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A fuzzy AHP-outranking framework for selecting measures of river basin management plans

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ABSTRACT

The selection of development measures is not merely a financial issue, but crucial parameters, such as environmental protection and socioeconomic security ought to be taken into consideration. In this research, the measures proposed by the Programmes of Measures (PoMs) through the Water Framework Directive implementation process are evaluated with the use of integrated hybrid multicriteria methods. Multicriteria outranking methods are coupled with a 0/1 linear programming in which the cost of the measures is induced as a constraint. The monocriterion scores of the applied method, in which 6 criteria and 37 alternatives are integrated, are proposed for the prioritization of the supplementary PoMs. The case study area is the River Basin District of Central Macedonia, Greece. Fuzzy analytical hierarchy processes are used to determine the weights of the criteria as crisp numbers even if fuzzy pairwise comparisons among the importance of the criteria exist. The advantages of these choices are presented in the article, and the results of the research demonstrate the usefulness of the methodology when financial constraints do not permit the implementation of the whole set of measures.

Keywords: Multicriteria outranking methods; Fuzzy AHP; 0-1 programming; River Basin Management Plans; Central Macedonia Water District

1. Introduction

The Programmes of Measures (PoMs) are included in the River Basin Management Plans (RBMPs), with the later to be amongst the outputs of the Water Framework Directive (WFD) implementation process. Since the aim of the WFD is to prevent deterioration of the aquatic environment and to achieve good status of all water bodies [1], the PoMs focus at ameliorating degraded water bodies as well as protecting the status of healthy water bodies. The measures proposed by the Programmes of Measures are organized in basic and supplementary measures [2], and all such measures must be commensurate with (a) the nature of the exerted anthropogenic pressures and (b) water use modalities. Data derived from the European Union (EU) environmental statistics [3] depict that the most common measures reported by Member States are categorized to (i) construction or upgradation of urban wastewater treatment, (ii) reduction of nutrient pollution in agriculture, (iii) improvement of river continuity and other hydromorphological measures, (iv) research, improvement of knowledge base reducing uncertainty and (v) drinking water protection measures. Moreover, the analysis indicates that at the end of 2016 at EU level, only 23% and 29% of proposed basic and supplementary measures, respectively, were reported as completed. At the same time 11% and 17% of the basic and supplementary measures have not been initiated. The process of both type of measures has not been initiated due to funding and financial obstacles

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[2,4]. Apart from those constraints, reasons, such as the lack of approved studies when dealing with construction measures, the absence of political decision and the low acceptance from the local societies, have a direct impact on the delay of the implementation process.

For the achievement of the PoMs, and thus the Directive's ecological objectives, the use of economic tools and financial principles is proposed by the WFD, with the specific approach to be considered as one of its most novel and interesting aspects of the Directive [5]. Environmental accounting deals with the integration of complex biophysical data, tracking changes in ecosystems and linking those changes to economic and other human activities [6]. The WFD states that the economic analysis shall 'make judgments about the most cost-effective combination of measures in respect of water uses to be included in the programme of measures under Article 11 based on estimates of the potential costs of such measures' [7]. The literature proposes various methods for the economic assessment, such as the cost recovery ratio for the irrigation sector [8], with cost recovery ratios to be computed by dividing the income generated from water services by the cost of their provision, and the cost-effectiveness analysis (CEA) [7,9]. The CEA can be expressed as the cost effectiveness ratio (R) [10], which is defined as the quotient of the annual equivalent cost (expressed in monetary terms e.g., Euros/year) vs. the effectiveness that attributes the quantitative change of either the impact or the pressure [11]. In the WFD, CEA can be conceived as an applied appraisal technique that classifies alternative measures on the basis of their costs and effectiveness to achieve the environmental objectives of the Directive [9]. However, the estimation of the cost-effectiveness of water quality measures is surrounded by environmental, economic and political uncertainty [12]. In addition, there are arguments that CEA put emphasis on the bias of the cost-effectiveness method toward large-scale actions [11,12,13].

The selection of the most-cost-effective combination of measures is not a solely financial issue, that is, measures with the lower cost are the most appropriate, but also include subjects related to the water resources and the environment, such as water bodies' quality status, socioeconomic and environmental impacts, synergies among the measures, and effectiveness of the measures against the environmental targets. In cases of multiple environmental and resource management conflicting criteria in the decision-making process, multicriteria analysis (MCA) could provide scientifically sound solutions [14,15]. MCA has also been used to explore non-market monetary values of water quality changes in the context of the WFD, and particularly a specific MCA method, namely the analytical hierarchy process (AHP), was proposed to investigate whether the water quality improvements were measured using a water quality ladder [16].

The main MCA methods could be classified as: (1) value measurement approach (e.g., utility theory), (2) satisfying approach, especially the distance methods (e.g., compromise programming, goal programming), and (3) outranking methods (e.g., Electre family, Promethee) [16]. The outranking methods focus on pairwise comparison of comparison of alternatives to discrete choice problems. The outranking methods differ from the value function methods on the fact that there is no underlying aggregative value function. The output of an analysis is not a value of each alternative, but an outranking relation on the set of alternatives. Moreover, the outranking methods do not treat the selection of the weighs between the criteria. Among the methods of pairwise comparison, the AHP is the most common especially when aiming to achieve the weight distribution of the criteria based on the pairwise comparison among them. Rather recently, several AHPs were developed in order to include the fuzzy values in the pairwise comparisons. In other words, fuzzy analytic hierarchy process (FAHP) can be used since it is based on pairwise comparisons and allows the utilization of linguistic variables. The FAHP is used to assess the weight distribution between the criteria. The outranking method is used to achieve a finally binary comparison between the alternatives over all criteria. To simplify the decision, the use of scoring functions is proposed which exploits the achieved binary comparison of the alternatives over all criteria. The net flow scoring function [17] can also be seen in the case of net flow in Promethee II method [18].

It is common to combine the AHP (or the FAHP) with a main selected multicriteria method [19,20] and thus, an integrated multicriteria method is created. The first choice treats the selection of the criteria weights, while the second choice treats the final (over all criteria) evaluation of each alternative. However, by applying multicriteria methods for the direct comparison of various alternatives and their rank is with no practical value. In practice, the final solution consists of a number of alternatives each of which have different level of acceptance [21] under a set of constrains (e.g., budget constraints, water availability constrains, cover the water demands etc.).

The application field of the proposed methodology is the Water District of Central Macedonia, Greece. The specific area includes both transboundary and national water bodies with different water uses and water demands. The aim of the research is to provide an integrated and rational framework in order to select the proposed measures by taking into account the available budget and the multiple dimensions of the examined water system. Hence, the proposed framework couples a comprehensive fuzzy MCA with 0/1 linear programming for prioritizing the measures included in the Programme of Measures of River Basin Management Plans, based on the availability of funds for the implementation process. The paper, apart from the introduction, is divided into the five following sections: (i) the case study area, (ii) the integrated multicriteria approach which is coupled with the 0/1 programming, (iii) the presentation of the results, (iv) the discussion and finally, and (v) the concluding remarks.

2. Study area and data

The Water District of Central Macedonia (WD GR10), Greece, extends over 10,163 km^2 and includes four river basins, namely Axios, Gallikos, Chalkidiki and Athos. According to 2011 census data, the permanent population of the WD GR10 is 1,420,321 inhabitants, with the employment structure to be allocated as 16.9%, 26.5% and 56.6% to the primary, secondary and tertiary sector, respectively [22]. The water uses are classified in water supply, irrigation, livestock, industry and mining, with the total annual demand on water for all uses to be about 1,600 hm^3 (approximately 22.4% of the water demands are covered from a neighboring Water District) [22]. Even though primary's sector labour force is relatively small, the irrigation demands on water are tremendous and equal to 1,360 hm^3, that is, 85% of the available water volumes. On the other hand, the water for the industry and water supply represents 3% and 11% of the water availability, respectively. As for the anthropogenic pressures, those related with urban wastewater, industry, livestock, landfill sites—uncontrolled waste dumping sites, mines and quarries, aquaculture and agriculture are the most intensive.

For the protection of the water bodies as well as the amelioration of those that were identified being at "not good" status, the river basin management plan (RBMP) of Water District 10 (WD10) propose a specific PoMs. The RBMP as well as the PoM was conducted by a consulting firm, and after the procedure, that is, denoted in the WFD, that is, public participation and stakeholder involvement in the evaluation of the plan, the specific strategic was ratified both by the Greek Ministry of Environment and Energy and the EU. The PoMs of WD10 consist of 39 basic and 37 supplementary measures to be presented in Table 1. The proposed methodology is implemented to the sum of the supplementary measures (SM). Based on the WFD nomenclature, the SM02-10 and SM03-10 belong to the category "Administrative Measures", that is, these measures have limited cost, SM04-10 to SM04-30 to the category "Environmental agreements after negotiations", with these measures to have zero cost, SM05-30 to SM05-50 to the category "Emission Limits Values", measures with moderate cost, SM07-10 and SM07-20 to the category "Recreation and Restoration of wetlands areas", that is, measures with significant cost, SM08-10 to SM08-40 to the category "Monitoring abstractions", that is, relatively small cost, SM11-10 to SM11-80 to the category "Construction projects", that is, measures with significant cost, SM15-10 to SM15-40 are classified as "Educational Measures", that is, measures with small cost, SM16-10 to SM16-30 are classified as "Research, development and demonstration Projects (best practices) ", that is, average cost measures, while SM17-10 to SM17-100 belong to the category "Other measures", with these measures to have variant but relatively small cost. The more general term "alternative" can also be used instead of "measure" which is used in the multicriteria theory.

The six criteria that are used in the specific research were retrieved by the RBMP of WD GR10 [22]. In particular the criteria are the:

- efficiency of the measure (Cr. 1);
- significance of the measure (area and water quality improvement) (Cr. 2);
- implementation cost (Cr. 3);
- potential socioeconomic and environmental impacts (Cr. 4);
- risk of implementation due to climate change (Cr. 5) and
- synergies among the measures (Cr. 6).

The importance weight of each criterion can be obtained by exploiting the pairwise comparisons of criteria [23] with the use of fuzzy analytical process. The selected criteria cover the multiple aspects of the decision linked to the environmental, socioeconomic, economic, technical efficiency and the reliability axis integrated to the River Basin Management Plan of Water District of Central Macedonia (case study area). The thorough presentation of the proposed methodology of the alternatives scoring is believed to be out of the scope of the present research, thus for demonstrating purposes only the scoring methodology of Cr. 1 and Cr. 4 is presented. The efficiency of the measure (Cr. 1) is computed by the following formula:

$$\text{Cr.1} = \frac{\text{Level of meas. implem* + time frame of meas. implem + time frame of meas. effect **}}{3} \quad (1)$$

*meas. implem: measure implementation
**meas. effect: measure effectiveness

where:

- Level of measure implementation corresponds to the progress that has been achieved to the implementation of a specific measure, with the scoring to be 0.33, 0.66 and 1.0 for low, medium and high level of implementation, respectively.
- Time frame of measure implementation corresponds to the time frame that is required to implement a measure, with the scoring of 0.33, 0.66 and 1.0 to be attributed to long-term, medium-term and short-term time frames, respectively.
- Time frame of measure effectiveness demonstrates the time frame that is required in order for a measure to pays off, with the scoring of 0.33, 0.66 and 1.0 to be attributed to long-term, medium-term and short-term time frames, respectively.

The score of the Cr.4 is given by the formula:

$$\text{Cr.4} = \text{social impacts} + \text{economic impacts} + \text{environmental impacts} \quad (2)$$

Each measure may have neutral or positive or negative impacts, and thus it gets a value of 0, 1 or –1, respectively, for each type of impact. The sum that is derived from the above formula is normalized from 0 to 1 range.

Table 2 expresses the score of each alternative regarding all the examined criteria according to River Basin Management Plan of Central Macedonia, Greece [22].

Therefore, the first point of the decision aid is the multicriteria aspect of the decision. The second point of the decision aid is the available budget. As aforementioned, the problem is the selection of the measures with respect to the budget constraints by taking into account the multi-aspect nature of the problem. Hence, the fuzzy AHP and the multicriteria outranking method based on fuzzy sets and logic sections deals with the multicriteria evaluation of the alternatives, whilst the 0–1 programming integrates the proposed methodology by taking into account both the budget constraints and the multicriteria aspect of the problem. The final solution, that is, the set of measures which are selected is modulated according to the solution of the 0–1 programming problem.

Table 1
List of supplementary measures of the RBMP of Central Macedonia River Basin District [22]

Alt.	Code	Description	Cost (×10³ €)
X_1	SM02-10	Increase of reporting frequency of the environmental licensing of companies operating in areas where there are strong pressures	0
X_2	SM03-10	Reform of water providers accounting systems	405
X_3	SM04-10	Agreements with industries that consume large water quantities or generate pollution in WB for adopting codes of good practices	0
X_4	SM04-20	Promotion of agreements with owners of tourist accommodation establishments	0
X_5	SM04-30	Promotion of producers' participation in the Agricultural Production Integrated Management Systems	0
X_6	SM05-30	Hydrogeological-hydrochemical survey to GWB with high concentrations of chemical substances, due to natural background	2,095
X_7	SM05-40	Special protection measures in areas with GW bodies where geothermal and mineral waters exist	0
X_8	SM05-50	Rehabilitation of Thessaloniki Gulf by mechanical means	240
X_9	SM07-10	Measures from the approved recovery plan of the National Park for the lakes Koroneia-Volvi and Macedonian Tembi	120,361
X_{10}	SM07-20	Integrated Coastal Monitoring of Environmental Problems in Sea Region and the Ways of their Solution (ICME)	1,070
X_{11}	SM08-10	Setting out terms for the protection of the granular system Ormylia after the completion of Chavrias dam	0
X_{12}	SM08-20	Installation of a functional valve in artesian wells	0
X_{13}	SM08-30	Definition of principle restriction zones for drilling new wells in coastal GW bodies where seawater intrusion is observed	0
X_{14}	SM08-40	Definition and delimitation of areas of GWB that have poor quality due to seawater intrusion or exhibit local seawater intrusion	1,295
X_{15}	SM11-10	Chavria's dam and networks of Chavria's dam	65,000
X_{16}	SM11-20	Petrenia Dam in the area Gomati and storage, treatment and distribution projects	46,265
X_{17}	SM11-30	Landfill Site expansion in the area of Cassandra	6,704
X_{18}	SM11-40	Landfill Site Development in the NW part of the Regional Unit of Thessaloniki	7,347
X_{19}	SM11-50	Landfill Site Restoration in the Municipality of Kilkis	4,761
X_{20}	SM11-60	Landfill Site / Residue at the 4th Management Unit in Chalkidiki	14,856
X_{21}	SM11-70	Completion of maturation processes of Fanos dam at Paionia (KotzaDere)	2,700
X_{22}	SM11-80	Construction of the main sewer of Thessaloniki	24,200
X_{23}	SM15-10	Enhancing the Environmental Education Centre of the Regional Units	150
X_{24}	SM15-20	Management of riparian habitats and visitors, knowledge spreading and public awareness raising in protected areas	867
X_{25}	SM15-30	Educational Actions to promote the prudent and rational utilization of water resources.	90
X_{26}	SM15-40	Consulting services to farmers for the improvement of practices of means and supplies for the protection of the environment.	30
X_{27}	SM16-10	Preparation of research studies for the artificial recharge of GW bodies with treated effluents from WWTP and Industrial WWTP	1,036
X_{28}	SM16-20	Integrated Green Cities (INGREENCI)	646
X_{29}	SM16-30	Actions for protection of coastal habitats and important avifauna species in NATURA 2000 areas (Epanomi&Aggelohori lagoons)	1,639
X_{30}	SM17-10	Further investigation of exceedances in chemical substances that are recorded in lake Koronia.	145
X_{31}	SM17-30	Further investigation of exceedances in chemicals substances that are recorded in lake Volvi	145
X_{32}	SM17-40	Mitigating the Vulnerability of Water Resources in the context of climate change	167
X_{33}	SM17-50	ENVI/Local Communities in Environmental Action	231
X_{34}	SM17-70	Sampling and analysis of water inside and outside the port of Thessaloniki	370
X_{35}	SM17-80	Further investigation regarding measurements and causes of exceedances in chemical substances in the Gulf of Thessaloniki	200
X_{36}	SM17-90	Masterplan for the Gulf of Thessaloniki	15
X_{37}	SM17-100	Evaluation of the dual-use of the united canal Aliakmonas-Axios concerning the water supply in the regional area of Thessaloniki.	15

Table 2
Scoring of the criteria regarding the supplementary measures of the RBMP of Central Macedonia River Basin District [22]

Alt.	Cr. 1	Cr. 2	Cr.3	Cr.4	Cr.5	Cr. 6
X_1	1	0.2	1	0.11	0.75	0.19
X_2	0.89	1	0.66	0.22	1	0.39
X_3	0.66	0.24	1	0.44	1	0.1
X_4	0.78	0.28	1	0.44	1	0.16
X_5	0.55	1	1	0.44	1	0.52
X_6	0.66	0.73	0.33	0.44	0.75	0.23
X_7	0.55	0.5	1	0.44	0.75	0.03
X_8	0.89	0.04	0.66	0.44	0.75	0.16
X_9	0.77	0.17	0.33	0.78	0.83	0.19
X_{10}	0.66	0.04	0.33	0.78	0.75	0.45
X_{11}	0.66	0.02	1	0.33	0.67	0.13
X_{12}	0.89	0.1	1	0.33	1	0.1
X_{13}	0.89	0.25	1	0.33	0.66	0.29
X_{14}	0.55	0.25	0.33	0.33	0.83	0.48
X_{15}	0.66	0.09	0.33	0.56	0.83	0.06
X_{16}	0.55	0.09	0.33	0.56	0.83	0.06
X_{17}	0.66	0.04	0.33	0.56	0.75	0.03
X_{18}	0.66	0.07	0.33	0.56	0.75	0.03
X_{19}	0.66	0.12	0.33	0.56	0.75	0.03
X_{20}	0.66	0.09	0.33	0.56	0.75	0.03
X_{21}	0.66	0.12	0.33	0.56	0.83	0.19
X_{22}	0.77	0.04	0.33	0.56	0.75	0.32
X_{23}	0.66	1	0.66	0.56	1	0.97
X_{24}	0.77	0.76	0.66	0.56	1	0.32
X_{25}	0.66	1	1	0.56	1	1
X_{26}	0.77	1	1	0.56	1	0.9
X_{27}	0.55	0.6	0.33	0.56	0.83	0.19
X_{28}	0.55	0.3	0.66	0.56	0.83	0.39
X_{29}	0.77	0.06	0.33	0.56	0.67	0.23
X_{30}	0.66	0.1	0.66	1	1	0.23
X_{31}	0.66	0.11	0.66	1	1	0.13
X_{32}	0.78	1	0.66	1	1	0.84
X_{33}	0.66	0.76	0.66	1	1	0.32
X_{34}	0.89	0.04	0.66	1	0.75	0.55
X_{35}	0.66	0.04	0.66	1	0.75	0.55
X_{36}	0.89	0.08	1	1	0.75	0.68
X_{37}	0.77	0	1	1	1	0.03

3. Proposed methodology

3.1. Integrated fuzzy multicriteria approach

In general, a decision problem is a problem in which we consider a set A of potential alternatives (possible solutions, feasible decisions, measures) among which we must: (1) either choose a unique alternative considered as 'the best', (2) or select a subset of actions considered as 'good' or more generally, classify the alternatives into categories, and (3) or order the actions from the best to the worse [24]. In this methodology, the authors deal with the third case [25].

A critical point is that the final decision is made in the next step where the 0/1 programming is implemented and this ranking process is used to construct the objective function of the 0–1 programming.

The proposed integrated fuzzy multicriteria approach addresses three points. The first one is the selection of the weights between the criteria. This is achieved with respect of the binary comparison between the criteria as it is achieved based on the experts and the public participation (in this article based on the literature [22]). The AHP addresses this point.

The second point is the final multicriteria ranking between the alternatives (measures). To address this point, the proposed outranking method is dealt. The outranking multicriteria method is used due to the fact that the outranking methods can incorporate the ambiguous in case of the binary comparison between the alternatives and the uncertainty of the multicriteria synthesis. In fact, ELECTRE methods were developed in order to account for heterogeneous criteria whose aggregation in a common scale is difficult, to prevent compensation behaviour and to account for differences in terms of preferences, leading in this way to the introduction of thresholds [24,26].

The third point is the fuzziness. The fuzziness is used in order to express the uncertainty during the evaluation of the criteria (e.g., the qualitative criteria) and furthermore, the uncertainty of the binary comparison between the criteria. Indeed, Perny and Roy, 1992 [27] founded the Electre method based on the fuzzy sets and logic.

3.1.1. Fuzzy AHP

First of all, the criteria are binary compared among them by asking the DM his preference on a scale from 1 to 9, with 1 indicating equal preference and 9 absolute preference [28]. Intermediate values are used to express increasing preference/performance for one weight/alternative.

The resulting output of this procedure is a matrix of comparisons expressed as ratios, and the next step is the reduction of the pairwise comparison matrix to a set of scores representing the relative importance of each weight and performance of alternatives (priority vectors) [29].

However, the standard AHP prioritization approach cannot be used, when the decision maker faces a complex and uncertain problem and expresses his/her comparison judgments as non-precise ratios, such as 'about two times more important', 'between two and four times less important', etc. [30]. In this research, a FAHP is developed to produce the weights among the criteria, since it seems more reasonable to use linguistic values to express the comparison between the criteria.

Let n the number of the criteria. Let also the following interval reciprocal comparison matrix of the type:

$$A = \begin{bmatrix} 1 & (l_{12}, m_{12}, u_{12}) & (l_{13}, m_{13}, u_{13}) & \dots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & 1 & (l_{23}, m_{23}, u_{23}) & \dots & (l_{2n}, m_{2n}, u_{2n}) \\ (l_{31}, m_{31}, u_{21}) & (l_{32}, m_{32}, u_{22}) & 1 & \dots & (l_{3n}, m_{3n}, u_{3n}) \\ \dots & \dots & \dots & \dots & \dots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & (l_{n3}, m_{n3}, u_{n3}) & \dots & 1 \end{bmatrix} \tag{3}$$

It is also considered that $l_{ij} = 1/u_{ji}$, $m_{ij} = 1/m_{ji}$, $u_{ij} = 1/l_{ji}$, $l_{ij} \le m_{ij} \le u_{ji}$ and $0 < l_{ij} \le m_{ij} \le u_{ji}$ for all $i, j = 1,2,...,n$, $j \ne i$. The index i indicates the examined criterion, whilst the index j indicates the criterion according to which the criterion i is compared.

In this research, the authors aim at concluding to a set of crisp weights regarding the criteria, and hence, the problem is to conclude to crisp priorities based on fuzzy pairwise comparison judgments.

Crisp weights from fuzzy pairwise comparison judgments can be produced by using the extent analysis [31] and it has a large field of applications. This is because this method does not conclude to an optimization problem and always leads to weight distribution. However, as it was suggested by Wang et al. [32] the extent analysis maybe invalid and the weights derived by this method may not represent the relative importance of selected criteria. For this purpose, the FAHP which is proposed by Wang and Chin [33] is developed in the article.

It is evident that first of all, the selected crisp weight must produce ratios which should satisfy the following fuzzy inequalities:

$$l_{ij} \tilde{\le} \frac{w_i}{w_j} \tilde{\le} u_{ij} \tag{4}$$

where symbol $\tilde{\le}$ means "fuzzy less or equal to".

To deal with these fuzzy inequalities, Mikhailov and Tsvetinov [30] proposed a new membership function in order to measure the degree of satisfaction for different crisp ratios w_i/w_j with respect to both inequalities. A key idea in order to modulate the membership functions is that the most possible value may be the center of a fuzzified interval, that is, where $l_{ij} = 1/u_{ji}$, $m_{ij} = 1/m_{ji}$, $u_{ij} = 1/l_{ji}$, $l_{ij} \le m_{ij} \le u_{ji}$. According to the strict mathematical formulation, the membership function expresses its values between zero and one. However, in practical cases, it is impossible to find a crisp solution which simultaneously satisfies $\frac{w_i}{w_j} = m_{ij}$. Thus, the approximated following membership function is proposed:

$$\mu_{ij}\left(\frac{w_i}{w_j}\right) = \begin{cases} \dfrac{\left(\dfrac{w_i}{w_j}\right) - l_{ij}}{m_{ij} - l_{ij}}, & l_{ij} < \left(\dfrac{w_i}{w_j}\right) \le m_{ij} \\ \dfrac{u_{ij} - \left(\dfrac{w_i}{w_j}\right)}{u_{ij} - m_{ij}}, & u_{ij} > \left(\dfrac{w_i}{w_j}\right) \ge m_{ij} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Having all the individual membership functions, the problem is to determine a global evaluation [34] through a proper fuzzy operator with respect to all objectives which in the article, represent fuzzy inequalities. For this purpose, various fuzzy operators can be used. The min intersection is implemented because it secures a common satisfaction of all the selected membership functions [35,36]:

$$\lambda = \min\left\{ \mu_{ij}\left(\frac{w_i}{w_j}\right) \middle| i = 1,...,n-1, j = i+1,...,n \right\} \tag{6}$$

Hence, λ according to Mikhailov and Tsvetinov [30] method expresses the common degree to which the crisp individual priority vector satisfies simultaneously each fuzzy pairwise comparison.

The larger the λ the larger the common degree of satisfaction of the inclusion concept. Indeed, since the decision maker should conclude in a crisp decision proposal, it seems more appropriate that he should suggest the dividend with the highest degree of membership function in the fuzzy set decision.

$$\max \lambda$$

s.t.

$$\begin{cases} \min\limits_{ij}\left[\mu_{ij}\left(\dfrac{w_i}{w_j}\right)\right] \ge \lambda, \quad i = 1,...,n-1,\ j = i+1,...,n \\ \sum\limits_{i=1}^{n} w_i = 1 \\ w_i \ge 0,\ i = 1,...,n \end{cases} \tag{7}$$

It is easy to see that all the fuzzy optimization problems presented above have a non-linear form. As Wang and Chin [33] demonstrated, they have the following drawbacks: negative membership degree could exist but this fact makes no sense. Furthermore, because of the nonlinear form, multiple optimal solutions exist. Finally, the priority vectors derived by using the upper or lower triangular elements of a fuzzy pairwise comparison matrix are not identical. However, the aforementioned authored some disadvantages of the above problem by using a logarithmic transformation to linearize the set of inequalities and furthermore, by introducing some non-negative deviation variables. First of all, instead of the row data, the methods work with the logarithmed values [33] and thus the following fuzzy triangular number is considered:

$$\ln \tilde{a}_{ij} \approx \left(\ln l_{ij}, \ln m_{ij}, \ln u_{ij}\right) \tag{8}$$

This approximation can be justified due to the extension principle and since the function $\ln x$ is a strictly increasing function. However, this equation is valid as an approximation since the linearity does not hold because of the logarithmic transformation. Hence, the membership function is formulated as follows:

$$\mu_{ij}\left(\ln\left(\frac{w_i}{w_j}\right)\right) = \begin{cases} \dfrac{\ln\left(\dfrac{w_i}{w_j}\right) - \ln l_{ij}}{\ln m_{ij} - \ln l_{ij}}, & \ln\left(\dfrac{w_i}{w_j}\right) \le \ln m_{ij} \\ \dfrac{\ln u_{ij} - \ln\left(\dfrac{w_i}{w_j}\right)}{\ln u_{ij} - \ln m_{ij}}, & \ln\left(\dfrac{w_i}{w_j}\right) \ge \ln m_{ij} \end{cases} \tag{9}$$

Consequently, the optimization problem could have the following form:

$$\max \lambda$$
s.t.
$$\min_{ij}\left[\mu_{ij}\left(\ln\left(\frac{w_i}{w_j}\right)\right)\right] \geq \lambda,\; i=1,\ldots,n-1,\; j=i+1,\ldots,n \tag{10}$$

The equality constraint $\sum_{i=1}^{n} w_i = 1$ may be omitted for simplicity reason whilst the normalization can be achieved later by establishing a normalization procedure. Indeed the approach of Wang et al. [32] linearize the constraints:

$$\begin{aligned} &\ln w_i - \ln w_j - \lambda\left(\ln\left(\frac{m_{ij}}{l_{ij}}\right)\right) \geq \ln l_{ij},\; i=1,\ldots,n-1,\; j=i+1,\ldots,n \\ &\ln w_j - \ln w_i - \lambda\left(\ln\left(\frac{u_{ij}}{m_{ij}}\right)\right) \geq -\ln u_{ij},\; i=1,\ldots,n-1,\; j=i+1,\ldots,n \end{aligned} \tag{11}$$

However, sometimes the above formulation cannot produce a positive value for the membership function. The first comment should be that the negative values regarding the membership function do not have a physical meaning. This means that there is no solution that can simultaneously satisfy all the fuzzy judgments of pairwise matrix $\tilde{A}$. To deal with this inconsistency, as in case of the goal programming, a solution should be made to relax the inequalities constraints by introducing non-negative deviation variables δ_{ij}, $n_{ij} \geq 0$. Finally, the following problem with linear constraints (with the assistance of the ln transformation) and the use of the non-negative deviation variables is modulated:

$$\text{minimize } (1-\lambda)^2 + M\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(\delta_{ij}^2 + n_{ij}^2\right)$$
s.t.
$$\begin{cases} x_i - x_j - \lambda\left(\ln\left(\frac{m_{ij}}{l_{ij}}\right)\right) + \delta_{ij} \geq \ln l_{ij},\; i=1,\ldots,n-1,\; j=i+1,\ldots,n \\ x_j - x_i - \lambda\left(\ln\left(\frac{u_{ij}}{m_{ij}}\right)\right) + n_{ij} \geq -\ln u_{ij},\; i=1,\ldots,n-1,\; j=i+1,\ldots,n \\ \lambda, x_i \geq 0,\; i=1,\ldots,n \\ n_{ij}, \delta_{ij} \geq 0,\; i=1,\ldots,n-1,\; j=i+1,\ldots,n \end{cases} \tag{12}$$

In this formulation, the constraints are linear while at the same time a nonlinear objective function is adopted. Where $x_i = \ln w_i$, $i = 1,\ldots,n$ and M is a specific real number aiming to achieve a non-negative level λ and to small deviation from the inequalities.

It should be clarified, however, that since the deviations δ_{ij}, n_{ij} have non-zero values, the level λ will not be identical precisely with the its initial meaning, that is, the common degree according to which the crisp individual priority vector satisfies simultaneously each fuzzy pairwise comparison. However, the smaller the values of the deviation (near to zero), the closer to the initial meaning will be the level λ in this new formulation. In other words, a high value of λ with small deviations can be interpreted as a rather high simultaneous satisfaction of all the inequalities which expresses the fuzzy pairwise comparison between the importance of the criteria.

The last step is the normalization of the weights. The normalized values of the (crisp) weights based on the optimal solution $x_i^*(i = 1,\ldots,n)$ can be determined as follows:

$$w_i = \frac{\exp\left(x_i^*\right)}{\sum_{j=1}^{n}\exp\left(x_j^*\right)},\; i=1,\ldots,n \tag{13}$$

Consequently, after simple algebraic transformations take place, it is easy to prove that the priorities derived by the methodology of Wang and Chin [33] from the upper triangular elements of a fuzzy pairwise comparison matrix are identical compared with the ones derived from the lower triangular elements. However, the consideration of fuzzy equal weights can lead to slightly different results. Furthermore the final optimization problem leads to a unique normalized optimal priority vector for any fuzzy pairwise comparison matrix. This can be easily proved since the objective function of the final optimization system is a strict convex function and simultaneously the constraints are all linear inequalities, which form a convex feasible region.

3.1.2. Multicriteria outranking method based on fuzzy sets and logic

After obtaining the weights of the criteria and having the score of the criteria for each alternative the next step is to achieve the multicriteria synthesis. The widely-used Electre family methods conclude to a binary relation between the alternatives (measures). Therefore, the term binary comparison now is referred to the comparison between the alternatives. The binary comparison initially takes place by comparing two alternatives (measures) with respect to each criterion. Then these monocriterion binary comparisons are aggregated to produce a binary comparison between two alternatives over all criteria. In this final aggregation, the veto principle is activated.

The use of fuzzy sets and logic is used to express the gray region between the binary comparison. However, the proposed method concludes to total scoring function which expresses the multicriteria ranking of a measure over the other alternatives. This is required in order to move to the 0–1 programming step.

The strict preference (P) and indifference (I) are defined as fuzzy concepts in order to express the granularity of the preference. In addition, the strict preference and indifference can be defined as a function of outranking relation (S), which is a fuzzy binary relation [37,38]. The statement aSb means "α is not worse than b" (i.e., α is at least as good as b). The statement $\alpha S_j b$ does not mean that α is better than b with respect to criterion j. It means that either the score $a_j - b_j$ is positive or that the difference is not significantly negative to suggest a preference favor of b with respect to criterion j. The S monocriterion (binary) relation can be defined axiomatically as a special case of fuzzy set [16,20]. Let the monocriterion binary comparison of two alternatives α, b with respect to criterion j. Then the monocriterion (binary) outranking relation can be defined as follows [37]:

$$S_j(a,b) = \frac{p_j - \min\{b_j - a_j, p_j\}}{p_j - \min\{b_j - a_j, q_j\}} \quad (14)$$

where p_j, q_j state the preference and indifference thresholds, respectively, and (p_j, $q_j \geq 0$). The p_j, q_j thresholds express the fuzziness of the monocriterion comparison.

As it can be seen from Fig. 1, the monocriterion outranking relation S has a gray zone of comparison when $b_j \in [a_j + q_j,\ a_j + p_j]$. In case that $b_j > a_j + p_j$, then the alternative b has a significant better score regarding the criterion j and compared with the alternative α and hence, the outranking relation $S_j(\alpha, b)$ has vanished and simultaneously, the veto principle could be partially triggered (that is, the monocriterion discordance measure with respect to the outranking relation, $D_j(\alpha, b)$ is greater than zero). When the difference is significantly large, that is, when $b_j \geq a_j + v_j$ then the veto rule is triggered (Fig. 1).

In general, aggregation operators among fuzzy sets can be used to evaluate the concordance measure. The aggregation operators can be seen as measures between maximum (which is the lower bound of the fuzzy union and corresponds to the union of the precise logic) and minimum (which is the upper bound of the fuzzy intersection and corresponds to the intersection of the crisp logic) [39]. In this work, the weighted sum aggregator is used so as to modulate the concordance measure in regard to all criteria (respect of the majority principle).

$$C_s(\alpha, b) = \sum_{j=1}^{n} w_j S_j(\alpha, b), \quad \sum_{j=1}^{n} w_j = 1 \quad (15)$$

Therefore, $C_s(\alpha, b)$ is the value of the concordance principle which begins by asking to what degree each criterion (or attribute or voter) agrees with the statement $H \in S$ for the pair of alternatives (α, b). These answers are aggregated to obtain an overall index $C_s(\alpha, b)$ measuring the overall agreement with the proposition αSb (over all criteria–right of majority).

The purpose of the non-discordance principle is to avoid a total compensation among the binary scores of criteria when the alternative α has imbalanced scores compared with the alterative b. Hence, the discordance with respect to a criterion aims at taking into account the fact that this criterion is more or less discordant with the assertion αSb. The main importance of the veto principle is that it leads to more commensurate solutions. Consequently, a disjunctive aggregative operator can be selected to combine the discordance monocriterion measures over all criteria. The discordance monocriterion measure is depicted in Fig. 1 whilst its mathematical foundation can be found in the literature [20,36]. The combination of the discordance monocriterion measures can be achieved by using fuzzy unions. Here, the maximum union is used which is also the union of the crisp logic:

$$D_s(\alpha, b) = \max\{D_1(a, b), \ldots, D_j(a, b), \ldots, D_n(a, b)\} \quad (16)$$

Therefore $D_s(\alpha, b)$ is the value of the discordance principle and measures the degree according to which at least one criterion where alternative α has a significant smaller evaluation compared with the score of alternative b. This low evaluation could either reduce or cancel all the overall multicriteria evaluation [38].

The synthesis between the concordance and discordant indices can be achieved based on the following principle: an overall outranking relation of the type αSb holds if and only if the coalition of attributes or criteria in agreement with this proposition is strong enough (respect of the majority), and if there is no significant coalition disagreement (respect of minorities) against it. This proposition can be expressed by the following logical equation in case of the outranking relation S:

$$S(\alpha, b) \equiv \left(C_s(\alpha, b) \wedge N\left(D_S(\alpha, b)\right)\right). \quad (17)$$

Particularly, by adopting the monocriterion outranking relation S_j which is applied in the Electre III method, by using the min intersection (which is the intersection of the crisp logic) and the classical complement, the overall outranking relation between two alternatives a and b is equal to:

$$S(\alpha, b) = \min\{(C_s(\alpha, b), (1 - D_s(\alpha, b))\} \quad (18)$$

Finally, the goal of the proposed MCA (first phase) is to achieve a multicriteria ordering between the alternatives, that is, the 37 supplementary measures. Let A be the set of

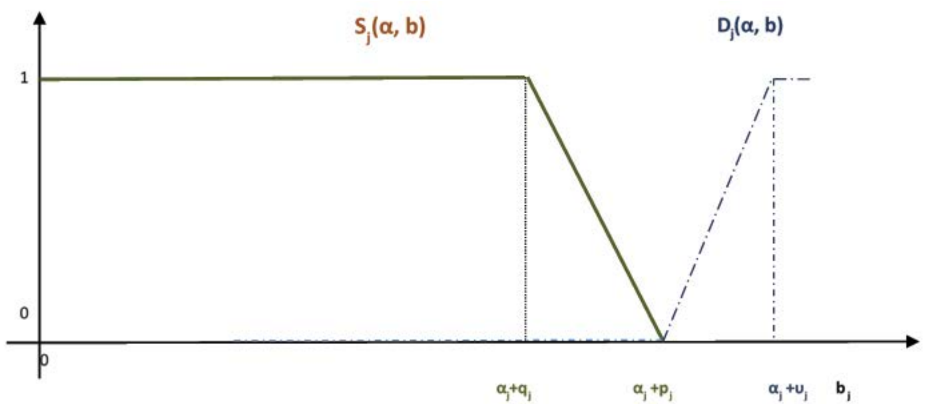

Fig. 1. Outranking relation and the corresponding discordance measure.

all alternatives. To simplify the decision process, the use of scoring function on A for the S relation can be used for the overall outranking relations (Eq. (18)) [20]. Hence, the net flow scoring function was adopted, since it incorporates both the sense of dominance and domination [31]:

$$\upsilon(\alpha, A, S) = 1/|A| \sum_{b\in A}\left[S(\alpha,b) - S(b,\alpha)\right] \tag{19}$$

where, A states the set of all alternatives; υ (α, A, S) states the scoring function of the alternative α with respect to the outranking relation S; $S(\alpha, b)$ states the outranking relation which indicates that the alternative α is not worse than the alternative b; b represents another alternative which is included to the set of all the alternatives, A. Function υ evaluates to which degree each alternatives dominates all the other alternatives in A (positive score) or it is dominated (negative score) [16].

3.2. 0/1 Programming formulation to deal with the budget constraint

The 0/1 linear programming method is used to devise a final set of alternatives (final solution) that potentially improve the water quality status, while the objective function is modulated based on the fuzzy outranking MCA [20]. Let the set of alternatives i = 1(1) N be the alternative α_i. Then the binary decision variables are in the form:

$$X_i = \begin{cases} 1 \text{ if } \alpha_i \text{ is selected} \\ 0 \text{ if } \alpha_i \text{ is not selected} \end{cases} \tag{20}$$

As objective function, the comprehensive global criterion is developed corresponding to each of the N alternatives by the aims of the scoring function of Eq. (19):

$$\max\left\{\sum_{i=1}^{N} v(\alpha_i, A, S) X_{ij}\right\} \tag{21}$$

Hence, the MCA is exploited, in the 0/1 programming, since it modulates the objective function. However, the combinations of alternatives that will be compatible with the budget's constraint should be also considered. This restriction is expressed in terms of the decision variables X_i as follows:

$$\sum_{i=1}^{N} C_i X_i \le B_{\text{available}} \quad (\text{Budgets' constraint}) \tag{22}$$

in which C_i states the cost (€) which corresponds to alternative i and $B_{\text{available}}$ states the available amount of money.

4. Research results

First of all, the FAHP of Wang and Chin [33] is implemented in order to determine the weights of the criteria. The pairwise comparison of evaluation criteria with fuzzy values is presented in Table 3. In Table 4, pairwise comparison is expressed as a fuzzy triangular number. The interpretation of these scores as linguistic terms is presented in Table 4 [40]. The crisp values of Table 4 were taken from the study by Tsakiris and Spiliotis [21].

According to the methodology of Wang and Chin [33], that is, with the assistance of the ln transformation and the use of the non-negative deviation variables, the following optimization problem can provide the non-normalized logarithmic values of the criteria:

$$\begin{array}{l}
\text{minimize } (1-\lambda)^2 + M\sum_{i=1}^{6-1}\sum_{j=i+1}^{6}\left(\delta_{ij}^2 + n_{ij}^2\right) \\
\text{s.t.} \\
+x_1 - x_2 - \lambda\ln(1/0.5) + d_{12} \ge \ln(0.5) \\
-x_1 + x_2 - \lambda\ln(1.5/1) + n_{12} \ge -\ln(1.5) \\
+x_1 - x_3 - \lambda\ln(3/2) + d_{13} \ge \ln(2) \\
-x_1 + x_3 - \lambda\ln(4/3) + n_{13} \ge -\ln(4) \\
+x_1 - x_4 - \lambda\ln(4/3) + d_{14} \ge \ln(3.0) \\
-x_1 + x_4 - \lambda\ln(5/4) + n_{14} \ge -\ln(5) \\
+x_1 - x_5 - \lambda\ln(3/2) + d_{15} \ge \ln(2) \\
-x_1 + x_5 - \lambda\ln(4/3) + n_{15} \ge -\ln(4) \\
+x_1 - x_6 - \lambda\ln(5/4) + d_{16} \ge \ln(4) \\
-x_1 + x_6 - \lambda\ln(6/5) + n_{16} \ge -\ln(6) \\
+x_2 - x_3 - \lambda\ln(3/2) + d_{23} \ge \ln(2) \\
-x_2 + x_3 - \lambda\ln(4/3) + n_{23} \ge -\ln(4) \\
+x_2 - x_4 - \lambda\ln(4/3) + d_{24} \ge \ln(3) \\
-x_2 + x_4 - \lambda\ln(5/4) + n_{24} \ge -\ln(5) \\
+x_2 - x_5 - \lambda\ln(3/2) + d_{25} \ge \ln(2) \\
-x_2 + x_5 - \lambda\ln(4/3) + n_{25} \ge -\ln(4) \\
+x_2 - x_6 - \lambda\ln(5/4) + d_{26} \ge \ln(4) \\
-x_2 + x_6 - \lambda\ln(6/5) + n_{26} \ge -\ln(6) \\
+x_3 - x_4 - \lambda\ln\left(\frac{1/2}{1/3}\right) + d_{34} \ge \ln(1/3) \\
-x_3 + x_4 - \lambda\ln\left(\frac{1}{1/2}\right) + n_{34} \ge -\ln(1) \\
+x_3 - x_5 - \lambda\ln\left(\frac{1/2}{1/3}\right) + d_{35} \ge \ln(1/3) \\
-x_3 + x_5 - \lambda\ln\left(\frac{1}{1/2}\right) + n_{35} \ge -\ln(1) \\
+x_3 - x_6 - \lambda\ln\left(\frac{1/2}{1/3}\right) + d_{36} \ge \ln(1/3) \\
-x_3 + x_6 - \lambda\ln\left(\frac{1}{1/2}\right) + n_{36} \ge -\ln(1) \\
+x_4 - x_5 - \lambda\ln(2/1) + d_{45} \ge \ln(1) \\
-x_4 + x_5 - \lambda\ln(3/2) + n_{45} \ge -\ln(3) \\
+x_4 - x_6 - \lambda\ln(2/1) + d_{46} \ge \ln(1) \\
-x_4 + x_6 - \lambda\ln(3/2) + n_{46} \ge -\ln(3) \\
+x_5 - x_6 - \lambda\ln(1/0.5) + d_{56} \ge \ln(0.5) \\
-x_5 + x_6 - \lambda\ln(1.5/1) + n_{56} \ge -\ln(1.5) \\
\lambda, x_i \ge 0, i = 1,\ldots,6 \\
n_{ij}, \delta_{ij} \ge 0,\ i = 1,\ldots,6-1,\ j = i+1,\ldots,6
\end{array} \tag{23}$$

Table 3
Pairwise comparisons of evaluation criteria based on the RBMP of Central Macedonia River Basin District [22]

	Cr. 1	Cr. 2	Cr. 3	Cr. 4	Cr. 5	Cr. 6
Cr. 1	(1,1,1)	(0.5,1,1.5)	(2,3,4)	(3,4,5)	(2,3,4)	(4,5,6)
Cr. 2	(0.5,1,1.5)	(1,1,1)	(2,3,4)	(3,4,5)	(2,3,4)	(4,5,6)
Cr. 3	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(1/3,1/2,1)	(1/3,1/2,1)
Cr. 4	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1,2,3)	(1,1,1)	(1,2,3)	(1,2,3)
Cr. 5	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,2,3)	(1/3,1/2,1)	(1,1,1)	(0.5,1,1.5)
Cr. 6	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1,2,3)	(1/3,1/2,1)	(0.5,1,1.5)	(1,1,1)

Table 4
Fuzzy evaluation scores for the weights

Extreme importance	Fuzzy triangular number
Equally contribute	(0.5, 1, 1.5)
Moderate Importance	(1, 3, 5)
Strong Importance	(3, 5, 7)
Very Strong Importance	(5, 7, 9)
Extreme importance	(7, 9, 9)

The solution to the above problem (M = 2) is λ = 0.32 but with some non-zero deviation variables. As aforementioned, although the pairwise comparisons of the criteria are expressed as fuzzy triangular numbers the final weights are crisp numbers. After the normalization, the final weights will be (Eq. (13)) $w_1 = 0.3240$, $w_2 = 0.3240$, $w_3 = 0.0782$, $w_4 = 0.1037$, $w_5 = 0.0888$, $w_6 = 0.0814$.

However, an interesting point is the selection of parameter M in Eq. (23). First of all, it should be admitted that the assessment of the crisp weight distribution based on fuzzy pairwise comparison is an ill-constructed problem. The selection of M should be made in such a way that a reasonable decision is reached. More specifically, a balance between the common level λ and the deviation variables from the given fuzzy thresholds should be achieved. The ideal outcome is λ = 1 with zero deviations but this is rare to be done in case of real applications. Obviously, the value of λ = 0 is an undesirable situation. In this study, when M = 2, this leads to $\lambda = 0.32$, $\sum_{i=1}^{6-1}\sum_{j=i+1}^{6}\left(\delta_{ij}^2 + n_{ij}^2\right) = 0.083$ which seems a balanced decision with a significant measure of the common level λ and simultaneously with a low infraction of the fuzzy inequality constraints. In case that M = 1 is selected, then $\lambda = 0.438$, $\sum_{i=1}^{6-1}\sum_{j=i+1}^{6}\left(\delta_{ij}^2 + n_{ij}^2\right) = 0.19$ which seems to be a rather significant infraction of the fuzzy inequality constraints. When M = 3, then $\lambda = 0.2644939$, $\sum_{i=1}^{6-1}\sum_{j=i+1}^{6}\left(\delta_{ij}^2 + n_{ij}^2\right) = 0.05$ which is rather a very low achievement of a common accepted solution with respect to all fuzzy pairwise comparisons between the criteria.

As aforementioned, having selected the weights of the criteria, the next step is to evaluate the scoring function of each alternative based on binary outranking comparisons over all criteria. First, a binary monocriterion evaluation between a pair of alternatives is performed. Then these monocriterion scores are aggregated over all criteria and by taking into account the veto principle. This procedure is repeated for each alternative and finally, the scoring function of each alternative is calculated.

The thresholds of the monocriterion comparisons, which as aforementioned express the gray region in the monocriterion binary comparison, are taken from the literature [37]. The overall (overall criteria) concordance and non-discordance measures were calculated and finally the overall outranking relation was calculated based on Eq. (18) (concordance and non-discordance principle). This process is repeated for each pair of different alternatives and hence a matrix 37 × 37 was produced with the elements of the main diagonal to be empty. To exploit these binary comparisons, the scoring function for each alternative is determined based on the net flow concept (Eq. (19)). Table 4 contains the values of scoring function.

An interesting point in the proposed analysis and implementation of the FAHP is that the criterion of veto is excluded from the criterion of "implementation cost", Cr.3, and the criterion of "risk of implementation due to climate change", Cr.5, since the budget's constraint (during the second phase of 0/1 programming) puts emphasis on the cost. In addition, the use of veto in the Cr.5 will exclude the water quality improvement measures. In case of Scenario 2, all the alternatives with scoring function greater than zero are selected apart from alternative SM07-10 because of its high cost.

Table 5 contains the values of scoring function. Based on the scoring function, a ranking of the measures can be achieved. However, the selection of the measure which will be implemented is not based directly of this list because of the budget constraint. A 0-1 programming problem must be established where objective function aims at maximizing the sum of the scoring function from the selected alternatives (Eq. (21)). Furthermore, the budget limit is added as a constraint. In other words, if a budget constraint did not exist, the decision process would be finished with the rank of Table 5. Due to the budget constraint the final decision is integrated within the 0/1 programming.

Several scenarios can be developed considering the funds that will be applied for the implementation of the proposed measures. Here, due to limited space, three scenarios based on the available budget are considered and demonstrated: 10^6 € for Scenario 1, 10×10^6 € for Scenario 2 and 150×10^6 € for Scenario 3. The final selection for each scenario is also presented in Table 5.

Table 5
Estimation of the alternatives' scores (Cr.1 to Cr.6), values of their scoring function (multicriteria ranking), and the final solution for proposed scenarios regarding the available budget

Alt.	Scoring function	Cost (×10[3] €)	Scenario 1	Scenario 2	Scenario 3
X_1	–0.07539	0	0	0	0
X_2	0.090037	405	0	1	1
X_3	–0.23957	0	0	0	0
X_4	0.08399	0	1	1	1
X_5	0.210816	0	1	1	1
X_6	0.163021	2,095	0	1	1
X_7	–0.03498	0	0	0	0
X_8	–0.02338	240	0	0	0
X_9	0.213212	120,361	0	0	1
X_{10}	–0.01179	1,070	0	0	0
X_{11}	–0.77598	0	0	0	0
X_{12}	–0.13813	0	0	0	0
X_{13}	–0.02718	0	0	0	0
X_{14}	–0.54485	1,295	0	0	0
X_{15}	–0.45873	65,000	0	0	0
X_{16}	–0.60391	46,265	0	0	0
X_{17}	–0.52267	6,704	0	0	0
X_{18}	–0.49479	7,347	0	0	0
X_{19}	–0.44379	4,761	0	0	0
X_{20}	–0.48333	14,856	0	0	0
X_{21}	–0.39185	2,700	0	0	0
X_{22}	–0.24737	24,200	0	0	1
X_{23}	0.439336	150	1	1	1
X_{24}	0.395667	867	1	1	1
X_{25}	0.459676	90	1	1	1
X_{26}	0.584077	30	1	1	1
X_{27}	0.056363	1,036	0	1	1
X_{28}	–0.164	646	0	0	0
X_{29}	–0.25152	1,639	0	0	0
X_{30}	0.247007	145	1	1	1
X_{31}	0.246153	145	0	1	1
X_{32}	0.868926	167	1	1	1
X_{33}	0.579872	231	1	1	1
X_{34}	0.409063	370	0	1	1
X_{35}	0.173498	200	0	1	1
X_{36}	0.48666	15	1	1	1
X_{37}	0.22583	15	1	1	1

In case of Scenario 1, the selection process of the proposed methodology demonstrated that among the 23 measures that their implementation cost is less than 106 €, only 11 fulfill the criteria and are designated for the next phase, while in Scenario 2, among the 36 measures with cost less than 10 × 106 €, 17 of them are selected for their implementation. Hence in case of scenario 1, the final decision consists of 11 measures (alternatives), whilst in case of Scenario 2 the final solution consists of 17 measures (alternatives). In both cases, the measures that are not qualified for their employment, apart from the budget constraint (Eq. (22)), have a negative scoring function. The reason behind the allocation of negative scores in certain alternatives is that the different level among the criteria scores plays an important role in the scoring function. In SM02-10, for example, the variance of scores between the sets of Cr.1 and Cr.3, which have attributed in the higher ranking of scores, and the Cr.2, Cr.4 and Cr.6 whose score is lower than 0.2 powers the final scoring function.

In a case that the budget increases significantly (Scenario 3) then the solution remains the same with Scenario 2 because of the negative score of the other measures. That is, even if there is money available, some measures can be excluded because of their negative impacts.

5. Discussion

As aforementioned, the proposed methodology leads to a set of measures which can be implemented based on the budget constraints (Table 5). These measures are produced based on the 0/1 programming. The solution is not a simple ranking of the alternatives but a set of measures based on the budget and other possible constraints.

However, the objective function of the 0/1 programming is modulated based on the integrated multicriteria methodology. The combination between the multicriteria evaluation and the 0/1 programming is used also in Promethee V multicriteria method and it is partially used in quantified water resources management problems [39,40]. However, compared with the proposed methodology in this article, the main difference is that the proposed method based on the outranking relation incorporates the veto principle, which leads to more commensurate solutions [20] and furthermore is less sensitive to the weights' selections [31]. Moreover, the use of multicriteria methods, such as the FAHP and the fuzzy outranking method and their coupling with 0/1 programming by having the cost as a constraint, for the categorization of environmental measures is not met in the literature. Nevertheless, the more frequent appearance of negative values of the scoring function exclude some measures to be selected. Therefore, the proposed method seems more suitable for a limited budget.

It is worth noting that the alternatives which are classified as "Monitoring abstractions" and "Construction projects" are excluded because of the low score of either the Cr.2, that is, "significance of the measure" criterion (e.g., because of the small area affected) or Cr.4, that is, "potential socioeconomic and environmental impacts". Indeed, it seems more reasonable, in this strategic and integrated scale evaluation, to select alternatives which affect positively a large area or in other words, measures which tend to have a generic implementation. The high score of the "potential socioeconomic and environmental impacts" regarding the alternatives which are classified as "other measures" and the right of veto lead to positive scoring function and high priority for some of them (Table 4).

In the case that at least one or two construction measures should be selected, additional constraints (during the 0/1 programming) must be added. For instance, regarding the case study under consideration, if at least one construction project must be selected, it holds (Table 4, modified Scenario 3, with 150 × 106 € maximum budget):

$$\sum_{i=15}^{22} X_i = 1 \tag{24}$$

In this case and by following modified Scenario 3 (i.e., by including Eq. (24)), the SM07-10 and the SM11-80 are additionally selected due to its cost together with the value of the scoring function within the optimization process. It is worth noting that although the SM11-80 has a negative scoring function it is selected because of the additional constraint (Eq. (24)).

Another interesting point of view is that the implementation of the scoring function in that outranking relations gives more general and comprehensive evaluation than the Promethee method since the used method incorporates the non-discordance principle. However, it should be clarified that the selection of the alternatives is not based on the multicriteria ordering itself, since, in practice, several alternatives modulate the final solution. Therefore, the final solution is controlled by taking into account the multicriteria evaluation and other technological constraints. In contrast with other applications [21], in this work the unique constraint arises from the available budget. It should be mentioned that additional constraints should be added such as the geographical dispersion of the constructions project, and the satisfaction of the water demand.

By adopting fuzzy outranking methods, first the indifference region and the granularity during the monocriterion comparison between two alternatives can be expressed. This is achieved by using proper thresholds. Second, the aggregation of the monocriterion scores can be performed with the use of fuzzy aggregators and thus, an interpreted structure rather than an arbitrary algebraic norm can be established to achieve the multicriteria synthesis. In addition, during the multicriteria synthesis, the veto principle can be incorporated to prevent the selection of non-commensurate alternatives [21].

Regarding the selection of the weights of the criteria, the used FAHP concludes to a convex problem with linear constraints and hence it can address the disadvantage of other similar fuzzy based methods. In addition, based on the examined case study, it seems that the used FAHP produces a more reasonable distribution of the weights. The final weights are similar with the considered crisp weights [22] by following a crisp approach $w_1 = 0.31$, $w_2 = 0.31$, $w_3 = 0.06$, $w_4 = 0.14$, $w_5 = 0.09$, $w_6 = 0.09$. Comparing the two solutions, apart from the fact that the FAHP deals with uncertain scores, it provides better results. Another interesting point is that, if the deviation variables were not used then the system would have no solution.

6. Concluding remarks

Budgeting availability and constraints play a crucial role in capital investment. The same rule exists even in cases of national funds that are oriented toward the fulfillment of environmental commitments to EU Directives. For that purpose, the development of methodologies that couple financial criteria with environmental, social and other objectives, such as the ones proposed in this research where multicriteria methods are coupled with 0/1 programming for issues derived from the WFD, are essential for providing sets of solutions that not only secure but also improve the environment and the socio-economic state under specific financial ranges.

The proposed methodology consists of two phases; in the first phase an integrated multicriteria methodology which combines the use of fuzzy AHP and the fuzzy outranking method is implemented and during the second phase a 0/1 programming is used in order to modulate the final set of alternatives. FAHP is proposed to determine the weights of the criteria as crisp numbers even if fuzzy pairwise comparisons between the importance of the criteria exist. The use of the developed FAHP concludes to a convex problem with linear constraints and hence it can address the disadvantage of other similar fuzzy based methods.

By using the outranking methods, we were lead to more commensurate and integrated alternatives which are compatible with the budgets' constraint, since the final selection is achieved with the use of 0/1 programming. It is demonstrated that the budget availability plays an important role in selecting and implementing measures for the protection of the water resources. However other parameters and criteria such as the efficiency of the measure or the potential socioeconomic and environmental impacts or the risk of implementation due to climate change have also a significant role in that final selection. It was proved that when implementing the FAHP method the differences of the criteria scores among affect the result. It is believed that the proposed methodology could contribute in prioritizing sets of measures in all the environmental sectors, that is, measures for flood protection and mitigation according to the Floods Directive or measures against drought phenomena as projected by climate change, when there is a lack of financial means.

Authors' contributions

Both authors have equally contributed to the identification of the PoMs, the implementation of FAHP method and the scoring algorithms, as well as the interpretation of the results.

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