4th International Symposium on Flood Defence:
Managing Flood Risk, Reliability and Vulnerability
Toronto, Ontario, Canada, May 6-8, 2008

Institute for Catastrophic Loss Reduction

INTEGRATING HYDRAULIC AND ECONOMIC ANALYSIS FOR SELECTING FLOOD PROTECTION MEASURES IN THE CONTEXT OF CLIMATE CHANGE

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ABSTRACT: In order to protect our societies from damaging impacts of climate change (floods, heat waves, droughts…), the most cost-effective adaptation strategies must be selected among a wide range of options (including structural and non-structural protection measures). The Belgian national project “ADAPT” aims to provide guidance for this choice by developing a *decision-support system* (DSS) for the selection of protection measures against increased risk resulting from climate change, and more specifically from floods. The DSS is based on a combination of cost-benefit analysis (CBA) and multi-criteria analysis (MA), taking into consideration hydraulic, economic, social and ecological indicators. For the purpose of demonstrating the relevance and efficiency of the DSS, the approach is applied for two case studies located in the two main Belgian river basins (Meuse and Scheldt).

Within this global framework, the present paper covers the description of the hydrodynamic modeling component and the economic analysis, focusing on their interactions and on their integration within the DSS. The paper also details the case study of the Meuse Basin (river Ourthe), for which the hydraulic simulations are conducted by means of the two-dimensional numerical model WOLF 2D, based on a finite volume scheme and entirely developed at the University of Liege. High resolution Digital Surface Models and geographic database are exploited, enabling to represent streets, buildings and parcels individually.

Relevant damage functions are validated and refined based on the analysis of four recent major flood events, for which a relationship may established between simulated local water depths (and possibly velocities or flow duration) and actual damage costs. Consequently, the combined hydrodynamic and economic analysis described in the paper may be judged as a valuable tool for assessing the effectiveness of specific flood protection measures.

Key Words: climate change, hydrodynamic modeling, finite volume, damage function, digital elevation model.

1. INTRODUCTION

The Belgian national research project "*ADAPT - Towards an integrated decision tool for adaptation measures*", aims at developing a decision-support system (DSS) dedicated to the integrated evaluation of flood protection measures in the context of increased flooding hazard as a result of climate change. This DSS is based on a combination of cost-benefit analysis (CBA) and multi-criteria analysis (MCA) and takes into consideration hydraulic, economic, social as well as environmental indicators.

The present paper focuses on the integration between two components of the DSS, namely the hydrodynamic modeling and the evaluation of the economic impacts of floods. The methodology is demonstrated for a study area located along the River Ourthe in the Meuse Basin (Belgium). The hydrodynamic simulations for this case study are conducted by means of 2D flow modeling and provide as an output high resolution flood maps detailing the 2D distribution of water depth and flow velocity in the floodplains.

The integration of hydrodynamic results and economic damage evaluation is based on four successive steps. The process starts by the exploitation of the flooding extent for indentifying the elements-at-risk, which are subsequently assigned a specific damage function. Next, the combination with water depth (and possibly flow velocity or flow duration) extracted from the flood map leads to the evaluation of the relative damage. Finally the absolute damage is estimated based on the value of the elements-at-risk. The damage functions exploited in the present case, linking the hydraulic parameters and the percentage of damage, are up to now derived from those reported in the ICPR Rhine atlas, while the specific value of the elements-at-risk is gathered from various sources, such as local authorities or land registry offices.

Besides a brief overview of the hydrodynamic modeling approach, the paper details the integrated assessment procedure and its application for the case study of River Ourthe. In particular, the validation of the economic damage evaluation procedure is depicted on the basis of comparisons between computed results and real damage data recorded by the Belgian Disaster Fund after recent flood events.

2. HYDRODYNAMIC MODELING

The HACH research unit from the University of Liege has been developing for more than ten years a hydrodynamic modeling system named WOLF, which includes a series of interconnected numerical tools dedicated to one- and two-dimensional modeling of a wide range of flows: open channel or pressurized flows; possibly accounting for sediment, pollutant or air transport (Dewals, 2006a; Dewals et al., 2008a); including sophisticated turbulence closures (Dewals et al., 2008b; Erpicum, 2006) as well as extended depth-averaged flow modeling features (Dewals, 2006a; Dewals et al., 2006). Optimization algorithms are also embedded in the modeling system (Erpicum, 2006).

The two-dimensional hydrodynamic model WOLF 2D used for flood mapping is based on the conventional depth-averaged equations of motion, named the shallow-water equations (Archambeau et al., 2004; Erpicum et al., 2007; Erpicum et al., 2008). Topographic data are extracted from an aerial LiDAR (Light Detection And Ranging) *Digital Surface Model* (DSM), with a horizontal resolution of 1 meter and a vertical accuracy in the range of 15 cm. Although widespread in hydrodynamic modeling, those remote sensing data require as a pre-processing task the removal of residual obstacles non relevant for the flow (e.g. vegetation impermeable to laser pulses).

Although the hydrodynamic model is perfectly suited for dealing with unsteady flow simulations, including for instance highly transient dam break flows (Dewals, 2006b), the steady-state approximation is exploited in the present case (Archambeau et al., 2004; Erpicum et al., 2007). This hypothesis has been demonstrated to be valid as a result of the relatively long duration of the flood, combined with a limited possible storage in the floodplains of the rather narrow valley of River Ourthe (*§* 4.2). As a result of this assumption, the computation time can be further reduced thanks to an automatic mesh refinement method (Archambeau et al., 2004).

3. ECONOMIC DAMAGE MODELING

The evaluation of the *risk* associated to floods relies basically on two main parameters: the *probability* of occurrence of a flood, which can be related to the statistically calculated return period of the corresponding discharge, and its *consequences*. The risk can thus be evaluated mathematically by the product of the two parameters, summed over the range of possible events (Figure 1).

Three major components must be considered for quantifying the consequences. First, the *exposure* characterizes the flood event and is directly obtained as an outcome of the flow modeling. Second, the *elements-at-risk* are deduced from the flood extent. For macro and meso-scale studies these assets potentially affected by flooding may be estimated as a percentage of the total studied area, but in the case detailed micro-scale studies, such as presently, they must be identified individually by combining the flood extent with a land use database (§ 3.1). Finally, the *vulnerability* of the elements-at-risk (depending on their susceptibility, adaptative capacity and resilience) is expressed by damage functions (*§* 3.2).

As summarized in Figure 2, the practical quantitative estimation of the absolute economic damage may be described as a four-step procedure: *(i)* extraction of the inundation extent from the flood maps and combination with land use data to identify the elements-at-risk; *(ii)* assignment of a specific damage function to each of the five classes of elements-at-risk, representing their respective vulnerability to flooding; *(iii)* application of the damage function, in combination with the water depths (and possibly the flow velocity or flood duration), to provide the relative damage encountered by each object; *(iv)* evaluation of the product of the relative damage by an estimated value of the element-at-risk. As a result, a complete distribution of the absolute value of the financial damage induced by flooding is obtained.

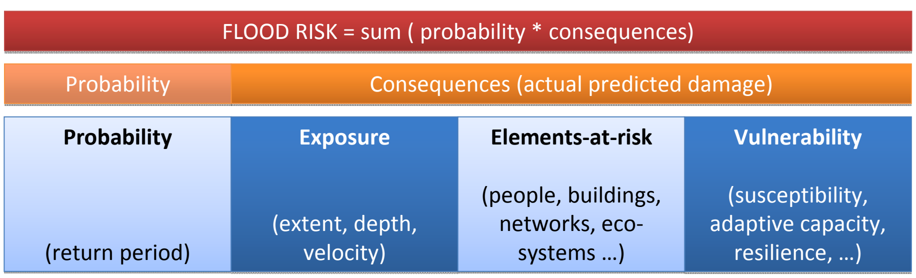

Figure 1: Main components of flood risk evaluation.

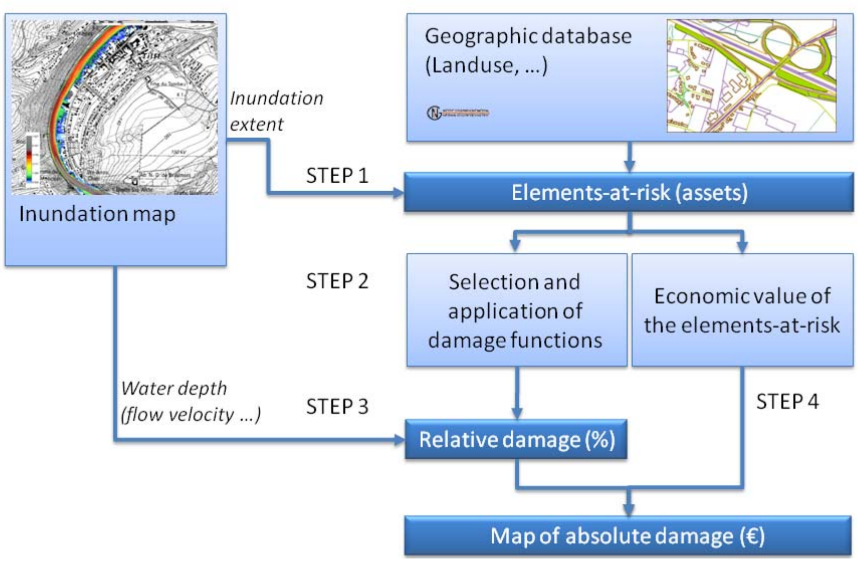

Figure 2: Sketch of the main steps of the economic damage modeling procedure.

3.1 Geographic database

In a micro scale damage assessment, the quality of available land use information plays a major part (Van der Sande et al., 2003). In the Walloon region in Belgium, two types of detailed geographic database are available: *Top10vGIS* and *PICC*. They are issued respectively by the National Geographic Institute (IGN) and the Walloon Ministry of Facilities and Transport (MET). The IGN database includes 18 layers of information, among which following data layers are extracted and exploited: residence, industry, road network, agriculture (crops, fields) and forestry. Among other sets of very useful information, the PICC database contains the cornice height of the buildings, which enables the identification of individual dwellings within a group of adjacent houses. By combining these two complementary datasets with the output of the 2D hydrodynamic simulations, economic damage analysis is made possible at a house scale without requiring extensive field surveys.

3.2 Damage functions

There are two main options for evaluating the economic damage (FloodSite, 2006): either the damage function provides directly an absolute value of damage in monetary terms, or it provides a relative damage in percent. Although the later approach requires the estimation of the value of the elements-at-risk (so called: *specific patrimonial value*), it is generally preferred because it may be easily transposed from one area to another and combined with relevant local evaluations of the specific patrimonial values. As illustrated in Figure 3, a large number of different relative damage functions are presented in literature (Dushmanta et al., 2003; International Commission for the Protection of the Rhine, 2001). As a result of their scattering results, much care is required in the selection and application of any of them.

For elements such as roads, meadows, crop fields … the damage function may be directly applied based on the output of the hydrodynamic model. In contrast, the required hydrodynamic parameters (water depth, flow velocity) are not available at the location of buildings (houses, industries) since such elements appear in the DSM as obstacles to the flow. Therefore, for these elements-at-risk, the value of the water depth, required as an input for applying the damage function, is obtained by simply averaging the water depths computed in the cells surrounding the building.

In the large majority of practical applications, water depth and flow duration remain the most influential parameters affecting the economic damage induced by flooding. Although significant in specific applications, others flood characteristics, such as flow velocity and contaminant concentrations, are disregarded in many analysis, partly due to the lack of validating sets of data and field survey.

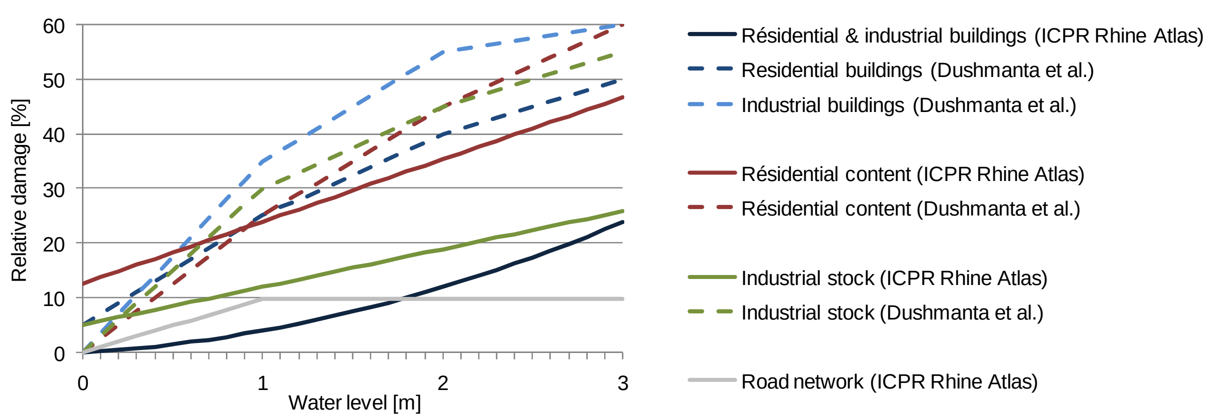

Figure 3: Examples of relative damage functions.

3.3 Value of elements-at-risk

The market value of elements-at-risk such as buildings may be either approximated by their selling price (provided by real estate agencies or solicitors), or deduced from cadastral income data. The latter is determined on the basis of normal net rental values taking into account the situation and the characteristics of the property. For some buildings, such as industrial and exceptional ones (offices, hospital, schools…), this cadastral income may be calculated by applying a rate to their standard market value.

4. APPLICATION: STUDY AREA ON THE RIVER OURTHE

In order to validate the combined hydraulic-economic evaluation of the damage induced by flooding, the methodology is tested for a case study area, which covers two reaches of the river Ourthe, located respectively 18.5 km (Reach n°1) and 10 km (Reach n°2) upstream of the mouth of river Ourthe into river Meuse (Belgium). The damage modeling procedure is first applied to past major inundation events, as detailed in § 4.1. Next, prior to eventually assessing the benefits of future flood protection measures to be designed to face climate change, an intermediary step consists in determining how inundation hazard and its economic impact are likely to be modified by climate change. Therefore, hydrodynamic modeling has been carried out to identify how climate change might affect the inundation characteristics (§ 4.2).

4.1 Hydrodynamic modeling and damage evaluation for past flooding events

For validation purpose, four recent flooding events in the case study area have been simulated with the hydrodynamic model: floods of 1993 (observed peak discharge: 742m^3/s), 1995 (520 m^3/s), 2002 (570 m^3/s^-) and 2003 (508 m^3/s). The flow simulations are based on a 2 m by 2 m Cartesian grid and they involve about 270,000 computation cells. The flow model has been slightly calibrated (roughness coefficient) and subsequently validated by comparisons with flood extents and water depths observed during those floods events (mainly the 2002 flood). Reference data were collected by field surveys and deduced from aerial pictures taken during the flood. Each simulation has been conducted taking into account the flood protection structures actually present at the time of the considered floods. In particular, a 700-meter long flood protection wall was built between the 1995 and the 2002 floods and it was extended 300 meters further before the 2003 flood. By the way, a quantitative substantiation for the steady-state approach (see section 2) may be easily obtained by comparing the total volume corresponding to the flood hydrograph with the volume stored in the floodplains. The former is evaluated to be at least tenfold the later for the recent flood events in the case study area.

In Belgium, population having suffered from flood damage may claim for compensation at the *Disaster Fund*, which analyzes the requests and compensates consequently. However, comparisons made with theses datasets reveal some discrepancies, such as underestimation of the number of affected buildings according to the Disaster Fund, compared to the simulated results shown in Figure 4(a). Therefore, more comprehensive investigations are being carried out on this issue, in order to clarify further the reasons for those discrepancies. Most important will be to extend the sources of validation datasets, and to adapt both the damage functions and the patrimonial values the local specificities of the studied area.

Available data from the Disaster Fund regarding real damages resulting from past flooding events, per street and per category, contain on one hand the values *claimed* by the population and on the other hand the values eventually *accepted* to be supported by the Disaster Fund. As mentioned above, mainly as a result of lacking information in the datasets collected by the Disaster Fund, computed values of damage are found to be globally overestimated. Nevertheless, as shown in Figure 4(b), the economic damage modeling procedure can be shown to succeed in providing a satisfactory overall picture of the *relative* cost of damage caused by the different recent flooding events along the river Ourthe.

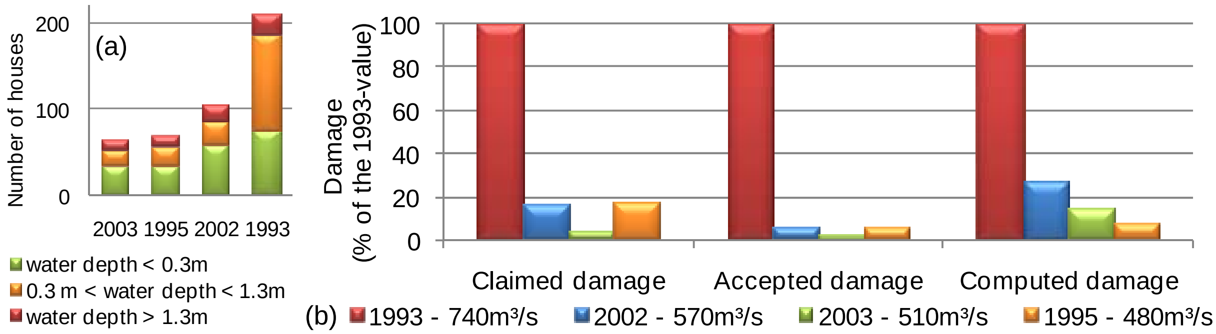

Figure 4: (a) Number of affected residential buildings (elements-at-risk); (b) damage claimed to / accepted by the Disaster Fund vs computed damage, expressed in percentage of the damage for the 1993-flood.

4.2 Hydrodynamic modeling accounting for climate change and preliminary assessment of flood protection measures

4.2.1 Flow modeling: main assumptions and results

Results of Global Circulation Models (GCM) and Regional Climate Models (RCM) provide estimates of the potential increase in precipitation (mainly during winter and early spring) and potential changes in evapotranspiration as a result of climate change (Boukhris et al., 2007). Those predicted changes are affected by a significant level of uncertainty due to the climate models themselves and, to an even greater extent, to the discrepancies in the scenarios used for running those climate models (Intergovernmental Panel on Climate Change, 2007).

At the present stage of the research project, simple assumptions have been considered regarding the expected changes in the peak discharges of the river Ourthe as a result of climate change (CC). Indeed, according to a comprehensive literature review (De Groof et al., 2006; Dewals et al., 2007a; Dewals et al., 2007b), an increase by 10% of flood discharge may be regarded as reasonable. Moreover, in order to evaluate the sensitivity of the results with respect to this perturbation factor on the discharge, increases by 5% and by 15% have also been considered. Finally, a more “extreme” case has been simulated as well (+30%). All those assumptions will eventually be confirmed and refined by comparison with the output of a hydrological model (De Groof et al., 2006). The study is performed for two different return periods, namely 25 and 100 years, for which the best flood protection strategies will be complementary, due to the significant differences in inundation extent and in the probability of occurrence.

Table 1: Discharge and average change in water depth compared to the base scenario, for two return periods and four different climate change (CC) scenarios.

		Base scenario	CC scenario n°1 (+5%)	CC scenario n°2 (+10%)	CC scenario n°3 (+15%)	CC scenario n°4 (+30%)
25-year flood	Discharge	726 m³/s	762 m³/s	799 m³/s	835 m³/s	944 m³/s
	Reach n°1	-	+ 10cm	+ 25cm	+ 40cm	+ 75cm
	Reach n°2	-	+ 10cm	+ 25cm	+ 40cm	+ 70cm
100-year flood	Discharge	876 m³/s	920 m³/s	964 m³/s	1007 m³/s	1139 m³/s
	Reach n°1	-	+ 15cm	+ 30cm	+ 45cm	+ 75cm
	Reach n°2	-	+ 20cm	+ 40cm	+ 60cm	+ 85cm

The assumed modifications in the expected discharges have been translated into updated evaluations of flood hazard for the two considered reaches of River Ourthe, by conducting two-dimensional hydrodynamic modelling. Table 1 summarizes the discharge values considered in the simulations and provides the average modifications in water depths for the corresponding climate change scenarios.

4.2.2 Elements-at-risk

After flow modeling, the next step consists in identifying and locating the elements-at-risk within the inundated area. Then, using the geographic database, the nature of each element-at-risk can be identified: residential properties, industries … Figure 5(a) illustrates the outcome of this analysis, performed for the base scenario and the four climate change scenarios defined above, both for the 25-year and the 100-year floods. Moreover the number of affected houses is classified in three categories as a function of the corresponding water depth. Similar results are displayed in Figure 5(b), for the 25-year return period and the mean climate change scenario (+15%), with or without a 1km-long protection wall. The analysis enables thus to quantify the benefits of erecting a flood protection structure, in terms of reduction of both the number of affected buildings and the water depth reached around them.

The cost of damage may be subsequently estimated through a procedure similar to the approach applied in subsection 4.1 for past flood events.

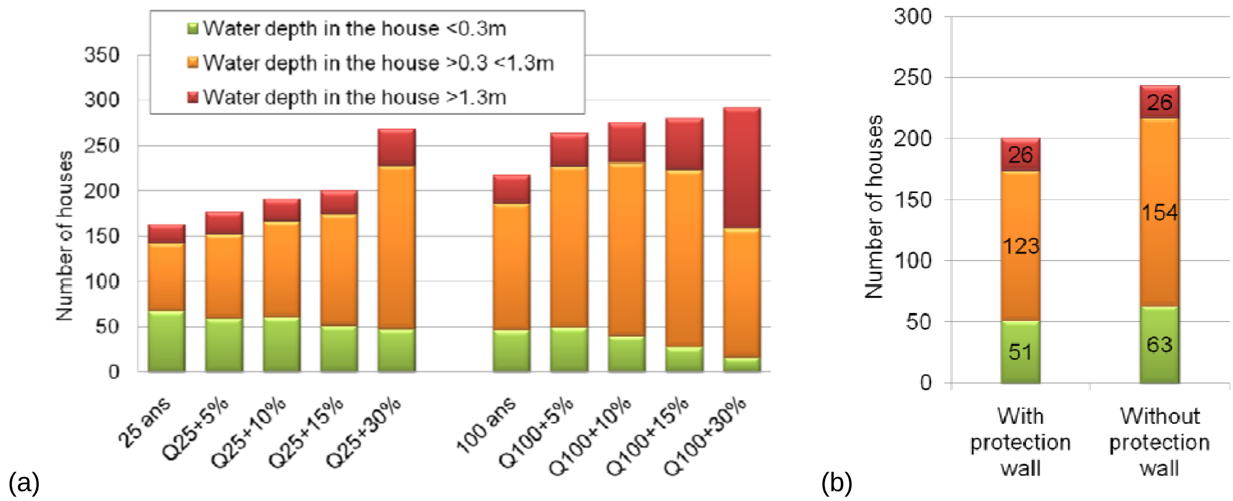

Figure 5: (a) Impact of climate change on the number of elements-at-risk of the type “residential buildings” (b) Example of quantification of the effect of a flood protection measure in the context of climate change.

5. CONCLUSION

The present paper describes the combination of two-dimensional hydrodynamic modeling with a procedure for economic damage evaluation in the context of climate change. The high resolution topographic data used for the flow simulations lead to very detailed flood maps, which serve as an input for identifying the elements-at-risk and computing the cost of damage. This evaluation is notably based on the following components: detailed vector geographic database, damage functions and specific values of the elements-at-risk. The overall procedure is first applied to the estimation of the cost of damage caused by a series of real flood events along the river Ourthe (Meuse Basin, Belgium), next it is used to predict the impact of climate change on the expected damage and finally it is exploited for assessing the benefits of adaptation measures. The overall procedure will be further validated and refined, and will subsequently be embedded within a decision-support system dedicated to the selection of the most cost-effective flood protection measures.

6. ACKNOWLEDGMENT

Part of this research was carried out on behalf of the Belgian Science Policy (BELSPO), in the framework of the program "Science for a Sustainable Development". The authors also gratefully acknowledge the Walloon Ministry of Facilities and Transport (MET) for the Digital Surface Model and other data.

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