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Assessment of flood hazard areas at a regional scale using an index-based approach and Analytical Hierarchy Process: Application in Rhodope–Evros region, Greece

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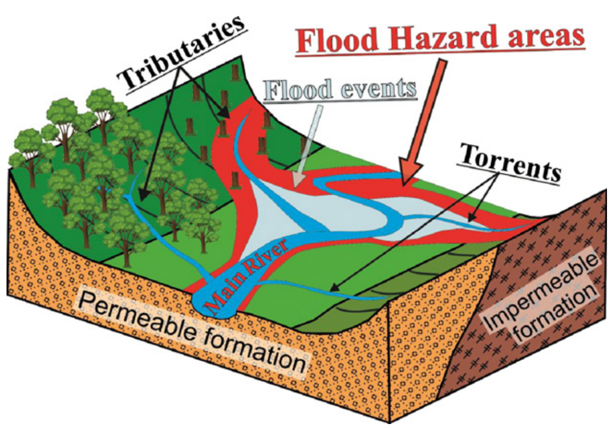
HIGHLIGHTS

- Literature review of spatial, GIS-based methods for flood exposure assessment.
- Development of an index-based methodology to assess the flood hazard areas.
- The methodology analyzes 7 parameters to assess flood exposure.
- Analytical Hierarchy Process is used to estimate the weights of the parameters.
- A sensitivity analysis results to a second more reliable index (FHIS).

GRAPHICAL ABSTRACT



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ABSTRACT

The present study introduces a multi-criteria index to assess flood hazard areas in a regional scale. Accordingly, a Flood Hazard Index (FHI) has been defined and a spatial analysis in a GIS environment has been applied for the estimation of its value.

The developed methodology processes information of seven parameters namely flow accumulation, distance from the drainage network, elevation, land use, rainfall intensity and geology. The initials of these criteria gave the name to the developed method: "FIGUSED". The relative importance of each parameter for the occurrence and severity of flood has been connected to weight values. These values are calculated following an "Analytical Hierarchy Process", a method originally developed for the solution of Operational Research problems. According to their weight values, information of the different parameters is superimposed, resulting to flood hazard mapping. The accuracy of the method has been supported by a sensitivity analysis that examines a range for the weights' values and corresponding to alternative scenarios.

The presented methodology has been applied to an area in north-eastern Greece, where recurring flood events have appeared. Initially FIGUSED method resulted to a Flood Hazard Index (FHI) and a corresponding flood map. A sensitivity analysis on the parameters' values revealed some interesting information on the relative importance of each criterion, presented and commented in the Discussion section. Moreover, the sensitivity analysis

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concluded to a revised index FHIS (methodology named FIGUSED-S) and flood mapping, supporting the robustness of FIGUSED methodology. A comparison of the outcome with records of historical flood events confirmed that the proposed methodology provides valid results.

1. Introduction

Flood is a major natural hazard with often immeasurable impact, affecting annually 170 million people (Kowalzig, 2008). Therefore, flood risk management needs to overcome national borders, geographic location and socio-economic limitations (Degiorgis et al., 2012). Flood risk management is usually divided into flood risk assessment and flood risk mitigation (Schanze et al., 2006). This distinction takes into account apart from the hazard also its impact, since the total elimination of risk is neither possible nor efficient. Indisputably, strategies against floods' impact at a region scale require the identification of prone areas (Tehrany et al., 2013) to provide early warning, facilitate quick response and decrease the impact of possible flood events (Kia et al., 2011).

1.1. Background: literature review

The application of GIS-based multi-criteria analysis in the context of flood risk assessment was rare until 2000. Black and Burns (2002) present an overview of changes in the estimation of flood risk on Scottish rivers with time by re-analyzing flood records. An early attempt to use GIS on water-related hazards has been presented in Meja-Navarro et al. (1994). The risk has been estimated for different hazards (debris, flood) on various zones of Glenwood Springs (Colorado), aiming to define land use suitability. In Correia et al. (1999) GIS is recognized as a powerful means to integrate and analyze data from different sources and flood risk mapping was provided for different scenarios of urban growth, simulating the consequences of alternative cases. In Zerger (2002) relative importance was introduced at the input parameters, underlining the necessity to connect spatial analysis to real-world decision making, thus directing the efforts towards concrete results rather than merely solving technical issues. In Schumann et al. (2000) a GIS-based methodology for rainfall-runoff modeling was developed, while the authors of Liu et al. (2003) incorporated several parameters in their rainfall–runoff model (slope, land use, soil type etc.) in order to estimate the spatial distribution of runoff and the average flow time in river basins. Their aim was to provide insight on river basins' hydrological processes and support flood risk management. In Van Der Veen and Logtmeijer (2005) flood vulnerability was linked with important economic activities for specific areas. The analysis combined economic information of 28 sectors with the borderlines of simulated flood events.

In Forte et al. (2005) the authors expanded an earlier work (Liu et al., 2003) and divided a peninsula in southern Italy into prone zones of different flood risk. They super-imposed GIS layers of both geological and hydrological information. They combined information on the location of karstic sinkholes and information of historical flood events. Thematic maps visualizing this information have been supported by geo-lithological, permeability and rainfall maps, producing a flood hazard map. Similarly, the authors of Dewan et al. (2007) developed flood hazard maps on Dhaka river basin in Bangladesh, by processing data of the historical major flood event of 1998 and considering the interactive effect of land cover, elevation and geomorphology. The severe flood events of 2000, 2005 and 2006 in Romania urged the generation of flood risk maps (Aldescu, 2008) to support water management experts and flood mitigation.

Flood hazard zones have been delineated for the Tucuman Province (Argentina), using multi-criteria decision analysis Fernández and Lutz (2010). A detailed work on the use of multi-criteria analysis for the estimation of flood vulnerability was also presented in Wang et al. (2011), while in Kourgialas and Karatzas (2011) flood-hazardous areas were estimated by superimposing GIS-layers that visualize spatial and climate information. Sensitive ecosystems and high hazard risk regions in the developing world have been identified in De Sherbinin et al. (2012), considering (among others) the impact of flood by developing a net migration model. In a recent work (Tehrany et al., 2013) 10 parameters have been included in an analysis, with the relative importance of each parameter defined following a statistical analysis. While studying flood hazard in Malaysia (Tehrany et al., 2014) this research group also included the parameter distance-from-river.

The present article deals with the first element of flood risk management, i.e. the definition of flood hazard areas in a specific region. The aim is to identify flood hazard zones, where mitigation measures should be taken. Thus, a spatial, multi-criteria index has been introduced to define such areas. The index was applied in the Rhodope–Evros region in Northern Greece. Although the index is based on the specific geological and Land use characteristics of the study site, it can be modified and applied in other regions.

2. Materials and methods

The authors selected the Rhodope and Evros prefectures in NE Greece as case study for the developed methodology. The study area is located in the north-eastern Greece, comprises the prefectures of Evros and Rhodope and covers an area of 5004 km^2. The northern boundary of the study area is Erythropotamos River which is end up to Evros River. The drainage network is a well-developed with a dendritic form. In the eastern part the torrents and steams end up to Evros River, whereas in the western part (prefecture of Rhodope) end up to Lissos River. The permanent population is about 260,000 and the main economic activities are agriculture and livestock. Forests and agricultural land cover the majority of both two prefectures. The mean slope of the study area is 8%, whereas the mean elevation is 253 m, the maximum elevation of the Rhodope Mountain is 1440 m and the minimum elevation is zero meters in the cost line. A variety of rocks and sediments composes the geological background of the study area. In the mountainous part of the region are placed the impermeable formations which are crystalline rocks such as Amphiboles, Gneiss, Ophiolites, volcanic rocks like Dacites, Ryolites, Andesites. The permeability of these formations increases locally in fault and fracture zones. In contrast, the permeable sediments are located in the lowlands and consist of alluvial deposits, marls, conglomerates, sandstones and sands. Marbles and limestones of the study area are included in the permeable formations due to their karstification. Groundwater is occurred in Fractured (crystalline and volcanic rocks), Karst and porous aquifers. The climate of the area is continental and is characterized by hot and dries summers and harsh and wet winters with large periods of snow.

This specific location encloses 10 sub-basins and was selected because of its evident flood susceptibility, justified by recurrent flood events (Ramos and Thielen, 2006); (Angelidis et al., 2010). Only during the last 10 years major flood events occurred in 2005, 2006, 2010 and 2015. Flooding in 2005 and 2010 was so severe that the authorities had no other option than to explode dikes in order to relief the flood wave. The most recent events of February 2015 resulted in 20,000–30,000 hectares of farm land being flooded and a huge impact to the local economy. Once again the necessity to prevent flood waves from

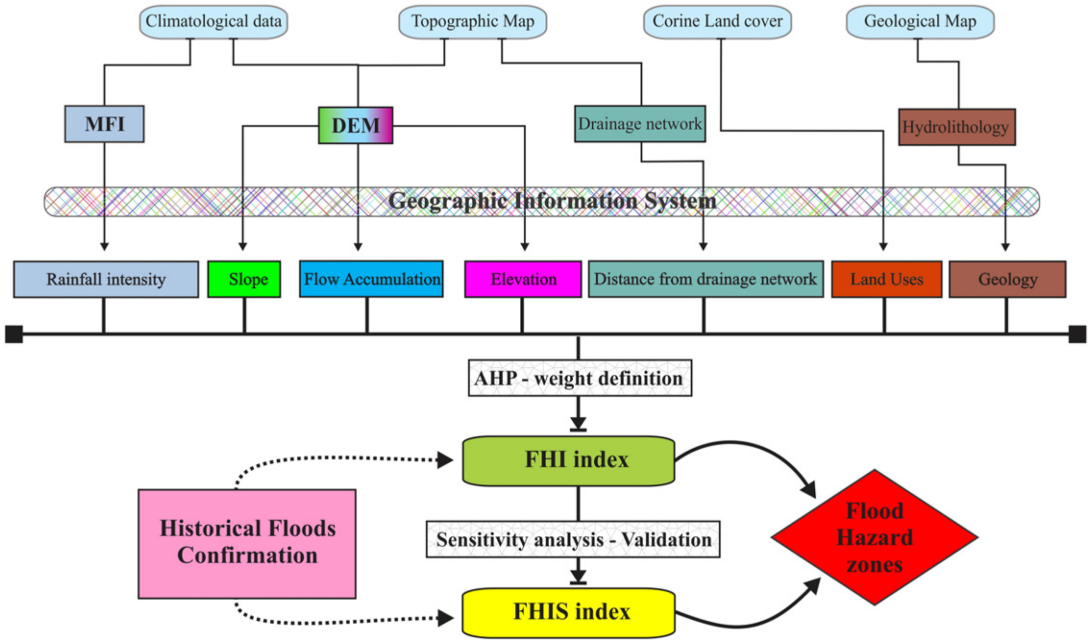

Fig. 1. Flowchart of the multi-criteria FIGUSED method.

reaching settlements resulted to a dike's destruction by explosion. The result of this explosion was a flooded arable area of 8000 hectares. Precautionary evacuation of villages and settlements was also applied. Although these events are mainly associated to Evros river discharge, the role of adjacent streams shouldn't be neglected.

2.1. Flood Hazard Index (FHI)

In the present research the authors have built on the aforementioned strategies and recent methodologies. Accordingly, an index model has been developed in a GIS environment aiming to define flood hazard areas with a regional focus. The developed model performs a multi-criteria analysis incorporating a Flood Hazard Index (FHI). The FHI aims to assist the identification of hotspots related to flood risk and allow a comparative analysis between different basins.

In Fig. 1 the proposed methodology is illustrated. Initially, information from various data sources is fed in the GIS. This information is processed in a second phase and along with the definition of the parameters' weights they result in the FHI index. FHIS is the outcome of the subsequent sensitivity analysis. Comparison of the two indices and the corresponding flood hazard maps supports the identification of prone areas, while records of historical flood events verify the accuracy of the methodology.

2.2. Parameters included in the FHI

FHI comprises seven criteria–parameters: flow accumulation (F), rainfall intensity (I), geology (G), land use (U), slope (S), elevation (E) and distance from the drainage network (D). The initials of these parameters name the methodology: “FIGUSED”.

The selection of these parameters has been theoretically based on their relevance to flood hazards as documented in the literature (Haan et al., 1994). On the other hand the selected parameters have been proved effective when included in relevant research studies and applications (Section 1).

Input data for each parameter is processed in a GIS environment and the seven parameters are visualized in independent thematic maps. Thematic maps of elevation, slope and flow accumulation are products of the digital elevation model (DEM). Moreover, geological information offers insight on the geological units, while land use information[1] results to the relevant thematic map. Distance from the rivers can be calculated by imposing buffer zones around the drainage network information. Finally, rainfall intensity is estimated from rainfall measurements, using a modified Fournier index.

2.3. Relative weights of the criteria

FIGUSED method considers the above hydrogeological, morphological and socio-economic parameters and the weight of each factor determines its role in the final result.

Thus, a spatial analysis of studied areas evaluates each grid-point on every parameter. Then, according to the local conditions, each grid-point is assigned values in a scale between 2 and 10 (rating score). The classes of the flow accumulation, elevation and rainfall intensity were defined using the grading method of natural breaks which has been used in similar studies (Huan et al., 2012; Kazakis and Voudouris, 2015). The slope classes were defined according to the Demek (1972) classification, whereas the classes of the distance from the drainage network have been defined by processing records of historical floods in the study area. The qualitative parameters of land use and geological formation were classified similarly to previous studies with modifications accordingly the characteristics of the study site (Kourgialas and Karatzas, 2011; Tehrany et al., 2013; Ouma and Tateishi, 2014). The acquired values are processed in order to calculate the relative significance of each criterion and the corresponding weighting factor (w). Following the calculation of the weights, the FHI can be calculated using Eq. (1).

$$\mathrm{FHI} = \sum_{i=1}^{n} r_i \cdot w_i = \mathrm{F} \cdot w_F + \mathrm{I} \cdot w_I + \mathrm{G} \cdot w_G + \mathrm{U} \cdot w_U + \mathrm{S} \cdot w_S + \mathrm{E} \cdot w_E + \mathrm{D} \cdot w_D \tag{1}$$

where:

r_i the rating of the parameter in each point
w_i the weight of each parameter
n the number of the criteria.

[1] Derived from: Corine Land Cover, 2006.

2.4. Analytical Hierarchy Process

The weight of each parameter is defined following the Analytical Hierarchy Process (AHP) (Saaty, 1990a,b). AHP is a structured technique used for analyzing complex problems, where a large number of interrelated objectives or criteria are involved. The weights of these criteria are defined after they are ranked according to their relative importance. Thus, once all criteria are sorted in a hierarchical manner, a pairwise-comparison matrix for each criterion is created to enable a significance comparison. The relative significance between the criteria is evaluated from 1 to 9 indicating less important to much more important criteria, respectively. It is worth noting that pairwise comparisons and variable hierarchization in AHP result from a Delphi consensus already used in other indexed approaches (Aller et al., 1987), which is subjective (Pacheco and Fernandes, 2013). However, weighting by AHP is widely used in many applications (Valle Junior et al., 2014; Oikonomidis et al., 2015) and is recommended to be used for regional studies (Ayalew and Yamagishi, 2005).

The proposed methodology suggests a pairwise comparison, using a 7×7 matrix, where diagonal elements are equal to 1. In Table 1 the criteria of the FIGUSED method are sorted in a hierarchical manner, for the studied basin. The values of each row characterize the importance between two parameters. The first Row of the Table illustrates the importance of Flow accumulation in regard to the other parameters which are placed in the columns. For example, flow accumulation is significantly more important from geology and therefore assigned the value 7. Row describes the importance of geology. Therefore the row has the inverse values of the pairwise comparison (e.g. 1/7 for flow accumulation). More details of how Analytical Hierarchy Process is applied can be found in Saaty (1990a).

Flow accumulation has been considered the most important parameter in alignment with relevant studies (Section 1). Distance from drainage network and elevation are assigned an equal importance since flooded areas are often located in low elevation and near the drainage network. Land use and rainfall intensity were considered as the third more important parameters, although in other studies these parameters have been prioritized (Liu et al., 2003; Kourgialas and Karatzas, 2011). However, since our research examines smaller basins containing urban areas, land cover has a higher influence in flood occurrence compared to large forest or agricultural areas. In areas with diverse terrain, like the studied area, rainfall intensity is also indirectly associated to elevation. The terrain slope is somehow considered in the elevation parameter, explaining its lower importance. Geology and permeability can be of critical importance for the runoff and the occurrence of flood, especially in smaller basins with sparse vegetation (e.g. due to deforestation). Since this is not the case of the studied area, geology has been assigned a lower weight. A pairwise comparison of the criteria significance resulted to the principal eigenvalues of Table 1.

Table 2 includes the normalized values of the parameters of Table 1, their mean and eventually the corresponding weight w of each factor.

Table 1
Parameters of flood hazard: Analytical Hierarchy Process.

Parameters	Flow acc.	Drain. dist.	Elev.	Land use	Rainf. inten.	Slope	Geol.
Flow acc.	1	2	2	3	3	5	7
Drainage distance	1/2	1	1	3	3	4	6
Elevation	1/2	1	1	3	3	4	6
Land use	1/3	1/3	1/3	1	2	4	5
Rainfall intensity	1/3	1/3	1/3	1/2	1	4	5
Slope	1/5	1/4	1/4	1/4	1/4	1	3
Geology	1/7	1/6	1/6	1/5	1/5	1/3	1

Table 2
Normalized flood hazard parameters: Analytical Hierarchy Process.

Param.	Flow acc.	Drain. dist.	Elev.	Land use	Rain. int.	Slope	Geol.	Mean	w_i
Flow acc.	0.33	0.39	0.39	0.27	0.24	0.22	0.21	0.30	3.0
Drainage distance	0.17	0.20	0.20	0.27	0.24	0.18	0.18	0.21	2.1
Elevation	0.17	0.20	0.20	0.27	0.24	0.18	0.18	0.21	2.1
Land use	0.11	0.07	0.07	0.09	0.16	0.18	0.15	0.12	1.2
Rainfall intens.	0.11	0.07	0.07	0.05	0.08	0.18	0.15	0.10	1.0
Slope	0.07	0.05	0.05	0.02	0.02	0.04	0.09	0.05	0.5
Geology	0.05	0.03	0.03	0.02	0.02	0.01	0.03	0.03	0.3

2.4.1. Consistency check

Following the creation of the eigenvector matrix of the AHP, its consistency needs to be evaluated. The required level of consistency is evaluated using the following index:

$$CR = \frac{CI}{RI} \tag{2}$$

where:

CR the consistency ratio
CI the consistency index
RI the random index.

In Table 3 the values of RI are tabulated. These values are dependent on the number of criteria. In this study the criteria are seven and as a result the RI = 1.32.

AHP's theory suggests that the consistency ratio (CR) must be <0.1. CI is calculated using Eq. (3), with λ_{max} being the maximum eigenvalue of the comparison matrix and n the number of criteria. RI values are given in specific tables.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

For the values of Table 2, CI was calculated for: $\lambda_{max} = 7.66$, $n = 7$ and RI = 1.32. Eventually, the consistency ratio has been calculated CR = 0.08. Since CR's value is lower than the threshold (0.1) the weights' consistency is affirmed.

3. Application-results

In the present analysis the impermeable geological formations of the western region have also been taken into account. Thematic maps in Fig. 2 illustrate the spatial distribution of the parameters' values in the study-area that has been analyzed in the FIGUSED method.

3.1. FIGUSED parameters

3.1.1. Flow accumulation

According to the initial hypothesis and the resulting values of Table 1, flow accumulation is the most important parameter in defining flood hazard. Accumulated flow sums the water flowing down-slope into cells of the output raster. High values of accumulated flow indicate areas of concentrated flow and consequently higher flood hazard. The flow accumulation values vary in a range between 0–50,250 (Appendix A: Table 6), with the highest values occurring in the outflow

Table 3
Random index (RI) used to compute consistency ratios (CR).

N	1	2	3	4	5	6	7	8	9
Random index (RI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

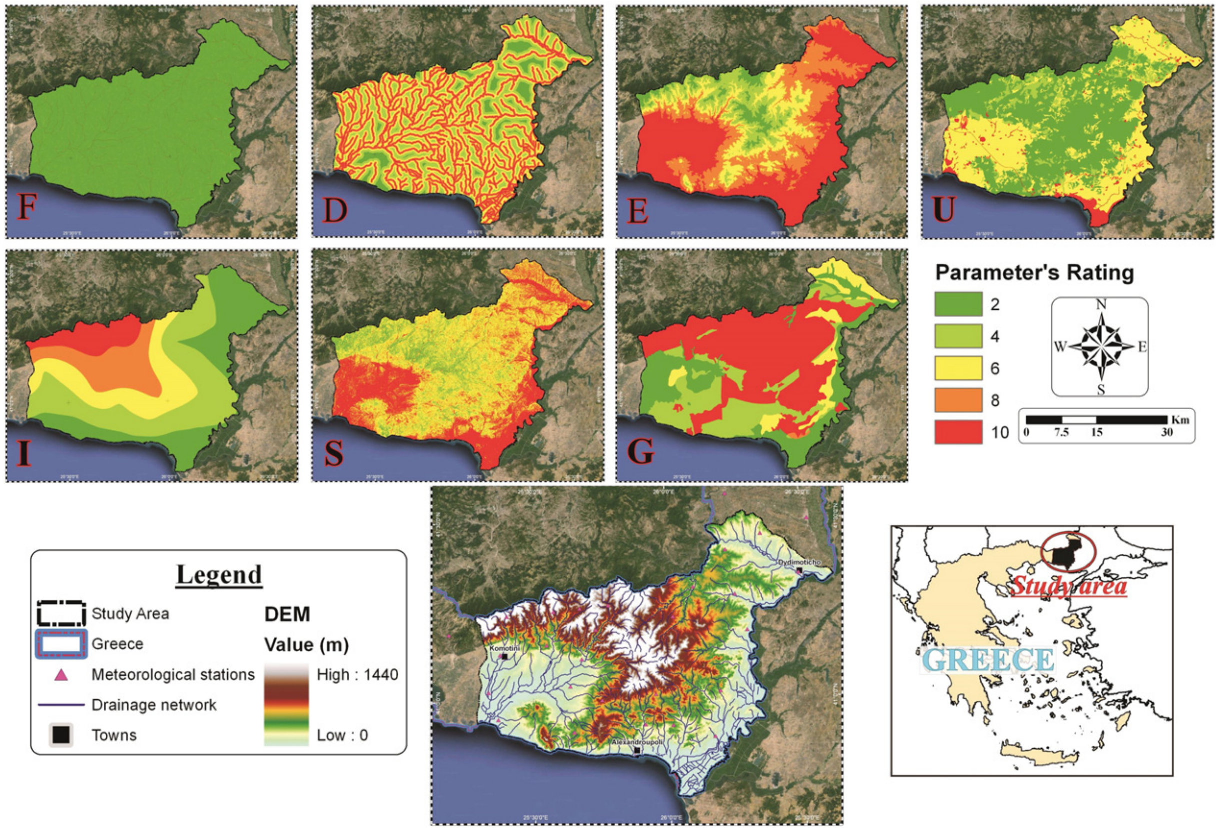

Fig. 2. Thematic maps of the FIGUSED parameters in under-study area.

of Erythropotamos and Lissos main tributaries. Lower values of this factor occur in streams of lower order.

3.1.2. Distance from drainage network

Apart from areas of concentrated surface water, river-overflows are crucial for the initiation of a flood event. Often the inundation emanates from riverbeds and expands in the surroundings. The role of riverbed decreases as the distance increases. That explains why "distance from the drainage network" has been assigned a high weight in the methodology. The classes of this criterion have been defined by processing records of historical floods in the study area. It appears that areas near the river network (<200 m) are highly flood hazard, whereas the effect of this parameter decreases in distances >2000 m (Fig. 2D).

3.1.3. Elevation and slope

Water flows from higher to lower elevations and therefore slope influences the amount of surface runoff and infiltration. Flat areas in low elevation may flood quicker than areas in higher elevation with a steeper slope. In the studied area high-elevation appears in the central and northern part, where the slope is also steeper. Naturally, low slope and low elevation have been assigned the highest rating, as prone areas (Fig. 2S & E).

3.1.4. Land use

Land use influences infiltration rate, the interrelationship between surface and groundwater as well as debris flow. Thus, while forest and lush vegetation favor infiltration, urban and pasture areas support the overland flow of water. A large proportion of the studied area is covered by mixed forests and vegetated areas which have been assigned rates equal to 2 and 4, respectively (Fig. 2U).

3.1.5. Rainfall intensity

Rainfall intensity is expressed using the modified Fournier index (MFI). MFI is the sum of the average monthly rainfall intensity at each rain gauge station. The spatial distribution of the rainfall intensity has been performed considering the allocation of stations in the studied area. Taking into account their relatively sparse set-up, the authors used the spline interpolation method, considering that a geo-statistical method would be more appropriate than ordinary kriging/co-kriging (Huang et al., 1998); (Hutchinson, 1998); (Lloyd, 2005). MFI ranges from 59 to 193 (Table 6), with the higher values located in the north-central part of the study area (Fig. 1I).

3.1.6. Geology

The geology of flood hazard areas is an important criterion, because it may amplify/extenuate the magnitude of flood events. Permeable formations favor water infiltration, throughflow and groundwater flow. On the contrary impermeable rocks, such as crystalline rock, favor surface runoff. Karst formations can also significantly affect the generation of flash floods (Bonacci et al., 2006). Therefore, karstic formations and lacustrine deposits (clays, marbles and loam) have been rated with 8 (Table 6). Lower rating has been assigned to alluvial and continental deposits due to their higher infiltration capacity.

3.2. Maps' interpolation

The proposed methodology linearly combines the selected parameters, taking into account the relative weights. This involves superimposing the thematic maps of Fig. 2 with different weights in a GIS environment. Eventually, the flood hazard map is created (Fig. 3a), defining 5 classes of flood vulnerability (very low, low, moderate, high, and very high). Classification is based on the inherent information

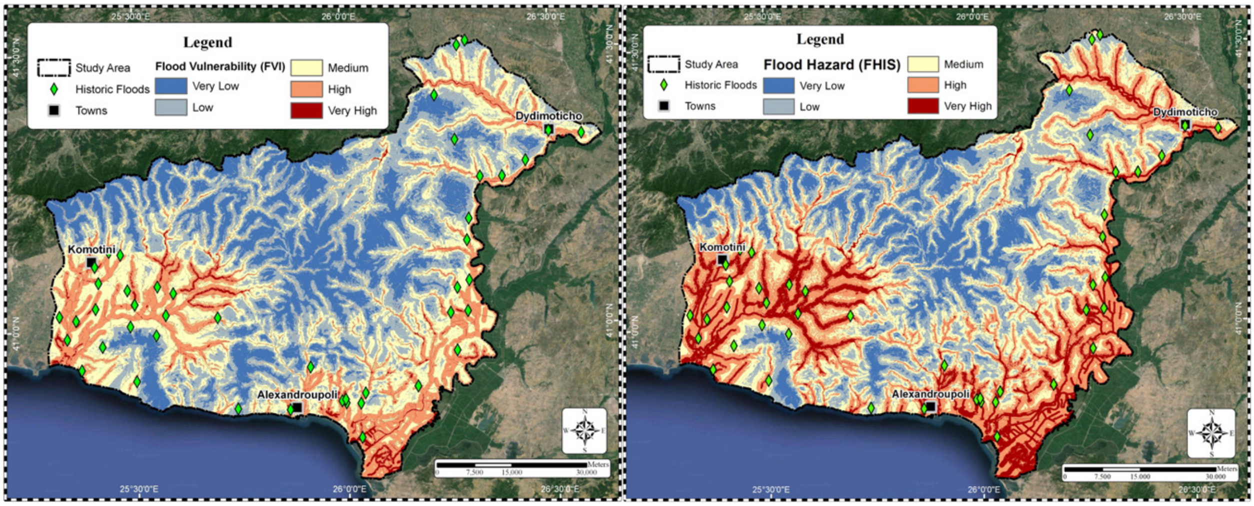

Fig. 3. Flood hazard maps: a) FHI index and b) FHIS index.

of the derived, linearly combined data. Thus, the break-points in the datasets are spotted by minimizing the variability inside each class and maximizing the variability among them, in a way similar to Statistics "Cluster Analysis". Accordingly, datasets are divided into clusters by setting boundaries where significant changes in data values appear.

The distribution of the land use in the susceptible zones to the flood in the study area is illustrated in the pie charts of Fig. 4. Accordingly, the 68% and 22% of the very high flood hazard zones are agricultural areas and urban-wetland areas, respectively. Similarly, the majority of prone zones are agricultural areas, whereas mixed forest constitutes 20% of this zone. Very low to moderate prone areas appears mainly at mixed forests and sparsely vegetated areas.

4. Validation — sensitivity analysis

The authors have coupled the FHI with a sensitivity analysis process that evaluates the impact of each criterion on the method. This helps to better understand the role of each parameter in flood risk, since sensitivity analysis elucidates the subjective significance of the various criteria, providing useful information on the influence of rating–weighting values assigned to each criterion. The technique of single-parameter analysis has been introduced by Napolitano and Fabbri (1996) to estimate aquifers' vulnerability to pollution and used in numerous studies (e.g., Napolitano, 1997; Pacheco et al., 2015; Kazakis and Voudouris, 2015), including the present study. A similar, single-

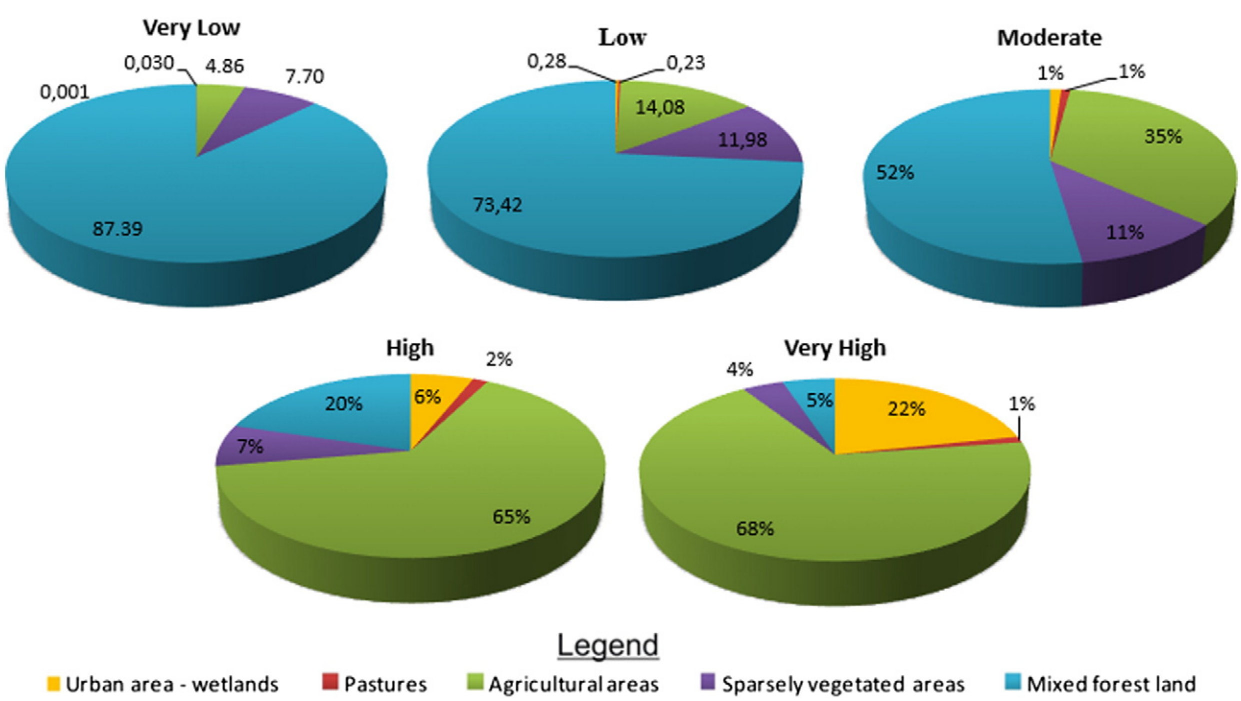

Fig. 4. Distribution of land use in flood hazard areas.

parameter sensitivity analysis has been implemented to estimate aquifers' vulnerability to pollution (Napolitano and Fabbri, 1996).

In the sensitivity analysis the initial arbitrary values of the indexes that AHP uses are replaced with some derivative indexes, the "effective weights" calculated from the following equation:

$$W = \frac{P_r \cdot P_w}{V} \cdot 100 \quad (4)$$

where:

W	the effective weight of each parameter
P_r	the parameter's rating
P_w	the parameter's weight
V	the aggregated value of the applied index

The theoretical background of the single-parameter analysis is beyond the scope of this paper and detailed description can be found in the original work of Napolitano and Fabbri (1996). The effective weights (Table 4) are then used to calculate the revised Flood Hazard Index of the Sensitivity analysis (FHIS). The FHIS index analyzes the same parameters and class rating with the FHI index, but with different weights (the average effective weight of the sensitivity analysis transformed in the scale of 10). Therefore it represents a modification of the FIGUSED method, named FIGUSED-S method (FHIS index). FHIS is, thus, estimated for a range of different values of the criteria and its comparison with the FHI shows the dependence (sensitivity) of flood on the different parameters of the FIGUSED method.

FHIS index map is illustrated in Fig. 3b and a visual comparison with Fig. 3a shows that sensitivity analysis generally coincides with the outcome of the FHI. In Table 5 a comparison between FHI and FHIS is illustrated, indicating a general under-estimation of high and very high flood hazard areas by FHI. This is also supported by the number of the historical flood events that have occurred in the high and very high flood hazard areas and have been assessed with the FHIS index. In total 71 flood events have occurred in very high flood hazard areas of FHIS index in contrast to only 4 historic flood events in the very high hazard areas of FHI index. Sensitivity analysis has revealed that very-highly and highly prone areas cover 12% and 26.8% of the total area, supporting the claim of underestimation in the initial FHI model (3% and 18%, accordingly). On the contrary, there are indications that the total coverage of areas with very-low and low susceptibility has been overestimated by FHI. Thus, instead of a large 50.3% of the total area being under very-low or low hazard, the sensitivity analysis suggests that only one third of the total area (36.8%) is less exposed to flood hazard.

On balance, the validation of the weights of the FHI index has significantly improved the reliability of the proposed methodology for the assessment of the flood hazard areas. Therefore, we propose the FHIS index expressed from Eq. (5) for the assessment of flood hazard areas. The parameters' classes of land use and geology are location-dependent and should be adjusted to the local characteristics of each studied area. Validation of the weights using single-parameter sensitivity analysis as well as reliability test using historical flood information are recommended when the method is applied for the estimation of flood hazard areas.

$$\mathrm{FHIS} = 1.2 \cdot \mathrm{F} + 0.5 \cdot \mathrm{I} + 0.4 \cdot \mathrm{G} + 0.7 \cdot \mathrm{U} + 1.6 \cdot \mathrm{S} + 3.0 \cdot \mathrm{E} + 2.5 \cdot \mathrm{D} \quad (5)$$

Table 4
Statistics of the effective weights-sensitivity analysis.

Parameters	Min	Max	Mean (μ)	SD (σ)
Flow accumulation (F)	6.6	45.9	12.0	3.2
Drainage distance (D)	6.1	50.5	25.6	7.8
Elevation (E)	7.9	51.7	30.4	7.7
Land use (U)	2.2	21.6	7.4	3.4
Rainfall intensity (I)	1.1	16.1	5.0	3.0
Slope (S)	4.3	27.3	15.5	3.9
Geology (G)	0.6	11.6	4.0	2.4

Table 5
Classes of flood hazard and number of historical flood events.

Flood hazard	FHI		FHIS	
	Area(%)	# of events	Area(%)	Number of events
Very low	20.7	0	13.7	0
Low	29.6	11	23.1	1
Medium	28.7	18	24.5	12
High	18.0	67	26.8	16
Very high	3.0	4	12.0	71

5. Discussion

The proposed methodology for the estimation of flood hazard areas can be a useful tool for the mitigation of the devastating impact of floods. Moreover, the applied validation technique that also considers historical flood events leads to the calculation of the modified FHIS index that can support the analysis. In the area under study the FHIS index has revealed the importance of tributaries and rivulets in flood events indicating the necessity to be included in flood prevention plans.

In particular the modified index (FHIS) indicates that riverbeds in the lowland are even more prone to flood, compared to the estimation of the FHI index. This claim is especially evident at the estuaries of the tributaries and rivulets, where FHI underestimates the hazard. Specifically, the sensitivity analysis includes Erythropotamos river and the surrounding area of Evros River in the class of very highly prone areas. In comparison, susceptibility at these locations was underestimated in the outcome of FHI analysis.

Records of historical flood events support the indications of the FHIS analysis through the recurrent flooding of Erythropotamos River. Furthermore, as shown in Table 5, FHIS analysis classifies as highly susceptible areaswith a high number of recorded flood events, an additional indication of accuracy.

The effective weights used in the sensitivity analysis (Table 4) reveal that elevation was underestimated in the FHI assumption. At the same time it is corroborated that geology is the least affecting parameter. Initially, FHI index considered flow accumulation as the dominant parameter. However, the sensitivity analysis concluded that elevation, distance from drainage network and slope have a bigger influence in the studied region. This interpretation has also been supported in Kourgialas and Karatzas (2011). Since rainfall intensity is associated both with the frequency and the amount of precipitation, it is crucial in identifying flood prone areas and therefore has been prioritized in several scientific studies (Ouma and Tateishi, 2014; Tehrany et al., 2014).

The comparison between the FHI and FHIS indices has revealed valuable information for the influence and the weight of each parameter in the assessment of flood hazard areas. However, the application of the FIGUSED-S method in other regions might reveal different weights and influence of each criteria in the estimation of flood hazard areas. The subjectivity of the AHP method for the estimation of the weights is the main drawback of this method. The single-parameter sensitivity analysis served as a validation technique in order to overcome this drawback. The method can be further modified using different techniques to determine the parameters' weights. It is also important to handle qualitative parameters such as geology and land use according to the specific characteristics of each region.

The present research doesn't suggest that Flood risk management is exclusively relied on static visualizations provided from index-based methods. Although these methods appear to be reliable, additional tools are needed. In urban areas, flood events can be also influenced by human behavior or operational deficiencies (roots etc.) (Cherqui et al., 2015). A detailed review by Birkholz et al. (2014) spotlighted the necessity for a re-invigoration of flood risk perception research so as to convey a more integrated understanding of how risk perceptions influence the capacity, resilience and vulnerability of individuals and communities against flood.

Accordingly, hydrological simulations under different flood scenarios can be a valuable tool, especially in areas where such data are available. An additional contribution of flood simulation models is a direct estimation of the role of the various criteria in a flood event. A further step is the estimation of the peak discharge and exceedance probability at locations where flood hazard is high/very high. In these areas depth, duration and velocity of flood should also be calculated.

A management tool has been developed in Angelidis et al. (2010), based on simulation scenarios. This tool supports flood management in the Evros River basin by simulating the operation of existing dams not only from the hydrologic viewpoint but also from the administrative one. A similar tool could also analyze smaller tributaries and rivulets of the basin also by geographically extending the analysis.

The main advantage of the proposed FIGUSED-S index is its ability to provide overall assessment of flood hazard areas. In the area under study, it successfully considers the role of torrents and tributaries. Since the role of the latter in major flood events can be significant, the construction of small dams (e.g. beaver dams) in tributaries can be an effective and sustainable measure with several side-benefits on groundwater recharge and soil erosion (Nyssen et al., 2011).

FIGUSED-S's applications can be extended to assess flood hazard zone in other areas. Its flexibility along with the provided validation by the sensitivity analysis facilitates this. Obviously, parameters can be added or removed according to local hydrogeological, hydrological and morphological characteristics.

6. Conclusions

The main aim of the present study is to develop a methodology that identifies flood prone zones and it is applicable in different regions. This is important for decision-making, because it creates a roadmap for the required flood mitigation measures.

An index-based methodology has thus been developed, named “FIGUSED” and it is expressed with the corresponding FHI index. The method spatially analyzes seven parameters, combining the information in the Flood Hazard Index (FHI). The parameters are flow accumulation (F), rainfall intensity (I), geology (G), land use (U), slope (S), elevation (E) and distance from the drainage network (D). The relative importance of each parameter is calculated by a sophisticated statistical method, the Analytic Hierarchy Process. The higher weight was assigned to flow accumulation and the lower to geology. Following that, the effect of each criterion is combined in a linear manner and their numerical superimposition results to mapping that visualizes highly prone zones.

A statistical sensitivity analysis on the values assigned to the different criteria validates the efficiency of the developed methodology. The revised weight factors and the corresponding maps are compared with those obtained in the initial hypothesis. The modified method is renamed to FIGUSED-S and is expressed with the FHIS index. In the revised index the elevation and the distance from the drainage network have the higher weights, while the lowest are assigned to rainfall intensity and the geology.

The application of the aforementioned methodology and indices in the Rhodope–Evros region has revealed the hazard areas to flood. The tributaries and torrents are pinpointed as high prone areas to flood and therefore, they might significantly contribute to flood events in the region. The reliability of the application is confirmed by the historical flood records.

The comparison of the flood hazard maps obtained with the FHI and FHIS indices indicate that FHIS index is more reliable according to the historical flood records and manages to describes better high- and very high-risk areas. Therefore, the FHIS could be applied in other regions to estimate the flood hazard areas. However, validation and reliability tests are required and the parameters of geology and land use should be adapted in the specific characteristics of the applied region of FIGUSED-S method.

Appendix A

Table 6
Classes of the parameters and according weights.

Parameters	Class	Rating	Weight
Flow accum. (pixels)	15,125–50,250	10	3
	3415–15,125	8	
	2195–3415	6	
	731–2195	4	
	0–731	2	
Distance from drainage network (m)	<200	10	2.1
	200–500	8	
	500–1000	6	
	1000–2000	4	
	>2000	2	
Elevation	0–124	10	2.1
	124–288	8	
	288–476	6	
	476–699	4	
	699–1440	2	
Land use	Urban-wetlands	10	1.2
	Pastures	8	
	Agricultural	6	
	Sparsely vegetated	4	
	Mixed forest	2	
Rainfall intensity units MFI	159–193	10	1.0
	132–159	8	
	108–132	6	
	88–108	4	
	59–88	2	
Slope (%)	0–2	10	0.5
	2–5	8	
	5–15	6	
	15–35	4	
	35–60	2	
Geology	Crystalline rocks	10	0.3
	Lacustrine, marbles	8	
	Neogene sediments	6	
	Continental deposits	4	
	Alluvial	2	

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