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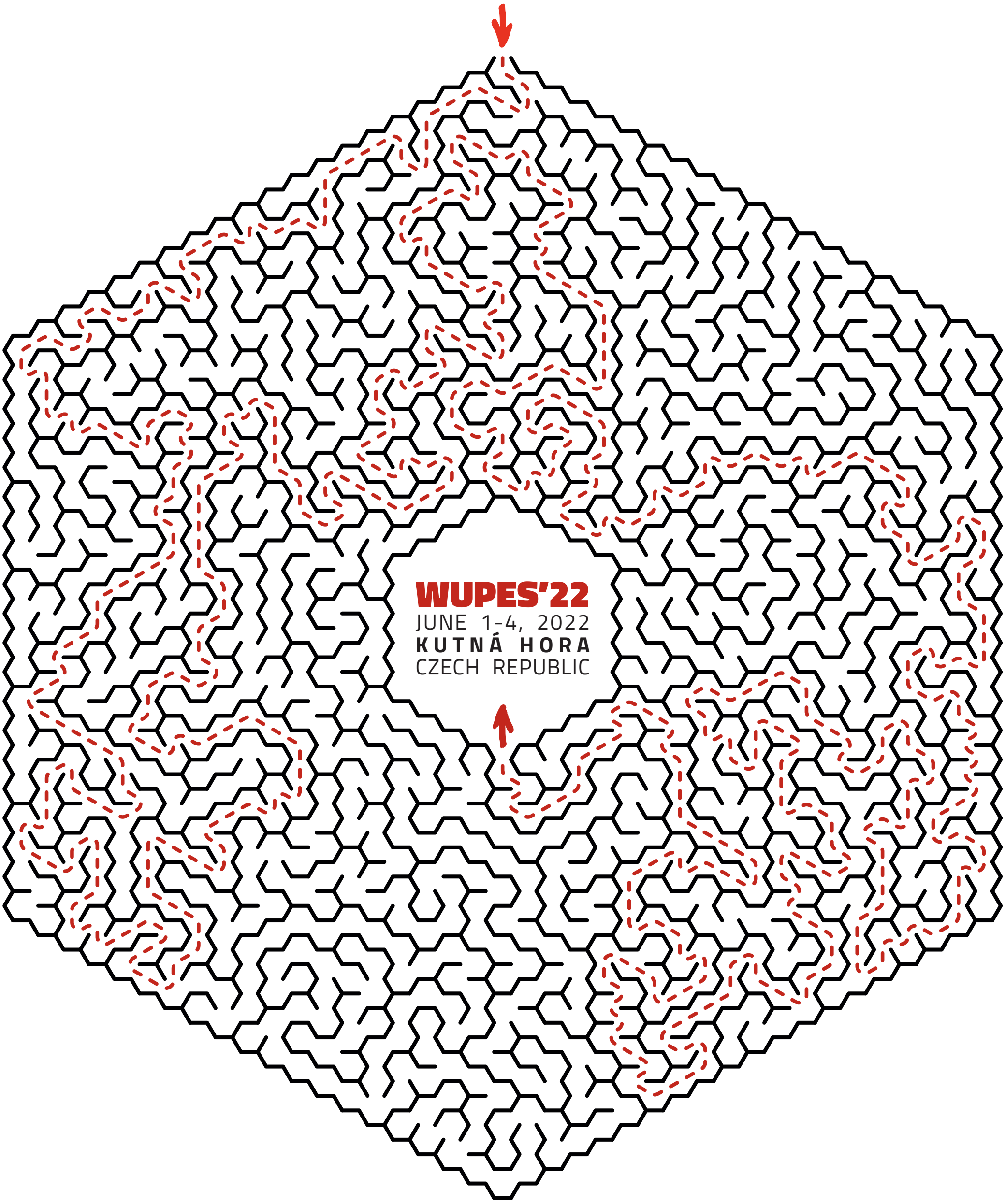

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Hybrid evaluation of the industrial global impact on Mexican aquifers under uncertain criteria evaluations

Horacio Flores Casamayor[1], Silvia Carpitella[2], Joaquín Izquierdo[3], Jesús Mora-Rodríguez[1], and Xitlali Delgado-Galván[1]

[1]Geomatics and Hydraulics Engineering Department, Universidad de Guanajuato, Av. Juárez 77, 36000, Guanajuato, México;
{h.florescasamayor,jesusmora,xdelgado}@ugto.mx
[2]Department of Decision-Making Theory, Institute of Information Theory and Automation, Czech Academy of Sciences, Pod Vodárenskou Věží 4, 18208, Prague, Czech Republic;
carpitella@utia.cas.cz
[3]Instituto Universitario de Matemática Multidisciplinar, Universitat Politècnica de València, Camino de Vera s/n, 46022, València, España;
jizquier@upv.es

Abstract

The present paper proposes an integrated methodological approach to address the problem of managing five aquifers of Guanajuato state, Mexico, according to such relevant criteria as environmental, social, economic and hydrological aspects. The goal of this research consists in formalizing a structured framework to first evaluate the various degrees of importance of criteria and to secondly get a classification of aquifers by minimizing uncertainty of evaluations. To such an aim, the Analytic Hierarchy Process (AHP) is used for calculating the vector of criteria weights, while the Fuzzy Logic (FL) theory supports in deriving quantitative evaluations of aquifers under each selected criterion. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is then proposed to formalize the final ranking of aquifers, something that will be helpful to understand which alternative matches all the differently weighted criteria in the most suitable way at a practical level. In such a way, getting a comprehensive and strategic overview about the problem of interest will be possible.

1 Introduction

Guanajuato state is located in northern Mexico, and a part of its territory is included within the region known as “El Bajío” which, due to its climatic and geographical conditions, has a rainfall regime whose average annual precipitation is lower than the national average (Figure 1). The region has scarce surface water sources and is susceptible to suffer periods of drought. Groundwater is the main water supply for different productive and domestic uses, which, due to the extraction and management policies implemented over time, presents various degrees of affectation due to overexploitation and pollution.

Problems of water scarcity are not new in this region, since it has suffered important allocation problems; ownership and use of waterways have been a cause of frequent disputes since the colonial period (Seligmann, 1988). The surface water has had important restrictions since 1931 (DOF, 1931), whose validity has recently been highlighted on April 8, 2014 (DOF, 2014). Use of groundwater restrictions date back to 1948 (DOF, 1948) and groundwater still continues nowadays to be restricted, giving priority to domestic use in any case. Due to the above, a new economic policy in the state of Guanajuato has stimulated the establishment of various industries. For example, those related to the automotive sector. Also, the change in the types of crops with the aim of increasing economic and social development by allocating the water of the area to activities considered more productive. And these actions have been taken without apparently measuring the costs in the ecological sustainability that this policy can cause in the whole area.

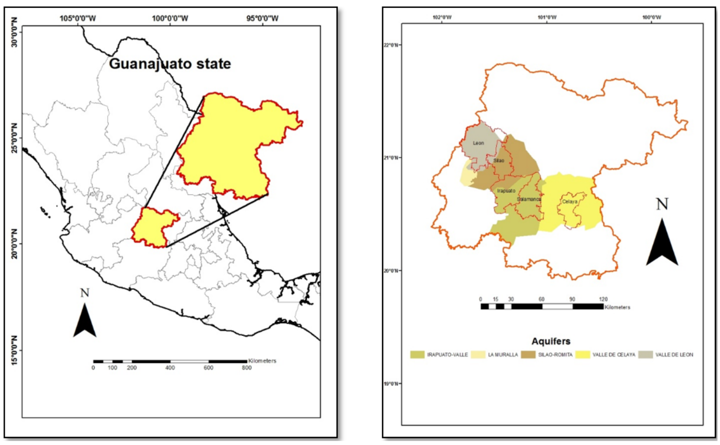

Figure 1: Localization of Guanajuato state, aquifers and municipalities of study

The present work selected five municipalities in the state of Guanajuato, namely Celaya, Irapuato, León, Salamanca and Silao, which are among the main recipients of investment in the state. They have industrial and agricultural sectors with plenty of economic weight, and currently have strong problems in hydrological matters due to scarcity, over exploitation, increased water demand and pollution of its main source of water, aquifers.

The main objective of this work is to analyze the elements that are important to evaluate water management, and the evolution of each one of these elements considering the available data, in order to determine if the water policy is achieving good results. The Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) were selected along with the Fuzzy Logic (FL) theory.

2 Methodological details

2.1 Basics of AHP and FL for uncertain criteria evaluations

The AHP methodology was developed by Saaty as a way to study and solve complex problems by dividing them into smaller components, constructing a tree of decision where the interrelation between elements is established visually; later, comparison matrices are formed (Saaty, 1977, 1987). The tree of decision is integrated by the problem or objective to be solved, which is placed in the upper part. Immediately below, there are the criteria, which are the main issues or elements that constitute the problem and, if it is convenient to be more specific, the criteria can be subdivided into subcriteria. Finally, at the bottom of the tree, the alternatives, which are the proposed options for solving the problem.

To solve the problem, AHP takes the opinion, experience and way of thinking of people with knowledge in the problem addressed to obtain, through mathematical processes, the most viable option to solve it. Now, in order to compare the opinions expressed by the experts, different ratio scales are used, which can be numerical, verbal or graphic. In this case, the numerical scale of values designed by Saaty (1977), which covers values from 1 to 9 to assign the importance to the options, where 1 means equal importance and 9 extreme importance; a detailed analysis of this scale is presented in (Ishizaka and Nemery, 2013).

The opinion is addressed by pairwise comparing elements, and comparisons are summarized into so-called pairwise comparison matrices. The Perron eigenvector, $W = [w_1, w_2, w_3, \ldots, w_n]$, of any of these positive matrices, gives the vector of priorities, whose components, w_n, indicate the weights or importance of the considered elements, to reach the best solution. Over time, AHP has been applied in various fields of science, technology, industry, among others, alone and in combination with other methodologies. The literature shows proposals of management of water supply problems by means of a multi-criteria point of view (Ilaya-Ayza et al., 2017; Kourgialas et al., 2019; Singh et al., 2017), demonstrating its efficacy. It is also fundamental to take into account such aspects as uncertainty affecting decisions in water management (Höllermann and Evers, 2017) and differences that may exist among opinions given by decision-makers (Tembata and Takeuchi, 2018).

In general, as asserted by Yager (2018), many modern technological tasks make use of multi-criteria methods, and evaluation criteria are usually categorized to express information about their mutual importance. Such authors as Safarzadeh et al. (2018) consider multi-criteria decision-making methods to be among the most helpful rational mathematical approaches of the last decades for selecting appropriate alternatives. Moreover, their combinations with other methodologies increases their accuracy (Che et al., 2010; Ramanathan, 2006).

FL theory, developed by Zadeh, was applied to determine the degree of belonging of an element within a set of elements (Zadeh, 1965). This is done using linguistic variables such as "a lot", "very", "a little", which are defined based on the opinion of experts. Therefore, a proposition may be partially true or false and allows to consider if an element belongs to a set with a certain degree of membership. This degree is expressed with a numeric value in the interval (0, 1), which allows one to simulate the human way of reasoning. To apply the methodology, it is necessary to follow the next steps (Mahabir et al., 2003).

a) *Defining a set of variables and assigning a membership function defining the degree of belonging that each variable has in a group, indicated usually with a linguistic term.*

b) *Defining rules to relate each variable to its membership function with the obtained result, usually through a series of IF-THEN rules, IF representing a condition and THEN a conclusion.*

c) *Evaluating statements or rules mathematically and applying defuzzification to get crisp results.*

There are various methodologies for defuzzification, such as the Center of Area (COA), Center of Gravity (COG), and Mean of Maxima (MeOA). In our case, the trapezoidal membership function was used, being the function that best adjusted to the behavior of the variables. Values are given for the corresponding intervals by Functions (1) and (2):

$$\mu_A(x) = \begin{cases} & 0 \leq x \leq a \\ \frac{x-a}{b-a} & a < x \leq b; \\ & x > b \end{cases} \tag{1}$$

$$\mu_A(x) = \begin{cases} & 0 \leq x \leq a \\ \frac{b-x}{b-a} & a < x \leq b. \\ & x > b \end{cases} \tag{2}$$

In the above, a indicates the lower limit; b indicates the upper limit; x is the value to estimate; $\mu_A(x)$ is the membership function for a fuzzy set A on the universe of discourse X, and is defined as $\mu_A(x) : X \rightarrow [0, 1]$. FL has been adapted over time to the control of processes related to production systems (McBratney and Odeh, 1997; Kommadath et al., 2012), management and treatment of water (Boiocchi et al., 2016; Mahabir et al., 2003), in transport systems (Rajak et al., 2016), agricultural production (Kavdir and Guyer, 2004; Center and Verma, 1998), mining (Hüllermeier, 2011), among many other areas which have been susceptible to be automated. Likewise, FL has been applied in conjunction with other analysis methodologies to increase the effectiveness of both as in the case of the method TOPSIS (Sanghvi et al., 2021).

2.2 TOPSIS procedure for ranking decision-making alternatives

The TOPSIS technique, originally developed by Hwang and Yoon (1981) with further developments by Yoon (1987) and Hwang et al. (1993), is an established multi-criteria decision-making method useful to rank alternatives representing potential solutions of a given decision-making problems in many application areas (Ouenniche et al., 2018; Nilashi et al., 2019; Meniz, 2021). The method is based on the concept of calculating distances between each alternative and two ideal points, namely, a positive ideal solution and a negative ideal solution. In such a way, the alternative(s) occupying the first position(s) in the final ranking will be that one(s) closest to the positive ideal solution and farthest from the negative ideal solution. TOPSIS-based approaches have been proposed within the context of water quality evaluation (Li et al., 2018) also in integration with the AHP technique (Xu et al., 2016; Zyoud et al., 2016; Fu et al., 2013). Regarding the practical application of the methodology, it is necessary to preliminary collect and organize the following input data: quantitative evaluations of alternatives under each criterion, vector of criteria weights (reflecting the mutual importance of the considered aspects), preference direction of criteria (establishing if criteria need to be maximized or minimized). Once weights have been assigned to criteria and established their preference directions, alternatives have to be ranked by implementing the phases described in such works as (De Anchieta et al., 2021). In particular, the following stages need to be implemented.

- *Compiling the input decision-making matrix by collecting the assessments g_{ij} related to each alternative i under each criterion j taken into account for the evaluation.*
- *Computing the weighted and normalised decision-making matrix, for which the generic element u_{ij} can be calculated as follows:*
$$u_{ij} = w_j \times z_{ij}, \forall i, \forall j; \tag{3}$$
where w_j represents the weight of criterion j, and z_{ij} the score of the generic alternative i under the mentioned criterion j, normalised by means of the following operation:
$$z_{ij} = \frac{g_{ij}}{\sqrt{\sum_{i=1}^{n} g_{ij}^2}}. \tag{4}$$
- *Identifying two points representing ideal solutions, namely the positive ideal solution A^* and the negative ideal solution A^-, by means of the following equations:*
$$A^* = (u_1^*, \dots, u_k^*) = \{(\max_i u_{ij} | j \in I^{'}), (\min_i u_{ij} | j \in I^{''})\}; \tag{5}$$
$$A^- = (u_1^-, \dots, u_k^-) = \{(\min_i u_{ij} | j \in I^{'}), (\max_i u_{ij} | j \in I^{''})\}; \tag{6}$$
where $I^{'}$ and $I^{''}$ are the sets of criteria to be, respectively, maximised and minimised.
- *Calculating S^* as the distance from each alternative i to the positive ideal solution A^* and S^- as the distance from each alternative i to the negative ideal solution A^- as follows:*
$$S^* = \sqrt{\sum_{j=1}^{k} (u_{ij} - u_{ij}^*)}, i = 1, \dots, n; \tag{7}$$
$$S^- = \sqrt{\sum_{j=1}^{k} (u_{ij} - u_{ij}^-)}, i = 1, \dots, n. \tag{8}$$
- *Computing, for each solution i, the closeness coefficient C_i^* representing how alternative i performs with respect to the previously calculated ideal solutions:*
$$C_i^* = \frac{S^-}{S^- + S^*}, 0 < C_i^* < 1, \forall i. \tag{9}$$
- *Ranking the available decision-making alternatives by ordering the calculated closeness coefficients in a decreasing way. This means that, when referring to two generic alternatives i and z, if $C_i^* \geq C_z^*$ solution i should be preferred to solution z.*

3 Application and results

AHP methodology has been carried out by involving 48 specialists in the water sector belonging to agencies such as the State Water Commission (CEA), Groundwater Technical Committees (COTAS), the Municipal Water Utilities and the University of Guanajuato (UG). The main objective was to define the importance that each criteria and subcriteria should have on the water management for the study area, considering the state policy to receive new companies, mostly industries. Once verified that the matrices met the conditions to use them, the results obtained for the different elements are shown below, close together with the tree of decision that was defined (Figure 2), and both are widely explained in Flores Casamayor et al. (2018). We can observe as, according to the opinions expressed by the involved experts, the criterion referring to "Hydrological Aspects" has been considered as the most important.

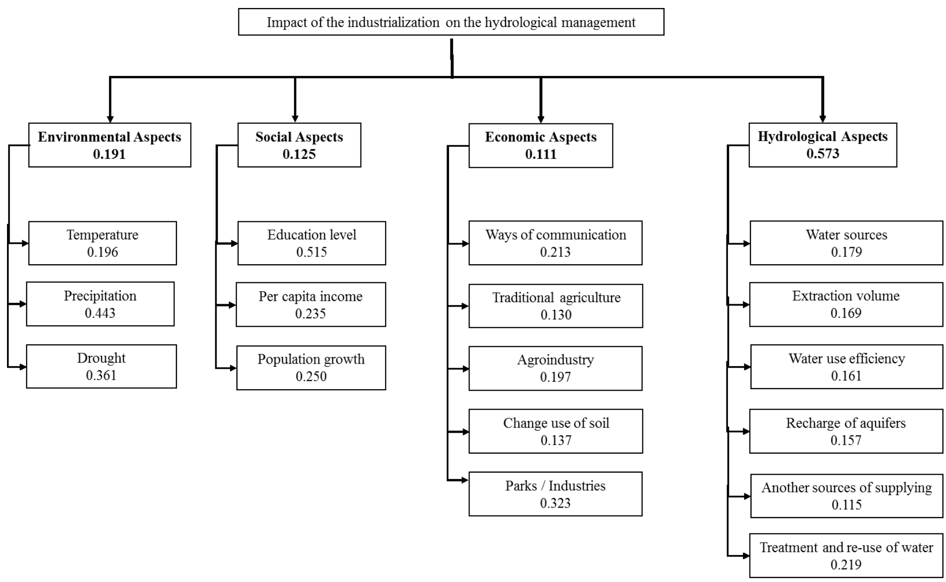

Figure 2: Tree of decisions and AHP results

This is congruent if we consider the current problem that the municipalities of the study present in the aquifers where they extract all the water to cover the requirements of their population and its economy. With relation to this criterion, subcriterion of "Treatment and reuse of water" was considered as the most important, which indicates that the water discarded by the various users is likely to be used in those activities that do not necessarily require potable water to be taken as a measure to reduce overexploitation of water sources. The order of importance in the rest of the criteria was: Environmental, Social and Economic Aspects; in the case of subcriteria, the most important were, respectively, Precipitation, Education level and Parks/Industries.

The FL methodology was applied to the whole set of subcriteria defined in AHP, with the aim to analyze the evolution of each parameter, by preferably considering the range of ten years. To get a broad explanation about the FL process, such as the type of graphic used in each case, the source of the values of the different parameters, the value of FL assigned to them according the performed methodology, and so on, it is necessary to consult Flores Casamayor et al. (2021). Next Table 1 shows a summary of the results of both methodologies, where we can see the relations and coincidences between the values calculated in all cases. In the case of "Treatment of water" and "Reuse of water" parameters, it is necessary to clarify that their values are equal because originally both of them were considered as a single parameter in the AHP (see Figure 2).

However, data obtained from official sources and used in the analysis of FL were provided as two separated parameters; so to keep the consistency it was decided to divide the AHP original value of 0.219, getting the value of 0.1095 reported in Table 1. In the beginning, the value 1 was assigned to the subcriterion "Water sources" to the municipality of León. Since 1995 El Zapotillo dam project was started to solve water supply problems in Jalisco y Guanajuato, including León (Briseño Ramírez, 2021). However, El Zapotillo did not advance in its construction due to various legal demands made by different civil organizations, issued on the great environmental, social, and economic impacts that such work would cause in the area where it is located. The project was finally resumed in November 2021, but no water resources were considered for León (CONAGUA, 2021). Then, the value in Table 1 was changed to zero.

				FL values				
Criteria AHP	**Values**	**Subcriteria AHP**	**Values**	**Celaya**	**Irapuato**	**León**	**Salamanca**	**Silao**
Environmental	0.192	Temperature	0.196	0.000	1.000	0.533	0.617	0.350
		Precipitation	0.443	1.000	1.000	1.000	0.912	0.564
		Drought	0.361	0.742	0.723	0.754	0.729	0.723
Social	0.125	Education level	0.515	0.520	0.467	0.487	0.413	0.278
		Per capita income	0.235	0.000	0.000	0.000	0.000	0.000
		Population growth	0.250	1.000	0.800	0.650	1	0.700
Economic	0.111	Ways of communic.	0.213	0.708	0.622	0.667	0.868	0.667
		Trad. agriculture	0.130	0.698	0.500	1.000	0.750	0.250
		Agroindustry	0.197	0.995	0.858	0.917	0.750	0.726
		Change use of soil	0.137	0.714	0.571	0.571	0.000	0.286
		Parks/Industries	0.323	0.693	0.663	0.286	0.773	0.767
Hydrological	0.573	Water sources	0.179	0.353	0.000	0.000	0.000	0.000
		Extraction volume	0.169	0.000	0.492	0.453	0.492	0.000
		Water use efficiency	0.161	0.419	0.419	0.419	0.419	0.419
		Recharge of aquifers	0.157	0.000	0.000	0.468	0.000	0.000
		Other sources	0.115	0.061	0.063	0.077	0.097	0.132
		Treatment of water	0.1095	1.000	0.498	1.000	1.000	1.000
		Reuse of water	0.1095	0.494	0.101	0.861	0.007	0.012

Table 1: Comparison of results AHP - FL

A feasibility criterion has been designed in order to interpret if the industries established in the area of study would have any positive impact on the defined criteria and subcriteria defined. The feasibility criterion was defined as reported in Table 2.

Next table shows the Industrial global impact to the municipalities under study. First, it was calculated by multiplying the AHP and FL values obtained for each subcriterion, adding the parameters that integrate each criterion and achieving a total result in each case for all the municipalities. Later, these values obtained for the subcriteria were multiplied for the corresponding AHP criterion value, added and finally, the Industrial global impact was obtained (Table 3).

$0 < X \leq 0.250$: **Very Unfavorable Trend** (VUT). The objective is not met and there is considerable deterioration or impact on various parameters. The establishment of new industries is not recommended until the parameters are balanced or consistent improvements are observed. The impact of industries on improving the water situation is irrelevant (they may be a factor that aggravates the situation).
$0.250 < X \leq 0.50$: **Unfavorable Trend** (UT). The objectives are not met and different levels of deterioration are presented in various aspects. It is not recommended to accept the arrival of new industries, and in those already established there must be strict supervision in their water consumption and waste discharge. Their contribution to solving water problems is marginal or unimportant.
$0.50 < X \leq 0.75$: **Positive but Insufficient Progress** (PIP). The objectives are being met, but there are still aspects that require special attention. The arrival of new industries can be considered, but with strict supervision of their water consumption and waste dumping, among other limitations. Their contribution to solving water problems has some relevance.
$0.75 < X \leq 1$: **Positive Trend** (PT). The goals are being reached and the parameters are in balance or close to being therein. New industries can be allowed to arrive if they meet the relevant standards and have resource-efficient technologies and infrastructure for the treatment of their wastewater. The contribution of present companies to solving water-related problems is remarkable.

Table 2: Feasibility criterion

For a wider explanation about the process that was followed to get the values shown in the table above, readers are encouraged to consult Flores Casamayor et al. (2021).

Criteria	AHP Values	Celaya	Irapuato	León	Salamanca	Silao
Environmental	0.191	0.711	0.900	0.820	0.788	0.579
Social	0.125	0.518	0.441	0.414	0.463	0.318
Economic	0.111	0.781	0.683	0.649	0.697	0.565
Hydrological	0.573	0.301	0.223	0.430	0.272	0.193
Industrial global impact		0.460	0.430	0.530	0.440	0.320
Feasibility criterion		UT	UT	PIP	UT	UT

Table 3: Industrial global impact on the municipalities of study

The TOPSIS methodology has been lastly applied to the dataset of Table 3 to obtain the ranking of the analysed aquifers, formalised in Table 4. The application has been led by normalizing subcriteria weights and defining their preference directions. Some preliminary considerations about preference directions of subcriteria need to be underlined.

- *Hydrological aspects: six out of seven subcriteria related to the hydrological aspects have been maximized. They are treatment and reuse of water, water sources, water use efficiency, recharge of aquifers and other supply sources, all of them representing measures aimed at reducing pressures on water sources. On the contrary, the subcriterion of extraction volume has been minimised because it represents the main problem with water sources in the analysed municipalities.*

- *Environmental aspects: precipitation subcriterion needs to be maximized, since higher associated values associated with such aspect have to be preferred in terms of aquifers management, while drought and temperature subcriteria need to be minimised.*

- *Social aspects: the proposal consists in maximizing subcriteria referring to the educational level and per capita income, that are the parameters for which an increase would be beneficial, while simultaneously minimizing the subcriterion of population growth, whose increase would be directly related with an increase of cost.*

- *Economic aspects: all the subcriteria belonging to this category should be maximized. In particular, subcriteria representing traditional agriculture and agro-industry currently represent the main sources of water consumption for the municipalities under study, occupying the vast majority of the available surface. Let us note that the maximization of subcriteria does not refer to the need of expanding the occupied surface but to their efficiency, so that reducing their impact on the geographical area of reference will be possible.*

The final ranking of alternatives confirms that the León aquifer occupies the first position. Results reported in Table 4 also confirm the considerations previously expressed when evaluating the industrial global impact in the municipalities of study (Table 3).

Aquifers	S_i^*	S_i^-	C_i*	**Ranking position**
Celaya	0.082	0.097	0.542	2^{nd}
Irapuato	0.109	0.046	0.298	5^{th}
León	0.060	0.084	0.583	1^{st}
Salamanca	0.107	0.049	0.313	4^{th}
Silao	0.101	0.083	0.449	3^{rd}

Table 4: Final ranking obtained by means of the TOPSIS technique

4 Discussion and conclusions

The region of El Bajío has been affected by problems of water management for many years. There is a close relationship between the opinions issued by the experts in the AHP, regarding the priority of water aspects, and the current situation of the aquifers that supply the municipalities. This also highlights the importance given to the treatment and reuse of water as a way to reduce water extraction from aquifers, where it surpasses the effort that needs to be made to better take advantage of the available treated water.

Considering the environmental aspects as a whole, despite the AHP results indicate greater importance to precipitation - supported in part by the values available from official sources - further observations of the parameters are still needed to get a clearer picture of the trend that will prevail in each municipality. Indeed, climatic changes will imply significant oscillations on the values of these parameters in medium and long term.

Considering the economic aspects, the most important criterion according to AHP was the industrial activity, which makes sense because of the current development policy implemented in the municipalities. This is supported by the number of companies arriving each year; in turn, to facilitate the arrival of industries, the construction of highways and roads in municipalities was promoted. So, if we take all the values obtained in both methodologies and the index of industrial global impact, this economic policies have provided results and benefits more than questionable in the municipalities, and it is necessary to re-think the type of development to follow in the municipalities of study, and in the region of El Bajío. El Zapotillo will not eventually allocate water for the water supply in León. The impact in the Feasibility criterion is remarkable, because in this case its value will be 0.530, which is catalogued as "Positive but insufficient progress" (PIP), closer to the rest of the municipalities. The final TOPSIS application confirms these results, since the León aquifer occupies the first position of the ranking in both situations, that is without the implementation of the project El Zapotillo for León.

Acknowledgements

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