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GIS tools for quantitative flood damage assessment in data-scarce environments

- PhD thesis Summary -

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Contents

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Introduction

Floods are phenomena that occur annually worldwide, being the main natural hazard with a devastating impact on societies. Considering that the climate change will continue to increase the frequency and intensity of the flood hazard and the socio-economic growth will increase the exposure to this hazard, the improvement of flood risk assessment and management is becoming an important task not only at local and national level but also at pan-European and global scale (Cirella et al., 2014; Albano et al., 2015; Scorzini and Frank, 2015).

The flood risk assessment, that has been focusing traditionally on hazard analysis and protection measures, has moved recently to a risk-based approach focusing not only on flood control and reduction but also on the damage analysis, the risk being a combination between hazard and its consequences; this change is supported by the adoption of Directive 2007/60/EC (Flood Directive) of the European Parliament and Council (EU Directive 2007/60/CE, 2007).

In this context, there is a need for a more comprehensive approach of flood risk management that should properly evaluate and quantify all the aspects of flood risk assessment such as hazard, exposure and vulnerability. These aspects play an important role in the decision-making process, in the identification of high flood risk areas and in the design of the appropriate of flood management strategies (Cirella et al., 2014; Scorzini and Frank, 2015). In this light, there is an emerging need for assessing flood consequences and for adopting different scenarios and courses of action.

Scope and objectives of the thesis

The main goal of this thesis is to quantitatively analyse the flood damages and its related uncertainties in data-scarce environments. For this purpose, a methodology that can offer cost-effective solution for the flood area delineation and damage calculation is applied. This approach could support different stakeholders in flood hazard delineation, damage estimation and flood risk analysis in different territorial and socio-economic contexts. Therefore, the presented approach could represent a starting point that can be useful for knowledge transfer from the scientific community to stakeholders.

In this context, the questions addressed in this thesis refer to: how the free and open-source GIS features potential could be used in quantitative flood damage assessment; which are the uncertainties related to flood damage assessment and how they can be analysed; how to assess the flood damages in data-scarce environments; how the accuracy of large-scale application could be improved using publicly available datasets and EO (Earth Observation) data.

This thesis is focused on the damage assessment in data-scarce environments, applying a method that is able to use the existing data in small areas and extend it over areas where the information is missing. In this way, useful knowledge can be provided in order to conduct a complete flood damage assessment, including all the flood affected areas. Moreover, the assessments from this thesis were done using high-resolution data that improve the accuracy and reliability of the results.

The main objectives of this thesis are:

- To present a theoretical background regarding the flood risk and damage assessment and the current tools and methods used in the literature;
- The quantitative estimation of the economic damages at large-scale and for data-scarce environments, using pan-European depth-damage functions;
- The application of a GIS-based model for water-depth calculation at large-scale and for data-scarce environments, using high-resolution data;
- The use of the machine learning techniques and Landsat 8 images in order to provide high-resolution land use data over large areas with limited availability of data;
- The use of free and open source tools for flood damage quantification;
- To conduct an uncertainty analysis regarding the flood damage assessment

Outline of the thesis

- Chapter 1 presents the main concepts related to floods, flood risk and damage, as well as the situation in Europe and Romania regarding flood hazard.
- Chapter 2 describes the methodological approach regarding flood damage assessment. The available methodologies are described, highlighting the current gaps in the field and how these gaps can be overcome.
- Chapter 3 presents a quantitative flood damage assessment approach and an uncertainty analysis for a basin in Romania.
- Chapter 4 presents a large-scale flood damage assessment methodology for data-scarce environments, combining EO high-resolution data (30 m) and free and open-source GIS tools. A case study for the entire Romanian territory was conducted.

- Chapter 5 and 6 bring together the conclusions from the case studies and put forward recommendations and potential applications for stakeholders and outline future potential research topics derived from the present thesis.

1. Theoretical concepts and statistical data regarding the flood risk

Regarding the flood risk there are two definition widely used and accepted in the scientific community:

$$R = P \times C \quad (1)$$

R (Risk); P (Probability); C (Consequence)

$$R = H \times E \times V \quad (2)$$

R (Risk); H (Hazard); E (Exposure); V (Vulnerability)

In the first definition the term „risk" is defined as the product between the probability of occurrence of the event and the consequences of this event on the population, economy or environment (Ozunu and Anghel, 2007; Klijn, 2009; Scorzini et al., 2015; Botezan et al., 2015). In the second definition the risk depends on three factors: hazard, exposure and vulnerability. The *hazard* refers to the characteristics and frequency of the flood; the characteristics of the flood provide information regarding the magnitude of the event and are represented by factors such as water depth, water velocity and flooded area (Albano.et al., 2015; Winsemius et al., 2013). The *exposure* refers to the population and the economic assets situated in the flooded area, being in this way exposed to the hazard. The *vulnerability* refers to the susceptibility of the population and the potential assets affected by a flood (Barredo et al., 2006; Ștefănescu et al., 2018).

Floods affect the exposed elements (such as population, economic assets, the environment), producing damages. In general, the potential damages produced by floods are classified in four categories: direct tangible damage, direct intangible damage, indirect tangible damage and indirect intangible damage (Scorzini and Frank, 2015; Meyer et al., 2013).

Table 1. Damage types and examples (Meyer et al., 2013)

	Tangible damage	**Intangible damage**
Direct damage	Destruction of buildings, infrastructure, goods and crops	Loss of lives, injuries
Indirect damage	Production loss, cost of traffic disruption, disruption of public services	Trauma, increased vulnerability of the survivors, negative effects on the environment

In the last three decades (1988 – 2018) the natural hazards with the highest frequency in Europe are represented by floods. The CRED EM-DAT database recorded a number of 506 events since 1988, representing 37% of the most important natural hazard events that occurred in this period. Moreover, 39% of the total economic damages related to natural hazards are caused by floods (CRED EM-DAT).

In Romania, floods are the natural hazard with the highest frequency, Romania being one of the most affected countries in Europe (Arghiuș et al., 2011). According to CRED EM-DAT, in the last 30 years, the economic damages caused by natural hazards are related to floods (86%) and droughts (14%). Regarding the loss of lives, the natural hazards that caused the highest number of deaths are extreme temperatures (529 deaths) and floods (436 deaths).

In this context the Directive 2007/60/EC regarding flood risk assessment and management was transposed in 2010 at national level by the G.O. 846/2010, regarding the National Strategy for Flood Risk Management for medium and long term. The main aim of this Strategy was the mitigation of damages and life loss prevention (G.O. 846/2010). The implementation process has three stages: preliminary flood risk assessment, development of hazard maps and flood risk maps, and the final stage regarding the development of flood risk management plans.

2. General methodological approach regarding flood damages assessment

The classical approach for flood damage assessment (Fig. 1) has the following three steps: hazard analysis, exposure analysis and vulnerability analysis (de Moel et al., 2015; Bubeck and Kreibich, 2011; Scorzini and Frank, 2015).

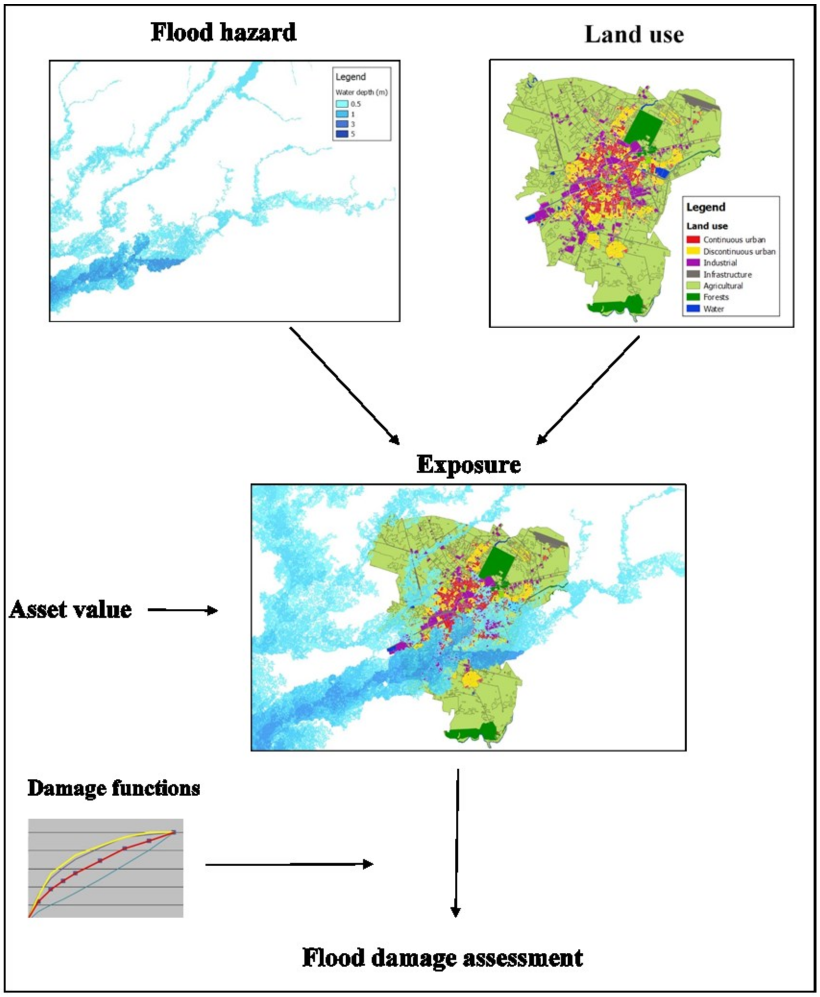

Fig. 1. Schematic representation of the flood damage assessment process

In the past years the use of free and open source GIS (Geographical Information Systems) software in the process of flood damage assessment has increased due to the fact that the GIS tools are able to provide adequate spatial data processing, analysis and mapping. These features are particularly useful for the development of flood hazard and flood risk maps as well as for the visualisation of the results. Furthermore, the free availability of data lead to an increase in the development of tools and models that can be used for flood hazard and flood consequence analysis (Steiniger and Bocher, 2009; Chingombe et al., 2015; Albano et. al, 2015). These tools can process data and provide information that are further used for hydraulic modelling with the aim of obtaining the flood characteristics such as flooded area, water depth and water velocity.

The hazard analysis implies the determination of the flood probability and intensity. The flood intensity can be represented by many parameters such as water depth, water velocity, duration and extent of the flood, however the most important and commonly used are the water depth and water extent (Sole et al., 2013). These parameters can be calculated using 1-dimensional or 2-dimensional hydrodynamic models (de Moel, 2012; Messner et al., 2007). However, there are ungauged locations where the data necessary for detailed modelling are not available, or the resources and the time are limited and therefore more simplified methods are needed. Such a methodology for the flood area estimation was proposed by Samela et al., 2017. This method is using the basin's geomorphology in order to obtain a large scale analysis of the flooded area in scarce-data locations. Based on this methodology the GFA (Geomorphic Flood Area) tool was developed as a QGIS plugin (Samela et al., 2018).

The elements at risk are usually represented by population, buildings, or type of land use. Usually, the elements at risk are classified into economic sectors (urban, industry, agriculture), individual elements of each sector having the same characteristics. Based on these sectors, land use maps were developed with different resolutions and different number of land use classes. These maps are used for the representation of the elements at risk. These information, which are represented by maps indicating the characteristic of the elements at risk and their location, are overlapped with the information regarding the hazard (flood maps) and in this way the exposed elements are obtained (de Moel et al., 2015; Albano et al., 2015).

Due to the rapid urbanization from the last years, there is a lack of up to date land use data, especially in developing countries (Wieland and Pittore, 2016). Furthermore, most of the available maps have a low resolution, containing limited land use classes, thus decreasing the accuracy of the results (Albano et al., 2015). Therefore, in the last years there is an increased interest in using the satellite imagery with the purpose of obtaining land use data. The current availability of high-resolution satellite imagery allows the automated detection of different land use classes and different settlement types. This trend led to the development of different approaches for land use classification based on satellite imagery (Ok, 2013).

The elements within the flooded area can be affected to a different extent, depending on their proximity to the river, the depth and velocity of the water in their locations as well as their characteristics (type of land use, building material in the case of constructions). The degree of the damage that can occur can be determined using damage functions. The most common used are the depth damage functions which determine the susceptibility of a certain exposed element depending to the water depth (Jongman et al., 2012; Cammerer et al., 2013).

The development and the use of damage models in the past years has increased, becoming an important tool for flood damage estimation and subsequently flood risk assessment. In this thesis the FloodRisk model was used. FloodRisk is a QGIS plugin that calculates the direct economic damages and the loss of lives caused by floods and can be applied in analyses at different scales. It is a free and flexible plugin based on a transparent and collaborative approach (Mancusi et al., 2015; Albano et al., 2017b).

The results of the flood damage assessment are affected by different uncertainties which can be induced by the input data, the modelling process as well as the spatial and temporal changes in the information that are used (de Moel and Aerts, 2011). The analysis of these uncertainties is important for a better understanding of the flood risk process, highlighting the parameters that induce the greatest errors in the results. In this way the data and the methods that are used can be improved, making the results more reliable and accurate (de Moel et al., 2012).

3. Case study 1. Flood damage assessment and uncertainties analysis for the 2006 flood event in Ilișua basin in Romania

In this chapter a quantitative flood damage assessment approach is implemented. For this purpose, the FloodRisk plugin, developed in QGIS software was used. In particular, the depth-damage functions collected and harmonized by the European Joint Research Centre (JRC), (Huizinga, 2007) have been used for a comparative assessment showing that the outcomes are strongly influenced by the shape of the depth-damage functions. Furthermore, an uncertainty analysis was performed comparing the assessed damage obtained through the use of JRC damage functions and real, surveyed damage of the proposed case study in North-Western Romania, i.e. Ilișua Basin, regarding the 2006 flood event.

In the hazard analysis process, the flood extent and water depth are calculated. For this purpose, the QGIS and HEC RAS software were used. The input data were processed in QGIS and exported in HEC RAS using the Q-RAS tool. For the hydraulic simulations, the 1D hydraulic model HEC RAS was used and the flow profile was developed. The initial and boundary conditions that were used are: Q = 280 m^3/s, flow conditions – critical depth upstream and normal depth downstream, mixed flow regime (Albano et al., 2017a). The results are presented in Fig. 2.

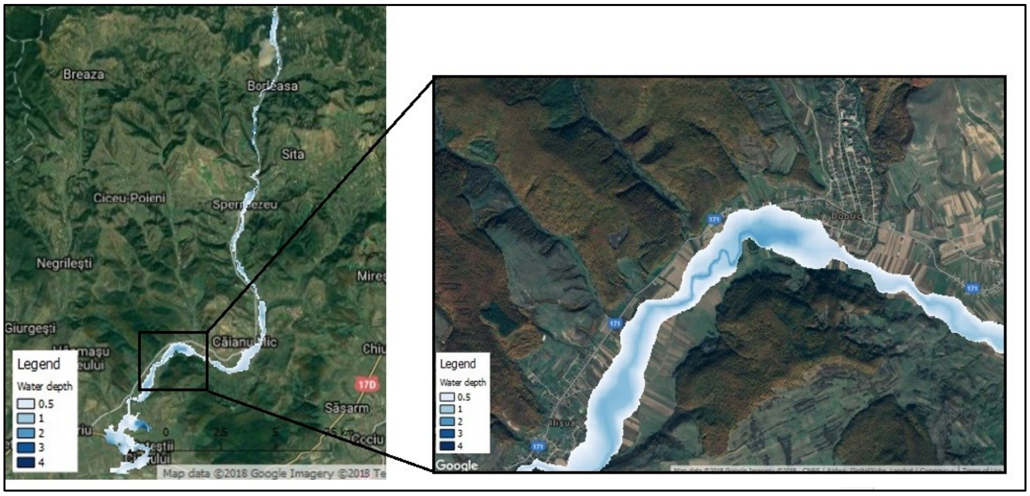

Fig. 2. Flood hazard map for Ilișua Basin developed in this study

For the exposure analysis, the Corine Land Cover database was used. Afterwards, the asset value was determined for each CORINE land use class. For each land use class affected by flooding a corresponding depth-damage function is associated.

For the estimation of direct damages in this study, the following input data were used: the water depth map developed in the hazard analysis step, the Corine land use map containing the asset value for each class and the JRC depth-damage functions. The results are presented in Table 2.

Table 2. Results of damage calculation using different JRC depth-damage functions and the reported damages (Albano et al., 2017a)

	Damages (MEuro)			
	urban	**roads**	**agriculture**	**Total**
Belgium JRC	8.3	0.09	0.85	9.2
Czech Republic JRC	5	0.14	0.69	5.8
Germany JRC	3.8	0.16	0.31	4.3
Netherlands JRC	3.2	0.10	0.81	4.2
Norway JRC	18.4	0.26	0.69	19.4
Switzerland JRC	13.8	0.13	0.58	14.6
UK JRC	32.4	0.13	1	33.6
Surveyed Ilișua Basin	**0.29**	**0.6**	**0.12**	**1.1**

The results are characterized by a large variability, therefore the relative error was calculated and an uncertainty analysis regarding the damage functions' transferability was conducted. The results are presented in Table 3.

Table 3. Relative error and function uncertainty determination (Albano et al., 2017a)

			Relative error	**Function uncertainty**
Total reported (MEuro)		**1.1**		
Total calculated (MEuro)	Belgium-JRC	9.2	**8.37**	**2.21**
	Czech Republic-JRC	5.8	**5.28**	**1.39**
	Germany-JRC	4.3	**3.92**	**1.03**
	Netherlands-JRC	4.2	**3.79**	**--**
	Norway-JRC	19.4	**17.53**	**4.63**
	Switzerland-JRC	14.6	**13.18**	**3.48**
	UK-JRC	33.6	**30.35**	**8.01**

The results show that overall applicability and transferability of depth-damage functions to other geographical regions may induce uncertainties in the flood damage modelling process, but the quantification of the uncertainties and its communication to stakeholders is the first step for the maximization of quantitative risk approach effectiveness, towards flood risk management objectives of the Flood Directive, ensuring that risk information is robust, credible and transparent.

4. Case study 2. GIS tools for large-scale analysis of direct economic flood damages. The case study of Romania

The increased development of tools and models that can be used for flood hazard and flood damage analysis proved to be particularly useful for large-scale analyses and has gained more attention over the past years. The flood risk assessment at large scale offers support for national and global policies and are used in the prioritisation of investments at national level, the principal stakeholders being the governments and the insurance companies.

However, the large scales approaches still present gaps given by the lack of consistent data over large areas and the lack of high resolution data. In many areas, there are ungauged basins that provide little information and therefore the hydraulic modelling is rather challenging and time-consuming. In this context, more simplistic approaches were developed, using available data, such as the DEMs, in order to extract the necessary information for the analysis of flood hazard. Moreover, the land use data available for large areas have a coarse resolution, which can induce uncertainties in the results. However, in the past years, many studies focused on using high-resolution EO datasets in order to extract land use information (de Moel et al., 2015; Alfieri et al., 2014).

In this work, a quantitative flood damage assessment methodology for data-scarce environments is proposed, using data that are easily available. The flood damage analysis was done for the entire Romanian territory, for a return period of 100 years, combining high-resolution EO data (30m resolution) and free and open-source GIS tools.

In the hazard analysis process the flood prone areas are identified and the water depth for these areas was calculated. For this purpose, a GIS-based model (Geomorphic Flood Area -GFA tool), that is using the geomorphology of the basin was applied (Samela et al., 2017). The GFA tool is based on the GFI methodology which combines the geomorphological information extracted from a Digital Elevation Model (DEM) with existing flood hazard information from smaller areas in order to extend this information over large areas.

The obtained hazard map (Fig. 3) contains the extent of the flood and the water depth for the entire territory including the second and minor rivers which usually are not considered in large scale analyses.

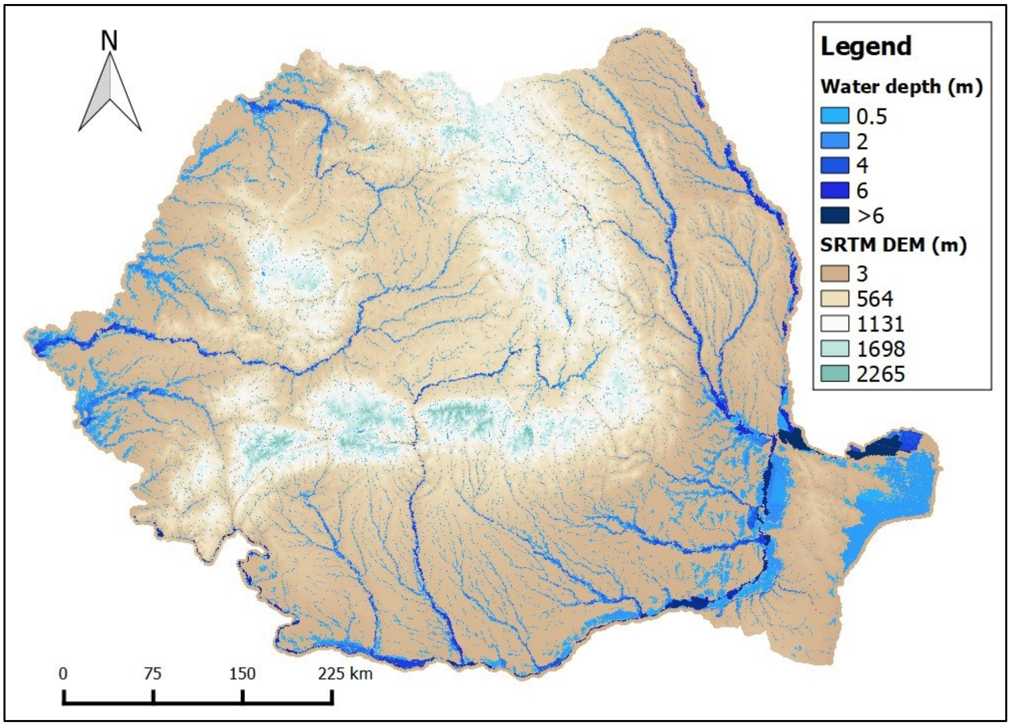

Fig. 3. Water depth map developed in this study (GFI hazard map)

Regarding the exposure analysis, in this study, a new land used map was developed from multi-spectral satellite images. For this purpose the Landsat 8 data with a resolution of 30 m were used and machine-learning classification algorithms were applied in order to identify the land use classes for the study area.

The method is using an object-based approach, which means that the analysis is done for segments of an image and not for each pixel. These segments are characterised by different features that can be analysed using a machine learning classifier in order to detect a certain object, in this case a land use class. For the classification an Artificial Neural Network (ANN) called Multi-Layer Perceptron (MLP) was applied, using as training data the available Urban Atlas land use maps for Romania.

The land use classes were determined for the area of interest – the flood prone areas. In this way, seven land use classes were obtained: continuous urban, discontinuous urban, industrial, infrastructure, agricultural, forests and water (Fig. 4).

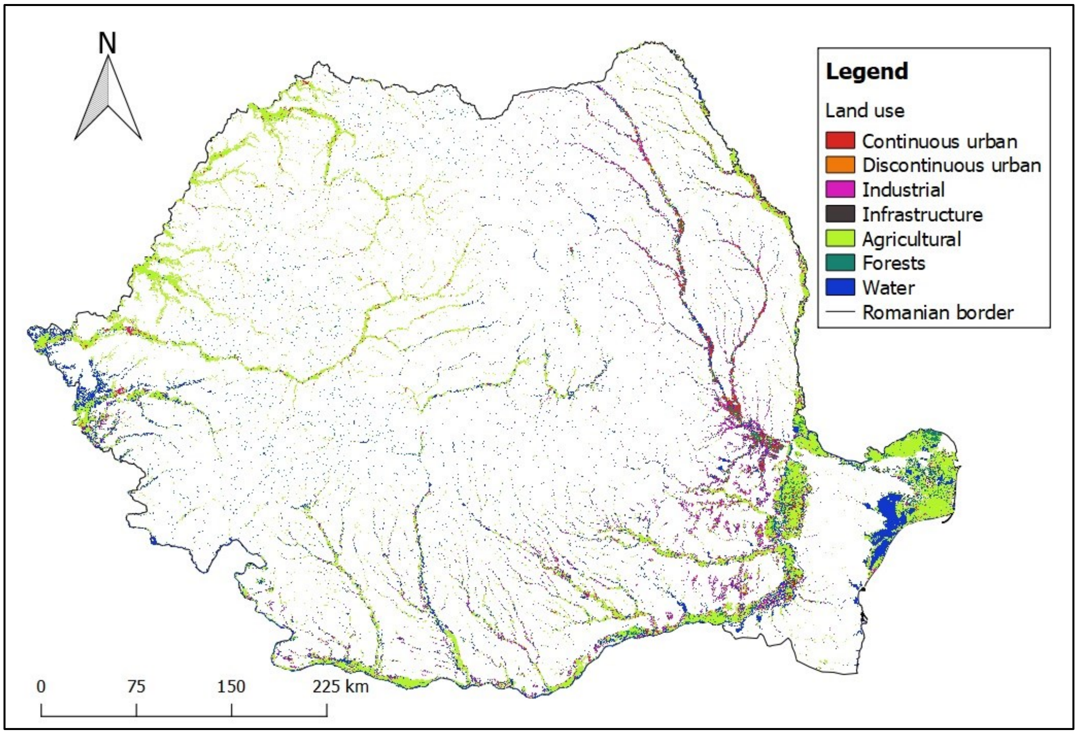

Fig. 4. Land use map developed for the flood prone area using Landsat 8 satellite imagery (*Landsat 8 land use map*)

In order to calculate the possible direct tangible damages at national level, the free and open source FloodRiks plugin was used. The damages were calculated for four sets of input data (Fig. 5):

- JRC water depth and Corine Land Cover (CLC)
- GFI water depth and Landsat 8 land use
- JRC water depth and Landsat 8 land use
- GFI water depth and CLC

The JRC water depth is the pan-European hazard map developed by Alfieri et al., 2014; the GFI water depth represents the hazard map developed in this study using the GFI methodology; the Landsat 8 land use represents the land use map developed in this study using Landsat 8 satellite images.

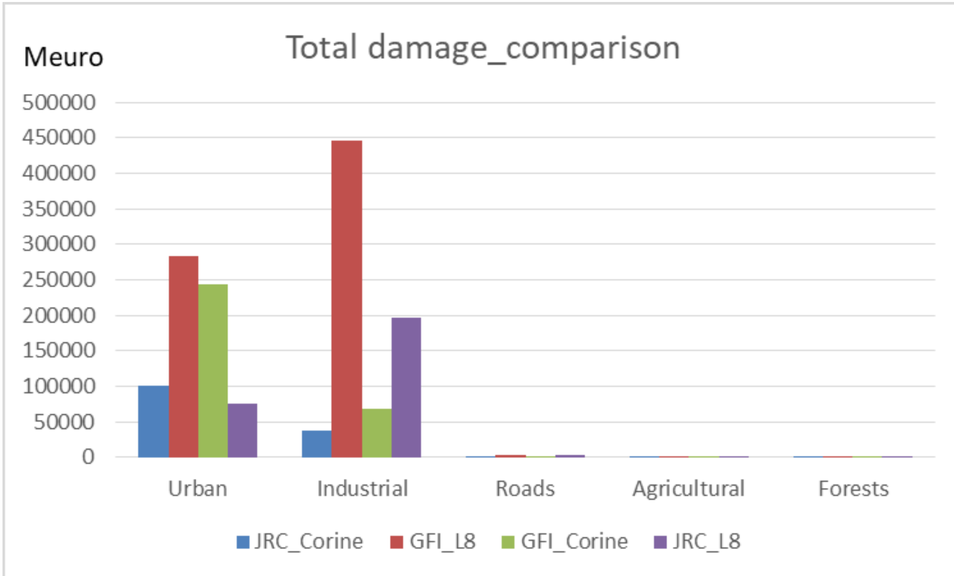

Fig. 5. Damage value comparison between the four scenarios

The results showed that when the GFI map is used the value of the damages is overestimated. However, this can be explained by the use of a more detailed flood map that was developed in this study, which includes all the rivers from the study area.

On the other hand, the simulations done with CLC show a larger percent of damages in the urban areas, while the simulations done with Landsat 8 have a larger percent of damages in industrial areas. This fact indicates that the Landsat 8 land use has a greater influence on the industrial damage results, overestimating them.

The differences caused by the use of separate land use maps may be given by the resolution of the data. The CLC has a resolution of 100 m, offering a coarse classification of the land use. The Landsat 8 land use map has a resolution of 30 m, offering therefore more accurate results. When the maps are analysed by simple visualization, it can be observed that the Landsat 8 contains larger industrial areas compared to CLC, this fact being a result of the higher resolution of Landsat 8 land use map.

In order to prove this hypothesis, that larger industrial areas are identified when the resolution of land use data is higher, the classification of CLC (100 m resolution) was compared with the classification of Urban Atlas (10 m resolution). A confusion matrix was apply for all areas in Romania where Urban Atlas data were available (35 cities). The results showed a general good accuracy, however when just the industrial class is considered, the results showed a low accuracy.

This demonstrates that the CLC fails to correctly identify the industrial area and therefore the damages resulted using this land use map may present large uncertainties.

5. Conclusions

This thesis focused on improving the understanding and the knowledge of the flood risk assessment process by applying a quantitative framework methodology for damage estimation and analysing the related uncertainties using innovative tools.

Personal contributions

- Identification and synthesis of the major gaps present today in quantitative flood risk assessment and damage modelling;
- Proposing the use of free and open source GIS tools for hazard, exposure and damage estimation;
- Application of GIS tools for the quantitative estimation of flood damages in data-scarce environments;
- Encouraging the use of freely available and high-resolution data (i.e. Landsat missions of the Copernicus EU funded program);
- Development of an uncertainty analysis associated to flood damage assessment and demonstrating its need for the transferability of flood damage assessment results to stakeholders and the general public.

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