**ORIGINAL ARTICLE**

# Hydrometeorological - Hydrometric Station Network Design Using Multicriteria Decision Analysis and GIS Techniques

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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) using a multicriteria decision making (MCDM) approach, which combines several spatial criteria to propose suitable locations for installation of such a station network in the Sarantapotamos River Basin in the western part of the Attica Region, Greece. Through the design of two networks that meet different requirements, various aspects concerning this methodology are illustrated, such as criteria weights determination, which is a problem that arises frequently in many MCDM techniques. The criteria weights for the hydrometric station network design are estimated using both the Analytic Hierarchy Process (AHP) and the Fuzzy Analytic Hierarchy Process (FAHP), while, for hydrometeorological station network design, all weights are equal. Hydrometeorological station final position selection is achieved by introducing the criteria of density and spatial distribution to the suitable locations. For hydrometric station network design, the analysis indicates that the criterion of slope mainly controls the MCDM outputs. According to station density thresholds proposed by the World Meteorological Organization (WMO), an optimum hydrometeorological and hydrometric station network for the region should comprise three and two stations, respectively.

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**Highlights**
- GIS tools and MCDM methods are combined for station network site selection.
- Different approaches are used for a hydrometric and a hydrometeorological network.
- Scenarios regarding MCDM implementation are discussed.

# 1 Introduction

With the aim of improving the efficient and equitable management of water resources, and of shielding against the adverse effects of floods, hydrometeorological and hydrological network design is a key component with a decisive contribution towards the collection of comprehensive and reliable data, as data are the life blood of hydrological models and the heart of the process of river flow condition simulation (Stephenson and Petersen 1991) in the frame of rational water resources management. Information of rainfall is the most important parameter of all flood forecasting models (Kar et al. 2015), while the accurate and reliable spatiotemporal estimation of precipitation is required for a successful prediction of a catchment's hydrological response (Volkmann et al. 2010). Hydrological data are needed for decision making, planning and management of water resources (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).

Accurate hydrometeorological measurements require well-organized networks of hydrometeorological (i.e., these meteorological parameters that are necessary for hydrologic applications) and hydrometric (i.e., streamflow) stations. The design of such networks has been of great interest since the 1970 s (Mishra and Coulibaly 2009), while, various techniques have been developed for the design of an optimum 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; Nguyen et al. 2021). Furthermore, the World Meteorological Organization (WMO 2008b; 2010) has fully investigated the development and dissemination of technology for the design of hydrometeorological data networks. Accordingly, methods applied for designing a stream gauging network, which monitors river flow, recommend the contribution of GIS capabilities to indicate proper sites, instead of the time-consuming field exploration; however, the GIS analysis should not be performed solely, but potential sites should also be evaluated *in situ* (e.g., Hong et al. 2016; Feloni et al. 2018; Theochari et al. 2019). Regarding network design, optimization approaches are increasingly being used, 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 the provision of different feasible solutions under several scenarios (Alfonso et al. 2010), and this capability is significant for a variety of applications, such as in soil erosion estimation (e.g., Thomas et al. 2018; Roy 2019; Phinzi and Ngetar 2019), and generally, in 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) postulated the need for optimization methods in regions where guidelines cannot be applied with confidence *a priori*. According to Huang et al. (2011), in recent years the use of GIS as a complementary tool in MCA for network design has been increased, as the technological development of GIS techniques made it an ideal tool for contributing to the management of spatial data of large volumes and from various sources (Karimi et al. 2016). GIS analysis provides a complete set of feasible locations based on geographical criteria, among which, the user needs, various distances, the land use distribution, the terrain slope, elevation, etc. The capacity of GIS to integrate spatial information make them a suitable tool for decision-making problems that comprise multiple factors (Shepherd et al. 2004).

The necessity for the design and installation of a network of comprehensive measuring stations is profound in countries such as Greece, where the eastern and the western parts of the country have complex topography and unequal distribution of water resources due to the particular geomorphological and climatic local conditions. Climate in Greece is generally Mediterranean, although it is characterized by a wide variety of climatic types, and ranges from humid in the northwestern regions to dry in the eastern. The intense relief is associated with the division of the country into numerous hydrological basins and several local station networks. Existing station networks have many disadvantages (Baltas and Mimikou 2009) and 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 several agencies (e.g., the National Meteorological Service, the National Athens Observatory, Ministries and Universities, etc.) and, consequently, each network serves different purposes. 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) to monitor the meteorological and hydrological properties of Athens. Baltas and Mimikou (2009) demonstrated the optimization of the existing national network of about 1041 station with the use of GIS methods. 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 agricultural water resource management. Finally, Theochari et al. (2019) proposed a method for evaluating eligible sites for stream gauge installation for various scenarios depending on the network purposes, viz. water resource management and flood warning systems development and operation in West Attica (Central Greece).

The present research work is intended to assist in designing hydrometeorological and hydrometric networks through a GIS-based multicriteria decision analysis approach. 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 considered for the network design, the computation of their standardized values, and the calculation of the weight of each criterion by using the Analytic Hierarchy Process (AHP) procedure proposed by Saaty (1977). AHP is chosen because it has been applied in various studies that incorporate MCDM for different problems regarding site selection and it has also the advantage of estimating weights through attributing hierarchy among criteria (Feloni et al. 2018). For the hydrometric station network establishment, three factor weighting scenarios are investigated through the implementation of the AHP method, as described in detail in Theochari et al. (2019); however, comparing the current analysis with previous ones, the design criteria are formulated in a different way into the GIS environment. Regarding hydrometeorological station network design, equal criteria weights are assigned. Finally, the criteria are combined using the weighted linear combination (WLC) technique resulting in a suitability map for each network. The role of GIS is of great importance in the whole methodology and can manage large volumes of spatial data from a variety of sources and execute various commands through toolset packages in order to solve this spatial decision-making problem. In the current analysis, the selected spatial criteria are expressed and combined into a GIS environment for both station network design. Regarding findings, GIS-based MCDM proposes several suitable locations, among which these of highest final score (FS) are selected for the station network

establishment. The limitations of previous relevant studies concern the scale in which the analysis is performed and the limited description of the design criteria handling in GIS. In the current analysis that applied at a river basin scale, numerous spatial criteria are incorporated and various aspects of the method are also discussed.

## 2 Study Area and Data Used

The whole methodology is presented through a case study for the Sarantapotamos 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). 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 and 19 °C (Baltas 2008). This 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 shows high intensities for small temporal scales, compared to other parts of the country, in combination with its location at 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 15, 2017, marked by the loss of 24 people (Feloni 2019). At present, there does not exist any uniform station network in the study area; however, after a recent catastrophic flood event, a telemetric network of three hydrometeorological stations was established under the research activities of the FloodHub service, Center for Earth Observation and Satellite Remote Sensing Sciences of the National Observatory of Athens (Fig. 1) (Beyond-eocenter 2021).

Among the spatial data that were necessary for the analysis, the digital elevation model (DEM) of the region is the most significant and it is provided by the National Cadastre & Mapping Agency of Greece. The dataset is a raster layer with pixel size equal to 5 m × 5 m, its geometric accuracy is RMSEz ≤ 2.00 m and the absolute accuracy is about 3.92 m for a 95 % confidence level. The information of land use/land cover distribution is provided by the CORINE Land Cover (CLC 2018). Furthermore, the layer of road network is obtained from the website of the OpenStreetMap (OSM) (n.d.) project (https://www.geofabrik.de/data/) that provides spatial data in various formats. The layer of boreholes is created by the authors based on the National Register of Water Intake Points (available at the website of the Greek Ministry of Environment and Energy (n.d.): http://lmt.ypeka.gr/public_view.html). Regarding the formulation of a criterion concerning station installation upstream from the flood vulnerable areas, the identification of the flood-prone areas is initially required. Thus, this information retrieved from the results of a GIS-based MCDM for flood vulnerability assessment in Attica region, including the Sarantapotamos basin, which was carried out by Feloni et al. (2020).

## 3 Methods

The GIS-based MCA technique is performed with the aim of combining a set of proposed geomorphological, technical and generally various spatial criteria, as selected after considering
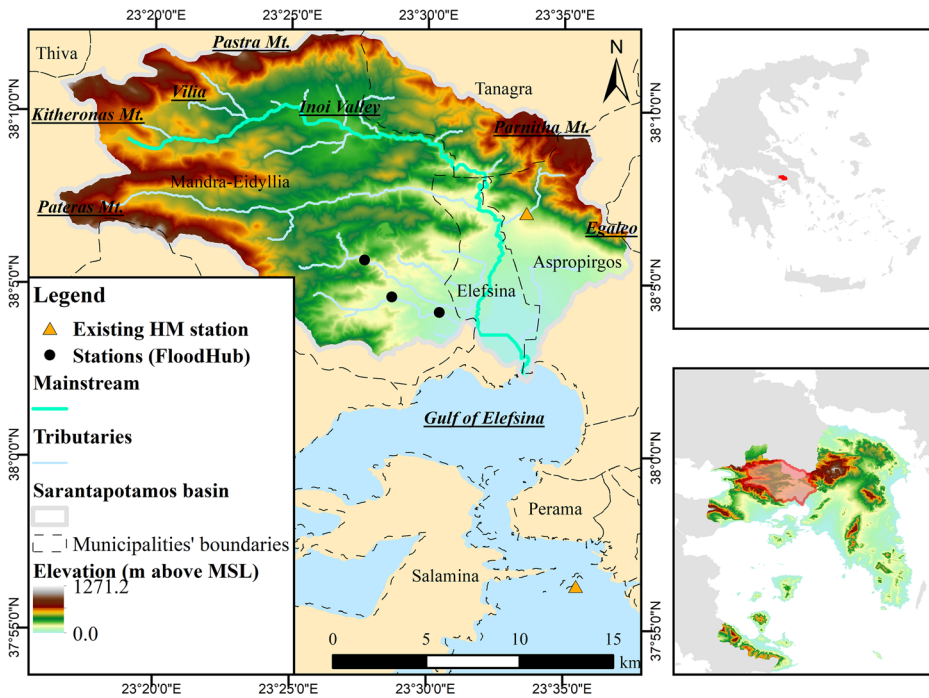
**Fig. 1** The Sarantapotamos river basin (left panel) and its location in Greece (upper right panel) and Attica Region (lower right panel)

available guidelines separately for the hydrometeorological and hydrometric station network design, using the AHP for the determination of the weights of the criteria, the linear scaling for the standardization of the criteria values and the WLC for the creation of a separate suitability map for each network. The main steps of the methodology are summarized in Fig. 2 and analyzed in the following paragraphs. The flowchart of the GIS–MCDM approach is presented in Fig. 2.

### 3.1 Selection of Criteria for Hydrometeorological Station Network

For hydrometeorological station network design, a number of geomorphological, administrative, technical, and geometric criteria are taken into account, as recorded in the detailed analysis of Baltas and Mimikou (2009). The optimal design relies on the stations' number and, finally, the positions that are required. The determination of the optimal station design concerns the optimal number and location of hydrometeorological stations, which provide more accurate and reliable data with minimum cost (Feloni et al. 2018). 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 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). More specifically, the altitude
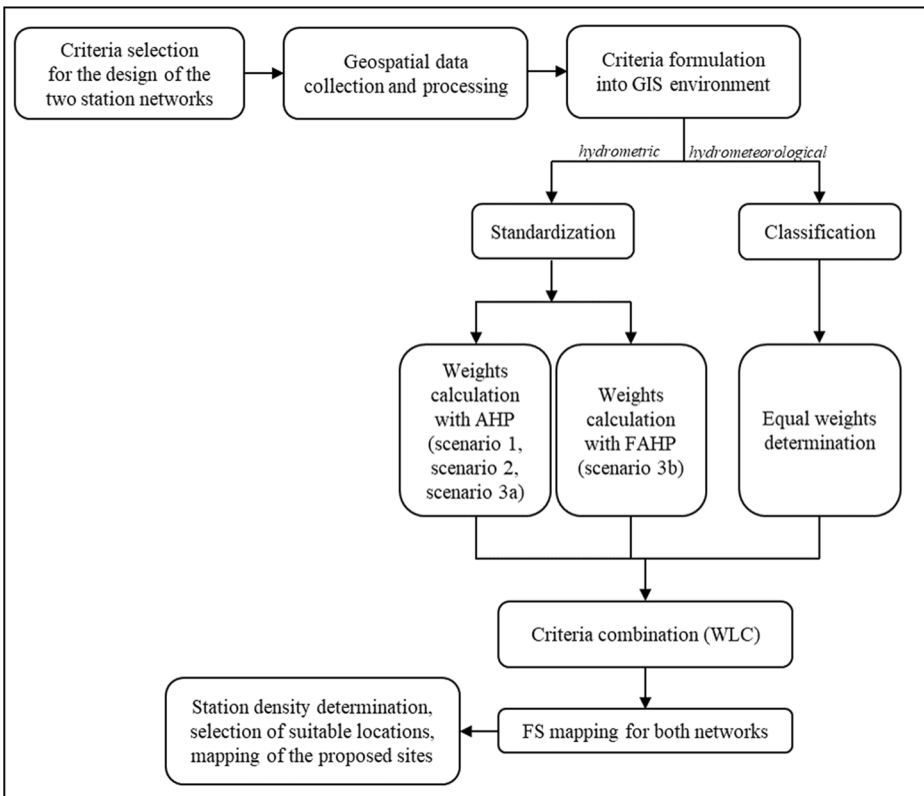
**Fig. 2** Flowchart of the GIS–MCDM methodology for hydrometeorological and hydrometric station network design

categorization consists of five zones: A (0-200), B (200–500 m), C (500–800 m), D (800–1200 m) and E (1200–1900 m). This first criterion is not incorporated in the WLC, but is applied in the final step of the proper site selection among these of high FS.

The second criterion indicates the suitable terrain slope that is used as a constraint in the problem, as guidelines indicate a suitable slope between 0 and 5 %, according to the specifications of the SOTER Service. The areas with terrain slope up to 2 % are characterized as flat, while the areas with a terrain slope between 2 and 5 % as gently undulating. Therefore, in the present application, the stations are 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 that 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 station site selection is the land cover type to describe the need for at least one station existence at each main category. Using the information of CLC, four main categories are created, corresponding to the following four main groups of land cover type: (1) Artificial surfaces; (2) Agricultural areas; (3) Forests and Semi-natural areas; and (4) Water surfaces - Water collections. In the study area, there are only three categories (Fig. 3); the forth category regarding water surfaces does not exist. However, it should be noted that, generally, there are cases, such as the current case study, where the
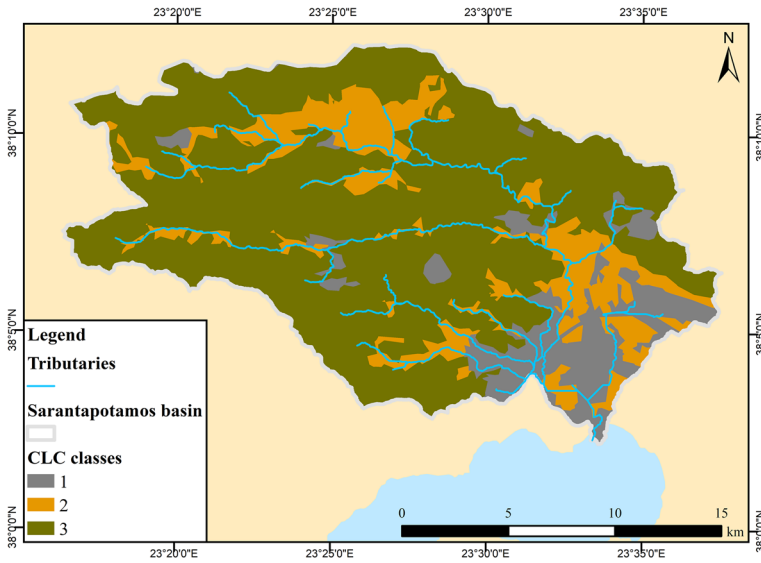
**Fig. 3** The three main categories of CLC classes used in the hydrometeorological station network design

necessary number of stations (first criterion) is lower than four (that is the number of land cover type categories).

Additionally, three criteria regarding proximity (distance from settlements; distance from roads; and boreholes) are introduced in the design, which are characterized as technical in the global literature (e.g., Baltas and Mimikou 2009; Feloni et al. 2018). The criterion "distance from settlements" is used 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. To formulate this criterion, the layer of settlements was obtained through the dataset of CLC (2018), through the selection of the CLC type: "Discontinuous urban fabric" and was updated, when needed, using satellite imagery as basemaps. Then, the buffer zones are determined, the layer converted into a Boolean map (raster format) to formulate the criterion.

The "proximity of stations to the road network" is the fifth criterion that is also considered necessary to express the ease of access. The OSM (n.d.) layer, which is used to extract the corresponding information, 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) are 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 that is a short distance to access any point on foot under any weather conditions.

The next criterion is linked to the existence of "boreholes". The establishment of stations is recommended in locations where clusters of boreholes exist for the integrated management of water resources. The corresponding buffer zone from these clusters is taken at a 500-meter distance.

Finally, additional criteria are applied to denote the spatial extend of the analysis; for instance, the analysis is performed within the river basin scale. Regarding final station position selection based on the suitability map results, a final selection criterion is 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.

## 3.2 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 cases, can be expressed through raster datasets (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) describes 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. At such a position, the total flow should be confined to one channel at all stages and no flow should bypass the site as subsurface flow, the streambed should be relatively free of aquatic vegetation and the banks should be stable and high enough for flood events and also free of brush. According to the WMO (2010), upstream of a candidate station location, a "pool" should be formed in order to ensure recording of a stage even at extremely low flow and to avoid high velocities at the streamward 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, most of the aforementioned criteria require the *in situ* evaluation of the positions suggested through the implementation of 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 uses seven criteria, where five of them can be expressed using GIS techniques: slopes (C1); distance from road network (C2); distance from confluence with another stream (C3); distance from settlements (C4); distance from flood-prone areas (C5).

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). The required number of stream gauges is one but 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 against floods. The "slope criterion" is among the

**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 2,750 km$^2$ |
| Mountainous | 1 station per 1,000 km$^2$ |
| Hilly | 1 station per 1,875 km$^2$ |
| Plains | 1 station per 1,875 km$^2$ |
| Small islands (area < 500 km$^2$) | 1 station per 1,985 km$^2$ |
| Polar, arid | 1 station per 20,000 km$^2$ |

WMO recommendations and denotes the station establishment on gently sloping terrain; the lower the slope is, the higher score the location gets.

The criterion "distance from confluence with another stream"; ensures that stream gauges are placed far from the junctions to avoid influence from the other stream 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. The Euclidean distance from the area's outer margin is then calculated. The final dataset that is standardized in the next step of the methodology; it is a raster dataset with zero values inside the buffer zones and the (standardized) values of distance from the nodes across the remaining part of the mainstream.

The criterion "distance from road network" is one linked to the accessibility to the location and it is formulated based on the OSM (n.d.) dataset, 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 dataset 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 and then standardized.

The criterion "distance from flood-prone areas" is used to identify suitable location upstream of 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 of the flood-prone area in a way that the maximum value is attributed to the outer margin of the vulnerable area and a gradually decreasing one is formulated by the Euclidean distance, which grows upstream of this margin across the mainstream (Fig. 4). To create the layer of C5, the zones of high and
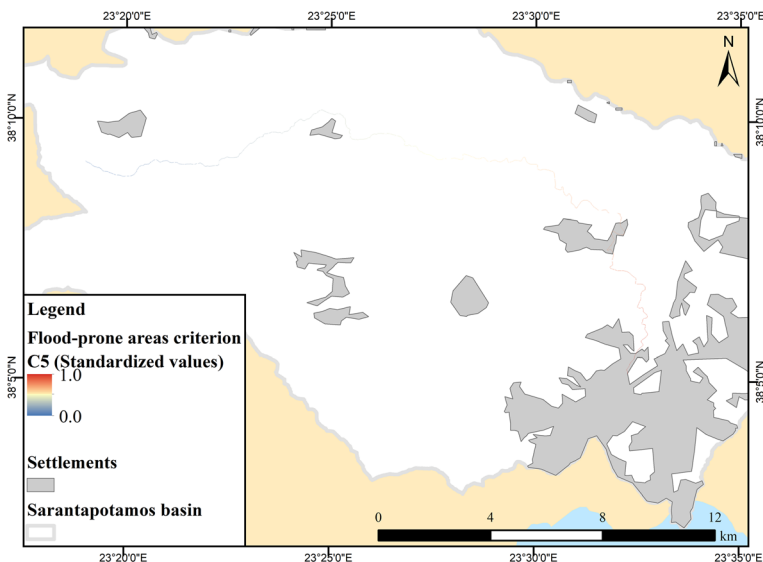


**Fig. 4** The "distance from flood-prone areas" criterion for hydrometric station network design

very high risk that were defined according to a best performance scenario regarding flood susceptibility assessment (named "FAHP.3K"), carried out by Feloni et al. (2020), are taken into consideration.

The aforementioned criteria are combined to finally create a suitability map with various scores across the mainstream. The suitability map, which is the MDCD output regarding this network, includes the site 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). Among the locations of highest score, the selection is also affected by a seventh criterion regarding the existence of bridges with a direction perpendicular to that of mainstream, as this fact technically serves the placement of equipment and also ensures the accessibility.

### 3.3 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 and 1). The simplest way to perform this standardization is by using a linear transformation as shown in Eq. (1), when the maximum value of the criterion corresponds to the best case, and Eq. (2), when the maximum value corresponds to the worst case that is interpreted depending on the MCDM problem (Voogd 1983). The standardization procedure is implemented in ArcGIS software (ESRI 2010) through Raster Calculator using a Map Algebra expression, as follows:

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

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

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 corresponds to the standardized value $x_i$; and SR is the standardized range, i.e., 0–1.

In addition to the standardization, the technique of classification is adopted. 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. The natural breaks classification method (Jenks 1967) is performed with the aid of the spatial analyst tool of ArcGIS. This is accomplished by seeking to minimize the average deviation of each class from the class mean, while maximizing the deviation of each class 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 | Standardization/ 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" (≤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 settlement 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 clusters 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 (S) with Eq. (2) in the class of low slopes | - | Slope is classified in two classes and then values of the class of low slope (≤5%) are standardized using Eq. (2) |
| (HY) Distance from road network | (S) with Eq. (2) | - | Euclidean distance from road network calculation (Con≤50) – "Times" ArcGIS geoprocessing tool to create a raster with values along the mainstream - Standardization using Eq. (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 Eq. (2) | Boolean Map "1" (>250 m); "0" (d<250) | Creation of a feature class (type point) with the intersection of streams – "Mosaic to new raster" with "Euclidean distance" layer |
| (HY) Upstream distance from settlements | (S) with Eq. (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 |

**Table 2** (continued)

| Criterion | Standardization/ Classification | Constraints | Remarks |
|---|---|---|---|
| | | | neighboring settlement -Standardization using Eq. (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 Eq. (2) | | "Euclidean distance" from flood-prone areas determination - Definition of the upstream mainstream for each vulnerable area – 'Times' between 'Euclidean distance' and 'upstream' – Standardization – "Mosaic to new raster" to combine the latter layer with that of the whole mainstream |
| (HY) Drainage line | - | 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 categorization. The criterion is applied to the suitability map for the final sites selection | | |

## 3.4 Determination of Criteria Weights

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 finally perform a combination for the FS determination. 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 weights estimation is executed using the AHP method (Saaty 1977). AHP 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. 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; Van 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 Satty (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.

In the present study, equal weights are set among criteria for hydrometeorological station design. On the other hand, for the hydrometric station network design, the relative importance of each factor affects the FS of the positions, as each design scenario presents a variety of values across the mainstream. For this reason, three factor weighting scenarios are investigated, as described in detail in Theochari et al. (2019). In the first scenario (scenario 1), higher weight is given to the technical criteria, i.e., slopes, distance from the road network, and

distance from confluence with another stream. In the second scenario (scenario 2), which focuses on flood protection, the criterion regarding distance from flood-prone areas is of high importance; and the third scenario (scenario 3a) is a moderate one between technical and flood-related factors. In the third scenario there is no priority for technical criteria or for flood protection criteria, but their importance is alternated in the hierarchy. However, for all scenarios topographic slope is the most preferable criterion because the establishment is feasible only in very low slopes. In addition, weights for the third scenario (scenario 3b) are also estimated using the Fuzzy Analytic Hierarchy Process (FAHP) that is proposed by Chang (1996), to illustrate the influence of the method used on weight estimation in the resulting suitability map. Fuzzy logic is a flexible and simple approach that links quantitative and qualitative information (Pourmeidani et al. 2020).

## 3.5 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 Eq. (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 Eq. (4). The FS layers are created for all alternatives regarding factor weighting, and the appropriate number of sites is finally selected seeking among positions of highest FS.

$$FS = \sum w_i x_i \tag{3}$$

$$FS = \Sigma w_i x \cdot \Pi c_i \tag{4}$$

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

In order to obtain the FS regarding sites suitability, the WLC method is applied for each station network separately, 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.

## 4 Results and Discussion

Two approaches regarding GIS-based MCDM for station network design are applied in the frame of the present analysis; one regarding the HM stations, which is an approach with equally weighted criteria that are set as constraints, and one regarding HY stations, which is an integrated approach that considers several criteria of different weights. The selected criteria concerning hydrometeorological station network design in Sarantapotamos basin are shown in Table 2, and are expressed as constraints in the entire process, as they denote proper and inappropriate locations. Thus, their combination results in the determination of suitable

locations and all design criteria are satisfied when the FS is equal to one. Figure 5 presents the Boolean maps accounting for each criterion. Proper locations correspond to a cell value equal to "1" and the cells where, according to the criterion values, should be omitted are shown in light grey (cell value: "0"). The formulation of the criteria as constraints controls the WLC results in terms of avoiding their selection when the WLC is applied, resulting in the suitability map of Fig. 6.

Since FS takes values between "0" and "1", in order to better illustrate the spatial distribution of FS, five equal classes are created (i.e., "0"; "0.25"; "0.50"; "0.75"; "1.00") that represent the possible values among criteria combinations. The first class (FS = 0) corresponds to 34 % of the total area of the river basin and it represents the areas where hydrometeorological stations are not permitted to be established. The percentage for the class of value "0.25" is 39 %, for FS = 0.50 is 16 % C, for FS = 0.75 is 7 %, and only 4 % of the basin reaches the highest score, that is when FS is equal to 1.0. The candidate positions with FS = 1 are shown in dark green color in the suitability map of Fig. 6.

The final selection of proposed locations among all suitable cases is linked to the criterion of density that depends on land elevation (Fig. 7). The calculation of the minimum necessary number of stations for each elevation zone is presented in Table 3. Zone B covers the largest area (163 km$^2$) and requires the installation of two stations. The installation of one station is required in Zone C. Subsequently, according to the station density criterion, the optimum number of stations is three and the locations are shown in Fig. 8. Finally, it should be noted that, in the current work, decision makers followed a practice that minimizes the number of
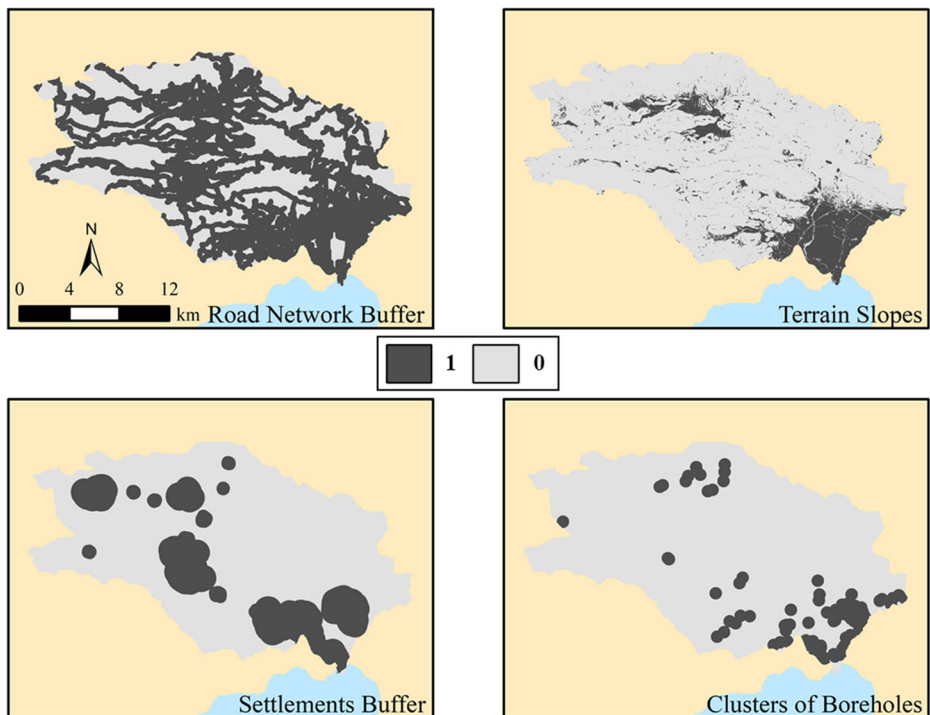


Fig. 5 Boolean maps of criteria for hydrometeorological station network design
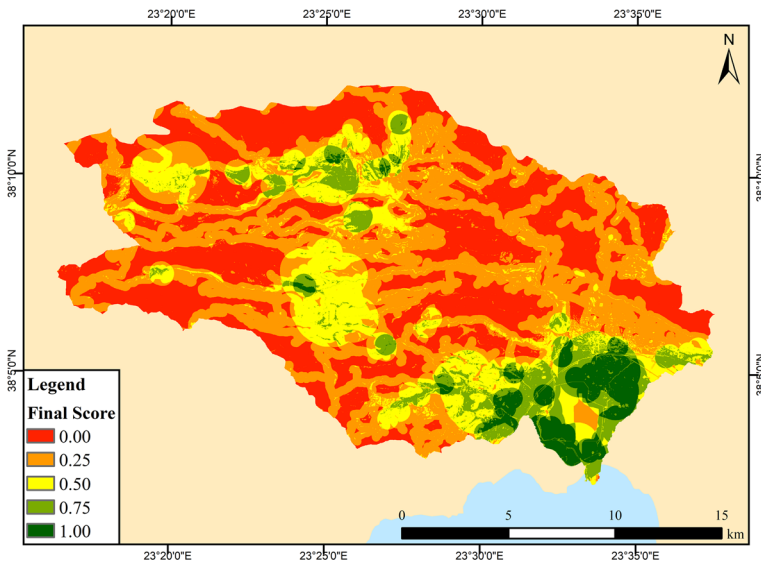
**Fig. 6** WLC among criteria for hydrometeorological station network design

necessary stations (Table 3), as the elevation areas that are not monitored by a station are small. When the decision is borderline, then the Ceiling method should be followed.

Regarding hydrometric station network, Table 4 shows the corresponding factor weights for each scenario; the calculation process is described in detail by Theochari et al. (2019). For reason of illustrating the results, two clusters regarding FS are created (Fig. 9); 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. The comparison of the three scenarios regarding weighting shows that the criterion of "slopes" is the most critical for all scenarios, while the criterion "distance from
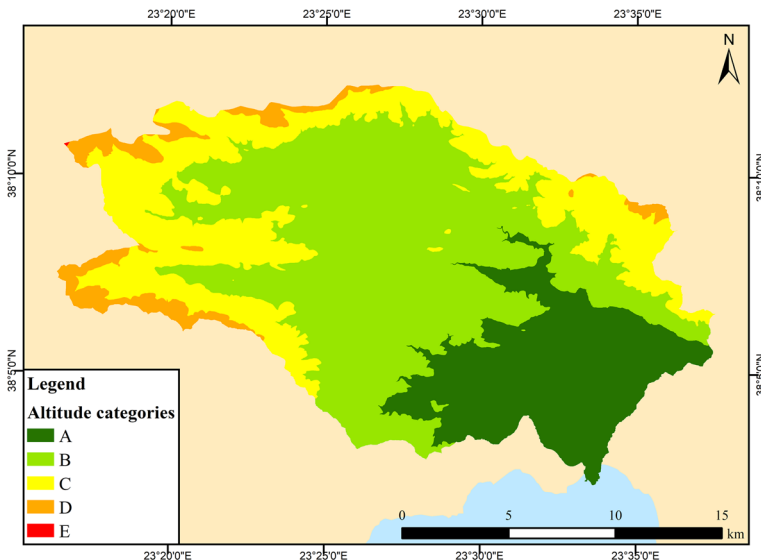


**Fig. 7** Altitude categorization for Sarantapotamos river basin

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

| Zone | Altitudes (m) | Station density | Area (km²) | 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 |
| Total | - | - | 341 | - | 3 |

settlements" is the least important for the first and the 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 the design serves the scope of developing a flood early warning system. For a FS > 90 %, all scenarios lead to the suggestion of the same optimal sites (the one of highest FS and the second best-case located in the southern part of the river; Fig. 8). Scenario 3a (Fig. 9c) (weights determination using AHP) results in 59 positions with high FS, while in scenario 3b (Fig. 9d) (weights determination using FAHP) the resulting map denotes 437 potentially suitable positions. This increase in suitable locations is observed as, when using the FAHP approach, only two criteria are finally considered to identify the optimal sites, hence, there are less constraints. The same result emerges from the corresponding analysis of Theochari et al. (2019). 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 the first scenario denotes proper locations across the entire length of the mainstream. The unique characteristic of the first scenario is that it attributes higher weights on low slopes, road network proximity and junctions to avoid the influence of other streams during flow recording, thus, it is preferable when decision makers select this criteria hierarchy.
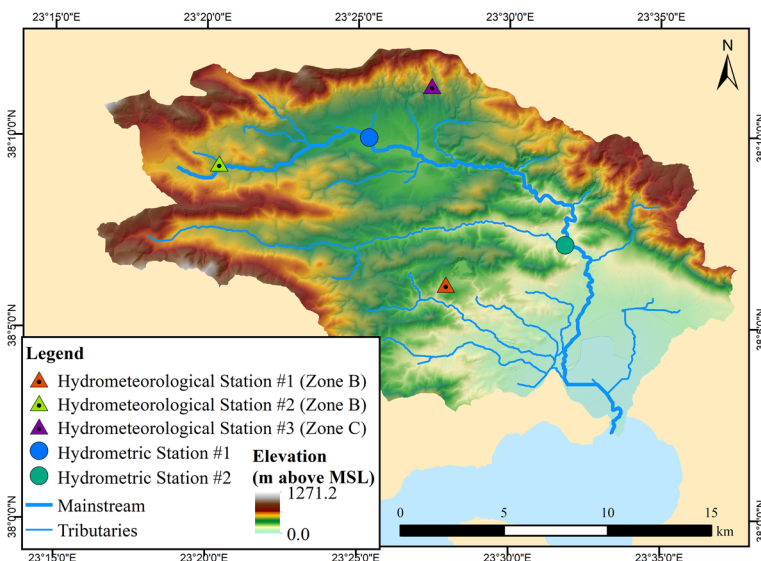


**Fig. 8** Hydrometeorological and hydrometric station network site selection
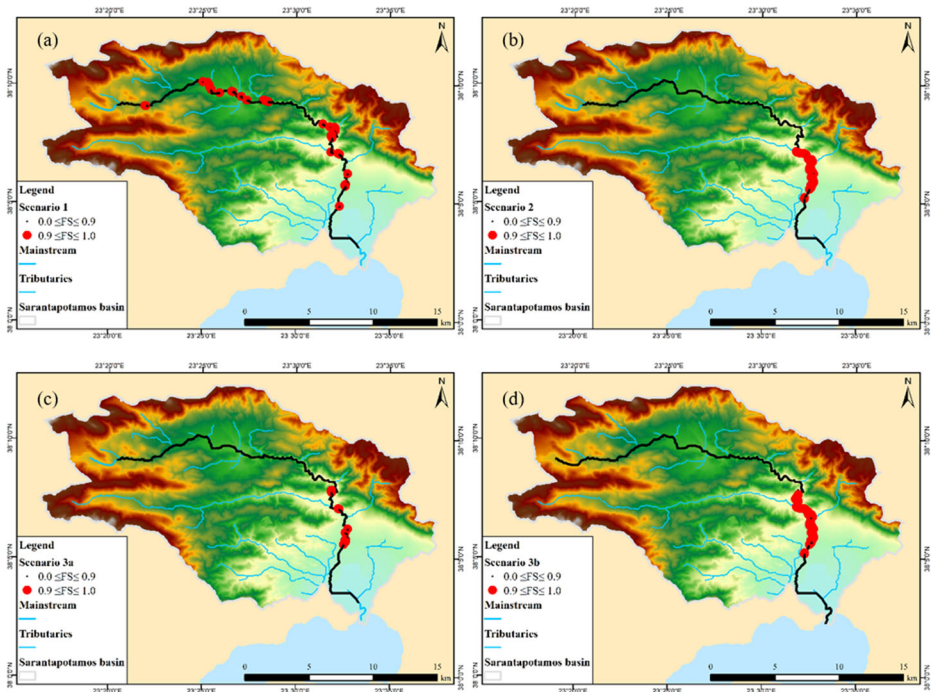
**Fig. 9** FS across the mainstream depicted in two clusters of $(0.0 \leq FS \leq 0.9, 0.9 \leq FS \leq 1.0)$ for (**a**) scenario 1, (**b**) scenario 2, (**c**) scenario 3a, (**d**) scenario 3b

The design criteria are determined across the entire length of the mainstream, then are combined, and resulting in this distribution of optimum locations. Taking into consideration the results from the previous relevant work of Theochari et al. (2019), it is observed that the distribution of the proposed positions for the same scenarios differs for the same study area, criteria, and criteria weighting, affected by the datasets used and the different formulation of the criteria between the two approaches. Therefore, the way of expressing the criteria in a GIS environment as well as the data used for the entire analysis are additional factors influencing the station network design. The latter strongly depends on the decision makers' perspective, especially concerning the HY station network design approach that is more flexible in the criteria formulation and hierarchy, compared to the HM one, where constraints are applied (i.e., the criteria are expressed as Boolean maps) instead of combining criteria in normalized values.

As shown in the map of Fig. 8, the required number of hydrometeorological stations is three and the required number of hydrometric stations is one; however, two locations are proposed for HY stations for better monitoring 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 best locations are selected according to the number of stations required by the recommendations of WMO (2008b) and the spatial distribution in the Sarantapotamos basin. Regarding the network of hydrometric stations, the location proposed at the northern part of the river basin along the bridge on the provincial road Oinois-Panaktou is the optimum according to the first scenario and it meets the criterion of technical adequacy of the position. The location of the second hydrometric station to the south is a location with

**Table 4** Criteria weights for each Scenario (Data adopted 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       |

FS > 0.9 for all scenarios examined and it is near the provincial road Oinoi - Magoula, close to the settlements of Mandra and Magoula, and it is proposed for flood protection reasons, as well.

## 5 Conclusions

This paper presents a GIS-based multicriteria decision making approach for the optimum design and establishment of a hydrometeorological - hydrometric station network. An application is made in the Sarantapotamos River basin, located in Attica (Central Greece). Results denote that the suitability score of the locations is highly affected by the selected criteria, their attributing hierarchy and their formulation in a GIS environment. This analysis also illustrates that the resolution and accuracy of the geospatial data used are also a decisive factor for final score determination, and thus, for the selection of suitable locations for a station installation. Moreover, the analysis shows that the optimum number of stations is determined only by the recommendations of the World Meteorological Organization, and not that of decision makers. The hydrometric station network design approach allows for various suggestions regarding station location, as, when 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 criterion. From this observation, it is concluded that the subjectivity in the analysis, which can be decreased using the FAHP method in weight estimation, is the main disadvantage when there is a need for a proposed network based on objective estimations regarding design. As an overall conclusion, the aforementioned methodology, which only requires a limited number of spatial data, can be particularly useful for the determination of suitable locations for station installation in large watersheds and can contribute to obtain a sense of suitability with minimum cost and short period of time.

Regarding future research, the introduction of further criteria for both networks is suggested. Modifications can be applied to the applied factor weighting methods, as well as, to the standardization and classification approach that is followed. The comparison among results using different approaches would be of interest, and also, the implementation of the methodology at different spatial scales and to catchments of different characteristics.

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

**Code Availability**   Not applicable.

## Declarations

**Conflicts of Interest/Competing Interests**   The authors declare that they have no conflicts of interest.

**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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