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A New Multi-Criteria Decision Analysis Methodology for the Selection of New Water Supply Infrastructure

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Abstract: Reliable and safe access to drinking water is necessary to ensure the economic and social sustainable development of human communities. This task requires a multi-criteria decision analysis (MCDA) methodology to select alternatives for new water supply infrastructure. These alternatives represent significant financial resources and are established for a long lifespan. To support decision-making in the context of building new water supply infrastructure, this study developed an MCDA methodology that integrates a hierarchy of non-economic benefits and the expected costs into a global index. Our methodology was implemented in the city of Santa Marta, Colombia. This city currently has a 60% drinking water shortage, and urgently needs to expand its capacity to satisfy the increasing water demand. The results of this study support the implementation of the best alternative for addressing Santa Marta's water supply problem by considering the preferences of stakeholders.

Keywords: multi-criteria decision analysis; analytical hierarchy process; water supply infrastructure

1. Introduction

Providing access to drinking water is a global challenge; it guarantees the quality of life and economic development [1]. The United Nations [2] stated that "the right to safe drinking water and sanitation is a human right essential to the full enjoyment of life and all human rights," and, therefore, states and international organizations must provide the necessary financial resources to guarantee them. Conversely, UNICEF and the World Health Organization (WHO) [3] estimate that 1.8 billion people have access to water that is unfit for human consumption, 663 million people do not have access to safe drinking water sources, and 2.4 billion people lack access to basic sanitation. As a result, major challenges exist to guaranteeing this right to a significant portion of the global population, particularly in developing nations [4].

Currently, more than 2 billion people in the world have significant restrictions on the access to potable water supply [5]. First, the availability of water over time is derived from the relationship between supply and demand; increases in demand relative to supply put pressure on the resource availability. Therefore, a relevant approach to quantifying the pressure on water sources is the ratio between the water withdrawn for different purposes (agriculture, industry, and domestic) and the total renewable water resources. A higher proportion of use indicates that the pressure on the resource increases, and it is substantially more difficult to satisfy an increasing demand for water [6].

According to the United Nations World Water Assessment Program (WWAP) [7], major pressure is exerted on water sources in the United States, North Africa, Middle East, Australia, India, and China. This pressure causes a condition in which approximately two thirds of the world's population will live in water-stressed countries by 2025 [8].

In addition to problems of availability, water supply also depends on the economic, institutional, and quality of resource factors [7]. Economic factors relate to water scarcity due to a lack of infrastructure—due to technical or financial constraints—independent of the availability of water. According to the Food and Agriculture Organization of the United Nations (FAO) [9], institutional factors arise when institutions are unable to ensure a safe, equitable, and reliable drinking water supply to users. Similarly, water quality is a restriction caused by the elevated costs of treating water from highly contaminated sources [10,11]. Note that the problems associated with the availability of drinking water in Latin America, Sub-Saharan Africa, and South Asia are primarily economic, whereas Africa, India, and China have an increased risk in relation to the water quality in watersheds. This finding implies an increase in the risks to human health, economic development, and ecosystems [12].

The demand for drinking water will proportionally increase as the world population increases. According to projections by the United Nations Department of Economic and Social Affairs (UNDESA) [13], the global population is expected to increase by approximately 32% between 2014 and 2050—from 7.24 billion people to 9.55 billion people. The population living in urban areas is estimated to increase by 64% between 2014 and 2050—from 3.88 billion people to 6.34 billion people. According to the Organization for Economic Co-operation and Development (OECD) [14], these population dynamics will cause an escalation in the global drinking water demand of approximately 55%, and an increase of more than 130% and 400% for the domestic demand and industrial demand, respectively, by 2050.

Additionally, in a scenario of increasing water scarcity, proper management of the water supply network becomes fundamental. According to Pietrucha-Urbanik and Żelazko [15] failures on water networks are the principal operating problems of potable water supply systems. In this line, the WHO has proposed the implementation of water security plans (WSP) in order to systematically assess and manage the risks of water supply from source to consumer [16,17]. Consequently, is necessary to identify, analyze, and make operative and strategic decisions to reduce the water supply network's failure frequency in order to minimize service interruptions and meet water quality standards to protect the final user [15,16,18].

Consequently, water resources management is a complex task that is aimed at ensuring economic development and improving the quality of life of people in subsequent decades [19]. The proposed solutions to ensure water supply must be linked to adequate infrastructure and strong institutional management that is focused on guaranteeing the sustainability of this resource. Several criteria must be considered to represent the non-economic benefits of new water supply infrastructure (e.g., operational time, infrastructure setup, operational risk, social and environmental factors). The complexity of the decision-making problems in water supply systems requires the integration of multiple criteria, models, and data sources [20], which confirms that the use of multi-criteria decision analysis (MCDA) is a suitable approach for addressing water resources planning and management problems, including the identification and selection of new water supply infrastructure [21]. MCDA methodologies have been employed in water sustainable management applications, such as water resources sustainability in the context of watershed management [22–24], urban drainage planning and management [25–28], and wastewater infrastructure planning and usage [29,30].

This paper is aimed at developing a methodology based on MCDA to improve the decision-making process for the selection of new water supply infrastructure that separately considers economic and non-economic criteria. This approach simplifies the global evaluation of alternatives and enables stakeholders to select an option given their economic restrictions or preferences. During the research for this paper, we discovered that many of the applications of MCDA for water supply infrastructure decisions have included economic criteria as part of the problem's main hierarchy. However, none of the investigated applications treated the economic criteria separately from the non-economic criteria. The use of four main non-economic criteria is proposed; the criteria are adaptable to other possible applications: operational time, infrastructure setup, operational risk and socio-environmental considerations. These additional criteria cover the global objective of providing a feasible and sustainable new water supply to a municipality, which is an assumption in this research. This structured methodology represents a new approach to address this type of decision-making problem. The proposed methodology is illustrated with a case study in the city of Santa Marta, Colombia, which has a water shortage and urgently needs to build new water supply infrastructure. The proposed methodology supported the decision-making process that facilitated the selection and future implementation of the alternative that will address Santa Marta's water supply problem.

2. Literature Review

MCDA is a structured approach for measuring the performance of alternatives that are based on multiple attributes [31]. The different methods that fall within this category can support the decision analysis process for issues in which more than one criterion—also known as attribute—is simultaneously evaluated [32]. These decision analysis tools enable the inclusion of relative importance, or weight, for each criterion. The weight is used to rank the performance of the alternatives to be implemented against the selected criteria [33]. These methods have the potential impact of improving transparency, auditability, and analytical rigor of decision-making processes in complex contexts [34].

Several MCDA techniques are discussed in the literature. Figueira et al. [35] developed an exhaustive state of the art of this field, as presented in Figure 1. MCDA techniques can be classified in categories such as outranking methods, multi-attribute utility and value theories (MAUT and MAVT), pairwise comparison methods, distance based methods, and fuzzy set theory. MCDA methodologies and their implementation is a relevant research field, given its impact on improving the decision-making process in complex environments and problems. Numerous MCDA techniques provide decision makers and analysts the opportunity to properly and effectively address decision problems.

MCDA has been extensively applied to support decision-making processes for issues related to the management and planning of water resources [31,32,36], for example, in several urban water supply case studies. Kabir et al. [37] reviewed more than 300 published MCDA methods for infrastructure management from 1980–2012, including 68 water resources systems applications. These publications included an extensive distribution of methods, including ELECTRE, PROMETHEE, MAUT, analytic hierarchy process (AHP), technique for order of preference by similarity to ideal solution (TOPSIS), compromise programming (CP) and combined methods.

MAUT and MAVT are well-known MCDA methods that have been implemented in various urban water planning infrastructure cases. Lienert et al. [21] developed a structured decision-making (SDM) procedure to guarantee the sustainability of water infrastructure planning, which is critically based on the stakeholder feedback and four scenarios, using a MAUT approach in a Swiss case study. Similarly, Scholten et al. [38] employed a MAUT model to consider the preference of ten diverse stakeholders to rank and evaluate the uncertainty of eleven water supply infrastructure alternatives for the region of Mönchaltorfer Aà, Switzerland.

One of the most extensively used pairwise comparison methods is the AHP. Okeola and Sule [39] used an AHP approach to select the best of three management operation alternatives for a new urban water supply scheme in the city of Offa, Nigeria. The conclusion was that the best management option for the system was public ownership and operation. Likewise, Jaber and Mohsen [40] implemented an AHP approach to evaluate non-conventional water resources supply alternatives to ensure water availability and sustainability in Jordan. They also concluded that desalination and water harvesting were superior to treated wastewater and water importation as potential solutions for water scarcity in the country.

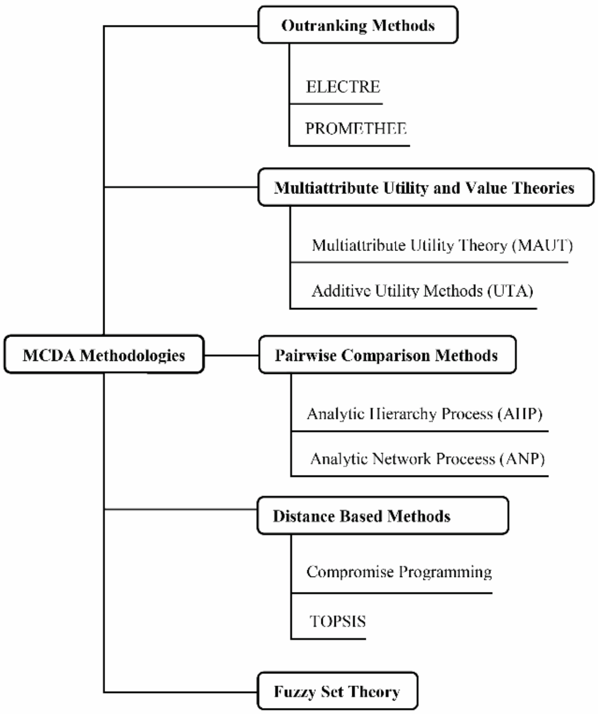

Figure 1. General multi-criteria decision analysis (MCDA) technique classification, adapted from Figueira et al. [35].

Other methodologies, such as CP and PROMETHEE, have also been implemented in urban water infrastructure decision-making and other water resources management applications. Abrishamchi et al. [41] proposed the CP approach to guide decision makers in the selection of the best alternative of water infrastructure intervention in the city of Zahidan, Iran. Additionally, Kodikara et al. [42] developed a PROMETHEE outranking method to evaluate alternative operating rules for urban water supply reservoir systems in Melbourne, Australia.

3. Methodology Based on MCDA to Improve the Decision-Making Process for the Selection of New Water Supply Infrastructure

The methodology proposed is summarized in Figure 2.

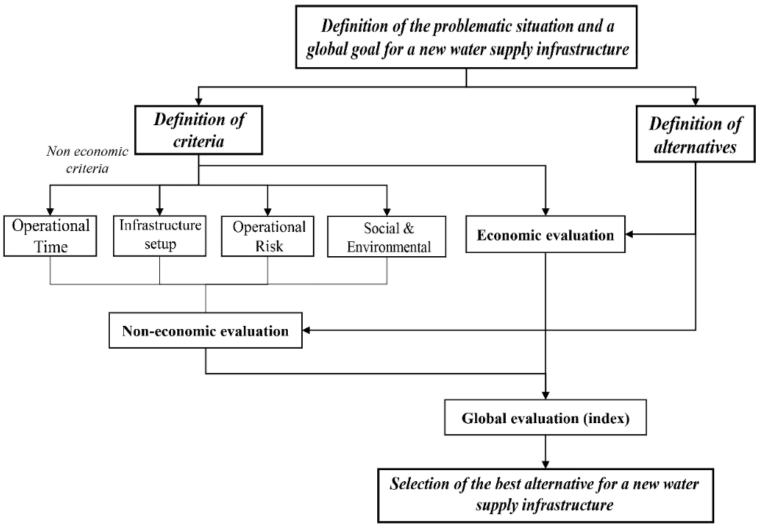

Figure 2. Methodology summary.

3.1. Definition of the Problematic Situation and a Global Goal for New Water Supply Infrastructure

The first step in the methodology is to describe the context, scope, and boundaries of the drinking water problem [21]. As suggested by Clemen and Riley [43], three principles must be fulfilled to obtain the correct decision-making context: (1) the decision context must capture the current situation ("Are you addressing the right problem?"); (2) the decision ownership must match the decision context ("Do you have the authority to make the decision within the specified context?"); and (3) the feasibility of the study ("Will you be able to perform the necessary study and analysis in the time allotted with the available resources?"). In addition to fulfilling these principles, our methodology suggests that a group of experts and stakeholders evaluate the current status of the water supply infrastructure system. This evaluation should present descriptive statistics that consider current and future demand and the expected drinking water shortage for the municipality. After the supply and demand trends are determined, the failures, weaknesses, opportunities, and population needs must be assessed. Once these items have been evaluated, the experts must envision a global goal for the new water supply infrastructure that satisfies the ongoing and future drinking water requirements for the city.

3.2. Definition of Criteria

As the water supply infrastructure serves to satisfy several purposes and has different benefits and costs, the criteria against which the performance of the system is going to be assessed must be defined [44]. These criteria depend on the context of every particular situation. However, a common approach has been to consider social, technical, environmental, and economic aspects, such as the main criteria [39,41,45]. As suggested by Saaty [46], the analysis of the problems in this research will be separated into two main groups: non-economic criteria and economic criteria.

Non-economic Criteria

The non-economic criteria to be used in this methodology are defined as operational time, infrastructure setup, operational risk, and socio-environmental criteria. These criteria attempt to represent the complexity of constructing these systems and the tradeoffs when several alternatives are considered. The characterization of these criteria is flexible for each problem of building new water supply infrastructure; thus, the stakeholders should define sub-criteria that further describe the non-economic criteria proposed in this paper.

The operational time criterion captures the importance of providing water as soon as possible to satisfy the demand or avoid shortages. This criterion has special importance in developing countries, where the current infrastructure is often either unable to provide a sufficient amount of drinking water to the inhabitants, or does not even exist. The duration of the construction phase of each potential alternative differs depending on the water treatment facilities and geographic conditions. If the duration of a civil project is excessive, the population will not be able to obtain a sufficient amount of safe water over a longer period. If the water supply is adequate but is forecast to be insufficient within a certain period, the durations of the new projects or expansions should be appropriate to avoid water scarcity in the municipality.

Infrastructure setup is a fundamental criterion for water supply that refers to the operational characteristics of different alternatives. To provide water in municipalities and communities, the construction of infrastructure is necessary; however, many approximations depend on the purpose of the system. For example, if you want to build a centralized water supply system for a big city, the technology for treatment and distribution would radically differ when compared with decentralized facilities in a smaller town. For the case of centralized systems, the operational ease should be considered. If the system has fewer treatment plants and pumping stations, it is easier to manage. Evaluating the possibility of future expansions is also important to satisfy future water demand and adapt the treatment facilities over time.

Risk is commonly defined as the frequency and severity of losses arising from each alternative of the system in its uncertain environment [47]. Operational risk has been defined by the Basel Committee as the risk of losses arising from problems from internal controls, systems, people, and external events [48]. For the selection of new water supply infrastructure, the operational risk criterion is concerned with ensuring a system's reliability to obtain sufficient water from surface and groundwater sources. In addition, vulnerability is defined as the characteristics of the severity of water deficits if a failure occurs [49]. This criterion is relevant for reducing the water distribution system's vulnerability by decreasing the network's maximum pressure and increasing redundancy, that is, the number of water conduction lines. Another common operational risk, especially in developing countries, is sabotage to the water infrastructure. For example, the risk of water adduction losses is proportional to the accessibility of the adduction pipelines to the population. Water resources planners must identify and describe the operational risk depending on the context and the characteristics of the water supply system.

The social and environmental impacts of water supply infrastructure should be considered. These impacts should be revised in each context, but a common concern is to minimize the area of influence of the project in social and environmentally protected areas, such as national parks or cultural reserves (e.g., indigenous reserves). Reducing the environmental impact of the construction process is desirable. A suggested method for measuring these impacts is to reduce the conduction line length; this method will decrease the impact on the vegetation coverage. Another method is to reduce the percentage of water withdrawn from rivers, to guarantee its ecological flows. As a special case, if the water supply infrastructure is going to satisfy the demand of a large city, the possibility of supplying water to small surrounding municipalities should be considered to maximize the local economic development [50].

3.3. Economic Evaluation

In addition to assessing the water supply alternatives against the previously discussed criteria, their respective costs should be evaluated. An appropriate estimation of these costs must include the construction and operation of the system. Numerous calculation methods are available to estimate the economic performance of the alternatives [45,51]. For this decision problem, however, we suggest evaluating the present value of the costs (PVC) instead of the net present value (NPV), because the estimated earnings of the project during its lifecycle should represent a cost recovery for water suppliers using a typically regulated water distribution tariff [52]. The PVC includes construction and operation costs. The main operative costs for drinking water systems are pumping and treatment equipment. Given the variety of water sources, treatment requirements, topographical conditions, and general planning, a relevant and dynamic difference exists in the variable costs among the alternatives. This difference represents an effort to estimate the financial performance for every alternative during the project lifecycle.

3.4. Definition of Alternatives

The next step is to determine the alternatives that can potentially satisfy the problem. Each alternative, or option, must represent a feasible and suitable resolution to the problem of the water supply, considering the financial, social, and environmental restrictions [53]. To maximize the diversity and relevance of the alternatives to consider, they should be proposed by the dialogue and discussion of different stakeholders [21]. Once the water supply alternatives are selected, they will be evaluated against the previously defined criteria.

3.5. Non Economic Evaluation

Because the evaluation of the best alternative based on non-economic criteria is complex, this decision-making process should be supported with a MCDA model. As noted, numerous MCDA approaches are available in the academic literature; the majority of these approaches have been increasingly applied during the last 20 years, particularly in the context of water resources planning and management [54]. The selection of the model should also be performed via agreement among stakeholders, to ensure that they are satisfied with the manner in which the model operates (i.e., assumptions, scales of preference, weighting and ranking) to subsequently implement its results [35]. The results obtained from the MCDA technique should be presented in a ranking of the alternatives. The alternatives must be evaluated against the previously defined criteria and subcriteria. Depending on the selected MCDA method, this evaluation can include objective and subjective assessment and perceptions. After the alternatives have been ranked, a sensitivity analysis should be performed. A sensitivity analysis helps to determine the robustness of the decision model. In a sensitivity analysis, various scenarios can be investigated; for example, how a change in the weight of the criteria, the inclusion of new criteria or the exclusion of applied criteria can impact the results.

3.6. Global Evaluation

For every decision, positive and negative factors to contemplate are usually psychologically interpreted in the form of benefits (gains) and costs (losses) [55]. The evaluation of a decision according to these factors is not easily directly performed. Saaty [56] suggests creating a cost hierarchy to paired comparisons with judgments using a scale of 1–9. However, we alternatively propose a direct estimation of the present value of the total cost (PVC), including OPEX and CAPEX.

Based on the four control merits of the benefits (B), opportunities (O), costs (C), and risks (R) formula proposed by Saaty [46], we suggest a simplification of his formula, which employs only benefits (B) and costs (C). Formula (1), which is proposed for this decision-making problem, is an alternative to the traditional marginal return (B/C), and is useful when both B and C have the same order of magnitude [46]. We globally evaluated each alternative by combining the normalized benefits (B) and normalized costs (C), as shown in Equation (1):

$$I_i = (1 - w_C) \cdot B_{N_i} - w_C \cdot C_{N_i},\ \forall\ i\ \in A \tag{1}$$

where I_i is the value of the index for alternative i; w_C is the weight given to the costs; B_{N_i} is the normalized benefits; C_{N_i} is the normalized costs for alternative i, respectively; and A is the set of alternatives. The range of the performance index will vary between −1 and 1.

3.7. Selection of the Best Alternative for Water Supply Infrastructure

The goal of the decision-making methodology presented in this research is to identify the best alternative for new water supply infrastructure, given the stakeholder preferences and the structure of the decision problem. Once the ranking of alternatives has been established, a decision maker should have sufficient information to determine the best alternative and proceed to its implementation to address the water supply problem.

4. Case Study: City of Santa Marta, Colombia

4.1. Definition of the Problematic Situation and a Global Goal for New Water Supply Infrastructure

Santa Marta is located in the Magdalena region in the northern coast of Colombia; it is currently experiencing serious problems regarding its water supply. In an average season, the inhabitants require 2.21 m^3/s of water; however, the water supply is approximately 1.55 m^3/s, that is, nearly 30% less of the required water supply. During the dry season, the supply can be as low as 0.88 m^3/s, which represents an approximately 60% shortage [57]. This scarcity has prompted the local water service provider to implement temporary solutions, including the distribution of drinking water via tanker trucks. Problems such as watershed deterioration—and its associated river flow reduction—decreased rainfall, illegal water collection, and rapid demographic growth contribute to this shortage.

Santa Marta has two potable water treatment plants (PWTPs), which are connected to a water distribution network that encompasses 79% of households [58]. The Mamatoco PWTP is the principal plant; it treats approximately 0.8 m^3/s from the Manzanares and Piedras Rivers—nearly 20% of its capacity—but associated river flow rates do not enable a full operation capacity. Similarly, the El Roble PWTP treats approximately 0.45 m^3/s from the Gaira River and does not operate at full capacity. In addition to the surface water sources, the city has an aquifer from which the local water service provider can extract 0.3 m^3/s during dry months without risk of seawater intrusion [58]. However, several non-controlled wells extract an unknown amount of water, which can compromise the water quality of the aquifer.

Anticipated rapid population growth will exert additional pressure on the city's water supply capacity in subsequent years. Santa Marta is an important tourist destination, with more than 500,000 inhabitants and approximately 51,000 additional tourists during peak seasons. The permanent population is expected to experience geometric growth at a rate of 2.82% every year for the next 50 years. The total population during peak tourism and low tourism season is expected to increase at a rate of 2.93% and 2.86%, respectively [58]. By 2040, the population is expected to double to nearly 980,000 permanent inhabitants and a floating tourist population of 133,000. Similarly, by 2065 the total population in the city will exceed 2.2 million. In less than 50 years, the city must be able to provide drinking water to a population that is four times larger than the current population. Considering that the demand is 0.15 m^3 per person per day, the city must provide an increasing water supply of approximately 5.7 m^3/s by 2065 [57].

For this case study, the judgments and preferences of eight experts in water management problems, particularly drinking water and basic sanitation issues in Colombia, were collected. These eight experts are stakeholders with academic, government, and local water service provider backgrounds. The academic experts included the project director of the Santa Marta's strategic water supply planning research and a professor of the Aqueduct and Sewage Research Center (CIACUA) at the Universidad de Los Andes. The three government experts included a project evaluator from the water and sanitation office at Financial Entity for the Territorial Development (Findeter S.A.), a project manager, and an official from the Vice-Ministry of Water and Sanitation of Colombia. The engineering planning chief, the general director and the technical director of the Santa Marta's water utility, Metroagua S.A E.S.P., were involved in the decision-making process.

4.2. Definition of Criteria

Table 1 defines the hierarchical structure of the non-economic criteria and sub-criteria. The goal of the decision problem is described at the top of the hierarchy: to determine the best alternative for the construction of a new water supply infrastructure for the city. Level 2 of the hierarchy includes the main non-economic criteria: operational time, infrastructure setup, operational risk, and social and environmental criteria. Level 3 of the hierarchy includes the sub-criteria within each main criterion. Similarly, Level 4 represents the second level of the sub-criteria for the Level 3 sub-criterion.

4.3. Definition of Altermatives

Generation of the alternatives requires an understanding of the water sources to be considered. The project's team developed studies that consider the hydrological, meteorological, topographical, and legal aspects related to the benefits and limitations of the possible water resources (e.g., rivers, groundwater, and seawater). Subsequently, the group of stakeholders (e.g., government, university, and water utility) joined in several sessions to discuss and select a reasonable combination of water sources that compiled the group of feasible alternatives to be subsequently evaluated using the MCDA based methodology. Strengthening the current system capacity by providing water from several additional sources, including various rivers and even from the Caribbean Sea, has been proposed. Seven alternatives have been proposed by the stakeholders to address the current water shortage condition in the city and guarantee its drinking water requirements during the next 50 years. As the criteria and alternatives have been identified, the next step is to create a matrix to be populated with the corresponding information.

Table 2 shows the matrix populated with the information.

Table 1. Global goal, criteria, and sub-criteria description.

Goal	Criteria	First Level Sub-Criteria	Second Level Sub-Criteria	Description
Find the best alternative of new water supply infrastructure for Santa Marta, Colombia	Operational time	Reduce time for operation beginning		Time in which the first stage of alternative will be in operation
		Reduce time to meet water demand		Time in which the demanded water is equal to the water supplied in the city
	Infrastructure setup	Ensure operational ease	Reduce number of potable water treatment plants (PWTP)	Number of PTWP and its required expansions
			Reduce number of pumping stations	Number of pumping stations required
		Provide the possibility to have future expansions		Possibility to have additional expansions at the end of the planning horizon
	Operational risk	Ensure system reliability		Related to the water availability and water withdrawals from rivers, this is the relationship between the minimal flow rate of the rivers and the water supply required by the end of the planning horizon
		Reduce system vulnerability	Reduce network maximum pressure	Estimated network pressure
			Increase the number of water conduction lines	Conduction lines required by the alternative
		Reduce the risks of losses during adduction		The risk of water adduction losses is proportional to the accessible area by population to the adduction pipelines
	Social and environmental	Minimize influence area at National Parks		The intersection area between a 100 m influence area of the alternative route and the area of the National Parks
		Minimize influence area at indigenous reserves and sacred sites		The intersection area between a 100 m influence area of the alternative route and the area of indigenous reserves and sacred sites
		Reduce environmental impact	Reduce conduction line length	The impact in the vegetation coverage is proportional to the conduction line length
			Reduce percentage of water withdrawn	This impact is assessed as the ratio between the flow withdrawals and the ecological flows of the respective rivers
		Guarantee possibility of bringing water to surrounding municipalities		Some alternatives have the possibility to supply water to small surrounding municipalities, namely: Ciénaga, Puebloviejo, Tasajera, and Nueva Venecia

Table 2. Matrix.

		Alternatives												
		A1	**A2**	**A3**		**A4**		**A5**			**A6**			**A7**
Time for operation beginning (years)		3	4	2		2		2			3			2
Time to meet water demand (years)		5	4	3		4		2			4			3
Water source		Guachacá Buritacá Don Diego	Magdalena	Toribio Córdoba	Guachacá Buritaca	Magdalena		Caribbean Sea	Toribio	Córdoba	Caribbean Sea	Piedras Guachacá Buriticá	Toribio	Toribio Córdoba Magdalena
New PTWP		Curval	Toribio	Toribio	Curval	Toribio	Curval	Desalination	Toribio	Curval	Desalination	Curval	Toribio	Toribio
Number of expansions		7	4	5	2	3	1	1	2	1	5	6	1	4
New Treatment Capacity at 2064	New Treatment Capacity per PWTP (m^3/s)	6.4	6	4.4	2	5.5	0.4	1	2	0.4	5	7	1	6
	Total Treatment Capacity (m^3/s)	6.4	6	6.4		6.9		7.4			8			6
Number of pumping stations		13	6	12		10		10			15			6
Possibility of future expansions		No	Yes	No		No		No			Yes			Yes
System reliability (-)		1.9	2.0	1.4		2.0		2.0			1.3			2.0
Estimated Network Maximum Pressure (PSI)		341	262	341		270		99			341			259
Number of conduction lines		4	2	5		3		2			6			6
Pipeline length in populated area (Km)		0.0	11.9	0.0		17.9		0.0			0.0			11.9
Influence area at National Parks (Ha)		1.7	834.7	0.2		14.1		0.1			0.2			582.2
Influence area at indigenous reserves and sacred sites (Ha)		986.98	220.42	922.4		220.4		88.2			1048.7			88.2
Conduction line length (Km)		166.07	140.45	124.04		210.68		7.32			128.46			147.80
Percentage of water resources withdrawn		0.14	0.00	0.59		0.00		0.50			0.64			0.50
Possibility of bringing water to surrounding municipalities		No	Yes	No		Yes		No			No			Yes

4.4. Non Economic Evaluation

AHP, which was first proposed by Saaty [56], is a MCDA methodology that considers objective and subjective criteria during the decision-making process in complex problems [55]. By the AHP, a problem can be represented using a hierarchical structure. The purpose of the hierarchical structure is to understand how the alternatives and criteria interrelate in relation to the problem [33]. The hierarchical structure is composed of levels: the first level is the global goal or general objective; the intermediate levels correspond to the criteria and sub-criteria that enable the global goal to be achieved; and the alternatives to evaluate are included in the bottom level.

The AHP functions by creating a pairwise comparison, first within each level, and secondly among the levels, to determine the preferences of decision makers. The first set of pairwise comparisons is made among the criteria to reflect the preference of a decision maker regarding the usefulness of each criterion toward solving a decision problem. These preferences are based on the judgment and knowledge of the decision maker. The values obtained from this first set of pairwise comparisons will be applied as the weight of each criterion. The second set of pairwise comparisons is a comparison of alternatives regarding a particular criterion. The third comparison involves multiplying the result of the second set of pairwise comparison by that of the first set of pairwise comparisons and ranking the results [33]. Because the AHP requires several pairwise comparisons, a common problem is consistency in the selections. To solve this problem, Saaty [56] proposed a consistency ratio to measure the consistency in the judgements of decision makers. Ratios higher than 0.1 often require re-examination. Based on this classification, the relative weights of the criteria and alternatives can be estimated by a mathematical method that is known as estimation of eigenvalues [55]. The AHP allows to show priorities of alternatives relative to the goal using a hierarchical structure. The AHP does not require the use of complex calculations or computer systems [33]. The AHP is a flexible, participatory, and appropriate methodology to structure complex decision problems and select the best alternative that successfully satisfies the total objective of a decision problem.

The stakeholder preference was measured using the scale proposed by Saaty [56], as shown in Table 3.

Table 3. The scale proposed by Saaty [56].

Numeric Rating	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or Slightly More Important	
3	Moderate Importance	Experience and judgement slightly favour one activity over the other
4	Moderate to Strong Significance	
5	Strong Importance	Experience and judgement strongly favour one activity over another
6	Strong to Very Strong	
7	Very Strong or Demonstrated Importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very Strong to Extreme	
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation

The eight experts completed an online survey; their judgments were pondered in their respective groups as the geometric average of the recorded values. Figure 3 shows each group's preference regarding the main criteria of the decision problem. Although differences exist among the interest groups, operational time was consistently considered as the most important criterion. Infrastructure setup was the second most important criterion for all groups, with the exception of Government, which considered operational risk to be second in importance. A consensus was obtained for Social and Environmental as the least relevant criteria among the main criteria. The relative weights of the sub-criteria are presented in Figure 4. Note that the judgement of the experts was systematically consistent; thus, every evaluated matrix had a consistency ratio less than 0.1, and the total model a value of 0.01.

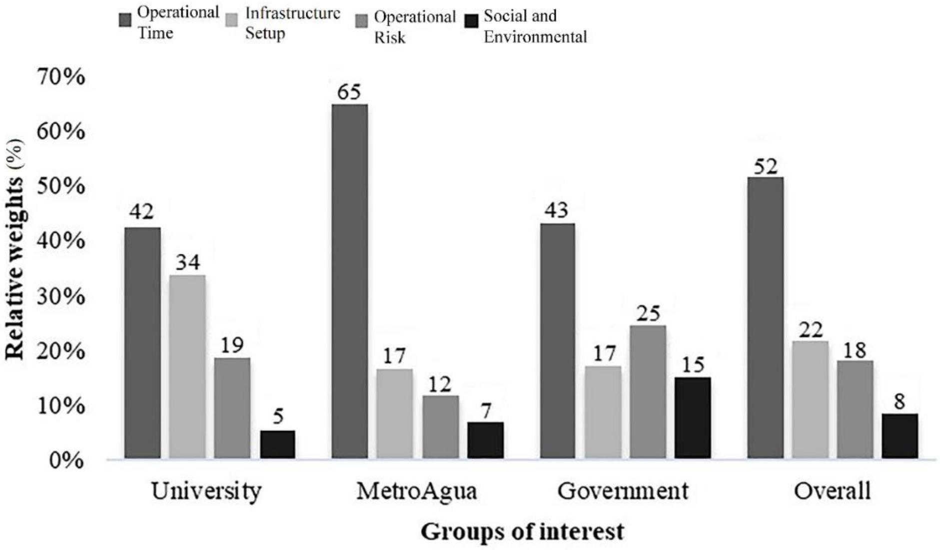

Figure 3. Relative criteria weight per group of interest.

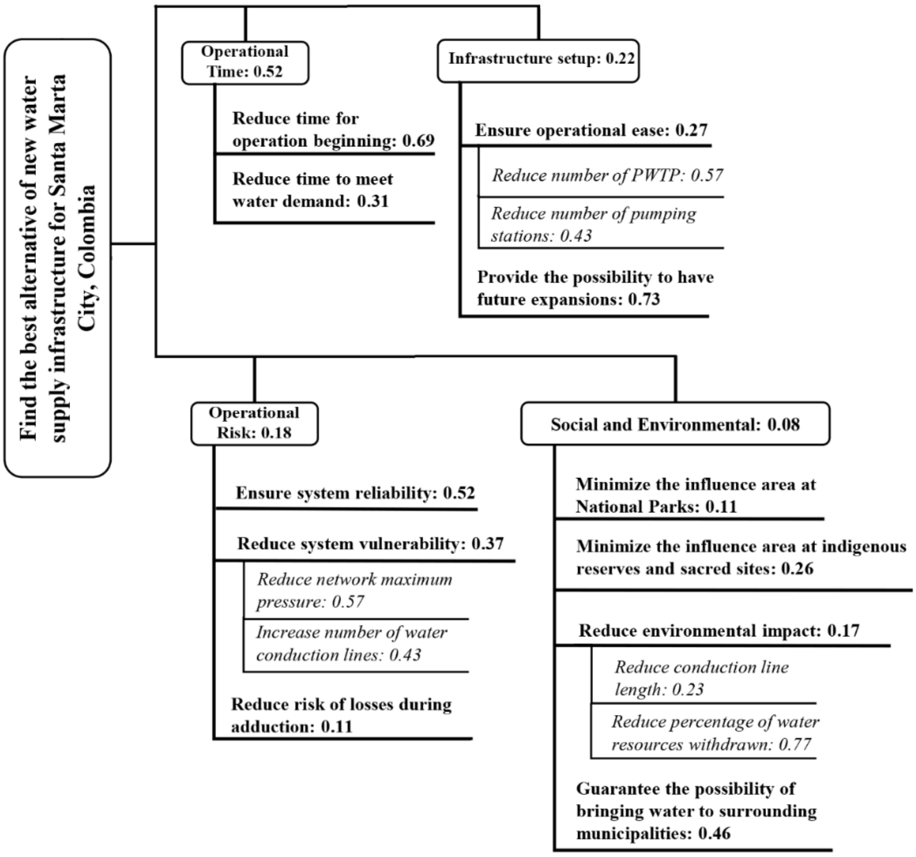

Figure 4. Hierarchical structure with relative weights.

To establish the ranking of alternatives, every alternative must be compiled and weighed throughout the hierarchical structure. The software Expert Choice 11.5 was used to compile the results of the decision problem. As shown in Figure 5, the best option is A7, followed by A4 and A5; in this order, Alternatives A2, A3, and A1 were similar, and the worst option was A6.

The robustness of the decision model was verified by a sensitivity analysis. Evaluating how the ranking of alternatives changes as the weight of the main non-economic criteria varies is important. The decision-making software facilitates the evaluation of the global alternatives performance as a function of the weight of the main criteria. With respect to the operational time criterion, A7 had the best performance until the weight of the criterion exceeded 0.79; the second and third places varied among A2, A4, and A5. In relation to infrastructure setup, A7 performed the best when the weight exceeded 0.09; the second and third places broadly varied among A1, A2, A4, and A5. Concerning the operational risk, A7 was the best when the weight was less than 0.67, otherwise A5 performed better. Regarding the Social and Environmental aspect, A7 was the best for weights below 0.32; however, A4 performed better when the weight was higher. The sensitivity analysis shows that the ranking obtained with the preference of a decision maker is generally consistent as the weight of the main criteria varies. Note that A7 remained the best alternative in most scenarios, even when the weight of the criteria extensively varied. Conversely, A3 and A6 were never in the first positions of the ranking during the sensitivity analysis.

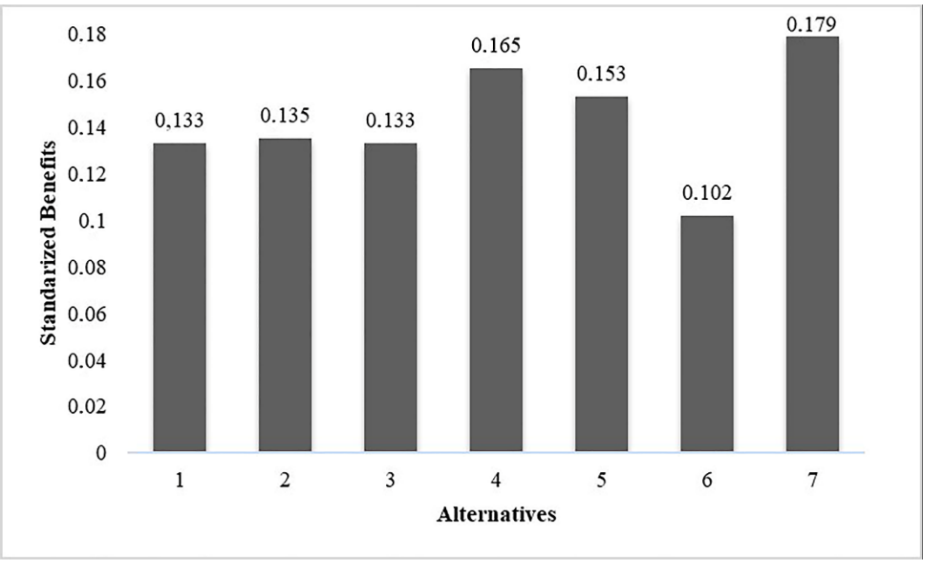

Figure 5. Ranking of alternatives by implementing the AHP model.

4.5. Economic Evaluation

The estimated annual pumping and treatment costs constitute the main variable cost driver. These costs were estimated throughout a 50-year planning horizon and are presented in Figures 6 and 7, respectively. Saldarriaga et al. [58] have estimated the construction costs for each alternative by considering the costs of excavation, pipelines, pumping stations, and new PWTPs. As shown in Table 4, the total costs of the alternatives have been valued as the sum of the discounted operative costs during the project lifespan and the associated constructive costs. In addition to the long lifespans of water supply infrastructure projects, the operative costs account for the majority of the total costs and represent the main difference among alternatives.

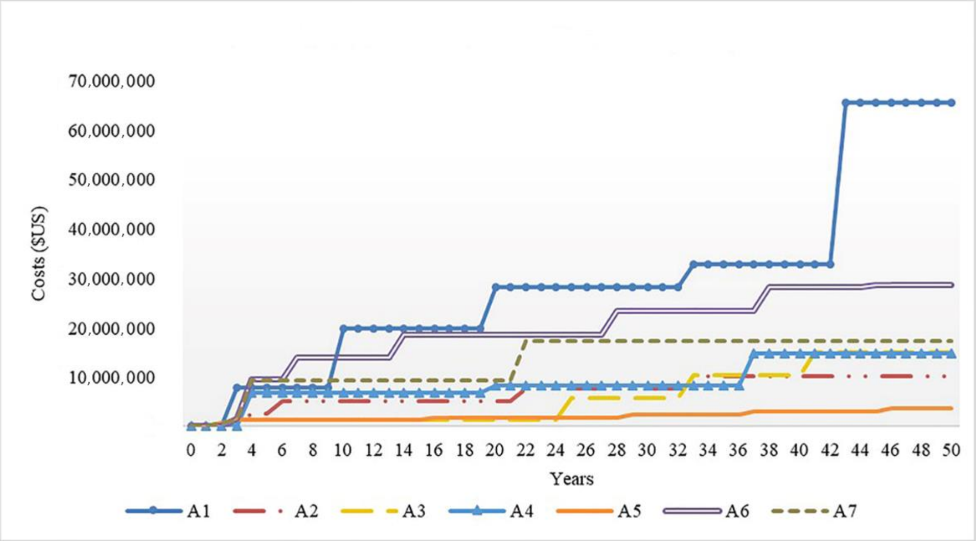

Figure 6. Estimated annual pumping costs by alternative.

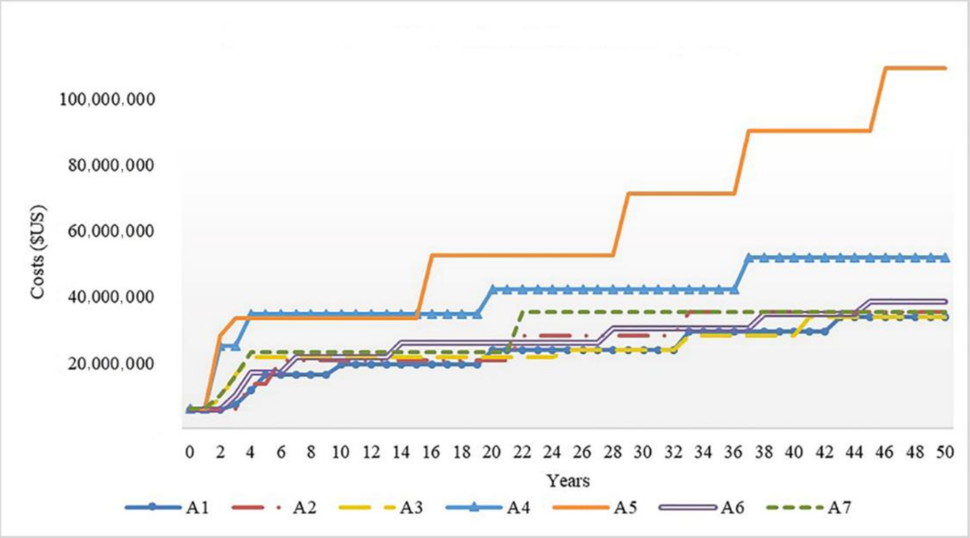

Figure 7. Estimated annual treatment costs by alternative.

Table 4. Costs summary by alternatives.

Alternatives	PVC of Treatment (US$)	PVC of Pumping (US$)	PVC of Variable Costs (US$)	Construction Costs (US$)	Total Costs (US$)
A1	321,827,094	323,299,388	645,126,482	47,440,763	692,567,245
A2	359,423,907	86,292,406	445,716,313	43,313,450	489,029,763
A3	363,610,315	51,672,610	415,282,925	44,998,266	460,281,191
A4	608,286,307	114,545,941	722,832,247	67,357,810	790,190,057
A5	770,633,787	26,119,599	796,753,386	70,747,453	867,500,839
A6	379,643,598	251,435,120	631,078,718	52,857,836	683,936,554
A7	424,633,418	174,198,263	598,831,681	38,782,207	637,613,888

PVC: present value of the cost.

4.6. Global Evaluation

Figure 8 shows the performance index (PI) for each alternative when varying the weight given to the cost along its range. Given a certain cost weight, note that the alternative with the highest PI is the best among its group. The graph illustrates the sensitivity of the ranking to the variation of the cost weight: A7 remains the best alternative when the weight of the cost criterion is lower than 0.56. However, when the weight exceeds 0.56, A3 and A2 are superior,r due to their lower cost. A4 and A5 rank second and third on the benefits scale but are the most expensive; thus, when the weight given to the cost criterion exceeds 0.32 and 0.19, respectively, they are exceeded by A3 and A2, which are equal. A1 and A6, which have poor performance in benefits, improve in the ranking only because they are less expensive than A3 and A2.

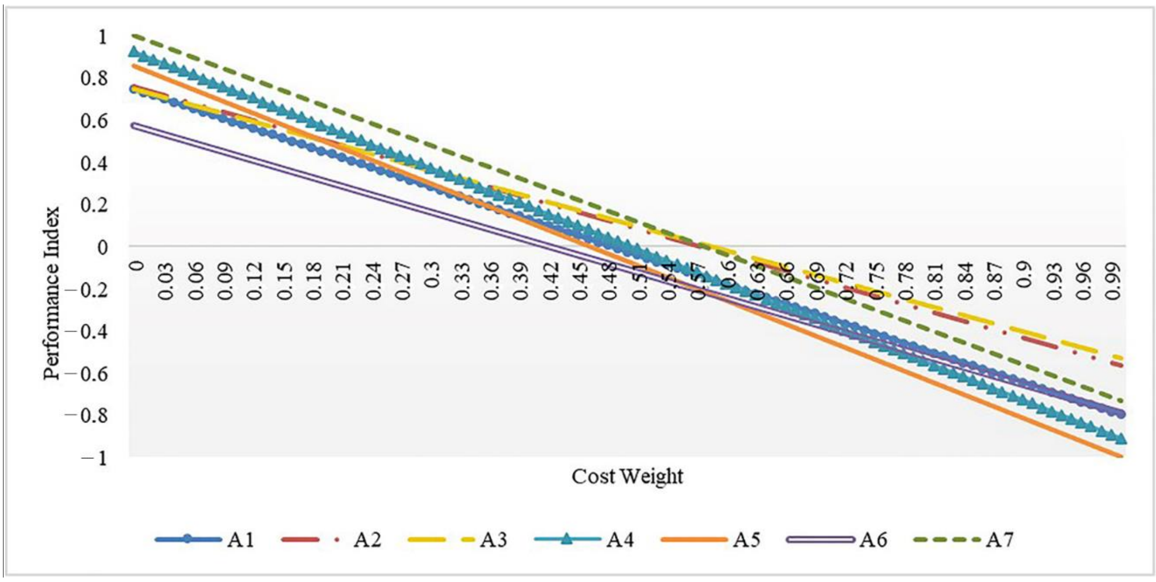

Figure 8. Performance index (PI) variation as a function of the cost weight.

Once the weight of the cost criterion is selected, the PI will establish a new ranking of alternatives that considers both non-economic criteria and economic criteria. In their study, Saldarriaga [58] determined that the weight of the total costs for this project is 0.22. The ranking is shown in Table 5. Alternative 7 is at the top of the ranking, followed by A4; A2, A3, and A5 performed similarly in the intermediate positions; and at the end of the rank, A6 and A1 have the lowest scores.

Table 5. AHP performance index score and rank when the cost weight is 0.22.

Rank	Alternative	AHP Performance Index Score
1	A7	0.618
2	A4	0.519
3	A2	0.466
4	A3	0.465
5	A5	0.448
6	A1	0.406
7	A6	0.272

5. Comparison with Previous Studies

Given the critical situation of Santa Marta's water supply, Universidad de los Andes, Findeter, and Metroagua S.A E.S.P collaborated to develop studies with the purpose of strengthening the city's water infrastructure for the next 50 years. The product of this research was subsequently published by Saldarriaga et al. [58] in a report that includes demographic and water demand forecasts, an anthropologic study, a characterization of surface and underground sources of water, a water network optimization, and an alternatives evaluation. This study seeks to complement this previous study and strengthen the tools that support the decision-making process of water resources management for the city.

A comparison of the results of this case study with the previous analysis for this decision-making problem is desired. Saldarriaga et al. [58] implemented a multiattribute utility theory (MAUT) model to determine the ranking of the seven alternatives of this project. MAUT is based on ordinal comparison of each alternatives using a multiattribute utility function. The most common approach of MAUT for evaluating multiattribute alternatives is to use an additive representation [35]:

$$U(A_i) = \sum_{\nabla j} w_j v_j(A_i) \tag{2}$$

where U is an additive multiattribute utility function, A_i is the alternative i, w_j is the weight of j criterion or attribute, and v_j is an utility function associated to j. The authors weighted all criteria (including the costs) and determined a unique performance score.

Figure 9 provides a comparison of the alternatives scores relative to the implemented methodology, namely, the AHP (performance index) and MAUT models. In general, the AHP score is lower than the score calculated by MAUT; however, similarities exist in the ranking obtained by both models. Table 6 shows the rankings obtained with the AHP and MAUT methods, where A7 is the best alternative, A2 ranks third, and A6 ranks last.

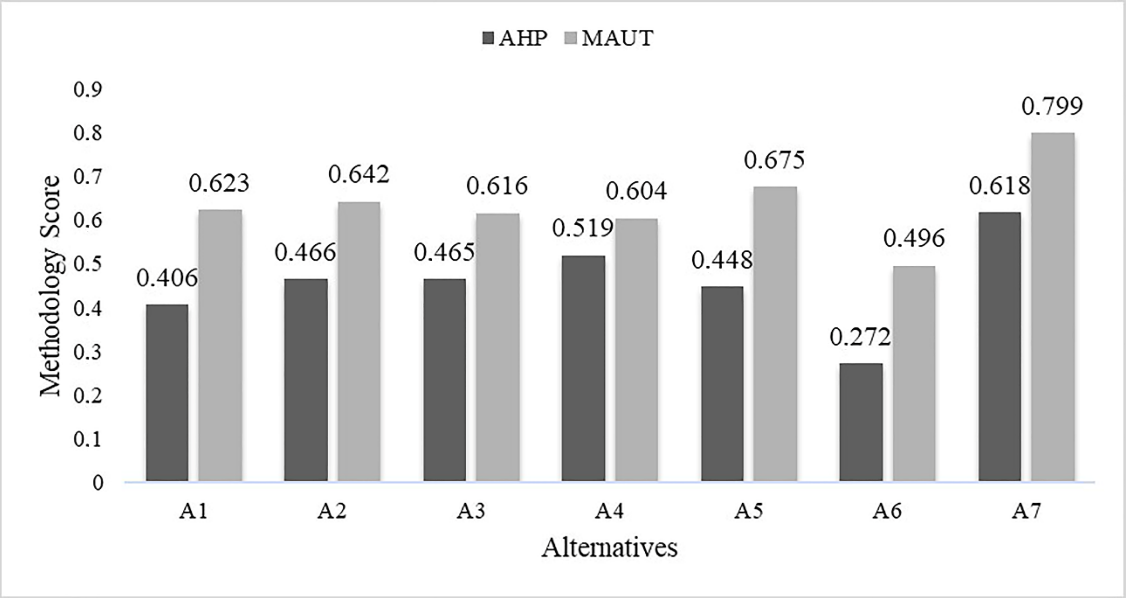

Figure 9. Alternatives' scores by methodology (AHP and MAUT).

Table 6. Alternatives' rankings by methodology (AHP and MAUT).

Rank	AHP	MAUT
1	A7	A7
2	A4	A5
3	A2	A2
4	A3	A1
5	A5	A3
6	A1	A4
7	A6	A6

Additionally, Figure 10 shows a dispersion plot that compares the normalized scores for both methodologies. If the two models were consistent, a linear relation would be expected. In this case, the obtained coefficient of correlation (ρ) between the alternative's score using AHP and MAUT was 0.876. However, is noteworthy that A4 and A5 diverge as a function of the method. MAUT penalizes A4, whereas the AHP promotes A4; the inverse case occurs with A5. This change can be attributed to the method by which the preference of the stakeholders was measured. Note that the remaining alternatives and their scores are consistent, and the scores given to A2, A3, A4, and A5 are similar using both methodologies. Considering the ranking obtained by the MAUT and AHP models, we obtained the best option (A7), followed by a group of average alternatives (A2, A3, A4, A5) and a group of alternatives with poor performance (A1 and A6).

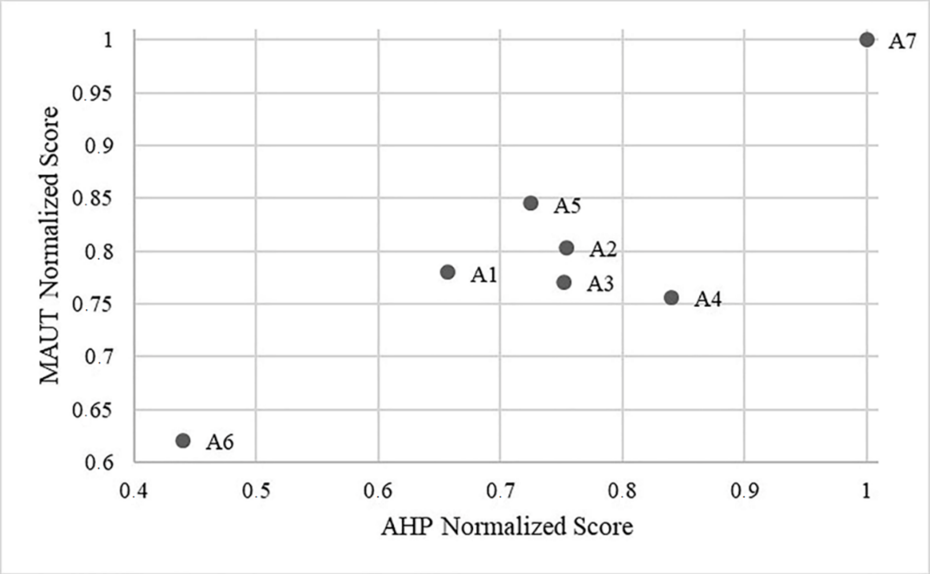

Figure 10. Normalized scores comparison for both methodologies.

Characterization of the performance of each alternative is useful as a tool to support decision-making related to the described problem. If only non-economic criteria are considered, A7, A4, and A5 systematically perform best even with strong weight variation. Conversely, when non-economic and economic criteria are simultaneously considered, A2 substitutes A5 in the ranking because A2 is less expensive. However, A7 remains at the top of the ranking. Note that the ranking is highly sensitive to variations in the weight of the economic criterion. As we compare the results of AHP with those of MAUT, a fair match is obtained with the best option and worst option (A7 and A6, respectively), and a group of intermediate alternatives is also obtained. These mid-ranking alternatives are very similar, especially with the MAUT results.

These results support the implementation of A7, given its outstanding performance when assessed against the selected criteria when corroborated with sensitivity analyses and compared with other methodologies. If A7 is implemented as planned, Toribio PWTP will treat water from the Magdalena, Toribio, and Córdoba rivers (Figure 11). To complement the analysis of the A7 features, Figure 12 shows the treatment capacity, water demand, and system losses throughout the lifecycle of the project. The first stage of the new plant should commence operations two years after the beginning of construction, and, within three years, the city is expected to eliminate their water supply deficit. In addition to addressing the water shortage, the total water demand for subsequent years will be broadly satisfied, including the domestic, commercial, industrial, and increasing tourist demand for the city. Water supply management also includes the project's implementation of a long-term plan of continuous technical losses and PWTP water requirement reduction implemented by the local water utility (i.e., initial system losses represent approximately 43%, and reductions of 17% are expected by 2035). A7 is a roadmap for providing safe water to Santa Mater City over the next 50 years.

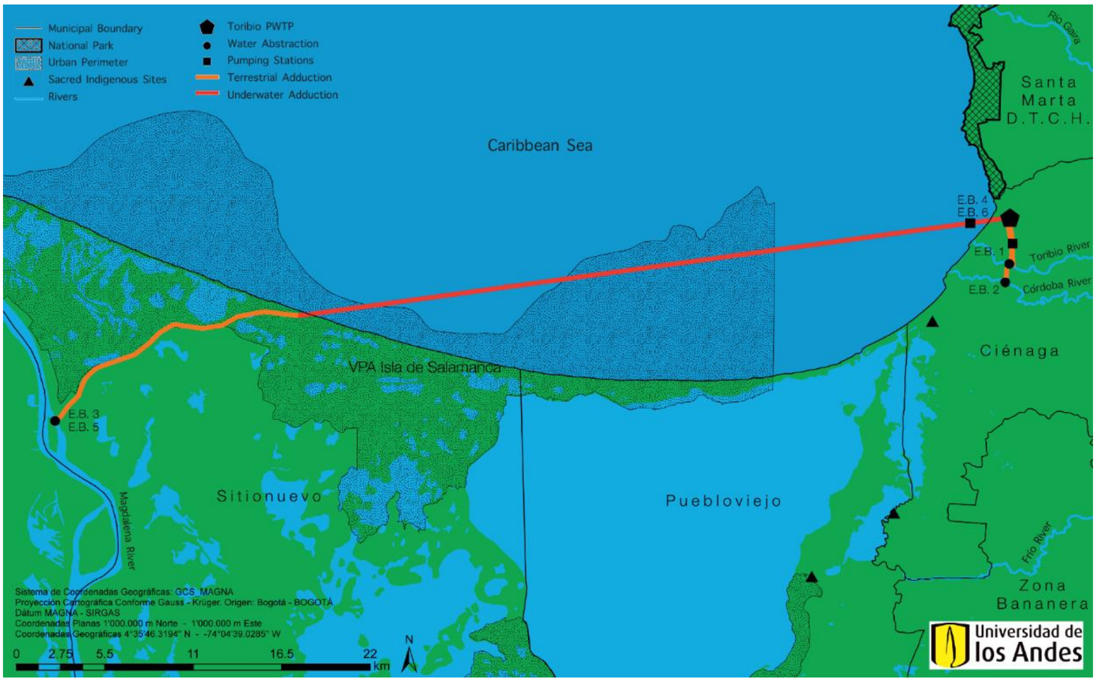

Figure 11. Selected alternative characteristics and geographical location, Adapted from [58].

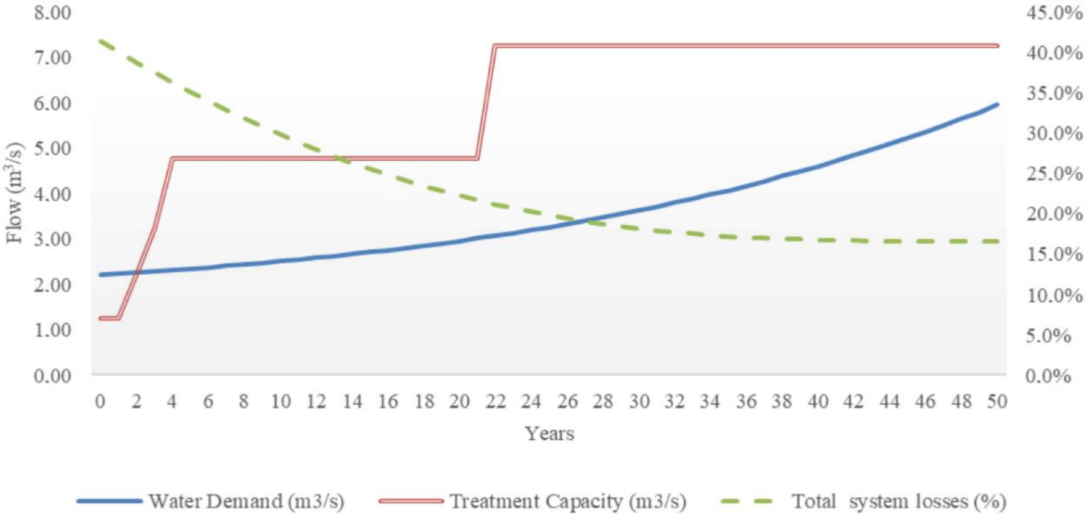

Figure 12. Alternative 7: water demand, treatment capacity and system losses.

6. Limitations and Future Research

Throughout this paper, we have presented a MCDA methodology and a case study for water infrastructure planning using a supply-based approach. This approach has important limitations, such as the supply uncertainty in a climate change scenario and the non-inclusion of the resilience criterion, which describes how quickly a system is likely to recover after the occurrence of a failure [49,59]. For this reason, the implementation of water demand management strategies to complement supply-oriented efforts is essential. As an illustration, one limitation of this case study was to assume a static per capita water demand during the lifecycle of the project, which was performed given legal requirements for new water supply infrastructure projects in Colombia. However, managing and reducing the per capita water demand represents several economical and sustainability benefits and important challenges for water planners [60–63]. For example, Cooley and Parishamban [64] discovered that urban water conservation and efficiency measures are the most cost-effective measures for satisfying current and future water needs in California. Additionally, the UK Environmental Agency [65] presented the economic, social, and environmental benefits of achieving water neutrality (i.e., total water consumed after development is equal to or less than total water use prior to development) for the Thames Gateway, which is the largest regeneration area in the UK.

Benefits of water demand management (WDM) can also impact the management of the new water supply system in Santa Marta. If demand reduction is incentivized, several benefits, such as the previously mentioned benefits and the deferment of PWTP expansions, are expected over time. Thus, future studies should articulate efforts of various stakeholders to evaluate which structural and non-structural measures or combination of measures will be more efficient to reduce the per capita demand in the city. Demand reduction is a continuous water management issue throughout the project lifecycle; however, a fixed demand value was required for the initial planning stage in Santa Marta City.

Further research should also be focused on the following planning stages of the Santa Marta's water supply system (WSS). According to highly developed countries' best water management practices, one of the main future considerations is to design a water safety plan (WSP) for the city, in order to assess and manage the water supply risk from the source to the final user [16]. A WSP is necessary to facilitate the decision-making process to properly manage the WSS under different scenarios (e.g., emergency situations, climate change, variability of water sources' quantity/quality, etc.).

Moreover, the use of MCDA techniques, such as the AHP, has intrinsic limitations. The AHP is one of the most popular MCDA techniques, although, it has been criticized for the issue of rank reversal (i.e., the relative rankings of the alternatives would change if an alternative were added or deleted) [66,67]. However, Wang and Luo [68] have shown that the rank reversal phenomenon occurs not only in the AHP, but also in many other MCDA approaches. Practitioners and researchers need to be aware of this limitation for MCDA techniques, particularly when selecting a group of feasible alternatives to consider in the decision-making process.

7. Conclusions

MCDA methods are powerful decision-making support tools for water infrastructure supply planning [31,32,37]. A MCDA methodology that treats economic criteria separately from non-economic criteria is proposed to address the water supply infrastructure planning problem. This structured methodology represents a new approach to address this type of decision-making problem. The use of four main non-economic criteria, which are adaptable to other possible applications, is proposed: operational time, infrastructure setup, operational risk, and socio-environmental. The selected economic criterion was the present value (PV) of the costs. A global evaluation that combines non-economic assessments and economic assessments was developed to analyze the tradeoff between benefits and net present of the costs.

This decision-making methodology enables stakeholders to evaluate the alternatives of the complex water supply problem in a systemic manner. The separation between economic criteria and non-economic criteria may increase the understanding of qualitative benefits and the financial performance of each alternative. Given a budget, decision makers can easily establish the economic importance relative to benefits to determine the best alternative. The selected alternative will represent the best tradeoff between benefits and costs by considering the preference of several stakeholders, given a budget. This tradeoff can produce a structural, rigorous, transparent, and auditable approach to easily understand and communicate the decision-making process for complex water related projects.

A common concern during the decision-making process is the selection of an adequate method for measuring and compiling the preferences of all stakeholders and decision makers. In this case study, we highlighted the important differences between the AHP and MAUT during the preference elicitation process. The AHP requires the estimation of the eigenvalues of several matrices and the weighted sum calculation by the hierarchical structure, whereas MAUT requires a weighted sum of utility functions. The convenience of the methods varies with the complexity of the problem and the number of criteria. For example, using MAUT in complex multi-criteria problems, such as water-related issues, becomes wasteful, as the utility functions and weights exponentially increase when the decision-making structure expands. This finding creates the need to simplify the decision-making problem [38,58]. Using a pairwise comparison method, such as the AHP, ensures accuracy during the relative judgement of elements and enables the stakeholders to develop a structured perspective of the problem throughout all decision processes, which simplifies the preference elicitation process [55]. Additionally, the available software facilitates the calculations, and the weights estimation effort is feasible even in complex problems with several stakeholders. Is necessary to consider the computation processes and tradeoffs of different MCDA techniques, such as the AHP and MAUT, to perform a non-economic evaluation.

The developed MCDA methodology was applied to Santa Marta, Colombia, which has a current water shortage and urgently needs a new water supply infrastructure. An AHP model was employed to determine the preferences of various stakeholders regarding non-economic criteria for water supply infrastructure alternatives, and to enable the ranking of alternatives to provide water in the city. After variations in the weights of the economic criteria, the top-ranked alternative remained. The proposed methodology supported the decision-making process that achieved the selection of the alternative that will address the water supply problem in Santa Marta. The recommended alternative has been implemented in Santa Marta since 2018.

Finally, our developed MCDA methodology could be applied to any city that urgently needs to expand its capacity to satisfy the increasing water demand. Our framework is designed to support this decision based on economic and non-economic criteria, such as operational time, infrastructure setup, operational risk, and socio-environmental considerations. The separation of economic and non-economic criteria might increase the understanding of qualitative benefits and the financial performance of each alternative. The global evaluation index represents the best tradeoff between benefits and cost, considering the preference of several stakeholders.

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