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AHP-TOPSIS hybrid decision support system for dam site selection

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Abstract. Inadequate selection of an area for the location of dams brings about social and economic disadvantages due to the non-fulfillment of its objective, as well as causes significant damage to the ecosystem of the river basin. This type of selection depends on a set of different criteria and variables, so it is necessary to develop a tool to support decision-making that allows reducing the collateral damage that a project of this type entails and increasing the project effectiveness. This paper proposes the development of a hybrid method of multicriterial analysis using the hierarchical analysis technique (AHP) and the technique for the order of preferences by similarity to the ideal solution (TOPSIS) with a specific focus on the selection of sites for dams. Modifications to traditional methods were established by eliminating the decision-maker as an evaluator of alternatives. The proposed method is based on the hierarchical ordering of alternatives taking into account the subjective judgments of decision-makers when considering the uncertainties of the selection process. The ordering of the alternatives is preceded by the analysis of a series of hydrological, geological, topographic and land use parameters extracted from a digital elevation model. According to the results obtained, it was possible to order hierarchically (better-worse) each of the river basins evaluated according to the established parameters.

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1. Introduction

The social and economic contributions of dams in most cases outweigh the damages and costs provided by the construction of dams worldwide. The selection of the best location for the construction of a dam is one of the most complex and controversial decisions in water supply management [1]. Just as optimal site selection can improve reservoir safety and groundwater regeneration in a region, poor site selection can undermine them. A well-selected site will not only provide direct benefits, but its careful design can also provide the additional benefit of a recreation area surrounding the reservoir. Conversely, a poorly selected site could cause harmful influences such as negative biophysical, socio-economic and geopolitical impacts, often through the loss of ecosystem services provided by fully functioning aquatic systems [2–5]. Therefore, for the selection of dam sites, it is necessary to conduct an accurate study of the area of interest considering the factors affecting this selection. However, this procedure is expensive and time-consuming. With advances in Informatics and Information Technologies, the determination of competitive solutions in terms of cost, time and a variety of other objective variables is greatly facilitated.

A powerful tool that plays a notable role in this process is the Geographic Information System (GIS) and its applications in hydrology. In addition to GIS, Multi-Criteria Decision Making (MCDM) helps decision makers select from alternative solutions, in this case sites for dam construction, where there are many criteria [6]. Two of the most commonly used MCDM techniques are known as analytical hierarchy process (AHP) [7] and technique for order of preference by similarity to the Ideal solution (TOPSIS) [8–11]. The integration of MCDM and other data analysis tools such as GIS have been commonly used by previous researchers, particularly in dam site selection studies [12–15]. It should be noted that GIS is powerfully used in the selection of dam sites [16–18]; however, its capacity in a certain region may differ from other locations. The AHP approach is an effective tool for System Analysis and solves decision problems by reducing complex decisions to a series of peer comparisons. AHP is an effective multi-criteria decision-making technique that has been used to solve decision problems in a variety of fields [19–20]. In addition, the AHP includes an effective technique for checking the consistency of the decision maker's assessments, thus decreasing the bias in the decision-making process [21]. The TOPSIS method is based on the idea that the best alternative has the shortest distance from the ideal solution and the furthest distance from the negative ideal solution. The ideal solution is assumed to be an alternative that has the best values for all criteria considered, while the negative ideal solution is identified as a hypothetical alternative that has the worst criteria values [8]. Many articles have been published in the field of dam site selection using MCDM techniques to choose a viable location to build a dam. However, the authors of the present research are not aware of any studies using TOPSIS and AHP as a hybrid method to solve dam site selection problems.

A wide range of risk or performance analysis studies have been conducted in multiple watersheds, dams or tunnels around the world with various hydroclimatological regimes [22–26]. Piadeh F. et al. (2012) carried out a study to prioritize the best locations for irrigation with treated wastewater (TWW) in Tunisia [26]. Potential viable locations were identified based on resource conflicts, cost-effectiveness, land suitability, social acceptance and environmental factor. Several researchers have applied fuzzy systems in decision-making methods [27–30]. Using fuzzy AHP combined with GIS, they were able to map and prioritize appropriate sites for different purposes. Reliable data and advanced technologies are two necessary elements for efficient classification management based on its overall performance using the TOPSIS technique. Kim et al. (2012) used the TOPSIS method in a diffuse environment to classify the best of ten sites for treated wastewater (TWW) in an urban Basin of South Korea [27]. They considered four main criteria, including technical, social, economic and environmental criteria. Uncertainty of weighting values and input data were considered using triangular fuzzy numbers, and data were collected through individual interviews.

Zyoud et al. (2016) used AHP and TOPSIS methods within a diffuse environment to create a framework for Water Loss Management in developing countries [29]. They proposed a hierarchical structure of the decision problem consisting of four levels: overall objective; main criteria; evaluation criteria; and options. In this study, the weightings of the criteria were determined by AHP fuzzy, and TOPSIS fuzzy was also used to rank the options in terms of their potential to meet the overall goal based on the assessments and preferences of decision makers. The most important option was supposed to be a pressure management and control strategy. In addition, the use of advanced techniques and the establishment of District measurement areas were identified as the second and third most important, respectively. In addition, based on the results of the sensitivity analysis, the stronger and weaker options were less sensitive to changes in the weightings of the evaluation criteria. Özcan et al. (2017) applied the AHP and TOPSIS methods for the selection of maintenance strategies in hydropower plants in Turkey [31]. In their study, a combined AHP-TOPSIS methodology was used to choose the most critical equipment. Nine units critical for hydropower plants were identified. A goal programming (GP) model was proposed to obtain combinations of maintenance strategies for the team. The results showed that there was a 77.1 % improvement in the frequency of plant failures as a result of employing an incorrect maintenance strategy on critical equipment compared to the period when the model was not used. Önüt and Soner (2018) conducted a comparison between AHP and TOPSIS techniques to select an optimal transshipment site in Istanbul, Turkey [32]. They used fuzzy sets to account for uncertainties in different criteria and derived criteria weightings based on a peer comparison using the AHP method. Mulliner et al. (2016) conducted a comprehensive analysis of five different MCDM techniques, including TOPSIS and AHP, to assess sustainable housing affordability using different economic, social and environmental criteria in Liverpool, UK [33]. Their results show that the overall classification of alternatives varies from method to method, and there is no perfect technique for this problem. Therefore, when possible, applying a selection of different methods to the same problem is ideal. Balioti et al. (2018) applied the AHP and TOPSIS methods with fuzzy logic to select the optimal type of Spillway on a dam in northern Greece [34]. They concluded that these tools are necessary to take into account additional parameters beyond technical and construction costs. Table 1 shows a quick review of a recent research study on dam site selection using AHP and TOPSIS techniques.

Table 1. The optimal dam site selection using a group decision-making method through fuzzy TOPSIS model [35].

Reference	Year	Site Selection for	Applied Method
[36]	2012	Underground Dam	AHP
[37]	2013	Dam	AHP
[38]	2013	Dam	TOPSIS
[39]	2013	Underground Dam	AHP
[39]	2014	Subsurface dams	AHP
[40]	2015	Small underground dams	AHP
[41]	2015	Dam	AHP
[18]	2016	Dam	AHP
[42]	2017	Dam	AHP
[43]	2018	Dam	AHP
[1]	2018	Dam	TOPSIS

In order to prevent the damage caused by floods and intense rains due to climatic phenomena Cuba has proposed to build new dams and reservoirs. In addition, the stages of drought deprive that part of the population of the necessary and continuous supply of water. The construction of new dams in strategic locations can contribute to improving these aspects. This article presents a study based on the selection of suitable dam sites in Manicaragua municipality, Villa Clara, Cuba. Therefore, a study on two MCDM models (TOPSIS and AHP) in the GIS environment is applied to determine the proposed locations for dam construction. For this, based on the literature and similar research experiences, several criteria were used in the selection procedure. Therefore, the main objectives of this study are as follows:

- Propose several factors that affect the selection of the dam site in Manicaragua municipality, Villa Clara province, Cuba, based on previous experiences around the world.
- Integrate MCDM and GIS into the study area for the purpose of selecting the dam site.
- Consider topographic and morphological conditions in the selection of the dam site.
- Assist decision makers in the construction of new dams in the area of interest.

The present research is organized as follows. At the beginning, the hybrid method and the way of combining the AHP and TOPSIS techniques to choose the best locations for dam construction is described. Subsequently, the results of the implementation of the proposed hybrid method are discussed and finally the conclusions obtained from the validation of the AHP-TOPSIS hybrid method are provided.

2. Methods

The hybrid method used in this study is based on the integration of hierarchical ordering methods AHP and TOPSIS. First, the AHP method is applied in order to determine what are the criteria and sub-criteria that should be taken into account and the weight that these should have when evaluating possible alternatives. Following this, the TOPSIS method is applied in order to select the closest solution to the ideal before all possible alternatives that exist, making use of a similarity index that is constructed by combining the proximity to the positive ideal and the distance from the negative ideal. Decision making in this integrated method involves several essential steps.

Step 1: Structure the problem as a hierarchy

The first step of the AHP method is to model the decision problem that is intended to be solved as a hierarchy. In this step, the effective criteria for locating the dam site are determined by using a thorough review of the literature and expert opinions. The hierarchy is then modeled as a graphical representation of a complex problem in which the objectives, criteria and alternatives are at the highest, intermediate and lowest levels, respectively (Fig. 1).

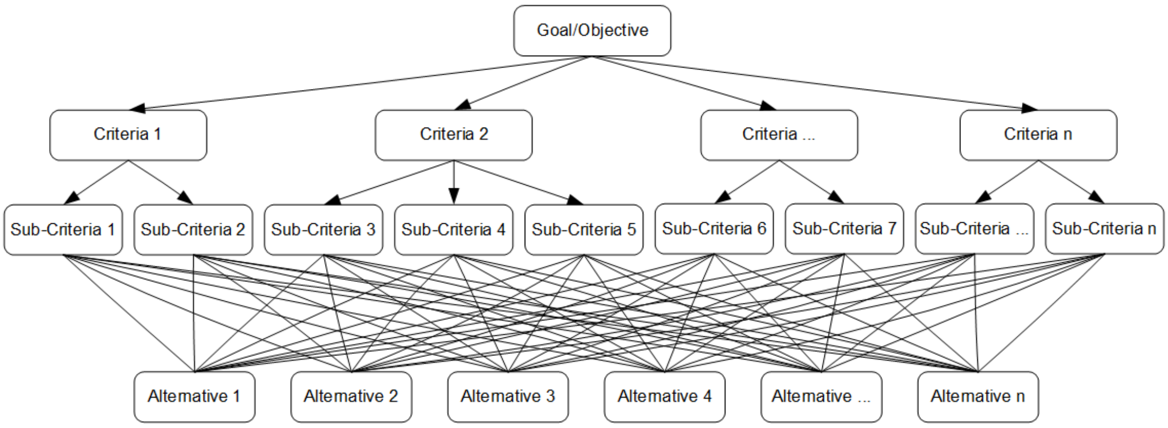

Figure 1. Outline of the AHP analysis regarding the context of the research.

Step 2: Prioritization among criteria

The fundamental idea of this study is to facilitate the work of the experts so the proposal in this step by the author is that the experts should only evaluate the criteria according to their opinion and not weigh each of the criteria in correspondence with the rest of the criteria. For this purpose, the author proposes to use two comparison scales, one that will be used by the expert to evaluate the criteria (Table 2) and another so that the GIS system itself creates the peer comparison matrix using the criteria established by the expert. The latter scale corresponds to the scale proposed by Saaty [7] (Table 3).

Table 2. Scale proposal for the direct assignment made by the expert.

Qualitative assessment	*Quantitative valuation*
Very Low Importance	1
Low Importance	3
Moderately important	5
Strong importance	7
Highest importance	9

Table 3. Fundamental paired comparison scale.

FUNDAMENTAL PAIRED COMPARISON SCALE		
Numerical scale	Verbal comparison scale	Explaining
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one element over another	Experience and judgment are in favor of one element over another
5	Strong importance of one element over another	One element is strongly favored
7	Very strong importance of one element over another	One element is very dominant
9	Extreme importance of one element over another	An element is favored by at least an order of magnitude difference

In order to establish priorities between the elements at each level, a measurement methodology proposal is made that allows connecting the scale proposed in Table 2 (expert assessments) and the scale proposed by Saaty in Table 3 for the paired comparison. For this the methodology is aided by 2 fundamental steps:

Step 2.1. The expert determines the importance of each criteria with respect to the objective and the sub-criteria with respect to each criteria. This is done by making use of Table 2.

Step 2.2. An intermediate value scale (Table 4) is created using Table 2 and 3. This scale will be used by the GIS system internally and will allow to know the values that are obtained from the paired comparison between the valuations given by the expert to each of the criteria. (These values are used to complete paired comparison arrays).

Table 4. Value comparison scale using Tables 2 and 3. (Source: Author's creation).

Comparison scales of the values assigned by the expert	Values obtained by comparison	Comparison scales of the values assigned by the expert	Values obtained by comparison
(1) to (n)	$\frac{1}{n};\left(n=1,3,5,7,9\right)$	(n) to (1)	$n;\left(n=1,3,5,7,9\right)$
(3) to (5) (5) to (7) (7) to (9)	$\frac{1}{3}$	(5) to (3) (7) to (5) (9) to (7)	3
(3) to (7) (5) to (9)	$\frac{1}{5}$	(7) to (3) (9) to (5)	5
(3) to (9)	$\frac{1}{7}$	(9) to (3)	7

On the basis of the information collected with the measurement methodology outlined above, we construct a matrix R of dimension $m \times n$ (Eq. (1)), where r_{ij} represents the priority between factor i and factor j, and the values of the lower half with respect to the diagonal values (reciprocal) correspond to the inverse values of the upper half $\left(r_{ij} = \frac{1}{r_{ij}}\right)$, being $r_{ij} = 1$, when $i = j$.

$$R = \begin{bmatrix} 1 & r_{12} & \cdots & r_{1n} \\ r_{21} & 1 & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & 1 \end{bmatrix}. \tag{1}$$

In the comparison matrix R, the columns represent the relative weights of each factor with respect to the others. To determine the factor of greatest preference, for a certain criterion, the values are normalized by dividing each element of column j by the sum of all elements of that column (Equation (2)) and then, estimating a vector of weights $\vec{w} = \left[w_1, w_2, ..., w_n\right]$. This weight vector is obtained by averaging each row of the normalized matrix (Equation (3)) and its value indicates the relative importance of each factor in a range between 0 and 1.

$$x_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}}, \tag{2}$$

$$w_i = \sum_{j=1}^{n} \frac{x_{ij}}{n}. \tag{3}$$

Subjective valuations may cause inconsistencies. Because of this it becomes necessary to measure the consistency of the paired comparison matrix. If a matrix is consistent it must be verified that, if the judgments are consistent, the matrix R would have a single eigenvalue $\lambda = n$, but since it is not possible for a person to be perfectly consistent then inconsistency will always exist. The important thing is that a certain permissible limit is not exceeded.

The above implies that the paired comparison matrix will have more than one eigenvalue λ_i. The maximum eigenvalue (λ_{max}) allows us to estimate the degree of consistency of the paired comparison matrix using the consistency index (CI) (Eq. (6)).

To obtain the value of λ_{max} first of all it is necessary to multiply the comparison matrix, row R by the vector of priorities $\vec{w}$ (Equation (4)) to obtain a vector of consistency $\overrightarrow{\lambda w} = [\lambda w_1, \lambda w_2, ..., \lambda w_n]$. If the matrix R were perfectly consistent, the sum of the elements of the obtained vector should be equal to n. The situation above does not usually happen, so to determine the degree of inconsistency it is necessary to divide each element of the consistency vector $\overrightarrow{\lambda w}$ by its vector $\vec{w}$ corresponding in the priority and in this way all possible values λ_i, are obtained. Then to finally obtain λ_{max} we proceed to perform Eq. (5):

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} \lambda w_1 \\ \lambda w_2 \\ \lambda w_3 \end{bmatrix}, \quad (4)$$

$$\lambda_{max} = \sum_{i=1}^{n} \frac{\lambda_i}{n}, \quad (5)$$

$$CI = \frac{\lambda_{max} - n}{n-1}. \quad (6)$$

Then to check if the degree of consistency is permissible, a Random Consistency Index (RI) is used as a reference (Table 5) [44, 45].

Table 5. Random Consistency Index (RI) as a function of the dimension (n) of the matrix.

n	1	2	3	4	5	6	7	8
RI	0	0	0.525	0.882	1.115	1.252	1.341	1.404
n	9	10	11	12	13	14	15	$16 \leq$
RI	1.452	1.484	1.513	1.535	1.555	1.570	1.583	1.595

The consistency ratio (CR) measures the degree of inconsistency of the paired comparison matrix and is calculated as follows:

$$CR = \frac{CI}{RI}. \quad (7)$$

If $CR = 0$ then the matrix is consistent, if $CR \leq 0.10$ the matrix has an allowable inconsistency, which means that it is considered consistent and therefore the vector of weights w is also accepted as valid. But if $CR > 0.10$, the inconsistency is inadmissible and it is advisable to review the assessments made.

Step 3: Establishing local priorities among sub-criteria

In the modeling of the decision problem as a hierarchy, the decomposition of all criteria into sub-criteria has been considered. The procedure is the same as that described in the previous step, but in this case paired comparisons between sub-criteria should be made to determine their relative importance with respect to the criteria immediately higher in the hierarchy.

Step 4: Setting local and global priorities among alternatives

The procedure is the same as explained in step 2, but this time the priority level of one alternative over another is established taking the degree of compliance or satisfaction of each criteria or sub-criteria as a basis of comparison.

After we obtained the weight vectors of each alternative with respect to each sub-criteria, they are coupled in a matrix of weight vectors. This matrix is multiplied by the vector of weights of the sub-criteria of the corresponding criteria, and this action is repeated for each criteria, obtaining the vector of local weights of each alternative with respect to the criteria that encompasses the respective sub-criteria: [46–48]. Let us illustrate what has been said by i.e. Eq. (1)

$$\begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_n \end{array}\left[\begin{bmatrix} \\ \\ \\ \\ \end{bmatrix}\begin{bmatrix} \\ \\ \\ \\ \end{bmatrix}\cdots\begin{bmatrix} \\ \\ \\ \\ \end{bmatrix}\right]\times\begin{bmatrix} \\ \\ \\ \\ \end{bmatrix}=\begin{bmatrix} \\ \\ \\ \\ \end{bmatrix} \quad (1)$$

Priority Vector of each alternative with respect to sub-criteria	Vector of priority of the sub-criteria over the criteria	Priority Vector of each alternative with respect to the criteria

Finally, the evaluation matrix of the alternatives with respect to the criteria is obtained (Table 6).

Table 6. Valuation matrix.

	w_1	w_2	$\cdots$	w_j	$\cdots$	w_n
	C_1	C_2	$\cdots$	C_j	$\cdots$	C_n
A_1	x_{11}	x_{12}	$\cdots$	x_{1j}	$\cdots$	x_{1n}
A_2	x_{21}	x_{22}	$\cdots$	x_{2j}	$\cdots$	x_{2n}
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
A_i	x_{i1}	x_{i2}	$\cdots$	x_{ij}	$\cdots$	x_{in}
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
A_m	x_{m1}	x_{m2}	$\cdots$	x_{mj}	$\cdots$	x_{mn}

where:

- $\overrightarrow{w}=\left[w_1,w_2,...,w_n\right]$ is the vector of relative weights or priorities associated with the criteria;
- $\overrightarrow{x_j}=\begin{bmatrix} x_{1j} \\ x_{2j} \\ \vdots \\ x_{mj} \end{bmatrix}$ is the vector of local priorities of the alternatives established based on the criteria C_j;
- $\overrightarrow{x_i}=\left[x_{i1},x_{i2},...,x_{in}\right]$ is the local priority vector associated with the alternative A_i, whose components are the local priorities associated with this alternative according to each of the criteria.

Standardization of the decision matrix

Let us move on to considering a combination of AHP and TOPSIS methods. The TOPSIS method evaluates the decision matrix obtained in the previous step (Table 6), which refers to m alternatives A_i, $i=1,2,...,m,$ which are evaluated based on n criteria C_j, $j=1,...,n.$ Where x_{ij} denotes the valuation of the i^{th} alternative in terms of j^{th} criteria. And where $\overrightarrow{w}=\left[w_1,w_2,...,w_n\right]$ is the vector of weights associated with C_j.

The dimensions of the various criteria are then converted to non-dimensional criteria. An element $\overline{n_{ij}}$ of the normalized decision matrix $N=\left[\overline{n_{ij}}\right]_{m\times n}$ is calculated as:

$$\overline{n_{ij}} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m}\left(x_{ij}\right)^2}},\ i=1,...,m;\ \ j=1,...,n. \tag{9}$$

Step 5: Creation of weighted normalized decision matrix

The weighted normalized value $\overline{v_{ij}}$ of the weighted normalized decision matrix $V = \left[\overline{v_{ij}}\right]_{m\times n}$ is calculated as:

$$\overline{v_{ij}} = w_j \otimes \overline{n_{ij}},\ i=1,...,m;\ \ j=1,...,n, \tag{10}$$

where w_j is such that $1 \in \sum_{j=1}^{n} w_j$ is the weight of the j^{th} attribute or criteria.

Step 6: Definitions of the positive ideal solution (PIS) and negative ideal solution (NIS)

The positive ideal solution minimizes cost criteria and benefit criteria; conversely, the negative ideal solution maximizes cost criteria and minimizes benefit criteria. The set of positive ideal values $\overline{A}^+$ and the set of negative ideal values $\overline{A}^-$ are determined as:

$$\overline{A}^+ = \left\{\overline{v_1}^+,...,\overline{v_n}^+\right\} = \left\{\left(\max_i \overline{v_{ij}},\ j\in J\right)\left(\min_i \overline{v_{ij}},\ j\in J'\right)\right\}; i=1,2,...,m, \tag{11}$$

$$\overline{A}^- = \left\{\overline{v_1}^-,...,\overline{v_n}^-\right\} = \left\{\left(\min_i \overline{v_{ij}},\ j\in J\right)\left(\max_i \overline{v_{ij}},\ j\in J'\right)\right\}; i=1,2,...,m, \tag{12}$$

where J is associated with the profit criteria and J' is associated with the cost criteria.

Step 7: Determination measures of distances between positive and negative ideal alternatives and solutions

In this step, the separation of each alternative from the positive ideal solution and the negative ideal solution is calculated and then two different GIS layers $\overline{A}^+$ and $\overline{A}^-$ are created, similar findings are found in [49–51].

The separation of each alternative from the positive ideal solution $\overline{A}^+$ is given as:

$$\overline{d_i}^+ = \left\{\sum_{j=1}^{n}\left(\overline{v_{ij}} - \overline{v_{ij}}^+\right)^2\right\}^{\frac{1}{2}};\ i=1,...,m. \tag{13}$$

And the separation of each alternative of the negative ideal solution $\overline{A}^-$ is as follows:

$$\overline{d_i}^- = \left\{\sum_{j=1}^{n}\left(\overline{v_{ij}} - \overline{v_{ij}}^-\right)^2\right\}^{\frac{1}{2}};\ i=1,...,m. \tag{14}$$

In this case the Euclidean m-multidimensional distance is used.

Step 8: Calculation of the performance of each alternative

The relative proximity of $\overline{R_i}$ to the ideal solution can be expressed as follows:

$$\overline{R_i} = \frac{\overline{d_i}^-}{\overline{d_i}^+ + \overline{d_i}^-};\ i = 1,...,m, \tag{15}$$

- If $\overline{R_i} = 1 \rightarrow A_i = \overline{A}^+$
- If $\overline{R_i} = 0 \rightarrow A_i = \overline{A}^-$

The closer the value of $\overline{R_i}$ is to 1, it implies a higher priority of the i^{th} alternative.

Step 9: Ranking alternatives

In the last step, the values of the layer (the relative proximity to the positive ideal solution) created in step 7 are determined for the selected sites based on topographic conditions. The set of sites can now be sorted by the descending order of the value of $\overline{R_i}$. The best sites are those that have higher $\overline{R_i}$ values and as they are closer to the positive ideal solution, they are preferable and should be chosen as is the case of the outputs obtained in [50].

3. Result and Discussion

The case study focuses on the selection of suitable sites for the construction of dams in the municipality of Manicaragua, Cuba. The objectives for the construction of these dams can be: support for the development of agriculture and industry, drinking water supply, power generation, fishing.

The municipality of Manicaragua has a surface area of 1064.4 km^2, of which 309 km^2 constitute a mountain area with limitations for habitat development, due to various risk factors that this area has. Only the mountainous area of the municipality represents approximately 29 % of the territorial total, standing out within the provincial statistics of Villa Clara. It is bordered to the north by the municipalities of Santa Clara, Ranchuelo and Placetas; to the South by the provinces of Cienfuegos and Sancti Spíritus; to the East by the province of Sancti Spíritus; and to the West by the municipality of Ranchuelo and the province of Cienfuegos.

Its relief is characterized by a fluvial plain and slightly dissected pre-mountain heights, the highest above mean sea level is the Pico Tuerto, with 919 meters, which in turn is the highest elevation of the province. Brown soils with carbonates, grayish brown and leached red ferralites prevail.

Within its hydrographic characteristics it can be commented that it presents a group of areas considered to be at risk for flooding, highlighting the area included within the Jibacoa Valley, which occupies an area of 12 km^2. Here, intense rains alone cause the incommunication of the area affecting 176 homes with a total of 486 people having to evacuate. Two more areas, popular councils of Las Cajas and Nicaragua I, are also subject to some significant damage, albeit not as severe as the popular council of Jibacoa.

In the first step, to determine the effective factors in the selection of an appropriate site for the construction of dams in the municipality of Manicaragua, an exhaustive review of the literature [52–56] was carried out. The most important criteria were selected and used in the current research. Below is a brief explanation of the selected criteria and the sub-criteria associated with each of them.

Hydrology (C_1): main stream length (C_{11}), mainstream slope (C_{12}), time of concentration (C_{13}), maximum flow estimate (C_{14}), runoff coefficient (C_{15}), rainfall intensity (C_{16}), real evapotranspiration (C_{17}), average annual rainfall of the basin (C_{18}), sinuosity of water currents (C_{19}), average annual rainfall volume of the basin (C_{110}), constant stability of the river (C_{111}), order of rivers (C_{112}), torrential coefficient (C_{113}), calculation of runoff coefficient (C_{114}).

Topography (C_2): basin area (C_{21}), compactness index (C_{22}), form factor (C_{23}), middle slope of the basin (C_{24}), drainage density (C_{25}), average elevation of the basin (C_{26}), watershed width (C_{27}), elongation index (C_{28}).

Geology (C_3): coefficient of massiveness of the basin (C_{31}), orographic coefficient (C_{32}).

Land Use (C_4): delimitation of areas suitable for location (C_{41}).

After collecting and evaluating the required information based on the selected criteria (mentioned above), 29 feasible alternatives were proposed for the dam site in Manicaragua. Three of them A_1, A_4, A_{28}, were not be included within the alternatives to be evaluated: A_1 turned out to be a false positive, while the analysis showed that the area of A_4 and A_{28} did not include tributaries of rivers. The locations of the proposed alternatives are show in Fig. 2 and are identified by numbers. Each of these alternatives represents the basins present in the municipality. This way the best area would be evaluated along with the best locations in each of these areas.

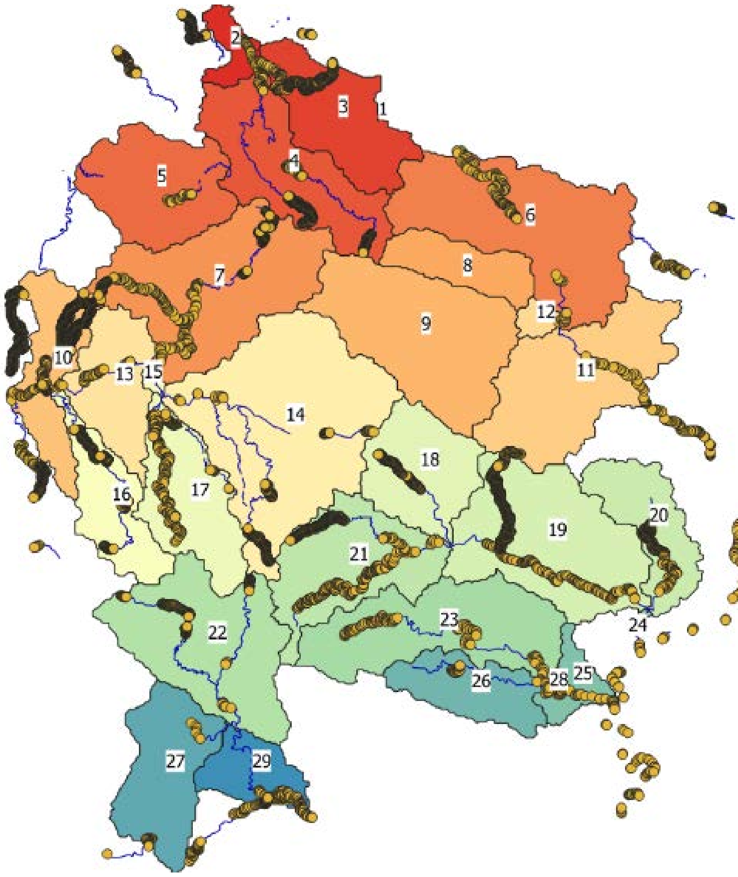

Figure 2. Alternatives for the site of the dam in the municipality of Manicaragua, Cuba.

After selecting the criteria for locating the dam site and considering alternatives (Fig. 2), the combination of AHP and TOPSIS methods for paired comparison was applied to select the best site. Fig. 3 shows the problem of site selection of the Manicaragua dam using a hierarchical structure. The structure has four levels: Objective (location of the dam site), criteria (C_1 to C_4), sub-criteria (C_{11} to C_{114}, C_{21} to C_{28}, C_{31} to C_{32}, C_{41}) and alternatives (A_1 to A_{29}).

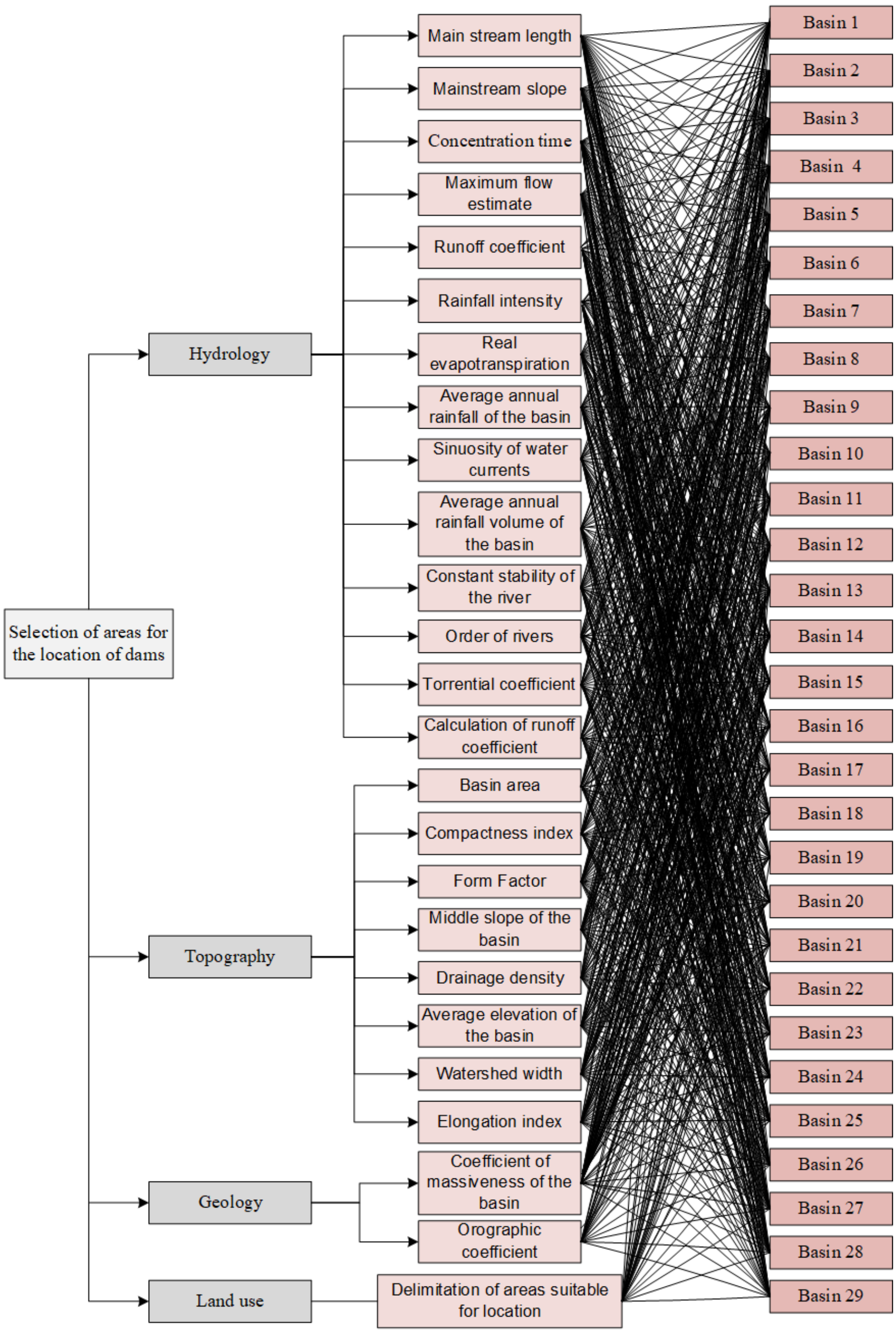

Figure 3. Selection of the dam site of the municipality of Manicaragua using a hierarchical structure.

To evaluate the relevance of the criteria incorporated in the AHP method, a questionnaire was developed, and an E_1 expert, involved in the dam construction project, was asked to express the importance of each criterion using linguistic variables established in Table 2. Then, a pair comparison matrix was formed to determine the weights of the criteria according to the description made in step 2. Once the paired comparison matrices are obtained and the local and global priorities for each of the criteria, sub-criteria and alternatives are established, the weighted normalized decision matrix is constructed, obtaining the distribution of values according to the graphs shown in Fig. 4.

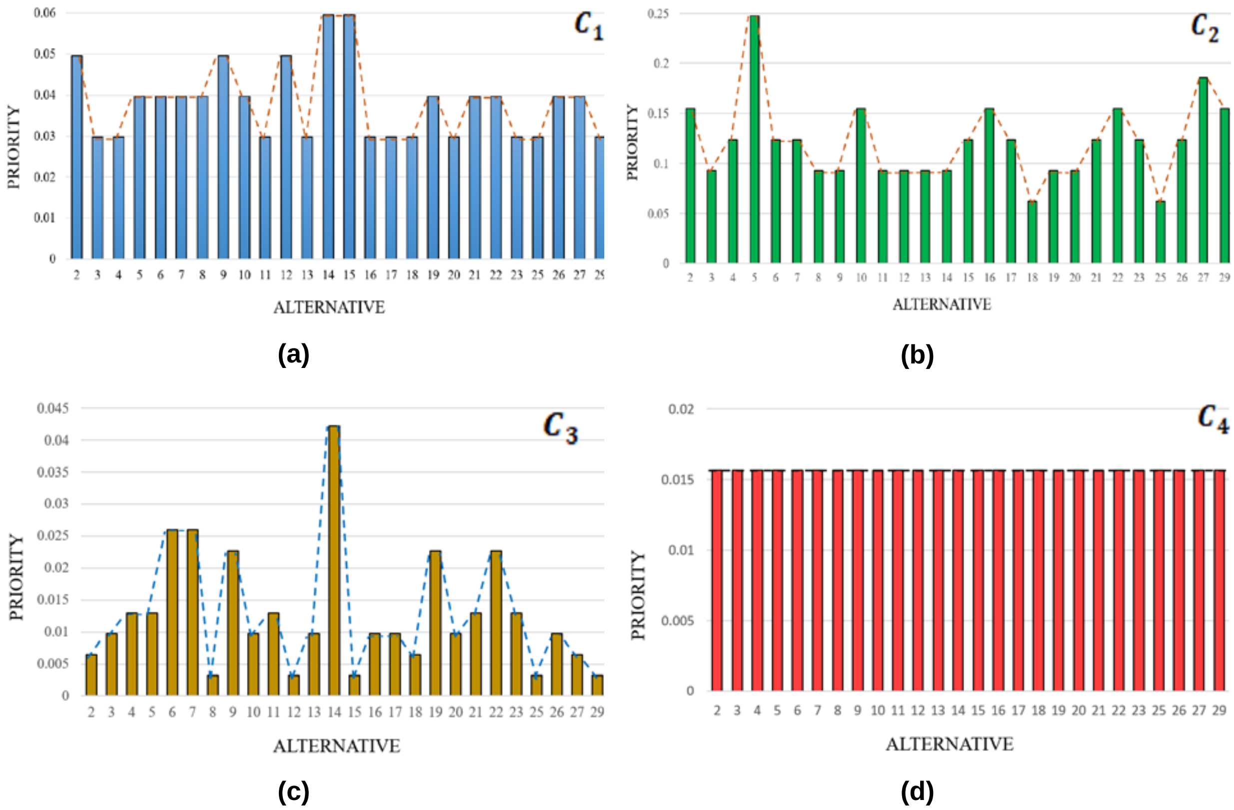

Figure 4. Prioritization of the weights of the alternatives according to the criteria in the normalized matrix. a) Criteria C_1, b) Criteria C_2, c) Criteria C_3, d) Criteria C_4.

The distances between alternatives and ideal positive and negative solutions are subsequently determined. The Euclidean distance is calculated for the best ideal value $\left(\overline{d_i}^+\right)$ and for the worst ideal value $\left(\overline{d_i}^-\right)$, Fig. 5. Then the relative proximity $\overline{R_i}$ to the ideal solution is calculated, Fig. 6.

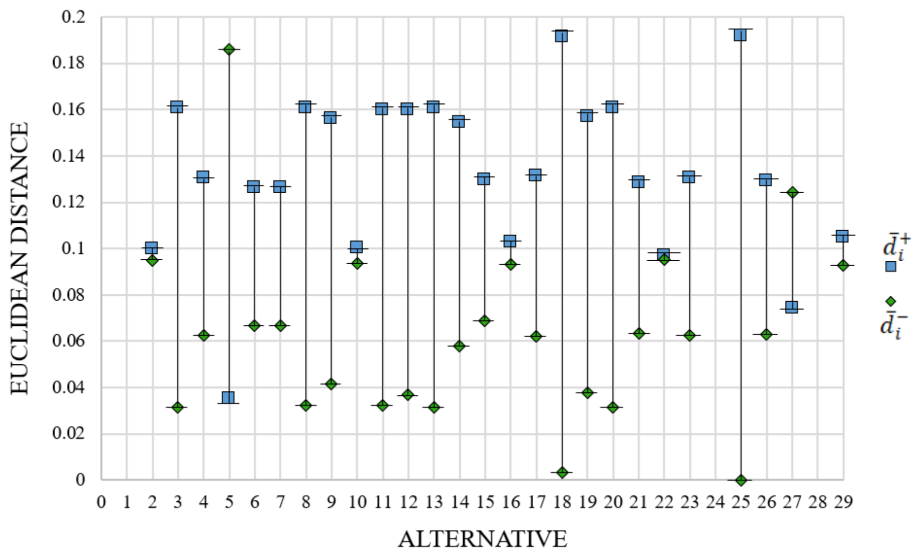

Figure 5. Best ideal value $\left(\overline{d_i}^+\right)$ and worst ideal value $\left(\overline{d_i}^-\right)$ of each alternative.

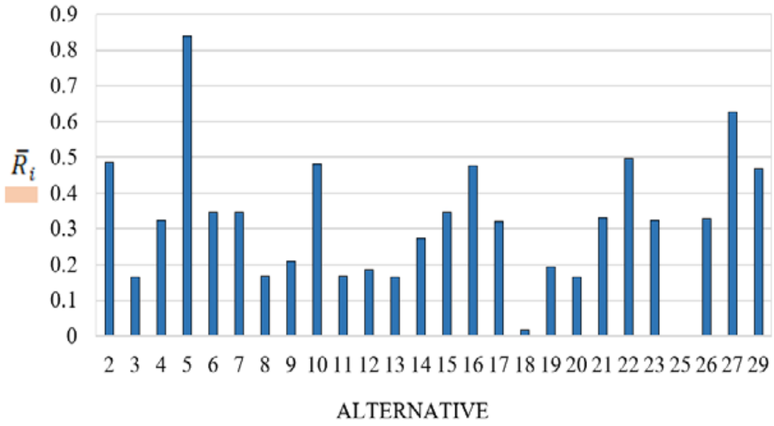

Figure 6. Graph of the relative proximity $\overline{R_i}$ to the ideal solution.

Finally, the best alternatives are sorted according to $\overline{R_i}$ in descending order.

Table 7. Hierarchical order of the alternatives evaluated.

Alternative	Weight	Ranking	Alternative	Weight	Ranking
A_5	0.8401	1	A_{23}	0.3241	14
A_{27}	0.6259	2	A_{17}	0.3213	15
A_{22}	0.4959	3	A_{14}	0.2729	16
A_2	0.4871	4	A_9	0.2104	17
A_{10}	0.4825	5	A_{19}	0.1943	18
A_{16}	0.4751	6	A_{12}	0.1869	19
A_{29}	0.4691	7	A_{11}	0.1683	20
A_{15}	0.346	8	A_8	0.1681	21
A_6	0.3453	9	A_3	0.1642	22
A_7	0.3453	10	A_{13}	0.1642	23
A_{21}	0.33	11	A_{20}	0.1642	24
A_{26}	0.3272	12	A_{18}	0.0167	25
A_4	0.3241	13	A_{25}	0	26

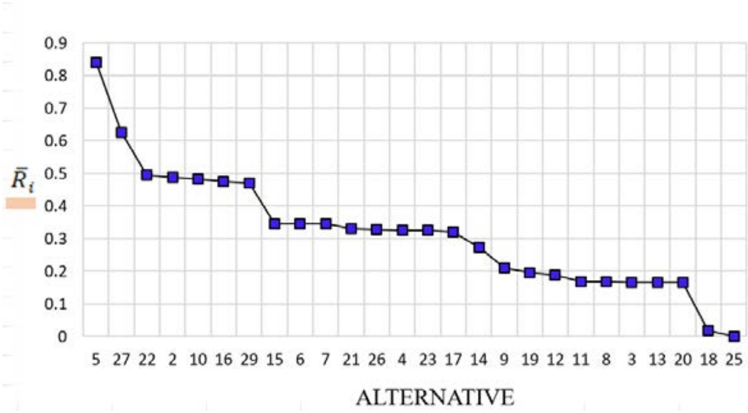

Figure 7. Hierarchical order of the alternatives evaluated.

As a result of using the proposed hybrid system, it was obtained that the best evaluated basin or its alternative turned out to be basin number 5, while the worst evaluated one was basin number 25. It is very important in all this type of research that the assessment of the expert(s) on each of the criteria and sub-criteria is correctly performed because a change or mistake in said assessment will change the results obtained. Taking into account the results of the conducted analysis and local surveys, the experts involved in the design of the dam confirmed the robustness of the research methodology and findings.

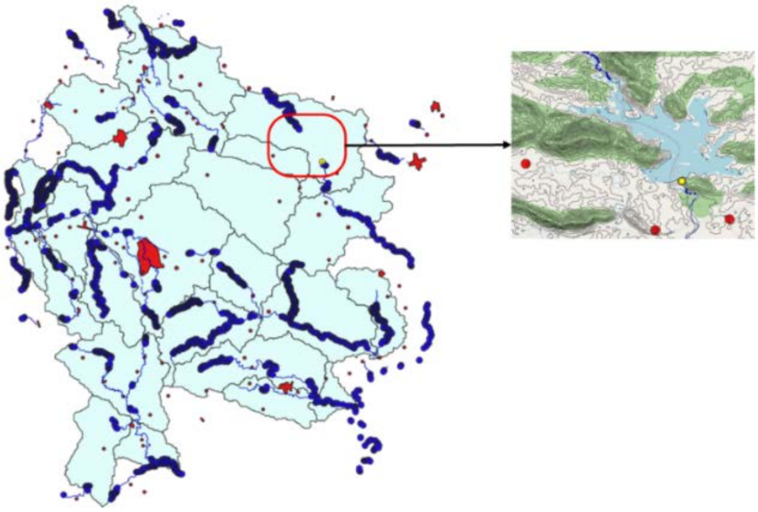

Figure 8. Analysis of one of the points determined by the model as a possible area for the location of dams.

4. Conclusion

This research presents the application of an AHP-TOPSIS hybrid method, integrating GIS, in the selection of dam sites in the Manicaragua municipality of the province of Villa Clara, Cuba. Based on the review of recent studies on dam site selection using MCDM, it can be commented that many researchers have mainly used AHP and TOPSIS in the application of dam site selection, but independently. Therefore, a method was implemented that worked with the advantages offered by each one in a study area in Cuba to evaluate its capacity for the selection of dam sites in a new local context. Based on previous experience and literature, several factors (criteria) were presented, including geology, land use, hydrology and topography. Once this hybrid method was implemented in the GIS environment, relatively suitable sites for dam construction were located in the area of interest. Finally, to verify the results obtained, the actual location of the dams built was used as a study area. The main conclusions of this study can be drawn as follows:

- The results show that the proposed hybrid method AHP-TOPSIS, as well as the modifications made for the adaptation of these methods to this type of problem is suitable for the selection of areas for the location of the dam with respect to the study area.
- A methodology has been proposed to take into account the blurred preferences of decision-makers when using the AHP-TOPSIS method based on the establishment of relationship intervals when assessing the importance of criteria and subcriteria. A quantitative indicator has been proposed that reflects the trend of decision makers in assessing criteria by translating utility (value) estimates

of criteria and sub-criteria into estimates of relative importance. This reduces the number of assessments by the decision maker by completing matrices of peer comparisons and ensures consistency.

- A procedure for comparing alternatives has been developed through the analysis of the subcriteria and subsequent construction of paired matrices eliminating the decision-maker as an evaluator object, something that is not contemplated within the standard methods.
- The use of MCDM provides an overview of the initial calculations to reduce expenses and arrive at a thorough study of the selection of the dam site; however, there is an evident need to collect accurate data to provide a correct assessment by the method implemented.
- To corroborate and verify the results obtained, an area in which there are dams built in advance was used as a study area.
- Correctly choosing the location of dams provides economic, social and ecological benefits. The economic benefits include a decrease in the costs allocated for direct studies on the areas, to the staff employed, as well as in services to other institutions or the purchase of support tools. The social benefits are evidenced by the improvement of the services provided by the dam being located in a hydrologically beneficial area. In addition, the construction of these dams in strategic areas allows the collection of water and the prevention of economic, social and environmental damage caused by floods. On the other hand, the ecosystem is benefited through the soil use criterion that is responsible for offering only areas of analysis that do not belong to the set of protected areas (cities, forests, industries, etc.) according to the laws of the country.

5. Recommendations for future research

1. Comparison of the results of the implementation of fuzzy TOSIS and fuzzy AHP with the results obtained in this investigation.

2. Collect more accurate reports on the selection of the dam site to improve and update the criteria and sub-criteria.

3. Consideration of more complete criteria can lead to more accurate results.

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