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Water Management Strategies Using Multi-Criteria Decision Analysis in Santa Cruz Island (Galapagos Archipelago)

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Abstract

Islands threatened by tourism around the world are under significant stress due to overutilization of (scarce) water resources. The continuous increase of water demand in Puerto Ayora, the main touristic centre of the Galápagos, has become a threat for the water supply system, portraying the current situation unsustainable on the long-term horizon. For this reason, a Multi-Criteria Decision Analysis (MCDA) is tested as a suitable methodology in the presence of scarce data, leading to a set of indicators and intervention strategies, aiming to mitigate the future water demand coverage. The current analysis revealed the most sustainable solution, including environmental, technical, economic and social criteria, by using the DEFINITE software. The results indicate that best option for most of the stakeholders' groups is the option combining all proposed-sustainable options like greywater recycling, specific demand reduction and rainwater harvesting.

Keywords: Multi-criteria decision analysis; Water supply indicators; Tropical islands; Intervention strategies; Galápagos.

1. Introduction

Tropical islands worldwide are threatened by the significant increase of tourism. Since tourist activities are high in water demand, municipalities and regional authorities are having difficulties to cope with these water-supply-growth trends [1]. For this reason, tourism is becoming a serious threat, as well as a limiting factor for further urban development [2]. However, the coverage of future water demand with supply needs to be ensured in the different sectors, including tourism in order to ensure economic growth. This paper evaluates different proposed intervention strategies, using Multi-Criteria Decision Analysis (MCDA), which aim to solve the future water crisis in Santa Cruz Island (Galápagos Archipelago).

1.1. Multi-Criteria Decision Analysis

The MCDA is an often-used tool to carry out analysis for decision making purposes. It is an integrated assessment, which is a form of combined sustainability evaluation [3]. It encompasses complete assessment of (multiple) suggested alternatives, providing a set of tools for any decision making process. These analyses evaluate different values and factors, and is usually carried out on situations with high uncertainty and conflicting goals, as well as multiple interests and perspectives [3]. The main objective of this methodology is to establish the most sustainable solution of a certain issue, considering cost-benefit options and considering the preferences of all participants [4].

The MCDA method has been considered as subjective; however, it has rapidly increase since the 1990s, especially in environmental issues because it provides a reliable method that allows to rank different proposed alternatives in the presence of numerous objectives and constraints [5]. MCDA methods have been tested to be suitable for water resources management and planning, and are usually considered the preferred method due to its transparency and accountability to decision procedures [6].

Moreover, the main advantage of this methodology is the capacity to involve several stakeholders. This allows the participatory process of different groups of people with different perspectives, resulting in a more thorough understanding of the points of view held by the implicated parties [7]. Also, it helps policy makers to involve different criteria within new policies, since it provides clear solutions to a previously defined problem.

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1.2. Study Area Description

Puerto Ayora is the main town in Santa Cruz Island (Galápagos Archipelago). It has approximately 12,000 inhabitants INEC -Censo de población y vivienda del Ecuador 2010 [8] and attracts visitors from all over the world. The annual growth rate of local population increased from 2.5% in 1960 to almost 5% in 2010, while tourism growth rate was between 8% and 11% during the same period [9]. This uncontrolled expansion has affected basic services, including water supply. Currently, the water supply system has a coverage of 95%, but is intermittent (average of three hours/day) [10]. Freshwater is scarce and the main source is brackish-water extracted from crevices. The situation is further worsened by the low quality of distributed water, due to its brackish nature and faecal contamination [11].

Based on the study carried out by Mena [9] and Retamal, *et al.* [12], several population growth rates were envisaged based on different stakeholder's priorities and objectives. The proposed growth scenarios have become the basis for the modelling of future coverage of water demand with supply. Retamal, *et al.* [12], considered several alternatives as solution strategies for the future water deficit. However, the previous analysis calls for an integrated multi-disciplinary analysis due to the environmental vulnerability of this archipelago. According to Linkov, *et al.* [4], any issue that involves natural resources assessment as part of the decision making process, applies for MCDA analysis, because the alternatives can be reviewed based on the preferences of relevant stakeholders.

1.3. Research Objective

The Galapagos Islands, as many tourist islands, have scarce information regarding water supply and demand. Because of this, water resources planning and management is particularly lacking in the absence of proper data. This type of analyses aids to propose solutions for future challenges regarding optimal water balance, overcoming water scarcity caused by high-tourism rates, and also helping to preserve such places for future tourism. Since Puerto Ayora is the main tourist centre of this archipelago, the current MCDA analysis will serve as a template for other tourist islands undergoing the same water-related issues. In addition, this will provide a scientific basis for the development of criteria and specific indicators when evaluating future intervention strategies on this matter.

This paper elaborates on the assessment of the five previously-developed intervention strategies proposed to solve the future water deficit in Puerto Ayora suggested by Reyes [10]. These strategies were assessed under the environmental, social, technical and economic criteria, using the DEFINITE software developed by Janssen, *et al.* [13]. The final results include the 'best' alternative considering these criteria, based on selected stakeholders' preferences. Then, a sensitivity and uncertainty analyses were carried, with the aim of analysing the effects on the final results, when variating the initially adopted scores and weights.

Table-1. Options proposed for solving water supply and demand crisis in Puerto Ayora

Option	Description	Input values	Assumptions	Total Costs[b] (EUR/m3)	Reference
1) Leakage Reduction	Reduction from 28%[a] to 13% (1% annually).	Energy consumption: 0.66 KWh/m^3 (current use of energy). The same values for all four growth scenarios	Installation of automatic and computerized leakage and control system (e.g. pressure and flow monitoring) and replacement of old pipes (17,800 m of PVC pipes).	0.66	Municipality of Santa Cruz and local providers
2) Desalination Plant	Installation of a new SWRO desalination plant (BWRO was not considered to avoid extra pressure on the basal aquifer and increase of salinity) with energy recovery system. Open seawater intake (35,000 ppm), 55% recovery rate, 99% salt rejection.	small growth (9,000 m^3/day) 2) moderate growth (16,000 m^3/day) 3) fast growth (28,000 m^3 day) 4) very fast growth (50, 000 m^3/day) Energy consumption: 3 KWh/ m^3	Cost includes plant, land, civil works and amortization costs, chemicals for pre and post water treatment, energy requirement, brine dissolution and discharge, cooling towers(including electricity and steam), spares and maintenance (including membrane replacement every 5 years), and labour.	1) 1.27, 2) 1.25, 3) 1.23, 4) 1.22	1) Ghaffour, *et al.* [14] 2)Al-Karaghouli and Kazmerski [15] 3)Lattemann, *et al.* [16]

3) Water Meter Installation	Installation of water meters per premise with a rate of 10% annually.	140 EUR/unit (including installation and maintenance) The same unit cost for all growth scenarios	Installation of Flodis-single jet turbine device)	0.04	Municipality of Santa Cruz
4) Rainwater Harvesting	Installation of a household rainwater harvesting tank for indoor and/or outdoor use (2 m^3)	Capacity calculated as 4000 m3 (approx. 2000 households) Energy consumption: 2 Kwh/ m^3	Water collected from roofs only. The collected rainwater used for toilet flushing, hand and kitchen basin, showers and outdoor use. The cost includes purchase cost of tank, pumping, delivery and installation, household plumbing, and mains water switching devices, energy consumption, maintenance and pump replacement (every ten years).	0.21	1)Tam, *et al.* [17] 2)Retamal, *et al.* [12] 3)Hauber-Davidson and Shortt [18]
5) Greywater Recycling	Installation of single house on-site greywater treatment using a submerged membrane (MBR), including disinfection unit	Based on household greywater treatment capacity of 350 L capacity and 2000 households; 5 inhabitants per household and 163 Lpcpd). Flow capacity of 200 L/population equivalent	Greywater collected from kitchen and hand basins and showers, which account to approximately 48% of total water demand). Household treatment assumed with membrane bioreactor plant (biological treatment, aeration, and membrane filtration. Treated greywater used on-site for toilet flushing and outdoor use.	1.08	1)Fletcher, *et al.* [19], 2)Boehler, *et al.* [20], 3)Gnirss, *et al.* [21] 4)Fountoulakis, *et al.* [22]
6) Water Demand Reduction	Reduction of specific demand of municipal water	Reduction from 163 lpcpd to 120 lpcpd (assuming 1% annual reduction on water demand starting on year 3, in order to complete the reduction at the end of the planning horizon	Assumed the change of water tariff structure to reduce the average specific demand	-	-

Taken from Reyes, *et al.* [23].

2. Methodology Development

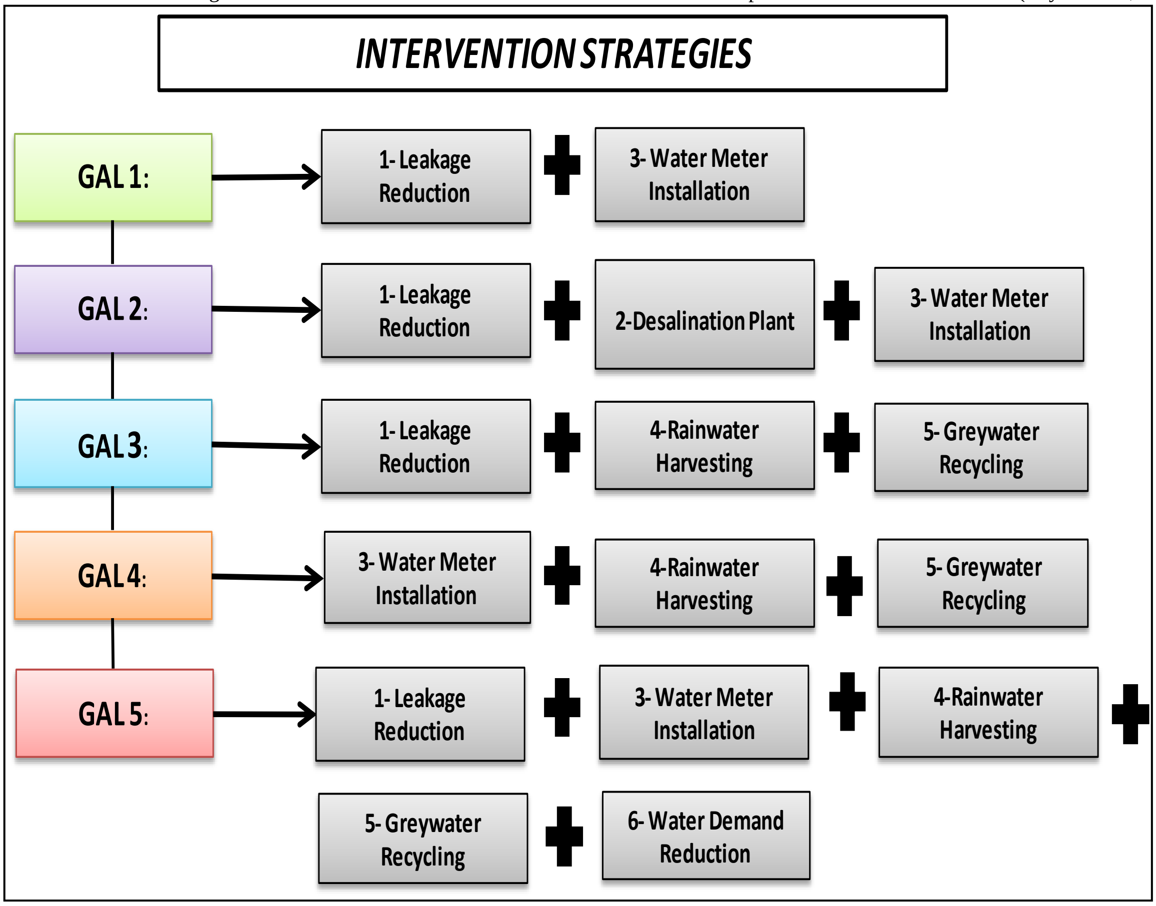
The following steps used to carry out the MCDA are listed below:

2.1. Criteria Definition and Alternatives' Selection for Puerto Ayora-Santa Cruz Island

First, the problem was defined as the water-supply deficit in the town of Puerto Ayora in the year 2045. The primary objective was to find the most suitable and sustainable solution to overcome lack of water supply. The five intervention strategies shown in Table 1 and Figure 1 were obtained from the study carried out by Reyes, *et al.* [23]. Therefore, the basis for the input data for the MCDA were the results obtained in the previous-mentioned study, for the end of the forecast period (2045). The four selected criteria for this study were: (1) environmental, (2) technical, (3) economic and (4) social. Afterwards, each of these criteria was further described with relevant and measurable indicators, which allowed to evaluate the performance of each suggested solution.

Then, different software were evaluated, and the DEFINITE software was selected as the tool for this analysis. DEFINITE was developed to help improve the quality of decision, by methodical procedures which lead experts through a number of interactive assessment sessions [23]. It uses an optimization approach, which integrates all the information provided by the involved stakeholders into a full set of value functions leading to a scientific based 'best' alternative [24].

Figure-1. Intervention strategies selected and modelled with WaterMet^2 software used as input information for the MCDA (Reyes Perez, 2017)



2.2. Effects Table, Score Definition and Standardization

After defining the criteria and its corresponding indicators, each strategy was scored under each indicator in the ´effects table´. In this table, which is the core of the MCDA, the input information for the DEFINITE is assessed as the performance of each intervention strategy against all the pre-defined indicators in a qualitative or quantitative way. The data used for scoring and populating the 'effects table' were obtained from Reyes, *et al.* [25], including the following Key Performance Indicators (KPIs): water demand, water losses, energy use and costs. In the study by Reyes, *et al.* [23], results were obtained for four growth scenarios. However, in the analyses for this paper, only the results from the moderate-growth scenario were used (4% annual growth for tourism and 3% for local population). The missing information such as potential waste quantities from the different selected strategies, as well as local laws and regulations, among others, were taken from the literature. Some information regarding the social and technical criteria were taken from interviews with local experts.

The scoring for each indicator was done using different types of scales/units. As a first step, the indicator values were defined either as qualitative or quantitative, assigning the scale/unit that will be used for the analysis. The scales/units used were: (1) ratio, (2) interval, (3) ordinal, (4) binary scale, and the (5) ---/+++ scale. The ratio scale refers to the proportionality of values, the interval scale portrays the ranges of amounts, the ordinal scale ranks the effects of an strategy against certain indicator, the binary scale indicates whether the effect does or does not occur and the ---/+++ scale estimates the values which could not be determined quantitatively. Table 2 explains the meaning of the last mentioned scale Reyes [10].

After defining the scale/unit to each indicator, the nature of each indicator as Cost (C) or Benefit (B) relation was determined. Cost refers to indicators portraying a negative correlation between the score and the effect (higher the score of the indicator, the worse the effect produced). On the other hand, benefit (B) refers to a positive correlation (the higher the score, the better the effect produced). Later, the 'effects table' was populated with the scores assigned to each indicator, corresponding to each intervention strategy.

Finally, the standardization of the indicators was carried out, since the values on the 'effects table' were not yet comparable and the units were not uniform. Therefore, each indicator was standardized with a unit-less value between 0 and 1. For this, different options available within the software were used to convert the original indicator scores [24] such as: the maximum method, the goal standardization, the convex function and the yes/no standardization. Table 2 presents the selected criteria, indicators, cost/benefit relation, units/scales, the standardization method used, as well as the ranges of scores for each indicator.

Table-2. Criteria categories, indicators, units/scale, standardization method and ranges selected for MCDA for the water supply system in Puerto Ayora

Indicator	Cost/Benefit Correlation*	Unit/scale	Standardization Method	Minimum Range	Maximum Range
ENVIRONMENTAL CRITERIA					
Land use	**C**	m^2	Goal	0	10,000
Discharge of wastewater	**C**	m^3/day	Goal	0	50,000
Seawater intrusion	**C**	Ordinal	Exponential value	2	5
Energy consumption	**C**	kWh/ m^3	Maximum	0	3
Chemical use	**C**	Binary	Yes=0, No=1	No	yes
Impact on endemic species	**C**	Ordinal	Exponential value	1	5
Impact on marine/land ecosystems	**C**	Ordinal	Exponential value	1	5
TECHNICAL CRITERIA					
Improvement on hours of service	**B**	Binary	Yes=0, No=1	No	yes
Coverage of demand with supply	**B**	% of demand	Goal	30	100
Water losses	**C**	% from water produced	Goal	9	28
Robustness of the WS system	**B**	Ordinal	Exponential value	1	5
O&M of the WS system	**B**	Ordinal	Exponential value	2	5
Alternative water sources contribution to overall balance	**B**	% annually	Goal	5	50
Compatibility with the existing system	**B**	0/++	Maximum	0	++
ECONOMIC CRITERIA					
Capital cost	**C**	M €	Maximum	0	21.6
O&M cost	**C**	M €/year	Maximum	0	5.4
NRW income generation	**B**	€/year	Maximum	0	312,412.16
WDM income generation	**B**	0/++	Maximum	0	++
Employment generation	**B**	0/++	Maximum	0	++
Increase in water tariffs	**C**	--/0	Maximum	--	0
Increase in tourist capacity	**B**	# of tourists	Goal	7,335	15,000
SOCIAL CRITERIA					
Social acceptability	**B**	0/+++	Maximum	0	+++
Willingness to pay	**B**	0/++	Maximum	0	++
Transparency on project implementation process	**B**	0/++	Maximum	0	++
Water quality improvement	**B**	0/++	Convex	0	++
Annual infection and other water-related diseases risk	**C**	--/0	Convex	--	0
Compatibility with current legislations	**B**	Binary	Yes=0, No=1	No	yes

Taken from Reyes, *et al.* [23].

2.3. Weight Allocation

The weights were obtained from different stakeholders' preferences. For this, a questionnaire was distributed to 32 previously-selected stakeholders, clustered into four different categories. The questionnaire had six questions regarding valuation and importance of the criteria and its indicators, rating them from 1 (the least important) to 5 (the most important). Finally, the answers from each stakeholder group were processed, allocating different weights for each criteria and indicator.

The results of the weights allocation were further calculated based on the average of the respondents belonging to each group, carrying out a different MCDA session for each stakeholder group. This was the key part for the ranking of alternatives in the MCDA as shown in Figure 2.

Figure-2. Ranked preferences of selected stakeholders based on distributed questionnaire in Puerto Ayora [10]

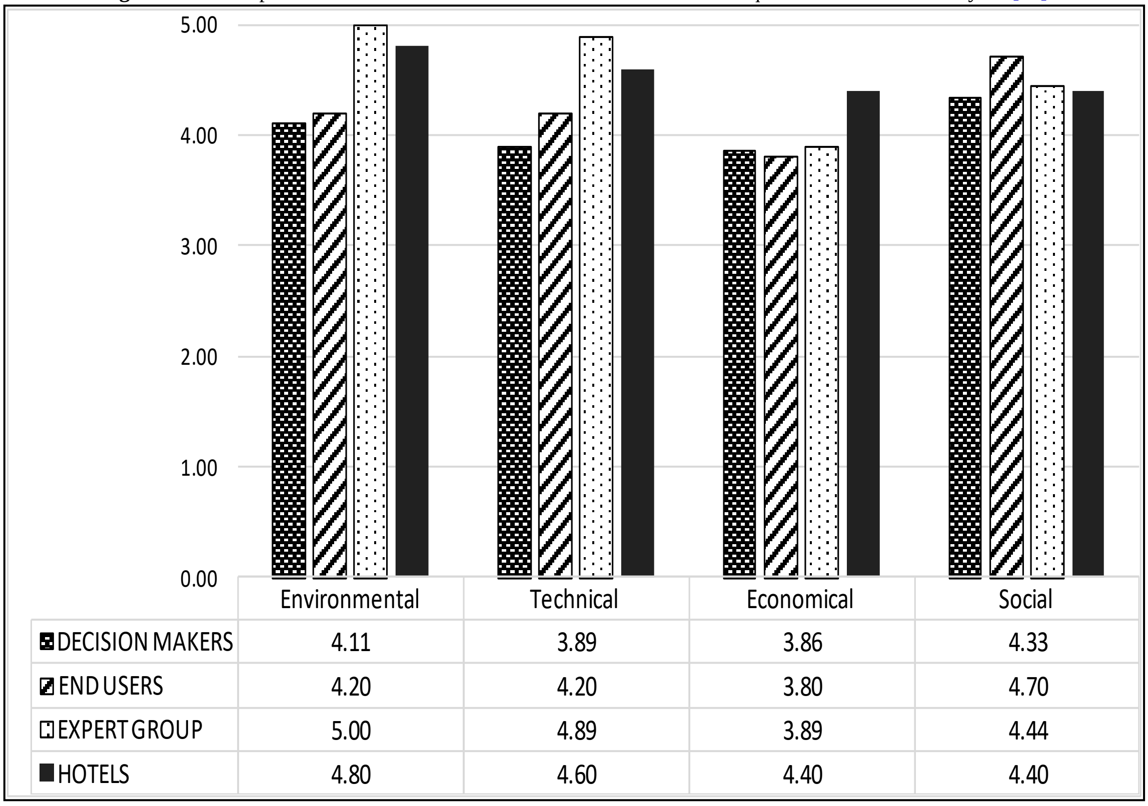


Table-3. Weight allocation for main criteria for Puerto Ayora

	Environmental	Technical	Economic	Social
Experts	0.273	0.273	0.212	0.242
Decision Makers	0.251	0.240	0.240	0.270
Domestic End Users	0.250	0.250	0.220	0.280
Hotels	0.263	0.253	0.242	0.242

Taken from Reyes, *et al*. [23]

3. MCDA Sessions' Results and Discussion

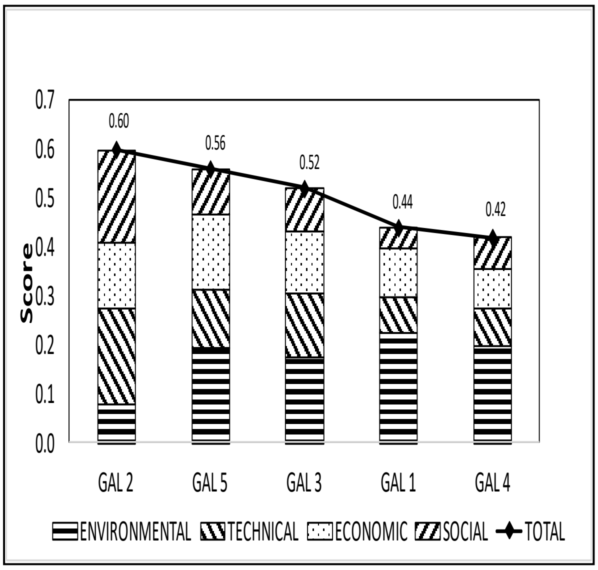
3.1. Distribution of Weights Based on Stakeholders' Input

In order to standardize the results from stakeholders' responses into values from 0 to 1, appropriate methods included in the DEFINITE software were used. For the criteria, defined as weight-level 1, the direct weighting method was chosen, due to its characteristic of assigning quantitative weights directly, according to the numerical input used by the stakeholder feedback. In the direct weighting, the sum of the weights of the criteria for each particular stakeholder session is equal to one. Moreover, the indicators were defined as weight-level 2, where the expected value method was used. This method ranks the effects in order of their importance, assigning quantitative values to each. Some effects may have the same ranking, which means they have equal importance in the analysis. Then, the total weight was calculated based on the product of weight-level 1 and weight-level 2. The result obtained from this calculation became the actual weight for the MCDA evaluation [23].

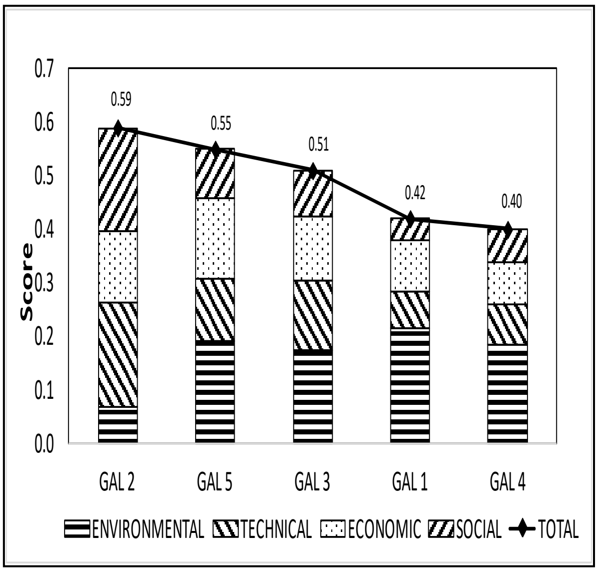
3.2. Ranking of the Alternatives

The software has several methods to rank: the Weighted Summation, Electre 2, Evamix and Regime. For this step, the weighted summation method was chosen, which is based on the MAUT (Multi Attribute Utility Theory) model. This method was selected because it is considered to be the most appropriate, due to its reliability, straight-forwardness and transparency [24, 26].

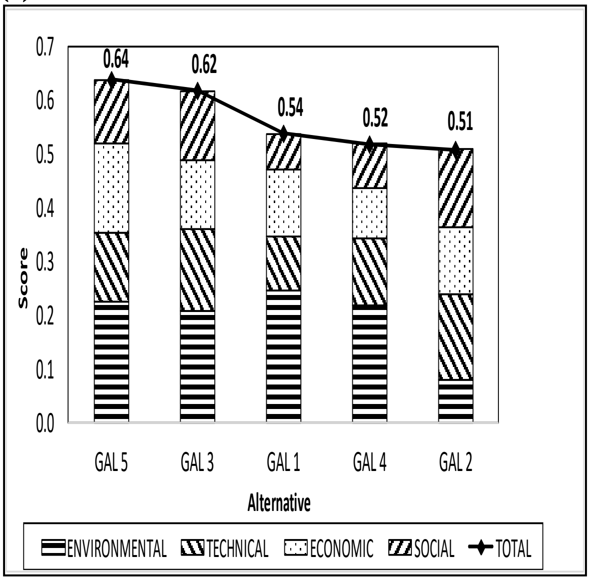
Figure-3. Ranking of alternatives based on (a)experts, (b) decision makers, (c) domestic end users and (d) hotels preferences (Taken from Reyes [10]



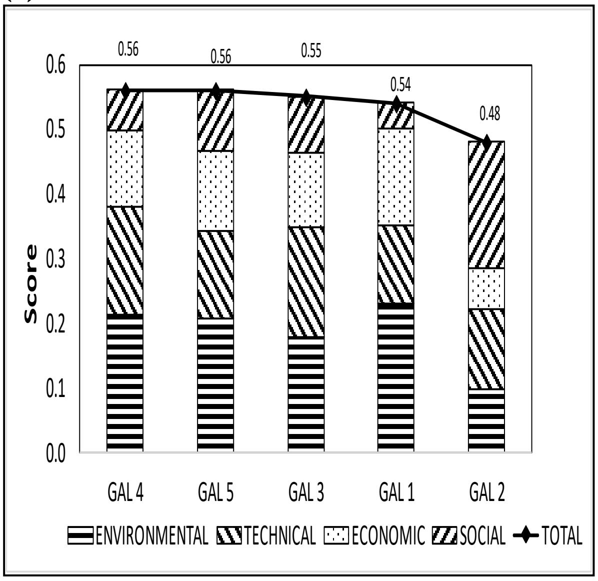
(a)



(b)



(c)



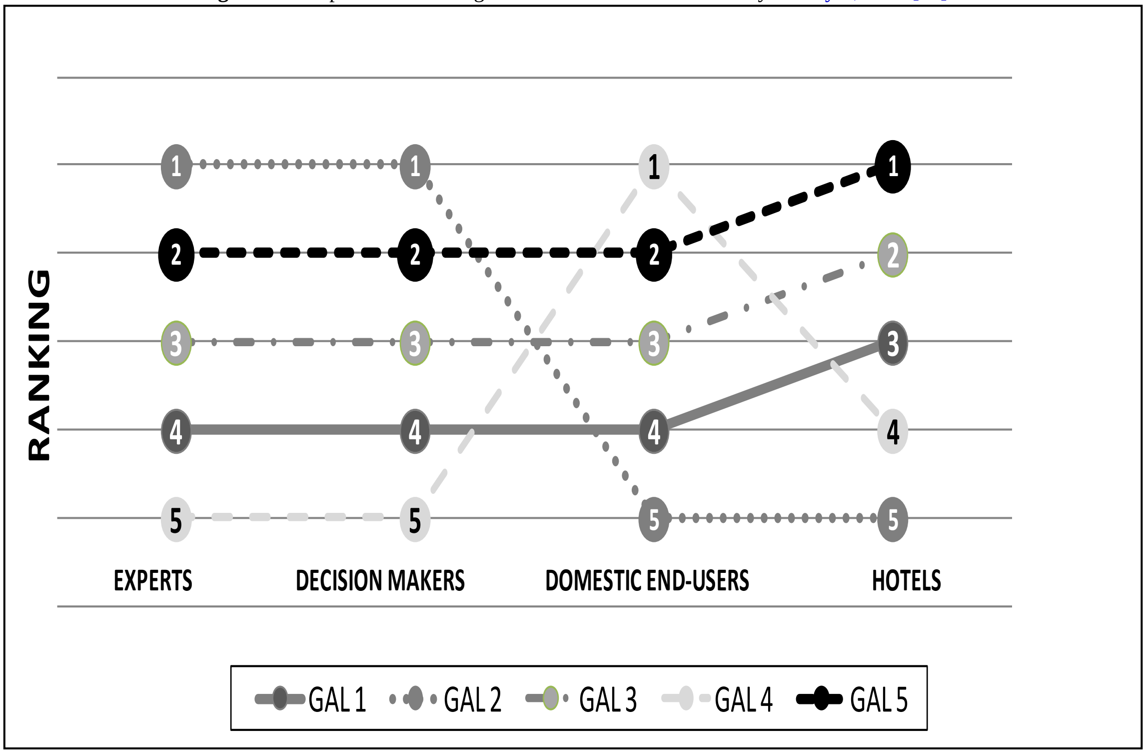
(d)

This method uses the effect scores to rank the proposed intervention strategies, processing the standardized table into a ranking of alternatives. A total of four sessions (one for each stakeholder group: decision-makers, experts, end-users and hotels) were conducted, and all alternatives were ranked using the same method in order to facilitate comparisons and conclusions [23]. The results of the ranking of the alternatives are illustrated in Figure 2.

Figure 3 shows that Gal 2 alternative prevails for decision makers and experts, due to the large contribution of the technical and social criteria (the only alternative covering 100% of water demand at the end of the planning horizon, and the only one improving water quality). For domestic end-users, priority was given to both alternatives Gal 4 and Gal 5, mainly due to the high preference by these groups to the environmental criteria, followed by the technical and economic criteria, respectively. Surprisingly, for the hotel end-users, a significantly high preference is given to the environment, grading Gal 5 alternative as the first option, and not the desalination option, as expected. Gal 5 scores reasonably well in all of the defined criteria, resulting in the most consistent distribution of ranking across all of the sessions (taking the first or the second position). On the other hand, for the domestic and hotel end-users, Gal 2 is always one of the last options. Gal 4 tends to be the last option for all sessions, expect for domestic end-users, where it is positioned as first.

In conclusion, for every analysis where either technical or social criteria have more influence, Gal 2 alternative is ranked higher, while Gal 5 takes the lead when environmental criteria has higher weighting.

Figure-4. Comparison in rankings of MCDA results for Puerto Ayora Reyes, *et al.* [23]

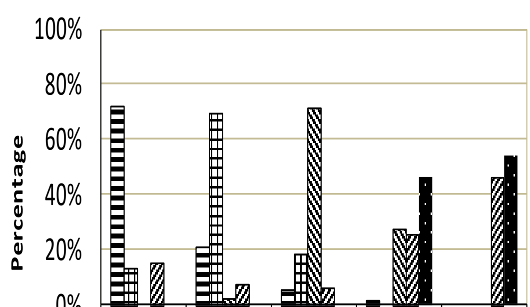


The ranking summary is shown in Figure 4. The alternative ranking the highest and showing more stability is Gal 5, which occupies the first and second places, followed by Gal 3, which is ranked third and second. On the other hand, Gal 2 is first for decision-makers and the experts group of stakeholders. However, it also takes the last place for both sessions involving the local population (hotels and end-users), capturing the noticeable different preferences, especially regarding the environmental criteria. These results show that for the local population, the preservation of the environment is more important than the stakeholders involved with research and decision-making.

3.3. Uncertainty Analysis

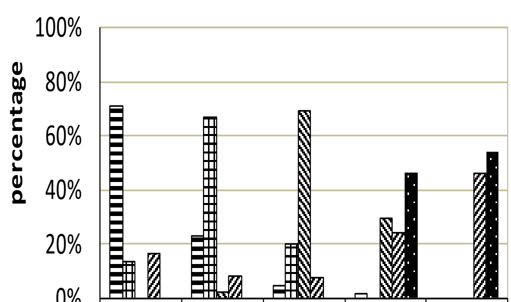
The DEFINITE software can also assess the sensitivity of the ranking of alternatives, when varying the effect scores and weights of the indicators. In order to evaluate the influence of uncertainties to a lower or higher extent, the percentages of the effect scores were examined with a ±50% variation. This was done based on the fact that some of the input data used to populate the effects table was assumed. Also, since some results showed small difference between the rankings (0.1 to 0.2), the uncertainty analysis was carried out in order to examine the impact on the ranking, when the effect scores were changed. This also reflected the consequences of higher-or-lower population growth impacts, since this analysis was done using only the moderate growth scenario.

Figure-5. Probability of alternative ranking with 50% uncertainty score for (a) Experts, (b) Decision makers, (c) Domestic End-users and (d) Hotels sessions [23].



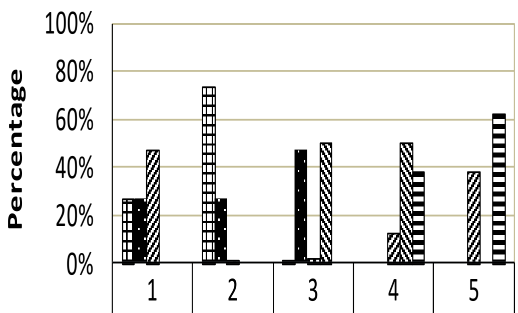
	1	2	3	4	5
GALAPAGOS 2	72%	21%	5%	1%	0%
GALAPAGOS 5	13%	69%	18%	0%	0%
GALAPAGOS 3	0%	2%	71%	27%	0%
GALAPAGOS 1	15%	7%	6%	25%	46%
GALAPAGOS 4	0%	0%	0%	46%	54%

(a)



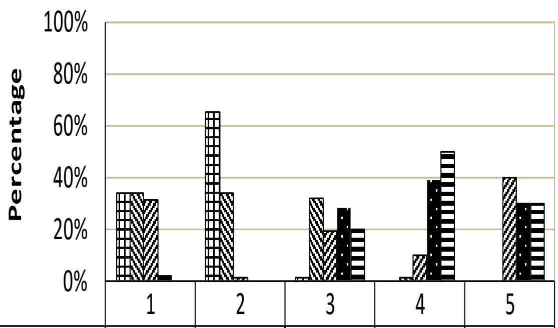
	1	2	3	4	5
GALAPAGOS 2	71%	23%	4%	1%	0%
GALAPAGOS 5	13%	67%	20%	0%	0%
GALAPAGOS 3	0%	2%	69%	29%	0%
GALAPAGOS 1	16%	8%	7%	24%	46%
GALAPAGOS 4	0%	0%	0%	46%	54%

(b)



	1	2	3	4	5
GALAPAGOS 4	27%	73%	1%	0%	0%
GALAPAGOS 5	27%	27%	47%	0%	0%
GALAPAGOS 1	47%	1%	2%	12%	38%
GALAPAGOS 3	0%	0%	50%	50%	0%
GALAPAGOS 2	0%	0%	0%	38%	62%

(c)



	1	2	3	4	5
GALAPAGOS 5	34%	65%	1%	0%	0%
GALAPAGOS 3	34%	34%	32%	1%	0%
GALAPAGOS 1	31%	1%	19%	10%	40%
GALAPAGOS 2	2%	1%	28%	39%	30%
GALAPAGOS 4	0%	0%	20%	50%	30%

(d)

Figure 5 shows the probability of an intervention strategy to change its ranking, if the scores are varied. For instance, Figure 5(a), which shows the experts group, explains that Gal 2 alternative has a high probability (72%) to stay in the first place, and a moderate probability to change to the second position. This states once again that the desalination option is the preferred option for this stakeholder group, giving preference to the water supply system reliability and public health indicators (demand coverage, and water quality improvement), over the environmental or economic criteria. The possibility of increasing tourist capacity, as well as 100% of the demand coverage at the end of the planning horizon, are advantages of the Gal 2 option, portraying that the desalination option would still prevail even if the scores are changed drastically. This suggests that the values of the effect scores are not very sensitive, reflecting that a small change would not alter the overall ranking.

Regarding the decision-makers' session Figure 5(b) Fountoulakis, the results show relatively-stable uncertainties, and is very similar to the previous session. This means that Gal 2 alternative will always be ranked first or second, as well as Gal 5 (as in the original ranking), with low or even null probabilities to take the rest of the other positions. This suggests that the given values would have to change to a significant higher or lower extent, in order for Gal 5 (originally ranked second) to take the first place.

Furthermore, the domestic end-users session shows a more unstable ranking. Gal 4 has low probabilities to keep the first places, and high probabilities to occupy the last one. Even though this group has the same values of preferences for the environmental and technical criteria, the desalination option may take the second place or even the first. This stakeholder group has a strong preference for options without additional water sources, and the cheapest options tend to be on the highest positions. Furthermore, this group gives extra emphasis to environmental preservation and water demand management measures, even with ±50% of score uncertainties. Furthermore, the water quality and demand coverage seems to be of lesser concern for this group.

The hotels session in Figure 5(d), also shows a stable ranking, showing that Gal 5, Gal 3 and Gal 1 compete for the first, second or third place, but not for the last two places in the ranking. Due to the environmental criteria and social contribution, the options that could be ranked first are the most sustainable ones (excluding the desalination option). Moreover, due to the high weight of the technical criteria, Gal 5 can also end up on the last place. Surprisingly, this stakeholder group has almost the same weight allocation as the previous one, despite the fact that this group is a major water consumer. Furthermore, this group is still concerned about the environment and the negative impact of the possible installation of a desalination plant.

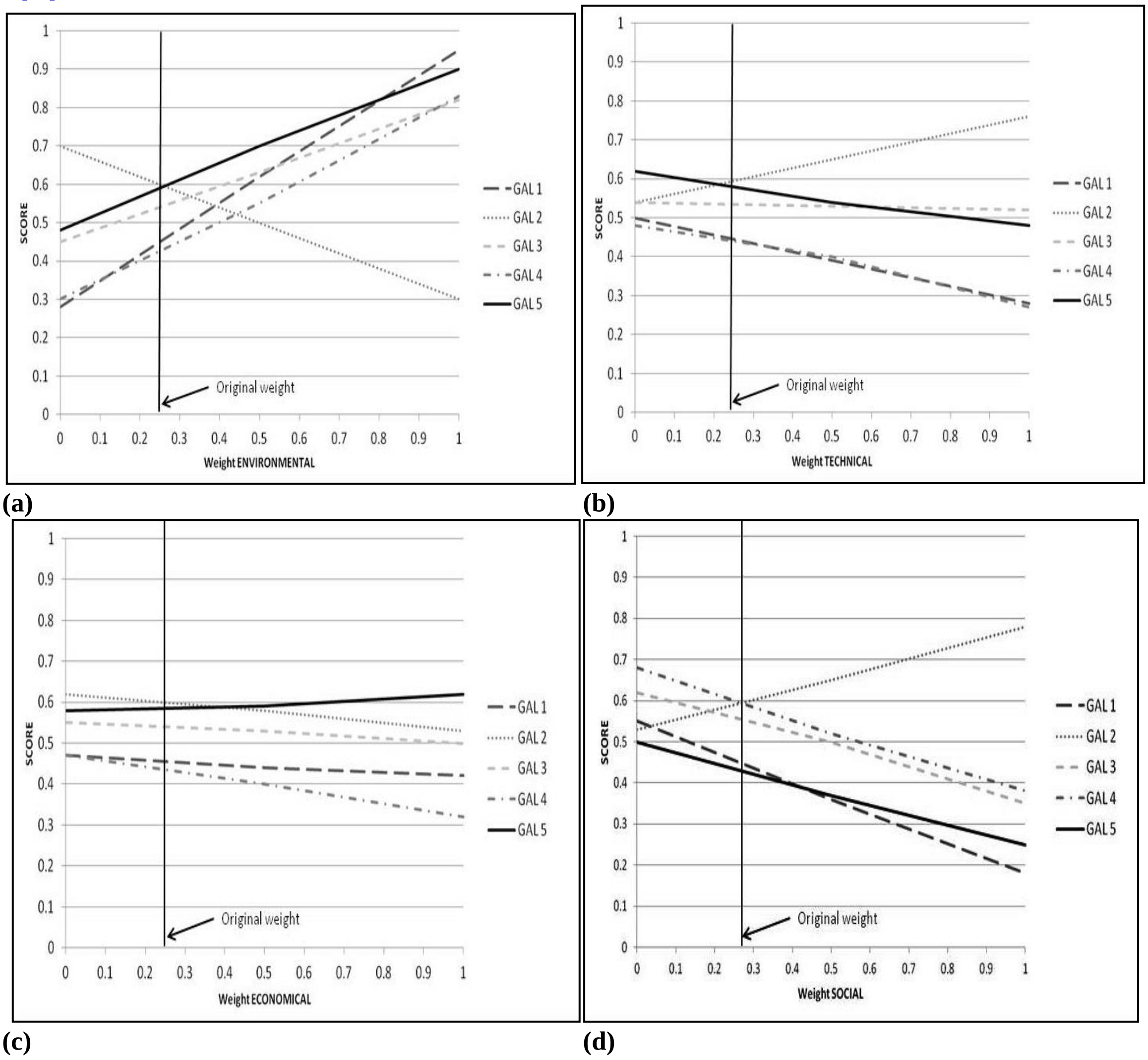
In conclusion, the most robust alternatives are Gal 2 and Gal 5 keeping their original positions (first, and last) in most of the uncertainty analysis sessions. Furthermore, Gal 3 and Gal 4 were moderately sensitive to the defined uncertainty variations because they often changed in the ranking, moving one position higher or lower depending on the stakeholders' preferences. Therefore, all of the options would never tend to have a dramatic change in their original position. Finally, Gal 1 was the alternative with the highest level of ranking uncertainty. In most of the analyzed sessions, this alternative competed for almost every position, originating from the wide uncertainty assumption.

Some of the preferred alternatives do not reach a 100% water demand coverage at the year 2045, but they assume lower environmental impacts, lower costs, and lower water tariffs (except desalination). If any of these alternatives would be adopted, this would mean that a large tourist expansion in Puerto Ayora is not possible, as many decision-makers prefer.

3.4. Sensitivity Analysis

The final analysis encompassed the sensitivity analysis of the selected criteria weights, provided by the stakeholders. Figure 6 shows the results only for the decision-makers' session. Only this group was considered for the current paper because they have the final word on the decisions adopted.

Figure-6. Sensitivity analysis of weight allocation on (a) environmental, (b)technical, (c)economic and (d) social criteria for the Decision Makers session [23]



In Figure 6, steeper slopes are observed in some of the graphs than in others. A steeper slope means that the criteria are more sensitive to a minor change on the weight, influencing greater on the final ranking of the alternatives. The X-axis indicates the extent of variation of the weight, and the vertical line is the original weight provided by the stakeholder's feedback. On the other hand, the Y-axis indicates the original score obtained by each alternative in the original analysis.

The Gal 2 alternative loses its advantage over Gal 5, which was ranked first. Under the environmental criteria sensitivity, Gal 2 alternative is ranked in the first place only until the weight value increases by 0.5. Within the range from 0.32 to 0.65, Gal 5 alternative would be ranked first. With the values of environmental criteria below 0.26 there is a steep inclination of the desalination alternative, meaning that it is firmly positioned on the first place. Regarding the technical criteria, it is more sensible and could be, by a very small change, replaced by Gal 5. Therefore, over this weight, the desalination alternative (Gal 2) provides the best results in technical criteria group, especially regarding the indicators of coverage of demand with supply (100%), improvement of hours of service (continuous water supply), and robustness of the water supply system. Since it is the only alternative that significantly increases water supply, the higher the weight allocation of technical criteria, the more it stabilizes this alternative on the first place. On the other hand, lower values of technical criteria, switches the rank in favor of alternatives with higher scores in environmental criteria. For the economic criteria, the sensitivity is low, which is shown by much less steep lines. Since Gal 2 is the most expensive alternative, desalination is the preferred option under the economic criteria only up to 0.3 values (the original value is 0.23). Finally, regarding the social criteria, when the weight value drops below 0.15, Gal 2 loses its advantage over alternative Gal 5. Therefore, the social criteria can be considered an important one, since once more; a small change can alter all the results. This criterion includes paramount public health indicators, and those can be improved only by the desalination option. Nevertheless, this alternative can be easily substituted with less environmentally hazardous and cheaper options with small alteration of the weight scores of the main stakeholders' groups.

4. Summary and Conclusion

The MCDA methodology has proven to be a suitable decision support tool that can be applicable in environmentally-sensitive areas such as the Galapagos Islands. This study provides a thorough analysis regarding future water supply and demand options for Santa Cruz Island, under various growth scenarios. Also, it provides clear results under pre-defined indicators, which will aid decision- makers and relevant authorities to make a scientific and supported decision to confront the future water crisis. However, the indicators, as well as their original values and ranges, have been proven to be case dependent and case sensitive.

In this paper, different sets of measures for improving the water supply system of Puerto Ayora were analyzed with four main groups of criteria. The aim was to obtain the most sustainable solution for mitigating the impact on the water supply by future local population and tourism growth. Also, it aimed to analyze the alternative which will provide an optimal balance between water supply and demand for the future conditions, with lowest impact on the fragile ecosystem, and with the most affordable cost.

As results showed, the Gal 2 and Gal 5 alternatives were ranked on the first position by the different stakeholder groups. Gal 2, which includes desalination, was preferred by decision makers and experts groups. On the other hand, Gal 5 was preferred by the two groups of local population (domestic end-users and hotels), which included all of the options, except desalination. These differences in the results can be attributed to the technical and environmental preferences given. Where the technical criterion has more weight, the desalination option tends to take the lead. However, if more weight is given to environmental or social criteria, Gal 5 takes the first position. Furthermore, based on the sensitivity analysis, Gal 2 tends to lose the first position easily by small changes on the weight values, because Gal 5 portrays a moderate environmental impact (low levels of wastewater discharge, lower impact to environment and sea water intrusion), moderate costs of implementation and operation and maintenance, but only 60% of water demand coverage at the end of the project horizon. On the other hand, Gal 2 is the only alternative that guarantees 100% coverage of water demand with supply, as well as improvement of the water quality to meeting drinking water requirements at the end of the project horizon (in 30 years). Therefore, decision-makers and experts give preference to this option. Nevertheless, despite these obvious advantages, due to the higher costs and negative environmental impacts identified, it can easily be replaced by Gal 5 in most of the sessions, suggesting the consideration of this type of fragile ecosystem by the different participants.

Regarding the uncertainty analysis, Gal 2 and Gal 5 have the highest probability to be ranked first or second in all of the sessions, as well as for the last ranked options, have probability to take the fourth or fifth place, but never the first place. This means that the results are certain and would not change drastically even if the effects scores are increased or decreased by 50%. As for the sensitivity analysis, it shows some criteria to be more sensitive than others. For instance, if more priority is given to environmental criteria, Gal 2 could never take the lead because of the negative impacts on the environment. This suggests that stakeholders prefer less quality, continue with the current situation, with little improvement in more sustainable terms, than installing a desalination plant. Moreover, it also showed that both groups analyzed (decision makers and experts) have high sensitivity to small weight changes, since Gal 2 may easily be replaced by any other alternatives. Moreover, the technical, social and environmental criteria showed higher sensitivity than the economic criteria, based on the steepness of the lines, suggesting that if the priorities of costs are changed, it would not have an impact on the final results, and that priority is given by stakeholders to other factors. Furthermore, sensitivity analysis of the effect scores did not show significant effect as the criteria weights.

Even though this analysis was done with just a moderate growth scenario, the total coverage of the demand according to the results from the WaterMet^2 software on the previous study done by Reyes [10] at the end of the project horizon would be limited to 60%. Consequently, other alternatives should be considered in conjunction with the desalination option, especially concerning the water quality improvement. For instance, a dual water supply system could be explored, where the drinking fraction of the demand could be covered by desalination and the rest by the current brackish-water system. Moreover, the consumption at household level could be reduced by introducing a volumetric or increased-block water tariff structure. Finally, the suggested tourist growth should be limited, and the current trend of tourist arrivals should be reconsidered. It would be necessary to adopt a minimum threshold value of the demand coverage for each of the assessed alternatives, and further develop the alternatives based on this predefined threshold. Also, it would be interesting to assess the full potential of the rainwater harvesting as a centralized system with more detailed studies.

Finally, more studies would be needed to arrive at more accurate values of certain quantitative indicators. Those studies would need to encompass various types of long-term modeling (hydraulic, hydro-geological, physical, demographic and economic, etc.). More detailed determination of social acceptance criteria is needed as well, in order to come up with proper descriptive values for the qualitative indicators. Appropriate methods would encompass public surveys, workshops, meetings at community levels, lectures with feedback, public discussions, etc.

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References

[1] Kondili, E., Kaldellis, J. K., and Papapostolou, C., 2010. "A novel systemic approach to water resources optimisation in areas with limited water resources." *Desalination*, vol. 250, pp. 297–301.

[2] Briguglio, L., 2008. "Sustainable tourism on small island jurisdictions with special reference to Malta." *ARA J. Tourism Research*, vol. 1, pp. 29–39.

[3] Wang, J. J., Jing, Y. Y., Zhang, C. F., and Zhao, J. H., 2009. "Review on multi-criteria decision analysis aid in sustainable energy decision-making." *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 2263-2278.

[4] Linkov, I., Satterstrom, F., Kiker, G., Batchelor, C., T., B., and Ferguson, E., 2006. "From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications." *Environment International,* vol. 32, pp. 1072-1093.

[5] Polatidis, H., Haralambopoulos, D. A., Munda, G., and Vreeker, R., 2006. "Selecting an appropriate multi-criteria decision analysis technique for renewable energy planning Energy Sources." *Part B,* vol. 1, pp. 181-193.

[6] Mutikanga, H., Sharma, S., and Vairavamoorthy, K., 2011. "Multi-criteria decision analysis: a strategic planning tool for water loss management." *Water Resources Management,* vol. 25, pp. 3947-3969.

[7] Kiker, G. A., Bridges, T. S., Varghese, A., Seager, T. P., and Linkov, I., 2005. "Application of multicriteria decision analysis in environmental decision making." *Integrated Environmental Assessment and Management Journal,* vol. 1, pp. 95-108.

[8] INEC -Censo de población y vivienda del Ecuador 2010. Instituto Ecuatoriano de Estadísticas y Censos.

[9] Mena, C., 2014. *Determination of social, environmental and economical relations which allow the development based on different processes of modelling, potential scenarios of sustainability of the socio-ecological system of the Galápagos Islands with emphasis on the dynamic of the flux of tourist visitors*. Report for the Ministry of Environment. Unpublished.

[10] Reyes, 2017. *Water supply and demand management in the galápagos: A case study of Santa Cruz Island*. CRC Press.

[11] d'Ozouville, N. and Merlen, G., 2007. "Agua Dulce o la supervivencia en Galápagos. Galápagos: Migraciones, economía, cultura, conflictos y acuerdos (Freshwater or the survival in Galapagos: Migration, economy, culture,conflicts and agreements." *Biblioteca de Ciencias Sociales (Social Sciences Library),* vol. 57, pp. 297–313.

[12] Retamal, M., Turner, A., and White, S., 2009. "Energy implications of household rainwater systems." *Australian Water Association,* vol. 36, pp. 70-75.

[13] Janssen, R., Van Herwijnen, M., and Beinat, E., 2001. *DEFINITE for Windows." A system to support decisions on a finite set of alternatives (Software package and user manual) Institute for Environmental Studies (IVM).* Amsterdam: Vrije Universiteit.

[14] Ghaffour, N., Missimer, T. M., and Amy, G. L., 2013. "Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability." *Desalination and Water Treatment,* vol. 309, pp. 197-207.

[15] Al-Karaghouli, A. and Kazmerski, L. L., 2013. "Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes." *Renewable and Sustainable Energy Reviews,* vol. 24, pp. 343-356.

[16] Lattemann, S., Kennedy, M. D., Schippers, J. C., and Amy, G., 2010. "Global desalination situation." *Sustainability Science and Engineering,* vol. 2, pp. 7-39.

[17] Tam, V., Tam, L., and Zeng, S., 2010. "Cost effectiveness and tradeoff on the use rainwater tank: An empirical study in Australian residential decision-making." *Resource Conservation and Recycling Journal,* vol. 54, pp. 178-186.

[18] Hauber-Davidson, G. and Shortt, J., 2011. "Energy consumption of domestic rainwater tanks " *Water Journal,* vol. 38, pp. 1-5.

[19] Fletcher, H., Mackley, T., and Judd, S., 2007. "The cost of a package plant membrane bioreactor." *Water Research,* vol. 41, pp. 2627-2635.

[20] Boehler, M., Joss, A., Buetzer, S., Holzapfel, M., Mooser, H., and Siegrist, H., 2007. "Treatment of toilet wastewater for reuse in a membrane bioreactor." *Water Science and Technology,* vol. 56, pp. 63-70.

[21] Gnirss, R., Luedicke, C., Vocks, M., and Lesjean, B., 2008. "Design criteria for semi-central sanitation with low pressure network and membrane bioreactor–the ENREM project." *Water Science and Technology,* vol. 57, pp. 403-410.

[22] Fountoulakis, M., Markakis, N., Petousi, I., and Manios, T., 2016. "Single house on-site grey water treatment using a submerged membrane bioreactor for toilet flushing." *Science of the Total Environment,* vol. 551, pp. 706-711.

[23] Reyes, Trifunović, N., Sharma, S., Behzadian, K., Kapelan, Z., and Kennedy, M., 2017. "Mitigation options for future water scarcity: A case study in santa cruz Island (galapagos archipelago)." *Water Research,* vol. 9, p. 597.

[24] Janssen, R. and Herwijnen, 2011. *M. DEFINITE for Windows. A system to support decisions on a finite set of alternatives (Software packages and user manual)*. Vrije Universiteit, Amsterdam: Institute for environmental studies (IVM).

[25] Reyes, M., Trifunovic, N., d'Ozouville, N., Sharma, S., and Kennedy, M., 2017. "Quantification of urban water demand in the island of santa cruz galápagos archipelago." *Desalination and Water Treatment,* vol. 64, pp. 1-11.

[26] Herwijnen, M. V. and Janssen, R., 2004. "Software support for multi-criteria decision making. Sustainable management of water resources." *An Integrated Approach.*