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GIS-Based Multi-criteria Approach Towards Sustainability of Flood-Susceptible Areas in Giofiros River Basin, Greece

A.-P. Theochari, et al. *[full author details at the end of the article]*

Abstract

This paper describes an approach for the identification of flood-susceptible areas contributing to the sustainability of these in the Giofiros river basin covering an area of 184 km^2, located in Southern Greece. This basin is prone to flooding with devastating consequences on people, environment, and the economy. In this context, a geographic information system (GIS)–based multi-criteria decision analysis (MCDA) method for the identification of potential flood-prone areas at basin scale is initially presented. Upstream of the very high flood–susceptible areas of a simulated point is selected, which is the outlet of the created subbasin (169 km^2). In this area, a hydrological analysis is conducted based on the unit hydrograph (UH) theory simulating the rainfall-runoff process. The UH is calculated by applying three different methods: the time-area diagram method into the GIS environment, the Soil Conservation Service (SCS) UH, and the Snyder synthetic UH. The results show that the two last methods underestimate the flood peak in relation to the results of the time-area diagram method. The hydrological analysis is completed through Hydrologic Modeling System (HEC-HMS) software from which three flood hydrographs are produced. The flood hydrograph calculated using the time-area diagram method is imported into the River Analysis System (HEC-RAS) software in order for a hydraulic simulation to be performed. The simulation output resulted in flood hazard mapping with the maximum depth and maximum velocity along the simulated section of the mainstream downstream of the simulated point. The results of this approach appear to be extremely useful for preventing flood disaster and making disaster mitigation plans.

Keywords Flood-susceptible areas · GIS-based multi-criteria decision analysis · Time-area diagram · Flood hazard map

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Introduction

The occurrence of extreme flood events is among Earth's most common and most destructive natural hazards due to the devastating consequences on both individuals and communities, e.g., social, economic, and environmental consequences. In Europe, overall losses as a consequence of floods have been increased over the last few decades [1]. Therefore, improvements in analysis, mitigation, and management are required for dealing with protection against flood's negative consequences [2–4]. In this context, European Union (EU) enacted the Directive 2007/60/EC on the assessment and management of flood risks [5]. According to the framework of this Directive, every EU Member is required to carry out a preliminary assessment, so that river basins and associated coastal areas that are at risk of flooding are identified. For such zones, flood risk maps should be drawn up and flood risk management plans should be established with a view to avoiding and reducing the adverse impacts of floods.

The detection for the flood-susceptible areas in the present study is considered to be the combination of the flood potential factor and the vulnerability factor. The growing magnitude of flood hazard and augmented vulnerabilities has uplifted the flood risk [6]. Flood potential factor can be represented as a combination of a set of geomorphological, technical, and generally spatial criteria. On the other hand, vulnerability factor measurement is influenced by several environmental, economic, and social or even political elements [7]. Additionally, environmental and economic aspects can be considered, resulting in a variety of research perspectives and term definitions [4]. These complex decision problems can be examined on the basis of multiple criteria and can be settled using MCDA methods in conjunction with GIS tools [8]. The framework for flood-susceptible area mapping using the analytic hierarchy process (AHP) decision-making technique for the combination of a flood-related criteria set is widely adopted. Various studies have implemented AHP, Fuzzy AHP, or GIS modeling techniques for the estimation of flood-prone areas, flood risk, flood hazard, and other natural disasters [1, 9–16]. Regarding the flood hazard mapping towards sustainability of flood-susceptible areas, there are two main types of quantitative models, advanced hydrologic and hydraulic models, which estimate flood peaks and volumes, and the propagation in time and space of the flood wave into the river banks and over the floodplains. The hydrologic model focuses mostly on the line-type distribution of floods [16]. The hydraulic model mainly explores flood routing problems of watercourses and flood risk zones [17]. In terms of exploring the concept of flood susceptibility and behavior a large spectrum of studies have been performed, e.g., [18, 19].

The aim of this paper is the identification of potential flood-prone areas and the flood hazard mapping at the ungauged Giofiros river basin of north-western Heraklion in Southern Greece (Fig. 1). The basin has a total area of 184 km^2, and the main watercourse has a length of about 35 km. It is located between the longitude 24°54′E–25°11′E and the latitude 35°6′N–35°2′N. According to the geomorphological analysis performed for the basin, elevation ranges from 0 to 915 m with mean elevation of 331 m and the mean slope is 17°. The mean annual rainfall is approximately 485 mm while the mean annual temperature varies from 14.8°C to 21.9°C, as it was measured from the weather station of Heraklion. The predominant land cover type according to Corine Land Cover (CLC) classification (2018) [20] is permanently agricultural land (86.73%).

The study area frequently suffers from intense sudden rainfall with severe consequences in human lives and both private and public properties. In this regard, application of GIS-based
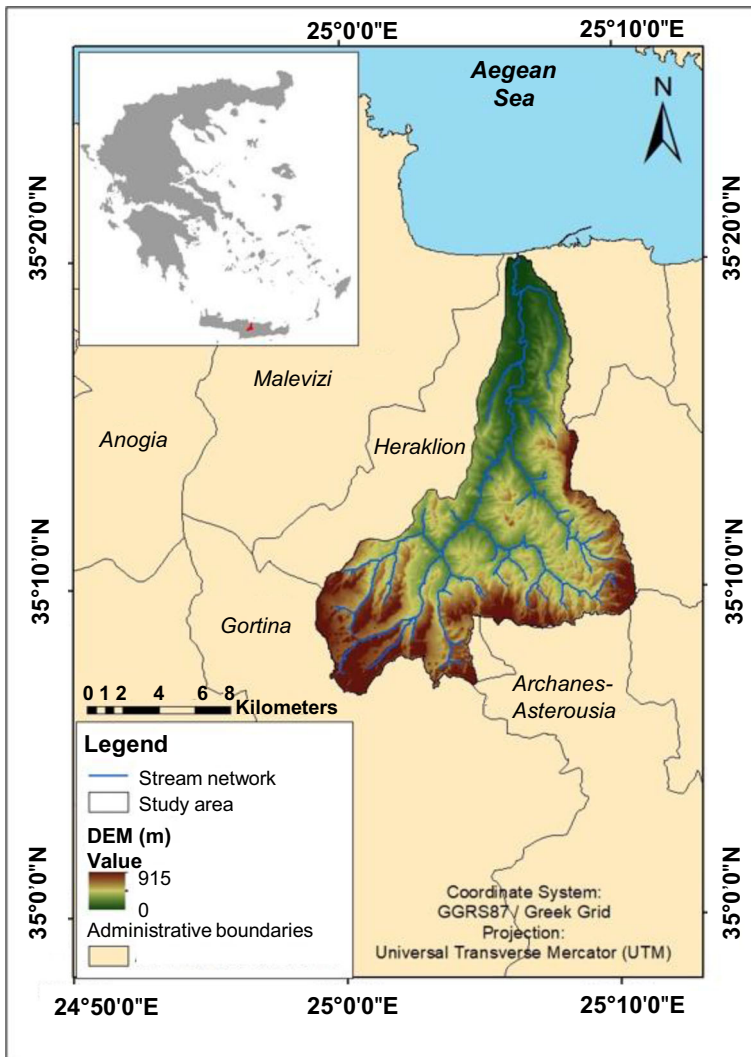
Fig. 1 The Giofiros river basin and its location in Greece

MCDA framework in a GIS environment for the identification of potential flood-prone areas at basin scale is highly required. Given the areas that are very high flood susceptible, hydrological analysis is carried out within the GIS environment and by utilizing HEC-HMS software, based on the UH theory, applying the time-area diagram method for rainfall-runoff process simulation at subbasin scale. Finally, hydraulic simulation is performed with the objective of producing the flood hazard map utilizing HEC-RAS software. The output of such an approach is flood-susceptible area map and flood hazard map that provides valuable findings for the integrated flood risk estimation, forecasting, and management contributing to environmental sustainability. Sustainability is an ecological concept and environmental development concerned with environmental stewardship, economic growth, and social justice, which are essential factors to characterize sustainable organizational development [21]. The issue of

the current paper concerns environmental sustainability as a spatial decision problem, which involves decision-makers in order to identify locations susceptible to flooding and assess flood hazard mapping. The results indicate the magnitude of flood heavily impacts the built environment (e.g., property loss, building damages) and the productive sector (e.g., agricultural activities) contributing to the circular economy issues. Organizational development of a generalized flood protection scheme (e.g., prioritizing flood defense works or laying out a flood protection master plan) has some basic constituents such as recognition and identification in an organizational diagnosis of the current situation and problems to be solved and improved [21].

Methodological Framework

GIS-Based MCDA Approach

MCDA is a useful tool that is used to evaluate a series of various possible alternatives of a complex problem comparing multiple criteria and ranking them from the most to the least important ending up with the optimum alternative. According to Malczewski [22, 23], the decision problems that include geographic data are referred to as geographic or spatial decision problems. Regarding the problem that needs to be addressed in this paper, instead of different alternatives, it is space itself that is being evaluated based on its susceptibility to flooding. In this approach, decision-makers, i.e., authors, use MCDA that includes the criteria selection taking into account environmental and social conditions within a sustainability context, the criteria standardization process, and the determination of the corresponding criteria's weights through the AHP method, which is proposed by Saaty [24]. The criteria are combined using the weighted linear combination (WLC) technique resulting in a flood-susceptible area map. The analysis is performed in a pixel size equal to 5 m × 5 m. This map is considered to be the product of the flood potential factor and the vulnerability factor combination. Flood potential factor is represented by five different criteria, which are expressed through GIS applications. These criteria are standardized through a linear transformation as shown in Eq. 1 when the maximum value of the criterion corresponds to the very high flood hazard and Eq. 2 when the maximum value corresponds to the very low flood hazard through the ArcGIS software [25], using a Map Algebra expression (Eqs. 1, 2) in Raster Calculator. Voogd [26] reviewed a variety of standardization processes usually using minimum and maximum values as scaling points [8].

$$x_i = \frac{(FV_i - FV_{\min})}{(FV_{\max} - FV_{\min})} \cdot SR \qquad (1)$$

$$x_i = 1 - \frac{(FV_i - FV_{\min})}{(FV_{\max} - FV_{\min})} \cdot SR \qquad (2)$$

where $FV_{\min}$ and $FV_{\max}$ are respectively the minimum and maximum values of the criteria, FV_i is the value of each raster cell, which then corresponds to the standardized value xi, and SR is the standardized range, i.e., 0–1.

The first criterion is the "rainfall" (C1), which is implemented using spatial data for the location of meteorological stations in the Water Department of Crete as well as data for the intensity-duration-frequency (IDF) curves from the Ministry of Environment and Energy. The IDF parameters are determined in the frame of the implementation of the 2007/60/EC directive. Based on IDF curves, the rainfall intensity of 24 h is calculated for each station for a return period of 20 years. Return period is determined through the IDF curves that are available for various stations in the region. Given the intensity, the rainfall depth is calculated and the resulting data is embedded as a point feature class in GIS. To create a surface grid in ArcGIS, the Spatial Analyst extension employs several interpolation tools. In this study, the Kriging interpolation method is performed for spatial interpolation of rainfall data. The C1 presents the flood potential on high rainfall depth; the higher the depth is, the higher flood potential the areas get, consequently it is standardized through Eq. 1. The second criterion concerns the "slope criterion" (C2) and denotes the flood has a high probability of occurrence on gently sloping terrain; the lower the slope is, the higher flood potential the areas get (Eq. 2). The slopes of the basin are created using the digital elevation model (DEM), which is obtained by the National Cadastre & Mapping Agency of Greece. The dataset pixel size is 5 m × 5 m, its geometric accuracy RMSE is $z \leq 2.00$ m, and the absolute accuracy is about 3.92 m for a 95% confidence level. The third criterion is the "imperviousness" (C3) which is implemented through the spatial information of CLC (2018). Different land cover categories are assigned different values for impervious surface coefficient, into a single grading scale, i.e., between 0 and 1. The C3 has very high values of potential flood on high imperviousness values and it is standardized through Eq. 1. The fourth criterion is the "elevation" (C4), which is expressed by standardizing the raster file DEM with the aid of Eq. 2, as very low values of elevation favor very high values of potential flood. Finally, the Euclidean distance across the mainstream is calculated in order to express the fifth criterion "distance from mainstream" (C5). The Euclidean distance is standardized through Eq. 2; the lower the value of the distance is, the higher flood potential the areas get.

Then, the methods of determining the relevant weights and combination of the criteria are selected from decision-makers. The AHP method is applied to calculate the criteria's weights. AHP is a multi-criteria decision method that uses hierarchical structures to represent a problem and, then, develops priorities for alternatives based on the judgment of the user [27]. It is a procedure based on the idea of pairwise comparisons of different criteria using the fundamental comparison scale introduced by Saaty [24] between 1 (equally significant) and 9 (absolutely more significant). The resulting weighting factors are verified with the Consistency Ratio (CR) approach according to which CR should not overcome 10% [24]. Regarding the combination of standardized criteria, in order to produce the flood-susceptible area map, the WLC technique is implemented. This process requires an aggregation of the weighted criteria and it is incorporated into the GIS environment. The vulnerability factor is represented by two different aspects (criteria): social and economic. In terms of social vulnerability, it is implemented through a file [28] that provides an estimate of energy consumption by households. The criterion presents the flood vulnerability on high energy consumption; the higher the consumption is, the higher flood vulnerability the areas get, so it is standardized through Eq. 1. The economic criterion describes the potential financial losses from possible flooding, and its implementation is conducted with the aid of spatial information of the CLC map. Different land cover categories are assigned different values for potential cost into a single grading scale, i.e., between 0 and 1. The higher the value is, the higher flood vulnerability the areas get, so it is standardized through Eq. 1. The flood-

susceptible area mapping is calculated as the semi-sum of the flood potential factor and vulnerability factor.

Hydrological Analysis and Hydraulic Simulation

The GIS-based MCDA approach resulted in producing of the flood-susceptible area mapping, with the assistance of which a simulation point across the mainstream upstream of very high flood–susceptible areas is selected. A subbasin is created upstream of the simulation point through HEC-GeoHMS within the Giofiros river basin. For the subbasin, a hydrological analysis is performed, which is based on the UH theory. In order to determine the UH, the time-area diagram method is applied mainly executed in the GIS environment. The time-area methods were developed in order for rainfall on runoff to be time distributed [29]. Derivation of the time-area diagram requires knowledge of the soil roughness, the terrain slope, and the distribution of flow directions and velocities over the watershed [30]. For the production of UH, the rainfall of unit depth (10 mm) is multiplied by the dimensions of each cell (5 m × 5 m) and, then, by the number of cells that result for each time step. The hydrological analysis is completed in the HEC-HMS environment. HEC-HMS is a widely used software developed by the U.S. Army Corps of Engineers, which performs rainfall-runoff simulations with the use of preselected sub-models [31]. The necessary input data for HEC-HMS are the UH, which is produced from the time-area diagram method, and rainfall data (design hyetograph) in order to estimate the discharge at the outlet of the subbasin, hence creating the corresponding flood hydrograph. The calculation of design hyetograph is performed through the parameters of the IDF curve for the Heraklion hydrometeorological station. The rainfall intensity is calculated by applying this IDF curve using a return period of 100 years and precipitation duration of 12 h.

Time distribution is an important factor that can affect the results of the rainfall-runoff analysis [32]. The time distribution of the design hyetograph is calculated by applying the alternating block method. This method is producing the rainfall temporal distribution (design hyetograph) through the rainfall IDF curve. Subsequently, other than the time-area diagram method for UH calculation, another two methods are being applied: SCS UH method and Snyder synthetic UH method. The application of them requires as input data into HEC-HMS the design hyetograph and also the lag time in case of the SCS UH method, while the standard lag and peaking coefficient in the case of the Snyder synthetic UH method are also required. Adopting the method of SCS UH, the peak discharge and the time to peak are determined in accordance with [33–38]. In the Snyder synthetic UH method, the standard lag is estimated from the center of the active rainfall gravity to the peak of the flood hydrograph. The peaking coefficient (Cp) is accounting for flood wave and storage conditions. Values of Cp range from 0.3 to 0.93 [39] with an average of 0.60 being assumed for the study subbasin. Regarding the hydrological losses, they are assumed to be constant (3 mm/h in this study) in all three methods. The results of hydrological analysis applying the three aforementioned methods are three flood hydrographs.

In the context of the sustainability of flood-susceptible areas, hydraulic simulation is attempted in the position downstream of the simulation point through HEC-RAS 5.0.7, which is one of the recognized spatial hydrological models used for channel flow analysis and floodplain delineation developed by the US Army [40, 41]. More specifically, a 2D hydrodynamic unsteady flow analysis is conducted. HEC-RAS is a freeware hydraulic model which can be used for one-dimensional steady and unsteady flow hydraulics computations. Regarding unsteady flow computations, Saint-Venant equations' numerical solution is approximated

using an implicit finite difference approach through the computational box scheme [42]. During the model building setup, the CLC (2018) is used to determine the land characteristics and the Manning roughness coefficient that is estimated according to the global literature, e.g., [43, 44]. As an upper boundary condition, the corresponding flood hydrograph as calculated in a previous stage is used. Finally, a flood hazard map for the maximum depth and maximum velocity is produced for the resulting floodplain area.

Results and Discussion

According to the GIS-based MCDA approach described in the above section for the identification of potential flood-prone areas within the Giofiros river basin, it is observed that the approach is affected by the process of criteria selection, standardization method used for criteria's values transformation into a common scale, the determination of the corresponding criteria's weights, and the weighted combination technique used. More specifically, the above methodology is implemented using only the specific criteria selected from the decision-makers. However, there are some more criteria concerning flood potential factors (e.g., soil type, vegetation) that can be selected for the analysis. Additionally, regarding the vulnerability factor, other decision-makers can also consider the environmental aspect as an additional criterion. Therefore, the criteria selection affects the result as flood-prone area identification depends on this selection. The standardization method can also affect the approach as there is a variety of different standardization processes (e.g., linear transformation, classification method). The linear transformation used in the current analysis uses the minimum and maximum values as scaling points, while the classification method reduces the variance within classes and maximizes the variance between classes [8]. Regarding the determination of the corresponding criteria's weights and the weighted combination technique used, they are based on the pairwise comparison by decision-makers, so the subjectivity of the process is evaluated. In this analysis, for flood potential factor determination, only the criteria that can be expressed into the GIS environment are considered and the calculation of their weights is based on the pairwise comparison matrix, which is constructed by comparing the relative importance per pair of criteria. According to this comparison that may involve a degree of subjectivity, the higher importance of increasing the level of potential flood is attributed to the weights of "imperviousness" and "distance from mainstream" criteria. Hence, flood-prone area identification depends mainly on these two criteria. It is also noted that in the present analysis, the two criteria of vulnerability are equal; therefore, 50% is assigned to each weight. The combination of all the standardized criteria is achieved using the WLC, with a result of the final maps that depict the flood potential factor and vulnerability factor within basin scale, as shown in Fig. 2a, b, respectively. The semi-sum of these two factors produces the flood-susceptible area map that is presented in Fig. 2c. In order to classify the flood susceptibility, the manual clustering technique is applied in the ArcGIS environment and five classes are determined: (1) very low, (2) low, (3) medium, (4) high, (5) very high. This is a method that influences significantly the flood-susceptible area mapping and is affected by the applied thresholds. Setting stricter thresholds in the high-risk class, areas that are prone to high flooding are limited leading to an underestimation of the real spatial distribution of the flood susceptibility. Conversely, broadening the thresholds of the most prone areas is extended to a larger scale. For this reason, the standardized flood-susceptible area map (single grading scale between 0 and 1) in this paper is classified manually equally in five

classes, i.e., 0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1, in order for a mean situation of flood-susceptible area mapping to be calculated. According to Fig. 2, one can see that the basin presents high or very high flood susceptibility in the largest area and the most prone areas are located downstream on the north. This is attributed not only to the fact that in this part of the basin there are many factors that increase flood susceptibility, such as low slopes, low altitude, and high impermeability due to urban land, but also to the increased social and economic vulnerability that exists, since the area is the most inhabited. Moreover, the lowest flood susceptibility occurs in the south and especially in the southwest. That can be explained by the fact that even though the rainfall is extremely high at this zone, all other criteria contribute to a low flood susceptibility evaluation (high elevation, high slopes, low imperviousness as a result of the vegetation, and low vulnerability both economically and socially). Apart from the north, there are also few areas that are characterized as high and very high flood susceptibility. These areas concern settlements which increase the vulnerability of the examined area, since they affect both the economic and the social part, and have high imperviousness. Such examples are the settlements of Krousonas, Tylissos, and Kato Asites located in the river basin of Giofiros. It is obvious as an overall conclusion that land uses have an important contribution to the mapping result because they affect both economic vulnerability and the criterion of imperviousness, so they have a participation weight in the final map of more than 25%.

Taking into account the very high flood–susceptible area resulting from the GIS-based MCDA approach, a simulation point across the mainstream upstream of these areas is selected in order for a subbasin upstream of it to be created. In subbasin that covers an area of 169 km^2, a hydrological analysis is applied in order to simulate the rainfall-runoff model. For the subbasin, the UH is determined using the time-area histogram method through the GIS techniques by creating the corresponding time-area histogram and calculating the maximum peak discharge on 98.3 m^3/s. The duration of UH base time is 9 h and the peak time reaches 3 h. Additionally, for the rainfall-runoff transformation other than the time-area methods, the Snyder synthetic hydrograph and SCS UH are used, while the calculation of design hyetograph is performed using a return period of 100 years and duration of 12-h precipitation. The integration of all the above data in HEC-HMS has as a result three different flood hydrographs, each one using a different method. By comparing the resulting hydrographs, the time-area
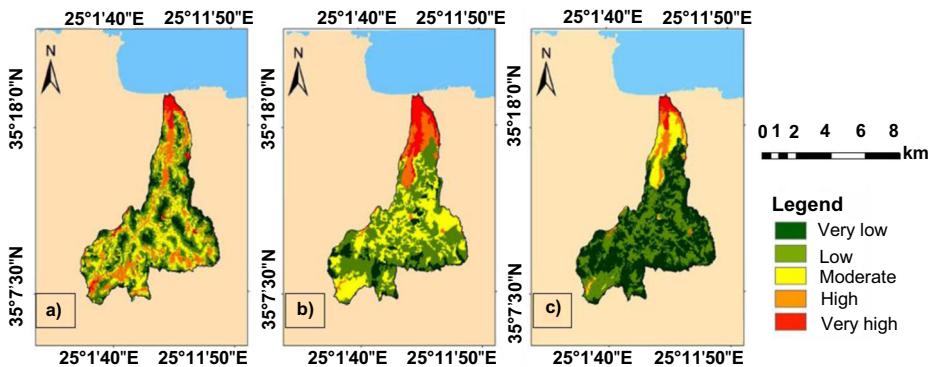

Fig. 2 The flood potential factor (**a**), vulnerability factor (**b**), and flood-susceptible area map (**c**) in Giofiros river basin

method produces a flood hydrograph with the highest peak discharge and that value occurs earlier than according to the other two models. More specifically, peak discharge is estimated at 676.2 m³/s and occurs at 8 h according to the method of time-area diagram method, while according to Snyder synthetic hydrograph and SCS UH methods, the peak appears at 13 h and the peak flow is estimated at 287.1 m³/s and 334.1 m³/s respectively. Regarding the comparison between SCS and Snyder methods, the former presents a larger discharge peak but remains in the same order of magnitude. From the above, it can be concluded that the SCS and Snyder methods underestimate the peak discharge. In contrast, the method of time-area diagram can use more data and is more time consuming, but it calculates the UH in a detailed way, which allows the designer to intervene in the method and adjust the variables for the optimal description of the rainfall-runoff model. It is assumed that the results of the time-area method are more reliable. For this reason, the hydraulic simulation in the present case study has as input the flood hydrograph as obtained from this method.

The hydraulic simulation is conducted downstream of the simulation point through HEC-RAS 5.0.7. The flood hydrograph is imported as an upper boundary condition in the HEC-RAS 2D model. The terrain, the stream network, and the land use are also imported. The terrain is defined by the DEM of 5 m × 5 m pixel size resolution, and the land use layer is based on the CLC (2018) shapefile in order to integrate Manning's roughness coefficient. In Fig. 3, the resulting floodplain area map (flood hazard map) with the maximum depth and maximum velocity along the simulated section of the mainstream is shown. It is obvious that alongside, generally relatively low flow velocities emerged apart from the main river. From the hydraulic simulation, it turns out that Giofiros stream has a wide floodplain and even at high depths, so such an overflowing can cause great damage, since within the reclining field, there is not only the settlement of Finikia with a population of 824 inhabitants and several agricultural holdings in the area (e.g., greenhouses), but also the infrastructure of the waste-water treatment plant of Heraklion. In relation to hydraulic simulation, it is worth noting the importance of data quality for extracting reliable results. Specifically, the analysis of DEM can affect the results, since a rough DEM that fails to accurately describe the geometry of the watercourse may lead to serious errors. Furthermore, flood wave transition is intensively influenced by the floodplain topography, as inaccurately defined by the DEM. Finally, the soil roughness coefficient (Manning coefficient) can significantly affect the hydraulic simulation results. There is rich literature on value performance, which suggests a wide range of
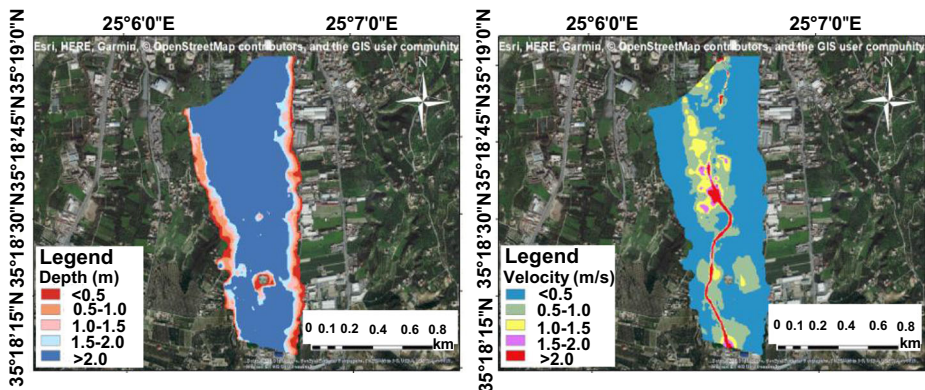

Fig. 3 Flood hazard map of Giofiros river subbasin (maximum depth and velocity)

coefficient values. The final choice of value is left to the designer, who can decisively affect the results.

Conclusions

This paper presents a GIS-based MCDA approach for the identification of potential flood-prone area and flood hazard map assessment through hydrological analysis and hydraulic simulation at an ungauged river basin of north-western Heraklion in Greece towards sustainability of flood-susceptible areas. It is initially concluded that MCDA is a useful tool for the preliminary assessment of variability in the flood susceptibility within the basin scale. The results indicate to the designer those locations which have increased susceptibility to flooding in order to be more detailed analyzed with hydrological and hydraulic tools. It is obvious from the analysis that land uses have an important contribution to the mapping result because they affect both economic vulnerability and the criterion of imperviousness. Regarding the hydrological analysis, it emerged that the application of the time-area method is considered satisfactory for the production of UH. The other two methods are considered to underestimate the flood peak and show a time lag in the flood peak in relation to the results of the time-area method. The accuracy of the hydraulic simulation results depends not only on the accuracy and precision of the data used, but also on the soil roughness coefficient (Manning coefficient). Land cover is a decisive factor for the production of flood-susceptible area map and flood hazard map, since it affects the final result in a number of ways in all stages of application. As an overall conclusion, the aforementioned methodology can contribute to the environmental sustainability and therefore in circular economy, as the flood-prone areas are identified and finally the flood hazard map is assessed, resulting in organizational development of a flood protection scheme. Regarding future research, a detailed sensitivity analysis for all criteria will be of interest as it may contribute to the evaluation of the impact of each criterion in the whole process. Furthermore, other studies can also conduct hydrological analysis for historic rainfall events inducing flood and carry out a hydraulic simulation for the most severe rainfall event. Finally, the implementation of the entire methodology at different basins with different characteristics will be of value for comparison reasons.

Abbreviations   *GIS,* geographic information system; *MCDA,* multi-criteria decision analysis; *UH,* unit hydrograph; *SCS,* Soil Conservation Service; *HEC-HMS,* Hydrologic Modeling System; *HEC-RAS,* River Analysis System; *EU,* European Union; *AHP,* analytic hierarchy process; *CLC,* Corine Land Cover classification; *WLC,* weighted linear combination; *IDF,* intensity-duration-frequency; *DEM,* digital elevation model; *CR,* Consistency Ratio approach; *Cp,* peaking coefficient

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Marina Develekou. The first draft of the manuscript was written by Aimilia-Panagiota Theochari, and all authors commented on previous versions of the manuscript. Review and editing were performed by Aimilia-Panagiota Theochari. Supervision, validation, final review, and editing were performed by Evangelos Baltas. All authors read and approved the final manuscript.

Declarations

Conflict of Interest The author declares no competing interest.

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Affiliations

A.-P. Theochari[1] · M. Develekou[1] · E. Baltas[1]

✉ A.-P. Theochari
   atheochari@chi.civil.ntua.gr

1 Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, 5 Iroon Polytechniou, 157 80 Athens, Greece