

Hydrometeorological - hydrometric station network design using multicriteria decision analysis and GIS techniques

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Research Article

Keywords: hydrometeorological station network, hydrometric station network, multi-criteria decision making, GIS, Sarantapotamos

DOI: <https://doi.org/10.21203/rs.3.rs-278188/v1>

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Abstract

The design of an optimum hydrometeorological and hydrometric station network constitutes a key factor for the collection of comprehensive and reliable hydrometeorological and flow data that are necessary both for decision making in water resources policy and management and for the hydrometeorological risk assessment. This article describes a methodology developed in a geographic information system (GIS) assisted by a multicriteria decision making (MCDM) approach, which combines a set of spatial criteria in order to propose suitable locations for such a station network installation. Through the design for two networks that meet different requirements, various aspects concerning this methodology are illustrated, such as, the methods regarding criteria classification and weighting, as well as, the effect of weighting itself on the location rating. In particular, the implementation is performed for the Sarantapotamos river basin, an area located in the western part of Attica region, Greece, which is characterized by a great diversity of economic activities, mainly industrial, rural and urban fabric in the lowlands. Finally, the analysis indicates that, in terms of station density as proposed by the World Meteorological Organization (WMO), the optimum hydrometeorological station network consists of three stations and the hydrometric one of two stations.

1 Introduction

With the aim of improving the efficient and equitable management of water resources and shielding against the effects of floods, hydrometeorological and hydrological network design is a key component with a decisive contribution toward the collection of comprehensive and reliable data. Data are the life blood of hydrological models and the heart of the systems, which can simulate river flow conditions upon which good water management decisions can be made (Stephenson and Petersen 1991). Information of rainfall is the primary requirement of all flood forecasting models (Kar et al. 2015), while accurate and reliable spatiotemporal estimates of precipitation are crucial to the successful prediction of a catchment's hydrological response and are particularly important in the case of flooding (Volkman et al. 2010). Hydrological data are needed for planning, decision making, and operation and management of water resources systems (Xu et al. 2017). Therefore, data collection is important to yield hydrological information for different purposes, including spatial planning, design and management of water resources and related activities, which enable informed decision-making (WMO 2008a).

In order to obtain accurate hydrometeorological measurements, the operation of well-organized networks with a proper density of hydrometeorological and hydrometric stations is required. The design of such networks has received considerable attention since the 1970s (Mishra and Coulibaly 2009). Since then, various techniques have been developed for the design of an optimum hydrometeorological station network for different purposes (e.g., Kuhn and Tucker 1951; Fujioka 1986; Sestak 1988; Shepherd et al. 2004; Barca et al. 2008; Baltas and Mimikou 2009; Hong et al. 2016; Kemeridis et al. 2017; Feloni et al. 2018). Furthermore, the WMO (WMO 2008b; 2010) has thoroughly investigated the development and dissemination of technology for the design of hydrometeorological data networks. For designing a stream gauging network, various approaches recommended, all of which contribute to the indication of

proper sites that are then evaluated in situ, instead of the time-consuming field exploration for site selection (e.g., Hong et al. 2016; Feloni et al. 2018; Theochari et al. 2019). Regarding methodologies applied for the network design, optimization approaches are increasingly used in network design, since optimally locating hydrometric stations can be seen as a multiobjective optimization problem where several criteria need to be satisfied simultaneously (Li et al. 2012). The advantage of multiobjective optimization and multicriteria analysis (MCA) is their provision of different feasible solutions under different scenarios (Alfonso et al. 2010), and this capability is significant for a variety of applications such as the soil erosion estimation (e.g., Roy 2019), and generally for applications incorporating surface characteristics and land use planning (e.g., Hill et al. 2009). Especially for studies relevant to station network design, Volkmann et al. (2010) postulate the need for optimization methods in regions where guidelines cannot be applied with confidence *a priori*. In recent years, GIS have been increasingly used in network design, particularly as a complementary tool in MCA, as reported by Huang et al. (2011). With the rapid development of computer technologies, GIS technology is an ideal tool for spatial analysis due to its ability to manage large volumes of spatial data from a variety of sources (Karimi et al. 2016). GIS analysis provides a complete set of feasible locations based on geographical criteria; the users' needs, various distances, the land use distribution, the terrain slope, elevation, etc. The capacity of GIS to integrate spatial information make them well-suited for decision-making procedures that have to account for multiple factors (Shepherd et al. 2004).

The necessity for the design and construction of a network of comprehensive measuring stations is profound in countries such as Greece, where the complex topography and the unequal distribution of water resources between the eastern and the western parts of the country are characteristic. Especially for the regime in Greece, the existing station network has many disadvantages (Baltas and Mimikou 2009), as due to the particular geomorphological and climatic factors, it is difficult to design a representative network capturing the different local characteristics to an adequate degree, while, at the same time, there are various local or national networks that are supervised by a large number of agencies (e.g., the National Meteorological Service; the National Athens Observatory; Ministries and Universities, etc.) and, consequently, each network serves different purposes. In order to monitor the meteorological and hydrological properties of Athens, the Department of Water Resources, Hydraulic and Maritime Engineering, School of Civil Engineering, National Technical University of Athens (NTUA), has installed a network of meteorological and flow measurement stations, and a Joss-Walvogel RD-69 disdrometer (JWD) (Baltas et al. 2015). Baltas and Mimikou (2009) demonstrated the optimization of the existing national network of about 1041 station with the use of GIS methods. Furthermore, recently, Feloni et al. (2018) suggested a multicriteria GIS-based approach for the optimization of a regional station network in the region of Florina in Northern Greece, both for the development of an up-to-date real time flood warning system and for water resources management for agricultural purposes. Finally, Theochari et al. (2019) proposed a method for evaluating eligible sites for stream gauge installation for various scenarios depending on the network purposes, i.e., water resources management; flood warning systems, through a case study for a rural basin in West Attica (Central Greece).

The present research work is intended to assist in designing networks according to a GIS-based methodology that incorporates MCDM. The latter technique is performed with the aim of combining a set of proposed geomorphological, technical and generally various spatial criteria, as selected considering available guidelines separately for the hydrometeorological and hydrometric station network design, using the Analytic Hierarchy Process (AHP) for the determination of the criteria's weights and the linear scaling for the standardisation of the criteria's values. The whole methodology is presented through a case study for the Sarandapotamos river basin. Geographically this area extends across the administrative boundaries of three municipalities; Mandra-Eidyllia, Elefsina and Tanagra, located in the regional unit of West Attica, Central Greece (Fig. 1). This particular area was selected as it is highly flood-prone and, therefore, requires comprehensive monitoring of hydrological and hydrometeorological parameters at a river basin level. Mandra settlement is characterized by severe historic floods, due to extreme rainfall that typically show high intensities for small temporal scales, compared to other parts of the country, in combination with its location in the outlet of two small watersheds and the existence of urban fabric in the lowlands. In recent years, severe floods have been recorded in the region, with the deadly one in November 2017, marked by the loss of 24 people (Feloni, 2019). The basin corresponds to a total area of 341 km² and is surrounded by Mount Pateras (west), Mount Parnitha (east), Mount Kitheronas (northwest) and Mount Pastra to the north. Sarantapotamos River flows along the valley of Inoi and the Thriassion basin up to the bay of Elefsina. The average annual rainfall varies from 300 mm to 400 mm, while the average annual temperature is between 17°C and 19°C (Baltas 2008). Today in the area there does not exist any uniform station network. Nevertheless, due to a catastrophic flood event that occurred in the area on November 15, 2017, the establishment of telemetric hydrometeorological stations in three critical locations has recently completed under the research activities of the FloodHub service of the Center for Earth Observation and Satellite Remote Sensing Sciences of the National Observatory of Athens (NOA 2020).

2 Methodological Framework

This section describes a GIS-based multicriteria decision analysis approach that is proposed for the hydrometeorological and hydrometric station network design and establishment. The selection of proper locations for the installation of stations is a spatial decision problem, in which decision-makers use MCDM to combine criteria for getting the locations scores. The main steps of the analysis include the selection of the criteria, which are taken into account for the network design, the computation of their standardized values, and the calculation of the weight of each criterion by using the AHP procedure (Saaty 1977). Finally, the criteria are combined using the weighted linear combination (WLC) technique resulting in a suitability map.

2.1 Selection of criteria for hydrometeorological station network

A number of geomorphological, administrative, technical and geometric criteria are taken into account, as recorded in Baltas and Mimikou (2009). The optimal design relies on the stations' number and, finally, the positions that are required. According to the recommendations of WMO (2008b), the station density can

be estimated as a function of the elevation classification and the spatial distribution in the administrative region. Thus, the first criterion of density is linked to the altitude categorization of the earth's surface that is taken according to the specifications of the Soil and Terrain Digital Database SOTER (Dobos et al. 2005) of the UNEP (United Nations Environment Programme) and that consists of the following five zones: A (0-200), B (200-500 m), C (500-800 m), D (800-1200 m) and E (1200-1900 m). The information of elevation is taken from the digital elevation model (DEM) of the region, provided by the National Cadastre & Mapping Agency of Greece. The data set is a raster layer with pixel size equal to 5×5 m, geometric accuracy RMSE is $z \leq 2.00$ m and absolute accuracy about 3.92 m for a 95% confidence level. The second criterion indicates the suitable terrain slopes that is performed as a constraint in the problem, as guidelines indicate a suitable slope between zero and 5%. Particularly, according to the specifications of the SOTER Service regarding the classification of slope, the areas with terrain slope up to 2% are characterized as flat, while the areas with terrain slope of 2% - 5% as areas with smoothly wavy hills. Therefore, in the present application, the stations were placed within these two categories in order to meet this constraint. For this purpose, a Boolean map is created, giving the value of "1" in case the slope is lower than 5% and the value of "0" to indicate the higher terrain slope. Thus, the criterion "slope" is expressed as a restriction through a Boolean map, which is a reclassification result from the layer "slope" that is created using the aforementioned DEM. The third criterion for hydrometeorological stations site selection is about the representation of all land cover types. Using the information of land use/land cover distribution provided by the CORINE Land Cover (CLC 2018), four main categories were obtained, corresponding to the following four main categories: (1) Artificial surfaces (2) Rural areas (3) Forests and Seminatural areas and (4) Water surfaces - Water collections, in order to finally select locations at different land cover types. However, it should be noted that, generally, in areas where the necessary number of stations (first criterion) is lower than four, the decision makers may select locations in a subset of these categories, to cover the potentially highest number of types. Additionally, there are introduced two critical criteria regarding proximity; the distance from settlements and the distance from roads; and a third one regarding monitoring close to areas that there is a number of boreholes, which is indication for local groundwater exploitation. These three criteria are characterized as technical in the global literature. The fourth criterion "distance from settlements" is introduced in order to facilitate the monitoring of the recording stations and the control of the instruments. The optimum sites are selected at a distance of 1 km from the large settlements and of 500 m from the small settlements, expressing this condition through a Boolean map, as well. To formulate this criterion, initially the layer of settlements was obtained through the data set of CLC (2018), that is, the Discontinuous urban fabric, and was updated when needed. In this layer, the buffer zones were determined and the buffer zones layer is finally converted into a raster layer that is the Boolean map. The "proximity of stations to the road network" is the fifth criterion that is also considered necessary for the same reasons, i.e., ease of access. The layer of road network was obtained from the website <https://www.geofabrik.de/data/> that provides geodata from the OpenStreetMap (OSM) project in various formats. This OSM layer includes all available thematic levels of roads, while for the analysis, levels up to the second class of rural roads, i.e., grade 2; track road were considered, to ensure the accessibility using conventional vehicles all year long. This criterion is also a Boolean map using a buffer zone of 200 m from the road network. The next criterion regarding the

existence of “boreholes” is created after accessing the national database of registered boreholes in the National Register of Water Intake Points (available for Greece at the website of the Ministry of Environment and Energy: http://imt.ypeka.gr/public_view.html). The establishment of stations is recommended in locations where clusters of boreholes exist. The corresponding buffer zone from these clusters is taken at a 500-meter distance.

Finally, additional criteria may be applied to denote the spatial extend of the analysis; for instance, the analysis can be performed within the administrative boundaries of a municipality or at river basin scale. The latter approach is also followed in the current analysis. Regarding final stations’ position selection based on the suitability map results, a selection criterion may be the spatial distribution of the stations across the study area. In this way, each station may represent an almost equal percentage of the total area.

2.2 Selection of criteria for hydrometric station network

The criteria describing when a location is suitable for a hydrometric station installation can be classified into two categories; the general criteria that, in most of the cases, can be expressed through raster data sets (e.g., criteria regarding proximity; density; etc.), and the special criteria that include the technical standards of the positions, as set out in ISO 1100-1 (WMO-No. 1044 2010). Hong et al. (2016) describe these specifications, which delineate that a stream gauge should be placed in a position where the general course of the river should be straight for approximately 10 times the stream width (both upstream and downstream from this site); it should be far enough (upstream) from the confluence with another stream to avoid any variable influence from another stream and also far enough (upstream and downstream) from sites vulnerable to tidal effects. In this position, the total flow should be confined to one channel at all stages and no flow bypasses the site as subsurface flow, the streambed should be relatively free of aquatic vegetation and the banks should be stable and high enough for floods events and also free of brush. Upstream of the candidate station location, a “pool” should be formed in order to ensure recording of a stage at extremely low flow and to avoid high velocities at the stream ward end of the stage recorder intakes, transducers, or manometer orifice during periods of high flow. Finally, the site of installation should not be affected by intense scour and fill, which is ensured by maintaining a steady slope upstream and downstream of the site, given the fact that the station is located in a straight enough part of the river; very low stream slope is preferred. As perceived, the majority of the aforementioned criteria require the *in-situ* evaluation of the suggested positions that may have been denoted after following a GIS-based methodology for site selection. Thus, the process in a GIS environment can suggest some candidate sites for station establishment, taking into account a number of criteria, assisting in minimizing the field work regarding site selection.

The proposed methodology introduces six criteria that can be expressed through GIS applications. The first criterion regarding station density follows the WMO (2010) recommendations that formulate the density of a hydrometric station network according to the type of area, here: “plain” (Table 1). Using these values, the required number of stream gauges is one, however, decision makers finally propose two

locations to ensure that the network will provide adequate data for all purposes and especially for this of early warning. The “terrain slope criterion” is among the WMO recommendations and denotes the station establishment on gently sloping terrain; the lower the slope is, the higher score the location gets. The second criterion is the “distance from confluence with another stream” and it is introduced as stream gauges should be placed far from the junctions to avoid the other streams’ influence during flow recording. To express this criterion, nodes are initially digitized at the junction points and then for these points, a 250-meter buffer zone is created to finally extract a Boolean map with zero values inside this zone that denotes the area close to nodes that should be avoided. Afterwards, the Euclidean distance from the area’s outer margin is calculated. The final data set that is standardized in the next step of the methodology is a raster with zero values inside the buffer zones and the values of distance from the nodes across the remaining part of the mainstream. The third criterion, “distance from road network”, is one linked to the accessibility to the location and it is formulated based on the OSM data set that is described in the previous paragraph, after calculating the Euclidean distance between the road network and the mainstream inside a buffer zone of 50 m. The criterion “distance from settlements” is introduced as the establishment of a station near and upstream of the settlements is particularly important both for the operation of flood early warning systems and for the ease of access to the position. For this purpose, the aforementioned data set regarding settlements is used in order to define the positions across the mainstream where each settlement borders on it. Finally, the upstream Euclidean distance from settlements across the mainstream is calculated. The criterion “distance from flood-prone areas” is the one introduced to ensure that MCDM will suggest suitable location upstream to the flood-prone areas, so as to be useful for the local early warning system operation. Therefore, this criterion requires the implementation of a process in GIS that delivers standardized values along the mainstream and upstream to the flood-prone area in a way to give the maximum value at the outer margin of the vulnerable area and a gradually decreasing one as the Euclidean distance upstream of this margin across the mainstream grows. To create this layer, the determination of the flood-prone area is required, an information retrieved from a GIS-based MCDM for flood vulnerability assessment in Attica region, carried out by Feloni et al. (2020). As in this analysis various scenarios are evaluated, for the formulation of the “distance from flood-prone areas” criterion, the zones of high and very high risk that were defined according to their best performance scenario (named “FAHP.3K”) are taken into consideration. The combination of the aforementioned criteria results in a suitability map with various scores across the mainstream. Among the locations of highest score, the selection is also affected by an additional criterion regarding the existence of bridges with a direction perpendicular to that of the mainstream, as this fact technically serves the placement of equipment and also ensures the accessibility. The suitability map, which is the final result of MDCD regarding this network, includes the sites’ scoring across the mainstream of Sarantapotamos river. The drainage line and the layers of river basin and the slopes of the basin are created using the aforementioned DEM, with the aid of the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS; HEC 2013), a software package for use with the ArcGIS software (ESRI 2010).

Table 1 Stream Flow Station Density according to Surface Characteristics Sources: Data adopted by WMO (2010), as cited in Theochari et al. (2019)

Type	Density
Coastal	1 station per 2,750km ²
Mountainous	1 station per 1,000km ²
Hilly	1 station per 1,875km ²
Plains	1 station per 1,875km ²
Small islands (area<500km ²)	1 station per 1,985km ²
Polar, arid	1 station per 20,000km ²

2.3 Standardization and classification of criteria

Standardization is an important procedure in the context of MCDM, as it categorizes the criteria into a single grading scale (e.g., between 0-1) before their combination for the production, for instance, of a suitability map in case there is the problem of hydrometeorological and hydrometric stations network design. Therefore, comparable sizes are created for each criterion in order to result in a final score (FS) of the same grading scale. There are various standardization processes, usually using minimum and maximum values as scaling points, as reviewed by Voogd (1983). The simplest way to perform this standardization is by using a linear transformation as shown in equation (1), when the maximum value of the criterion corresponds to the best case, and, equation (2) when the maximum value corresponds to the worst case that is interpreted depending on the MCDM problem. Using the ArcGIS software (ESRI 2010), where the entire analysis is performed, the standardization procedure is implemented through Raster Calculator that is an ArcGIS geoprocessing tool for performing raster analysis using a Map Algebra expression, as follows:

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

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

where, FV_{min} and FV_{max} are respectively the minimum and maximum values of the criteria, and FV_i is the value of each raster cell, which then corresponds to the standardized value x_i .

In addition to the standardization, which is used for the majority of criteria, the technique of classification is adopted when a criterion is expressed through categories or discrete data (certain values). In the current problem, classification is used for all criteria involved in hydrometeorological station design. When classification margins are not predefined, there is a number of classification methods that can be performed. In relevant applications the natural breaks classification method (Jenks 1967) is usually performed with the aid of the spatial analyst tool of ArcGIS. This optimization method, also called the "Jenks natural breaks classification method", is a data classification method designed to determine the best arrangement of values into different classes. This is accomplished by seeking to minimize each class' average deviation from the class mean, while maximizing each class' deviation from the means of the other groups. In other words, the method seeks to reduce the variance within classes and maximize

the variance between classes (Theochari et al. 2019). Table 2 summarizes the decision criteria for both networks, as well as, the method performed regarding standardization (S)/classification (C) of values.

Table 2 Summary of decision criteria for the hydrometeorological (HM) and hydrometric (HY) station network design

Criterion	Standardisation/ Classification	Constraints	Remarks
(HM) Density	(C) Five (predefined) Elevation zones	-	Estimation of the required number of stations (density) per elevation zone. The criterion is applied to the suitability map for the final sites selection
(HM) Terrain slope	(C) Two (predefined) classes	Boolean Map "1" ($\leq 5\%$); "0" ($> 5\%$)	Terrain slope calculation using the available DEM - Classification in two classes and Reclassification for the Boolean Map creation
(HM) CLC classes	(C) Four main categories	-	Classification of CLC in four categories. The criterion is applied to the suitability map for the final sites selection
(HM) Distance from settlements	(C) Two (predefined) classes	Boolean Map "1" (≤ 1 km from large settlements or ≤ 500 m from small settlements); "0" (> 1 km or > 500 m, respectively)	Buffer zones of two sizes depending on a settlements categorization - Boolean map creation ("1" for Buffer zones)
(HM) Distance from road network	(C) Two (predefined) classes	Boolean Map "1" (≤ 200 m from the road network); "0" (> 200 m)	Road network classification to extract specific categories - Buffer zones of 200 m from the road network - Boolean map creation ("1" for Buffer zones)
(HM) Existence of boreholes	(C) Two (predefined) classes	Boolean Map "1" (≤ 500 m from boreholes); "0" (> 500 m)	Buffer zones of 500 m from the boreholes - Boolean map creation ("1" for Buffer zones)
(HM) Administrative boundaries	The analysis is performed within the administrative boundaries of a Municipality or at river basin scale		
(HM) Spatial distribution of the stations	Each station may represent an almost equal percentage of the total area. The criterion is applied to the suitability map for the final sites selection		
(HY) River channel slope	(C) Two (predefined) classes and	-	Slope is classified in two classes and then values of the class of low slope ($\leq 5\%$) are

	(S) with equation (2) in the class of low slopes		standardized using equation (2)
(HY) Distance from road network	(S) with equation (2)	-	Euclidean distance from road network calculation (Con \leq 50) - "Times" ArcGIS geoprocessing tool to create a raster with values along the mainstream - Standardisation using equation (2) - 'Mosaic to new raster' to combine the latter layer with that of the whole mainstream ("0")
(HY) Distance from confluence with another stream	(S) with equation (2)	Boolean Map "1" (>250m); "0" (d<250)	Creation of a feature class (type point) with the intersection of streams - "Mosaic to new raster" with "Euclidean" layer
(HY) Upstream distance from settlements	(S) with equation (2)	-	Upstream mainstream part determination when close to a settlement - "Euclidean distance" - "Times" between the upstream Euclidean distance and the upstream mainstream part of each neighboring settlement - Standardisation using equation (2) and "Mosaic to new raster" to combine the latter layer with that of the whole mainstream ("0")
(HY) Distance from flood-prone areas	(S) with equation (2)	"Euclidean distance" from flood-prone areas determination - Definition of the upstream mainstream for each vulnerable area - 'Times' between 'Euclidean distance' and 'upstream' - Standardisation - "Mosaic to new raster" to combine the latter layer	

(HY) Drainage line	-	with that of the whole mainstream Boolean Map "1" (along the mainstream), "0" (outside the mainstream)	To define the processing area
(HY) Density		Estimation of the required number of stations (density) according to the area's categorization. The criterion is applied to the suitability map for the final sites selection	

2.4 Determination of criteria weights

In an analysis based on MCDM, the decision criteria can be combined in many ways, one of which is the WLC and its variants, which requires an aggregation of the weighted criteria. In the present analysis, criteria's weights estimation is executed using the Analytical Hierarchy Process (AHP) method. AHP, proposed by Saaty (1977), is an analytical method used to weigh criteria and structure the problem into a hierarchy, with the aim of reducing its complexity through its decomposition into subproblems. It is one of the most applied multicriteria decision analysis methodologies in environmental issues and constitutes a robust and flexible MCDM tool that considers qualitative and quantitative criteria (Soto-Paz et al. 2019). This method has been applied in various studies that incorporate MCDM for different problems regarding site selection (e.g., Sestak 1988; Chung and Lee 2009; Aken et al. 2014; Feloni et al. 2018; Deng and Deng 2019; Theochari et al. 2019; Ikram et al. 2020; Bertsiou et al. 2020; Matomela et al. 2020). The method implementation begins with the deconstruction of the problem in a hierarchical model, consisting of its basic components, allowing for pairwise comparisons, using the fundamental scale of Saaty (1977). For each comparison between two design criteria, the relative significance is awarded a score, on a scale between 1 (equally significant) and 9 (absolutely more significant), whilst the other option in the pairing is assigned a rating equal to the reciprocal of this value.

Regarding the case study presented for the Sarantapotamos river basin, for the hydrometeorological stations network design, equal weights are set among criteria, as the suitability map results from the combination of criteria that are introduced as constraints. On the other hand, for the hydrometric station network establishment, the relative importance of each factor affects the FS of the positions, as each design scenario appears a variety of values across the mainstream. For this reason, three factors' weighting scenarios are investigated, as described in detail in Theochari et al. (2019). In the first scenario, higher importance is attributed to the technical criteria, i.e., slopes, distance from the road network and from settlements, in the second scenario that focuses on flood protection, the criterion regarding distance from flood-prone areas is of the highest importance, and the third one is an average scenario between technical and flood-related factors. In addition, weights for the last scenario are also estimated using the Fussy Analytical Hierarchy Process (FAHP) that is proposed by Chang (1996), to illustrate the influence of

method used for weights estimation in the resulting suitability map. Fuzzy logic is a flexible and simple approach that links quantitative and qualitative information (Pourmeidani et al. 2020).

2.5 Combination of criteria

The last step of the MCDM is the development of the suitability map. This process involves the creation and calculation of the required level of information regarding the suitability of the areas for the optimal positioning of hydrometeorological and hydrometric station network in the study area. The WLC is incorporated into the GIS environment through Raster Calculator (Map Algebra Toolset) as well, and the FS is then calculated using equation 3. In cases where constraints also apply, the process can be modified by multiplying the FS value with the layer of constraints (c_i), as shown in equation 4. The FS layers are created for all alternatives regarding factors' weighting and the appropriate number of sites is finally selected seeking among positions of highest FS.

$$FS = \sum w_i x_i \quad (3)$$

$$FS = \sum w_i x_i * \prod c_i \quad (4)$$

where, FS: the final value for each cell, w_i : the weight of criterion i as calculated using the AHP method, and x_i : the standard value of criterion i .

A decisive step in the whole process that incorporated MCDM on GIS is the selection of criteria and the way they are expressed and then standardized or classified, to finally acquire the design criteria transformed to the scale of [0,1]. In order to obtain the FS regarding the suitability, the WLC method is applied using the weights calculated according to the method mentioned in the previous section. As all criteria are expressed through standardized values in the same scale, the resulting suitability map attributes scores between zero and one.

3 Implementation To The Sarantapotamos River Basin

Regarding hydrometeorological station network design in Sarantapotamos basin, the selected criteria (Table 2), which are expressed as constraints in the entire process, are shown in Fig. 2. A Boolean map accounts for each criterion indicating the proper locations with cell code "1" and the cells where, according to the criterion values, should be omitted with the value "0" in order to avoid their selection when the WLC is applied for the FS calculation. The criteria combination results in the suitability map (Fig. 3).

Since FS takes values between 0 and 1, five classes are observed that represent the possible combinations among criteria values. The first FS class is equal to zero and corresponds to 34 % of the total area of the river basin, which is the second largest amount of area and represents the areas where hydrometeorological stations are not permitted to be established. The other four classes have FS values up to "0.25", "0.50", "0.75" and the last one is equal to "1.00". The percentage for the class of "0.25" is 39

% and constitutes the largest percentage of area in the basin, for FS = 0.50 is 16 % C, for FS = 0.75 is 7 % and 4% of the basin reaches the highest score, that is, when FS = 1.00. The candidate positions with FS = 1 are shown in dark green color in the suitability map. The selection of proposed locations is linked to the criterion of density resulting from the altitude categorization of the earth's surface in five zones (Fig. 4). The calculation of minimum number of stations for each elevation zone is presented in Table 3. Zone B covers the largest area (163 km²) and requires the installation of two stations. The installation of one station is also required in Zone C. Subsequently, according to the station density criterion, the optimum number of stations is three.

Table 3
Grouping altitudes and calculating the desired number of hydrometeorological stations

Zone	Altitudes (m)	Station density	Area (km ²)	Density	Final stations
A	0-200	600	71	0.1	0
B	200–500	100	163	1.6	2
C	500–800	75	90	1.2	1
D	800-1,200	50	17	0.3	0
E	1,200-1,900	50	0	0.0	0
Sum	-	-	341	-	3

The MCDM for hydrometric station network design is conducted across the mainstream. The design criteria that considered in this GIS-based MCDM analysis are five, namely, the slopes (C1); the distance from road network (C2); the distance from confluence with another stream (C3); the (upstream) distance from settlements (C4); and the (upstream) distance from flood-prone areas (C5). The influence of criteria significance is further compared in the basis of three scenarios regarding hierarchy (as proposed by Theochari et al. 2019) and Table 4 shows the corresponding factors' weights for each of them. As all criteria are standardized in a scale of [0,1], FS gets values in the same range, and, for demonstration purposes, two clusters regarding FS are created (Fig. 5); the first one (small black dots) corresponds to FS lower than 0.90 and the second (big red circles) indicates the sites of higher FS.

Table 4
Criteria weights for each Scenario Sources from Theochari et al.
(2019)

	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b
W_{C1}	0.566	0.474	0.476	0.565
W_{C2}	0.183	0.039	0.118	0.000
W_{C3}	0.124	0.036	0.061	0.000
W_{C4}	0.060	0.166	0.032	0.000
W_{C5}	0.067	0.284	0.312	0.435

The comparison of the three scenarios illustrates the importance of the criterion of “slopes” that is the most critical for all scenarios, while the criterion “distance from settlements” is the one of lowest weight for the first and third scenario. In the second scenario, the criterion “distance from confluence with another stream” is the least significant. The “distance from settlements” is considered of high importance in case that the design serves the scope of developing a flood early warning system, in which the position of the station is decisive in the entire system. For a FS > 90%, all scenarios lead to the suggestion of the same optimal sites, i.e., the best two locations. In scenario 3b (using FAHP approach for weights determination), the resulting map denotes 437 potentially suitable positions, while scenario 3a (using AHP) results in 59 positions with high FS. For all scenarios apart from the first one, suitable locations (FS > 90%) are observed in the southern part of the river (lowlands), closer to the settlements and the flood-prone areas, while, as expected, the first scenario denotes proper locations across the entire length of the mainstream.

According to the above described methodology for the design of a hydrometeorological and hydrometric station network, the implementation for Sarantapotamos river basin case study resulted initially in the determination of the number of stations that are necessary for the area, as well as, in the suggestion of suitable locations for their installation. The required number of hydrometeorological stations is three, while the required number of hydrometric stations is at least one and, finally, two locations are proposed for the better monitoring of the hydrological response of the basin. The proposed positions of the hydrometeorological stations are selected according to the criteria of density and spatial distribution. The one hydrometric station, at the northern part of the river basin, is optimum according to the first scenario, as it meets the criterion of technical adequacy of position, and specifically the proposed location is at a bridge on the provincial road Oinois - Panaktou. The location of the second hydrometric station to the south comes as an optimum solution for all scenarios examined and it is near the provincial road Oinoi -

Magoula, close to the settlements of Mandra and Magoula. The locations for the proposed network of stations are presented in Fig. 6.

4 Conclusions

This article presents a GIS-based MCDM approach for the optimum design and establishment of a hydrometeorological and hydrometric station network that is further implemented at the Sarantapotamos River basin, located in Attica (Central Greece). The entire analysis is based on the MCDM combined with GIS techniques proposing a set of geomorphological, technical and generally spatial criteria, according to the design requirements that can be, for instance, the protection against floods, after taking into consideration the main guidelines of WMO and the constraints regarding the desired density of stations. The AHP was used as a methodological tool for criteria's weights calculations. Then, the criteria's values were transformed to a common scale of [0,1] using a standardization or classification method. The combination of the criteria to create the suitability maps was performed with the WLC, resulting in one map for each network with FS ranging between 0% and 100%, indicating the suitability of the candidate locations. The results from the above analysis showed that the number and the suitability score of the locations is highly affected by the hierarchy.

For the case study presented, the optimum hydrometeorological network consists of three stations; two of them in the elevation zone B and one in zone C, and according to the results the proposed locations reach the highest FS. Regarding the optimum hydrometric station network, even the required number of stations is one, two stations are proposed for better monitoring purposes. The comparison of the three scenarios that were investigated regarding factors' weighting shows that the criterion of slopes is the most important for all scenarios examined. Furthermore, all scenarios result in the same optimum locations for a performance score higher than 90%. In this class of FS ($FS \geq 0.9$), the fuzzy version of the third scenario (3b) is the one suggesting the highest number of optimum locations (437), while the AHP approach of this scenario (3a) corresponds to the fewest positions (59). Comparing results for all scenarios, the first allocates the proposed locations along the entire mainstream, in contrast to the other scenarios where there is a tendency to allocate the optimum sites to the southern part of the river basin, due to the incorporation of the flood-prone areas related factor.

Regarding future research, the introduction of further criteria for both networks is suggested. Modifications can be applied to the factors' weighting method, as well as, to the standardization and classification approach that is followed in the current analysis. The comparison among results using different approaches would be of interest, and, finally, the implementation of the methodology at different spatial scales, as well as, to catchment areas with different characteristics would be of value.

Declarations

Author contributions

All authors contributed to the study conception and design. Material preparation and data collection were performed by Apollon Bournas. The GIS-based multicriteria decision analysis was performed by Aimilia-Panagiota Theochari. Review and editing were performed by Elissavet Feloni. Supervision, validation, final review and editing were performed by Evangelos Baltas. The first draft of the manuscript was written by Aimilia-Panagiota Theochari and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding No funding was received.

Conflicts of interest/Competing interests The authors declare that they have no conflicts of interest.

Availability of data and material The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Ethics approval The manuscript was not submitted to more than one journal for simultaneous consideration. The work is original and not published elsewhere.

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