water

Article

Water Supply Management Index: Leon, Guanajuato, Mexico

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Abstract: In order to guarantee the sustainability of the potable water supply service, a water utility must generate improvements in its performance in an integrated manner. The objective of this research is to analyze and provide information about the components and indicators used by the water utility of Leon, Guanajuato, Mexico, which directly impact water management. The Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL) methodologies were applied. The study determined the trends and evolution over time from 2002 to 2017. From the combination of both methodologies, a Water Supply Management Index was obtained with an average value of 0.79, which shows positive progress for water resource management by the water utility. However, the traditional indicators are insufficient and require particular attention. The analysis helped to identify those indicators that do impact water management and their ability to measure the sustainability of the city's water utility. This may make it possible to monitor the progress toward the accomplishment of Sustainable Development Goal 6 (SDG 6), by performing an evaluation and thorough analysis of the status of water resources.

Keywords: indicators; water management; Fuzzy Logic; Analytic Hierarchy Process; water utility

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1. Introduction

One of the great development challenges the international community is facing at the beginning of the 21st century is to provide universal potable water and sewage services to the population. This is why the United Nations General Assembly for Human Rights (2011) established that "The human right to water is fundamental for a dignified life". In Mexico, Article 4 of the Political Constitution establishes that everyone has the right to access, use, and sanitation of water for personal and domestic consumption in a sufficient, safe, acceptable, and affordable manner. Due to the Millennium Development Goals (MDGs), 2000 million people have gained access to basic water and sanitation services. In 2015, the MDGs were replaced by the Sustainable Development Goals (SDGs), which were designed to be comprehensive rather than isolated objectives, still with precise requirements. Such is the case of SDG-6, which aims to ensure the availability and sustainable management of water and sanitation for all [1]. The Water Resources Assessment Program (WWAP) [2] states that the achievement of SDG 6 targets, in particular, for water and sanitation services, requires improvements in planning, capacity, governance, and financing at national and local levels.

In Mexico, as in many countries, water is scarce, which is why water management represents one of the greatest challenges and has become more complex due to climate change [3]. The Mexican Government, in the National Development Plan 2007–2012 [4], established Sustainable Human Development as a core policy. According to this, municipalities should prioritize the supply of public services over others. The current National Development Plan 2019–2024 [5] aims toward a development model that respects the inhabitants and the habitat; it is equitable and oriented to remedy rather than increase inequalities.

Today, performance can be measured through different parameters, such as the efficiency of the water supply, wastewater collection and treatment, quantity, and quality, as well as the operation and the resolution of technical issues [6]. However, this set of indicators has limitations when faced with the approach to the social and environmental dimensions demanded by SDG-6. Based on these arguments, the objective is to analyze and provide information on integrated elements (components and indicators) related to water management, which the water utility should consider in the context of SDG compliance. In order to make a contribution to the problem of water resource management, this document will analyze the components of the water management indicators of the current water utility in charge of potable water, sewage, and sanitation services in the city of Leon, Guanajuato. Two reasons led to the selection of this case study. The first was related to the economic and population growth experienced by the municipality, which, by 2020 became the third most populated municipality in Mexico, implying greater pressure on the water utility [7]; the second reason was that the municipality of Leon was excluded in 2021 from the "Zapotillo dam project" by presidential decision, a project that aimed to transfer 120 million cubic meters of water from the Río Verde to Leon to overcome the water supply challenges faced by the potable water and sewage system of Leon (SAPAL), thus allowing the rehabilitation of the aquifer of the Leon Valley. The analysis was performed by applying the Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL) methodologies. The AHP methodology was used to determine the importance of each component (quantity, quality, continuity, user expectations, services provided, and cost recovery), with their respective indicators. Subsequently, the technical performance indicators of water management were defined using the Fuzzy Logic method (FL).

This article is structured as follows. The second part details the AHP and FL methodologies used in this research, as well as a description of SAPAL, since it is in charge of managing the city's water supply. The third section develops the results used to determine the importance and status of each component through the respective most relevant performance indicators, which are considered by a water utility in order to manage water resources. This is followed by the discussion of the combination of both AHP and FL methodologies from which the Water Supply Management Index was estimated for SAPAL. Finally, conclusions are presented.

2. Methodology

The methodological steps were as follows:

1. Information was collected on performance indicators, which were grouped into the components listed in Table 1;
2. Based on the approach of these five components, a multi-criteria analysis (AHP) was applied to determine the importance of each component;
3. Then, FL theory was applied to determine the trends and/or evolution of the different indicators. R software (Core Team, 2020) was used for this analysis;
4. Finally, the AHP and FL methodologies were combined to integrate the Water Supply Management Index in order to evaluate the current situation of water resources from an integrated approach.

Potential components and indicators were identified through a review of several publications. The most relevant ones are mentioned herein: references [8–20] focused on management criteria, water resources sustainability guidelines, and existing water sustainability indexes. The relevance of these components and indicators is related to the dynamics of modern societies, where the environment, society, and economy require water. The components used in the analysis were based mostly on [21], who specifically mentions that the mission of a water utility is not limited to the technical and operational aspects of the service, it also covers the promotion of the health of the community it serves.

The State Water Commission of Guanajuato (CEAG) provides water utility information through the Information System of Water Utilities (SIOO). It is mandatory for the water utilities of Guanajuato State to provide data to SIOO. At the federal level, The Mexican Institute of Water Technology (IMTA) gathers information at the PIGOO (Water Utilities Management Indicators Program). It is recommended to provide information to PIGOO, but it is not mandatory. The challenge of this Water Supply Management Index is to be part of both databases.

Table 1 shows the water management indicators that were evaluated in our work. The cutoffs for each of the indicators were defined taking into account historical information from 2002 to 2017 from 387 Potable Water, Sewage, and Sanitation water utilities (OOAPAS) [22]. The less than column shows the minimum average value expected for this indicator. The between column shows the value considered as normal among the participants. Finally, the greater than represents the value above which it is considered outstanding.

Table 1. Evaluated water management indicators.

Components	Indicators	Less than	Between	Greater than	Information Source
Quantity	Potable water coverage (PWC) (%)	85	85–95	95	[22]
	Micrometering (Mimed) (%)	35	35–85	85	
	Macrometering (Mamed) (%)	50	50–90	90	
	Endowment (Edt) (l/inhab/day)	160	160–350	350	
	Physical efficiency (PE) (%)	40	40–80	80	
Quality	Sewage coverage (SC) (%)	75	75–95	95	[22]
	Treated volume (TV) (%)	30	30–80	80	[22]
	Water disinfection (WD) (%)	84	84–97	97	[23]
	Water quality, potability (WQP) (%)	85	85–100	100	
Reliability and Continuity	24 h service outlets (HSO) (%)	35	35–95	95	[22]
	Hours in zones with intermittent supply (HZI) (h)	6.5	6.5–16.5	16.5	
User expectations	Average water service fee for domestic use (AWD) ($\$/m^3$)	0	0–14	14	[24]
Cost recovery of the services provided	Work relation (WR) (%)	80	80–130	130	[22]
	Net benefit per m^3 (NB)	0	0–3	3	[25]
	Cost–price relation (C-P)	1	1–10	10	[22]

2.1. SAPAL

Leon is located in the state of Guanajuato, in the Bajío region. The city has a total population of 1,721,215 according to [26]. It is the third most populated municipality in the country. It has strong economic, social, and urban dynamics; from 2010 to 2020, housing in Leon increased from 330,062 to 440,870, which implies an annual growth of 20.9% [26–28]. During the last few years, the demand for water generated by socioeconomic development has increased considerably due to the increase in population and agricultural and industrial production [29]. The city of Leon has experienced water problems since the 1980s; the extraction of its aquifer reaches 312.5 Mm^3/year, with an excess of 51.8 Mm^3/year, which is equivalent to a decrease in the water table by 1.5 to 2.0 m/year [30]. This is due to the overexploitation of the aquifer; the deepest values are recorded between 120 and 160 m [31]. This water crisis generated from the social sphere not only results from the responsibility of the uses and users of the aquifer but also, to a large extent, responds to the implications of the management model of the local water utility, which has supported the logic of the expansion of the economic dynamics in the northern part of the Bajío Guanajuato, which is classified as semi-arid [7,32]. However, for the new paradigms of sustainable development, with an integrated concept aimed at the SDGs that enables guaranteeing water resources for current and future generations, water services are the main vehicle to guarantee this right.

This study has focused on evaluating the performance of SAPAL through the indicators that a water utility should take into account in order to provide a good service and produce a positive impact on water resource management (See Figure 1). SAPAL is a decentralized public water utility, which is legally and financially autonomous.

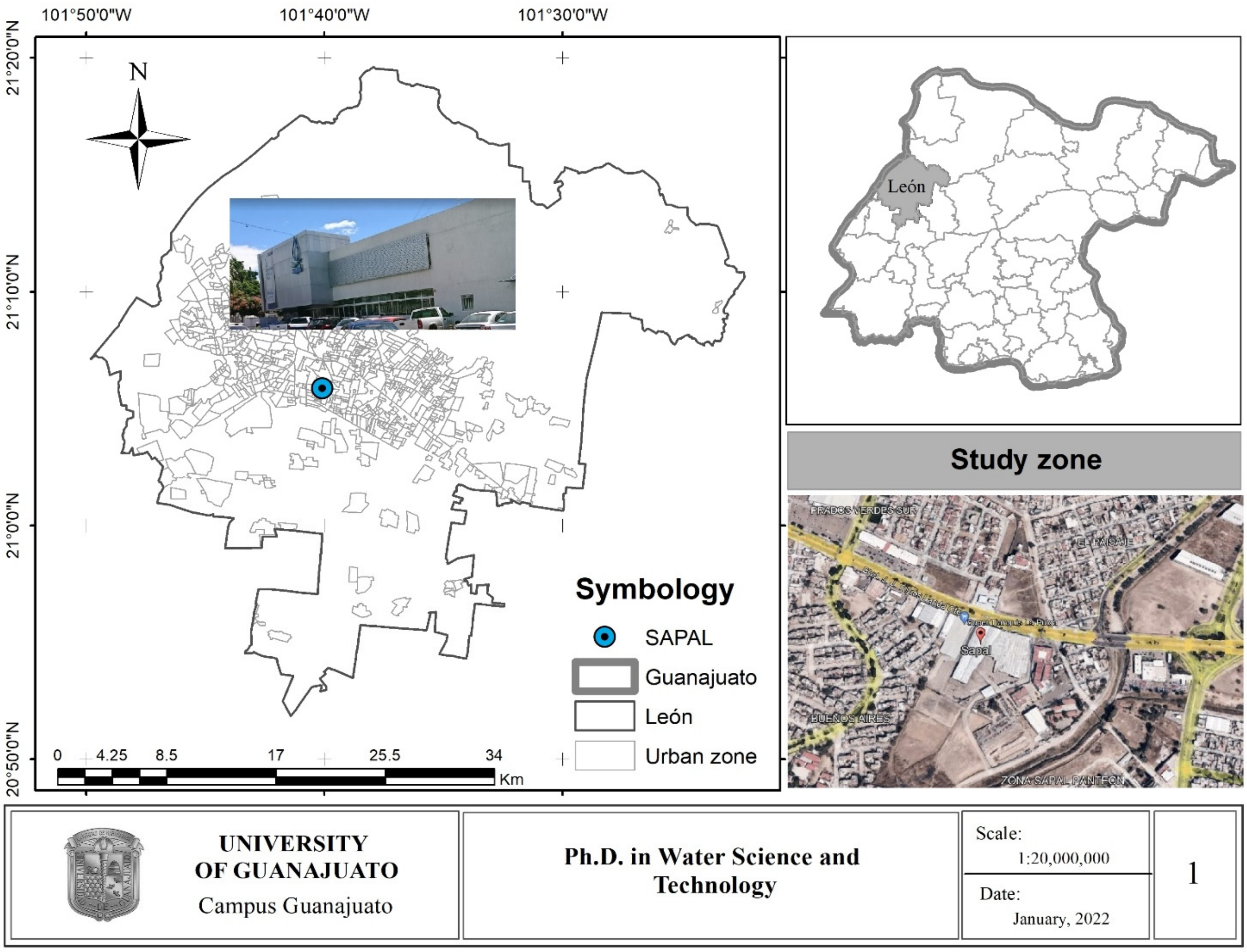


Figure 1. Location of Leon (SAPAL).

2.2. The Analytic Hierarchy Process [AHP]

The AHP method consists of decomposing a problem into a hierarchical structure, to formalize an intuitive understanding and hierarchically construct the problem, so that the elements that constitute it can be graphically represented to identify different levels (objectives, criteria, and alternatives) [33,34]. The idea of the hierarchical structure is to establish relationships between the objective (the objective is at the top of the hierarchy), its factors, (criteria and sub-criteria) and the alternatives and to present them in a logical order within the decision-making process [35]. The AHP method has been widely used since its development in several fields of study, and it is still used today [36–41].

The rationale of the process is based on the fact that it enables giving numerical values to judgments or opinions issued when comparing components, measuring how each element in the hierarchy contributes to the level immediately above, from which it is derived [42]. For these comparisons in terms of preference or importance, the fundamental scale of pairwise comparisons established by [43,44] is used. For data analysis using AHP methodology, the judgment matrix was developed using pairwise comparisons. In this study, ten experts were consulted, including decision makers from water utilities (Leon and Guanajuato, two experts from each city), experts in water management (two experts from CEAG), water resources, hydraulics, and environmental protection (four academics from the University of Guanajuato). The subject matter experts were contacted, and the information was made available to them through digital media. The ten experts were familiar with the importance of the included elements (components and indicators), and the professional profiles of the experts were in Hydraulic, Environmental, Civil, and Chemical Engineering. Moreover, some of them were involved in social science and legal areas. Therefore, they could directly provide the scores of the pairwise comparison matrices. The experts were asked to express the elements' relative importance using a nine-point scale.

A decision matrix A_{nxn} was constructed from the square matrices created using the different comparisons. This matrix complies with the reciprocity properties (if $a_{ij} = x$, then $a_{ji} = 1/x$), homogeneity (if *i* and *j* are equally important, $a_{ij} = a_{ji} = 1$; moreover, $a_{ii} = 1$ for every *i*), and consistency (the matrix must not contain contradictions in the performed evaluation) [43,45]. In order for the weights to be considered valid, Saaty's method requires that the decision matrix be consistent; this means, that the judgments that the decision maker has made in forming the decision matrix must be consistent with each other [45]. A direct result of such coherence is that $a_{ij} \times a_{jk} = a_{ik}\ \forall$ i, j, k [45]. Consistency is obtained through the consistency index (*Consistency Index*, *CI*) $CI = \frac{\lambda_{max} - n}{n-1}$, where λ_{max} is the maximum eigenvalue, and *n is* the decision matrix's dimension; a matrix is considered consistent only if *CI* equals zero [43]. The value will be zero if and only if the decision matrix is consistent. To obtain the magnitude of the inconsistency, the *CI* value is compared with the random consistency value (*CI**), which is an average value for each matrix size, considering that the decision matrix's numerical judgements were random. The random consistency values depend on the number of items being compared, and they have a value given in [46,47].

In consistency matters, a matrix is considered as valid provided that when obtaining the consistency rate $CR = \frac{CI}{CI^*}$, the value does not exceed 10% [47,48]. If it is not possible to obtain the above, then in order to improve the analysis reliability, the judgments made must be modified to improve the consistency rate [47,49]. In fact, it was necessary to perform iterative feedback with the experts to improve the consistency.

The consistency of the matrices was analyzed with the results obtained by the specialists, following the process established by the AHP method, applying the pairwise comparison matrices of the components and indicators, and it was verified that the Consistency Index (*CI*) would have a value of $\leq$0.10; for this reason, it was not necessary to apply any consistency improvement method.

2.3. Fuzzy Logic [FL]

"The world is a fuzzy place" [50]. Most of the phenomena occurring every day are naturally inaccurate. This inaccuracy may be associated with their shape, position, timing, color, or texture, among other elements. Generally, the same concept may present different degrees of inaccuracy in different contexts or over time. For example, a warm day in winter is not the same as a warm day in spring. The exact definition of when the temperature changes from cold to warm is imprecise, as it is impossible to identify a cutoff point such that, by a variation of only one degree, the ambient temperature may be considered to go from cold to warm. This type of inaccuracy or blurriness continuously associated with phenomena is typical in almost all fields of study: sociology, physics, biology, finance, engineering, and psychology among many others [50].

Aristotelian logic has been studied by thousands of scientists and philosophers [51]. It is based on the idea that a proposition is either true or false. There are no intermediate positions between these two opposing ends. Nonetheless, FL studies elements of traditional logic applied to fuzzy values. The elements of a fuzzy set are ordered pairs that indicate the value of the element and its degree of membership to that set. This degree of membership is not only 0 or 1 as in Aristotelian logic but can also take intermediate values. In this way, FL handles the uncertainty embedded in the structure of a dataset. In a way, ML can be seen as a "language" that allows the transference of natural language sentences into a formal mathematical language [52].

The traditional mathematics of logical judgements is based on binary logic, which is also referred to as the law of bivalence [53]. The law of bivalence responses is that they are either completely true or completely false (1, 0 m respectively) but not both at the same time; in other words, there is no intermediate degree of truth [53]. According to [54], as a consequence of this principle, in the theory of sets, for a subset A defined on a universe set or referential X, an element of the universe belongs or does not belong to that set $\boldsymbol{A}$; in other words, there is no membership ambiguity. Mathematically, a set membership is expressed by a characteristic function $\mu_A(x)$, which assigns values to all elements pertaining to $\boldsymbol{A}$ in the discrete set {0,1}. This value is 0 when the element does not belong to the set and 1 when the element belongs completely. This means that, mathematically the characteristic function is given by:

$$\mu_A : X \rightarrow \{0.1\} \qquad x \in X \rightarrow \mu_A(x) = \left\{ \begin{array}{c} 1x \in \boldsymbol{A} \\ 0x \notin \boldsymbol{A} \end{array} \right\} \tag{1}$$

The principle of exclusion is derived from the principle of the excluded third party. This indicates that, if an element x from the X universe belongs to a set $\boldsymbol{A}$, it does not belong to its complement, $\boldsymbol{A}^c$ and vice versa. Mathematically, we can express the exclusion principle as:

$$\forall x \in X, \;\; If\ \mu_A(x) = 1 \Leftrightarrow \mu_A c(x) = 0 \tag{2}$$

In many situations, the principles of classical mathematical logic may be applied without variation to reflect the phenomenon under study [54]. In the field of water resources, several authors have proposed modifications to the general methodology followed by FL in order to adapt it to the particularities associated with water management [55]. In the field of water resources management, the fuzzy set theory has been used since the early 1980s in a limited way as a refinement of optimization algorithms by introducing fuzzy constraints. Reference [56] is the oldest work on the use of fuzzy sets in water resources management, in this case in multi-criteria analysis. Reference [57] applied fuzzy linear programming for the rationalization of water use, creating for this purpose a flow network with different demands and constraints, expressed in fuzzy form, obtaining the optimal use of available water by means of a fuzzy optimization algorithm. Further, [58] has described the development of a Mamdani fuzzy inference system for the Yildiz and Lake Terkos reservoirs, used in the supply for Istanbul (Turkey) [55]. These problems cannot be analyzed with the limited principles of the excluded third party and the exclusion principle but must start from a more flexible one, that of gradual simultaneity. The latter reflects that an element can pertain to a given set and at the same time to the complementary set, as long as both memberships are assigned a degree, or a proposition can be true and false at the same time, as long as it is assigned a degree of truth and falsity [59].

In order to deal with inaccurate information, different mathematical theories have emerged, such as probability theory [60], evidence theory [61] or the certainty factor theory [62]. These theories have aroused increasing interest in scientific research. The tool par excellence for modeling phenomena ruled by the principle of gradual simultaneity is the Fuzzy Subsets Theory, whose basis is the multivalent logic developed in the first three decades of the 20th century [63]. The concept of a fuzzy set (which appropriately characterizes inaccuracy in information) was introduced in the 1960s by [64] who is considered the father of FL. Since its appearance, this theory has been used countless times in the world of research in general, and in particular, in the "Mother Science" Mathematics [60].

A fuzzy set is a set for which the membership of an element is fuzzily defined. Thus, if X is defined as the universe or referential set, a fuzzy subset, defined as $\overline{A}$, is one in which the membership of an element $x \in X$ is assigned a truth level that can take values within the continuous set [0, 1]. The level of membership of an element x will be given by its membership function or characteristic function $\mu_{\overline{A}}(x)$. Thus, a fuzzy subset can be defined as: $\overline{A} = \{(x, \mu_{\overline{A}}(x)) \mid x \in X\}$, with the membership function as follows:

$$\mu_{\overline{A}} : \mathrm{X} \to [0,1]\ x \in \mathrm{X} \to \mu_{\overline{A}}(x) \in [0,1] \tag{3}$$

where 0 represents the non-membership of the set $\overline{A}$ and 1 the absolute membership. Evidently, there is a gradation in the level of membership, so that it if $\mu_{\overline{A}}(x) = 0.9$, the level of membership of element x is very high, and if $\mu_{\overline{A}}(x) = 0.1$ the level of membership of x is too low. In this way, it can be interpreted as the degree to which a particular element under consideration meets the specifications that define the elements of the set in consideration. Therefore, the membership function provides a measure of the degree of similarity of an element of X to the fuzzy set.

The form of the membership function used depends on the criteria we apply to solve a specific problem and will vary depending on the user's point of view. The use of complex functions to define fuzzy concepts does not provide greater precision. Therefore, membership functions are generally simple, because they seek to simplify the mathematical calculations but not to lose accuracy. The membership functions commonly used for their mathematical simplicity and manageability are: triangular, trapezoidal, gamma, and L (1 minus gamma), among others. Conceptually, there are two approaches to determine the characteristic function associated with a set: the first approach is based on the human knowledge of experts, and the second approach is to use a collection of data to design the function [65].

3. Results

3.1. AHP

Figure 2 shows the weighting of each indicator according to the five components and their relative importance and, therefore, allows us to choose the most relevant components and indicators. According to the model, the most important categories that SAPAL should take into account in order to offer a better water management service are the quantity and quality components with a weighting of 45.63% and 25.62%. This helped identify and prioritize those components that require particular consideration and are relevant to water resource management. The results in Figure 2 show which indicators should be given greater attention for quantity and quality: potable water and sewage coverage, physical efficiency, and volume of treated water. In regard to the reliability and continuity of service, at 16.21%, this indicates that the water utility should have continuous 24-h service outlets. User expectations (8.1%) and recovery of the cost of services rendered (4.13%) did not represent a significant impact on water management, although they do have a significant impact on the economic side of the water utility. Therefore, greater attention should be paid to these two indicators (average water service prices for different uses and net profit per cubic meter extracted) from which the water utility obtains economic remuneration.

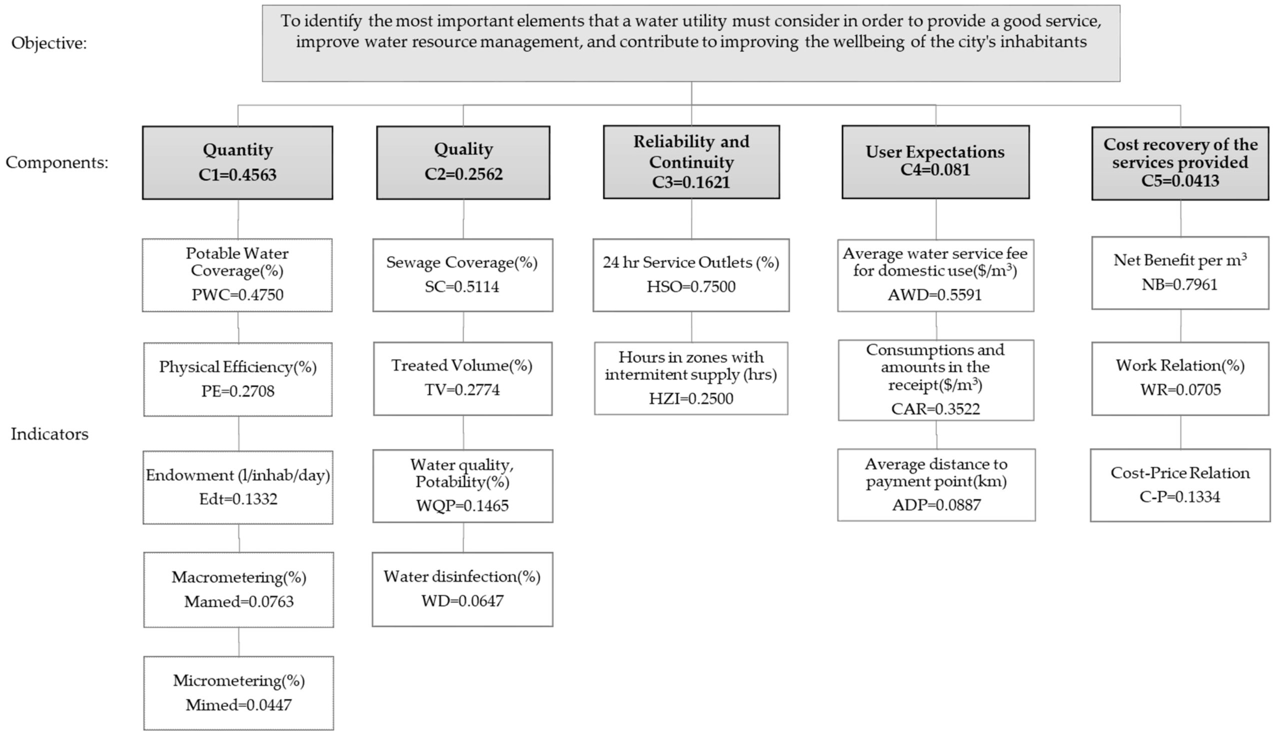


Figure 2. Hierarchical model to determine the elements that have an impact on water management.

3.2. Data Analysis Using Fuzzy Logic

The historical information of the water utility management indicators was obtained from [22–25]. The range of values was applied to the elements that possess the property expressed by the linguistic variables. The ranges assigned to most of the elements were: 0, 0.25, 0.5, 0.75, 1.

Next, a linguistic value was assigned to each of the linguistic variables, i.e., the classification of the different indicators. With the above, a fuzzy set was defined, which is the union between the linguistic values, their corresponding value contained in the discourse universe, and the supporting fuzzy sets [8].

Then, based on the structure of the available information, the function that best fit was defined, starting from an ideal or deteriorating situation, the successive values indicated a point from which the situation of a given indicator could evolve toward improvement or further deterioration. An adjustment was made to the membership function according to the characteristics of each indicator, in order to represent its evolution conditions in the best possible way. R software [66] was used to analyze the data and, thus, obtain the fuzzy values, the corresponding graphs, and the implementation of the membership functions of the FL method (Table 2).

Table 2. Results of the FL method for each component with their respective indicators.

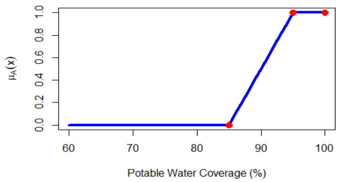
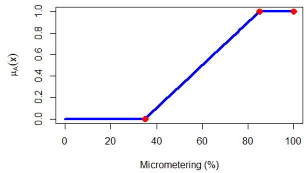
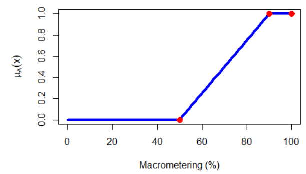
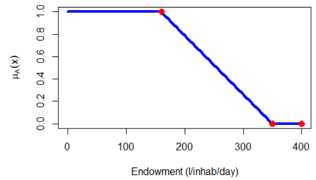
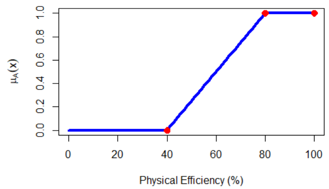
Quantity Component				
Indicator	**Values**	**Linguistic Terms**	**Fuzzy Value**	**Graph**
Potable water coverage (%)	PWC $\geq$ 95	Excellent	1	
	92.5 < PWC $\leq$ 95	Very high	0.75–1	
	90 < PWC $\leq$ 92.5	High	0.50–0.75	
	87.5 < PWC $\leq$ 90	Good	0.25–0.50	
	85 < PWC $\leq$ 87.5	Low	0–0.25	
	PWC $\leq$ 85	Very low	0	
Micrometering (%)	Mimed $\geq$ 85	Excellent	1	
	72.5 < Mimed $\leq$ 85	Very high	0.75–1	
	60 < Mimed $\leq$ 72.5	High	0.50–0.75	
	47.5 < Mimed $\leq$ 60	Good	0.25–0.50	
	35 < Mimed $\leq$ 47.5	Low	0–0.25	
	Mimed $\leq$ 35	Very low	0	
Macrometering (%)	Mamed $\geq$ 90	Excellent	1	
	80 < Mamed $\leq$ 90	Very high	0.75–1	
	70 < Mamed $\leq$ 80	High	0.50–0.75	
	60 < Mamed $\leq$ 70	Good	0.25–0.50	
	50 < Mamed $\leq$ 60	Low	0–0.25	
	Mamed $\leq$ 50	Very low	0	
Endowment (l/inhab/day)	Edt $\leq$ 160	Optimal endowment	1	
	160 < Edt $\leq$ 208	Medium endowment	0.75–1	
	208 < Edt $\leq$ 255	Medium-high endowment	0.50–0.75	
	255 < Edt $\leq$ 303	High endowment	0.25–0.50	
	303 < Edt $\leq$ 350	Very high endowment	0–0.25	
	Edt $\geq$350	Extremelly high	0	
Physical Efficiency (%)	PE $\geq$ 80	Very good	1	
	70 < PE $\leq$ 80	Good	0.75–1	
	60 < PE $\leq$ 70	Media high	0.5–0.75	
	50 < PE $\leq$ 60	Medium	0.25–0.5	
	40 < PE $\leq$ 50	Low	0–0.25	
	PE $\leq$ 40	Very low	0	

Table 2. *Cont.*

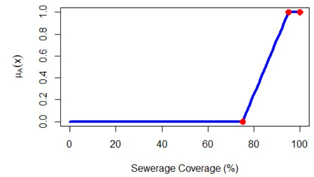
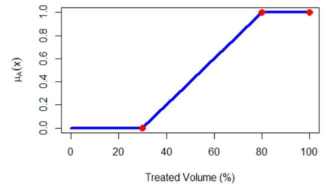
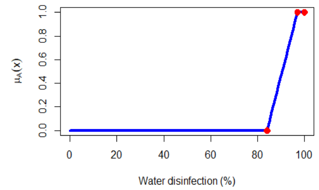
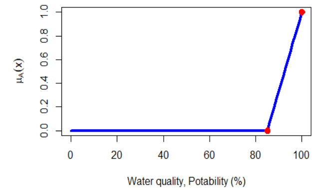
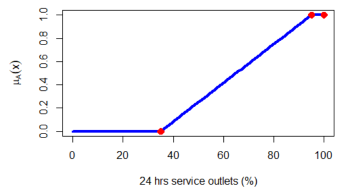
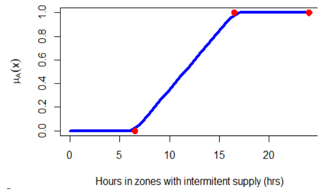
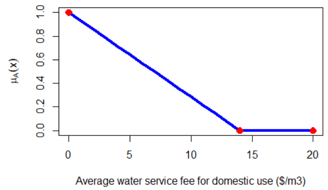
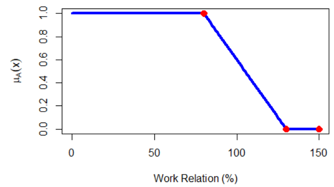
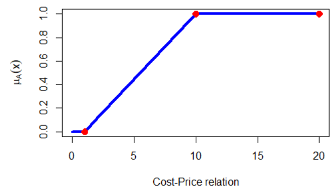
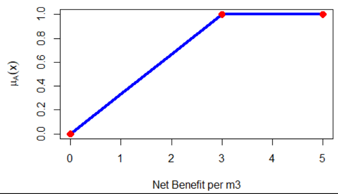
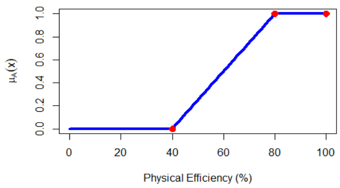
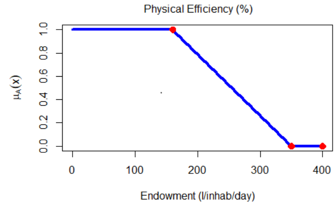
Quantity Component				
Indicator	**Values**	**Linguistic Terms**	**Fuzzy Value**	**Graph**
Sewage coverage (%)	SC ≥ 95	Excellent	1	
	90 < SC ≤ 95	Very high	0.75–1	
	85 < SC ≤ 90	High	0.50–0.75	
	80 < SC ≤ 85	Good	0.25–0.50	
	75 < SC ≤ 80	Low	0–0.25	
	SC ≤ 75	Very low	0	
Treated Volume (%)	TV ≥ 80	Excellent coverage	1	
	67.5 < TV ≤ 80	Very good coverage	0.75–1	
	55 < TV ≤ 67.5	Good coverage	0.50–0.75	
	42.5 < VT ≤ 55	Medium coverage	0.25–0.50	
	30 < TV ≤ 42.5	Bad coverage	0–0.25	
	TV ≤ 30	Very bad coverage	0	
Water disinfection (%)	WD ≥ 97	High	1	
	93.8 < WD ≤ 97	Very good	0.75–1	
	90.5 < WD ≤ 93.8	Good	0.50–0.75	
	87.3 < WD ≤ 90.5	Medium	0.25–0.50	
	84 < WD ≤ 87.3	Bad	0–0.25	
	WD ≤ 84	Very bad	0	
Water quality, Potability (%)	WQP ≥ 100	High	1	
	96.3 < WQP ≤ 100	Very Good	0.75–1	
	92.5 < WQP ≤ 96.3	Good	0.50–0.75	
	88.8 < WQP ≤ 92.5	Medium	0.25–0.50	
	85 < WQP ≤ 88.8	Bad	0–0.25	
	WQP ≤ 85	Very bad	0	
Reliability and Continuity Component				
24-h service outlets (%)	HSO ≥ 95	Excellent	1	
	80 < HSO ≤ 95	Very High	0.75–1	
	65 < HSO ≤ 80	High	0.50–0.75	
	50 < HSO ≤ 65	Good	0.25–0.50	
	35 < HSO ≤ 50	Low	0–0.25	
	HSO ≤ 35	Very Low	0	

Table 2. *Cont.*

		Quantity Component		
Indicator	**Values**	**Linguistic Terms**	**Fuzzy Value**	**Graph**
Hours in zones with intermitent supply (h)	HZI ≥ 16.5	High	1	
	14 < HZI ≤ 16.5	Very good	0.75–1	
	11.5 < HZI ≤ 14	Good	0.50–0.75	
	9 < HZI ≤ 11.5	Medium	0.25–0.50	
	6.5 < HZI ≤ 9	Low	0–0.25	
	HZI ≤ 6.5	Very low	0	
		User Expectations		
Average water service fee for domestic use ($/m^3)	AWD ≤ 0	No cost	1	
	0 < AWD ≤ 3.5	Very affordable	0.75–1	
	3.5 < AWD ≤ 7.0	Affordable	0.50–0.75	
	7.0 < AWD ≤ 10.5	Moderately affordable	0.25–0.50	
	10.5 < AWD ≤ 14	Not very affordable	0–0.25	
	AWD ≥ 14	Very unaffordable	0	
		Cost recovery of the Services Provided		
Work Relation (%)	WR ≤ 80	Profit	1	
	80 < WR ≤ 93	Acceptable profit	0.74–1	
	93 < WR ≤ 105	Acceptable loss	0.50–0.74	
	105 <WR ≤ 118	Loss	0.24–0.50	
	118 < WR ≤ 130	High loss	0–0.24	
	WR ≥ 130	Deficit	0	
Cost–Price relation	C-P ≥ 10	Very high profit	1	
	7.8 < C-P ≤ 10	High profit	0.75–1	
	5.5 < C-P ≤ 7.8	Medium profit	0.50–0.75	
	3.3 < C-P ≤ 5.5	Acceptable profit	0.25–0.50	
	1 < C-P ≤ 3.3	Low profit	0–0.25	
	C-P ≤ 1	Very low profit	0	
Net Benefit per m^3	NB ≥ 3	Very high financial autonomy	1	
	2.3 < NB ≤ 3	High financial autonomy	0.77–1	
	1.5 <NB ≤ 2.3	Medium financial autonomy	0.50–0.77	
	0.8 < NB ≤ 1.5	Very acceptable financial autonomy	0.27–0.50	
	0 < NB ≤ 0.8	Acceptable autonomy	0–0.27	
	NB ≤ 0	Financial deficit	0	

A membership level was established to determine whether the indicators related to each component have shown optimal or poor conditions in water management, according to the ranges of values shown in Table 1. In this study, the membership functions generated for the different indicators were: the gamma function and L function (1 minus gamma). The indicators that best fit the gamma function were (potable water coverage, micro-measurement, macro-measurement, physical efficiency, sewage coverage, treated volume, water disinfection, water quality, potability, intakes with continuous 24-h service, hours with service in batch zones, cost–rate ratio, and net benefit per m^3) and those indicators that resulted in an L function (provision, average water service rate, and work ratio). Table 3 shows, as an example, the gamma and L membership functions of two of the studied indicators.

Table 3. Result of gamma membership functions.

Indicator	Membership Function	Graph
(a) Physical Efficiency	Gamma Function	
(b) Water Endowment	L function: is defined as 1 minus the Gamma function.	

3.2.1. Physical Efficiency Indicator

The graph in Table 3a shows the fuzzy sets contained in the indicator, which are characterized by the membership function that associates the values contained in the indicator; in this case, a gamma membership function. The level of membership of the indicator was established through the characteristic function of the equation. The following conditions were formed from the linguistic variables: a physical efficiency of less than 40% was considered to be very low and shows the worst condition of the indicator; this may be due to high leakage volumes in the water network. Between 50% and 70%, the unfavorable potential decreases and shows an average situation of physical efficiency levels. With values greater than 80%, it becomes more important; however, it is not considered to be entirely beneficial for better resource management. This means that the membership values will grow linearly to the right, so that, as long as the values are closer to 0, this indicates in this case, that the physical efficiency is not favorable, while the best situation would be a positive trend with values close to 1.

3.2.2. Water Endowment Indicator

According to the results of the FL for this indicator, the values with a water endowment as close to 160 L/inhab/day were acceptable volumes for the minimum recommended by the UN, which was 150 L per day to meet all the needs in an optimal condition. However, if the values are greater than 300 L/inhab/day, it is very high. This means that as the endowment values increase, they are closer to 0, which implies a disadvantageous situation due to the high volumes of water used to supply the population. As the endowment values decrease and are closer to 1, it represents a healthy endowment to cover basic needs. Table 2 shows the results of the FL method for the different indicators for each component; no specific explanation is given, since the content of the results can be logically interpreted as in the two previous examples, depending on the type of membership function they possess.

4. Discussion

As shown in Table 4, the overall water management impact index for the SAPAL operating agency was estimated using the combination of both AHP and FL methodologies.

Table 4. Water Supply Management Index for Leon, Guanajuato.

Year	Quantity C1 = 0.4563	Quality C2 = 0.2562	Reliability and Continuity C3 = 0.1621	Cost Recovery of the Services Provided C5 = 0.0413	User Expectations C4 = 0.081	Water Supply Management Index
2002	0.393	0.148	0.095	0.003	0.00	0.64
2003	0.392	0.148	0.095	0.003	0.02	0.65
2004	0.396	0.211	0.111	0.003	0.02	0.74
2005	0.402	0.183	0.102	0.002	0.01	0.70
2006	0.408	0.210	0.102	0.003	0.01	0.73
2007	0.403	0.213	0.111	0.003	0.01	0.74
2008	0.400	0.219	0.153	0.003	0.00	0.78
2009	0.394	0.254	0.160	0.023	0.00	0.83
2010	0.393	0.255	0.160	0.017	0.00	0.82
2011	0.407	0.255	0.160	0.021	0.00	0.84
2012	0.407	0.255	0.160	0.018	0.00	0.84
2013	0.415	0.256	0.160	0.036	0.00	0.87
2014	0.416	0.256	0.160	0.029	0.00	0.86
2015	0.410	0.256	0.152	0.036	0.00	0.85
2016	0.411	0.256	0.150	0.036	0.00	0.85
2017	0.408	0.256	0.162	0.025	0.00	0.85
Average	0.40	0.23	0.14	0.02	0.004	0.79

Following the same reasoning as for FL, when the fuzzy value is closer to 1, this is an optimal condition for the water utility to provide a good service that impacts water management. On the contrary, the closer it is to 0, the worse the service provisions are, thus, having a negative impact on water management and the welfare of the city.

As shown in Table 4, there was a variation among the different components; it can be seen that the quantity component had an average value of 0.403 in linguistic terms, which means that the results of the indicators were the most favorable because it was the closest to 1. In short, it indicates that the water utility had good potable water coverage, consumption measurement, and supply sources, and had an optimal endowment, although it did not have a proper physical efficiency. According to the FL results for the quality component, a value of 0.23 was very close to 0, which indicated an unfavorable trend, although this component was considered one of the most important that SAPAL should take into account in order to offer a better service that positively impacts water administration services.

As for the continuity and reliability component, it related to the 24-h continuity service and the intermittent water supply. The average value obtained was 0.14, which showed an unfavorable trend for the water utility. This means that SAPAL does not have 24-h service, which has led to an increase in an intermittent water supply, which represents an uneven distribution of the resource. The worst results yielded were for the cost recovery of the services provided component with a value of 0.02. This is because the set of indicators that integrate it did not significantly affect water management, although it does represent an important impact on the economic side of the water utility.

In the evaluation of these indicators, the financial growth of the water utility was observed through revenues for the services offered. Lastly, the user expectations component was integrated by the domestic water rate indicator. When the results were evaluated, it was very close to 0, which, as the previous component, had no relevance in the impact of water management. This is due to the fact that this indicator represents a way for the water utility to increase its revenues due to the type of rate scheme established by SAPAL, maintaining a flat rate without considering the ability to pay of users of the different socioeconomic zones. This should be an important indicator in water management because it implies the affordability of water as a human right.

Finally, the historical (average) Water Supply Management Index obtained was 0.79, which could be considered acceptable with a trend that indicates that significant but insufficient progress has been made; while the best situation for the water utility would result in a positive trend with values closer to 1.

The way in which the official indicators of success have been developed contrasts with the current water (social and environmental) context by failing (or omitting to) reflect the full panorama of local water management in Leon. The management of water through the indicators used by the water utility is focused only on the management of the service itself. This makes the indicators relevant, but at the same time, limited. This is due to the fact that no important improvements have been made, and there is a lag in terms of innovation in water management [67]. Some efforts have been made in several studies, and those were used as references to the proposed index [8–20,68]. For this reason, they are not up to the current international requirements for integrated water management that aims to guarantee the sustainability of water resources. Therefore, the proposed Water Supply Management Index aims to adhere to the 6 SDG targets.

5. Conclusions

The study presented a Water Supply Management Index, analyzed data from the 2002–2017 period, and took into account 17 indicators distributed in five categories: quantity (5 indicators), quality (4 indicators), reliability and continuity (2 indicators), recovery of the cost of the services provided (3 indicators), and user expectations (3 indicators). The Water Supply Management Index calculated according to the selected indicators, showed an average value of 0.79; however, it is insufficient. According to the orientation of traditional indicators, a significant portion of all investments in public water services is targeted to expand, maintain and renew infrastructure. Thus, the management indicators used by potable water and sewage systems are designed to develop and implement programs to make processes more efficient. They do not cover all the related areas that need to be monitored for integrated management purposes (company, stakeholders, users, and environment). Therefore, the water utility does not have comprehensive indicators to carry out the planning and programming processes of water resources in an integrated manner. They do not follow up on the sustainability of water use, which is fundamental to guide the public management of water resources (towards sustainable development), in view of the water crisis that is currently being experienced. This analysis has made it possible to determine whether the construction of these evaluated indicators is sufficient for the approaches that are currently being taken at the institutional level. With this, the limitations of the organization are marked by the new approaches and perspectives that are currently salient for the issue of water management such as: the human right to water, the human right to a healthy environment, and the SDG-6. Therefore, there is an inability to show in a cross-cutting manner the problems that Leon is going through, since one of the challenges the city is facing is the social and environmental water crisis, and if the management of water resources is not improved, the population will bear the social costs of the partial management of the resource in the future.

The proposed index uses data from the city of Leon and represents the first approach to extend it to other water utilities. This work aims to make this index and its components mandatory. At a state level, from the government of the state of Guanajuato, CEAG gathers information indicators from water utilities, and they annually make available the sectorial drinking water and sewerage diagnostics. CEAG also has data from the Information System of Water Utilities agency (SIOO). Our goal is to have our index, components, and indicators integrated into the SIOO, so that they can be used at every water utility in the state of Guanajuato. Another of our goals is to integrate our proposal to the PIGOO (Water utilities Management Indicators Program), which collects this type of data, but at a federal level. Some financial programs at state and federal levels are based on indicators from SIOO and

PIGOO. The mandate and the possibility of obtaining financial support may encourage water utility managers to improve their performance according to the proposed index.

The institutional effort for collecting the information and generating indicators is positive but insufficient. It is urgent to adopt public policies to integrate the environment, society, and economic activities as water users. In addition, managers of water utilities must recognize that their mission is not limited to the technical and operational aspects of the service.

The analysis of indicators helps enrich political decisions regarding water management for cities with characteristics of water stress and population growth. In addition, it is necessary for managers to question themselves about the relevance of incorporating new indicators such as those established by SDG-6 (level of water stress, percentage of water safely treated, change in water use efficiency over time, changes in the extent of water-related ecosystems, affordability, etc.).

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