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Groundwater Sustainability Assessment in Small Islands: The Case Study of San Andres in the Caribbean Sea

Camilo Lesmes Fabian[1*], Jose Wilson Ibañez[2] , Ferney Smith Prieto[3], Carlos Caro Camargo[4]

[1] Faculty of Civil Engineering, Universidad Santo Tomas Seccional Tunja; camilo.lesmes@usantoto.edu.co
[2] Faculty of Civil Engineering, Universidad Santo Tomas Seccional Tunja; jose.ibanez@usantoto.edu.co
[3] Faculty of Civil Engineering, Universidad Santo Tomas Seccional Tunja; ferney.prieto@usantoto.edu.co
[4] Faculty of Civil Engineering, Universidad Santo Tomas Seccional Tunja; decano.civil@ustatunja.edu.co

Abstract: Groundwater is an important resource for many countries and its scarcity is a major concern in small territories, especially in the islands where the constant extraction is creating a high risk of public calamity. This issue has been increasing because of the anthropogenic activities and the climate change and it has called the attention of scientists and stakeholders in order to assess the sustainability of the water management system, and therefore, to establish strategies for a more sustainable water use. San Andres island was taking as case study and a description of the water balance was carried out in order to understand the management system. Then, a water system sustainability assessment was performed with indicators such as water security, water quality, drinking water, sanitation, infrastructure, climate robustness, biodiversity, attractiveness, and governance, according to the City Blueprint Methodology. The result for the 24 evaluated indicators was a score of 3.2, whose interpretation is "an unsustainable water management". The qualitative assessment was the base to propose water security, water quality, and governance strategies to improve the water management in the island. The assessment and its discussions are relevant for the water management in small islands across the world whose economy is based on the tourism and whose water security is at a high risk.

Keywords: groundwater; sustainability assessment; small islands; Caribbean islands, sustainability assessment indicators; water management.

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1. Introduction

The world´s largest volume of unfrozen and accessible source of freshwater comes from groundwater [1-3], and for most nations is considered as an important resource of drinking water for agricultural and human supply [4-7]. Approximately, 25 % of humans rely on groundwater for their domestic needs and 50 % use it as potable water supply [8]. It is also recognized that groundwater has become an important issue from the socioeconomic perspective around the world [9,10]. Recently, water resources managers and politicians are recognizing the important role played by groundwater resources in the demands of water for domestic, agricultural and industrial activities, and for sustaining the different ecosystems [11]. In the last decades, hydrogeologists and other scientists have made a remarkable progress in collecting information about the word´s groundwater systems, understanding their role and functions, observing the behaviors, and identifying the threats that need to be addressed to safeguard the sustainability of this resource [1]. The increasing global demand for groundwater has resulted in the need to measure and monitor this resource [12] in a sustainable context that balances the environment, the society and the economy [13,14]. This implies the

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characterization and analysis of the agents involved in the system, and the development of strategies to maintain this resource in the long term without causing unacceptable consequences [11].

Worldwide, groundwater represents about 30% of the fresh water which is mainly used for drinking water and sanitation (22%), food production (67%) and industrial activities (11%) [15]. It is considered that groundwater is a resource in transition because its exploitation started in the twentieth century and this resulted in a large amount of benefits, but also this called the attention of experts in order to evaluate the sustainability in the exploitation [1]. This issue is of special interest in the small islands where freshwater comes mainly from groundwater, which is primarily recharged by precipitation and its recharge depends on climate, topography, geology and vegetation cover [16]. Most of these islands are situated within a small territory, with a lack of resources, remoteness from the mainland, a susceptibility to natural disasters and a vulnerability to climate change, issues that create a pressure on stakeholders in order to formulate an adequate water resource management [17]. Additionally, there is still a lack of understanding of the groundwater system, especially in these territories, where there is an excessive withdrawal and therefore a sustainability assessment is required for a proper planning to ensure a constant availability of the groundwater resources [18].

Nowadays, the availability of groundwater in small islands is affected mainly by two issues: the anthropogenic activities and the climate change. Small islands are usually affected by a rate of population growth which exceed the rate of economic growth, issues that are within a context of several disadvantages such as excessive dependence on international trade, overuse and premature depletion of resources, relatively small watersheds, threatened water supplies, costly public administration and infrastructure, including transportation and communication, and limited institutional capacities. In addition, the domestic markets are unable to provide significant scale economies, while their limited export volumes, sometimes from remote locations, lead to high freight costs and reduced competitiveness [19]. The second factor is the climate change in which the carbon dioxides levels in the atmosphere are increasing and, if this trend continues, the climate characteristics are altered and these have effects on the hydrologic cycles that control weather patterns [20]. While increased temperatures would likely lead to an increase in precipitation at the global scale, it may result in either increase or decrease in rainfall at the local scale, depending on the local climatic conditions and geomorphological characteristics [21]. However, there is a proved relationship between precipitation, temperature, and loss of fresh groundwater resources which highlight the complexity of hydrological consequences because of climate change [22]. Considering these two issues, a sustainable assessment in small islands is required in order to understand the consequences of actual groundwater exploitation and formulate strategies to protect the aquifers.

The Archipelago of San Andrés, Providencia and Santa Catalina forms part of the Colombian territory and is located to the northeast of the Colombian continental coast and to the West of the Caribbean Sea from about 240 kilometers of the Central American coast. It consists of three main islands: San Andrés, Providencia and Santa Catalina [23]. The island of San Andres is located at the northern end of the so-called Inter-Tropical Convergence Zone (ZCIT), formed by the winds coming from the northeast with those coming from the southeast. It has an extension of approximately 26 km^2 and a current population of 65,000 inhabitants. Its main economic activities are tourism, trade and services derived from them. Its average temperature is 26°C and its annual average rainfall is 1900 mm [24]. The exploitation of the water is made through the drilling and exploitation of deep wells. The company that manages the aqueduct has built a total of 32 wells [23]. Currently, the population of San Andrés depends on groundwater by 80%, exploited by wells, deep wells and drilled wells [25]. However, the accelerated population growth and the increasing touristic activities are causing a negative environmental impact with a strong pressure and deterioration of the main ecosystems in the island like mangroves, coral reefs and watershed [23]. These problems suggest that it is necessary to evaluate the sustainability of the exploitation system, and to have a monitoring of the groundwater flows, in order to seek strategies for a water management, within an ecological,

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social and economic context [24]. This requirement is a challenge that is embedded in the 2030 Agenda as the sixth of the sustainable development goals [26].

Taking into account the previous problem contextualization, the goals of this research were: a) To study the water balance system in the small island of San Andres from a holistic point of view, by understanding the interaction between the processes and by making a quantification of the water flows; b) To assess the sustainability level from the economic, social and environmental perspective; and c) To propose a series of water security, water quality and governance strategies to improve the water management in the island.

2. Materials and Methods

The water system in the archipelago of San Andrés, Colombia was studied focusing on the different processes and flows of water in the island, including the catchment sources, the processes by which the water flows, and the final wastewater discharge. In order to build the system, the information was obtained from official published documents. The system was structured based on the Material Flow Analysis (MFA) methodology [27]. The sustainability assessment started with a revision of the available methods and the City Blueprint Framework was chosen as it takes into account 24 indicators divided into eight categories [28-30]. These categories are water security, water quality, drinking water, sanitation, infrastructure, climate robustness, biodiversity and attractiveness and governance including public participation, and all of them can be applied in the case study of San Andres. The results obtained from the implementation of these two methodologies were the base for the proposal of strategies to improve the sustainable water management.

3. Results

3.1 Water Management System in the San Andres Island

In order to understand the water management system in the island, a description of the water consumption, wastewater management and aquifer pollution is provided, following the material flow analysis methodology, taking into account four compartments: the atmospheric compartment (precipitation and effective precipitation), the soil compartment (soil, subsoil, and aquifer), the water treatment (desalination plant and water treatment plant), and the water use (population use, septik tanks, sewage system, and marine outfall). Figure 1 shows the water flows between the processes in the island in terms of $m^3/s.m^2$.

- *Water Consumption:* The water cycle in the system begins with two sources: the natural precipitation and the uptake of salt water from the sea. The official documents [23] report that, as an average, there is a precipitation of 1900 mm per year in the island (0,388 $m^3/s.m^2$). The most critical months are December to Abril with a precipitation between 1 to 13 mm per month. The period from June to November has the highest precipitation between 147 to 183mm. The water system depends on the precipitation (67%), the aquifer (18%) and the sea water (14%). The total consumption of water by the population is 0,072 $m^3/s.m^2$, 36% comes from the water treatment plant, 35% comes from the desalination plant, 21% comes from the direct rain harvest, and 8% comes directly from the aquifer. There are around 58 wells across the island where the inhabitants take water from the aquifer. Only 51% of the population has access to the water supply system. It is important to consider that the hotels and resorts have the priority of access to treated water, especially in the high touristic seasons.
- *Wastewater Management:* The inhabitants in the island discharge the wastewater in 10.266 septic tanks located across the whole territory of the island [25]. Some of them have and adequate maintenance, and the wastewater is collected in tank cars by the local company. However,

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because of the high number of septic tanks, most of them work as natural filters with infiltration of the wastewater through the soil layers. The collected wastewater by the tank cars is discharged into the sea by means of the marine outfall. According to the official reports, the marine outfall discharge is around 0.07 $m^3/s.m^2$. The island has no wastewater treatment plant.

- *Aquifer Pollution:* There are two sources of water pollution in the aquifers. Because of the constant water extraction, there is an intrusion of the sea water into the aquifer. In addition, there is a filtration of wastewater from the septic tanks into to the subsoil which increase the level of water pollution. Only 1% of the groundwater is potable, 69% is very polluted, and 30% moderately polluted [31,32].

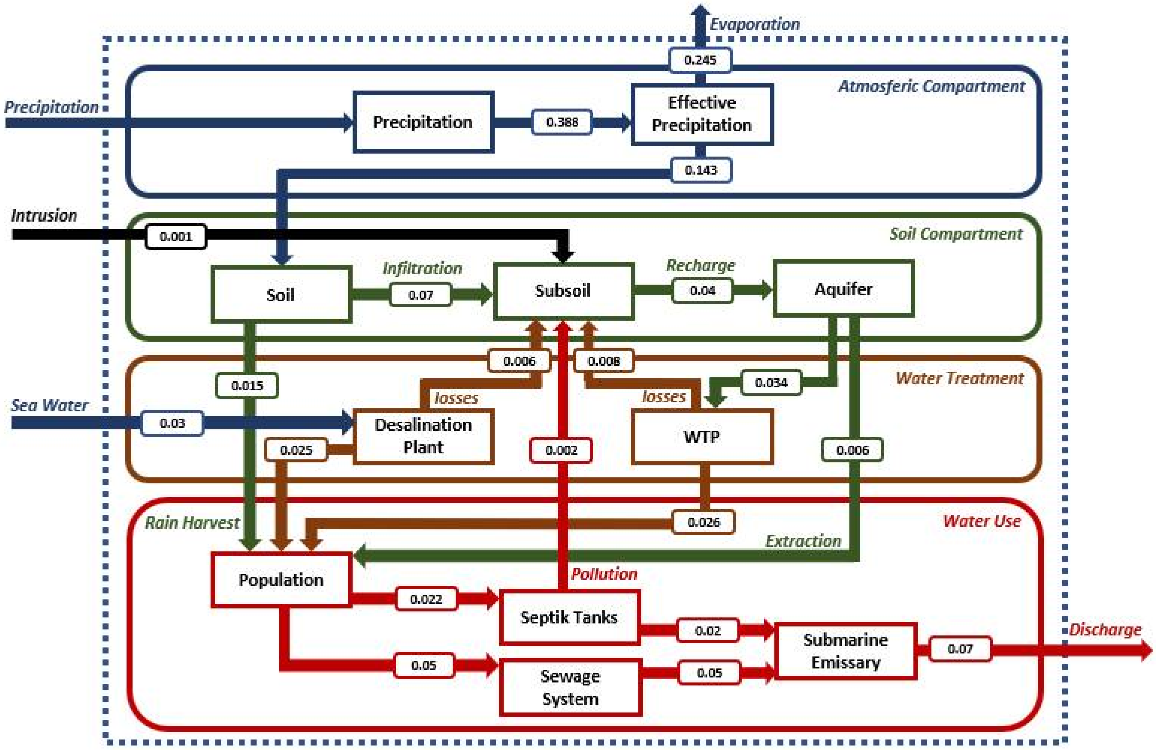

Figure1: Water System in San Andres Island. Units are in $m^3/s.m^2$

3.2 Sustainability Assessment of the Water System in the Island

The status quo of the water management in the island was evaluated in order to propose measures and strategies to improve the water security, the water quality and the water governance. The sustainability assessment was based on the indicators proposed by the City Blueprint Framework Methodlogy. 24 water sustainability indicators were evaluated and to designate the value, official reports were revised to have all the required information (Table 1). Figure 2 shows the summary of the assigned values. The sustainability assessment shows that water securitiy is affected by the climate, the indaquate supply system, and the increasing tourim. Because of the increasing population and the lack of environmental policy measures, the quality of surface water is at medium risk of being polluted. In the case of groundwater, 99% of the wells are polluted because of the infiltration of contaminants through the soil layers and the lack of maintenance of the septic tanks.

Even though, the treated water quality parameters fullfil the requirements, half the population does not have access to the water supply system and there is a leakage of treated water of 78%, which is very high for a region with water scarcity. There is wastewater treatment plant under construction, however, there are delays in the operation and this issue put at high risk the level of pollution of the water system in the island. In the case of the infrastructure indicators, only 26% of population has access to the sewage system and 56% has access to the water supply system. The local government has reported a development plan for 2019, however there are no specific maeasures for adaptation to climate change such as a risk assessment and the implementation of sustainable strategies for energy consumption and building construction. Finally, even though, the San Andres territory is located within the Sunflower Biosphere Reserve, declared by UNESCO in 2000, only until 2005 the Colombian environmental authorities declared the location as "Protected Marine Area". This shows a problem about the environmental policy management and it is reflected by the low public participation of the communities. In summary, by making an average of the values assigned to the indicators, the quantitative result is 3,2 and the qualitative assessment is "an unsustainable water management system" requiring an urgent intervention plan because of its high vulnerability in the context of climate change.

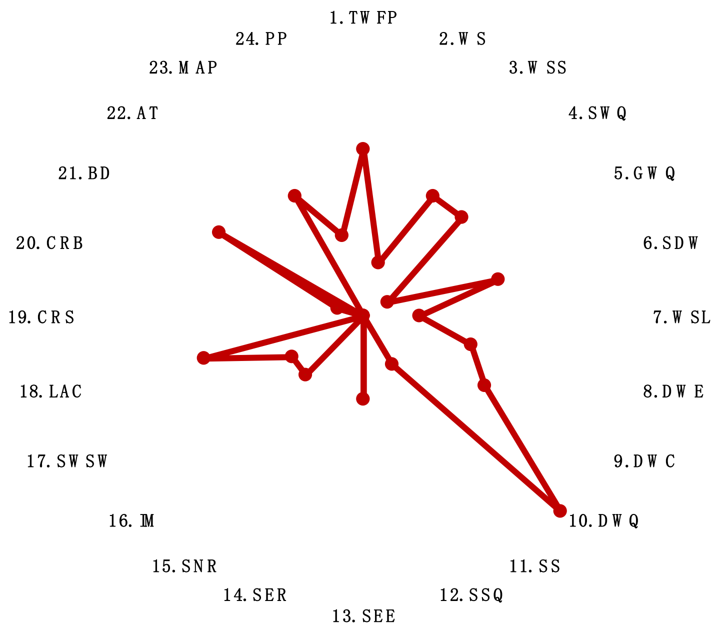

Figure 2: Values assigned to the 24 indicators according to the City Blueprint Methodology (See Table 1).

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Table 1: Evaluation of indicators according to the City Blueprint Methodology

Category	Indicator	Description	Value	Justification
Water Security	Total Water Footprint (***1. TWFP***)	Total volume of freshwater that is used to produce the goods and services consumed by the community	6	• 56% of the population residing on the island has a potable water service, according to the local company which manage the water supply [23].
	Water Scarcity (***2. WS***)	Ratio of total water footprint to total renewable water resources.	2	• From 2013, the island has suffered a decrease in the precipitation rate because of the climate change and the "El Niño" phenomenon. The water scarcity reaches an 80% [33].
	Water Self Sufficiency (***3. WSS***)	Ratio of the internal to the total water footprint. Self-sufficiency is 100% if all the water needed is available and taken from within own territory.	5	• Despite the fact that inhabitants in the island use the water supply network, the tourism industry carries water in bottles from the Colombian continental territory for the tourist consumption. There is a deficit of 49% of water supply [34].
Water Quality	Surface Water Quality (***4. SWQ***)	Assessment of the water quality, preferably based on international standards for e.g. microbial risks, BOD and organic/inorganic micro-contaminants.	5	• According to the national report about the water quality which takes into account the risk of diseases related to microbial and chemical pollution, there was no risk for 2015 and a medium risk for 2016. This means, there is an increasing tendency in the risk [35].
	Groundwater Quality (***5. GWQ***)	Assessment of the water quality preferably based on international standards for e.g. microbial risks, BOD and organic/inorganic micro-contaminants.	1	• Different studies have shown that only 1% of the groundwater is potable, 69% of water is very polluted, and 30% is moderately polluted [31,32].
Drinking Water	Sufficient to Drink (***6. SDW***)	% of city population with potable water supply service.	5	• Approximately 56% of the population has access to potable water supply service [34]. However, the service is not constant.
	Water System Leakages (***7. WSL***)	% of water lost in the distribution system.	2	• The leakages of water are around 78% [34].
	Water Efficiency (***8. DWE***)	Assessment of the comprehensiveness of measures to improve the efficiency of water usage.	4	• 64% of the tourists ignore the problematic of water usage. Only 40% of the small hotels promote the efficient water usage. There are multiple conflicts of interests between the small hostels, big hotels, the local water supply company, and the national government [34].
	Consumption (***9. DWC***)	Domestic water consumption per capita.	5	• The population requires 150 l/day per capita. However, there is a deficit of 49% of water service supply [34].
	Quality (***10. DWQ***)	% of drinking water meeting the WHO water quality guidelines.	10	• The water quality has the quality standards according to the Colombian regulations [36].
Sanitation	Safe Sanitation (***11. SS***)	% of city population served by wastewater collection and treatment.	2	• Only 26% of the territory has access to the sewage system. 65% of the houses use septic tanks. There is no wastewater treatment plant in the island [36].
	Sewage Sludge Quality (***12. SSQ***)	% of sewage sludge that can be safely used in agriculture based on organic/inorganic micro-contaminants.	0	• The sewage sludge is discharged in the septic tanks and the submarine emissary.
	Energy Efficiency (***13. SEE***)	Assessment of the comprehensiveness of measures to improve the efficiency of wastewater treatment.	3	• In 2001 was built a wastewater treatment plant, however, it does not operate [36].
	Energy Recovery (***14. SER***)	% of wastewater treated with techniques to generate and recover energy.	0	• There is no wastewater treatment plant in operation.
	Nutrient Recovery (***15. SNR***)	% of wastewater treated with techniques to recover nutrients, specially phosphate.	0	• There is no wastewater treatment plant in operation.
Infrastructure	Maintenance (***16. IM***)	% of infrastructure of wastewater collection, distribution, and treatment younger than 40 years.	3	• There is a separated system for wastewater and rainwater. However, only 26% of the territory has access to the sewage system [36].
	Separation of wastewater (***17. SWSW***)	% of separation of the infrastructures for wastewater and storm water collection	3	• There is separated system for wastewater and rainwater. However, only 26% of the territory has access to the sewage system [36].

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Climate Robustness	Local authority commitments ***(18. LAC)***	Assessment of how ambitious and comprehensive strategies and actual commitments are on climate change.	6	• There is a development plan which includes: a) Protection of seas, costs, and beaches; b) Environmental Protection; c) Sustainable energy; d) Improvements of water supply and sanitation services; e) Spatial planning; f) Mitigation of climate change effects. However, the mitigations plans do not have specific vulnerability studies in the island [36].
	Safety ***(19. CRS)***	Assessment of measures taken to protect citizens against flooding and water scarcity, including sustainable drainage.	0	• According to the development plan, there are no specific and detailed measures [36].
	Climate-Robust Buildings ***(20. CRB)***	Assessment of energy efficiency for heating and cooling, including geothermal energy.	1	• The sustainable energy is included in the development plan, however, sustainable buildings are not considered [36].
Biodiversity and Attractiveness	Biodiversity ***(21. BD)***	Biodiversity of aquatic ecosystems according to the WFD.	6	• In 2000, UNESCO designated the San Andres Island as part of the Seaflower Biosphere Reserve because of the coastal and marine areas that include coral reefs, mangroves, islands and dry tropical forest. In 2005 the Colombian Government recognized 65.000 km^2 of this area as "Protected Marine Area". Therefore, there are environmental management plans to regulate and monitor these ecosystems.
	Attractiveness (***22. AT)***	Water supporting the quality of the urban landscape as measured by community sentiment within the city.	0	• Because of the water scarcity, the low percentage of wastewater collection, the high risk of pollution of the aquifer by the septic tanks and the no existence of wastewater treatment plant, there is no connection between the adequate water management and the attractiveness of the island related to the water systems.
Governance	Management and action plans ***(23. MAP)***	Measure of local and regional commitments to adaptive, multifunctional, infrastructure and design for the integrated urban water management.	5	• There is a development plan, however, there is not specificity of the measures for the island and there is still no vulnerability and risk assessments [36].
	Public Participation ***(24. PP)***	Proportion of individuals who volunteer for a group or organization as a measure of local community strength and willingness of residents to engage in activities for which they are remunerated.	3	• 20% of the population participates in political processes. 15, out of 49 community organizations, have participated in public calls for projects, and 13 projects have been approved. The development plan includes to promote the inclusion of more communities in the public participation [36].

4. Discussion

4.1 Water Security Strategies

The water security in the island of San Andres is at high risk, taking into account that the population has a low level of access to the water supply which has two sources of water: the groundwater and the water disalination plant. In addition, the whole system depends directly on the natural phenomenons such as precipitation, runoff, soil infiltration and seawater intrusion. In the context of the climate change, there must be a strategy that focuses on the hydrologycal system understanding and the incorporation of the social dynamics in the island, whose economy is based on the tourism. Therefore, a socio-hydrology approach is required in order to reach a better prediction, planning, and decision making [37]. This will allow to strengh the water security by following phases such as: a) Understanding the system, developing hydrologycal models in extreme climate scenarios to assess the risk derived from climate change; b) Integrating relevant stakeholders in the island such as the hotel owners, travel agencies, environmental authorities, governmental authorities, community organizations, and small business owners; c) Implementing strategies for the integrated water management involving all the stakeholders in the context of the climate change and the risk assessment [38]. The implementation of strategies need an investment to fullfill the water requiremetns by the community, establishing emergency plans, and a continuos monitoring of the system [39].

4.2 Water Quality Strategies

The economic development in the island is based on tourism activities which generates large amounts of wastewater and solid waste. In addition, the absence of wastewater treatment plant and the poor infrastructure in the sewage system, which is only available for 26% of the population, results in high levels of pollution in both the groundwater and the seawater that surrounds the territory of the island. There is a constant monitoring of the groundwater which has given information about the low quality in 99% of the wells. Taking into account that wastewater is a source of pollution of groundwater, soil, and the ecosystems [40], this baseline helps to generate a strategy which must include the massification of plastic septic tanks with a frequent wastewater collection, the extension of the sewage system network, and the beginning of the operation of the wastewater treatment plant. The wastewater collection from septik tanks and its treatment must include the energy and nutrient recovery, which are valuable sustainable indicators, and they are important targets in the sustainable development goals for 2030. Besides, an adequate waste management is a priority in order to avoid the use of landfills which are also an important source of pollution.

4.3 Ecotourism as a Water Management Strategy

Taking into account that the economy in the island depends on tourism, the water management strategies should move towards an ecotourism programme which, as it has been discussed in previous studies, it should include a nature-based policy, ecologically sustainable activities, environmentally educative programmes, economically benefits to the local community, and optimum satisfactions to the tourists [41,42]. San Andrés is a Biosphere Reserve, declared by UNESCO, and this issue is a potential to improve the water management and to develop the ecotourism strategies. Tourists must be instructed about the water problem in the island, the water management strategies, the solid waste programmes, and the policies about the protection of the ecosystem.

4.3 Governance Strategy

Water governance is a complex and diverse process with different jurisdictions, governance powers and functions, and dispersed in institutions at different scales and hierarchical levels. The governance strategies for the island are discussed, following the approach by Woodhouse and Muller [43]. In the case of water scarcity, it is evident that water demand exceeds available supplies, therefore, the water availability is determined by the financial capacity to generate additional supplies, increasing the desalination plant capacity, and improving the quality and efficiency of the water supply network. In the case of participation, stakeholders at high levels must promote the participation of all the associations, communities, inhabitants, governamental and environmental authorities, and tourism agencies, in order to open the field for discussion of the environmental interests related to water. In the case of scale, the water management strategies must be discussed taking into account the relevant sectors, such as the urban area, the rural area, and the specific locations accross the island with high populations, which somehow have an impact and interest in the water resource. From the economic perspective, there are strategies, such as establishing properties rights to water quantity, water quality management, operational issues, pollution charges,

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waste discharge charges, adaptation of water use because of climate change, and changes in public and private priorities about the environmental and water resource protection. However, these issues must be discussed by stakeholders at all hierarchy levels. Finally, in the case of the governance, as it is highly contextual, there must be a network or collective organization for the small-scale economy of the island which discuss the water issues as a common property with a high risk of scarcity in the context of climate change. It is important to take into account that the network, as discussed by Woodhouse and Muller, is influenced by physical factors, different levels of economic and social development, as well as political and cultural norms that have evolved over long periods.

5. Conclusions

In the context of climate change, the islands are small territories which represent, in small scale, the global situation of the water security and water scarcity. This paper has provided a description of the water management system in San Andres island and a sustainability assessment which has evidenced an "unsustainable water management". However, the integration of stakeholders, the improvements in the soild waste and wastewater management, the increase in the capacity of the water supply infrastructure, and the implementation of ecotourim programmes, are strategies that might help to improve the level of sustainability in the island.

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