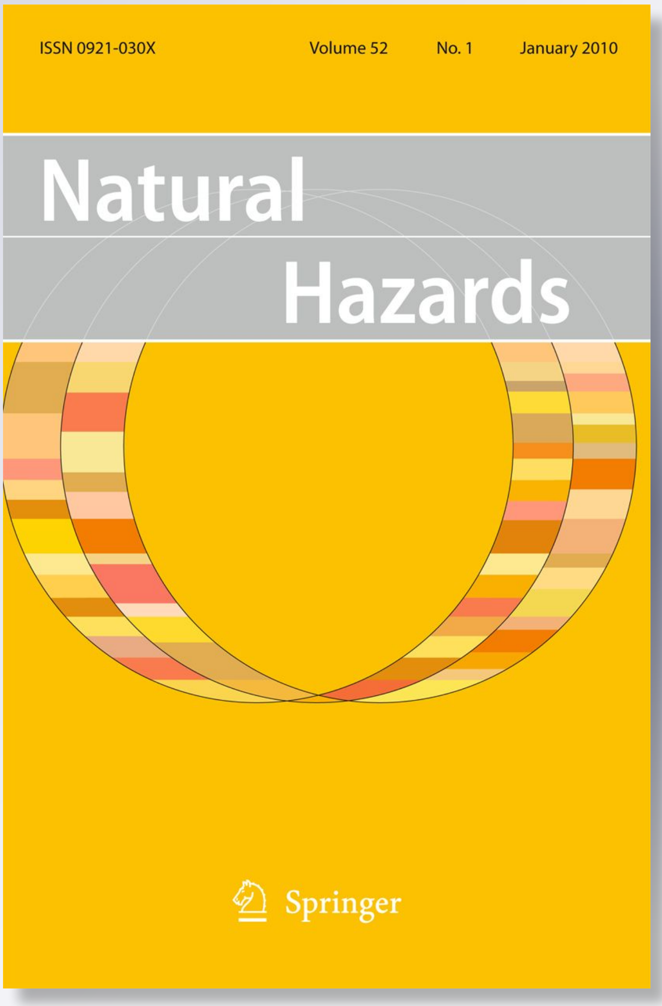
Preliminary flood risk assessment: the case of Athens

Georgia Kandilioti & Christos Makropoulos

Natural Hazards
Journal of the International Society for the Prevention and Mitigation of Natural Hazards

ISSN 0921-030X

Nat Hazards
DOI 10.1007/s11069-011-9930-5



Springer

Your article is protected by copyright and all rights are held exclusively by Springer Science+Business Media B.V.. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your work, please use the accepted author's version for posting to your own website or your institution's repository. You may further deposit the accepted author's version on a funder's repository at a funder's request, provided it is not made publicly available until 12 months after publication.

Author's personal copy

Nat Hazards
DOI 10.1007/s11069-011-9930-5

ORIGINAL PAPER

Preliminary flood risk assessment: the case of Athens

Georgia Kandilioti · Christos Makropoulos

Received: 3 May 2010 / Accepted: 8 August 2011
© Springer Science+Business Media B.V. 2011

Abstract Flood mapping, especially in urban areas, is a demanding task requiring substantial (and usually unavailable) data. However, with the recent introduction of the EU Floods Directive (2007/60/EC), the need for reliable, but cost effective, risk mapping at the regional scale is rising in the policy agenda. Methods are therefore required to allow for efficiently undertaking what the Directive terms "preliminary flood risk assessment," in other words a screening of areas that could potentially be at risk of flooding and that consequently merit more detailed attention and analysis. Such methods cannot rely on modeling, as this would require more data and effort that is reasonable for this high-level, screening phase. This is especially true in urban areas, where modeling requires knowledge of the detailed urban terrain, the drainage networks, and their interactions. A GIS-based multicriteria flood risk assessment methodology was therefore developed and applied for the mapping of flood risk in urban areas. This approach quantifies the spatial distribution of flood risk and is able to deal with uncertainties in criteria values and to examine their influence on the overall flood risk assessment. It can further assess the spatially variable reliability of the resulting maps on the basis of the choice of method used to develop the maps. The approach is applied to the Greater Athens area and validated for its central and most urban part. A GIS database of economic, social, and environmental criteria contributing to flood risk was created. Three different multicriteria decision rules (Analytical Hierarchy Process, Weighted Linear Combination and Ordered Weighting Averaging) were applied, to produce the overall flood risk map of the area. To implement this methodology, the IDRISI Andes GIS software was customized and used. It is concluded that the results of the analysis are a reasonable representation of actual flood risk, on the basis of their comparison with historical flood events.

Keywords Floods · GIS · Multicriteria evaluation (MCE) · Sensitivity analysis · Uncertainty · Vulnerability

G. Kandilioti · C. Makropoulos (✉)
Department of Water Resources and Environmental Engineering, Faculty of Civil Engineering,
National Technical University of Athens, 5, Iroon Polytechniou Str, Athens, Greece
e-mail: cmakro@mail.ntua.gr

Published online: 24 August 2011

Author's personal copy

1 Introduction

Flooding can result not only in costly damage to property, but can also pose a risk to life and livelihood. The flood damage caused by heavy rainfall is one of the most important natural disasters and affects human life and social development. The most severe impacts of floods, whether it happens as a result of climate change or otherwise, are most likely to occur in urban areas where people, resources, and infrastructure are concentrated. This will affect not only the city's inhabitants but also its industries and commerce and even lower the potential for investment. According to the EU Floods Directive (2007/60/EC (COM 2007)), *"flood risk" means the combination of the* ***probability of a flood event*** *and of the potential adverse* ***consequences*** *for human health, the environment, cultural heritage and economic activity associated with a flood event,* associated with that flood event. Sayers et al. (2002) assume that risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred (Eq. 1). Risk therefore has two components—the probability (or chance) of an event occurring and the consequence (or impact) associated with that event (see also Smith 1996)

$$R = \text{Occurrence} \times \text{Consequence}. \tag{1}$$

The process of assessing flood risk can be conceptualized using the Source-Pathway-Receptor-Consequence (S-P-R-C) model (Fig. 1) as proposed by the UK Institution of Civil Engineers (ICE 2001).

The schematic shows the conceptual link between the hydrological events (sources) through discharge and inundation (pathways) to the physical impacts on elements at risk (receptors) and the assessment of their effects (consequences). Here, "source," "pathways," and "receptor" refer to the physical process and are linked to the *occurrence* part of Eq. 1, whereas the assessment of the "(negative) consequence" refers to the socioeconomic domain and is linked to the *consequence* part of Eq. 1 (Schanze et al. 2006).

The Source-Pathway-Receptor-Consequence (SPRC) model helps with the identification of the association between occurrence and consequence (Sayers et al. 2002; Wallingford 2002). For a risk to arise, there must be a "source" or event (i.e., high rainfall), a "receptor" (e.g., households in the floodplain), and a pathway between the source and the receptor (i.e., flood routes). Clearly, there can be multiple sources, pathways, and

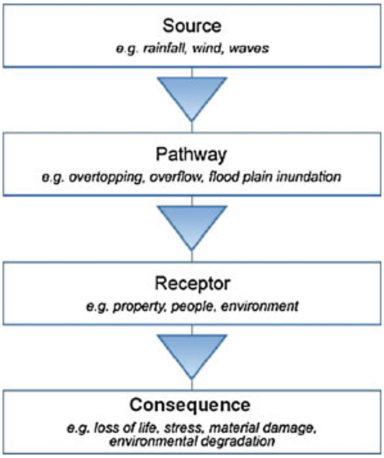


Fig. 1 Source-Pathway-Receptor-Consequence model. *Source:* Sayers et al. 2002

Author's personal copy

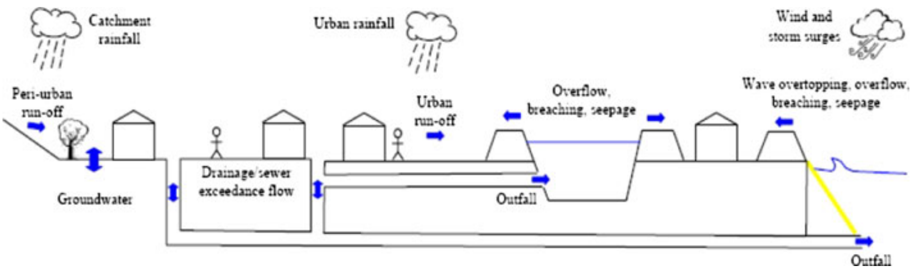


Fig. 2 The interactions between source-pathway-receptors in integrated flood risk management. *Source:* Dawson et al. 2008

receptors. Therefore, the methodology to determine the likelihood of a consequence occurring (e.g., damage to property or life) must, in principle, be capable of integrating several (possibly interacting) mechanisms and of capturing the links between the various sources, pathways, and receptors (Fig. 2). The SPRC model is now widely used to provide such an underlying structure (Sayers and Calvert 2007). Evans et al. (2003), for example, adopted it as the framework for considering the drivers of future floods for the UK. In this paper, the SPRC model was used as the basis for structuring the flood risk assessment methodology.

The quantification of flood risk results in monetary units and/or in loss of life units (or DALYs[1]), if the losses are measurable, or in qualitative terms (e.g., allocation in classes) in the case of non-monetary damages (social, environment, and cultural) to the affected areas. The EU Floods Directive requires, in article 6, risk mapping that encompasses social, economic, cultural, and environmental dimensions of consequences.

However, quantitative flood risk assessment, particularly in urban areas, represents a genuine challenge as urban flooding is driven by a complex interaction of natural and engineered processes, some of which operate at very local scales (Dawson et al. 2008). This paper briefly presents the main methods used to quantify flood risk in urban areas, develops a spatial analysis methodology for screening areas for the "most appropriate" risk quantification method, and proposes a process for quantifying flood risk, using topographic criteria (suitable for preliminary flood risk assessment). The key theories, methods, and software used are briefly presented and discussed. The results of the methodological screening analysis are then used to assign "levels of comfort" to the topographic risk quantification, and both methodologies are applied for the case of the Greater Athens area. Finally, the maps created are compared, for validation purposes, with flood events recorded in the central and most urban part of Greater Athens, between 1887 and 2007.

2 Methodology

2.1 Background

Multicriteria analysis (MCA) is at the center of the proposed methodology. It is clearly a wide topic (e.g., Bana and Costa 1990; Munda 1995; Belton and Stewart 2002) that includes various approaches and methods, three of which were used in this study:

[1] DALYs = Disability Adjusted Life Years: The sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability (source: www.who.int).

Author's personal copy

1. Analytical Hierarchy Process (AHP) (Saaty 1980,1992),
2. Weighting Linear Combination (WLC) (Hopkins 1977; Tomlin 1990; Carver 1991; Eastman et al. 1993; Eastman 1997; Heywood et al. 1995; Malczewski 1999, 2000; Makropoulos et al. 1999) and
3. Ordered Weighting Averaging (OWA) (Yager 1993, Rinner and Malczewski 2002; Makropoulos and Butler 2006).

As the method developed here is one of the spatial analyses, work concentrated on spatial MCA, which can be defined as a set of procedures for combining Geographical data and an agent's knowledge (preferences, priorities), to obtain information for decision making (Malczewski 2006). This is a relatively new but growing research field, which is still developing with the further improvement of GIS (geographic information systems), (Malczewski 2006). As the discussion of these methods is outside the scope of this paper, the reader is referred to the comprehensive textbook on the combination of MCA and GIS, written by Malczewski (1999) as well as to work by Tkach and Simonovic (1997), Malczewski (1999), Malczewski et al. (2003), Thinh and Hedel (2004), Simonovic and Nirupama (2005), Malczewski (2006), Strager and Rosenberger (2006), and Meyer et al. 2008.

Despite the extent of published literature on spatial MCA, flood risk has not been often considered. Tkach and Simonovic (1997) analyze the spatial distribution of the multiple effects of different flood protection alternatives in the Red River Basin, using a GIS-based variant of the Compromise Programming (CP) MCA technique that they term Spatial Compromise Programming (SCP). Simonovic and Nirupama (2005) expand this approach by integrating fuzzy set (Zadeh 1965) techniques in order to deal with uncertainties in the evaluation criteria. Makropoulos et al. (2007) present a new spatial MCA technique that they term spatial ordered weighted averaging and illustrate its application on an urban flooding example. However, most multicriteria approaches in the context of flood risk focus on the evaluation of flood mitigation measures rather than flood risk mapping (Meyer et al. 2008).

In this study, spatial MCA was used as the method of choice for incorporating relevant criteria influencing the occurrence and consequence of floods, standardized against a common scale. GIS was selected as the software of choice due to its ability to handle spatial data (topographic, geological, socioeconomic, rainfall, and meteorological). The approach presented in this paper combines MCA techniques with GIS (specifically Arc Map 9.2 and IDRISI Andes). The overall process consists of three main steps, resulting in an equal number of maps:

1. The flood risk assessment **methodological** mapping
2. The flood **occurrence** mapping
3. The flood **consequence** mapping.

These three steps are explained in detail in the next sections.

2.2 Flood risk assessment methodological mapping

With regard to the replication and prediction of floods in urban areas, a large number of different assessment methods can be used. The level of suitability of each assessment method depends on the characteristics of the area under study but also on the study's requirements and the availability of data. For example, preliminary flood risk assessment for screening purposes cannot and indeed should not be undertaken through detailed

Author's personal copy

modeling. According to Bamford et al. (2008), the main methodologies for flood risk assessment can be summarized as follows:

- *Topographic index analysis*. This approach utilizes information derived from a digital elevation model (DEM) to identify areas at risk from flooding. The topographic index comes from a score that combines (1) areas identified as flat, (2) areas identified as local depressions, and (3) areas close to drainage pathways from an analysis of slope and contributing area.
- *2D Overland routing of a spatially uniform rainfall event*. A rainfall hyetograph is applied to each 2D model grid cell during simulation. It is used to route the resulting flood water overland, and determine the locations at which flood water accumulates and the areal extent of flooding (Hunter et al. 2008; Bradbrook et al. 2004).
- *Decoupled hydraulic sewer model and 1D overland routing*. This approach has two major modeling steps. Firstly, the sub-surface sewer and pipe network system is modeled using an appropriate hydraulic model. Secondly, the flow/volume expelled from manholes is routed overland using simple one dimensional flow routing paths. Properties are associated to sewers to replicate below-ground flooding mechanisms (flooding due to backing up from overloaded sewers).
- *Decoupled hydraulic sewer model and 2D overland routing*. This approach is similar to the above methodology, but a 2D approach to surface flood routing is used. The water leaving the below-ground system is fed into an overland flow model. The overland flow remains above ground, and this method does not enable water to re-enter the below-ground system (Djordjevic et al. 2005).
- *Coupled hydraulic sewer model and 2D overland routing*. This approach is similar to the *decoupled hydraulic sewer model and 2D overland routing* method (above), but the surface and subsurface hydraulic models interact dynamically providing feedback to each other within a single model (Carr and Smith 2006; Chen et al. 2005).

Each method requires different levels of information. Table 1 lists the key information needed by each method, although additional data could also be required (e.g., detailed topographic information including fences and walls are not listed here). In addition to the data identified here, the collection of actual flood data is vital to validate predicted results (Bamford et al. 2008). Table 1 further categorizes the methods in order of increasing complexity.

To be able to identify which areas could be handled with simple methods (such as topographic analysis) and which need more complex assessment methods (such as 1D or 2D modeling), the study collected the following information (treated as criteria):

1. The digital elevation model (DEM)
2. Slope
3. Drainage pipes density
4. Streams density
5. Combined sewer network density
6. Land use

The above datasets and their assumed effect on methodological complexity requirements are listed in Table 2.

Table 2 presents the selected criteria (column 1) together with indicative literature explaining how the specific criterion affects the choice of flood risk assessment methodology (column 2). In column 3, the classes identified within each criterion are presented and linked (through their id number) to the methodological categories in column 4. For

Author's personal copy

Table 1 Summary information required for each assessment method and complexity level

Flood Risk Assessment Methodologies					
Data	Topographic Analysis	2D Overland Routing	Sewer Model and 1D Routing	Decoupled Sewer Model and 2D Routing	Coupled Sewer Model and 2D routing
Rainfall Data		√	√	√	√
Historical Flood Data		√	√	√	√
Sewer Network Models			√	√	√
Topographic Data	√	√	√	√	√

Simple Method → Complex Method

example, in the land use criterion, natural environment is associated with simpler methodologies, while urban environments are associated with complex methodologies, with peri-urban and other land uses in the middle.

Every criterion was standardized against a common scale (0–255) by means of fuzzy inference (Makropoulos et al. 2008) and result in output maps that depict the level of methodological complexity required on the basis of the specific criterion. In the output maps, 0 represents strong support for simple methodologies, while 255 represents strong support to complex methodologies (Fig. 3).

After standardizing the six criteria above, equal weights were applied to all of them, in the absence of scientific evidence suggesting otherwise, and a methodological complexity map was created (Fig. 14). This analysis was performed for two reasons:

- To assess the appropriate level of attention needed to calculate detailed flood risk maps for various areas (hence focusing future work, including, for example, work by consultants working for the implementation of the Floods Directive)
- To assess the "level of comfort," one could have with the results of a simplified methodological approach, such as the one proposed here, which, we argue, would be different for different areas. For areas that are characterized as "requiring a simple approach" (by the above process), a higher level of comfort can be assigned than for results in areas that have been characterized as "requiring a more complex approach." This is discussed further in the results section below.

Both these aspects are not case specific and could be in principle applied to any case study resulting in similar benefits. It is therefore included as (an initial) part of the overall proposed methodological approach.

2.3 Flood occurrence mapping

The following criteria that are related to flood occurrence have been selected:

Author's personal copy

Table 2 Methodological mapping criteria

Criteria	Description	Classes	Methodology
Height (m)	Height is associated with low flow accumulation by virtue of (necessarily) limited upstream catchments. It is also associated with less urbanization, more natural conditions of water flow and limited potential for water storage/ponding and reduced infiltration capacity as compared to lowland areas. It was assumed therefore that flood risk in areas of higher altitude can be assessment using simpler methods (see also Sauer 2002; Yalcin and Akyurek 2004)	1. Great height 2. Median height 3. Low height	1. Simple 2. Medium complexity 3. Complex
Slope (degrees)	Steep slopes are a major mechanism for water flow toward lowland areas. As the direction of flow is driven by gravity, simplifying assumptions, such as steepest descent paths, can be employed to assess flood risk. By contrast, in low slope areas (e.g., in lowland areas), a more detailed hydraulic model may be required to assess water flow and hence flood risk (see also Sauer 2002; Yalcin and Akyurek 2004; Butler et al. 2005)	1. High slope 2. Medium slope 3. Low slope	1. Simple 2. Medium complexity 3. Complex
Urban drainage network density (m/m^2 per municipality)	In areas where the density of drainage network is high, complex interactions may occur between water flowing overland and water flowing in the network itself. This is primarily the domain of 1D–1D and 1D–2D modeling (see also Schmitt et al. 2004; Sauer 2002; Djordevic et al. 2005)	1. Low density 2. Medium density 3. High density	1. Simple 2. Medium complexity 3. Complex
Combined network density (m/m^2 per municipality)	The same rationale as above applies to the combined sewer networks	1. Low density 2. Medium density 3. High density	1. Simple 2. Medium complexity 3. Complex
Streams density (m/m^2 per municipality)	High stream density indicates the potential for complex pathways for overland flow, hence the need for more complex methods of calculation (Schmitt et al. 2004; Sauer 2002)	1. Low density 2. Medium density 3. High density	1. Simple 2. Medium complexity 3. Complex
Land use (infiltration)	In urban areas, water can flow into and from underground sewer network, along streets (as primary preferential paths), but also can create surface ponds and flow across the urban catchment (preferential paths different from streets). Moreover, surface barriers create more potential pathways. All the above components make an urbanized area much more complex, and detailed analysis should be applied to estimate flood risk. (Yalcin and Akyurek 2004; Schmitt et al. 2004; Nunes Correia et al. 1999; Butler et al. 2005)	1. Natural environment 2. Peri-urban or medium intensity 3. Intensively urbanized	1. Simple 2. Medium complexity 3. Complex

Author's personal copy

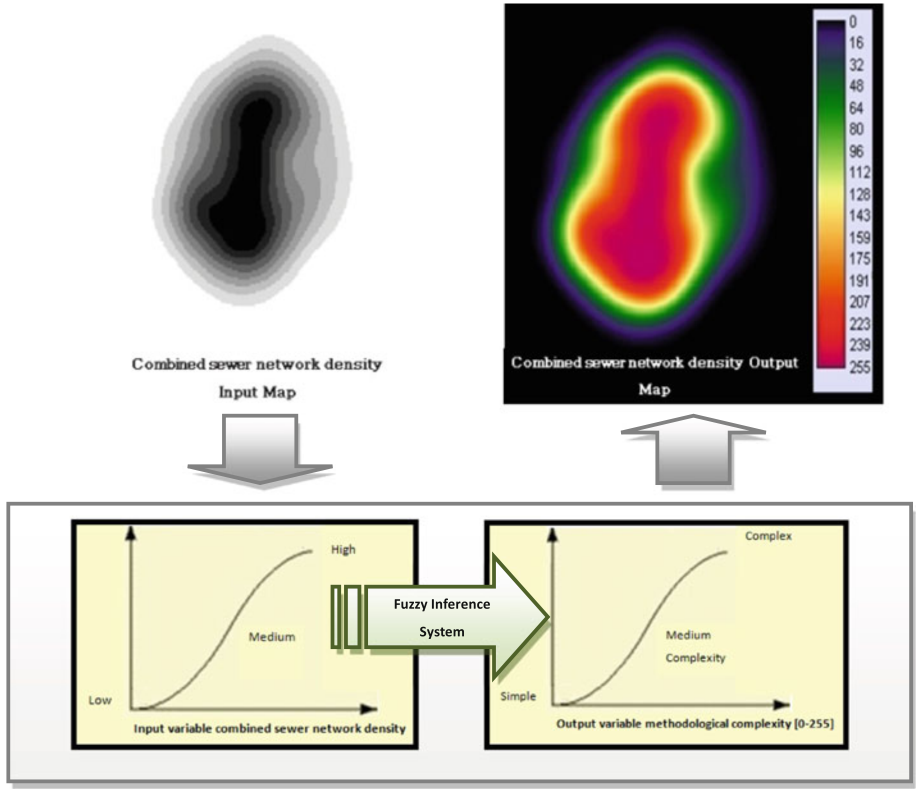


Fig. 3 Example of a criterion map standardized into a methodological complexity map through the fuzzy inference system procedure

1. Height (DEM)
2. Slope
3. Drainage pipes density
4. Streams density
5. Streams proximity
6. Land use

Table 3 presents the link between criteria, classes within criteria and flood occurrence.

The same procedure, as in the case of methodological complexity assessment, was followed standardizing the occurrence criteria. In this case, value 0 represents a low probability of occurrence and 255 a high probability. Following criteria standardization, flood occurrence maps are created under different aggregation scenarios.

To develop these scenarios, two aggregation methods were employed: AHP and WLC.

1. In AHP, standardized criteria are compared in pairs to evaluate their relative preference, by developing a pairwise comparison matrix (Fig. 4). Based on the matrix, different weights are derived for each criterion (Table 4). An important part of the process is the calculation of a consistency ratio (CR). Matrix values are acceptable if CR does not exceed 0.1 (otherwise value judgments are considered inconsistent and have to be revised).

Author's personal copy

Table 3 Classification of flood occurrence criteria

Criteria	Description	Classes	Flood occurrence
Height (m)	Lowland areas tend to accumulate water, due to their limited draining potential and the fact they are downstream (by definition) of higher elevation areas. Hence, the probability of flooding is higher in lowland areas (Sauer 2002; Yalcin and Akyurek 2004; Messner and Meyer 2006)	1. Great height 2. Medium height 3. Low height	1. Low probability of flood occurrence 2. Medium probability of flood occurrence 3. High probability of flood occurrence
Slope (degrees)	The flatter the slope, the higher is the probability of the area to be inundated because of reduced drain potential. Steep slopes enable higher velocity flows. (Sauer 2002; Yalcin and Akyurek 2004; Butler et al. 2005; Sharada et al. 1997)	1. High slope 2. Medium slope 3. Low slope	1. Low probability of flood occurrence 2. Medium Probability of flood occurrence 3. High probability of flood occurrence
Drainage pipes density (m/m^2 per municipality)	Drainage pipes are designed to reduce the occurrence of flooding. High density if taken as an indication of a fully functioning network and hence as an indication of increased flood protection (Schmitt et al. 2004; Sauer 2002). Arguably, the level of protection is also linked to network maintenance, but this level of detail was not taken into account in this study	1. High density 2. Medium density 3. Low density	1. Low probability of flood Occurrence 2. Medium probability of flood occurrence 3. High probability of flood occurrence
Combined network density (m/m^2 per municipality)	The same rationale as with drainage pipes is also applied to the case of combined networks. Although these networks differ in the impact of their failure (due to quality—considered in flood impacts below), the level of the protection they offer can be associated with their presence (and hence density)	1. High density 2. Medium density 3. Low density	1. Low probability of flood occurrence 2. Medium probability of flood occurrence 3. High probability of flood occurrence
Streams density (m/m^2 per municipality)	The same rationale as with drainage pipes and combined is also applied to the case of (urban) streams that often act as large, open drainage channels. Higher density indicates the presence of enough capacity to carry excessive flow downstream without overflowing (and hence flooding)	1. High density 2. Medium density 3. Low density	1. Low probability of flood occurrence 2. Medium probability of flood occurrence 3. High probability of flood occurrence

Author's personal copy

Table 3 continued

Criteria	Description	Classes	Flood occurrence
Land use (urbanization)	The removal of vegetation in and around the urbanized areas increases the runoff volume that is directly related to sprawling impervious surfaces. In comparison with well-vegetated land covers that influence the infiltration and saturated hydraulic conductivity via roots and pores, impervious surfaces are regarded as an extreme example in increasing overland flow velocity and floodplain flow rates. The more urbanized is the area the higher is the probability of flood occurrence. (Yalcin and Akyurek 2004; Schmitt et al. 2004; Nunes Correia et al. 1999; Butler et al. 2005; Sharada et al. 1997)	1. Natural environment 2. Peri-urban or medium intensity 3. Intensively urbanized	1. Low probability of flood occurrence 2. Medium probability of flood Occurrence 3. High probability of flood occurrence
Streams proximity (m)	Streams overflow in the case of extreme discharges, onto their floodplain, which is usually taken up by human settlements and activities. Proximity to streams indicates receptors within the floodplain of the stream and hence increases probability of flood occurrence (Ologunorisa and Abawua 2005; Butler et al. 2005)	1. High proximity 2. Medium proximity 3. Low proximity	1. Low probability of flood occurrence 2. Medium Probability of flood occurrence 3. High probability of flood occurrence

2. WLC was also employed, mostly for comparative purposes, assigning equal weights to all criteria.

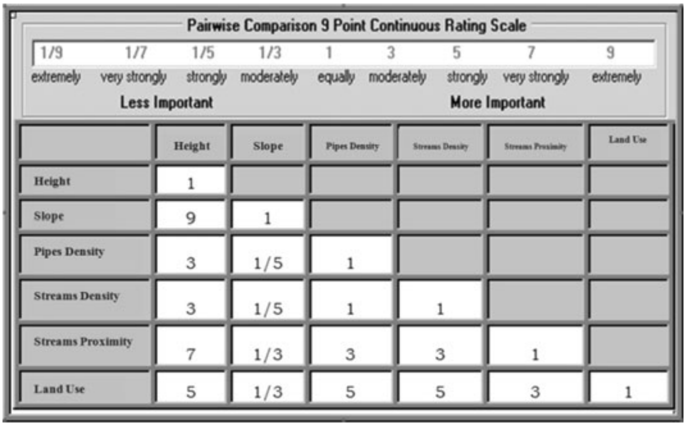
Clearly, the choice of (pairwise) importance for these criteria is highly subjective. To examine the impact of this subjectivity on the resulting maps, several scenarios have been developed and discussed in following sections.

2.4 Flood consequence mapping

The criteria selected to assess flood consequence are listed below, and their assumed influence to flood consequence quantification can be seen in Table 5.

1. Natura 2000: special protection areas (SPA) and sites of community interest (SCI)
2. Population density
3. 75 + Population density
4. Education level
5. Property value (per parcel)
6. Suburban train density
7. Railway density

Author's personal copy



Pairwise Comparison 9 Point Continuous Rating Scale

1/9	1/7	1/5	1/3	1	3	5	7	9
extremely	very strongly	strongly	moderately	equally	moderately	strongly	very strongly	extremely

Less Important — More Important

	Height	Slope	Pipes Density	Streams Density	Streams Proximity	Land Use
Height	1					
Slope	9	1				
Pipes Density	3	1/5	1			
Streams Density	3	1/5	1	1		
Streams Proximity	7	1/3	3	3	1	
Land Use	5	1/3	5	5	3	1

Fig. 4 Pairwise comparison matrix for assessing the comparative importance of flood occurrence factors

Table 4 Occurrence criteria weights, based on the AHP analysis (CR = 0.05 < 0.1)

Criteria	AHP weights
Height (DEM)	0.0311
Slope	0.4145
Pipes density	0.0653
Streams density	0.0653
Streams proximity	0.1573
Land use	0.2666

8. Combined network density
9. Economic activity

The criteria were then aggregated using AHP. In this case, we used three stakeholder-driven scenarios to capture the effect of (subjective) judgments on criteria importance to the results of the assessment. Three scenarios were created and applied:

1. An ecological scenario (placing more emphasis on the environmental impacts) was developed by the authors, based on their own experience. In this scenario, Criterion 1 (Natura 2000: special protection areas (SPA) and sites of community interest (SCI)) and Criterion 8 (the Combined network's density) were given more importance. The latter is included because of its environmental impact due to pollution incidents (e.g., CSO discharges). Actual figures used can be seen in Fig. 5.
2. A socioeconomic scenario (placing more emphasis on the economic and vulnerable population). This scenario was also developed by the authors and promoted the criteria related to general population's density, +75 population's density, economic activity, primary sector, and land use. Actual figures used can be seen in Fig. 6.
3. A more open-ended multiple stakeholder scenario, which was elicited from distributing questionnaires to ten people from different educational backgrounds: two economists, a psychologist, an English tutor, a software engineer, a geologist, an oceanographer, two banking employees, and a private employee. These people were selected at random and cannot be assumed to be representative of any population. They were included in the analysis (a) as an illustration of a possible approach to

Author's personal copy

Table 5 Classification of flood consequence criteria

Criteria	Description	Classes	Flood consequence
Natura 2000: special protection areas (SPA)	The increasing importance of environmental regulation, particularly of EU directives, such as the Habitats and Species Directive, requires member states to designate areas of importance such as special protection areas (SPAs)	1. Existence of area 2. Non-existence of area	1. High flood consequence 2. Low flood consequence
Natura 2000: sites of community interest (SCI)	Additionally, sites of community interest (SCI) can be further designated for areas of ecological or social importance (Tapsell et al. 2002; Evans et al. 2003; Butler et al. 2005; Messner and Meyer 2006; OPW 2007). The existence of such areas indicates sensitive receptors and hence increased potential consequence	1. Existence of area 2. Non-existence of area	1. High flood consequence 2. Low flood consequence
Population density (number of citizens per municipality)	The presence of population is an indication of potential danger to human life and health, which are at the center of flood impact assessment	1. Low density 2. Medium density 3. High density	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence
75 + population density (number of citizens per municipality)	Further than presence of general population (taken into account as a criterion above), the consequence of floods is more pronounced when the population has a reduced ability to cope with effects of the flood. The elderly, the uneducated, and the unemployed, for example, are especially vulnerable populations groups (Messner and Meyer 2006; Tapsell et al. 2002; King 2000). In this case, due to the unavailability of data from statistical services about population per se, the assumption was made that employees of the primary sector are in general less educated than employee of other (more service-oriented) sectors	1. Low density 2. Medium density 3. High density	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence
Education level Ratio (%) of population working in the primary sector/overall population.		1. Low ratio 2. Medium ratio 3. High ratio	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence
Economic activity Ratio (%) of employed/ total potential workforce		1. Low Ratio 2. Medium Ratio 3. High Ratio	1. Low Flood Consequence 2. Medium Flood Consequence 3. High Flood Consequence
Combined network density (m/m^2 per municipality)	Combined sewer networks are related with increased pollution loads that could be released into the environment in the case of overflow during a flood event. (Schmitt et al. 2004; Sauer 2002)	1. Low density 2. Medium density 3. High density	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence

Author's personal copy

Table 5 continued

Criteria	Description	Classes	Flood consequence
Suburban train density (m/m^2 per municipality)	Floods disrupt communication lines like roads and railways. This directly impacts social and economic activities, and potentially endangers human health (RPA 2008; Butler et al. 2005; Sharada et al. 1997)	1. Low density 2. Medium density 3. High density	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence
Urban train density (m/m^2 per municipality)		1. Low density 2. Medium density 3. High density	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence
Property value (primary land value) (parcel value €/m^2)	Flood events are followed by changes in residential land values. The negative aspects of the flood risk are shown to be capitalized in the value of the property (EA 2009; Lamond et al. 2009; Tapsell et al. 2002; Alkema 2001). Flood risk insurance that assists in the restoration of damaged property could also be used as a criterion, whose presence reduces flood risk, but relevant data were unavailable to be taken into account in this study	1. Low value 2. Medium value 3. Great value	1. Low flood consequence 2. Medium flood consequence 3. High flood consequence

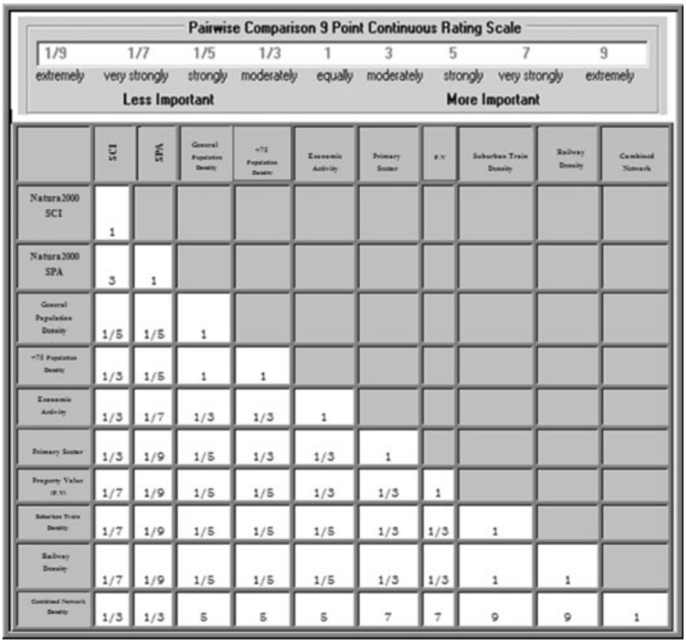
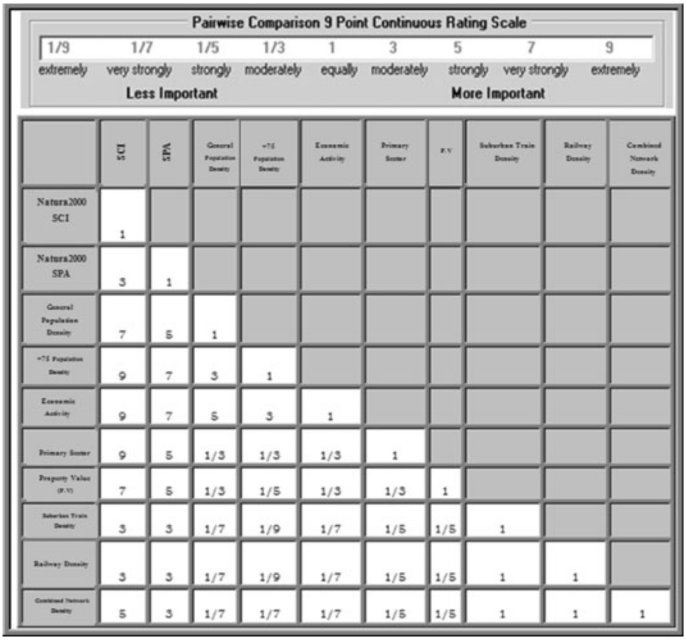


Fig. 5 Ecological scenario: pairwise comparison matrix

Author's personal copy

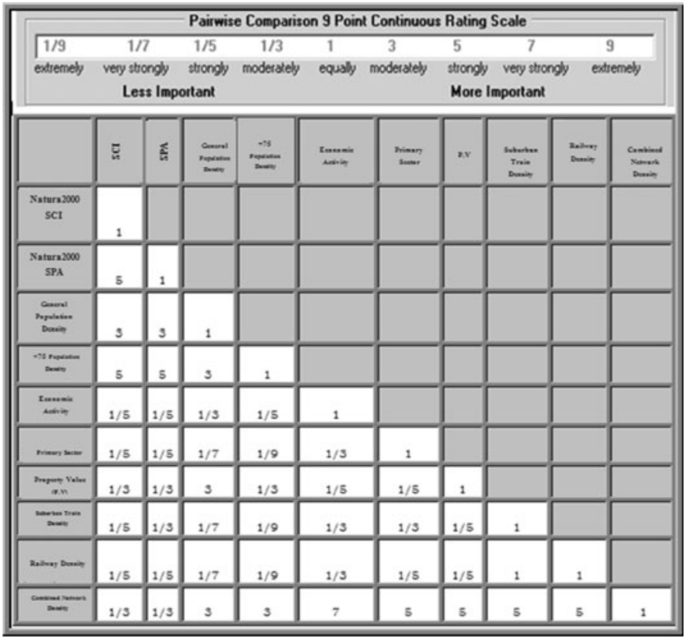


Pairwise Comparison 9 Point Continuous Rating Scale

1/9	1/7	1/5	1/3	1	3	5	7	9
extremely	very strongly	strongly	moderately	equally	moderately	strongly	very strongly	extremely
Less Important						More Important		

	SCI	SPA	General Population Density	+75 Population Density	Economic Activity	Primary Sector	P.V	Suburban Train Density	Railway Density	Combined Network Density
Natura2000 SCI	1									
Natura2000 SPA	3	1								
General Population Density	7	5	1							
+75 Population Density	9	7	3	1						
Economic Activity	9	7	5	3	1					
Primary Sector	9	5	1/3	1/3	1/3	1				
Property Value (P.V)	7	5	1/3	1/5	1/3	1/3	1			
Suburban Train Density	3	3	1/7	1/9	1/7	1/5	1/5	1		
Railway Density	3	3	1/7	1/9	1/7	1/5	1/5	1	1	
Combined Network Density	5	3	1/7	1/7	1/7	1/5	1/5	1	1	1

Fig. 6 Socioeconomic scenario: pairwise comparison matrix



Pairwise Comparison 9 Point Continuous Rating Scale

1/9	1/7	1/5	1/3	1	3	5	7	9
extremely	very strongly	strongly	moderately	equally	moderately	strongly	very strongly	extremely
Less Important						More Important		

	SCI	SPA	General Population Density	+75 Population Density	Economic Activity	Primary Sector	P.V	Suburban Train Density	Railway Density	Combined Network Density
Natura2000 SCI	1									
Natura2000 SPA	5	1								
General Population Density	3	3	1							
+75 Population Density	5	5	3	1						
Economic Activity	1/5	1/5	1/3	1/5	1					
Primary Sector	1/5	1/5	1/7	1/9	1/3	1				
Property Value (P.V)	1/3	1/3	3	1/3	1/5	1/5	1			
Suburban Train Density	1/5	1/3	1/7	1/9	1/3	1/3	1/5	1		
Railway Density	1/5	1/5	1/7	1/9	1/3	1/5	1/5	1	1	
Combined Network Density	1/3	1/3	3	3	7	5	5	5	5	1

Fig. 7 Stakeholder scenario (economist $_1$): pairwise comparison matrix

Author's personal copy

Table 6 Flood consequence criteria weights for the various scenarios

Criteria	Weights AHP—ecological scenario	Weights AHP—socioeconomic scenario	Weights AHP—scenario stakeholder
Natura 2000: sites of community interest (SCI)	0.2051	0.0135	0.1159
Natura 2000: special protection areas (SPA)	0.3091	0.0212	0.1561
General population density	0.0805	0.1538	0.1306
+75 population density	0.0773	0.2305	0.2307
Economic activity	0.0524	0.2907	0.0547
Education level	0.0315	0.1140	0.0451
Property value	0.0243	0.0866	0.0603
Suburban train density	0.0159	0.0289	0.0168
Railway density	0.0159	0.0289	0.0148
Combined network density	0.1880	0.0320	0.1751

eliciting judgment from individuals and (b) as a form of sensitivity analysis. It should be noted that not all answers were kept for consideration in this scenario—as some of the answers were found to contain unacceptable levels of inconsistency (i.e., CR > 0.1). Given the high educational level of all participants, this is in itself an interesting (and somewhat alarming) result. Figure 7 presents an example of these responses.

The resulting weights for all the scenarios considered can be seen in Table 6.

2.5 Calculating flood risk

As suggested earlier, flood risk is a combination of occurrence and consequence (risk = f (occurrence, consequence). To combine the two, the OWA aggregation method was applied to the results of the above analysis. OWA provides a continuum of fuzzy operators between the logical AND (fuzzy intersection) and the logical OR (fuzzy union) and is effectively a weighted sum, with ordered evaluation criteria. The order weights allow for the control of the degree of trade-off among criteria, thus providing control of the degree of optimism (attitude to risk), allowed into the aggregation (and hence risk evaluation) process (Malczewski 1999; Makropoulos and Butler 2006).

Four OWA scenarios have been developed and applied:

(i) The risk averse scenario (0, 1) that takes into account the highest risk evaluation while ignoring the lower, for each location (cell) of the study area.
(ii) The risk taking scenario (1, 0) that takes into account the lowest risk evaluation while ignoring the highest, for each location (cell) of the study area.
(iii) A balanced scenario (0.5, 0.5) that assigns the same importance to both values, for each location (cell) of the study area.
(iv) An intermediate approach (0.8, 0.2) which assigns more importance on the highest risk evaluation, but does not ignore the lower one, for each location of the study area. This is (intuitively) a more policy-relevant scenario than either (i) which over emphasizes or (ii) which ignores risks and more probable in real life than (iii) which assigns equal importance to a high and low evaluation.

Author's personal copy

Table 7 Combinations of methods and order weights to assess flood risk

Occurrence	Consequence	OWA-weights	Flood risk maps
$AHP_{Weights}$ (CR = 0.05) (0.2666, 0.1573, 0.0653, 0.0653, 0.4145, 0.0311)	Ecological scenario $AHP_{Weights}$ (CR = 0.08) (0.2051, 0.3091, 0.0805, 0.0773, 0.0524, 0.0315, 0.0243, 0.0159, 0.0159, 0.1880)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $1_{(1,\ 0)}$ Map $1_{(0.8,\ 0.2)}$ Map $1_{(0.5,\ 0.5)}$ Map $1_{(0,\ 1)}$
$AHP_{Weights}$ (CR = 0.05) (0.2666, 0.1573, 0.0653, 0.0653, 0.4145, 0.0311)	Socioeconomic scenario $AHP_{Weights}$ (CR = 0.09) (0.0135, 0.0212, 0.1538, 0.2305, 0.2907, 0.1140, 0.0866, 0.0289, 0.0289, 0.0320)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $2_{(1,\ 0)}$ Map $2_{(0.8,\ 0.2)}$ Map $2_{(0.5,\ 0.5)}$ Map $2_{(0,\ 1)}$
$AHP_{Weights}$ (CR = 0.05) (0.2666, 0.1573, 0.0653, 0.0653, 0.4145, 0.0311)	Equal weights (=0,1)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $3_{(1,\ 0)}$ Map $3_{(0.8,\ 0.2)}$ Map $3_{(0.5,\ 0.5)}$ Map $3_{(0,\ 1)}$
Equal weights (=0,1667)	Equal weights (=0,1)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $4_{(1,\ 0)}$ Map $4_{(0.8,\ 0.2)}$ Map $4_{(0.5,\ 0.5)}$ Map $4_{(0,\ 1)}$
Equal weights (=0,1667)	Ecological scenario $AHP_{Weights}$ (CR = 0.08) (0.2051, 0.3091, 0.0805, 0.0773, 0.0524, 0.0315, 0.0243, 0.0159, 0.0159, 0.1880)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $5_{(1,\ 0)}$ Map $5_{(0.8,\ 0.2)}$ Map $5_{(0.5,\ 0.5)}$ Map $5_{(0,\ 1)}$
Equal weights (=0,1667)	Socioeconomic scenario $AHP_{Weights}$ (CR = 0.09) (0.0135, 0.0212, 0.1538, 0.2305, 0.2907, 0.1140, 0.0866, 0.0289, 0.0289, 0.0320)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $6_{(1,\ 0)}$ Map $6_{(0.8,\ 0.2)}$ Map $6_{(0.5,\ 0.5)}$ Map $6_{(0,\ 1)}$
Equal weights (=0,1667)	Scenario stakeholder $AHP_{Weights}$ (CR = 0.28) (0.1159, 0.1561, 0.1306, 0.2307, 0.0547, 0.0451, 0.0603, 0.0168, 0.0148, 0.1751)	(1, 0), (0.8, 0.2), (0.5, 0.5), (0, 1)	Map $7_{(1,\ 0)}$ Map $7_{(0.8,\ 0.2)}$ Map $7_{(0.5,\ 0.5)}$ Map $7_{(0,\ 1)}$

The combinations of methods and order weights examined can be seen in Table 7.

Although all these maps were created in this study, only maps $5_{(0.8,\ 0.2)}$, $6_{(0.8,\ 0.2)}$, and $7_{(0.8,\ 0.2)}$, which are respectively presented in Fig. 16, 17, and 18, are included in this paper as an example. The overall methodology developed here can be seen in Fig. 8.

The application of the methodology in the case of Athens is presented and discussed next.

3 The case study: Greater Athens area

Athens is located on the plain of Attica and is surrounded by the Saronic Gulf and the mountains Aigaleo (468 m), Parnitha (1,412 m), Pendelikon (1,109 m), and Hymettus

Author's personal copy

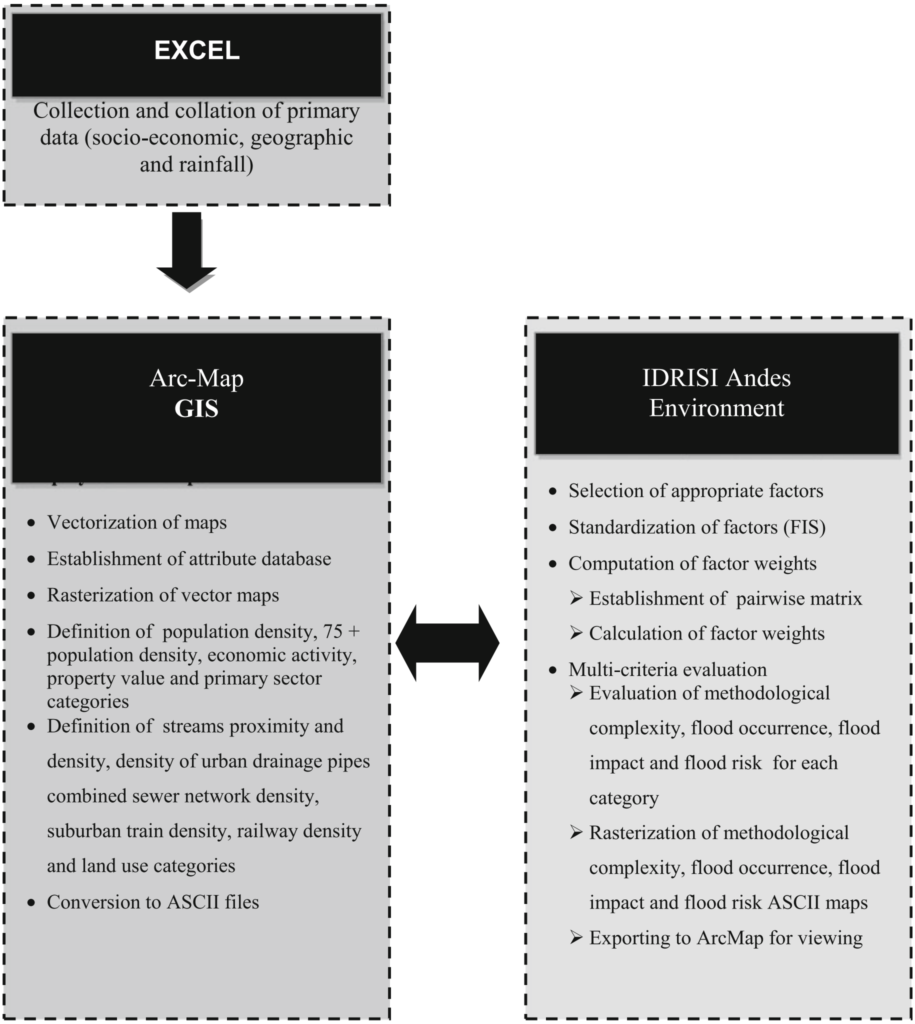


Fig. 8 Flowchart and main software components used in the study

(1,027 m). It is (by far) the largest city of Greece, housing almost half of its entire population, and is a significant administrative, economic, and cultural center. Greater Athens (Fig. 9), which includes the port of Piraeus and numerous suburbs, is a transportation hub, served by rail lines, major roads, airlines, and oceangoing vessels. The study area is characterized by extensive human interventions, a dense road network, and intensive urbanization. In addition, the western, northern and eastern parts of Attica region include significant agricultural activities. Flood events are not uncommon in Athens and have resulted in significant damage and even loss of life, as recently as 1994 (Evelpidou et al. 2009).

The data that were collected and analyzed for Athens included the following:

– Historical rainfall and flooding data (rainfall height, dates, and consequences of flood events)

Author's personal copy

Fig. 9 Maps of study area, Greater Athens area

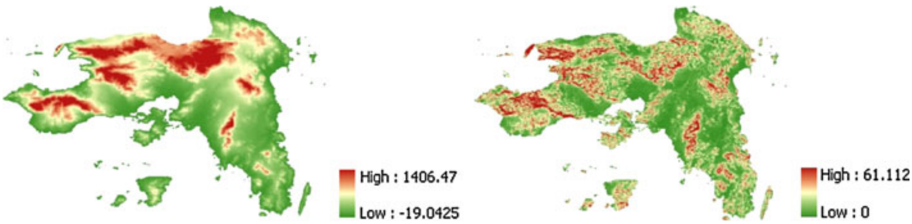


Fig. 10 Digital elevation model (*left*) and raster slope map (*right*) for Athens

– Geological, geomorphological, and geographical data
– Topographic data
– Socioeconomic and demographic information
– Networks (sewer, rainfall, and combined)

Each dataset (example of which can be seen in Figs. 10, 11, 12 and 13 below) was imported into a GIS environment and was considered a separate criterion (Eastman et al. 1995). Each criterion (including all the criteria presented in Tables 2, 3, and 5) was saved into a separate GIS layer and was imported to IDRISI Andes to perform the MCA analysis presented above. It should be noted that all the analyses discussed above, including development of occurrence and consequence maps from multiple criteria and their combination, are performed at a cell-by-cell level. To achieve this, primary data are stored in a vector format, but transformed to raster data for the spatial analysis.

4 Results

The results of the criteria analysis process are presented next:

Figure 14 presents the result of the methodological complexity mapping.

Author's personal copy

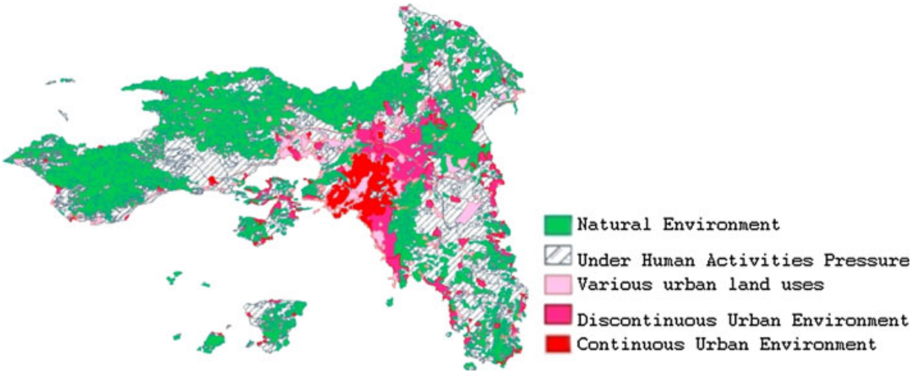


Fig. 11 Land use map for Athens, derived from Corine 2000

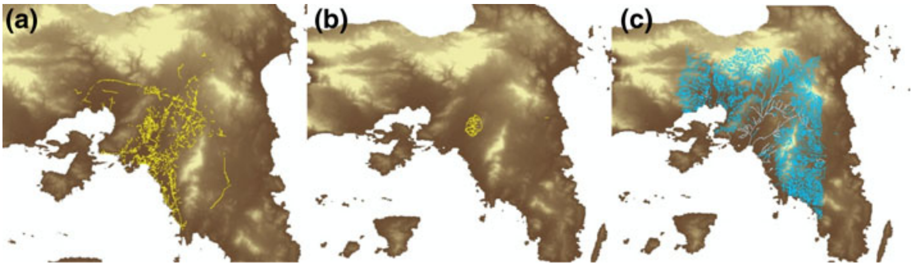


Fig. 12 Maps of **a** pipes, **b** combined sewage network, and **c** streams

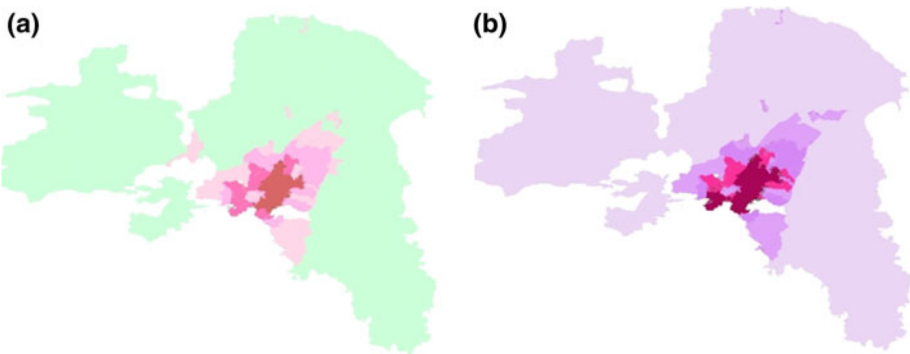


Fig. 13 Density maps of **a** general population and **b** +75 population

As was expected, the center of Athens, which is highly urbanized, requires a more complex methodological approach, due to the existence of surface barriers and networks, which require a detail study of the Source-Pathway-Receptor model with application of flow 1D, 2D models than the less urbanized peri-urban regions. The effect of slope is also observed, which is more pronounced in the presence of mountainous areas all around the metropolis. As discussed, this mapping will be used to assign level of comfort values to the

Author's personal copy

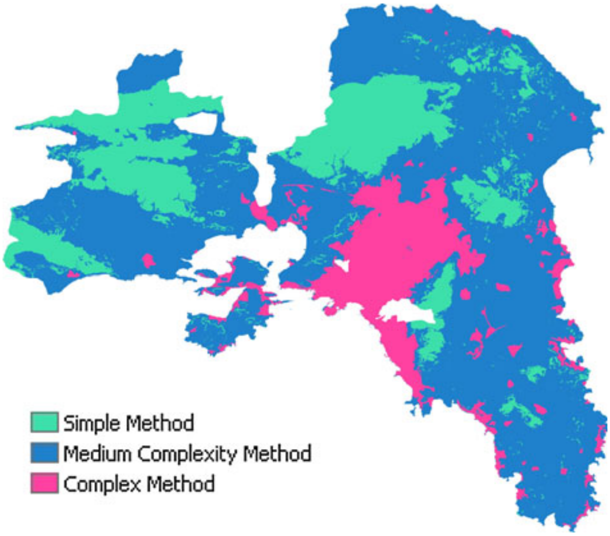


Fig. 14 Methodological complexity map

results of the proposed simplified (and preliminary) flood risk assessment approach (Fig. 19).

Figure 15 is a map of (potential) flood occurrence. The areas that are flagged as more at risk from flooding (on the basis of probability of occurrence) are mainly intensely urbanized areas, with low slopes, at the plain field. From these, increased probability of occurrence is assigned to areas close to the Kifissos and Ilisos rivers (which act as the main routes of urban runoff conveyance). The figures below present the results of the flood consequence mapping for a number of scenarios.

In the ecological scenario, importance was given to Natura 2000 regions and to the combined sewer network in the center of Athens due to its potential to pollute the environment. This can be seen in Fig. 16 where environmentally sensitive areas are included in the high and medium, together with the part of Athens that is served by the combined sewer network. It can be observed that some environmentally sensitive areas are also included in the medium scale of flood consequence. This is due to the additional criteria (such as population) inherited by the administrative regions in which the environmentally sensitive areas are.

In the socioeconomic scenario, importance was given to population metrics (density and vulnerability), as well as to economic activities and property value. This is presented in Fig. 17, where high flood consequences are assigned to areas with high population density, lower education levels and high property value.

In the combined stakeholder scenario, importance was given to general and older population's density, to Natura 2000 regions (SCI and SPA), and to the polluting effects of the combined network in the center of Athens. This is an interesting finding on its own right, as stakeholders seem to be sensitive to quality issues (environmental and pollution loads) associated with flooding, which are not the primary focus of the Floods Directive. Figure 18 depicts these priorities.

Figure 19 presents the combination of the methodological complexity and flood risk mappings. For the development of this map, the occurrence map was combined with the socioeconomic consequence scenario, using 0.8 and 0.2 as OWA, respectively. It can be seen that the zones that have been identified as high flood risk zones also fall into the

Author's personal copy

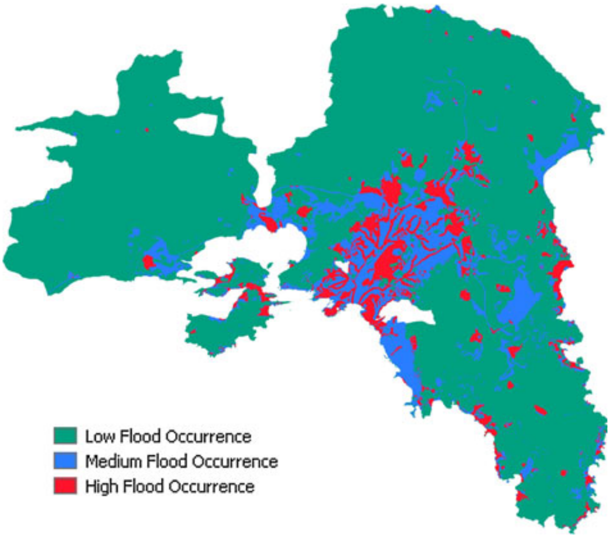


Fig. 15 Probability of flood occurrence map: occurrence $_{\text{AHP- WLC}}$

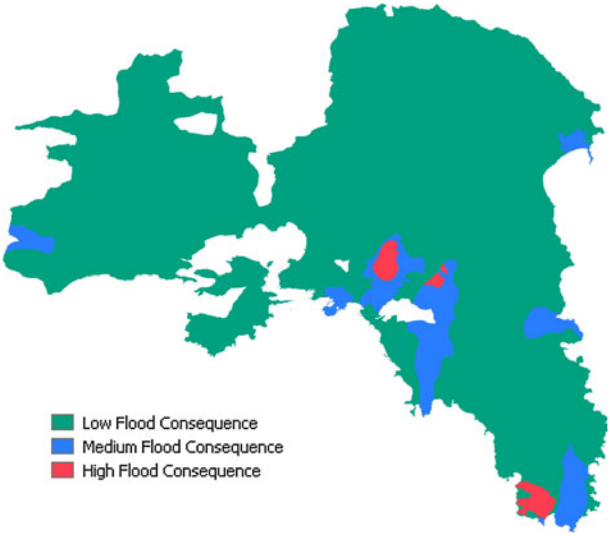


Fig. 16 Flood consequence map: ecological scenario

medium or high complexity methodology mappings. This indicates that the level of comfort (or certainty) that can be assigned to the flood risk assessment, using a simple (cartographic) methodology, such as the one presented here, is relatively low. However, they are an indication of the need for further investigation with more sophisticated tools for these specific areas—potentially acting as a prioritization mechanism for further studies. For areas that have been assigned as medium or low risk and are flagged as requiring simple methodologies, it can be assumed that the assessment is more reliable, while the rest should be seen as good indications rather than reliable forecasts.

Author's personal copy

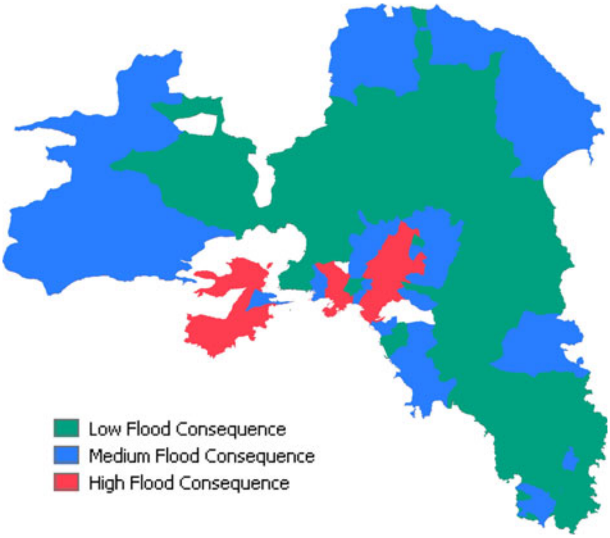


Fig. 17 Flood consequence map: socioeconomic scenario $_{\text{AHP-WLC}}$

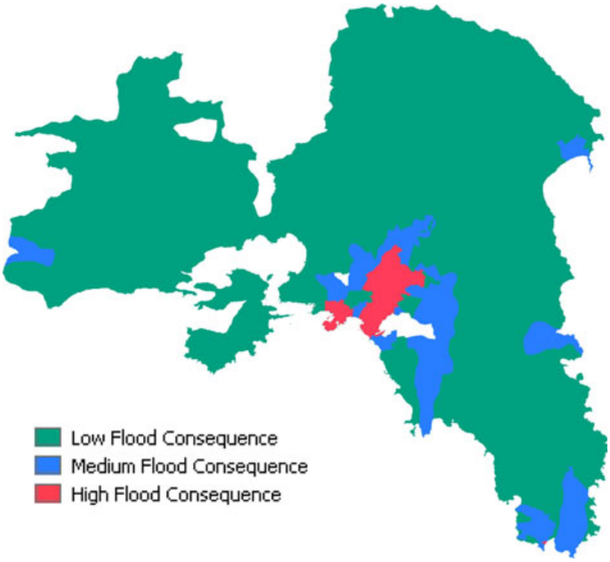


Fig. 18 Flood consequence map: scenario stakeholder

5 Sensitivity analysis

A sensitivity analysis was performed to examine how sensitive the results are to changes in criteria weights. Figure 20 presents the differences between the ecological and socioeconomic scenario.

With intense color, negative values indicate areas where the ecological scenario results in higher values than the values of the socioeconomic scenario, while softer color (positive

Author's personal copy

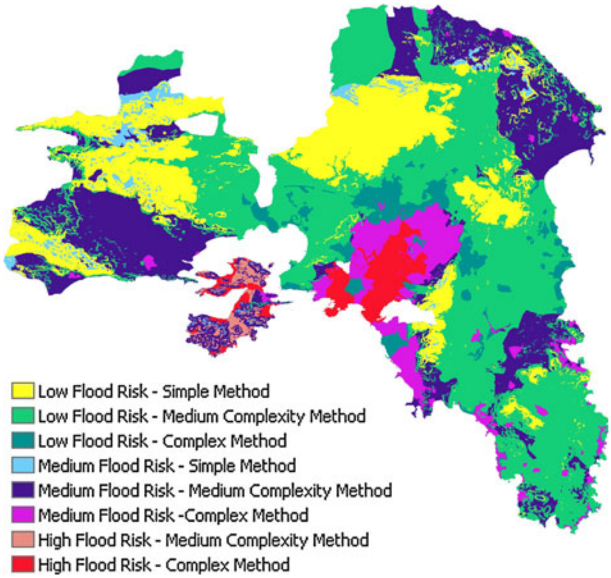


Fig. 19 Flood risk and methodological complexity map

values) indicates areas where the opposite is true. In both cases, the difference indicates sensitivity to criteria change. Gray color, on the other hand, illustrates differences that are very near to zero and imply no change to flood consequence (and for the same flood occurrence maps, to flood risk). It appears that the process is not particular sensitivity in changes of criteria, possibly due to the large number of criteria used in the evaluations.

6 Results validation

To assess the quality of the analysis, the final flood occurrence map was compared to historical data, from floods recorded in the central part of the Greater Athens area between 1887 and 2007 (Table 8). Figure 21 presents the area in which these events have taken place. Note that this is the most urban part of Greater Athens, for which the analysis has been undertaken, and consists of the municipality of Athens and a number of major municipalities around it. This collection of flood events was undertaken for the needs of this study, from a variety of sources (incl. ENM 2004; Floros 2009) and is to the best of our knowledge the most complete set of such records. Unfortunately, no such records exist for the remaining of the study area.

In Table 9, the percentage of areas of Fig. 21 characterized as high, medium, and low flood risk (taking into account only the occurrence part of the Risk equation) is compared to the number of incidents actually recorded in these areas and the resulting percentage. As the events were recorded at the municipality level, there were cases where a municipality in which an event had occurred had within it more than one characterization (for example, a small area that was characterized as having high occurrence and a larger one characterized as medium occurrence within the same municipality). In such cases, the incident was assigned (for the purposes of producing Table 9) to the predominant characterization of the municipality.

Author's personal copy

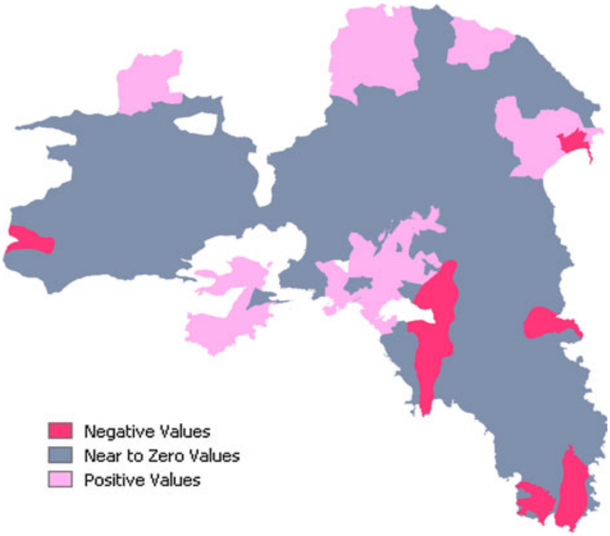


Fig. 20 Comparison between the ecological and socioeconomic scenario

Table 8 Recorded flood events in the Greater Athens area (1887–2007)

Municipality	Flood events	Municipality	Flood events
Athens	20	Cholargos	3
Peristeri	7	Agia paraskeui	3
Nea liosia (ilion)	7	Chalandri	1
Aigalew	3	Filothei	1
Moschato	8	Psuchiko	2
Falhro	8	Kamatero	1
Peiraias	12	Neo hrakleio	2
Agios ioannis renti	3	Marousi	1
Kallithea	6	Kifisia	1
Korydallos	2	Zwgrafos	1
Nikaia	2	Gluka nera	1
Keratsini	3	Perama	1
Glufada	5	Nea chalkidona	1
Ellhniko	3	Elliniko	3
Nea ionia	8	Voula	2
Nea filadelfeia	3	Paiania	2
Galatsi	3	Pallini	1
Alimos	5	Vouliagmeni	2
Nea xalkidona	1	Papagos	1
Agioi anarguroi	3	Penteli	1
Anthoupoli (anthousa)	1	Dionysos	1
Total flood events	145		

Author's personal copy

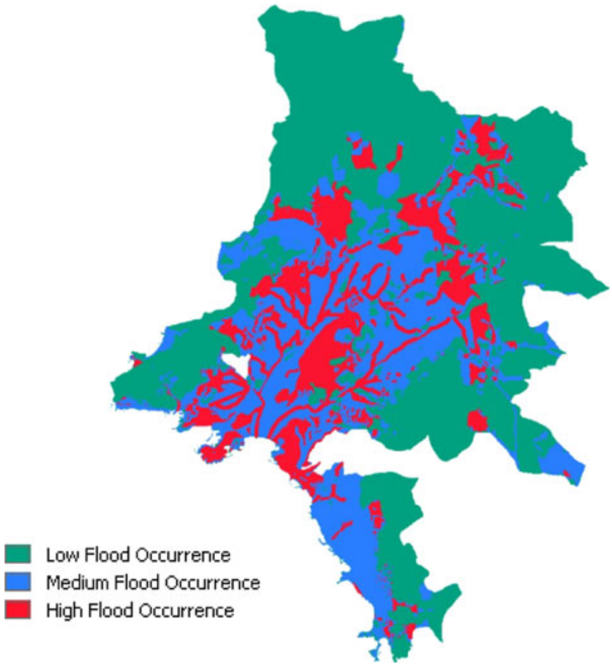


Fig. 21 Flood occurrence map of Athens basin areas

Table 9 Results validation

Flood risk level	% Area	Flood events	% Incidents
High flood risk	18	70	48
Medium flood risk	28	65	45
Low flood risk	54	10	7
Total	100	145	100

The table suggests that the methodology (although not taking into account past events as criteria), correctly characterized as high occurrence areas, areas where a large number of events had actually happened and that this allocation cannot be explained on the basis of areal coverage. In other words, although only 18% of the area was identified as a high occurrence area, it has experienced approximately half of the recorded flood event on record.

Although the limited nature of the support base (in this case the recorded flood events) does not allow for a more detailed statistical analysis, it is suggested that the comparison does provide a useful, quantitative metric for the method's validity and provides some confidence that the criteria used were able to correctly capture the main mechanisms of flood occurrence.

7 Conclusions

The main conclusions of the study can be summarized as follows:

Author's personal copy

Flood risk assessments are data-intensive processes. In this case, an extensive database for relevant criteria to the city of Athens was collected and analyzed. Although this is not a methodological issue, such a dataset did not exist prior to this work and no formal flood risk assessment analysis has ever been completed for the entire Greater Athens region. A spatial multicriteria methodology was then developed to perform preliminary flood risk assessment (applicable for example to the first step of the Floods Directive implementation). The method calculates occurrence and consequence separately and then applies an aggregation method that can be biased to become more or less conservative in its final output (Makropoulos and Butler 2006) depending, for example, on policy attitudes. Scenarios were developed to test the dependence of the process to value judgments by individuals and groups, reflecting the tension between the various objectives stated in the Directive (including human health, the environment, cultural heritage, and economic activity).

There are certainly limitations, in the proposed, preliminary analysis, method discussed here. An important limitation is that rainfall heterogeneity is not taken into account in the criteria. This is because, in this case, the area in question is small enough not to present significant differences in rainfall characteristics, but would certainly be an issue in large catchments. Having said this, spatially variable rainfall parameters could easily be incorporated in this methodological framework. Another limitation, which is actually highlighted by the method itself, is that although the method is promising for screening purposes, its results for highly urbanized areas are, necessarily, less reliable than its results for less dense peri-urban areas, as in the former case, modeling of the extended urban drainage system (including pipes and roads) plays an important role in specifying flood parameters (including extents, velocities, and duration of floods). This is why the method introduces the notion of a "level of comfort" that can be assigned to the results obtained, through an identification of areas that required more detailed, complex methodologies to reliably perform a detailed analysis—on top of the preliminary, cartographic method used here. This approach can be used as a prioritization mechanism for further, more targeted studies.

The results obtained appear to be able to capture reality, as seen from the comparison with historical flood events. It is suggested that this method is applicable for the type of preliminary flood risk assessment that is required by the Floods Directive, and that it can be applied to relative large regions, while yielding results that are reliable enough to be used for screening purposes as the Directive requires. The method can easily be used to also account for long-term scenarios (such as urban development and land use change), provided modeled outputs exist for such scenarios.

References

Alkema D (2001) Flood-risk assessment for EIA. Studi Trentini Sci Nat Acta Geol 78:147–154

Bamford TB, Digman CJ, Balmforth DJ, Waller S, Hunter N (2008) Modelling flood risk, an evaluation of different methods, WaPUG. Org. Autumn Conference, UK

Bana E, Costa CA (1990) Reading in multiple criteria decision aid. Springer, Berlin

Belton V, Stewart TJ (2002) Multiple criteria decision analysis—an integrated approach. Kluwer, Boston

Bradbrook KF, Lane SN, Waller SG, Bates PD (2004) Two dimensional diffusion wave modelling of flood inundation using a simplified channel representation. Int J River Basin Manag 2(3):211–224

Butler D, Kokkalidou A, Makropoulos CK (2005) Supporting the siting of new urban developments for integrated urban water resource management. In: Hlavinek P, Kukharchyk T (eds) Integrated urban water resources management, NATO scientific series. Springer, Berlin, pp 19–34

Carr RS, Smith GP (2006) Linking 2D and pipe hydraulic models at fine spatial scales. 7th International conference on urban drainage modelling and 4th international conference on water sensitive urban design, vol 2, Melbourne, pp 361–368

Author's personal copy

Carver SJ (1991) Integrating multi-criteria evaluation with geographical information systems. Int J Geogr Inf Sci 5:321–339
Chen AS, Hsu MH, Chen TS, Chang TJ (2005) An integrated inundation model for highly developed urban areas. Water Sci Technol 51(2):221–229
Dawson RJ, Speight L, Hall JW, Djordjevic S, Savic D, Leandro J (2008) Attribution of flood risk in urban areas. J Hydroinform 10(4):275–278
Djordjević S, Prodanović D, Maksimović Č, Ivetić M, Savić D (2005) SIPSON–Simulation of Interaction between pipe flow and surface overland flow in networks. Water Sci Technol 52(5):275–283
EA (2009) Flooding in wales: a national assessment of flood risk. Environment Agency, Wales, p 24
Eastman JR (1997) IDRISI for windows, tutorial exercises. Version 2.0, Clark University
Eastman JR, Kyem PAK, Toledano J, Jin W (1993) GIS and decision making. UNITAR, Geneva
Eastman JR, Jin W, Kyem PAK, Toledano J (1995) Raster procedures for multi-criteria/multi-objective decisions. Photogramm Eng Remote Sensing 61:539–547
ENM (2004) Basic information and proposals for updating the flood protection of Attica. Ministry of Public Works, Athens
Evans EP, Penning-Rowsell EC, Hall JW (2003) Foresight flood and coastal defence project, phase 1 technical report. Drivers, scenarios and work plan. Office of Science and Technology, UK
Evelpidou N, Mamassis N, Vassilopoulos A, Makropoulos C, Koutsogiannis D (2009) Flooding in Athens: the kephisos river flood event of 21–22/10/1994. COST22 Conference, Paris, France
Floros I (2009). Developing a database for recording flood incidents. MSc Thesis, Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens (in Greek)
Heywood I, Oliver J, Tomlinson S (1995) Building an exploratory multi-criteria modelling environment for spatial decision support. In: Fisher P (ed) Innovations in GIS2. Taylor and Francis, London, pp 127–136
Hopkins LD (1977) Methods for generating land suitability maps: a comparative evaluation. J Am Inst Plann 34:19–29
Hunter NM, Bates PD, Neelz S, Pender G, Villanueva I, Wright NG et al (2008) Benchmarking 2D hydraulic models for urban flooding. Proceedings of the institution of civil engineers. Water Manag 161(1):13–30
ICE (2001) Learning to live with rivers. Institution of Civil Engineers, London, UK
King D (2000) You're on our own: community vulnerability and the need for awareness and education for predictable natural disasters. J Conting Crisis Manage 8:223–228
Lamond JE, Proverbs DG, Hammond FN (2009) Accessibility of flood risk insurance in the UK: confusion, competition and complacency. J Risk Res 12(6):825–841
Makropoulos C, Butler D (2006) Spatial ordered weighted averaging: incorporating spatially variable attitude towards risk in spatial multicriteria decision-making. Environ Model Softw 21(1):69–84
Makropoulos C, Butler D, Maksimovic C (1999) GIS supported evaluation of source control applicability in urban areas. Water Sci Technol 32(9):243–252
Makropoulos C, Argyrou E, Memon FA, Butler D (2007) A suitability evaluation tool for siting wastewater treatment facilities in new urban developments. Urban Water J 4(2):61–78
Makropoulos CK, Memon FA, Shirley-Smith C, Butler D (2008) Futures: an exploration of scenarios for sustainable urban water management.Water Policy 10(4):345–375. doi:10.2166/wp.2008.014
Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, USA
Malczewski J (2000) On the use of weighted linear combination method in GIS: common and best practice approaches. Trans GIS 4(1):5–22
Malczewski J (2006) GIS-based multicriteria decision analysis: a survey of the literature. Int J Geogr Inf Sci 20(7):703–726
Malczewski J, Chapman T, Flegel C, Walters D, Shrubsole D, Healy MA (2003) GIS—multicriteria evaluation with ordered weighted averaging (OWA): case study of developing watershed management strategies. Environ Plan A 35(10):1769–1784
Messner F, Meyer V (2006) Flood damage, vulnerability and risk perception—challenges for flood damage research. Chap. 13. In: Schanze J, Zeman E, Marsalek J (eds) Flood risk management—hazards, vulnerability and mitigation measures. Springer, Berlin, pp 149–167 Nato Science Series
Meyer V, Scheuer S, Haase D (2008) A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany, Nat hazards 48. Springer, Berlin, pp 17–39
Munda G (1995) Multicriteria evaluation in a fuzzy environment—theory and applications in ecological economics. Physica Verlag, Heidelberg
Nunes Correia F, Da Graca Saraiva M, Nunes Da Silva F, Ramos I (1999) Floodplain management in urban developing areas. Part I. Urban growth scenarios and land-use controls. Water Res Manag 13:1–21

Author's personal copy

Ologunorisa TE, Abawua MJ (2005) Flood risk assessment: a review. J Appl Sci Environ Manag 9(1):57–63

OPW (Office of Public Works) (2007) Screening of Natura 2000 sites for impacts of arterial drainage maintenance operations. ISSN 1649-9840. Series of ecological assessments on arterial drainage maintenance. No. 1. Office Public Works, 51 St Stephens Green, Dublin 2, Ireland

Rinner C, Malczewski J (2002) Web-enabled spatial decision analysis using ordered weighted averaging (OWA). J Geograph Syst 4(4):385–403

RPA (2008) Railway procurement agency. Metro north railway order application—further information request. Item 4. Flood Risk Assessment (downloadable from: http://www.dublinmetronorth.ie)

Saaty TL (1980) The analytic hierarchy process. McGraw-Hill, New York

Saaty TL (1992) Decision making for leaders. RWS Publications, Pittsburgh

Sauer VB (2002) USGS, The national flood frequency program, version 3: a computer program for estimating magnitude and frequency of floods for ungaged sites. Water-Resources Investigations, Report 02-4168, pp 8–10

Sayers P, Calvert M (2007) National flood risk assessment for Northern Ireland. Flood mapping strategy (Interim). Report EX 5299. Release 5.0. HR Wallingford

Sayers PB, Gouldby BP, Simm JD, Meadowcroft IC, Hall JW (2002) Risk, performance and uncertainty in flood and coastal defence-a review, Defra/EA R&D Technical Report FD2302/TR1

Schanze J, Zeman E, Marsalek J (2006) Flood risk management. Hazards, vulnerability and mitigation measures, vol 67. Springer, Dordrecht (NL), pp 3–4 (Nato science series—IV. Earth and Environmental Sciences)

Schmitt TG, Thomas M, Ettrich N (2004) Analysis and modeling of flooding in urban drainage systems. J Hydrol 299(3–4):300–311. doi:10.1016/j.jhydrol.2004.08.012

Sharada D, Kaveri Devi D, Prasad S, Kumar SS (1997) Modelling flash flood hazard to a railway line: a GIS approach. Geocarto Int 12(3):77–82. doi:10.1080/10106049709354600 Taylor & Francis

Simonovic SP, Nirupama A (2005) A spatial multi-objective decision-making under uncertainty for water resources management. J Hydroinform 7(2):117–133

Smith K (1996) Environmental hazards. Routledge, London

Strager MP, Rosenberger RS (2006) Incorporating stakeholder preferences for land conservation: weights and measures in spatial MCA. Ecol Econ 57(13):627–639

Tapsell S, Penning-Rowsell EC, Tunstall SM, Wilson TL (2002) Vulnerability to flooding: health and social dimensions. Philos Transact R Soc Lond A Math Phys Eng Sci 360:1511–1525

Thinh NX, Hedel R (2004) A fuzzy compromise programming environment for the ecological evaluation of land use options. Conference proceedings of the Enviro Info 2004

Tkach RJ, Simonovic SP (1997) A new approach to multi-criteria decision making in water resources. J Geogr Inform Decis Anal 1(1):25–43

Tomlin CD (1990) Geographical information systems and cartographic modeling. Prentice-Hall, Englewood Cliffs

HR Wallingford (2002) Risk performance and uncertainty in flood and coastal defence—A review. SR587 (Second Draft)

Yager RR (1993) Non-numeric multi-criteria multi-person decision making. Group Decis Negot 2:81–93

Yalcin G, Akyurek Z (2004) Analysing flood vulnerable areas with multicriteria evaluation. XXth ISPRS Congress, Istanbul, Turkey 12–23 July

Zadeh L (1965) Fuzzy sets. Inf Control 8:338–353