. In Figure 10.2 the intra-dependencies between network components are represented by the structural links between the components A, B, C and D, and the networks interdependence is represented by the structural link between the components B and D. Considering the dysfunction of the component A, the transfer of dysfunctions may follow the pathway indicated in Figure 10.2. We can notice that a component individual mission can also be compromised independently of its direct contact with floodwater (components B in Figure 10.2). The impact of infrastructure dysfunctions on the functioning of other components is related to the structural vulnerability of these components, *i.e.* domino effect (Gleyze and Reghezza, 2007).

Each component of a network has its own vulnerability to floods and network hazards, highly increasing the complexity of these analyses. The evaluation of network-related risks is inherent to substantial uncertainty (Røstum et al., 2008). The needs for network damage and dysfunction evaluation methods are highlighted by several studies (Bouchon, 2005; Røstum et al., 2008; Petit, 2009; Merz et al., 2010b; CEPRI, 2008; D4E, 2007). Despite the fact that the understanding of this process is crucial to work on the resilience of a territory, no standard method exists for forecasting dysfunctions of network infrastructure. Supplementary approaches are necessary for taking into account the functional and systemic aspect of networks (Gleyze, 2005; Léone, 2007). A systematic approach that takes into account network infrastructures internal damage and dysfunction potentials in an elementary scale is therefore needed for analysing the disruption and external damage of networks (Robert, 2002).

1.4. Objectives of this chapter

The present work aims at reducing the lack of damage and dysfunction assessment methods highlighted in literature. We propose a new methodology to analyse network infrastructures' internal vulnerability to floods. In contrast to existing approaches, this method provides an elementary description of networks by the development of damage-dysfunction matrices, which puts the individual components of the network at the centre of the analysis. We focus on both damage and dysfunctions generated inside the network environment, possibly leading to disruption of services. The methodology takes into account the systemic organization of networks, their material and functional vulnerability and their intra- and interdependency. It is based on the following principles: the network is considered as a grouping of components with specific functions and vulnerabilities, the creation of damage-dysfunction matrices for summarising the information concerning the different components of networks, and the help and involvement of network experts in order to develop the damage-dysfunction matrices. These different principles as well as the different steps of the method are presented in the first part of this article. We illustrate the method with a case study in Alsace, eastern France. The second part of the work presents the results of the method highlighting its advantages, limits and drawbacks.

2. Method principles

The analysis developed here brings together qualitative and quantitative aspects of the flood risk in order to summarise the functioning and vulnerability of networks. It determines damage and dysfunction of components of a network in the case of floods as well as the types of action required, and resources necessary for dealing with them. A network component damage-dysfunction matrix is organised in six charts correlated as follows (Figure 10.3).

We consider that each component of the network is vulnerable to external hazards by direct contact with floodwater, *i.e.* flood hazard, or by transfer of vulnerability from other components, *i.e.* network hazard. The chart I (Figure 10.3) is the core of the methodology. It provides a quantitative description of the circumstances that may cause damage and/or dysfunctions to the component analysed. The damage and dysfunctions of this component can be the origin of other network hazards, by transferring dysfunctions to other components. Charts II and III provide qualitative descriptions of the component potential types of damage and dysfunction. They describe the consequences of the hazards on the component analysed. Chart IV identifies which components from the same network can be impacted by the dysfunction of the given component. This impact depends on the potential of the component to transfer vulnerability, according to the structural organisation of the network analysed. Chart V describes the different actions necessary to ensure the functioning of the given component or to repair damage. Finally, the Chart VI summarizes quantitative data concerning time and monetary values necessary to ensure the component functions and to repair the damage incurred. The construction of these damage-dysfunction matrices is organized in three steps, described hereafter.

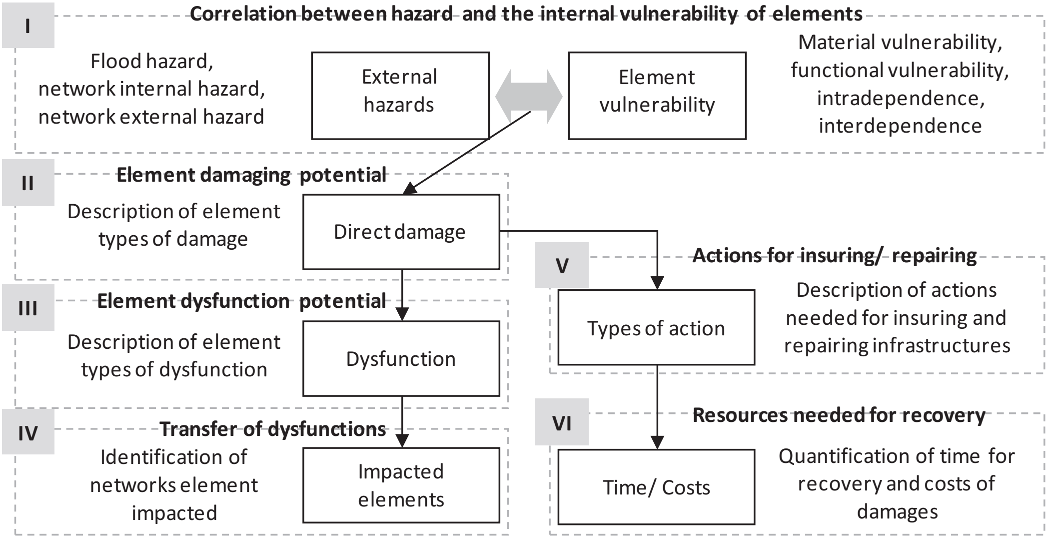

Figure 10.3. Structure of damage-dysfunction matrices.

2.1. STEP 1: Data collection and interviews organisation

The first step of the present method is used to gather information about the network under analysis in order to: (1) rank its different components according to their functional hierarchy and their damage-dysfunction potential; (2) identify experts and organize the interviews.

2.1.1. Elementary organisation of the network

The understanding of the network structural organisation starts with the classification of the different missions inside the network. It is also essential to identify the different components supporting these missions as well as their technical apparatus. For example, we present in Table 10.1 the different components and technical apparatus insuring the different missions of the combined sewerage and drainage network. This stage establishes a synthetic network by listing its different elements and their specific missions. It also promotes a first level of understanding of the different relationships between the components inside the networks (*cf.* Figure 10.2). Technical studies describing the organisation and the composition of network infrastructures are necessary to summarise the structural functioning of networks. They are also necessary to identify which components of the network are potentially impacted by floods, for further construction of damage-dysfunction matrices. According to Petit (2009), the functions of the components of a network can be classified as “critical” and “support”. This classification is established according to the difference of functional importance of components of a network, *e.g.* the failure of an electricity transformer leads to the dysfunction of several subsequent components of the power network, which is not the case for the dysfunction of an individual electricity connection that would not affect the functioning of the system. Penning-Rowsell et al. (2005) and Scawthorn et al. (2006b) have proposed classifications based on filtering processes, in which only part of the network components are selected for in depth analysis. They focused on the actual relationships between network components at risk, *e.g.* comparison of the number of nodes connected to specific components. Instead, the classification proposed here focuses on the general systemic organisation of networks. We hierarchically classify its components according to their theoretical structural dependencies. This classification allows establishing the functional hierarchy between the different network components.

Table 10.1. Description of the combined sewerage and drainage network distinguishing its missions, components and the technical apparatus.

Missions	Components	Technical apparatus
Collect sanitary and storm flows	Customer service connection	Customer sewerage, backwater valve, inspection chamber, public sewage water pit.
	Drain system	Curb, gully pot (catchbasin), manhole.
Transport wastewater	Sewerage pipelines	Gravity pipes, pressure pipes, connections.
	Pumping station	Screens, collection tank, pump, power supply box, alarm equipment, ventilation pipe, backwater valve, isolating valve.
Maintenance of network	Manhole	Inspection chamber, ventilated manhole,
	System cleaning	Flushing tank, outlet mechanism.
Retention of fines and suspend solids	Sludge/mud trap	-
	Screening system	Screen, chamber, motor.
Discharge excess wastewater	Combined Sewer Overflow	Related Bypass, wastewater storage tank, control device.
Store and treat wastewater	Sewage treatment plant	Utility buildings, coarse screens, tanks (sedimentation, aeration, sludge...), clarifier, sludge digesters, mechanical equipments, electric equipments, chlorine contact chamber, control rooms.
	Reservoir, Lagoon	-
Discharge treated water in environment	Outfall system	Outfall sewer, backwater valve.

2.1.2. Semi-structured interviews

The involvement of network operators, utilities and technical staff is crucial for the understanding of networks (CERTU, 2002). The construction of these damage-dysfunction matrices is mainly based on expert knowledge in order to fully comprehend the links between different components of networks and determine their technical characteristics and vulnerability. As for the construction of damage functions (Green et al., 2011), we suggest that a variety of experts should be consulted. It is indeed necessary to identify the different stakeholders as sources of practical knowledge, and to prepare the expert interviews. Individual and grouped semi-structured interviews need to be prepared in order to completely apprehend the expert technical knowledge. The interviews developed here focus on three main topics:

- direct impacts and cost of damage – to identify which components are the most susceptible to suffer damage in case of floods, and to describe the types of damage and induced costs for the different network components;
- vulnerability indicators – to describe the essential vulnerability parameters for the different network components, their material and functional vulnerabilities, their dependence on other networks infrastructure, their probability to suffer damage considering different scenarios of floods, and the potential vulnerability reduction measures;
- indirect impacts and transfer of vulnerability – to list and quantify what is necessary for re-establishing the functions of the different network components, to analyse the relationship between direct and indirect internal dysfunctions, to identify the consequences of the components dysfunction on other network components analysed.

A fourth topic related to Geographic Information System (GIS) and feedback data availability was also developed in order to guide the construction of damage-dysfunction matrices for general applications. These discussions have to be oriented for a general hypothetical network analysis, in order to avoid and/or identify site-dependent characteristics.

2.2. STEP 2: Damage-dysfunction processes

This step analyses the way the different components of a network can suffer damage or compromise their specific functions considering their multiple vulnerabilities, *i.e.* damage-dysfunction processes. On the one hand, this step consists of determining the material and functional vulnerabilities of different components in direct contact with floodwater. On the other hand, this step analyses the components structural vulnerability, in correlation with the potential of networks to transfer vulnerabilities, due to their systemic organisation. These two aspects are analysed based on expert knowledge. It is the core of the method leading to the development of the Charts I, II, III and IV of damage-dysfunction matrices (Figure 10.3).

2.2.1. Material and functional vulnerability

The evaluation of both material and functional vulnerabilities is necessary in order to comprehend the potential dysfunctions of network infrastructures (Hubert and Ledoux, 1999). Different types of internal damage can occur in given component, *e.g.* short-circuit of electronic devices, destruction of fragile technical apparatus, etc. However, the network components can be exposed to floodwater and continue to ensure their function, *e.g.* an electronic device within a specific network can be vulnerable to floodwater and suffer damage without ceasing to function; or not suffer damage but nonetheless stop functioning, *e.g.* a mechanical device can be protected against water by an interruption mechanism which will stop its functioning in case of flood. The technical analysis of the different components of the network is necessary at this stage of the methodology in order to distinguish and identify both vulnerabilities of network components. The understanding of the component susceptibility to floodwater is crucial for the analysis. The adopted approach is based on the *ex ante* analysis using "what-if" questions to construct stage-damage functions (Merz et al., 2010b; Messner et al., 2007). During the semi-structured interviews with experts, several flood scenarios are considered to analyse the different types of component (*cf.* Figure 10.4). This approach makes it possible to establish the correlation between hazard characteristics and components' vulnerabilities, with the ultimate goal of determining which circumstances could cause damage and/or dysfunctions to components. This leads to the construction of qualitative damage functions that describe the types of potential material damage of a component ($Dam_{material}$) as a function of flood hazard parameters (F_{par}), the component material vulnerability (V_{mat}), *cf.* Equation (10.1). Further, we describe the types of potential direct dysfunction of a component (Dys_{direct}) as a function of its potential material damage, the component functional vulnerability (V_{func}) and crises organizational aspects, *cf.* Equation (10.2). These functions are integrated to the Chart I of the damage-dysfunction matrices (Figure 10.3):

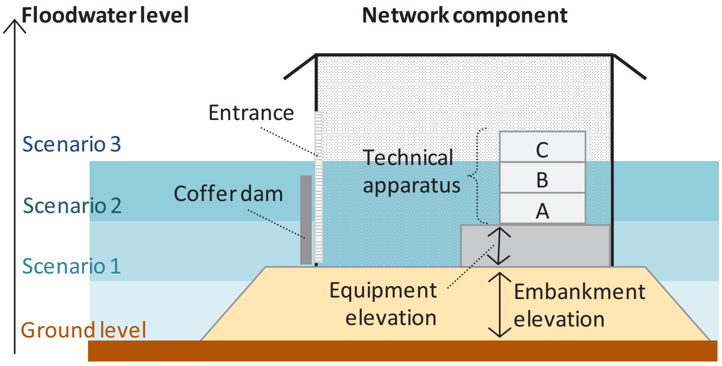

Figure 10.4. Flood vulnerability indicators to consider in the analysis of network components susceptibility to suffer damage and dysfunctions due to direct contact with floodwater.

$$Dam_{material} = f\,(\,F_{par},\,V_{mat}\,) \tag{10.1}$$

$$Dys_{direct} = f\,(\,Dam_{material},\,V_{func},\,C_{org}\,) \tag{10.2}$$

In order to illustrate this stage, we describe the vulnerability analysis concerning the *pressure regulator station* of the gas distribution network. We represent this specific component in Figure 10.4 considering that: the technical apparatus "A" corresponds to the *utility box;* and the technical apparatus "B" corresponds to the *distance-monitoring device*. The contact of the equipment with floodwater depends on the water level, on the elevation of the infrastructure supporting the component, on the disposition of the technical apparatus inside the component and finally on the existence of flood protection devices (*e.g.* coffer dam). Only the flood scenario "3" implies the contact of floodwater with the technical apparatus (Figure 10.4). In this case, the contact of floodwater with the apparatus "A" can induce the *failure of the equipment due to over-pressure* or the *device mechanical failure* depending on the type of equipment. The contact of floodwater with the apparatus "B" may lead to *short-circuit* of the equipment. These types of direct damage have to be described in Chart II (Figure 10.3) of the corresponding damage-dysfunction matrix, *e.g.* Figure 10.5. The failure of the apparatus "A" may lead to different dysfunctions of the network component. These dysfunctions may compromise its mission inside the network, *e.g. disruption of distribution*, *reduction of delivery pressure* or *increase of delivery pressure*. These types of dysfunctions have to be described in Chart III (Figure 10.3) of the corresponding damage-dysfunction matrix, *e.g.* Figure 10.5.

Concerning the hydraulic hazard parameters, *i.e.* water depth, flow velocity, duration of submersion, sediment and debris transport, they play different roles regarding damage potential, depending on the type of asset analysed (Thieken et al., 2005; Léone, 2007; Messner et al., 2007; Merz et al., 2010b). Each component of the network has to be analysed separately taking into account detailed technical characteristics in order to identify their main damaging influencing parameters. The correlation of damage and dysfunction with water depth is preferable for practical applications. The influence of other parameters should be further analysed to refine this analysis.

2.2.2. Structural vulnerability

We qualitatively describe the types of potential structural dysfunctions of a component as a function of two variables: the component degree of intra-dependence, and the component degree of interdependence. We measure the degree of intra-dependence between two components by evaluating the potential of the network component to transfer dysfunctions to other components hierarchically equal or inferior to it. For example, the dysfunction of a *control/power supply box* in the public lighting network may lead to the dysfunction of all the *street lighting columns* connected to this equipment. Another example concerns the dysfunction of the gas network *pressure regulator station* that may induce the dysfunction of *other gas pressure regulator stations* as well as *service boxes* connected to it. The interdependence is correlated to the dependence of a component on services supported by other networks (Røstum et al., 2008), *e.g.* exchanges between the components B and E (Figure 10.2). The same analysis is undertaken to consider this parameter in the evaluation process. We measure the degree of interdependence of a component by investigating the dependence of its technical apparatus on components from other networks. Considering the example of the gas network *pressure regulator stations*, the *distance-monitoring device* represented now by the apparatus "C" (Figure 10.4) may dysfunction if the telephone network fails, even though it is not reached by floodwater. This information has to be represented in Charts I and IV (Figure 10.3) of the damage-dysfunction matrix (*e.g.* Figure 10.5).

2.3. STEP 3: Quantification of damage and dysfunctions

This step quantifies damage to networks considering the different actions and resources needed to deal with it. We describe the types of action and quantify the costs and time necessary to ensure or recover the functioning of a network component. This last step achieves the damage-dysfunction matrices development, completing the Charts V and VI (Figure 10.3). It is also based on expert information, and can be carried out in parallel to the second step. However, the quantitative aspect explored here is linked to the context in which the analysis is realised, *i.e.* site-dependent.

2.3.1. Measures for insuring functions /repairing infrastructures

Network utilities and operators have to deal with the dysfunctions of component in order to avoid damage and disruptions of services offered by their network. At this stage, we describe the interventions that need to take place during a flood event (generally to avoid material damage and/or ensure the continuity of services offered by the network); or after a flood event (to repair damage, check the components and recover the disrupted services). We correlate these actions with the different types of damage identified in the precedent steps. For example, if floodwater reaches a *power transformer station*, the precedent step allows to conclude that it may be damaged by *short-circuit*, inducing the dysfunction of the *service boxes* connected to it (due to absence of power). At this stage of the analysis, we conclude that: (1) during the flood event, the dysfunction of other network components may be avoided by insulating the damaged component (*installation of by-pass system to ensure service*); (2) after the flood event, the equipment may be *cleaned*, and it should be *repaired* or *replaced* depending on the degree of damage incurred. Organizational aspects of the network operators and utilities shall be comprehended through the expert interviews at this stage. This information has to be represented in Chart V (Figure 10.3) of the damage-dysfunction matrix, *e.g.* Figure 10.5.

2.3.2. Resources necessary for adopting measures

Methods used for earthquake damage also consider this aspect (Scawthorn et al., 2006a; Scawthorn et al., 2006b), which is essential in order to proceed from the “evaluation stage” to the “acting stage”. On the one hand, we identify the amount of time necessary for adopting a specific measure, *e.g.* time necessary for replacing a water pump, or time necessary for cleaning a gas distribution network component. On the other hand, we quantify the costs necessary in order to repair, replace and/or clean affected elements. This data must be represented in Chart VI (Figure 10.3) of the damage-dysfunction matrix, *e.g.* Figure 10.5. Several studies propose quantifying the damage potential of an asset as a percentage of its initial value (Léone, 2007; Messner et al., 2007; Jonkman et al., 2008; Penning-Rowsell et al., 2005). In the case of network infrastructures, we notice that the replacement costs have also to incorporate the expenses induced by the short delay in insuring the continuity of services. This can compensate the real damage that can be more significant than material losses, justifying the correlation of the resources with the different potential measures for insuring the functions of the element or repairing infrastructures.

2.4. Case study

In applying the methodology proposed in this paper, several national studies were used in order to understand and gather the information related to the different networks analysed (method’s step 1). Technical information of networks could be found in professional documentation (RTE, 2004; SETRA, 1996b, a; Hamou, 2005; Vazquez et al., 2006) and on network stakeholders’ websites[71]. The following lifelines and infrastructures were analysed: sewerage and drainage, water supply, public lighting, gas distribution and power supply networks. Sixty experts from different institutions dealing with networks were interviewed[72] to construct damage-dysfunction matrices (method’s steps 2 and 3). Together with them, we analysed the structure of the different networks redefining the specific functions of the different components and the links between them. Twenty-five components of the different networks were selected for in-depth analysis (Table 10.2).

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[71] DirectIndustrie, Schneider-Electric, VHM-Heinrich, laviedesreseaux.fr, BVP, RTE, EDF, GRT-Gaz, GDF-SUEZ, Afgaz, Astee.

[72] The list of the experts and their institutions may be requested from the authors.

Table 10.2. The network components analysed for the construction of damage-dysfunction matrices.

Network	Components
Water supply	Water borehole, water treatment plant, pumping station, water pipelines.
Sewerage and drainage	Pumping station, sludge/mud trap, combined sewer overflow, automatic screening, outfall sewer, drain system, lagoon, sewage treatment plant, sewage pipelines.
Power supply	Electrical substation (high voltage), power transformer station (high voltage/low voltage), pole and distribution line (high voltage), service box.
Gas distribution	Pressure regulator station, switching substation, cathodic protection box, service box, shut-off valve, gas pipe.
Public lighting	Control and power-supply box, street lighting columns, floor luminary.

The damage-dysfunction matrices were used to analyse the potential impacts of the Bruche river floods on six towns in eastern France: Holtzheim, Oberschaeffolsheim, Wolfisheim, Eckbolsheim, Lingolsheim and Strasbourg. GIS data concerning a theoretical 100-years flood return-period event was used for evaluating network infrastructures damage and dysfunction potential. The application of the damage-dysfunction matrices implies the gathering of data related to network infrastructures analysed, following the application of a classic flood damage evaluation method (Merz et al., 2010b). Exposure analyses were realised for locating the network components inside the area in study (networks local GIS datasets were used during these analyses). Susceptibility analyses were made to identify the components vulnerability criteria and technical characteristics (*cf.* Figure 10.4) in cooperation with network local managers. Finally, a GIS-based method (Eleutério et al., 2010) was used to automatically combine the different data and calculate damage and dysfunction potentials for the different components analysed.

3. Results

3.1. Damage-dysfunction matrices

Damage-dysfunction matrices were developed for the different components analysed[73]. As an example, we present in Figure 10.5 a simplification of the damage-dysfunction matrix developed for analysing the *pressure regulator station* of the gas distribution network. This damage-dysfunction matrix summarises how damage and dysfunctions can occur to the component in question when it is reached by floodwater or when it is impacted by the dysfunction of components of other networks (in this case, telephone network access). The Chart I (Figure 10.5) of this damage-dysfunction matrix schematically represents qualitative damage functions, *cf.* Equations (10.1) and (10.2), and the different dependencies between the component analysed and other components. The interviews

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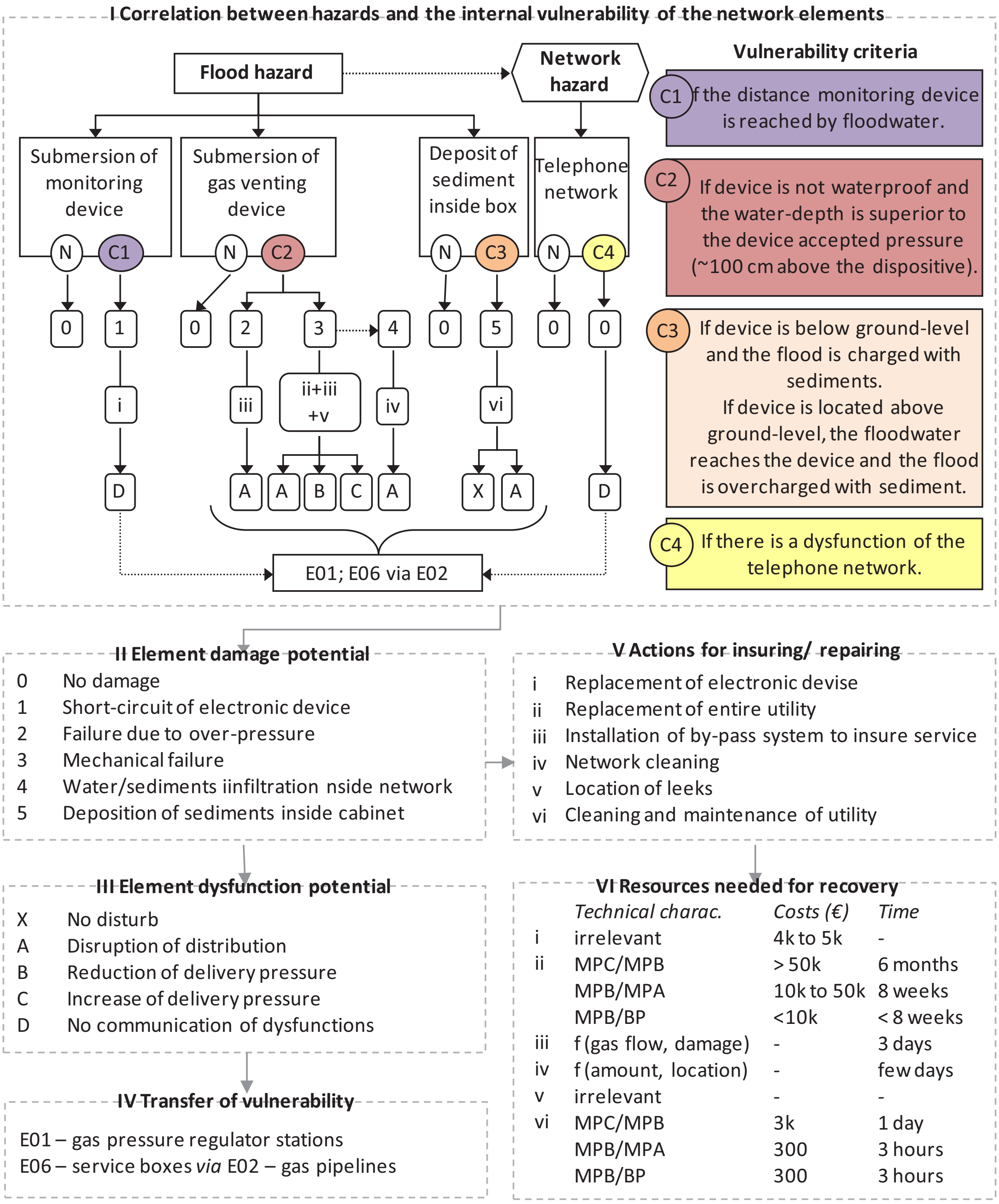
[73] The set of damage-dysfunction matrices used to illustrate this case-study can be found in Hattemer, C.: Méthodologie d'évaluation de l'endommagement primaire des réseaux d'infrastructures face au risque inondation, Master of science thesis, Montpellier III, Université Paul Valéry Montpellier, 142 pp., 2010.

revealed that the network experts are not able to quantitatively take into account other parameters than water depth, even though they insisted that those parameters could play an important role on the damaging of components. The resources for recovering from floods take into account the replacement costs of the damaged material (technical apparatus and work costs) and the estimated time necessary to do it (Chart VI Figure 10.5). These resources depend on the technical characteristics of the component and the context of the study.



C1 If the distance monitoring device is reached by floodwater.

C2 If device is not waterproof and the water-depth is superior to the device accepted pressure (~100 cm above the dispositive).

C3 If device is below ground-level and the flood is charged with sediments. If device is located above ground-level, the floodwater reaches the device and the flood is overcharged with sediment.

C4 If there is a dysfunction of the telephone network.

II Element damage potential

0	No damage
1	Short-circuit of electronic device
2	Failure due to over-pressure
3	Mechanical failure
4	Water/sediments iinfiltration nside network
5	Deposition of sediments inside cabinet

III Element dysfunction potential

X	No disturb
A	Disruption of distribution
B	Reduction of delivery pressure
C	Increase of delivery pressure
D	No communication of dysfunctions

IV Transfer of vulnerability

E01 – gas pressure regulator stations
E06 – service boxes *via* E02 – gas pipelines

V Actions for insuring/ repairing

i	Replacement of electronic devise
ii	Replacement of entire utility
iii	Installation of by-pass system to insure service
iv	Network cleaning
v	Location of leeks
vi	Cleaning and maintenance of utility

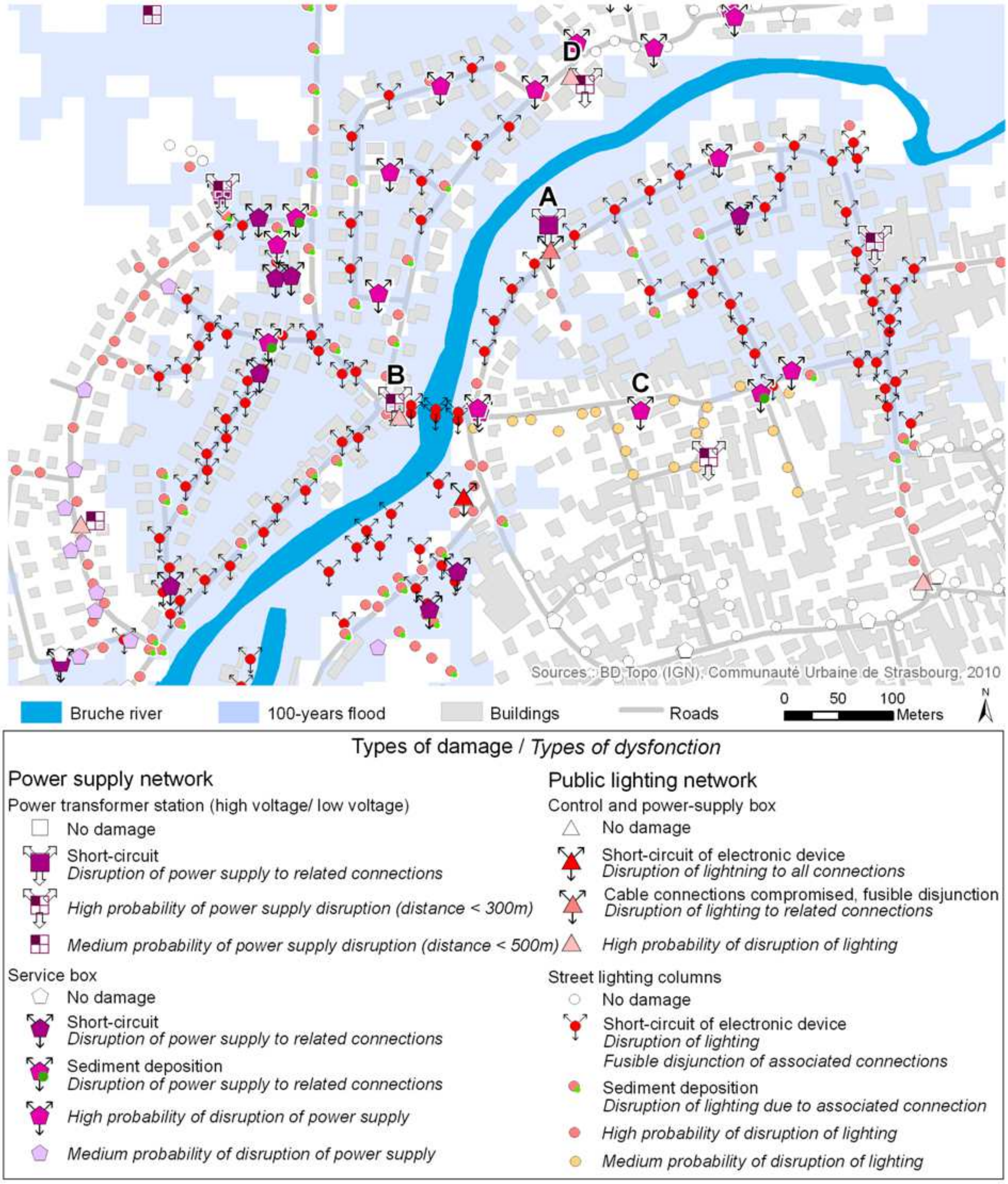
VI Resources needed for recovery

	Technical charac.	*Costs (€)*	*Time*
i	irrelevant	4k to 5k	-
ii	MPC/MPB	> 50k	6 months
	MPB/MPA	10k to 50k	8 weeks
	MPB/BP	<10k	< 8 weeks
iii	f (gas flow, damage)	-	3 days
iv	f (amount, location)	-	few days
v	irrelevant	-	-
vi	MPC/MPB	3k	1 day
	MPB/MPA	300	3 hours
	MPB/BP	300	3 hours

Figure 10.5. Damage-dysfunction matrix - pressure regulator station of the gas distribution network.

3.2. Evaluation of damage and dysfunctions

The key result of this method is the determination of the types of potential damage and dysfunctions generated by the floods on the networks analysed. In Figure 10.6 and Figure 10.7, we present the network internal dysfunction maps obtained through the application of the matrices developed in this work.



Sources : BD Topo (IGN), Communauté Urbaine de Strasbourg, 2010

Figure 10.6. Map of damage-dysfunctions induced by a 100-years return-period flood for the components of public lighting and power supply networks.

In Figure 10.6, we analyse two interdependent networks in a flood context: the power supply and public lighting networks. We demonstrate the different relationship between components of those networks (*cf.* Figure 10.2) taking a *power transformer station* (component A in Figure 10.6) as an example. This component is potentially damaged because of the submersion of its technical apparatus: *short-circuit* revealed by the technical analysis of the relationship between the flood hazard and the component vulnerability indicators (*cf.* description of example in Figure 10.4). This damage generates a primary dysfunction of the component, the *disruption of power supply to related connections*. The dysfunction of this component generates other subsequent dysfunctions due to the structural vulnerability of the network:

- dysfunction of components of same hierarchic level - other *transformers* directly connected to it (series connection), *e.g. transformer* not reached by water (component B in Figure 10.6). The experts suggested that the components located in a distance of less than 300 meters from the damaged transformer have a high probability to be affected by the dysfunction. In an urban context, the bigger the distance from the dysfunctional *transformer* is, the bigger the uncertainty is, once there is a possibility of the component being linked to another transformer in parallel. Network node analyses may be used to reduce this uncertainty. The second level of dysfunction is not represented in the map due to the high level of uncertainties, *e.g.* crises management can be structured in order to avoid this second level of dysfunctions by isolating the dysfunctional *transformers* and by using different sources of power supply for the others.
- dysfunction of service boxes because of the absence of energy. The transfer of vulnerability to hierarchically low components (*service boxes*) connected to the failure component, *e.g.* service box not reached by floodwater (component C in Figure 10.6). The dysfunction of *service boxes* induce other dysfunctions, *e.g.* other service boxes connected in series, and external damage, *e.g.* damage to the clients connected to the service boxes.

The analysis of the public lighting network dysfunctions is similar to the precedent one. The contact of floodwater with network components may generate damage and/or dysfunctions. Those dysfunctions may be transferred to other components inside the network because of their intra-dependencies, *e.g.* transfer of dysfunctions from *control/power supply boxes* to *street lighting columns* in Figure 10.6. A difference from the precedent example is that the public lighting network functioning depends on the power supply network, *i.e.* networks interdependence. The dysfunction of a *power transformer station* may induce the dysfunction of public lighting network components. For example: the public lighting *control and power supply box* (component D in Figure 10.6) may suffer from absence of power, due to the disruption of the *power transformer station* (component B in Figure 10.6); this disruption generates secondary indirect dysfunctions to *street lighting* columns connected to this element. Modelling approaches based on the structural links of the network can be used to enhance the analysis of the transfer of vulnerability between components.

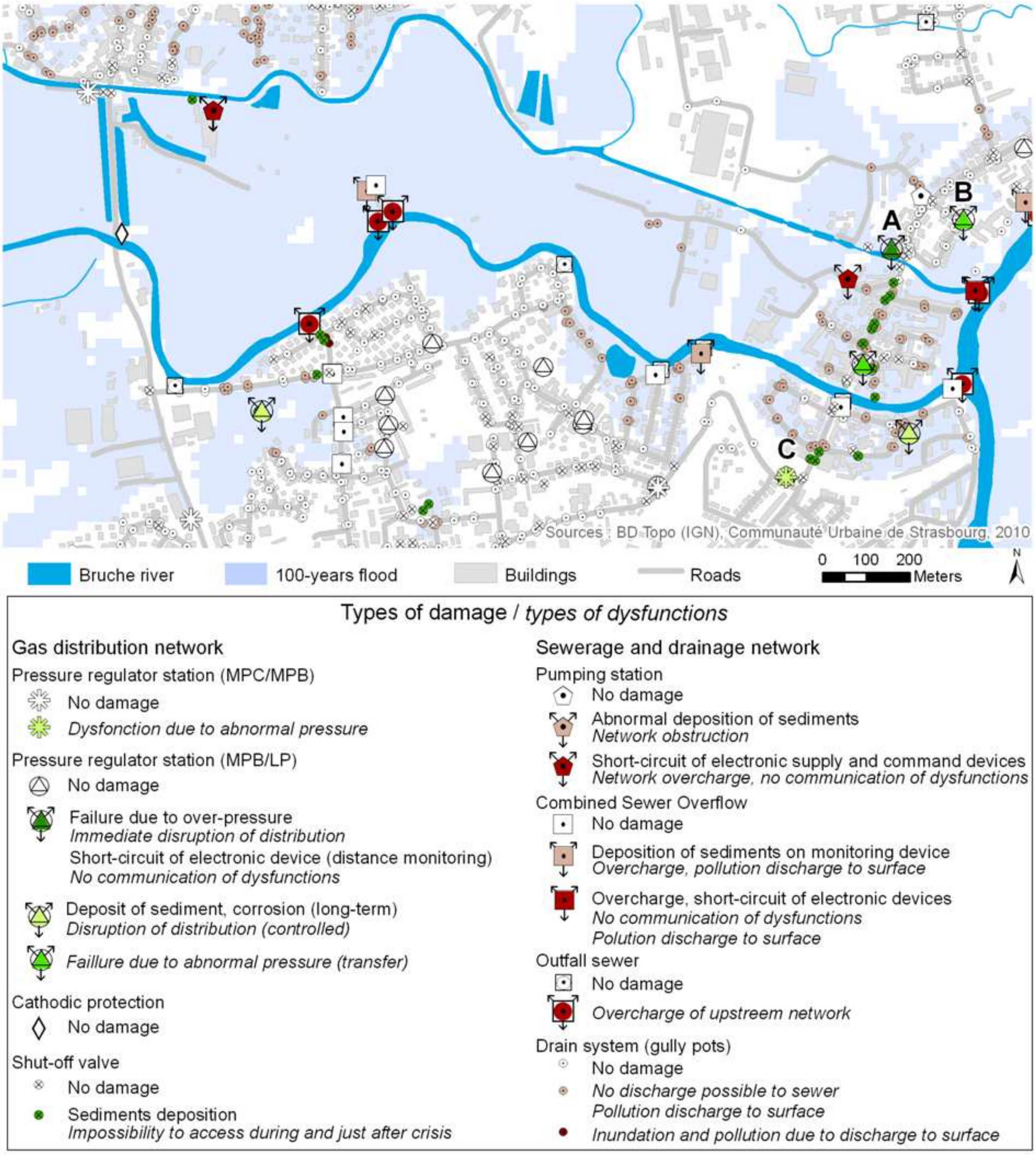
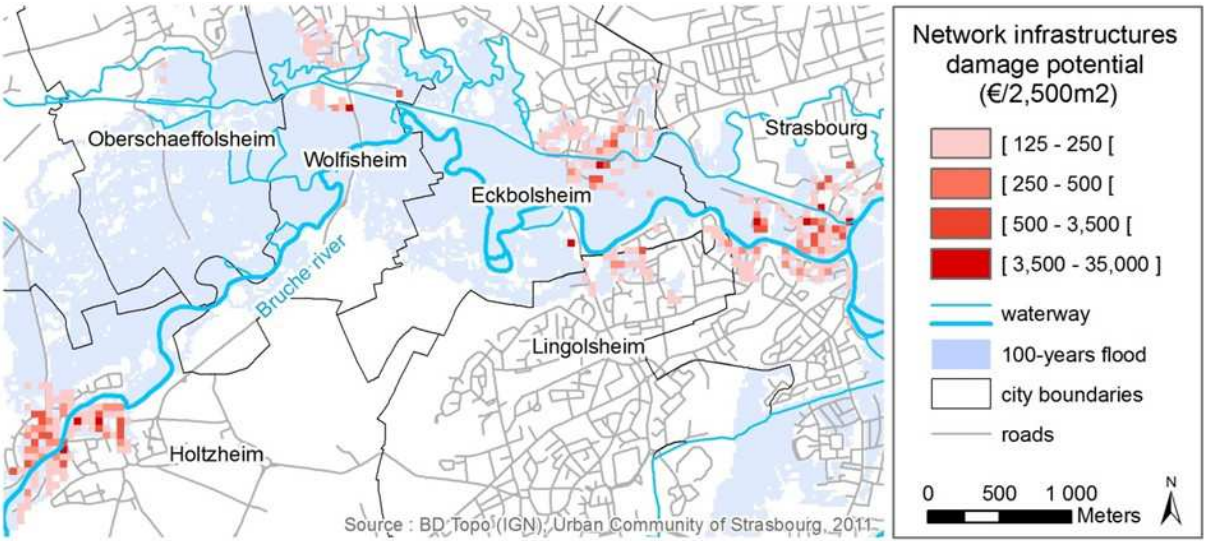


Figure 10.7. Map of damage-dysfunctions induced by a 100-years return-period flood for the components of gas distribution and sewerage/drainage networks.

Figure 10.7 analyses the damage and dysfunction potential of the gas distribution and sewerage/drainage networks. As an example, we analyse the dysfunction of the *pressure regulator station MPB/LP* due to the *submersion* of its *gas venting device* and *monitoring device* (component A in Figure 10.7). The damage-dysfunction matrix of this component (Figure 10.5) displays its vulnerability to floods and its relationships with other network components. Damage caused to these apparatus induces on the one hand the *immediate disruption of gas distribution*. Similarly to the precedent example, this dysfunction is propagated to other components outside the flooded area, *e.g.* to other *pressure regulator stations MPB/LP* connected to it (components B and C in Figure 10.7), and to the costumers' service boxes connected to it (not represented in the map). The components reached by this deregulated pressure may automatically stop functioning and suffer from the interruption of gas distribution. On the other hand, the damage to the *distance-monitoring device* (inside the *pressure regulator station*) may lead to the non-communication of the *pressure regulator station dysfunction* to the network managers. This type of dysfunction will reduce the possibility of the managers to act during the crisis period, increasing the risk of propagation of dysfunctions inside and outside the network.

These maps can be used for anticipating potential network dysfunctions, fostering crises management policies. The information contained in this case study promotes the reflexion of what kind of measure should be adopted in order to reduce the flood risk, insuring the continuity of the networks. It reveals for example that in case of flood, a damaged component (component A in Figure 10.7) should be insulated by the *installation of by-pass system* to ensure the service to subsequent equipment. It also reveals that the dysfunction of this component would not necessarily be known during the crisis period. The interdependence of this component to the telephone network, can also lead to the *no communication of dysfunctions* in case of dysfunctions. This information allows the crises manager to anticipate, and re-think crisis management policies. The identification of the location of *shut-off valves,* which could not be accessed during or just after crisis (*cf.* Figure 10.7) also feeds the crisis organisation planning, once their accessibility is essential for avoiding the propagation of dysfunctions. We can also display the results of this evaluation in a general damage map (Figure 10.8).



Source : BD Topo (IGN), Urban Community of Strasbourg, 2011

Figure 10.8. Map of damage costs induced by a 100-years return-period flood on the grouping of network components analysed: sewerage and drainage, public lighting, gas distribution and power supply.

This map represents the 100-years flood internal direct damage potential of the networks infrastructure analysed. It represents the sum of the damage potential (replacement/repairing costs) for the different components of the overall networks analysed. This damage is exclusively located inside the flood area and they represent only part of total damage induced by floods on networks infrastructure.

This estimation of potential monetary damage is an important aspect to take into account for supporting flood management projects (Messner et al., 2007; Merz et al., 2010b). It allows locating areas that concentrates direct damage. The spatial location of damage potential supports the design of flood protection and the quantification of damage costs can be useful for realising cost-benefit analyses for large management planning.

4. Discussion of results

These results presented here describe the potential of the method to apprehend the complexity of networks in case of floods. Maps identifying the different components of a network and their damage-dysfunction potentials are powerful tools for supporting actions to reduce vulnerability, as well as for estimating the external consequences of hazard networks, *i.e.* indirect damage. The elementary comprehension of the network should considerably support *ex ante* policies for the protection of networks from risks. However, the present case study reveals the difficulty in correlating flood parameters with network components' vulnerability due to technical lack of knowledge of how the different components of the network react to different flood parameters. Nevertheless, experts have highlighted that the duration of submersion, flow velocity and the amount of sediments/debris carried by floodwater are crucial damage-dysfunction influencing parameters. It is in accordance with Kreibich et al. (2009), that has identified that transport infrastructures are strongly influenced by flow velocity. It also revealed the difficulty in apprehending the intra and interdependences of different network components. However, they highlighted the essential roles of the power-supply and transport networks related to the interdependence of networks in case of floods. Several crisis management actions depend on the accessibility to a specific local and the power availability.

A disadvantage of this method is the amount of data needed for the application of damage-dysfunction matrices. The gathering of data relative to the different network infrastructures proved to be the most difficult step during the application of damage-dysfunction matrices. It has been stated that little data is available concerning network infrastructures, as highlighted by Merz et al. (2010b). When data is available, it often barely corresponds to the level of details required for the analysis. We also noticed that network managers and operators do not completely comprehend the systemic complexity of their networks, as inferred by lack of data and models within their organisation. The application of graph theory for analysing network's complex organization is one of the approaches that could be used for estimating that network's complexity (Gleyze, 2005; Jenelius et al., 2006; Sohn, 2006; Winkler et al., 2010). In order to conserve the systemic character of the evaluation, we suggest that it be conducted in a long-term perspective, within organisations and companies responsible for managing networks, thereby fostering a better understanding of the systemic complexity of networks.

A considerable degree of uncertainty is still associated to this method, notably, to the estimation of resources necessary for repairing/recovering involves These values depend on several criteria, *e.g.* the importance of the component for the functioning of the network, the possibility to temporally replace the component with a bypass system, the existence of the component in the local market, component specific characteristics if civil engineering works are necessary, the labour cost, etc. This uncertainty must be considered when using these matrices. The lack of former damage feedback and the number of factors governing damage to infrastructure could provide an explanation for this high-level of uncertainty (Dutta et al., 2003). Field surveys and the involvement of network technical apparatus constructors can help to reduce these uncertainties.

5. Conclusions and perspectives

The evaluation of damage and dysfunctions inside the network environment as well as the structural vulnerability of network infrastructures proved to be essential for understanding a network's susceptibility to floods. The general methodology presented here aimed at reducing the lack of damage and dysfunction evaluation methods highlighted in literature (Bouchon, 2005; Røstum et al., 2008; Petit, 2009; Merz et al., 2010b; CEPRI, 2008; D4E, 2007). The significant involvement of network experts in our method makes a comprehensive understanding of the organisation of networks and their vulnerabilities. When considering the elementary scale of networks, we were able to identify the most relevant infrastructures in terms of damaging and dysfunction potential, thus providing operators with the knowledge necessary to improve the resilience of their networks. This approach also fosters the analysis of interdependencies between networks promoting multi-network analyses (Petit, 2009; Dudenhoeffer et al., 2006; Røstum et al., 2008). Further research should focus on the comprehensive description of interdependences between networks in an elementary scale. The elementary description of assets implies large efforts in data collection. However, it limits uncertainties concerning the functioning of a network. The elementary asset-centred description of networks allows the method developed here to be easily transposed to other hazards.

The application of this method in the French context revealed network managers and operators to be extremely interested in this kind of information. The large number of experts and their significant involvement during the different interview sequences reflected this fact. Network stakeholders were curious about our method as soon as they are interested in both their vulnerability to floods and in reducing infrastructures damage/dysfunctions. The method's application also revealed that a great deal of detail regarding data is required for the understanding of networks, encouraging managers and operators to develop their organization. The level of uncertainty in the evaluation is completely dependent on the amount of data, its quality and the local operators experience with flood events. The improvement of network knowledge through the increasing use of GIS platforms within network institutions and the attention given to networks' vulnerability to floods should incite practitioners to apply systemic methods for understanding the functioning and dysfunction potential of network infrastructures more frequently.

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GENERAL CONCLUSIONS

Economy is the main pillar of the organization of contemporary society. The growing level of damage caused by natural hazards and their economic consequences lead to the fact that economic risk-based analysis became a fundamental issue for guiding risk management and control strategies. Flooding is the most damaging natural hazard in the World. The damage they cause and their climate-change potential influences are both at the origin of several apprehensions all over the world. In Europe, this concern was translated into the EU Floods Directive 2007/60/EC that states that flood management should be based on the results of flood risk assessments including the economic valuation of flood consequences. Better understanding on the flood hazard phenomenon and its potential consequences is crucial for the development of flood control policies, risk reduction projects and other types of flood management strategies. Despite that the great technological improvements occurred over the last decades contributes to better understanding of the different components of the risk, practical aspects of risk assessments still lead to different uncertainties on flood risk appreciation.

This thesis aimed at improving the global understanding about the flood risk by exploring the different sources of uncertainty related to flood risk assessments. It focuses on how different strategies used to model flood hazards and assess the vulnerability of a territory affect the results of potential flood damage estimations. With this purpose, we proposed in PART I of this manuscript a method to analyse the sensitivity of flood direct damage estimations to uncertainty of their different modelling processes, *i.e.* hydrology analysis, hydraulic modelling, vulnerability assessments and assets damage modelling. The uncertainty tests achieved in PART II of this thesis revealed the importance of each aspect of the evaluation on its accuracy. It revealed that direct damage estimates can be highly influenced by the methods used during the estimation process. On the one hand, uncertainties linked hydrological aspects together with those related to hydraulic modelling and flood protection structures efficiency play an important role on the evaluation process. Similarly, uncertainty on vulnerability and susceptibility assessments induced important variability on damage estimations. On the other hand, uncertainty linked to scale considerations of the river system as well as the scale considered to apprehend the vulnerability of territory are both crucial aspects to consider in the evaluation process. Large-scale analyses induced to relevant overestimation of damage in relation to analyses based on detailed descriptions of hazard and vulnerability. These results highlight the needs for in-depth analyses of data-related uncertainties when producing and using existing flood maps and asset datasets for flood risk assessment purposes. In despite that the use of complex methodological approaches to quantify global uncertainties is nowadays unrealistic in practical evaluations; the method developed here and its results should bring support for practitioners in the investigation of uncertainties, determination of evaluation priorities and optimisation of the distribution of resources between the different modules of the evaluation process.

Another supplementary and important source of uncertainty on flood risk estimations is linked to the indirect and secondary effects of floods. In the same manner that economy plays an important role on the organization of contemporary society, networks infrastructure are the core of the structural organization of cities and their functioning. The understanding of networks related-risks is essential for apprehending indirect effects of floods, and for insuring the good functioning of our society. The PART III of this manuscript explored this second level of complexity in the context of flood risk estimations. We developed a systemic method to analyse the damaging and dysfunction potentials of networks infrastructure in relation with the resilience of a territory to floods. The methodology developed should provide more detail possibilities in the estimations of flood damage bringing the possibility to improve indirect damage estimates.

In spite that these estimations are charged with uncertainty, they are powerful tools to improve the understanding of flood risks. Beyond the flood consequences analyzed in this thesis, floods also cause several human, social and environmental damage, which is much harder to appreciate in economic terms. The economic appreciation of the risk leads to a detail description of different aspects of the risk. The consolidation of standard estimations taking into account the different sources of uncertainty existing in the process as well as the different types of potential damage induced by floods remains a challenge for research.

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UNIVERSITÉ DE STRASBOURG

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Flood risk analysis: impact of uncertainty in hazard modelling and vulnerability assessments on damage estimations

By **Julian ELEUTÉRIO**

Abstract

This thesis aims at exploring different sources of uncertainty related to the economic analysis of the flood risk. It embraces several fields of knowledge in order to determine how the selection of strategies used to model flood hazard and assess the vulnerability of a territory may affect damage potential estimations. We measured the variability of damage estimations as a function of the datasets, methods, models and scales considered to: analyse the probability of floods (hydrology); model and map flood hazard (hydraulics); assess the vulnerability and susceptibility of properties to floods (civil engineering, geography and environmental economics). It highlights that the level of epistemic uncertainty linked to these evaluations is considerably high. The relative contribution of the different modules to global uncertainty depends on several aspects of the evaluation, including scale considerations and site specificities like the distribution of flood probabilities. The flood hazard module represents great part of uncertainties. The methods and analyses developed here should bring support for practitioners in the investigation of uncertainties, determination of evaluation priorities and optimisation of the distribution of resources between the different modules of the evaluation process. In order to explore a second level of complexity of flood risk evaluations, we developed a method for analysing the systemic vulnerability of infrastructure networks, in relation with their resilience. The methodology developed should provide more details in the estimates of flood damage, bringing the perspective of improvement of indirect damage estimations.

Keywords: hydraulic model; hydrology; flood simulation; expected annual damage; sensitivity test; scale analysis; natural hazard; GIS.

Résumé

Cette thèse contribue à l'amélioration des connaissances sur les différentes sources d'incertitude dans l'évaluation économique du risque inondation. Elle explore plusieurs disciplines afin d'analyser l'impact des stratégies utilisées pour modéliser l'aléa inondation et la vulnérabilité d'un territoire, sur l'évaluation des dommages potentiels. On a mesuré la variabilité des estimations en fonction des bases de données, modèles, méthodes et échelles considérés pour : analyser la probabilité des inondations (hydrologie) ; modéliser et cartographier l'aléa inondation (hydraulique) ; caractériser la vulnérabilité des enjeux et leur susceptibilité à subir des dommages (génie civil, géographie et économie de l'environnement). Il s'avère que ces évaluations sont chargées d'incertitudes épistémiques. La contribution relative des différents modules à l'incertitude globale dépend de plusieurs aspects, comme l'échelle d'analyse et les particularités du site analysé, dont la distribution des probabilités des crues. L'aléa demeure une importante source d'incertitudes. Les analyses et méthodes développées dans cette étude devront appuyer la prise en compte d'incertitudes, la détermination de priorités et l'optimisation de la distribution des ressources entre les différents modules de l'évaluation. Afin d'explorer un degré de complexité supplémentaire de ces évaluations de risque, nous avons développé une méthode d'analyse de la vulnérabilité systémique des réseaux d'infrastructure en lien avec leur résilience. La méthode développée devra permettre une analyse plus détaillée de cet aspect, ouvrant une perspective d'amélioration de l'estimation de dommages indirects.

Mots-clés: modélisation hydraulique ; hydrologie ; simulation de crues ; coût moyen annuel ; test de sensibilité ; échelle d'analyse ; risque naturel ; SIG.