European Water 30: 3-11, 2010.

Flood Damage Estimation based on Flood Simulation Scenarios and a GIS Platform

A. Pistrika
National Technical University of Athens
Centre for the Assessment of Natural Hazards and Proactive Planning
9 Iroon Politechniou, 15773-Zografou, Athens, Greece
E-mail: aimilia.pistrika@gmail.com

Abstract: The objective of the paper is to improve the insight in economic estimation of direct damage due to flooding by analysing the direct flood damage to built-up areas and agricultural areas. Relative depth-damage functions are constructed in a stepwise fashion that allows them to be as fined or descriptive as required. The paper presents also a tool, developed in GIS environment that uses the locally-developed depth-damage functions for the estimation of direct flood damage. The usefulness of the tool is demonstrated by estimating expected flood damage over several land-use categories under flood simulation scenarios in a case study located in Erasinos Basin within Eastern Attica Prefecture. The visualisation of analysis results in GIS environment allows the identification of flood-prone areas and provides an indication of the spatial distribution of expected damage under specified flood scenarios. These findings aim to support policy- and decision- making in the context of flood risk management, spatial planning, and further economic development.

Key Words: Depth-damage functions, flood damage estimation, land-use categories, GIS-based tool, Eastern Attica Prefecture.

1. INTRODUCTION

The range of consequences that a flood brings about includes economic, political, social, psychological, ecological and environmental damages and damages to cultural heritage. There is a substantial body of international literature that provides evidence of extensive expertise in the field of damage estimation. However, experts and academics still disagree about the methods and models to be applied mainly due to the various definitions of damage used.

First of all, numerous definitions of damage exist. The categorization of damage into direct (related to physical contact of water) and indirect, or into tangible (quantified in monetary terms) and intangible is commonplace, but interpretations and delineations of categories differ (Jonkman et al. 2008). Secondly, various approaches exist regarding the damage appraisal, such as financial and economic valuation based on market values (i.e. based on historical values or replacement values), while variation in the scale of analysis (micro-, meso- or macro-scale) is also found (Messner et al. 2007; Pistrika and Jonkman 2009). Today the typical approach is the economic estimation of direct damage, mostly by applying depth-damage functions. An integrated, unifying approach is, however, missing. For consistent decision making it is desirable to have a more or less standardized approach for damage estimation at least at higher aggregation levels, such as a river basin or a complete region.

With this in mind, this paper aims to improve the insight in the economic estimation of direct flood damage to residential and industrial built-up areas and to several agricultural land-use types. This is done based on a dataset that contains detailed information on economic data for the area under study and historical records of flood direct damage occurred in the recent past. This study aims at contributing to a stronger empirical basis of flood damage analyses.

The paper is structured in six sections. Section 2 gives a short presentation of the chosen case study area. Section 3 describes in summary the derivation of the flood simulation results under specific flood scenarios. Section 4 focuses on the development of relative depth-damage functions whereas in Section 5 the automatic calculation and visualisation of damage estimates is illustrated by applying the locally-developed depth-damage functions at a GIS-based tool. Finally, some concluding remarks and recommendations are given in Section 6.

2. CASE STUDY

The chosen case study is located in Erasinos basin (A=208 km^2), within Eastern Attica Prefecture. It comprises of two main tributaries, Ag. Georgios and Erasinos streams and a buffer zone of 1 km width alongside the streams (see Figure 1). The chosen area is characterised by rapid urban development and population rate boost and simultaneously it includes different types of landscape (woodland, cultivated land-mainly olive trees and vineyards-, wetland and areas of cultural interest). Above of all, it is described as a flood-prone area due to the inadequate drainage network filled with human interventions. Figure 1 gives an overall view of Erasinos basin and the area under study where the Digital Terrain Model (DTM) and the digitised Land Use map of the buffer zone are also illustrated.

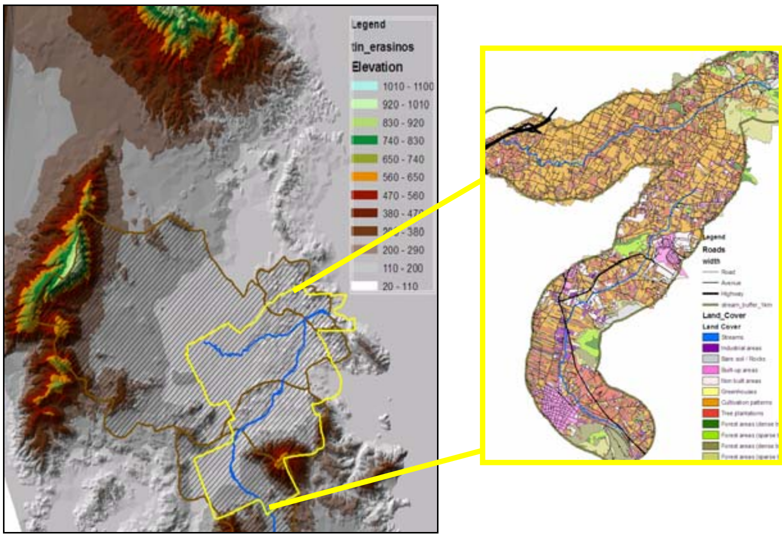

Figure 1. Digital Terrain Model and digitised Land Use map for the case study within Erasinos basin

Further details about the derivation of the DTM, the Land Use map and the socio-economic state of the area under study can be found in the final technical report of the project DISMA (Disaster Management GIS with emphasis on cultural sites) (2007) and the published work of Tsakiris et al. (2008).

3. FLOOD SCENARIOS AND FLOOD DEPTH SIMULATION

3.1 Flood Scenarios Derivation

It is common practice to select a set of standardized flood scenarios corresponding to certain exceedance probabilities in order to perform flood damage estimation. According to the EU Flood Directive recommendations (2007/60/EU) the flood scenarios are prepared for a 0.2-0.1 exceedance probability as a high probability scenario while medium- and low-probability floods could correspond to 0.02-0.01 and 0.002-0.001 exceedance probability and return periods of 50-100 and 500-1000 years respectively. However, these three scenarios are not sufficient to describe fully the probability range of flooding (Tsakiris et al. 2009). For a more comprehensive description some intermediate exceedance probabilities might also be of importance such as 0.04. These supplementary scenarios can be formulated in case more information on flood statistics is required (e.g. in case of rational estimation of design discharge of flood protection or river training works). It should be mentioned that normally flood insurance involves categorization of flood-prone areas in accordance with their flooding potential. According to FEMA (1993), two return periods are used in the US for characterizing flood hazard areas, the 100-year and the 500-year return periods. Areas within the 100-year boundary are characterized as "special flood hazard areas" and areas between 100-year and 500-year boundaries are characterized as "areas of moderate flood hazard".

However, since the work presented here focuses on the development of local depth-damage functions, the chosen flood scenarios should be indicative of the most usual type of flooding conditions of the area under study. The chosen flood scenarios are:

- a 0.05 exceedance probability (or return period T=20 yr) as a high probability scenario based on the local history of flood events
- a 0.01 exceedance probability (or return period T=100 yr) as a medium probability scenario to indicate a 'special flood hazard area' boundary
- a 0.001 exceedance probability (or return period T=1000 yr) as a low probability scenario to indicate the worst case scenario

3.2 Hydrologic and Hydraulic modelling

The simulation of the flood-prone area along the main tributaries under the specified flood scenarios was performed by using HEC-RAS software v.3.1.3. The procedure implies that natural channels meet uniform flow conditions, that the energy grade is approximately equal to the average channel bed slope, and that water surface elevations can be obtained from a normal-depth calculation. These assumptions are conservative in most natural channels. The hydrologic / hydraulic computations involved are:

- Design flood hydrograph derivation for each sub-basin by using the method of Synthetic Triangular Unit Hydrograph
- Steady flow hydraulic computations alongside Ag.Georgios and Erasinos streams (upper and lower reach) by using HEC-RAS software

After completing the river hydraulics model, HEC-RAS simulation run results were exported for processing inundation mapping in ArcMap environment by using the HEC-GeoRAS tool. Floodplain boundary and inundation depth datasets were created from exported cross-sectional water surface elevations and then they were converted to depth grid maps. This action was performed through a layer setup dialog window where the grid cell size was determined and set for all the analyses equal to 25m x 25 m. The definition of the grid cell size was based on the resolution of the Digital Terrain Model used. Hence the flood simulation runs were generated over a 25m x 25m cell grid under three flood scenarios: (1) T= 20 yr (2) T=100 yr and (3) T=1000 yr. Analytical description of the usage of HEC-GeoRAS tool for inundation depth mapping in ArcMap environment is given in HEC-GeoRAS user's manual (2005).

4. DEPTH-DAMAGE FUNCTIONS

4.1 General

The central idea in the traditional approach for direct flood damage estimation in monetary terms is the concept of depth-damage functions or loss functions. These functions relate flood depth with the extent of economic damage that usually is the maximum possible damage in the flood prone area. Depth-damage curves which were first proposed in the USA in the 1960s are currently internationally accepted as the standard approach to assessing urban flood damage (Smith 1996).

Usually, depth-damage functions include water depth as the only determinant of direct damage. However flood damage is influenced by many more factors among which are flow velocity, flood duration, sediment concentration, lead time and information content of flood warning, and the quality of external response in a flood situation (Penning-Rowsell 1977; Smith 1996; USACE 1996; Kelman and Spence 2004). The above factors are, though, scarcely included in flood damage models. Moreover, varying temporal and spatial scales may be applied in practice when modelling flood damage and economic damage estimates may be associated with considerable uncertainty (Merz et al. 2004; Pistrika and Jonkman 2009).

The estimation of direct damages to built environment involves two related steps (see Figure 2) (Pistrika and Jonkman 2009). The first one is the analysis of structural damage caused by the flood effects. This will be determined by the flood actions (or loads) and the building resistance (or strength). The next step is the economic valuation of the physical damages e.g. 'costing' of the physical damages. To convert the structural damage to economic estimates, insight in the building's pre-disaster market value and the replacement cost is required.

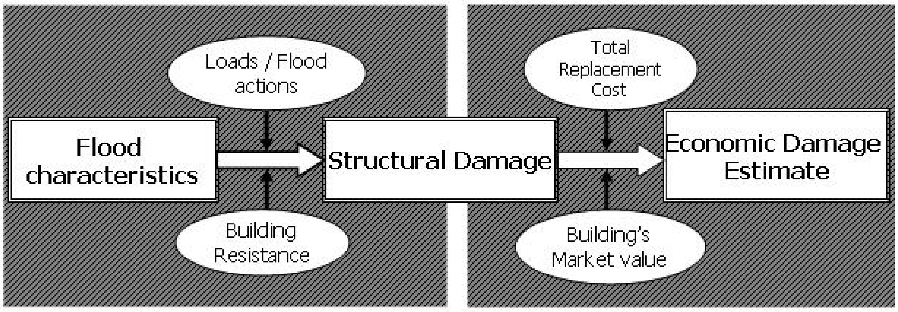

Figure 2. Scheme of flood damage analysis to built environment (Pistrika and Jonkman 2009)

However, in practice the assessment of direct (economic) damage to buildings is often directly related to the flood characteristics without a direct analysis of the physical mechanisms that cause the damage (Kelman and Spencer 2004).

The general procedure for the estimation of direct physical damage involves: (1) determination of flood characteristics; (2) assembling information on land use and maximum damage amounts; (3) development of depth-damage functions. The following paragraph refers to the development of the local depth-damage functions and the costing of the physical damages to the following land-use categories: (1) the built-up areas and (2) the agricultural areas. Based on international literature and by assembling local information the derived depth-damage functions developed for these land use types are presented in detail in the following paragraph.

4.2 Structuring the development of depth-damage functions

Since flood depth is the result of a flood simulation generated over a 25m x 25m cell grid, the smallest possible spatial scale of damage analysis is the 25m x 25m cell size. According to recent studies (Merz et al. 2004; Thieken et al. 2008; Pistrika and Jonkman 2009) the smaller the spatial unit is the poorer the relationship between flood depth and damage resulted. At a high level of detail and for a limited sample size of buildings the variations in building damage may be considerable. If the sample size becomes larger variations are averaged out. Consequently, in the context of the use of depth-damage functions they may be useful to estimate damage for larger areas with many buildings (Pistrika and Jonkman 2009). Keeping this in mind, the damage analysis for built-up areas is performed at a higher scale than the one-structure scale.

Damage is calculated as a percentage of the maximum possible damaged property value. The depreciated value of the replacement / reconstruction cost (in € / m^2) is used as the maximum possible damaged property value. The replacement / reconstruction cost values are derived from the available economic data about reimbursements due to flood damage to buildings of the Ministry of Structural Works and Environment. This study of local depth-damage functions for built-up areas took into consideration the work of Clausen (1989) and Black (1975) for estimation of potential flood damage to brick and masonry homes. Also, for the estimation of building's inventory it was used the concept of the exponent 'a' to parameterise the depth-damage function according to building type. This concept was first developed in Switzerland in a project called 'AFORISM' (1996) that involved a significant study on flood damages to buildings.

Finally a detailed survey was conducted by the author on the historical records of flood damages to buildings that occurred in the recent past in the broader area of Attica Prefecture. Two inundation incidents, occurred in 2002, and in 2005 within Attica Prefecture had kept records of flood damage to buildings and thus these were taken into consideration for the development of local depth-damage functions. It should be mentioned that the public access to these records was extremely limited due to strict laws of violation of private character data. However, studying the site inspections of affected buildings immediately after the event, it was concluded that the process of flood direct damage estimation was purely empirical and it resulted in a rough classification of the structural damage into two groups: (1) the inundation damage that allowed for reimbursement only for repairing the building structure and (2) the major structural damage / total destruction that allowed for reimbursement for reconstructing the building structure.

Given all the above considerations, the analysis resulted into three original sets of local depth-damage functions for built-up areas in order to estimate each of the following type of damage:

- Structural damage to single-family, two-storey residence, made of concrete walls with average quality of structure
- Damage to inventory of single-family residence
- Structural damage to industrial, one-storey building, made of concrete walls and iron roof with average quality of structure

Figure 3 shows the original depth-damage function empirically developed for the economic estimation of structural damage to the type of a single-family, two-storey residence.

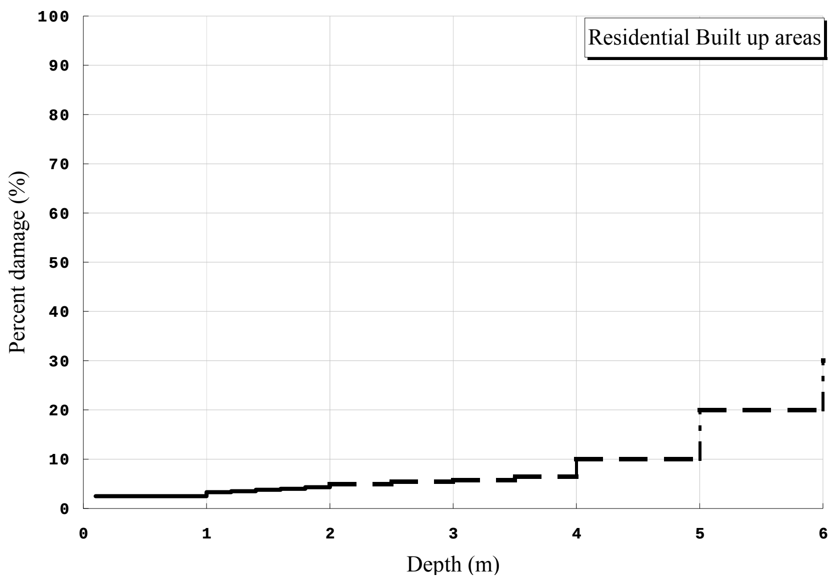

Figure 3: Relative depth- damage functions for structural damage estimation to single-family residence

The flood related damage to agricultural areas within the case study resulted in the development of local depth-damage functions for the following crop types:

- areas under trees (e.g. fig trees)
- olive trees
- vineyards
- garden-farming areas (complex cultivation patterns)

In general the damage functions for crops do not depend primarily on flood depth. Damage to crops depends mainly on when the flood occurs and the duration of flooding. Losses are estimated based on the area of inundation versus total area of crop land and the subsequent reduction in output, investment, and income. However, the developed damage functions for agricultural loss do not include any variable to account for flooding duration since the area under study experienced only short term floods – flash floods (less than one day inundation) so far. Also, it is assumed for all crop types that the growing season occurs during the flooding. Hence the damage estimation for agricultural loss is assumed as time independent.

The development of depth-damage functions is mostly empirical and is strongly based on flood – related damages to agriculture that happened within the area under study in the recent past. The flood damage data for agricultural loss were gathered from the Ministry of Agricultural Development. The maximum possible economic damage refers to the replacement cost of the agriculture product and it is taken to be equal to the yield production achieved per land area multiplied by the market value of the crop type. There is no consideration for the harvest cost and other expenses, and therefore the maximum yield loss in monetary values refers only to the replacement cost.

To identify the crop yield we used the crop inventory of the Ministry of Agricultural Development by calculating the average yield for the last 40 years. To identify the market value of each crop type and to capture the annual fluctuations in pricing for each crop type we used the average market value over the last five-year prices from the same inventory. Table 1 shows the maximum values of crop yield estimated for each of the aforementioned crop types.

Table 1. Maximum values of crop yield in € / m^2

Land Use Category	***Market value of crop (€ / kg)***	***Crop yield (tn / 1000 m^2)***	***Market value of crop (€ / m^2)***
Areas under trees	2.84	0.60	1.36
Olive trees	2.38	0.05	0.13
Vineyards	0.29	1.50	0.43
Garden farming areas	0.60	3.00	1.90

5. A GIS-BASED TOOL FOR FLOOD DIRECT DAMAGE

5.1 Theoretical Background

A GIS-based tool for direct flood damage estimation was developed by the Centre for the Assessment of Natural Hazards and Proactive Planning of National Technical University of Athens under the auspices of the EU Programme INTERREG IIIC-Sud Initiative and the Regional Operation Framework of NOÉ Programme - subproject DISMA (Tsakiris et al. 2007). The tool is an ESRI ArcMap extension that provides flood damage estimates in monetary terms for pre-specified types of land uses, given a set of ArcGIS raster layers that contain the required information.

The tool achieves to automate the calculation of direct flood damage estimation by applying the aforementioned depth-damage functions. Depending on known land-use categories, such functions will return the estimated monetary damage per area unit (e.g. one sq. metre). The monetary estimation in M€ of expected flood damage comes as a result of a percent damage that depends on a given flood depth, over the total maximum possible damage in monetary units for the type of the given area. In addition the depth-damage functions are imported in a stepwise fashion through a simple and intuitive interface. Hence the tool can be used to define new (improved) or alter existing damage functions so as to allow for convenient future development.

The main output of the tool is an estimated break-down of damages, depending on the input flood-map and land-use layers that the user has previously chosen. Furthermore a visual projection of the spatial distribution of expected flood damage under every flood scenario in ArcMap environment is feasible so that the user can easily identify the areas where the most damage is estimated to occur. Further details about the technical characteristics of the tool can be found in the technical report of subproject DISMA (Tsakiris et al. 2007).

5.2 Implementation and Results

The derivation of flood depth maps under specified flood scenarios allowed the estimation of expected flood damage over the area covered by the Digital Terrain Model extent. For every flood scenario the inundation depth map is integrated with the land use map in ArcMap environment and by applying the damage estimation tool (and thus the originally developed depth-damage functions) the total expected flood damage is computed in M€ over the land-use categories for which depth-damage functions were derived.

Table 2 gives the estimated break-down of damages under every flood scenario for the area under study. It is observed that the cost for flood damage only to the structure of residential built-up areas covers about 75 – 80 % of the total cost estimated over all land-use categories under each flood scenario. Hence developing a depth-damage function for residential built-up areas is crucial for the reliability of the damage results. Furthermore the damage figures of Table 2 verify the fact that the smaller the exceedance probability gets, the higher the expected flood damage becomes.

Table 2. Flood damage figures in M€ for every land-use category under every flood scenario

Land Use Category	Flood scenario 1 (T=20 yrs)	Flood scenario 2 (T=100 yrs)	Flood scenario 3 (T=1000 yrs)
Residential built-up areas (structural)	9.96	11.70	19.54
Residential built-up areas (content)	0.94	1.16	1.92
Industrial built-up areas	0.32	0.38	0.46
Areas under trees	0.01	0.02	0.05
Olive trees	0	0	0.01
Vineyards	0.08	0.14	0.32
Garden farming areas	2.11	2.24	2.66
Total (in M€)	**13.42**	**15.64**	**24.96**

Finally the visualisation of the analysis results in ArcMap environment provides an indication of the spatial distribution of expected damages and thus it allows the identification of flood-prone areas. This finding aims to support policy- and decision- making in the context of flood risk management and spatial planning. For instance Figure 4 illustrates partially the visual projection of the damage analysis results for residential built up areas (including both building structure and inventory) under the flood scenario of T =1000 yr.

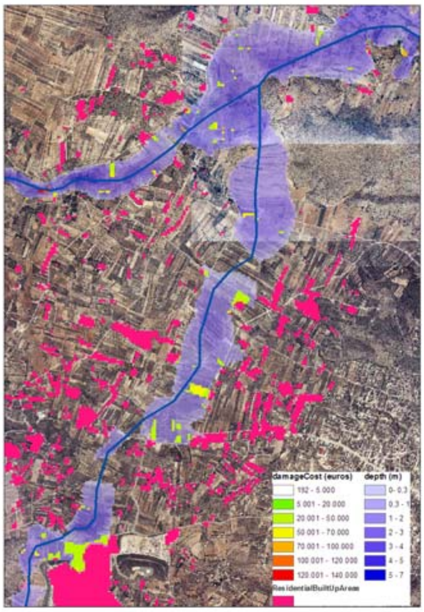

Figure 4. Visualisation of damage analysis results for flood scenario T=1000 yr

6. CONCLUSIONS AND RECOMMENDATIONS

In this paper the relationship between flood depth and economic damage to built-up and agricultural areas has been investigated for potential inundation due to overflowing of Erasinos stream in Eastern Attica (Greece) under specified flood scenarios. The study develops local depth-damage functions for the abovementioned land-use categories in an attempt to contribute to achieving a standard approach for expected flood damage estimation. The main findings can be summarized as follows:

- Structural damage to residential built-up areas is distinguished empirically into two groups: (1) the inundation damage for flood depth less than two meters and (2) major structural / total destruction for flood depth more than four meters. For flood depth values between two to four meters, building susceptibility to flooding is crucial and therefore the economic estimation of damage presupposes site inspection of an affected building.
- Damage to inventory of residential built-up areas is parameterized by the exponent 'a' so as to account for luxury, average or poor type of residence.
- Analysis results showed that flood damage to built-up areas covers nearly 80 % of the total damage estimation.
- Inundation depth may not be a crucial factor for the economic estimation of physical damage to agricultural areas due to flooding.
- The spatial level of detail of the analysis is a determining factor for the correlation between predictions and observations. At a high level of detail and for a limited sample size of buildings the variations in building damage may be considerable. If the sample size becomes larger variations are averaged out. This also implies that any depth-damage functions should not be used at a too high level of spatial detail, e.g. for individual structures.

Based on this study the following recommendations are made:

- Further investigation of the adequate spatial aggregation level of damage analysis in relation to the variations in the data that were used for the derivation of the stage damage functions.
- It is recommended to collect further information about the variation in building types, structures, and materials. For damage to building structure a division of the damage data according to building types (timber structure, masonry, concrete buildings etc.) may lead to better results.

ACKNOWLEDGEMENTS

The work presented in the paper was supported partly by the State Scholarship Foundation of Greece.

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