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# Identifying how the strategies used to assess potential damages of future floods can affect the results of the evaluation

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## Abstract

The aim of this paper is to develop a research framework to analyze the impact of different strategies used to evaluate urban flood damages on the feasibility of the evaluation and on the accuracy of its results. Two main parts of the evaluation process are discussed: (1) hydrodynamic simulation of flood events and its hydrological components and (2) assessment of assets vulnerability to floods. The framework compares two aspects of the evaluation: uncertainty - variability of the evaluation results according to the choice of models and methods; feasibility - time and investment required to realize and maintain the evaluation. The objectives of this methodological framework are to better understand the whole flood damage evaluation process and to identify the relevance of the different steps of the evaluation. We intend to help stakeholders in the choice of evaluation strategies with a good compromise between evaluation efforts and results reliability.

## Keywords

Urban water, flooding, risk assessment, modelling, decision support systems

## INTRODUCTION

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 (LCL et al. 2007). This scenario is still quite common all over the world. The use of economic evaluation should improve flood management effectiveness and sustainability. In Europe, cost-benefit analysis (CBA) and multi-criteria analysis (MCA) tend to become more frequent over time in this purpose: “Flood risk management plans shall take into account relevant aspects such as cost-benefit analysis” Water Framework Directive 2007/60/EC. The benefits of flood alleviation projects are measured in terms of avoided damages enhanced by the project. The work of Penning-Rowsell and Chatterton (1977) is one of the first references introducing this concept. The assessment of potential damages of future floods is a fundamental key in flood management decision making process. It allows comparing several projects between them in relation to expected costs and benefits. The “correct” evaluation of potential damages of future floods is therefore crucial for the well achievement of the analysis.

Flood inundation maps, vulnerability maps and feedback on previous flood damages are used to evaluate flood damages. Each set of data is issue of different modelling processes and involves uncertainties (Penning-Rowsell and Green, 2000). In addition to uncertainty in the evaluation process, current CBA applications consider only direct damages, like houses material losses, and few indirect damages, like industrial exploitation losses, as benefits of flood management. The works of LCL et al. (2007) and Hubert and Ledoux (1999) synthesise several applications in France, United Kingdom, United States of America, Germany, Holland and Switzerland.

Accurate assessment of flood potential damages should allow assessing the overall benefits of projects. However, full damages evaluation including direct, indirect, tangible and intangible damages is a complex process which involves dynamic systems, i.e. flood hydrological hydraulic aspect and human systems, and several modelling requirements (Green et al. 1994).

Overall uncertainty in the results of benefit analysis depends on the strategies used to assess flood damages potential. These strategies concern mainly the definition of types of damages that will be evaluated, of datasets and methods used in the assessment process and of models and programs which will be used to process data. The contribution of individual uncertainty propagation for the overall uncertainty of damages evaluation results is not well understood. The understanding of the dependence of strategic choices and uncertainty potential is fundamental in the choices of these strategies in practical applications. According to our knowledge, only one study has been carried in order to compare different strategies and results variability (Apel et al. 2008a).

The aim of this paper is to highlight the significance of pre-studies in flood damages evaluation processes and to develop a research framework to analyze the impact of different strategies used to evaluate urban flood damages on the feasibility of the evaluation and on the reliability of its results. The application of this framework should allow better understanding on the whole evaluation process and bring support to flood damage evaluation pre-studies. In the first part of this paper, we present the state of the art of the assessment of future flood damages potential. The second part describes the research framework proposed. In the third part of this paper, we discuss the first results together with the research implications and perspectives of this work.

## **THE ASSESSMENT OF POTENTIAL DAMAGES OF FUTURE FLOODS**

### **Flood consequences, losses and damages**

Flooding is the first damaging natural hazard in the world (Messner et al., 2007). “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” Water Framework Directive 2007/60/EC. Floods can also have positive consequences, like the fertilization of floodplains. The term loss is used to define negative consequences of floods. The losses of floods are classified in bibliography according to the cause of losses (contact with water or other) and to the possibility to express them in monetary terms. The term damage is used to designate economic losses. Tangible losses, or damages, can be expressed in monetary terms, e.g. material losses. Intangible losses are hardly expressed in monetary terms, e.g. psychological trauma, loss of life. Direct damages are consequences of direct contact of flood water, e.g. houses furniture and electronics losses. Indirect damages are consequences of services and activities disruption due to direct or other indirect losses, e.g. cleaning costs, disruption of industrial production caused by interruption of energy provision.

### **The state of the art**

Several methods have been developed all over the world in order to estimate future flood damages: in the United States (US), first flood damage evaluations have been developed at the beginning of the 60s (White, 1964) followed by the development of application guidelines by US Army Corps of Engineers; in the United Kingdom (UK) a first procedure have been developed in the 70s (Penning-Rowsell et al., 1977) and since then a sequence of guides have been published improving the evaluation over time (Parker et al., 1987; Penning-Rowsell et al., 1992; Penning-Rowsell et al., 2005); in Australia a national guide has been developed together with the experience of the UK (Thompson and Handmer, 1996; DNRM., 2002); in France, the works of Torterotot (1993) and Hubert at Ledoux (1999) are the main national references. Lots of national

and international projects have been developed on this context (Floodsite, EUROflood...). An European guideline has been published in this context (Messner et al., 2007). Therefore, a large number of methods to evaluate flood damages are available in literature. These methods are mainly different in relation to the scale of the evaluation, varying from an elementary (unit/micro scale) to international scale and to the level of detail which flood damages are evaluated.

### Overview of flood damages evaluation

“Flood risk is considered as the product of hazard, i.e. the physical and statistical aspects of the flood, and the system vulnerability, i.e. the exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damages”. (Apel et al. 2008a). In flood damages evaluations, hazard is represented by flood maps (inundation extent, water depth, duration of submersion, flow velocity...) and flood frequencies or return periods; vulnerability is represented by vulnerability maps (land-uses, assets location, structural and functional characteristics of assets) and damage-functions (damaging potential expressed by a relationship between flood hydraulic parameters and assets characteristics). Two methods can be used to evaluate flood damages: “unit damages evaluation” which is a property-by-property assessment methodology, and homogeneous areas evaluation which considers areas with similar characteristics in the calculation process. For both, the evaluation process consists of 3 main steps: data assessment, data combination, damages calculation (Hubert and Ledoux, 1999). Flood maps and frequency are obtained by means of hydrologic/hydraulic modelling. Vulnerability maps are built by means of satellite/aerial photography, field surveys, interviews... Damage-functions are developed by statistical analysis of observed floods damages or by assumptions and laboratory tests. Geographic Information Systems (GIS) are largely employed to store and combine data, playing an important role in the evaluation process. Data combination consists of overlaying flood and vulnerability data. Damage-functions are applied to different assets in order to calculate individual damages caused by a flood event with specific return period. Finally, total damages are calculated by summing the overall assets damages for one specific flood event. This process will be detailed further in this work.

### Uncertainty in the evaluation

Hazard modelling consists in hydrologic, geospatial and hydrodynamic aspects. Uncertainty is an issue of these different elements and of the interaction between them (Merwade et al., 2008). 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). The work of Xu et al. (2007) highlights the importance of the accuracy of floods frequency determination in the results of damages evaluation. The assessment of vulnerability to floods also counts on different sources of uncertainty. The scale of the exposure assessment and the quality of datasets and field surveys determines the accuracy of this step. The accuracy of damage-functions is fundamental in the evaluation process. The work of Torterotot (1993) describes uncertainty on the construction of damage-functions. The works of Apel et al. (2004) and Penning-Rowsell and Green (2000a, 2000b) describe uncertainty in the overall process. Another type of uncertainty is due to categories of flood damages untreated in the evaluation.

### **Future directions**

The evaluation of flood damages is generally realised by local authorities, associations or by private companies. The greater the scale of the evaluation is, the harder it is to assess and forecast hazard and vulnerability data. Even though lots of methods and guides exist to support flood damages evaluations, rare are the countries which adopted national standard methods (Dutta et al. 2001). The adoption of national standard methods should contribute over time to the

development of robust evaluation methods adapted to different contexts which is observed in the UK experience. A common point between all the methods is that direct damages, especially for buildings and contents, have been the main point studied. Direct damages to infrastructures, networks, environment, indirect and intangible losses in general have been less explored. Therefore, in practical applications direct damages to buildings and contents are more frequently evaluated; direct and indirect damages to networks are rarely included in. We also notice that great effort has been made in flood mapping, with the development of several computational programs to support the operation. Contrary to hazard modelling, few models have been developed to simulate vulnerability and to realise the overall evaluation of flood damages (Xu et al., 2007). The construction of flexible GIS-based models to evaluate full flood damages could contribute to the improvement of the evaluation process.

Sophisticated methods are available and can be employed for the purpose of obtaining accurate results. 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 and it can be still more relevant in developing countries. 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. These pre-studies should also take into account uncertainty potential linked to strategic choices, in order to improve the evaluation results optimizing evaluation investments. The identification and quantification of uncertainty sources in the evaluation is crucial for acting on the evaluation uncertainty reduction. Individual uncertainty linked to the hazard modelling part of the evaluation propagates in the results of the evaluation, as well as individual uncertainty linked to the vulnerability assessment step. The choice of the strategies to evaluate flood damages and the variability of the evaluation results in practice has rarely been discussed before (Apel 2008). Research has yet to be done in order to guide the choice of different strategies to model hazard, assess vulnerability and evaluate flood damages, taking into account the objectives of the evaluation, feasibility parameters, long-term perspectives, and results reliability.

## **DEVELOPING THE RESEARCH FRAMEWORK**

The evaluation of flood damages has different objectives: support cost-benefit analysis, multi-criteria analysis, insurance programs, post-crisis recovery (resilience), etc. The level of detail and reliability on the evaluation depend on the demands in terms of objectives. The definition of these objectives is a fundamental key for the evaluation. In this context of CBA and MCA, a maximum of reliability and detail is required from the damage evaluation. The choices of the strategies used to assess future flood damages are crucial for the accuracy of the evaluation results. These choices are made in a pre-study phase of the evaluation process. The objective of the present research framework is to develop uncertainty analysis correlated with feasibility analysis in order to support the choices of strategies in damage evaluation pre-studies.

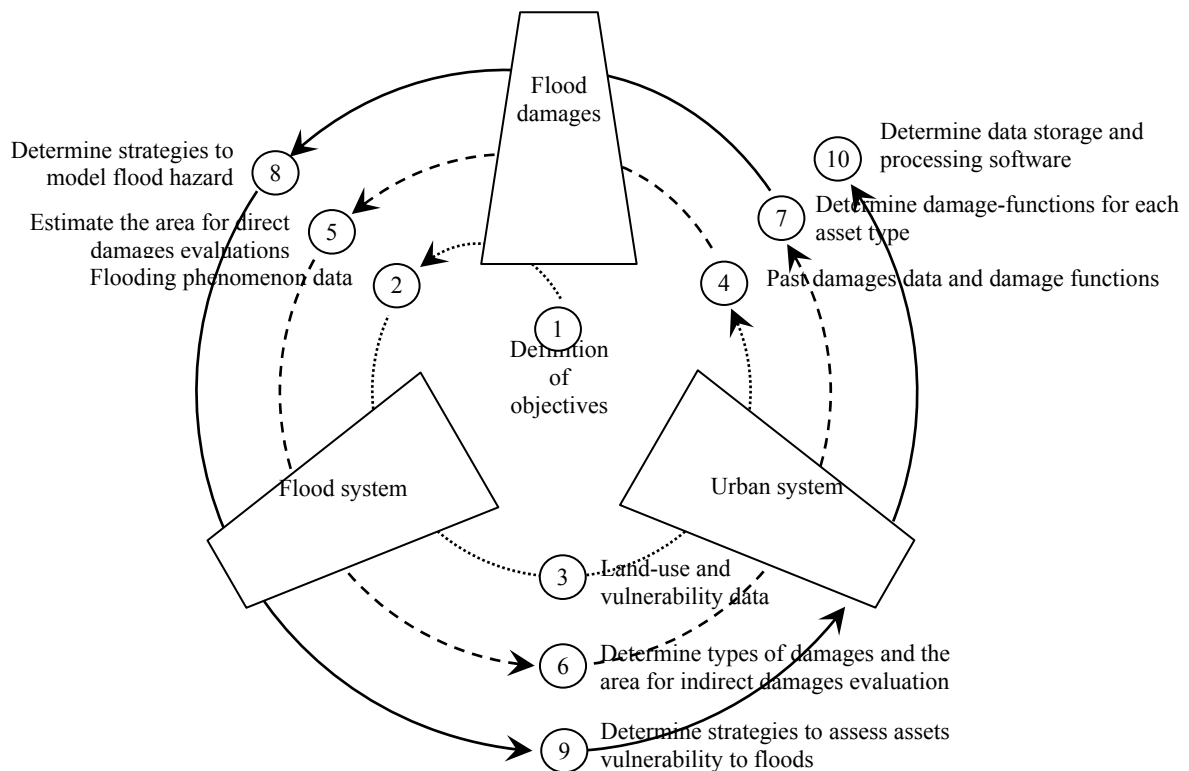
### **Feasibility vs. uncertainties**

In practical assessment of damages, the choice of strategies, models and methods is mainly determined by budgetary factors. The question evocated in the Messner et al. (2007) study “How much time and money is at hand to carry out the study?” is an important element for determining the evaluation strategies. Unfortunately, in real application the answer to this question is the strongest factor in the choices of models and methods. An example is that indirect and intangible damages are often neglected or roughly evaluated, because of the high exigency level of these evaluations in terms of investments. Another example is the option for using free-license hydrodynamic models for simulating floods. The costs of the assessment process can range a lot

according to the strategies adopted. A myriad of studies have been carried in order to identify uncertainty of individual models to some modeling aspects. However, rare are the studies which compared and measured the uncertainties generated by different steps of the evaluation in terms of evaluation results variability (Apel et al. 2008a). A pre-study phase is essential to the determination of time and evaluation efforts repartition.

### Development of a general pre-study method

Different methods and guides present different pre-studies methods. Based on the studies analysed on this paper, we propose a general pre-study method called 3C pre-study for assessing potential damages for future floods (Fig.1), which define a precise workflow plan.



**Figure 1: 3C pre-study for assessing potential damages for future floods**

The 3C method referred to the 3 circles which should be studied in relation to the objectives of the evaluation. The definition of the objectives of the evaluation must be its first step.

#### Internal circle

The first circle consists in gathering all existing data for the evaluation. (2) In the first step one should look for all available existing data concerning the flood phenomenon: historical flood maps, hydrological/meteorological data, topographic, bathymetric and digital elevation models (DEM), flood models, etc. (3) Secondly, all information concerning land-uses and characteristics of assets at risk should be gathered: vulnerability maps, land-use maps, GIS databases, GIS platforms, etc. (4) The third step consists in gathering existing data concerning previous flood damages and existing damage-functions. If no data exist in the site, regional and national data should be gathered.

#### Middle circle

The second circle consists in a general reflexion in relation to the method which will be used to calculate flood damages in accordance with the objectives of the evaluation and to the analysis of

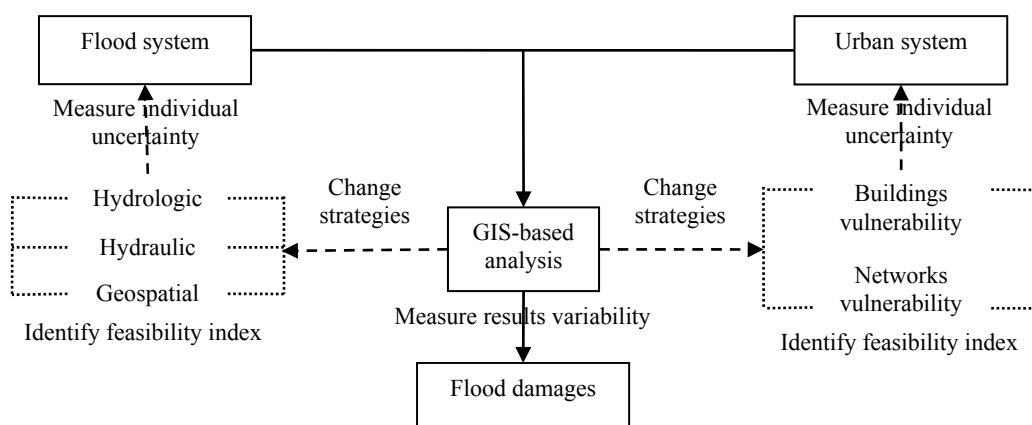
data gathered in the first circle steps. (5) The first step estimate the area which will be studied in relation to direct damages based on the extent of previous flood inundations or expert knowledge. (6) In the second step, we should determine all the types of assets that will be evaluated and all kinds of damages which will be calculated. The area for indirect damages evaluation should be determined. This step is based on previous information concerning flood damages and actual-land use occupation. (7) In this step, we should determine the applicability of available flood damages and gather damage-functions for all type of assets considered in the evaluation. An exhaustive analysis of the existing damages function, the actual land-use information and the types of damages adopted should be established. One damage-function should be related to each typology of assets considered.

### External circle

This last circle consists in determining all the strategies which will be used during the flood damages evaluation process. (8) The first step consists of determining the strategies which will be used to model hazard: what kind of hydraulic model to use, how to obtain lacking data. (9) In the second step, one should determine the strategies which will be adopted to assess lacking land use and exposure information necessities to assess vulnerability to floods. (10) Finally, the last step consists of determining how data will be stored and process in order to calculate flood damages. A GIS software should be used, and not only calculation procedures must be determined but uncertainty analysis methods must be defined.

### **Research framework**

The strategic choices to evaluate flood damages are made from the step 6 to 10 (both included) presented in the pre-study (Fig.1) The objective of the framework is to compare different strategies and measure their impact on the evaluation results. Strategic choices should be made considering several aspects: objectives of the evaluation, existing data and models availability, uncertainty potential linked to the different strategies, costs and time availability and requested by the different strategies. Two of these aspects must be studied *a priori* in order to support these considerations in practical applications: uncertainty potential linked to different strategies and data and time requested by the different strategies available. The framework developed in this paper intends to correlate uncertainty potential and feasibility indexes to different possible strategies adopted in the evaluation. The research framework is presented above (Fig.2).



**Figure 2: Research framework to identify how the strategies used to assess potential damages of future floods can affect the results of the evaluation**

The principle of the framework is based on a repetitive method. Flood damages should be evaluated several times using different strategies. In order to measure the relative importance of each aspect of the evaluation process, we should compare the impact of the different strategies in

the global results of the evaluation. A sensitivity analysis principle is used: a unique parameter should be changed at time and overall damages should be evaluated. Uncertainty propagation for each parameter is measured in the results of the evaluation.

## **Applying the research framework**

In this framework we consider that hazard is controlled by hydrologic, hydraulic, and geospatial aspects and urban systems are composed by buildings and networks (Fig.2). The choice of demonstration sites should be based on data availability. Not only real study cases but also hypothetical cases should be studied to allow extrapolation of results.

### Define a general methodology to evaluate flood damages

Independent on the method, potential flood damages evaluations are based on three main components of datasets: hazard parameters maps with associated intensity and frequency, vulnerability maps containing assets exposure characteristics, and damage-functions expressing the susceptibility of assets in the floodplain to suffer damages. A general damage evaluation consists of 3 main steps: (1) assess data, (2) combine data and (3) calculate damages (Humbert and Ledoux, 1999). These steps should be preceded by a pre-study. In the first step, data describing vulnerability, hazard and economic aspects should be obtained. This step is the key of this study and will be detailed in the two next sections.

In the second step, vulnerability and hazard data are correlated in order to determine the risk, and economic data is associated to them. GIS software is used to overlay spatial data and combine tabular datasets (Reference). This procedure consists of determining for each specific flood event, how the assets at risk will be affected by the hazard. Water depth is the most common hydraulic parameter used in this context (Penning-Rowse et al., 2005). The GIS procedure consists in overlaying vulnerability maps with flood water depth maps. Therefore, each asset will be associated to hydraulic parameters and vulnerability characteristics.

The third and last step consists of calculating damages and expected annual damages. Direct material damage depends of hazard parameters and vulnerability characteristics of the asset at risk. For each asset at risk we could then express direct damages ( $D_{dir}$ ) in function of hazard parameters ( $H_{par}$ ) and assets vulnerability to floods ( $A_{vul}$ ):  $D_{dir} = f(H_{par}, A_{vul})$ . Indirect damages ( $D_{ind}$ ) are usually estimated by using ratings ( $R$ ) of direct damages:  $D_{ind} = D_{dir} \times R$ . After calculating potential damages for each asset at risk, the sum of all damages represent the total damages ( $D_{tot}$ ) caused by one specific flooding event in the impacted area:  $D_{tot} = \sum [D_{dir} + D_{ind}]$ . Average Annual Costs (AAC) are calculate by summing the product of total damages related to floods ( $i$ ) with their frequency of occurrence ( $f$ ):  $AAC = \sum [Dt(i) \times f(i)]$ .

The two last steps, involving the overlaying of flood and vulnerability maps and the sequence of calculation mentioned will be the same independent of the methods used to assess data. In order to apply the research framework, and compare the impact of different strategies on the results of the evaluation, the second and third steps of the evaluation must be automated. In this context, it's extremely necessary to define the tool used combine data and calculate damages.

### Different strategies used to assess vulnerability data

In this study we consider that an urban context is composed by buildings, i.e. all sorts of structures and contents, and networks, i.e. interrelation between structures and/or services. These systems have different susceptibility to suffer damages in case of floods. The first strategic choice occurs in the step 6 when following the proposed pre-study (Fig.1): one should decide the types of damages which will be considered and the extent of the evaluation. Buildings and contents damages generally represent the greatest part of damages in urban areas, which leads practical applications to focus on these damages. However, network direct damages and indirect

damages in general can be really significant, depending on particularities of each area in study. Different typologies of damages could be considered when applying the proposed framework.

The others strategic choices occur in the step 7 - one damage-function should be constructed are determined for each typology of assets considered representing different susceptibilities to suffer damages, and step 9 - one should determine the methods to assess exposure characteristics of assets in the flood plain (Fig.1).

The construction of damage-functions is a laborious work which demands great efforts on evaluating *a posteriori* real flood damages or high level of expertise (Penning-Rowse and Chatterton, 1977; Hubert and Ledoux, 1999). The impact of uncertainty on damage-functions is easily measured on the final results of the evaluation.

Different methods can be used to describe exposure characteristics of assets to floods: field surveys, interviews, aerial photo analysis, expertise, etc. Detailed analysis implies big investments requirement. The great development of GIS databases and the advances in field measurement techniques guarantee more accuracy in these analyses. However, some key characteristics can be wrongly assessed or not assessable by these methods. In the case of residential, commercial and industrial buildings the level of the ground floor, the characteristics of occupation, the structural characteristics of the buildings and other parameters could be assessed in different manners. In the case of networks, different hypothesis can be made in relation to the existing interrelation. The application of the framework consists in identify key uncertainty elements and realising the evaluation in order to measure uncertainty and variability of results.

#### Different strategies used to assess hazard data

In this study we consider that the flood hazard is controlled by 3 aspects: hydrologic aspect determining the frequency of floods and the temporal distribution of flow discharge intensity; geospatial aspect determining the spatial characteristics of the terrain of the flood plains; and hydraulic aspect determining the distribution of flood parameters over the flood plain. All these aspects are linked. All strategic choices concerning modelling hazard occurs in the step 8 when following the proposed pre-study (Fig.1). Different strategies can be adopted two determine the three aspects controlling the flooding phenomenon. These strategies can differ based in different aspects of the evaluation: which flood parameters must be modelled - determined by the damage-functions in step 7 (Fig.1); what data is already available - step 2 (Fig.1).

In relation to hydrological data, we depend on the type of data available. Hydrological data also direct affect the relationship between flood frequency and flow intensity. The analysis of hydrological uncertainty propagation in the results of damages evaluations have been done by Xu et al. (2007).

The geospatial aspect concerns topographic and bathymetric information. Digital Elevation Models accuracy directly affects the results of the hydraulic model independent of the software used. Flood maps are made based on this data. The resolution of the DEM pixel will determine the precision of the hydraulic modelling. Small pixels mean good resolution but great efforts on DEM construction and longer calculation time for hydraulic models. Different technologies can be used to obtain DEM (Moglen and Maidment, 2005). The accuracy of the main channel bathymetry is also extremely important (Merwade et al., 2008).

There is a large amount of hydrodynamic models available to simulate floods. They are used to simplify and solve the three equations of hydrodynamics in order to simulate floods: conservation of mass, momentum and energy. The programs are different because different methods and hypothesis can be used to simplify and solve these equations, and different dimensions can be considered (1D, 1D/2D, 2D and 3D). 1D/2D hydraulic models are currently considered a good compromise for river flooding (Stelling and Verwey, 2005).

## **FIRST RESULTS AND RESEARCH PERSPECTIVES**

The application of the present framework is the main objective of the thesis project in progress. We present in this section the first major results obtained so far, and the perspectives.

### **Construction of a GIS-based model to evaluate flood damages**

We developed a tool using the computational language Visual Basic for Applications® (VBA) within ArcGIS 9.2® in order to automate the damages evaluation process. The tool has a simple interface and its algorithm has been developed with relatively large possibilities. It has been written in order to easily process hazard and vulnerability data during the second and third steps of the evaluation of flood damages potential, i.e. combine data and calculate damages. Detailed results of this tool have been presented in Eleutério and Martinez (2009). Time and expertise requirement reduction allowed by this kind of tool are extremely relevant for practical applications and for applying the framework developed in this paper. GIS calculation steps play a central role in the framework (Fig.2). The application of this framework to analyse uncertainty is only possible by the automation of this analysis.

### **First applications of the proposed framework**

We tested the sensitivity of damage evaluation results to three aspects of the evaluation process: hazard prediction stage, buildings vulnerability assessment method and the methodology used to combine hazard with vulnerability data. Easily applicable methods have been compared to hardly applicable ones in terms of damage evaluation reliability. Hazard prediction showed to be the key uncertainty in the process, generating more uncertainty in the final results than the other aspects tested. More detailed results can be seen in Eleutério (2009).

### **Work in progress and perspectives**

Two tests are being currently done by our research team. We are comparing 3 different programs for simulating flood hazard: HEC-RAS which is a free-license 1D hydrodynamic model largely used in the world scale; Mike Flood which is a powerful composed 1D/2D commercial hydrodynamic model; and Hydrariv which is another composed 1D/2D commercial hydrodynamic model. The comparison is being built using the present framework, in order to test the influence of the hydraulic model into the final results of the damage evaluation. We also use different DEM resolutions in order to expand the comparison. A real study case and several theoretical/fictional tests will be developed in order to generalize the results of this study.

The second test consist in taken network direct and indirect damages into account the evaluation. An attempt to normalize a standard method to asses this kind of damages is been done. Network damages are usually roughly or not evaluated.

## **CONCLUSIONS**

In this paper we proposed a framework to improve flood damages evaluation results by developing pre-study elements. The main points of this method consist in define the evaluation objectives (results demands) and chose the appropriate strategies to achieve them conciliating evaluation feasibility and results reliability. We identified the mains aspects of flood damages evaluations which should be taken into account in order to realise these pre-studies. We identify the main factors inducing uncertainty in the evaluation process. Further research is being developed in order to apply the framework developed and analyse the variability of results according to the strategies used to evaluate flood damages.

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