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ORIGINAL ARTICLE

Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece

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Abstract Flood events have often occurred in the metropolitan urban area of Athens, capital of Greece, causing loss of property and in many cases human lives. In this study a flood hazard assessment model for urban areas is examined. The Kifisos and Ilisos Rivers flowing through the plain of Athens was the case study of the present work. The quantitative analysis of the Kifisos and Ilisos Rivers drainage networks was performed to identify flash-flood prone areas. The major factors affecting urban floods were estimated. The slope angle, elevation, distance from open channel streams, distance from totally covered streams, hydro-lithology and land cover of the study area were used. to evaluate these factors the analytical hierarchical process method was applied in a geographical information system. A sensitivity analysis was made to assess the effect of the various factors on the flood hazard map. Three scenarios were developed to examine the effect of uncertainty of the factors' values to the flood hazard assessment results, leading to the corresponding urban flood hazard assessment maps. The produced map showed that the areas of very high flood hazard are located mostly along the lower reaches of Kifisos and Ilisos Rivers, particularly to the southern and to the western part of the study area. These areas are characterized by lowland morphology, gentle slope, totally covered streams, expansion of impermeable formation and intense urbanization. The uncertainty analysis shows no significant differences on the spatial distribution of the hazard zones. The produced urban flood hazard map proves a satisfactory agreement between the flood hazard zones and the spatial distribution of flood phenomena that have affected the study area in the past 117 years. Furthermore, the comparison between the flood-prone areas that were derived from the geomorphological analysis of the drainage networks and the high flood-hazard zones of the final map indicated reliable results and a high accuracy of the proposed methodology.

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Introduction

Floods are among the most dangerous natural hazards affecting the development of an area. Worldwide, flood events cause the largest amount of deaths and property damage (CEOS 2003). On the other hand, increasing urbanization and population have brought significant effects on the natural environment. In urban areas, human activities such as uncontrolled building construction, land-use changes and lack of urban planning affect flooding.

More than 40 % of the national population lives in the metropolitan urban area of Athens, capital of Greece. The plain of Athens has been extremely urbanized during the last 70 years and the environment has changed dramatically. Dense, uncontrolled building constructions at locations blocking the axis of drainage network have caused several flood events (Karymbalis et al. 2012; Skilodimou et al. 2003) resulting in the loss of property and in many cases, human lives (Diakakis 2013; Diakakis et al. 2012; Maroukian et al. 2005; Mimikou et al. 2002; Mimikou and Koutsoyiannis 1995). Therefore, flood management constitutes a very demanding condition for the protection of a human community. The geomorphologic characteristics of the basin's drainage network influence the flood-hazard zones. Morphomertic analysis is used to determine the influence of drainage-network morphometry on flooding and to estimate the potential flood hazard in several works (Angillieri 2008; Mesa 2006; Migiros et al. 2011; Moussa 2003; Ozdemir and Bird 2009; Patton and Baker 1976; Youssef et al. 2011a).

The urban flood-hazard assessment is important for the mitigation of floods and a necessary step for government policies on urban planning worldwide. Urban flood-hazard maps classify the various parts of land surface according to the degree of actual or potential flood hazard. They help the planners manage better the sites for urban development and recognize areas that probably need stormwater runoff infrastructure (Büchele et al. 2006). The reliability of hazard maps depends mostly on the available data and the applied methodology (Papadopoulou-Vrynioti et al. 2013a, b). To this direction, geographical information systems (GIS) may help a lot with the spatial analysis of a flood, which is a multi-dimensional phenomenon.

Multi-criteria analysis methods are decision support tools for the solution of complex decision problems. The analytical hierarchical process (AHP) is a semi-quantitative and multi-criteria methodology designed for hierarchical representation of a decision-making problem (Saaty 1977, 2004). The AHP has gained wide application in land use suitability (Bathrellos et al. 2012, 2013; Kamberis et al. 2012; Kokinou et al. 2015; Panagopoulos et al. 2012; Papadopoulou-Vrynioti et al. 2013a, b, 2014; Skilodimou et al. 2014; Thapa and Murayama 2008; Youssef et al. 2011b), in landslide susceptibility analysis (Ayalew et al. 2004; Rozos et al. 2011; Youssef et al. 2015) and in flood hazard estimation (Fernández and Lutz 2010; Tehrany et al. 2014a, b). Moreover, the integration of the AHP in a GIS is able to improve decision-making methodology with powerful visualization and mapping capabilities and facilitates the production of hazard maps. However, the AHP method does not have the ability to identify the uncertainty associated with spatial outputs (Benke et al. 2009).

The Kifisos and Ilisos Rivers flowing through the plain of Athens were the case study of the present work. Morphometric parameters of the drainage network were used to examine its structural irregularities, as well as to identify areas prone to flash floods and compare them with the results of the proposed model.

The aim of this study is to present a flood hazard assessment model for urban areas. Geomorphological and geological factors along with land use data were used for that purpose. The AHP is implemented to support the evaluation of these factors, whereas the data processing and the compilation of the urban flood-hazard map were performed in a GIS environment. Furthermore, a sensitivity analysis of the factors was made to examine their variations' effect on the spatial and quantitative distribution of hazard areas.

Study area

The climate of the study area is typical Mediterranean. According to the hydrometeorological data of the meteorological station of Piraeus, the mean annual precipitation for a time-period of 30 years (1973–2003), is 332.2 mm. The rainy period begins in October and ends in May. The mean annual air temperature reaches 18.8 °C, whereas the hottest month is August with a mean maximum temperature of 27.8 °C. January is the coldest month with a mean minimum temperature of 10.3 °C.

The Kifisos River operates as the major drainage channel for the largest part of the plain of Athens, which includes the city of Athens and most of its suburbs (Fig. 1). The length of the main Kifisos channel is 33.7 km, and follows a NNE–SSW flow direction. It is a sixth-order stream flowing through the urban area of Athens for approximately 25 km and discharges into the Saronic Gulf. Its drainage basin has an area of 374.6 km^2 and is surrounded by the mountains of Parnitha (1413 m a.s.l.), Penteli (1109 m a.s.l.), Egaleo (468 m a.s.l.) and Ymittos (1026 m a.s.l.).

Regarding the geological formations of the drainage basin, at the upper reaches of the Kifisos River alpine and post-alpine geological formations occur, with post-alpine ones covering the 65 % of the total extent of the drainage area. The formations of the alpine basement belong to the geotectonic units of Attica and Ypopelagoniki and are easily distinguishable near the adjacent mountains. The Attica geotectonic unit consists of schists (Permian–Triassic age), marbles (Triassic–Jurassic), the Athens' schists of Cretaceous age and the Upper Cretaceous limestones of Athens. The geological formations of the Ypopelagoniki unit include clastic rocks (sandstones, schists and phyllites)

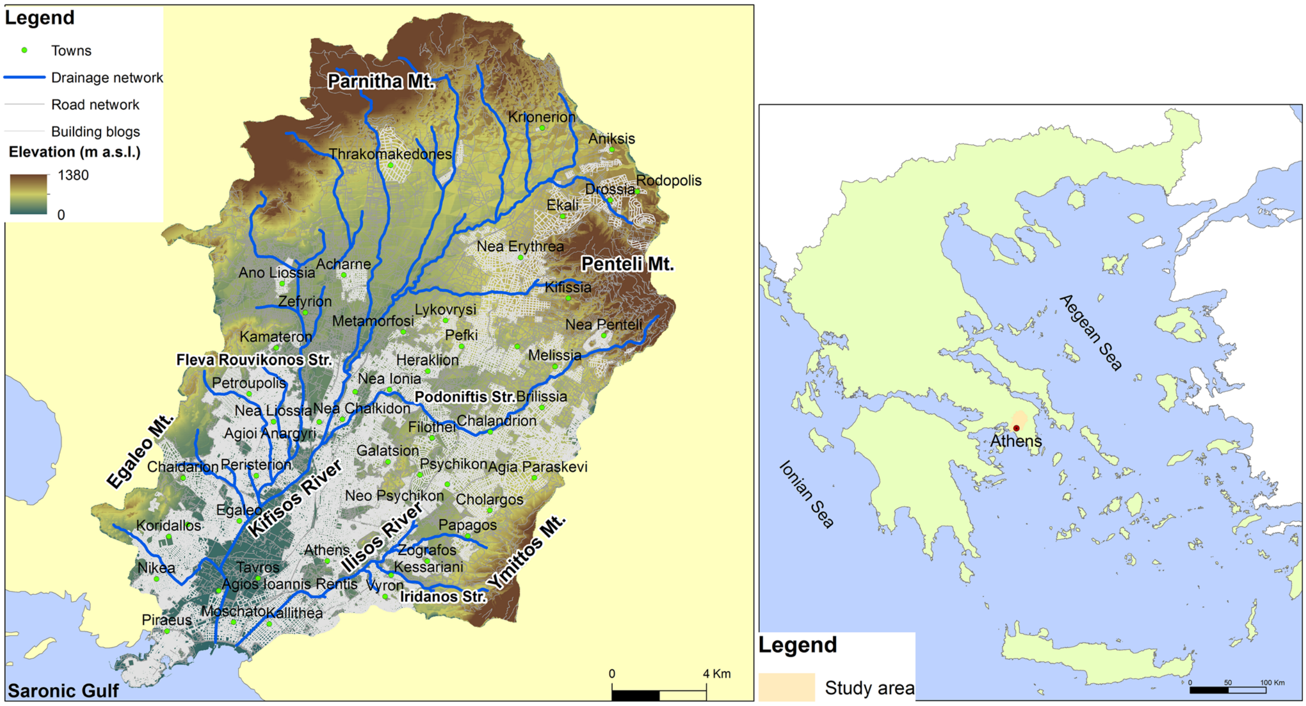

Fig. 1 The location map of the study area with elevations, main channels of drainage network, building blogs and road network

of Middle Triassic age, limestones (Triassic–Jurassic), ophiolites, Upper Cretaceous limestones and flysch (Lepsius 1893). An extensive area of the low-lying plain of Athens, as well as the slopes of the surrounding mountains are composed of post-alpine formations, which can be divided into Tertiary and Quaternary deposits of terrestrial and marine origin (conglomerates, marls, sandstones, limestones, marly limestones and alluvial deposits of various grain size) (Niedermayer 1971).

Artificial embankments made of stone, have been made along the greatest part of the main course of the river, whereas a motorway has been constructed over its lower part, converting that into a covered canal of 9 km length. Although the cross section of the lower part of the river has been enlarged providing water discharges of up to 1400 m^3/s, flood episodes during intense rainstorms are usual (Panagiotopoulos et al. 2010).

On the eastern side of the Athens Basin is Ilisos River, originating from multiple converging seasonal creeks and draining the western slopes of Ymittos Mt. It was one of the major tributaries of Kifisos River until the beginning of the previous century, when its main channel was artificially diverted flowing directly into the Saronic Gulf, east of the Kifisos River mouth. In the 19th and early 20th century the main channel of the river became a source of pollution due to the urban expansion of Athens and was gradually converted into a rainwater runoff conduit, covered by streets.

The urbanized area along the Kifisos River, as well as the area around the older path of Ilisos River has often suffered extensive damage during extreme storm events. More than 25 severe flood events have happened during the last 117 years (Maroukian et al. 2005).

A severe flood happened on February 22, 2013 where more than 100 mm of rainfall was locally recorded in 5 h. The heavy rain was the worst seen in the Greece's capital for the last 50 years. The storm flooded roads and houses in Athens overturning parked cars (Fig. 2). The flood caused one death, power cuts across the city and forced authorities to close major roads and a central subway station. The most recent flood was on October 24, 2014. The storm event took place in the entire basin, but the greatest rainfall intensity was reported at the western part, at the area of Ano Liosia and Acharne, where the point rainfall depth was 77.6 and 69.8 mm, respectively. The 10-min time distribution of the rainfall at the station of Ano Liossia is shown in Fig. 2. The highest 10-min rainfall depth was reported on the Acharne region with 14 mm. The mean value of the surface rainfall in the entire basin was 36.5 mm. The important characteristic of the specific storm was the high intensity and its limited spatial scale, which led to intense floods and consequent damages.

Data and methodology

The data used in this study include: four old topographic maps of Attica, drawn by Curtious and von Kaupert (1878–1894), four recent topographic maps (map scale 1:50,000), published by the Hellenic Army Geographical

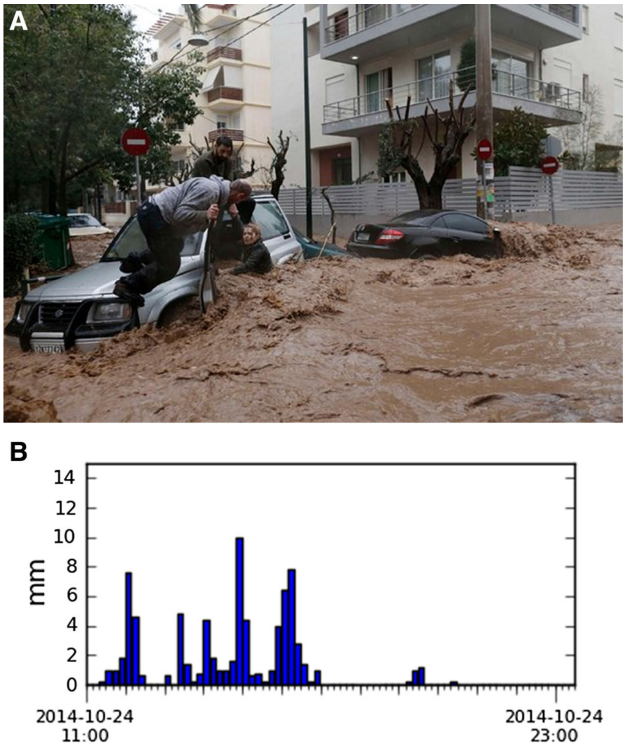

Fig. 2 **a** On February 22, 2013 intense rainfall flooded roads in Athens overturning cars (*photo* from J. Kolesidis/Reuters). **b** Ten-minute time distribution of the rainfall at the station of Ano Liossia

Service (HAGS); the geological map (scale 1:500,000) (IGME 1983); the corine land cover map and a map of urbanized areas (scale 1:25,000).

A spatial database was created, and ArcGIS 10.0 software was used to process the collected data.

The quantitative geomorphological analysis of the Kifisos and Ilisos river drainage networks was performed to identify flood-prone areas along the major channels of the study area. The drainage networks, derived from the topographic maps (at the scale of 1:50,000), were numbered according to Strahler's (1957) stream order system, the drainage basins were delineated and both drainage network and catchments were quantitatively analyzed. The hierarchical drainage by stream order was also investigated.

For the urban flood hazard assessment, a multi criteria model was applied. The model was based on factors controlling the water route when drainage system capacity is exceeded by high runoff. The selected factors include the slope angle, the elevation, the distance from open channel streams, the distance from totally covered streams, the hydro-lithology and the land cover. Each factor was divided into various classes with specific boundary values and their determination was based on topographic maps, extended field observations, and literature (i.e. Bathrellos et al. 2013; Fernández and Lutz 2010; Maroukian et al. 2005).

The Digital Elevation Model (DEM) was created by digitizing the contours of the topographic maps (with 20 m contour interval) and was used for the production of the slope layer. The slopes were classified into five classes (Fig. 3a). The elevation grid was divided into five categories (Fig. 3b).

The drainage networks were derived from the topographic maps. They consist of open channel streams and streams totally covered by urban area. Third and higher order streams were taken into account (Fig. 4). The open channel streams were digitized and buffer zones were drawn around third order streams at distances of 50, 100, 200 and 300 m, fourth order at distances of 100, 200, 300 and 400 m, and fifth order at distances of 100, 200, 400 and 600 m (Fig. 5a).

The comparative observation of the old topographic map of 1878 and the recent topographic maps of the study area lead to a preliminary mapping of the streams with covered channels. Furthermore, these covered streams were identified and mapped in detail through extensive field work. For the consideration of this factor, buffer zones were created around the totally covered streams of the study area, namely: third order streams at distances of 50, 100, 200 and 400 m, fourth order at distances of 100, 200, 300 and 500 m, fifth order at distances of 100, 200, 400 and 700 m and sixth order at distances of 100, 300, 600 and 1000 m (Fig. 5b).

The geological formations of the study area, derived from the corresponding geological map, were classified into three categories according to their hydrolithological behavior (Fig. 6a):

1. Permeable formations consisting of sandstones, limestones and marbles. According to Stamatis et al. (2006) the carbonate rocks show a high permeability due to their fractured system and karstification and comprise an important aquifer of the study area.
2. Semi-permeable formations comprising of loose to semi-coherent Quaternary and Neocene deposits along with thin-bedded limestones and ophiolites (Antoniou 2002). The Quaternary deposits host an aquifer that may be of sufficient potential when their thickness is significant. The alluvial aquifer of the study area has an annual discharge of 30 hm^3/year (Kallioras and Marinos 2015). Shallow aquifers develop in the Neocene deposits (Stamatis et al. 2006).
3. Impermeable formations consisting of schists. Low and poor aquifers develop in the weathered mantle of schist formations. The intense urbanization of the study area along with the overexploitation of the aquifers have led to the degradation of the ground water quality (Bathrellos et al. 2008).

Urban areas were recorded from a map of urbanized areas of Attica. Moreover, land-use data were obtained

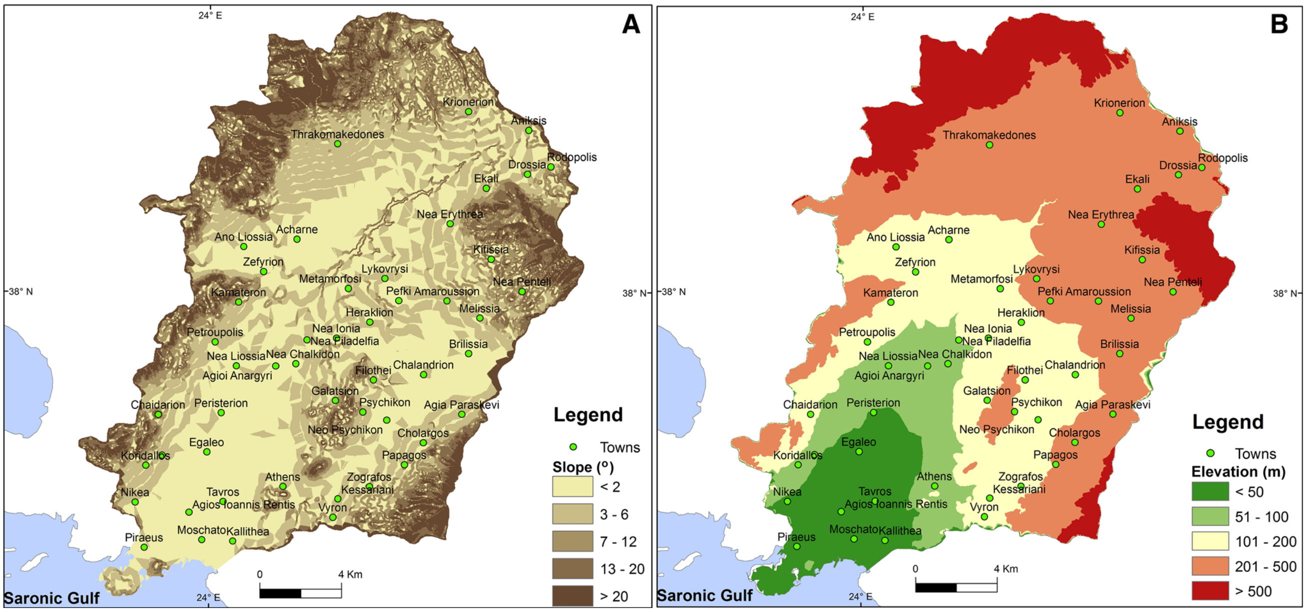

Fig. 3 **a** Map showing the spatial distribution of slopes. **b** Map showing the spatial distribution of elevations

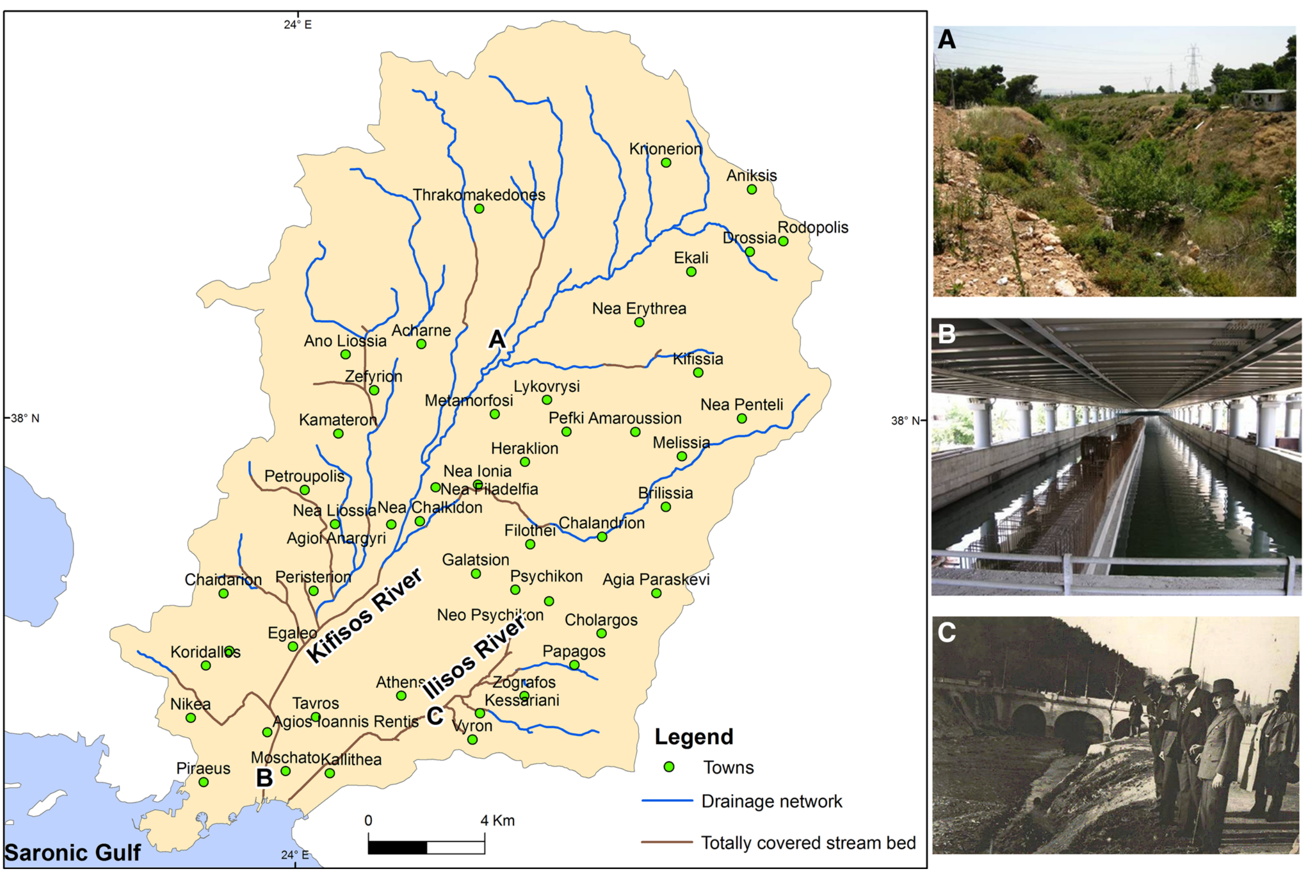

Fig. 4 Map showing the covered (*brown line*) and open channel (*blue*) streams. Photographs of: **a** an open channel, **b** a total covered stream bed and **c** the public works of the coverage of Ilisos River in front of Olympic Stadium in 1937 (Karali et al. 1996)

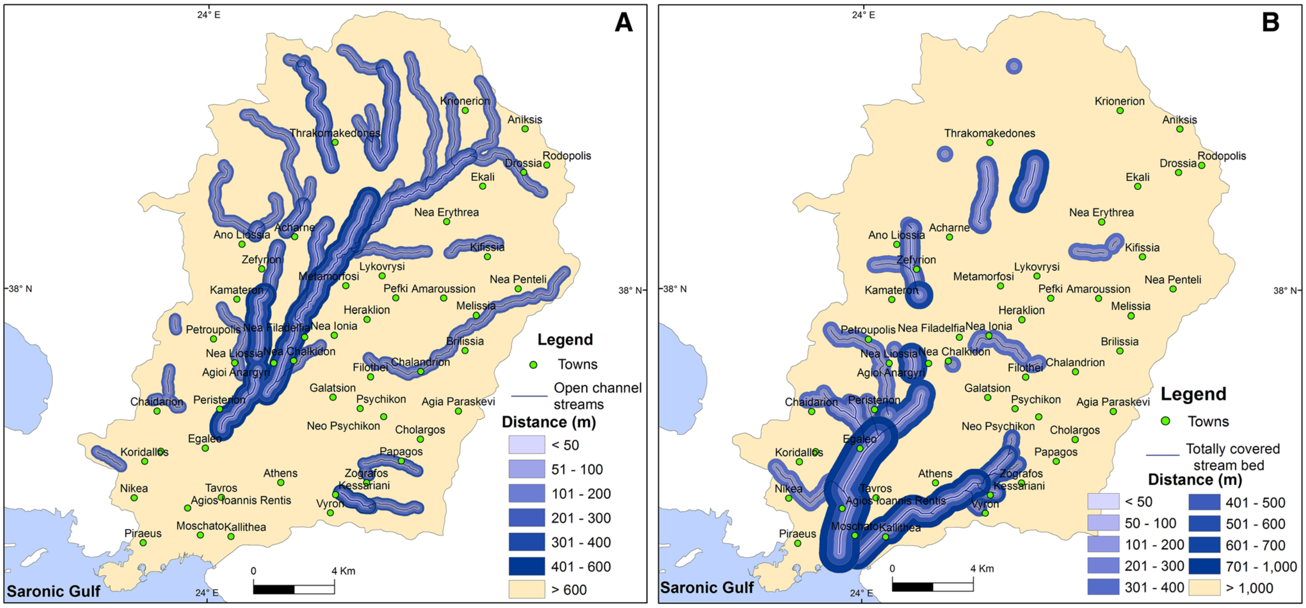

Fig. 5 **a** Map showing distance from open channel streams. **b** Map showing distance from totally covered streams

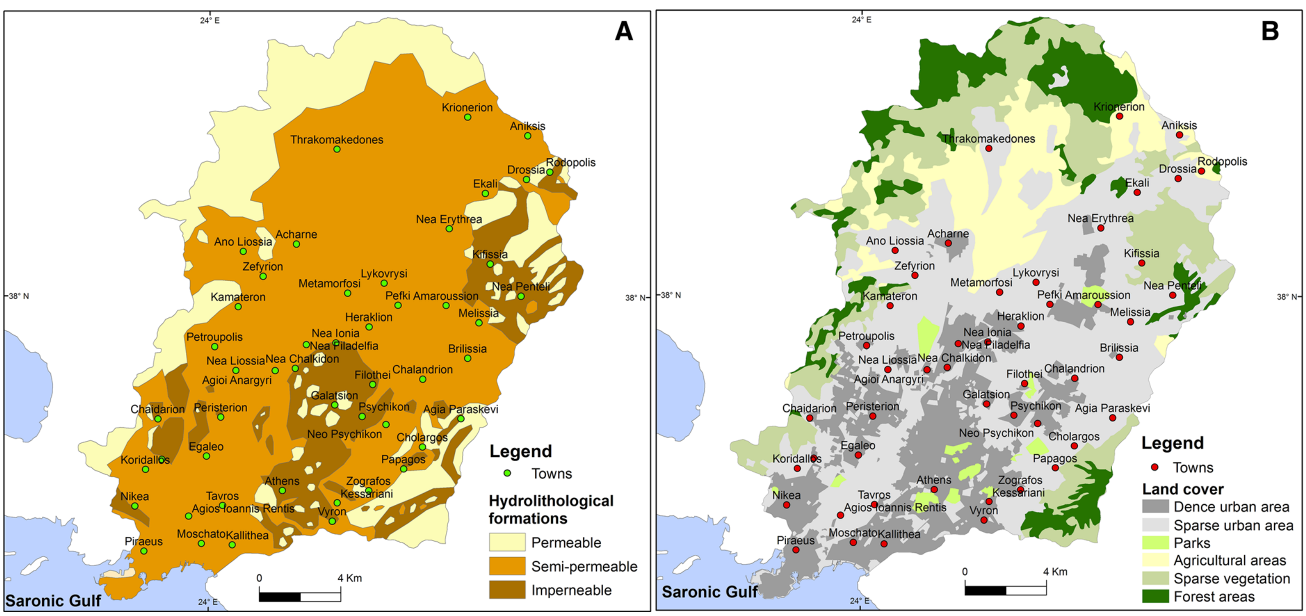

Fig. 6 **a** Map showing the spatial distribution of hydrolitological formations. **b** The land cover in the basin of Athens

from CORINE land cover (Bossard et al. 2000). For the necessities of this study, the land cover was classified into five categories: (1) densely urbanized areas, (2) sparsely urbanized areas, (3) agricultural land, (4) land covered by sparse vegetation, and (5) forests (Fig. 6b).

A primary step in the process of urban flood-hazard assessment is the classification of all the factors. Therefore, the classes of the involved factors have to be standardised to a uniform suitability rating scale. The standardisation method used in the analysis was consistently based on a five-grade scale. Integer numbers, ranging from 0 to 4, were assigned to every class. Thus, the class, which was rated as 0, represented low hazard, and the one rated as 4 represented very high hazard.

The rules of the AHP method were applied to get the final weights for each factor. The first step in the AHP is the computation of the pair-wise comparison matrix, where each entry represents the relative significance of a factor to the others. The relative importance between two factors is measured according to a numerical scale from 1 to 9. The correlation between the numerical values and the intensity of importance is the following: 1 = equal importance, 2 = weak or slight, 3 = moderate importance, 4 = moderate plus, 5 = strong importance, 6 = strong plus, 7 = Very strong, 8 = extremely strong, 9 = of extreme importance. Inversely, less important variables were rated between 1 and 1/9 (Saaty 1977, 2004).

The method requires normalization of all factor weights by the following equation:

$$\sum_{i=1}^{n} W_i = 1 \quad (1)$$

It is important to verify the consistency of each table matrix after the calculation of the weight values. So, the implication of each one was checked with the consistency ratio (CR):

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \quad (2)$$

where RI is the random index which was developed by Saaty (1977) and it is a constant which depends on the order of the matrix and the CI is calculated by the equation:

$$\mathrm{CI} = \lambda_{\max} - n/n - 1 \quad (3)$$

where $\lambda_{\max}$ is the largest eigenvalue of the matrix, and n is the order of the matrix. This ratio is used to avoid the creation of any incidental judgment in the matrix and when $\mathrm{CR} < 0.1$ an acceptable level of consistency has been achieved. The CR values are less than 0.1, which means that the corresponding matrixes have an acceptable level of consistency.

The classes of every adopted factor, their ratings, the calculations of the weighting coefficient and the consistency ratio (CR) are given in Tables 1 and 2.

The overall score of the basic urban flood hazard assessment for the study area was calculated with the correlation of the estimated factors. This correlation was performed using the weighted linear combination method, according to the following mathematical operator:

$$H = \sum_{i=1}^{n} W_i X_i \quad (4)$$

where H is hazard degree, n is the number of the factors, W_i is the weight of the factor i and X_i is the rating of the factor i.

The influence of uncertainty of the adopted factor weights on the flood hazard assessment was examined. According to Burrough and McDonnell (1998) the error ΔS produced by independent errors ΔW_i in the weighting coefficient values is given by:

$$\Delta S = \sqrt{\sum_{i=1}^{n} (\Delta W_i X_i)^2} \quad (5)$$

Table 1 Assigned rate values for each adopted factor/class of the study area

Factors	Classes	Rating
Slope (°)	<2	4
	3–6	3
	7–12	2
	13–20	1
	>20	0
Elevation (m a.s.l.)	<50	4
	51–100	3
	101–200	2
	201–500	1
	>500	0
Distance from open channel streams (m)	*3rd order stream*	
	0–50	4
	51–100	3
	101–200	2
	201–300	1
	>300	0
	4th order stream	
	0–100	4
	101–200	3
	201–300	2
	301–400	1
	>400	0
	5th order stream	
	0–100	4
	101–200	3
	201–400	2
	401–600	1
	>600	0
Distance from totally covered streams (m)	*3rd order stream*	
	0–50	4
	51–100	3
	101–200	2
	201–400	1
	>400	0
	4th order stream	
	0–100	4
	101–200	3
	201–300	2
	301–500	1
	>500	0
	5th order stream	
	0–100	4
	101–200	3
	201–400	2
	401–700	1
	>700	0
	6th order stream	
	0–100	4
	101–300	3
	301–600	2
	601–1000	1
	>1000 m	0

Table 1 continued

Factors	Classes	Rating
Hydrolithological formations	Permeable	1
	Semi-permeable	2
	Impermeable	3
Land cover	Dense urban	4
	Sparse urban	3
	Agricultural	2
	Sparse vegetation	1
	Forests	0

Table 2 The weighting coefficient of every factor and the consistency ratio (CR)

	F1	F2	F3	F4	F5	F6	Weighs, W_i
F1	1	4	1/2	3	1/2	2	0.207
F2		1	1/3	1/2	1/4	1/4	0.058
F3			1	3	1	1/3	0.088
F4				1	1/3	1	0.260
F5					1	1/3	0.104
F6							0.283

CR = 0.04

F1 = slope, F2 = elevation, F3 = distance from open channel streams, F4 = distance from totally covered streams, F5 = hydrolithological formations and F6 = land cover

Each weighting coefficient value was altered 20 % from the original factor weight that was used for the basic hazard assessment. The changes of weight values (ΔW_i) of every factor are: 0.041 for slope, 0.012 for elevation, 0.018 for open channel streams, 0.052 for totally covered streams, 0.021 for hydrolithological formations and 0.057 for land cover. Equation (3) was applied to calculate the error (ΔS). Then, it was multiplied by 1.96 to compute 95 % confidence level of the suitability values S. This process led to the creation of a map which was added and subtracted from the basic flood hazard map to estimate the upper and lower S values at 95 % confidence level, respectively. Thus, two maps representing two extreme scenarios of maximum and minimum S values were produced for urban floods.

Finally, the spatial distribution of the flood events was used for the verification of the potential urban flood hazard assessment. This map was produced by plotting the areas affected by severe flood events during the last 117 years (Fig. 7). The verification was done by applying a frequency ratio statistical analysis. For that purpose, firstly, the frequency distribution of flood events was calculated for each zone of the basic flood hazard map. Then, the area ratio of each zone area to the total area was computed. The frequency ratio for each flood hazard zone was calculated by dividing the frequency of flood events to the area ratio.

Results

The quantitative geomorphological analysis of the Kifisos river drainage network showed irregularities in the hierarchical drainage by stream order. Table 3 includes the number of streams, channel length and basin area for each stream order, which drain directly into higher order streams. The most important irregularities concern the first-order streams that drain directly into third-order streams, as well as the third-order streams that drain directly into fifth and sixth order main channels. For the first-order streams, 23.6 % of their total number and 25.8 % of their total channel length, which drain 25.0 % of their total drainage basin area, join third-order streams especially at the west and northeast part of the catchment. For the third-order streams, 30.8 % of their total channel length which drains 41.4 % of their total catchment area drains directly into fifth-order main channels. This high percentage can be attributed mainly to the third-order Podoniftis Stream that joins the main channel of Kifisos about 10.4 km before the river mouth. Thus, during extreme rainfall events, the surface runoff of an area of 77.6 km^2 is directly added to the runoff of Kifisos River in the densely urbanized area of Agioi Anargyri. Additionally, Podoniftis stream for a significant length of 2.9 km before its junction with Kifisos River, as well as many other lower order channels of its drainage network are totally covered under the city.

The major irregularity of the Ilisos River drainage network is the third-order Iridanos stream which drains directly into the fourth-order main channel of Ilisos. The runoff of a relatively steep area of 7 km^2 at the western slopes of Ymittos Mt. is directly added to the Ilisos main channel which has been converted into a rainwater runoff conduit, covered by streets. This junction is located 7.8 km upstream from the river mouth (Table 3).

The results of the urban flood hazard assessment are given in the maps of Fig. 8. Three alternative maps were derived for different scenarios. The first scenario was the application of AHP method, which led to the basic flood hazard assessment map (H_b). The second map (H_{max}) represents the maximum value of the hazard assessment of each pixel, whereas the minimum value scenario is expressed in the third map (H_{min}).

In the present study, the calculated flood-hazard index values of the three flood-hazard assessment maps were

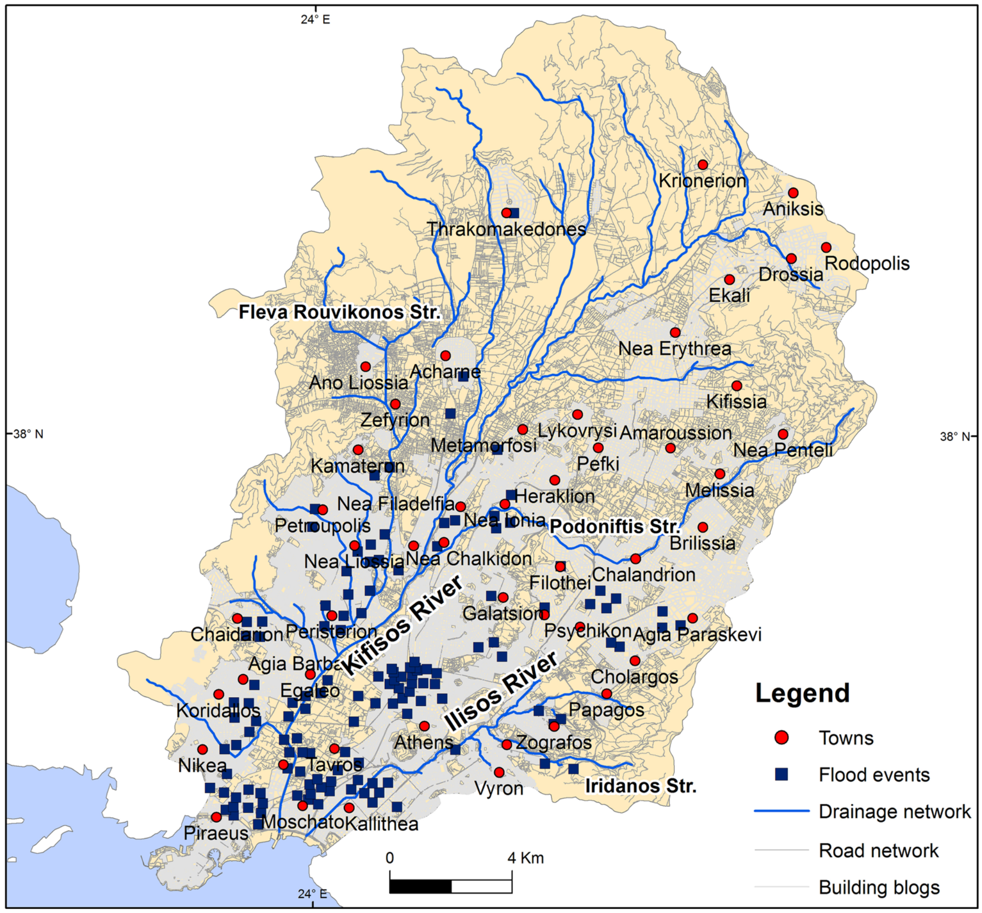

Fig. 7 Map showing the spatial distribution of flood events in the study area

categorised using the Standard Deviation method of classification. The study area of each map was classified using into five sections corresponding to very high, high, moderate, low and very low flood hazard zone. The percentages of these classes, in relation to the entire area of the drainage basin are given in Table 4.

Table 5 presents the computed frequency ratio of the flood events for each flood hazard zone. The frequency ratio value of 1 is an average value (Pradhan and Lee 2010; Rozos et al. 2013). Thus, ratio values higher than 1, indicate a strong relationship between floods and the given hazard zone, whereas ratio values lower than 1, indicate a poor relationship between floods and the given hazard zone.

Table 5 shows that the "very high" flood hazard zone is strongly correlated with flood events. In this class, the frequency ratio was >4 indicating an extremely high probability of flood occurrences. For the high flood-hazard zone the frequency ratio value was found to be 2.4 and thus it shows a very high probability of flood events. Regarding the moderate and low classes, the frequency ratio values were found much lower than 1, indicating a very low probability of flood occurrences. As the frequency ratio value was equal to zero in the very low class and therefore the probability to flood is minimal.

Discussion

In the present work, multi-criteria decision analysis and GIS techniques were employed to estimate the flood hazard zones in the drainage basins of Kifisos and Ilisos Rivers. Six factors were taken into account as the most influencing parameters on the water course when high stormwater runoff exceeds drainage system capacity. The AHP method was applied to evaluate the factors and the final outcome was a potential flood hazard map. In an attempt to identify flood-prone areas along the main stream of the study area and compare them with the produced flood hazard maps, the drainage networks were quantitatively analysed and the hierarchical drainage by stream order was investigated.

The drainage basin morphometry, along with geology, rainfall intensity and duration are significant factors in maximizing the rainfall runoff (Costa 1987). For example, as shown in Fig. 2, the maximum 10-min rainfall is more than 60 mm. By using the idf curve for the Athens area that

Table 3 Number of streams (NS), channel length (CL) and basin area (BA) for each order that drain directly into streams of higher order for the drainage networks of Kifisos and Ilisos Rivers

Stream order	NS	%	CL (km)	%	BA (km^2)	%
Kifisos River						
1st to 2nd	271	77.2	197.8	73.5	93.37	70.95
1st to 3rd	64	18.2	52.7	19.6	21.7	16.49
1st to 4th	19	5.4	16.76	6.2	11.18	8.5
1st to 5th	–	–	–	–	–	–
1st to 6th	1	0.3	2461	0.9	5.433	4.13
2nd to 3rd	80	88.9	288.9	83.8	151.2	85.9
2nd to 4th	7	7.8	42.06	12.2	19.5	11.1
2nd to 5th	2	2.2	7.049	2	1.93	1.1
2nd to 6th	1	1.1	6.602	1.9	3.325	1.9
3rd to 4th	20	80	272.4	62.3	122.4	51.9
3rd to 5th	4	16	134.7	30.8	97.62	41.4
3rd to 6th	1	4	30.03	6.9	15.81	6.7
4th to 5th	6	85.7	351.2	94.4	179.2	95.9
4th to 6th	1	14.3	20.68	5.6	7.564	4
5th to 6th	2	100	517.7	100	316.8	100
Ilisos River						
1st to 2nd	46	92	38.53	82.9	15.25	75.5
1st to 3rd	3	6	4.33	9.4	1.67	8.3
1st to 4th	1	2	3.59	7.7	3.24	16.1
2nd to 3rd	13	86.7	44.75	87.5	17.92	88.4
2nd to 4th	2	13.3	6.39	12.5	2.15	11.6

has been constructed elsewhere correspond to a return period of little less than 50 years (Mimikou et al. 2000). In the present study, the quantitative geomorphological analysis of the drainage networks showed irregularities in the hierarchical drainage by stream order which enhance flash floods. The most significant among them concerns third-order streams, which drain directly into the sixth-order main channel of Kifisos drainage network and its fifth-order tributary Fleva Rouvikonos. Regarding the Ilisos river network the major irregularity is the third-order Iridanos stream that drains directly into the fourth-order main channel of Ilisos, which in fact is a rainwater runoff conduit, covered by the city.

Concerning the produced H_b map, the areas of very high and high flood hazard are distributed mostly on the lower reaches of Kifisos and Ilisos Rivers, particularly to the southern and to the western part of the study area. Regarding the spatial development of these flood hazard zones, their percentages to the total area are: 24.6 % for the "high" zone and 5.8 % for the "very high" zone (Table 4). According to Papagiannaki et al. (2015) the southern part of the study area is a densely populated area, with around 17,000 inhabitants per km^2 and was the most frequently suffered area from flood occurrences during the period 2005–2014. The high population density is directly associated with the intense urbanization of this area, which increase the surface runoff and contributes to increase the vulnerability of the flood hazard. On the contrary, at the northern part of the study area, very few regions of limited area are classified into areas of high and very high flood hazard. Since this area is sparsely urbanized and has low population density, the flood hazard is at low level.

According to Diakakis (2013) certain segments of the drainage networks at the southern and western part of the plain of Athens often overflowed in flood events. The map shows that the urban areas in the vicinity of the main channels of Kifisos and Ilisos Rivers are more prone to flood hazard. The lowland morphology, gentle slope, the totally covered streams, considerable part of impermeable formations, along with intense urbanization of these areas increase the surface runoff and create favorable conditions for flooding. Moreover the junctions of third-order streams with Kifisos, Fleva Rouvikonos and Ilissos rivers are located at areas characterized as "very high" flood risk. This fact shows that the flood-hazard map is in good agreement with the results of the drainage network quantitative analysis.

Since, the applied AHP method has limitations to determinate the uncertainty (Benke et al. 2009), two more scenarios were developed to examine the influence of the uncertainty on the hazard assessment results. The uncertainty analysis of the proposed methodology proved that the weight coefficient of land cover presents the greatest variation, whereas the elevation has the lowest one among all the involved factors for the flood-hazard assessment. According to Bathrellos et al. (2013) the variation of the weighting coefficients affects the spatial distribution of the hazard zones. The results of the uncertainty analysis showed no significant variations of the presentences of the flood hazard zones between the H_b and H_{min} maps. The percentages of the flood hazard zones for the H_{max} map have changed in comparison to the H_b map. The highest variation of the percentages is observed in the low and very low zones of H_{max} map (Table 4).

The accuracy of the produced urban flood hazard map was verified using flood events of the last 117 years. The results demonstrated that the vast majority of the flood events, 83 % occurred within the limits of the high to very high hazard zones. The applied analysis proved satisfactory results about the positive relationship between the urban flood hazard assessment map and the flood events since the flood hazard intensity raises as the frequency ratio values increase.

The urban flood hazard assessment map provides valuable information for land-use planning at a regional scale leading to the determination of the safe and non-safe areas for urban development (Baltas and Mimikou 2002; Nunes Correia et al. 1999; Ologunorisa and Abawua 2005; Quintero et al. 2012; Salvati et al. 2010). Planners,

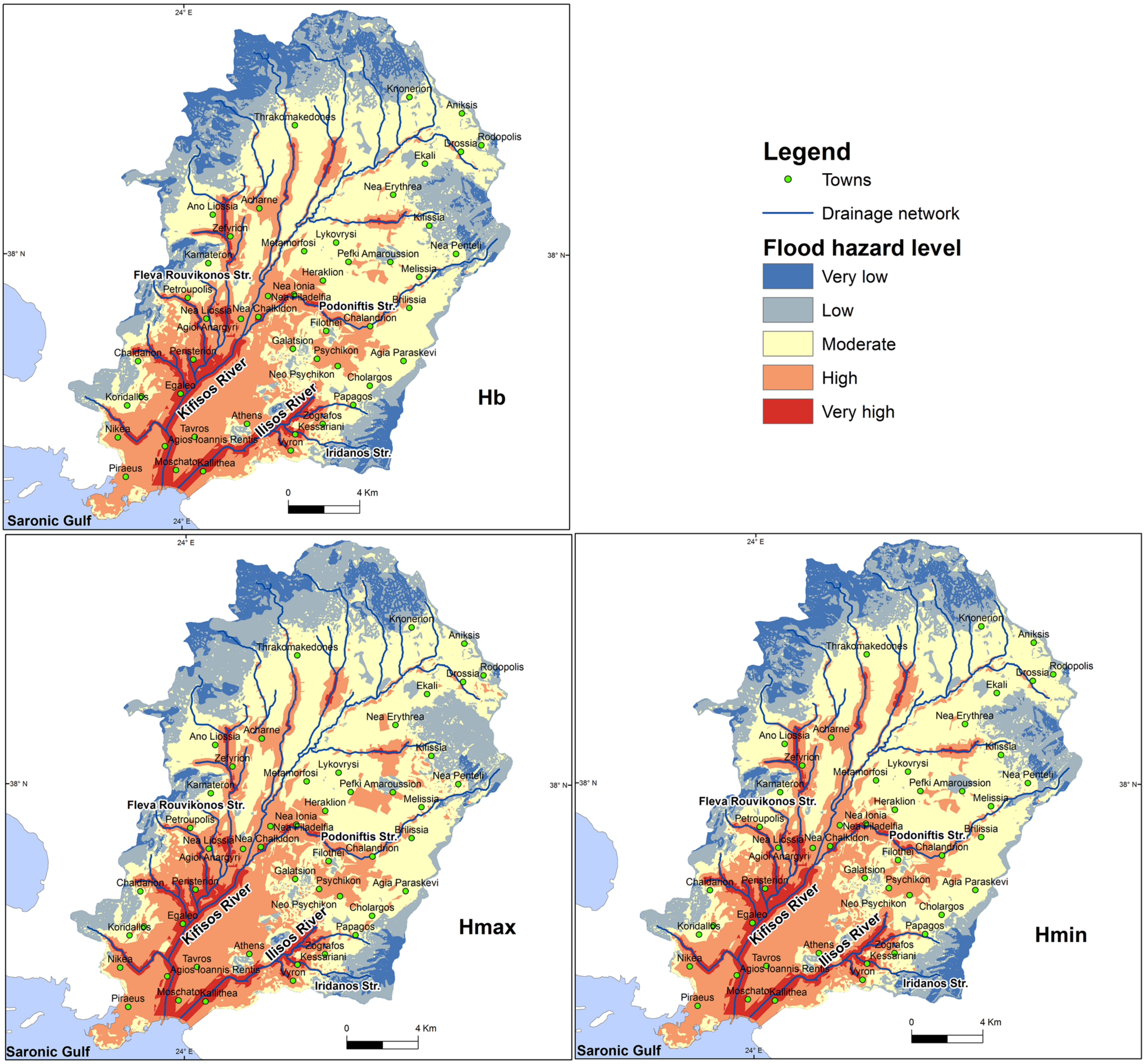

Fig. 8 Potential flood hazard assessment maps. H_b: the basic flood hazard assessment, H_{max}: the maximum value of the flood hazard assessment and H_{min}: the minimum value of the flood hazard assessment

Table 4 Percentages of each flood hazard zone in the cases of basic, maximum and minimum scenarios for both drainage networks of Kifisos and Ilisos Rivers

Flood hazard zone/percentage of total basin area	H_b	H_{max}	H_{min}
Very low	9.1	7.1	8.9
Low	19.1	21.1	19.0
Moderate	41.4	40.3	41.7
High	24.6	25.9	24.2
Very high	5.8	5.6	6.2

engineers, and policy makers may use the flood hazard map for the selection of suitable areas for sustainable urban development.

Conclusions

In this study, an urban flood-hazard assessment map was produced using the AHP method and a GIS. The developed framework was implemented in the Athens metropolitan area (Greece).

Table 5 Frequency ratio values of flood events into each flood hazard zone

Flood hazard zone	Pixel in domain	Area percentage (*a*)	Number of flood events	Floods (%) (*b*)	Frequency ratio (*b*/*a*)
Very low	95,612	9.1	0	0.0	0.00
Low	202,018	19.1	1	0.7	0.04
Moderate	436,885	41.4	22	16.4	0.40
High	259,447	24.6	79	59.0	2.40
Very high	61,621	5.8	32	23.9	4.09
Total	1055,583	100.0	134	100.0	1

The proposed methodology showed that 24.6 % and 5.8 % of the area belongs to "high" and "very high" hazard classes, respectively. The southern and the western parts of the basin of Athens, along with urban areas in the vicinity of the main channels of Kifisos and Ilisos Rivers, present the highest flood hazard. They are characterized by lowland morphology, gentle slope, totally covered streams, expansion of impermeable formation and intense urbanization.

The junctions of third-order streams with the main channels of Kifisos and Ilisos Rivers enhance flash floods and are located at areas of very high flood hazard. This indicates a good agreement between the results of the drainage network quantitative analysis and the flood-hazard assessment map.

The uncertainty involved in the AHP was determined by introducing an uncertainty in weighting coefficient of the adopted factors. The analysis showed no significant differences on the spatial and quantitative distribution of the hazard zones.

The produced urban flood hazard map presents a satisfactory agreement between the flood hazard zones and the spatial distribution of flood phenomena. The validation indicated reliable results and a high accuracy of the produced map. Therefore, the proposed methodology and the flood hazard map should be taken into account by the local authorities to adopt policies and strategies aiming towards sustainable urban development.

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Compliance with ethical standards

Conflict of interest No conflict of interest.

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