Selection of water treatment technology for small indigenous communities in the arid region of La Guajira, Colombia

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Master of Science Thesis
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Abstract

La Guajira, Colombia, is one of the most arid regions in Colombia. Indigenous communities such as Wayuu, are scattered around the region and account for 40 % of the population. However, the access to safe water has been an obstacle for more than ten years and has put the communities on great health risks. The lack of information regarding water demand, uses, customs and water quality, does not allow for correct selection of appropriate water treatment technologies that could solve this problem. The purpose of this research is to select the most adequate water treatment. To achieve this, water demand and water quality will be investigated.

Nine communities and a boarding school were visited during fieldwork. Surveys were done to locals to find information on water uses and demand. Additionally, leaders were surveyed in order to find general information of the communities. Water samples from the wells found in the communities were analysed. Water quality variation was statistically analysed with ANOVA and t-tests, complemented by the use ArcGIS, in order to evaluate the influence of spatial factors such as proximity to the sea and the geological and hydrogeological features in the salinity levels. Lastly, water companies, academia, NGOs and the communities were surveyed to determine criteria weights in order to perform a multi-criteria decision analysis (MCDA) for the selection of the water treatment technology using DEFINITE software.

Domestic water demand and schools demand was 27.5 lpcd (litres per capita per day). The use of water for agriculture as for crops and goats dramatically increases the demand to 230 lpcd. Water quality is mainly influenced by coliform contamination and the high concentration of totals dissolved solids (TDS). The high levels of contamination by coliform bacteria require that disinfection strategies must be put in place immediately to prevent further water-borne diseases. The spatial variation of water quality has a high probability of being caused because of seawater intrusion, probably by the lack of control in the operation of the extraction wells. The MCDA was run in DEFINITE software and through this methodology, presented reverse osmosis (RO) as the most recommended technology for water treatment.

This research was able to gather data that will help make informed decisions to provide water treatment systems to the indigenous communities in La Guajira. This investigation also contributes to the analysis of different contexts where decisions must be taken considering the complex characteristics of the area, such as aridity, small scale, lack of accessibility, etc. Investigation on more robust methodologies to improve the selection of water treatment processes is encouraged.

Keywords: water supply in arid conditions, small-scale treatment systems, brackish water treatment, multi-criteria decision analysis, seawater intrusion.

Dedication

To my mother, Olga Aristizábal, that has always supported me in all my projects.

To my father, Antonio Medina, for supporting me.

To my grandmother Lola, whose life and character inspire me.

To Manuel and Chuni, who read and advised me on how to have better English.

To my family, because they are the ones that have taught me what a good person is made of.

To Emma and Franco. Welcome!

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Last but not least, I would like to mention that without Juliana Otálvaro, this project might have not occurred in the first place.

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Abbreviations

AHP	Analytic hierarchy process
BWRO	Brackish water reverse osmosis
CP	Comprise programming
DANE	Departamento Administrativo Nacional de Estadística
EC	Electrical conductivity
ED	Electrodialysis
DO	Dissolved oxygen
FAO	Food and Agriculture Organization of the United Nations
FO	Forward osmosis
HCA	Hierarchical cluster analysis
HDH	Humidification dehumidification
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
LPCD	Litres per capita per day
LSI	Langelier saturation index
MCDA	Multi-criteria decision analysis
MD	Membrane distillation
MED	Multiple effect distillation
MSF	Multi-stage flash distillation
MVC	Mechanical vapour compression
NF	Nanofiltration
NGO	Non-Governmental Organization
PCA	Principal component analysis
RO	Reverse osmosis
SGC	Geological Colombian Service (Servicio Geológico Colombiano)
SINIC	Sistema Nacional de Información Cultural
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
TOPSIS	Technique for order performance by similarity to ideal solution
UF	Ultrafiltration
UN	United Nations
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
USGS	United States Geological Survey
VC	Vapour compression
WHO	World Health Organization

CHAPTER 1

Introduction

1.1. Background

Colombia is a country which is characterized by its numerous water sources. It has approximately 2,300,000 million m^3/year of renewable water sources, making it one of the richest nations in this matter (Expo Milano, 2015). According to (Steduto, et al., 2012), if there is less than 500 m^3/year of water per inhabitant, it is considered a chronic scarcity situation. A simple division of the available water and the approximate 48 million Colombians results in approximately 48,000 m^3/year/person (FAO, 2014). This would mean that there are no scarcity problems in Colombia. However, water distribution is not uniform and there are regions which have serious scarcity difficulties.

La Guajira, in the north of Colombia, is one of these cases where water is not easily available. This is a desert-like, arid coast region where many indigenous communities have settled. The Wayuu, are the most numerous, accounting for almost 40 % of the population in La Guajira. There are also the Kogui, the Wiwa, and many other ethnic groups (SINIC, 2017). For these communities, water is not easily available as in other places of Colombia. According to the Department of National Statistics (DANE in Spanish), approximately 4,150 children died in La Guajira between 2008 and 2013. Almost 10 % of these children died due to food scarcity which is directly related to the absence of access to water (Verge, 2017).

When water is available, it is usually by means of wells. There are indications that water in the region is high in total dissolved solids (TDS) which makes water inappropriate for consumption (Verge, 2017). In some settlements there is no water treatment but where there are, most of the times they have fallen into disrepair. This might be due to the lack of political planning and execution of plans and the unavailability of skilled labour to adequately maintain the infrastructures.

This research investigates the actual demand of water in some indigenous communities, evaluates the water quality of the sources and aims to select the most appropriate technology of water treatment that can benefit the region. It is of great importance that the technology selected is able to adapt to the variation of quantity and quality in the region.

1.2. Problem statement

La Guajira hosts very important cultural heritage with the indigenous communities that live in the region. However, the living conditions in which the communities live poses a risk to its preservation through time. The fact that water is one of the many problems the communities have to face, in addition to corruption, puts them at risk. The situation is aggravated further by the fact that relevant information regarding water demand and water quality is not available. As a result, investigation in this subject is the first step towards bringing effective strategies and solutions for the well-being of these groups.

By evaluating the quantity and quality of the water sources, a better understanding of the water needed for their consumption can be obtained. Additionally, knowing the needed treatment to bring quality to the approved physicochemical properties, based on the challenges found, will help identify appropriate technologies for water treatment.

There are suggestions that water quality varies in the region. Based on the characteristics of the settlements, a technology should be able to adapt to the different contexts where they are located. This will filter the range of alternatives from which a technology can be selected, as flexibility is required.

Collecting the information mentioned above allows to apply a methodology for the selection of a water treatment processes. Data regarding water demand and quality, allows decision makers to select from a range of possible alternatives, which is the most appropriate one. For this, a set of criteria must be defined, evaluated and analysed in order to make a final recommendation. This methodology gives a theoretical and technical basis to structure decisions, from the evaluation of the water needs, to the development of criteria, weights and evaluation of technologies available.

1.3. Research questions and objectives

The main research questions in this thesis are:

- What is the water demand in the present and in the future in the study area?
- Is the water quality at the source adequate for consumption?
- Is there a variation in the water quality in the wells in the region studied?
- What is the most appropriate technology for water production in the region?

The main objectives of this research are:

- To study the population growth, water sources, uses and customs and the quantity of water available in the study area.
- To evaluate the quality of water in the study area by investigating the presence of toxic compounds, pathogens and/or other quality related parameters.
- To analyse the water quality variation in the region
- To determine the most appropriate water treatment system in the region.
- To propose a treatment scheme for the water treatment.

1.4. Justification

Ancla Foundation[1] has been supporting communities, since 2002 in La Guajira by building schools to improve children's accessibility to education. With the help of Entropika[2], the schools already built and the ones that will be built in the future, are expected to have water systems that can provide safe drinking water for the use within the schools and the communities. This requires a well informed decision to decide on the best technology to provide adequate water to the people with a treatment system able to meet the requirements that will be described by the findings in this research.

With the results of this investigation, it is expected that the living conditions of the indigenous communities in La Guajira improves. The fact that this problem has been occurring for more than ten years has put an obstacle in the development of the communities in the region. Furthermore, the indigenous groups that live in La Guajira are a very important cultural heritage for Colombia and the world and they should be guaranteed their access to safe water.

This case study can be used as a reference for selecting water treatment technologies in similar contexts. It creates a background for decision making for scenarios that have similar characteristics such as the ones presented in this investigation.

[1] Swedish foundation. http://www.ankarstiftelsen.com/

[2] Colombian NGO. http://www.entropika.org/en/index.html

CHAPTER 2

Literature review

2.1. Water supply: centralized vs. decentralized

Universal access to water has not been an easy goal to achieve. The United Nations (UN) Sustainable Development Goals (SDGs) state that 663 million people still don’t have access to improved water sources (UN, 2016), in other words, 663 million people still drink from water sources that are not protected and that are possibly contaminated with faecal waste. Furthermore, climate change has exacerbated the problem of already existing arid areas. Since the last century, efforts to increase the number of people with basic drinking water and sanitation coverage have been realized. However, results are still far from reaching the goal to give water for all.

The 70s decade was declared the International Drinking Water Supply and Sanitation decade. Its focus was to achieve by 1990 full coverage but it fell short and created enormous debts in developing countries due to its centralized view to solve this issue (Nicol, et al., 2012). In 1993, the United States Agency for International Development (USAID) reported that the main constraints for supplying water and sanitation services were:

- physical and technical;
- economic and financial;
- institutional; and
- structural (USAID, 1993).

In a centralized-oriented solution, the aforementioned constraints are not alleviated for not densely populated settlements. The physical limitation is increased due to the almost constant isolated and remote location of unserved populations. The solutions for such situations involve complex engineering infrastructures which in turn elevate the costs for deployment. As a result, the financial aspects are compromised as little income can be collected either because of unwillingness to pay or because prices cannot be covered by the people served. This results in institutional and structural constraints.

On the other hand, decentralized solutions have been able to reduce the problems that centralized systems were not able to solve. It has been applied in many developing countries and has included the use of alternative water sources (Peter-Varbanets, et al., 2009). Furthermore, it has empowered communities to decide for themselves, in order to fulfil their interests. This has also allowed for more effective and quicker responses to problems that arise (Sharma, 2017). Overall, decentralized approaches have been able to close the gap between the served and unserved.

2.2. Desalination technologies

There are various technologies available for the treatment of saline water. Table 2-1 summarizes the technologies and classifies them as thermal desalting or membrane filtration desalination (Kennedy, et al., 2002; Narayan, et al., 2010).

Table 2-1 Desalination technologies

Thermal desalination	Membrane filtration desalination
Multi-stage flash distillation (MSF)	Reverse Osmosis (RO)
Multiple effect distillation (MED)	Nanofiltration (NF)
Vapour compression (VC)	Electrodialysis (ED)
Solar Stills	Forward Osmosis (FO)
Water Pyramids	Membrane Distillation (MD)
Humidification dehumidification (HDH)	

2.2.1. Thermal desalination technologies

The principle of thermal desalination is the evaporation of saline water in order to obtain freshwater from the vapour and a concentrated brine. These technologies use large amounts of energy for the production of freshwater (Kennedy, et al., 2002). However, there are differences among the technologies on how they use the input of heat.

In MED, a set of sprinklers spray saline water onto heat exchanger tubes, which use a boiler to produce the vapour service stream. This causes the water to evaporate and the vapour is later used for the heat exchanger tubes in the following chamber. Brine from the first chamber, which has been heated, is later pumped and sprayed into the second chamber. The pressure in this chamber is set lower than in the first one to enhance the evaporation at a lower temperature. Vapour is condensed and freshwater obtained. The process is repeated in multiple chambers, in order to increase the efficiency of the whole operation (Cipollina, et al., 2009; Kennedy, et al., 2002). Figure 2-1 presents a scheme of the process.

Similarly, MSF evaporates the feed saline water. However it is different because the vapour produced is not used later in different chambers but to heat the feed stream. The chambers that follow the first one have lower pressures to evaporate the water coming from the previous chambers (Cipollina, et al., 2009; Kennedy, et al., 2002). The main difference with MED is that water is not sprayed into the heat exchanger tubes.

Finally, VC can either be thermal or mechanical but the main process is the compression of the vapour. Feed saline water is evaporated and vapour is collected. Later, the vapour is compressed, which increases its temperature. The heat exchanger in the chamber evaporates the feed saline water with the compressed vapour heat. Finally, the vapour condenses by pre-heating the feed saline water (Cipollina, et al., 2009; Kennedy, et al., 2002).

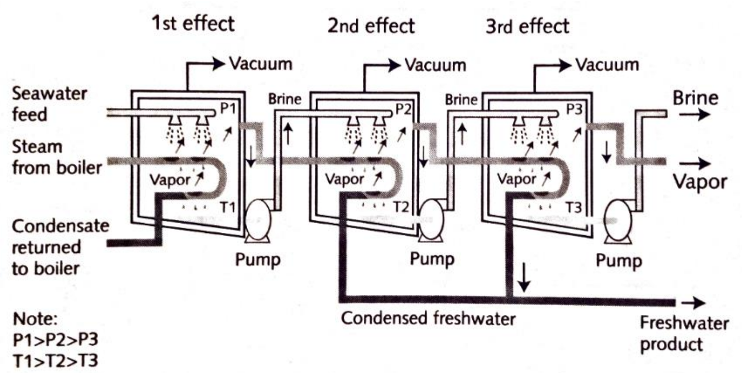


Figure 2-1 MED scheme. Source: (Kennedy, et al., 2002)

Thermal technologies are all energy intensive. Costs are high, units are expensive and large installed capacities are needed to compensate for the investment. For this reason, MED and MSF treatment plants are usually installed in cogeneration plants in order to reduce their costs (Cipollina, et al., 2009). Large scale infrastructures with installed capacities ranging from 100,000 to 1,000,000 m^3/day are commonly seen for MED and MSF (Narayan, et al., 2010). In 2008, MSF and MED had a global market share of 27 % and 9 %, respectively (IDA and GWI, 2018).

2.2.2. Membrane desalination technologies

Different from thermal desalting technologies, the principle of membrane desalination technologies is that water passes through a semi-permeable membrane able to separate dissolved ions in the feed (Kennedy, et al., 2002). Membrane filtration can either be pressure or electrically-driven (Cipollina, et al., 2009). NF and RO are pressure-driven while ED is electrically-driven. Independent of the driving force, these technologies produce a filtrate, which is diluted and a concentrate, which has high salinity concentration. Figure 2-2 presents a basic representation of the mechanism in a membrane process.

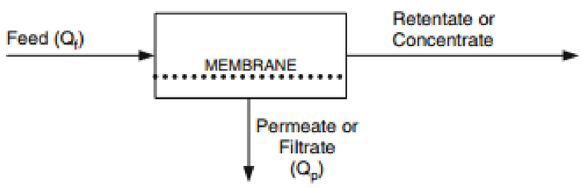


Figure 2-2 Membrane filtration scheme. Source: (Cipollina, et al., 2009)

NF has been used for desalination of brackish water. Experiments have shown that removal of hardness has been very good but not for salinity (Galanakis, et al., 2012). This can be expected as NF membranes have better rejection of divalent ions as Ca^{2+} and Mg^{2+}, which are responsible for water hardness. On the other hand, Na^+ and Cl^-, monovalent ions responsible for salinity, are not rejected. Some applications suggest a limited use of NF for salinity concentrations higher than 1100 mg NaCl/L (Galanakis, et al., 2012).

RO, unlike NF, is able to reject ions up to 99.8% (Cipollina, et al., 2009) and has been used for brackish and seawater treatments. However, higher pressures have to be exerted due to its pore size. For instance, in NF, 1-30 bars must be applied whereas for RO 10-100 bars (for BWRO, pressure can be as low as 5 bar). As a consequence, higher energy is consumed for RO. Nevertheless, its high salt rejection is able to reject divalent and monovalent ions.

FO is the opposite of RO. In this technology, water's natural osmotic diffusion is used to separate water into a carrier liquid. In this manner, freshwater is mixed with a carrier solution which later can be separated. Oppositely, RO applies pressure to reverse the natural osmotic diffusion (Cipollina, et al., 2009). For this reason, energy consumption is much lower than RO. However, FO uses draw solutions that might leave traces in the freshwater separated that might not comply with drinking water standards, which has reduced its application for potable water production (Nasr and Sewilam, 2015).

For ED, an electrical current and a membrane reject the ions in the feed water. Advantages of this technology is that vulnerability to scaling and fouling is less than for RO and NF (Kennedy, et al., 2002). Laboratory scale prototypes that could be placed in isolated areas, which use solar or wind energy, were able to treat water up to 5500 mg TDS/L was treated (Malek, et al., 2016; Ortiz, et al., 2008). Figure 2-3 displays a basic scheme of the ED membrane desalination.

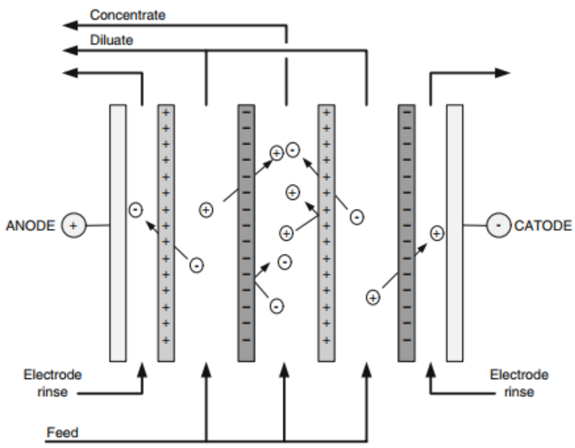


Figure 2-3 ED filtration scheme. Source: (Cipollina, et al., 2009)

Membrane distillation (MD) is a combination of thermal and membrane technologies. This hybrid configuration uses heat to evaporate brackish water which later passes through a membrane to a cooler chamber for condensation. Different settings are available as direct contact (DCMD), air gap (AGMD), vacuum (VMD) and sweeping gas membrane distillation (SGMD) (Qtaishat and Banat, 2013). Additionally, coupling solar collector for water heating or solar panels for electricity has been done. One example is the pilot plant SMADES which produced 120 L/day and consumed between 200-300 kWh/m^3 (Banat, et al., 2007). There are commercially available technologies such as TNO memstill (TNO, 2017).

RO is the leading technology in the global market of desalination as it is present in 56 % of the desalination treatment plants (IDA and GWI, 2018). This is due to its flexibility, compatibility, ability to scale-up and lower energy consumption compared to thermal technologies. Compared to thermal desalination, RO energy consumption is about 5 kWh/m^3 and for MSF and MED are about 10 – 15 kWh/m^3 (Cipollina, et al., 2009). Additionally, small capacity systems from 10 m^3/day have been designed (Choi, et al., 2009) and commercial systems for decentralized and/or small scale installations are now available, as (AAWS, 2017; Elemental WaterMakers, 2017).

2.2.3. Desalination technologies used for small communities.

From the technologies that were mentioned previously, NF, RO, MD and ED have the potential to be used for decentralized purposes for brackish water treatment (Walha, et al., 2007). In addition to these technologies, solar stills, water pyramids and HDH are also considerable candidates to produce drinking water for small communities in remote and arid areas.

Solar stills, also known as solar distillation basins, use sun's radiation to evaporate saline water. It is a thermal desalination unit but it can be further classified into passive or active (Cipollina, et al., 2009). In passive units, pumps, heaters, or fans are not installed, whereas they are in active solar stills. Therefore, for active solar stills, energy costs increase unlike for passive configurations, where all energy is taken from the sun. However, efficiency is comparably increased when convection is enhanced by using fans (Cipollina, et al., 2009).

There are various kinds of solar distillation units as basin stills, wick stills, stills coupled with greenhouses, double-effect basin stills, among others (Ahsan, et al., 2012; Fath, 1998; Qiblawey and Banat, 2008). Remote arid areas in the Mediterranean, the Persian Gulf and the Caribbean have made use of such technologies as precipitations are not frequent but high solar radiation and warm temperatures were suitable for these low-cost technologies (Al-Sahali and Ettouney, 2008). However, if rains occur, water pyramids, which are derived from the same principles as of solar stills, can also collect rain (AAWS, 2017).

HDH is one innovative method for small-scale seawater or brackish water desalination. There have been many researches in the last years that study possibilities to improve this system. The quantity of water produced is a major target in research as currently, water production levels are not high and the recovery ratio (the fraction of water produced from the feed) is very low (Giwa, et al., 2016). However, its simplicity has attracted many investigations and there are already commercially available systems that can produce up to 10 m^3/day (Narayan, et al., 2010; Photon Energy Systems Limited, 2017). A simple scheme of the mechanism is shown in Figure 2-4.

Overall, alternative technologies such as solar stills, water pyramids and HDH, offer low-cost solutions to provide water to isolated communities that count with brackish water as their only source. These technologies are also able to use alternative renewable energy sources in case it is needed. Limitations on the water production are compensated with the low maintenance required. On the other hand, membrane systems are also comparable for small communities' applications. Decision support systems can evaluate different criteria to assess the best technology for different contexts.

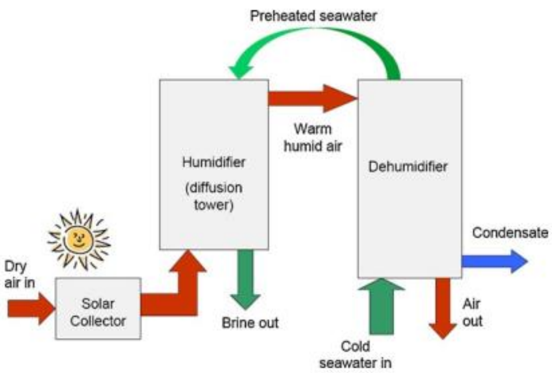


Figure 2-4 HDH mechanism. Source: (Narayan, et al., 2010)

2.3. Multi-criteria decision analysis

To evaluate the potential technologies for brackish water desalination, different criteria and target groups must be included. The parameters used to perform this analysis, should be able to integrate holistically different aspects regarding water production for a small scale system. For instance, environmental, economic, social and technical aspects. Some parameters have been used in different practices and can serve as a guide for this research (Peter-Varbanets, et al., 2009; Wright and Winter, 2014). However, different perspectives may occur when surveying actors such as end users, researchers, government, etc. That is why, an assessment of which target groups should be included in the analysis is of high importance (Anarna, 2009).

2.3.1. MCDA methodology

The process in which a MCDA is generally carried out is presented in Table 2-2. There exists many different methods that can be used to do one specific steps. Table 2-3 presents some of them.

Table 2-2 MCDA process step-by-step. Source: (Hajkowicz and Collins, 2007)

Step		Description
1.	**Alternatives selection**	Available options are chosen which are further analyzed to come to a decision.
2.	**Evaluation criteria**	Criteria evaluate how the alternatives perform. They can be chosen from similar studies and/or surveys.
3.	**Performance scores**	A score will be associated to each alternative for each criteria. This may come from expert opinions, studies, models, etc.
4.	**Scores transformation**	As scores may be qualitative or quantitative, they all need to be transformed to a homogeneous scale. Usually, values from 0 to 1 are used.
5.	**Criteria weighing**	The importance of criteria must be assessed by giving weights. This task can be performed by different techniques as some of the presented in Table 2-3.
6.	**Alternatives ranking**	Different algorithms can be used to rank the alternatives after criteria's weights and performance scores are known. Some common algorithms are presented in Table 2-3.
7.	**Sensitivity analysis**	Variations on scores and/or weights can yield different rankings. An analysis of the variations give better results.
8.	**Decision making**	After the ranking is completed, an informed decision can be taken based on the results of the previous steps.

Hajkowicz and Collins (2007) analysed 39 applications of MCDA on water management issues. They came to the conclusion that no single technique is better than the other. The use of different techniques must be evaluated by the time available and the characteristics of the decision to be taken.

Table 2-3 MCDA methods. Source: (Zarghami and Szidarovszky, 2011)

Methods	Characteristics
Dominance methods	An alternative must be equal or better than all the other alternatives for all criteria. At least for one criteria is should be the best alternative. However, this seldom occurs. And if it occurred, a decision could be taken without a MCDA.
Sequential optimization	Criteria are ordered in a certain preference. Alternatives will be analyzed according to that order and in case there is a tie, the second most important criteria is evaluated. However, this method overlooks alternatives' performance in other criteria which may have worse scores.
The ε-constraint method	To make sequential optimization methods better, an interval for a minimum necessary score are defined for all criteria. As a result, alternatives that don't have admissible scores are discarded. Afterwards, the same process done for sequential optimization is performed.
Simple additive weighting	This method requires that specific weights are assigned to the criteria. Afterwards, the scores each alternative have for the criteria are multiplied by their relative weight and added (weighted average). The alternative with the highest score is ranked first. This method is widely used because of its simplicity.
Distance base methods	In these kinds of methods, an ideal or a least desired set of scores for each criteria is set. The distance the alternatives have to these set of scores ranks the order of the options. For instance, in an ideal scenario, the closer an alternative is to the ideal the better. Conversely, the farther an alternative is from the least ideal solution, the better. Comprise programming (CP) or TOPSIS[3] are the most popular methods for these approaches.
Analytic hierarchy process (AHP)	Giving weights to criteria is systematically done by AHP. A pair-wise comparison between criteria is done. This yields an order of importance for criteria which can later be translated in numeric weights. This method is used to solve conflicting criteria weighing, especially when target groups have opposite opinions.

2.3.2. Common criteria found in brackish water technologies evaluation

Studies comparing brackish water technologies have been performed to find the best system for a specific scenario. Criteria found in some of these studies are summarized in Table 2-4.

2.3.3. Target groups

Different criteria might have more importance for different groups of people. For instance, Anarna (2009) study on pre-treatment systems for seawater desalination plants showed that the groups surveyed (academia, researchers, commerce, environmentalists and plant managers) perceived water quality differently. For instance, among 8 other criteria, ranking for water quality varied from first to fourth position. The opinions each group have usually vary and the careful selection of different target groups can lead to a better MCDA (Linkov, et al., 2006).

[3] TOPSIS: Technique for Order Performance by Similarity to Ideal Solution

Table 2-4 Criteria considered for evaluation of different alternatives. Sources: (Peter-Varbanets, et al., 2009; Wright and Winter, 2014)

Criteria	Description
Daily water production	The amount of water needed for a certain population must be determined by its needs. Therefore, water demand characterization and a water demand forecast help to determine the size for an appropriate brackish water treatment system. Systems have to be evaluated on their ability to fulfil the needed water production.
Contaminants removal	The main purpose for the technologies that are going to be evaluated is brackish water desalination. Nonetheless, pathogens and inorganic pollutants removal, are also taken into consideration. In the end, biological, chemical and physical quality aspects should at least meet WHO drinking water guidelines (WHO, 2011) or local standards.
Recovery ratio and brine disposal management	The volume of fresh water produced from the volume of brackish water fed to the system can change for different technologies. As a result, recovery ratios have an effect on the amount of water produced but also on the concentration and volume of brine. Brine disposal management must be considered in the evaluation of all the technologies. For inland brackish desalination this represents an environment implication as soils can be damaged or other groundwater sources can be contaminated.
Energy use	Energy used by the technologies can be obtained from the grid or by alternative renewable sources. Different locations may require different means to obtain energy. Technologies must be able to adapt to the available energy meeting the production water.
Capital and operational costs	Initial investment and running costs are important for the overall sustainability of the system. Technologies can be costly to purchase and may also require special operation and maintenance procedures. For instance, membranes, pumps, anti-scalants and other kind of accessories may need to be changed or repaired often and the overall cost of a system may become inaccessible for a small-scale system.
Maintenance and operation	Technical knowledge on how to operate a technology can be an obstacle for certain populations where there is no skilled labor. However, some systems are easier to operate and maintain by training local operators. The degree of complexity is an important aspect as it can become a limitation for the use of certain system.
Sustainability	Certain technologies may have a larger life span than others. Additionally, some technologies may require continuous accessories to be replaced and in remote areas this can hardly be done frequently. Furthermore, environmental impacts can occur in the future as a result of a prolonged use of certain system. These aspects must be assessed for the sustainability of the technology.
Social acceptability	Social acceptability may vary for different technologies for reasons that must be surveyed. The willingness to use a technology can be limited as it may change habits that the community is reluctant to change.

2.4. Groundwater and hydrogeology

There are different mechanisms by which groundwater increases its salinity. Analysis of groundwater chemistry may reveal the different processes that have taken place in a specific aquifer. The following sections describe the mechanisms and how different analysis are done to study the processes occurring in the salinization.

2.4.1. Sources of dissolved solids in groundwater

Sources that increase salinity in groundwater can either occur by natural processes or by anthropogenic activities. Some of the natural mechanisms are the dissolution of soluble salt deposits, movement of saline aquifers to freshwater aquifers and saline soil leaching. Human activities include saline intrusion and agricultural/oil/gas activities (USGS, 2017).

The natural mechanisms happen spontaneously. Soluble salt dissolution occurs when gypsum or halite are in contact with groundwater. This interaction enhances ion exchange which dissolves the minerals and increases the salinity of the groundwater. These kinds of geochemical processes are considered one of the main processes of salinization (Fadili, et al., 2016).

Movement of saline aquifers and soil leaching can be natural and anthropogenic. The first one happens when more saline aquifers are able to mix with freshwater aquifers. It can happen naturally or when boreholes exist which enable mixing. Figure 2-5 shows an example of this process. As for soil leaching, agricultural activities can increase the infiltration of salts in shallow groundwater (Fadili, et al., 2016). Additionally, arid regions, may have higher evapotranspiration rates and lower precipitation rates, which concentrates salts in the soil that finally infiltrate (USGS, 2017).

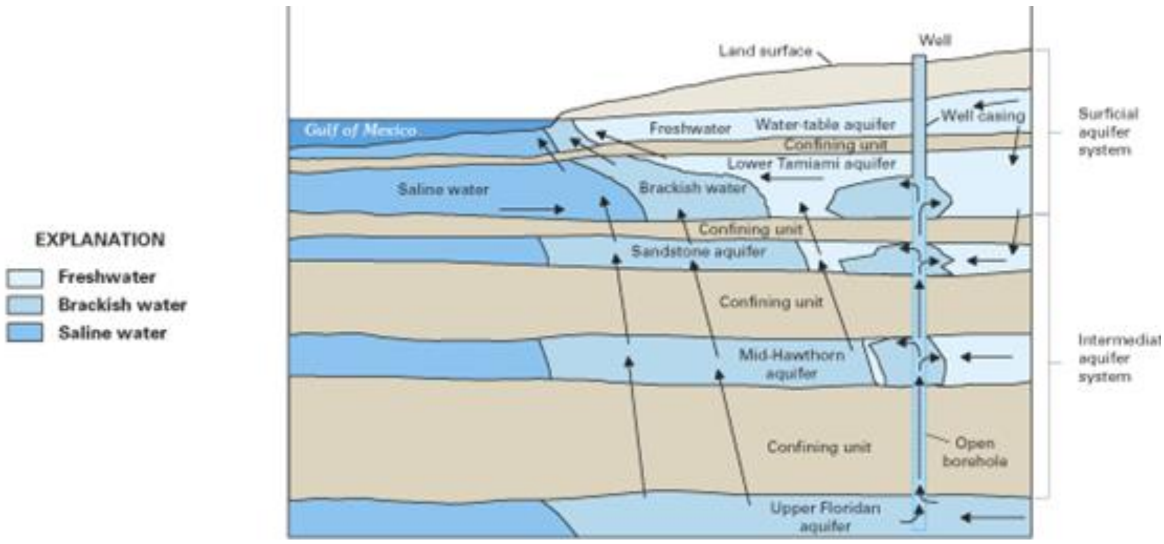


Figure 2-5 Saline water movement. Source: (USGS, 2017)

Saline intrusion is similar to movement of saline aquifers that mix with freshwater aquifers. The main difference is that seawater in contact with coast aquifers are mixed when pumping is done. Figure 2-6 presents a schematic of this process.

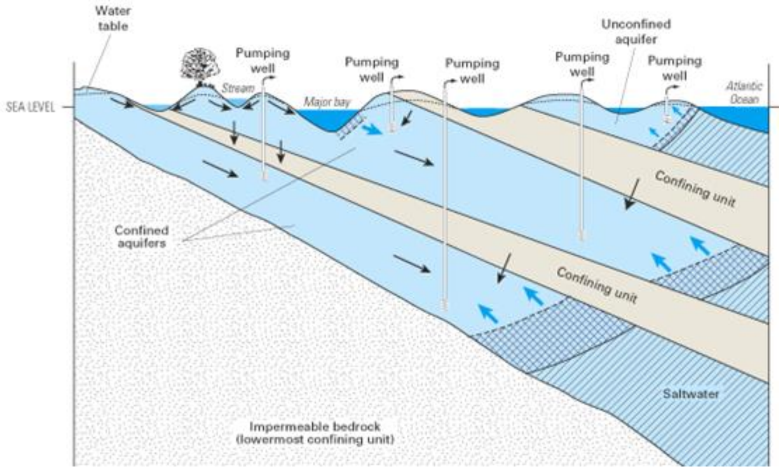


Figure 2-6 Seawater intrusion. Source: (USGS, 2017)

Finally, oil and/or gas extraction produce brines. These brines are disposed by re-injecting into the soil or by spraying in the land surface. Either way, infiltration and mixing occur with freshwater groundwater.

2.4.2. Hydrogeochemical analysis of groundwater salinization

Analysis of the chemical composition of groundwater can give an explanation to the geochemical processes occurring in the water/minerals interaction. An example of such analysis is the by Fadili, et al. (2016) in which the Moroccan coast groundwater of Oualidia was studied. In this study, by georeferencing the wells to the geological structures of the area lead to understand that proximity to seawater had effects on the salinity concentration of the aquifers and further dissolution of minerals. Furthermore, the saturation index of gypsum and halite indicated that dissolution was occurring as the concentrations were below saturation level. The hydrogeochemical analysis allowed a better understanding of the study area.

Different methodologies exist to analyse the hydrogeochemical interaction in groundwater. Common approaches include hierarchical cluster analysis (HCA), principal component analysis (PCA), and graphical tools as bivariate scatter plots, piper diagrams and saturation index analysis.

HCA is a tool that identifies an optimal grouping of different water samples based on their composition. PCA is used to reduce data size and reveal patterns of the water samples into principal components (Walter, et al., 2017). This identifies outliers and can lead to recognition of different phenomena (Powell and Lehe, 2017). Bivariate scatter plots help determine if a pattern found is correlated. For instance, fluoride occurrence in Ghana analysis by Salifu (2017) studied the inter-relationship between electrical conductivity (EC), calcium and magnesium with fluoride by means of bivariate scatter plots. Furthermore, to analyse groundwater types, piper diagrams were used and six groundwater types were recognized. Finally, saturation indexes revealed that minerals participating in the geochemical processes were anhydrite, aragonite, calcite, dolomite, fluorite, gypsum and halite. The under-saturated concentration of fluorite explained the occurrence of fluoride concentration in the wells sampled.

2.5. Case study

La Guajira is located in the northern part of Colombia. Figure 2-7 presents a map of the location of the region. It has an area of about 21,000 km^2 (Gobernacion La Guajira, 2017), its capital city is Riohacha and it can be divided into 3 regions, the southern Guajira, the central and the northern Guajira. The central and northern part of la Guajira are characterized by dryer and arid conditions than in the southern part. As a result, more agricultural activities are performed in the southern part where banana, coffee, yam and maize are produced. Rural settlements are dispersed along the region. Approximately 45 % of the people who live in La Guajira, don't live in the major urban centres. This is not convenient for centralized water supply systems nor for sewerage infrastructure or road accessibility (Bonet Morón and Wilfried Hahn de Costa, 2017).

Figure 2-7 La Guajira in the north of Colombia. Source: www.mapsofworld.com

Riohacha has a water treatment plant with a capacity of 500 L/s. It has a 46 km transmission line that connects the source to the city and a conventional surface water treatment scheme (ASAA, 2017). Manaure, the second most important city of the region, also has a water treatment plant but information of the system is not available. There is an indication, however, that it uses a desalination scheme (Bonet Morón and Wilfried Hahn de Costa, 2017) but is not clear if the source is seawater or brackish water.

La Guajira has high solar radiation intensities (approximately 5.0 to 5.5 kWh/m^2 annual average (IDEAM, 2010)) and low precipitation rates[4]. Bonet Morón and Wilfried Hahn de Costa (2017) collected information on the precipitation levels from 1972 to 2015 and found that rainfall records in the last years had decreased substantially due to El Niño (see Figure 2-8). These conditions have worsened the problem for access to water.

[4] Precipitation in the southern region is higher than in the central part and much higher than in the northern part. In Riohacha, in the central part, precipitation is about 339 mm/a, in Cabo de la Vela in the north about 328 mm/a while in Palomino, in the south, 2046 mm/a (IDEAM, 2010).

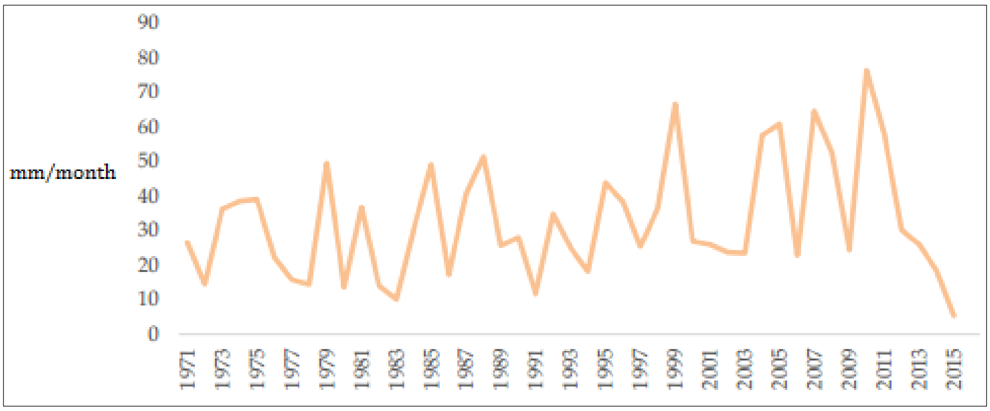


Figure 2-8 Monthly precipitation volume from 1972 to 2015

As for the geology of the region, various kinds of sedimentary, metamorphic, plutonic and volcanic structures are found. Figure 2-9 presents a map where it can be observed that the southern and northern region have more diversity of geologic structures than the central zone.

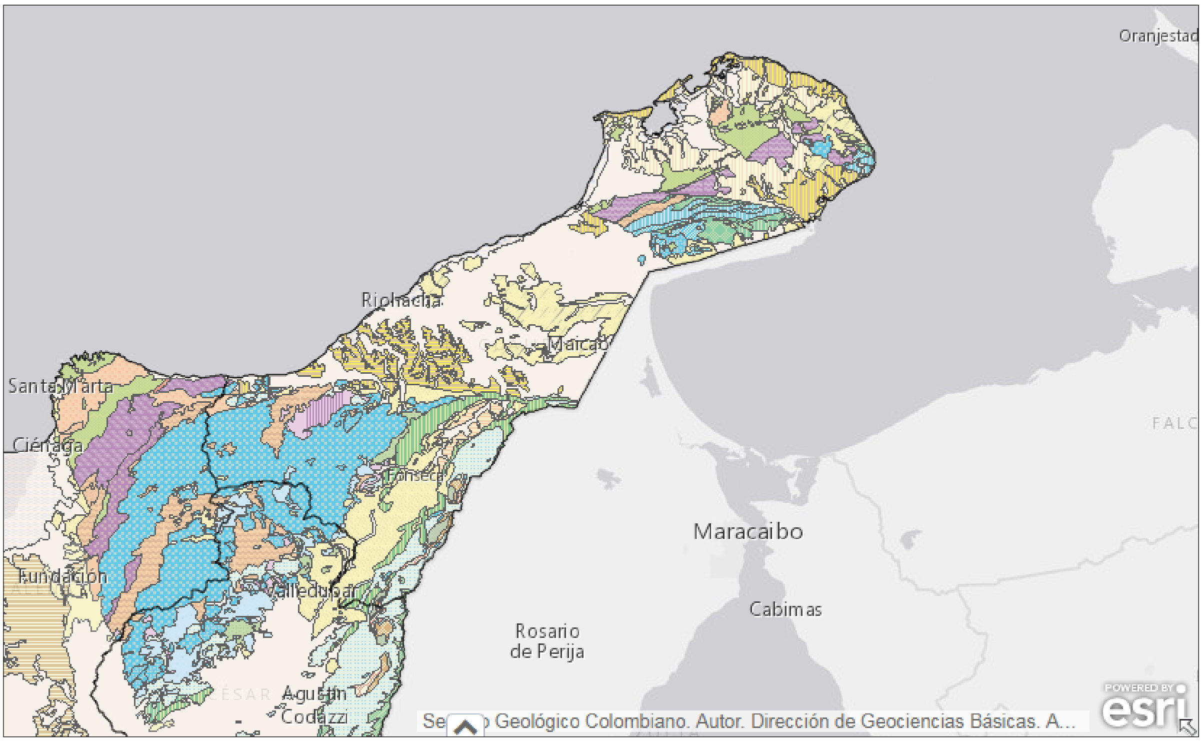


Figure 2-9 Geology of La Guajira. Source: (Servicio Geológico Colombiano, 2015)

The hydrogeological structures in the region are summarized in Table 2-5. Class A features have more content of groundwater than the class B and class C. It is important to highlight that the class A hydrogeological units are more present, occupying 54% of the territory.

Table 2-5 Description of the hydrogeological features in La Guajira

Hydrogeological units	**Hydrogeological characteristics**
	Sediments and rocks with intergranular flow
A2	Continuous aquifer systems of local and regional extension, formed by unconsolidated quaternary sediments and tertiary sedimentary rocks of fluvial and marine environments. Confined and unconfined aquifers.
A3	Continuous and discontinuous aquifers of local and regional extension with moderate productivity. Formed by unconsolidated quaternary sediments and sedimentary rocks of fluvial, glaciofluvial, marine, and volcanoclastic. Generally unconfined and confined aquifers.
A4	Discontinuous aquifer systems of local extension, with low productivity. Formed by unconsolidated quaternary sediments and sedimentary rocks of alluvial lacustrine, colluvial, eolic and marginal marine environments. Unconfined and confined aquifers.
	Rocks with flow through fractures and/or karstified.
B2	Discontinuous aquifers systems of local and regional extension, high productivity, formed by consolidated clastic sedimentary rocks, tertiary carbonated and cretacic consolidated transitional to marine environments. Confined aquifers.
B3	Continuous aquifer systems of local and regional extension, with moderate productivity. Formed by sedimentary rocks from marine and continental environments and metamorphic rocks. Unconfined and confined aquifers.
B4	Discontinuous aquifer systems of regional to local extension and low productivity. Formed by sedimentary and volcanic rocks, tertiary to paleozoic consolidated, of marine and continental environments. Generally, confined aquifers.
	Sediments and rocks with limited groundwater sources
C1	Sediments and rocks complexes, with very low productivity. Constituted by unconsolidated quaternary deposits of lacustrine, delta and marine environments, and by unconsolidated and consolidated tertiary to cretacic sedimentary rocks of marine or continental origin.
C2	Igneous-metamorphic rocks complex with very low to no productivity, very compacted and in some cases fractured, tertiary and precrambric.

CHAPTER 3

Methodology

3.1. Study area

The study area is located in the northern part of La Guajira. In this part of the region, Ancla Foundation has built schools in different settlements (see Table 3-1). Nine communities and a boarding school were visited. The wells were located with a GPS (see Appendix A). Afterwards, they were overlaid over the map of the different hydrogeological features found in La Guajira. Schools were selected in order to have distinct characteristics to further analyse the effect of geology on the groundwater salinity but also based on time and distance restrictions for the fieldwork.

Table 3-1 Schools with Ancla's sponsorship

School	Location	School	Location	School	Location
Aujero	Riohacha	Una Puchon	Riohacha	Casuchi	Manaure
Aujero II	Riohacha	Kousachon	Riohacha	Wayetakat	Manaure
Jarijinamaña	Riohacha	Jarijiñamana	Riohacha	Chubatamana	Manaure
Galilea	Riohacha	Belen	Riohacha	Villa Sara	Manaure
Las Delicias	Riohacha	Yuntamana	Manaure	Mapuain	Manaure
Cucurumana	Riohacha	Parralain	Manaure	Jocolibao	Manaure
Paraíso	Riohacha	Ishasihamana	Manaure	Mocochirramana	Manaure
Anaralito	Riohacha	Karinasirra	Manaure	Hurraichichon	Manaure
Paraver	Riohacha	Amalita	Manaure	Casiskat	Manaure
Mañature	Riohacha	Porolimana	Manaure		
Nueva Esperanza	Riohacha	Ishorshimana	Manaure		

3.2. Water sampling

Water sampling was done in the wells from the communities visited. The list of parameters that were analysed include pH, temperature, EC, total dissolved solids (TDS), Na^+, K^+, Ca^{2+}, Mg^2+, Mn^2+, Fe^{2+}, SO_4^{2-}, HCO_3^-, Cl^-, NO_3^-, NO_2^-, F^-, SiO_2, Br^-, Sr^{2+}, NH_4^+, $As^{3+ \text{ or } 5+}$ and microbiology. This required that some parameters be measured in situ and some other in the laboratory. NH_4^+ was analysed in Colombia and in IHE's laboratory.

3.3. Water demand characterization and forecast

To determine the demand of the communities, present domestic water use must be measured first. Tamason, et al. (2016) analysed 21 different studies where domestic water use measurements were performed. They recalled that the absence of standardised methods for water measurement in unmetered or low-income areas is an obstacle. However, they concluded that a combination of surveys and direct measurements increase the accuracy of the measurements. Additionally, comparing reported against measured data can contribute to find missing information or inconsistencies.

In this research, both surveys[5] and direct measurements were done. Information on other issues as health, family size, and additional data were also collected. Moreover, other uses as water use in the schools or other community shared activities was investigated.

Finally, official information from governmental institutions in the region and from the leaders of the communities was used to project population for the water demand forecast.

3.4. Water quality analysis

3.4.1. Identification of challenging water parameters.

After the quality of the sampled wells was known, an analysis of the conditions of the water sources was assessed. Identification of presence of pathogens, arsenic, fluoride, iron, etc., was used to determine the robustness, efficiency and operation of the technologies that were evaluated for the selection of a water treatment.

3.4.2. Hydrogeochemical analysis

As the number of communities was not large, no HCA or PCA was necessary. However, scatter plots and piper diagrams were used to identify the correlations and groundwater types encountered. Using GW CHART and PHREEQC piper diagrams were drawn and saturation indexes were calculated.

The results of EC were georeferenced using ArcGIS. A spatial analysis relating hydrogeological features and geologic structures was done. Additionally, the proximity of the sea as a factor influencing the salinity concentration was also studied.

Finally, by performing analysis of variance (ANOVA) and t-tests, the factors were statistically analysed with 95 % confidence lever to confirm if there was a significant effect on the water quality.

3.5. Selection of water treatment

3.5.1. Criteria definition

Using the procedure for problem definition and means-end diagrams, recommended by Enserink, et al. (2010), criteria were defined. This methodology consisted of identifying a

[5] See Appendix B to see the model of surveys for locals and leaders.

problem and the means and strategies that could be followed to solve it. Afterwards, by recognizing there can be inconvenient side-effects, “dilemmas”, one can translate them into criteria.

3.5.2. Criteria weighing

Different groups were selected to weigh the criteria identified based on their knowledge and experience. Academia, NGOs, water companies and community leaders were the actors that were surveyed for the criteria weighing.

Surveys asked the different groups to compare pairs of criteria. After having compared all the possible pairs of criteria, by normalising the matrix that resulted from these results, criteria’s weights were obtained. These procedure is based in the AHP process (see section 2.3.1). Appendix C presents the survey format and the step to step to determine the weights.

3.5.3. Performance of technologies

Once the water demand, water quality analysis and the criteria were selected, technologies that were able to treat water to acceptable parameters were selected. The performance of each technology according to the different criteria was assessed based on different articles and investigations.

3.5.4. Ranking of technologies

MCDA was used as a tool to rank the technologies that were compared. DEFINITE was used as the software to run this analysis. The information on the criteria weights and the technologies scores was uploaded to DEFINITE. Standardization and sensitivity analysis was implemented to all the groups surveyed and analysis on these results were discussed. Finally, a recommendation based on the outputs of the software was given.

3.6. Dimensioning of selected technology

After selecting the most suitable technology for water treatment, a description of the treatment scheme is done.

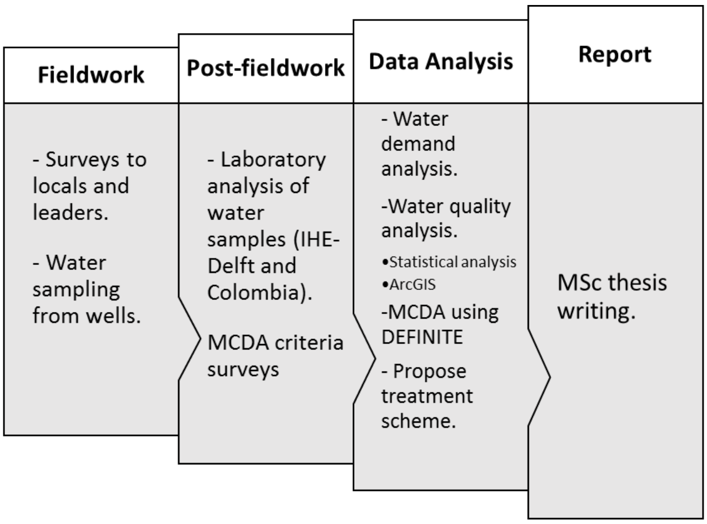


Figure 3-1 Summary of methodology

CHAPTER 4

Results and discussion

During fieldwork, nine different communities and a boarding school were visited. These communities were selected with previous authorisation of their leaders and also because accessibility was convenient. Additionally, based on the fact that during sampling, samples had to be kept cool, time between sampling and surveying had to be optimized as much as possible. The boarding school of Aremasain was chosen because during the fieldwork, it was found out that a water treatment system had been installed recently there. For this reason, it was of interest to evaluate water quality and the technology installed. The fieldwork took place on November 28th to December 3rd 2017. A brief photographic gallery is presented in Appendix P.

A total of 58 surveys were conducted among locals and 10 with community leaders, to find out the population size, water sources, water consumption, water-borne related diseases occurrence, sanitation and other related information. Water samples collected from the wells were analysed. Physical, chemical and microbiological parameters were determined for the different locations visited. The number of surveys done was dependent on time and the number of people available and willing to help with the information. It is also expected that the information and analysis drawn from these is representative of other communities.

The different sections that will follow, will be divided firstly, in the background characterisation of the different communities, where population, income and water demand will be discussed. Secondly, water quality will be analysed, discussing the presence of pathogens, toxic compounds and other relevant parameters such as total dissolved solids. Furthermore, the analysis of water quality variation will be studied. Thirdly, the selection of a water treatment technology will be analysed. Finally, based on the conclusions from the previous section, a preliminary design of the selected technology will be done.

4.1. Quantification of water demand

In this section, demographic characteristics such as income and population growth are analysed. With this information, appropriate water demand projections are estimated. Different scenarios for the projections will be considered, to have a broad picture of the possibilities in the future for the communities.

4.1.1. Population growth

The communities visited have a population size ranging from 80 to 352 inhabitants. The number of houses ranged from 12 to 64 and the number of persons living in a house ranged from a single person to up to 30. Additionally, the schools found in the communities have between 80 and 520 children, which in some cases exceeds significantly the size of the population of the community. Schools represent an important consumer of water.

According to the surveys of communities' leaders, population is very stable and there is no significant growth. However, it was also mentioned that recently, many families that had left the community have decided to return from Venezuela, which is very close to the studied region in La Guajira, due to the political issues occurring in the neighbouring country. As a result, it is probable that the size of the population in the future will increase.

Additionally, it was also seen in some communities that for certain reasons, either the size of the population, or even disagreements, the community divides into two or three different groups. Nonetheless, they would still share some goods and resources from their common territory. For instance, wells and *jaweis* would still be used together.

Table 4-1 presents the different communities' population size and number of houses. In the case of Aremasain, the number of students in the school is what is indicated by the population and the number of houses is not applicable. Furthermore, the municipality to which each community belongs to is also shown.

Table 4-1 Communities, population and number of houses

Community	Municipality	Inhabitants	Houses
Ahumao I	Riohacha	350	50
Ishasihamana	Manaure	352	34
Yuntamana	Manaure	100	12
Chojochón	Manaure	120	25
Aremasain[6]	Manaure	2000	
Aujero	Riohacha	80	17
Cucuramana	Riohacha	300	33
Guachaquero	Riohacha	160	35
Paraíso	Riohacha	100	21
Kamuchasain	Riohacha	274	64

Population growth in La Guajira has increased in the last years. According to Figure 4-1, based on the census done in 2005 by DANE (2005), the growth in the region until 2005 has been steady. Additionally, the projections done in 2005, predicted an average growth rate for La Guajira, Riohacha and Manaure, of 3.0 %, 3.7 % and 4.0 %, respectively.

The census in 2005 did not include indigenous communities but instead focused on the urban centres. However, data from the indigenous *resguardos*[7] in Manaure and Riohacha (DANE, 2017; DANE, 2009; DANE, 2012; DANE, 2018) collect population data specific for the indigenous communities. According to these records, the annual rate of growth for the communities in Riohacha is 2.6 % and for Manaure 5.3 %. Figure 4-1 shows the population behaviour during the period studied.

[6] Boarding school.

[7] Indigenous *resguardos*: It is a group of different indigenous communities that join together to make their territory autonomous.

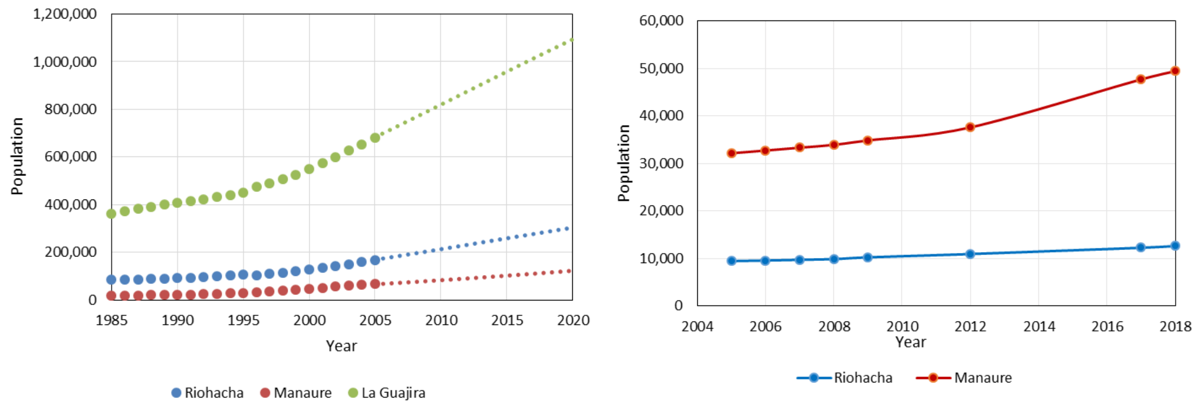


Figure 4-1 Left: urban centres population growth. Right: indigenous communities' growth

With annual growth rates obtained from the previous analysis, a projection of the communities' population for 2030 was done. The rates were used for all the communities indifferently of their original municipality or closest urban centre, as a specific growth rate is uncertain and in this way, arbitrarily choosing a rate is avoided. Table 4-2 shows the population change for the nine communities visited.

Table 4-2 Population forecast for 2030

Community	Initial Population	Annual growth rate				
		2.6%	3.0%	3.7%	4.0%	5.3%
Ahumao I	350	459	476	505	518	573
Ishasihamana	352	462	479	508	521	576
Yuntamana	100	131	136	144	148	164
Chojochón	120	157	163	173	178	196
Aujero	80	105	109	116	118	131
Cucuramana	300	394	408	433	444	491
Guachaquero	160	210	218	231	237	262
Paraíso	100	131	136	144	148	164
Kamuchasain	274	359	373	396	406	448

Three different scenarios can be considered for the future analysis of water demand. The first scenario is the one with the lowest annual growth rate, 2.6 % (Scenario I). The second scenario is the moderate growth rate of 4.0 % (Scenario II). The third scenario is the one with the highest rate of 5.3 % (Scenario III). The distance between these rates is approximately the same, which allows water demand projections to give a range that includes the highest, the lowest and the moderate growth.

4.1.2. Income

In the communities, the surveys made to the households also asked for their income and what they considered they would contribute for a water system. In some cases, the income question was not answered, as there is jealousy between the members of the community regarding this. However, with the collected information an average income was determined for each community. Some communities have a higher income than others, as it is the case of Aujero.

However, some data is rather high as the people who answered the income question were teachers in the schools, which means that they are better paid and have a “regular” salary. On the other hand, some persons were fishermen or artisans that don’t have fixed incomes and depend on demand and other variables.

It is important to note that most of these incomes are below Colombian minimum wage, $780,000 COP, which is equivalent to approximately €220 per month. This reflects the low acquisitive power they have and that money not spent on their daily needs represents an obstacle. Table 4- 3 shows that the percentage of what they would contribute to the water system ranges from 0.5 % to 6.7 %, which is around €1.3 to €4.2 per month per household.

According to the global affordability index, from 4 % to 12 % of the income spent on water is common for developing countries and between 2 % to 3.5 % in developed countries (Smets, 2008). However, in this case, the percentage doesn’t include for this context in La Guajira the fact that their income is below the minimum wage even 10 times lower.

Table 4-3 Average income and willingness to pay for water

	Income COP/month	Willingness to pay COP/month	Income €/month	Willingness to pay €/month	Percentage (%)
Ahumao I	374,000	9,400	107	2.7	2.5
Ishasihamana	875,000	14,500	250	4.2	1.7
Yuntamana	460,000	10,000	132	2.9	2.2
Chojochón	100,000	6,700	29	1.9	6.7
Aujero	1,576,000	14,600	450	4.2	0.9
Cucuramana	700,000	9,250	200	2.6	1.3
Guachaquero	573,000	7,500	164	2.2	1.3
Paraíso	837,000	8,875	240	2.5	1.1
Kamuchasain	1,108,000	4,600	317	1.3	0.4

Note: Willingness to pay is per household.

4.1.3. Water demand

Water demand was categorized into domestic, agricultural and public use. Domestic consumption includes water used for drinking, cooking, personal hygiene and house cleaning. Agricultural uses include water used for goats and crops. Finally, public uses of water are attributed to schools.

From the information collected in the surveys it was possible to derive the demands of each of the categories. The way it was calculated was, first, calculating the joint demand of drinking and cooking. All households that only reported these uses were used to find the average. This demand was found to be 10.5 lpcd (litre per capita per day). Afterwards, households that reported all the domestic consumptions were averaged and subtracted the previous joint drinking and cooking demands. The result for personal hygiene and house cleaning was 6.9 lpcd.

For the agricultural category, certain relationships were considered. Regarding goats’ water consumption, an approximation of the number of goats per person was estimated. In this case, for every 4 persons there is one goat. Additionally, the water consumption of a goat was compared to one study carried in the north of Nigeria where similar arid conditions are found. This study in the Sahel Savannah, stated that goats consume 1,364 mL/day (Aganga, 1992).

Crops' water requirements depend on factors related to climatic conditions and the kind of crop. However, a specific and detailed calculation for every kind of crop is out of the scope of the research. Instead, approximation on water requirements were used. For instance, maize, beans, yam, watermelon, were reported to be cultivated. However, for a matter of simplicity, maize crops were the only ones considered[8]. A period of 110 days is usually what maize takes to grow, which in turn means that three times a year, maximum, maize could be grown. In fact, more than 2 crops a year is very difficult for this region. Additionally, about 500 to 800 mm/period of water is required for maize crops (Critchley, et al., 1991). In Colombia, there are between 0.11 to 0.25 hectares per person (Global Croplands, 2017). This estimation, however, is too high for the specific region of La Guajira. In turn, a community has approximately 1 hectare of crops, which is equal to 0.005 hectares per person, on average. As a result, considering the water requirements, the number of crops per year and the area, it was found that agriculture has a demand of 219 lpcd.

Finally, schools' consumption is calculated based on the boarding school of Aremasain. There, a treatment plant provides about 2,000 L/day for 1,300 students. Therefore, about 1.5 L/student/day are consumed. The number of students per school varies in the communities. However, the biggest difference is about 6.5 times the population of the community. So the demand associated to schools is about 9.8 lpcd.

The total average water demand for a community is 247 lpcd. Domestic demand is 7 % of the total demand, agriculture is 89 % and schools are 4 %. Table 4-4 presents all data mentioned before.

Table 4-4 Water demand per categories

Category	Sub-category	Demand (lpcd)
Domestic	Drinking Cooking	10.5
	House cleaning Personal Hygiene	6.9
Agricultural	Goats	0.4
	Crops	219
Public	Schools	9.8

4.1.4. Water demand forecast

Water demand and water treatment capacities were also projected until the year 2030. Three different cases were considered:

A. Water demand will not increase: In this consideration it means that 27.5 lpcd will be needed for domestic demand and schools. Agriculture is not included in this projection because if a water treatment is implemented, due to the context of the communities, water will not be treated for agricultural purposes as the demand would be very high.

[8] C*hicha,* which is a fermented beverage made out of maize, is much related to the Wayuu customs. Other reported crops sometimes were not successful.

B. Water demand increases: Considering the fact that if a water treatment system is installed, there is a probability that water demand increased due to the ease of access to water. In this consideration, agricultural demands are not included for the same reasons as in A.
C. Climate change and the need for water in agriculture: In order to consider a worst case situation, if water becomes less accessible for goats and crops, water might be needed to be treated in order to satisfy this demand. This situation supposes all demands are included for the water capacity forecast and also, the highest growth rate (Scenario III).

For case A and B two additional considerations are assumed. Based on the observations in the fieldwork, house cleaning and personal hygiene sometimes use different sources of water, which are sometimes not appropriate. This consideration is also taken into account by only including only a 75 % for A (A.1) and 65 % for B (B.1) of the water demand.

Table 4-5 and 4-6 summarize the results.

Table 4-5 Water capacity projections projection for case A and B

A: 27.5 lpcd				**B: 40 lpcd**			
Capacity of treatment system (m^3/day)				***Capacity of treatment system (m^3/day)***			
	Scenario I	Scenario II	Scenario III		Scenario I	Scenario II	Scenario III
Ahumao I	12.1	13.5	14.7	Ahumao I	17.6	19.6	21.4
Ishasihamana	12.2	13.6	14.8	Ishasihamana	17.7	19.7	21.5
Yuntamana	3.5	3.9	4.2	Yuntamana	5.0	5.6	6.1
Chojochón	4.2	4.6	5.0	Chojochón	6.0	6.7	7.3
Aujero	2.8	3.1	3.4	Aujero	4.0	4.5	4.9
Cucuramana	10.4	11.6	12.6	Cucuramana	15.1	16.8	18.4
Guachaquero	5.5	6.2	6.7	Guachaquero	8.1	9.0	9.8
Paraíso	3.5	3.9	4.2	Paraíso	5.0	5.6	6.1
Kamuchasain	9.5	10.5	11.5	Kamuchasain	13.8	15.3	16.8
A.1: 75% of 27.5 lpcd				**B.1: 65% of 40 lpcd**			
Capacity of treatment system (m^3/day)				***Capacity of treatment system (m^3/day)***			
	Scenario I	Scenario II	Scenario III		Scenario I	Scenario II	Scenario III
Ahumao I	9.1	10.1	11.0	Ahumao I	11.1	12.3	13.5
Ishasihamana	9.1	10.2	11.1	Ishasihamana	11.2	12.4	13.6
Yuntamana	2.6	2.9	3.2	Yuntamana	3.2	3.5	3.9
Chojochón	3.1	3.5	3.8	Chojochón	3.8	4.2	4.6
Aujero	2.1	2.3	2.5	Aujero	2.5	2.8	3.1
Cucuramana	7.8	8.7	9.5	Cucuramana	9.5	10.6	11.6
Guachaquero	4.2	4.6	5.0	Guachaquero	5.1	5.6	6.2
Paraíso	2.6	2.9	3.2	Paraíso	3.2	3.5	3.9
Kamuchasain	7.1	7.9	8.6	Kamuchasain	8.7	9.7	10.6

The range of capacities projected for case A, range from 2.8 m^3/day to 12.2 m^3/day for the most conservative growth and demand. In the highest growth, the range is between 3.4 m^3/day and 14.8 m^3/day. If 75% of the capacity is considered, case A.1, the ranges are 2.1 – 9.1 m3/day and 2.5 - 11.1 m^3/day for the conservative and highest growth scenario. For Case B, the conservative scenario ranges from 4 – 17.7 m^3/day and for the highest growth between 4.9 – 21.5 m^3/day. Case B.1, which corresponds to 65% of the demand, ranges from 2.5 – 11.2 m^3/day for the conservative scenario and for the highest growth 3.1 – 13.6 m^3/day.

Case B.1 results are very close to Case A. Case A.1 has the lowest values which are most likely not be very accurate for predictions. Case B has the highest values and considers feasible assumptions.

Table 4-6 Case C: Agriculture demand included

C: 260 lpcd	
Capacity of treatment system (m^3/day)	
Ahumao I	149
Ishasihamana	150
Yuntamana	43
Chojochón	51
Aujero	34
Cucuramana	128
Guachaquero	68
Paraíso	43
Kamuchasain	117

On the other hand, Case C is extremist. The capacities in this projection exceed almost by 7 times the forecast of Case B. Although the assumptions in this projection are also feasible, it reveals that the size of a treatment plant that includes agricultural activities, for some communities can correspond to large urban water treatment systems.

The population growth in Scenario III combined with the demand increase in the future of Case B, gives a range of water treatment capacities that should be installed in the communities. As the goal of the project is that the technology selected can be installed in the different communities and that it can be scaled to higher or lower capacities when needed, this scenario and assumption establish the base for the further evaluation of technologies available in section 4.3.

Chapter 4.1 Recap

Population:

The population in the different communities in La Guajira is expected to grow. Additionally, schools are a considerable floating population that must be considered for an appropriate and sufficient water supply.

Projections for 2030:

- *Scenario 1 has a population ranging from 105 to 462 inhabitants. Average is 268.*
- *Scenario 2 has a population ranging from 118 to 521 inhabitants. Average is 302.*
- *Scenario 3 has a population ranging from 131 to 576 inhabitants. Average is 334.*

Income:

The acquisitive power of the communities is very low. Their income ranges from €28 to 450€ per month, which for 5 out the 9 communities is below Colombian minimum wage (€220).

Their contribution to water systems ranged between €1.3 to €4.2 per month per household. This presents a challenge to avoid costly water systems for the selection.

Water demand:

From the surveys it was calculated that water demand is 247 lpcd. 7 % corresponds to domestic demand and 4 % to schools and the rest, 89 % for agriculture.

Water demand forecast:

The most likely situation in the future is that water demand increases for domestic and uses in case a water treatment is installed. The range of water capacities that will be considered for design are between 5 – 21.5 m^3/day. These values are obtained by combining Scenario III and Case B analysed in *section 4.1.4*.

4.2. Water quality analysis

This section introduces the water sources that were observed during the fieldwork. Additionally, it analyses the quality of each source and focuses on the wells. These were sampled for every community visited. Finally, based on the results obtained, statistical analysis of the region water quality is done using ArcGIS.

4.2.1. Water sources

Different sources of water were found in the communities that were visited. Wells, *jaweis*, water tankers, and water bidons, bags and bottles, are the common sources reported by the surveys.

All wells have windmills to pump water out, taking advantage of the eolic potential of La Guajira. Depth of the wells varied from 30 m to almost 200 m. However, uncertainty regarding depth was common. The main cause for the depth variance is the salty taste of water according to leaders' statements. There was no evidence of previous studies to know the relationship of water quality and depth. Furthermore, it seemed as if wells were dug to depths that were not defined before the excavation. For instance, in Ahumao I, during the fieldwork, a well was being dug and workers said they were already 200 m deep and still had not found freshwater, so they would continue digging.

Most of the times there were elevated tanks to store water but in most cases, leaders informed that they don't make use of them. Apparently they don't like storing water in the tanks because it seems that the aggressive characteristic of water has damaged the tanks. Additionally, they said that they would rather pump water out only when needed. The municipality does not have control on the operation of water extracted from the wells.

Artisan wells were also mentioned by some community leaders. These kind of wells are shallow and located near river beds. They only have water during rainy seasons or a couple months past it.

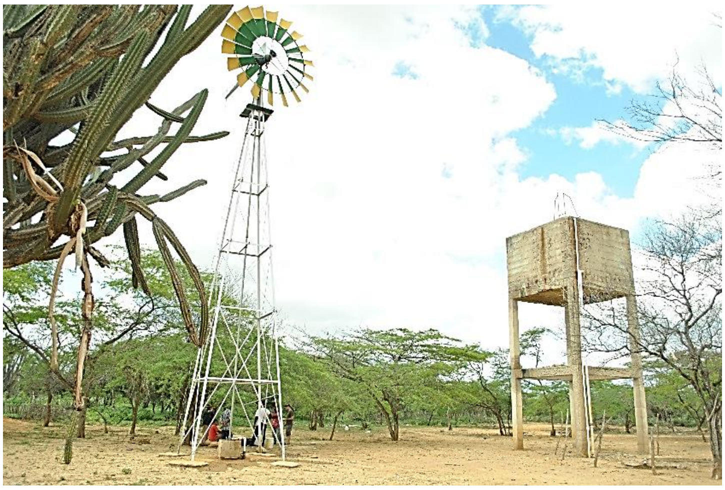


Figure 4-2 Well and elevated tank in Yuntamana

Jaweis are big excavations that the Wayuu have used to collect rainwater during wet seasons. They are used by the people in the community but no protection from animals going into the jawei is installed. Goats drink water from this source and other animals, such as dogs, go in it as well. The expected water quality from jaweis is therefore not adequate and it poses a potential risk to human health because of its contamination.

Figure 4-3 Example of jawei in Ahumao I

Water tankers are also one of the means the communities have to get water. The municipality offers this service but on an irregular basis. Therefore, communities are forced to collect money and pay a private company to send a truck. The price is around $150,000 COP, which is equivalent to approximately €50[9], for 10,000 L. Leaders stated that this amount of water usually lasts one or two days. Compared to the demands calculated in the previous section, if the average population size is 200 inhabitants, approximately 25 litres per person per day were consumed (in section 4.1.4, water demand for the water capacity forecast is increased to 40 lpcd).

Triple A, the water utility in Manaure, has authorized the use of the lines some communities illegally connected to their main line, which comes from Casa Azul. This is brackish water. Additionally, some communities have also connected a hose that is laid around the houses where they can get brackish water from another line.

Finally, those communities that are located closer to urban centres such as Manaure and Riohacha, buy water bottles and bags for their personal use. The cost of 20 L of water is approximately $3,500 COP, approximately €1. However, not all members of the community can afford this expense to fulfil their water needs on a daily basis.

The available quantity of water from the wells doesn’t seem to be a problem. All wells need wind to be able to pump water and there is constantly a continuous wind in La Guajira. Artisan wells depend on the wet seasons. Jaweis, can be big and hold large volumes. However, they are only available after rainy seasons. Water tankers can only offer up to 10,000 L and even if municipalities offer them for free to the communities, they are not regularly distributed. Water tankers, as well as water bottles, bidons and bags, to which communities have to resort to, are expected to have a proper water quality for human consumption.

[9] From section 4.1.2 it was found that the amount of money for willingness to contribute was around €2.7 per household, which is approximately what they collect for the water tanker.

4.2.2. Water sources reported uses

The sources and the overall use for the different communities is presented in Table 4-7.

Table 4-7 Communities' water sources overall reported use

Community	Jaweis	Artisan Well	Well	Brackish Water Line	Water Tanker	Water Bidon/Bags	Casa Azul
Ahumao I	50%				50%		
Ishasihamana[10]	✓		✓	✓	✓	✓	
Yuntamana[8]	✓	✓	✓	✓		✓	
Chojochón	44%	3%		41%			12%
Aujero			68%		14%	18%	
Cucuramana			95%			5%	
Guachaquero			100%				
Paraíso	9%		69%			22%	
Kamuchasain	30%		60%			10%	

The specific amount of water obtained from the sources is not known. However, the water source for the different uses was mentioned. In Table 4-8, a deeper look on the use according to source is done for all the communities together. The focus is specifically for domestic consumption as for agriculture jaweis was the source used. For detailed information of the communities see Appendix D.

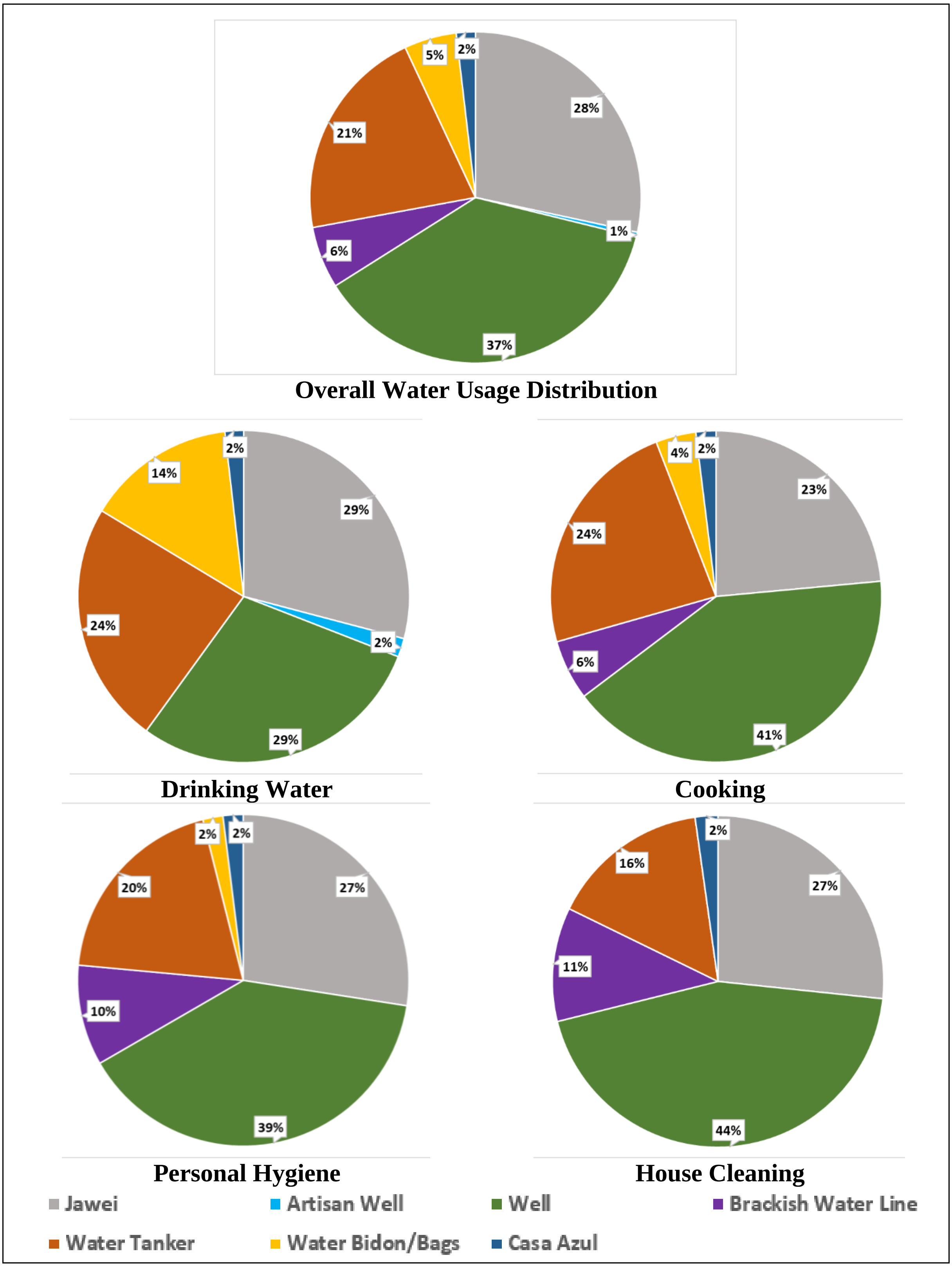
Globally, it was observed that the overall situation reflects a higher use for well water (37 %) followed by jaweis (28 %) and water tankers (21 %). Specific use of the different categories reflect the following:

- drinking water most reported source are wells (29 %) and jaweis (29 %) followed by water tankers (24 %);
- water used for cooking behaves similarly with wells being the most used (41 %), followed by water tankers (24 %) and jaweis (23 %);
- personal hygiene similarly has a distribution of wells (39 %), jaweis (27 %) and water tanker (20 %);
- house cleaning wells (44 %), jawei (27 %) and water tanker (16 %) ; and
- goats and crops, according to leaders' statements, use water from jaweis and rain, respectively.

It is very concerning to find that Jaweis, which water quality is expected to be very low, is still highly used for cooking and drinking purposes. This behaviour poses enormous health risks to the vulnerable members of the communities as new-borns, children and the elderly.

[10] These communities did not report specifically source-use in the surveys. Therefore, the exact information is not available. However, ticks indicate the presence of a specific source.

Table 4-8 Water use according to source



4.2.3. Water quality

Samples from the water coming from the wells were collected. Water from the jaweis were not sampled as the main focus were the wells. However, a water sample from the jawei in Ahumao I was grown on an agar plate. The results were as expected. A massive growth of coliform bacteria was seen in the plate (Figure 4-4). Contrarily, water from the wells have a detailed ion composition that is shown in Table 4-9.

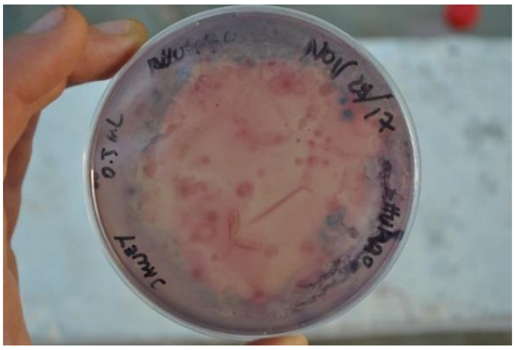


Figure 4-4 Jawei microbiologic growth on plate

No toxic compounds as arsenic were found and no indications of diseases caused by arsenic were observed during the fieldwork. Fluoride concentration was always less than 1.5 mg/L, which complies with WHO guidelines (WHO, 2011) and Colombian water laws (Resolution 2115 of 2007) (MinSalud and MinAmbiente, 2007). On the other hand, coliform bacteria were present in different concentration in the different communities. Finally, there was a significant variation of EC, between 1,000 μS/cm to 7,500 μS/cm, with very elevated values that correspond to brackish water in some communities.

It was observed during the fieldwork that goats usually water from jaweis. According to Ayers and Westcot (1985), water quality between 1,500 μS/cm to 5,000 μS/cm is tolerable by goats as they get used to the salinity. Between 5,000 μS/cm to 8,000 μS/cm, goats may experience diarrhoea while they get used to that kind of water. On the contrary, for crops, salinity is a concern. The accumulation of salts in the roots zones makes crops less productive and deteriorates the soil properties (Ayers and Westcot, 1985). As seen in the fieldwork and reported in many surveys, the frustration by poor crops is common.

It is also worth noting that the collection of water from all sources is done using containers. The volume of storage tanks ranged from 20 L to 100 L. Further analysis on water quality during and after storage was not considered in this research's scope but should be studied in the future.

Figure 4-5 Water storage containers

4.2.4. Coliform contamination

From Table 4-9 it is important to note that the level of contamination associated to coliforms is concerning. However, direct sampling from the wells was not always possible during sampling. For this reason, the pipe connecting the well to the tank was followed and water was sampled before it was in contact with the water in the storage tank. Although water quality from tanks was not measured, it was not expected to be good as in some cases frogs, leaves and plastic bags were found inside the tank. Additionally, the possibility of biofilms being present in the pipe connecting the well to the tank probably caused the high readings of coliforms, given that the intermittent use of windmills can aid the formation of these in the inner walls of the pvc pipes.

Phosphate[11] and ammonium concentrations, Table 4-9, are not high for the coliform contamination readings obtained. This might be an indication that an external factor, probably the hygienic conditions of the storage tank, are influencing on the water quality after water is drawn from the well.

It is recommended that appropriate measures on the storage tank hygienic conditions are taken. For instance, a better isolation to prevent animals or leaves coming in contact with the water stored in the tank. Additionally, given the high concentration of coliforms, it is very important that the community should be disinfecting the water before consumption using chlorine tablets or other disinfection methods.

[11] The limit of detection of this compound was 0.09 mg/L in the IHE laboratory facility.

Table 4-9 Water physical and chemical properties

Parameter	Unit	Ishasihamana	Yuntamana	Chojochón	Aremasain	Aujero	Cucurumaná	Guachaquero	Paraíso	Kamuchasaín
Temp	°C	32.3	32.8	31.5	32.1	31.8	32.3	30.5	29.6	31.5
pH		8.06	7.62	7.86	7.95	8.23	7.27	8.28	7.67	7.86
DO	mg/L O_2	6.1	1.4	3.8	1.6	5	1.02	5.23	1.57	1.96
EC	ms/cm	6.53	6.02	7.69	2.61	1.825	1.159	0.91	1.08	2.76
TDS from EC[12]	mg/L	3918	3612	4614	1566	1095	695	546	648	1656
TDS	mg/L	3885	3667	4558	1557	1095	984	794	865	1627
Na^+	mg/L	1326	1258	1508	526	356	214	207	211	470
K^+	mg/L	15	13	18	5	8	<3	<3	<3	6
Ca^{2+}	mg/L	57	36	82	38	29	47	18	26	95
Mg^{2+}	mg/L	62	43	85	14	17	23	13	20	39
Mn^{2+}	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	<0.1	0.2
Fe^{2+}	mg/L	<0.2	0.24	<0.2	<0.2	<0.2	<0.2	<0.2	0.27	<0.2
Sr^{2+}	mg/L	2.7	1.8	3.2	1.5	1.9	0.6	0.4	0.8	3
Cl^-	mg/L	1985	1720	2312	678	424	79	51	55	709
SO_4^{2-}	mg/L	6	6	109	41	62	87	54	73	183
NO_3^-	mg/L	1	1.5	0.7	0.6	0.6	0.9	0.4	0.3	0.4
PO_4^{3-}	mg/L	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
HCO_3^-	mg/L	405	561	413	237	179	500	423	451	103
F^-	mg/L	0.2	<0.2	<0.2	<0.2	0.2	0.8	0.7	0.4	<0.2
Br^-	mg/L	8.6	7.2	9.4	1.8	1.0	0.3	0.1	0.2	1.7
SiO_2	mg/L	17	19	17	14	16	30	26	27	16
NH_4^+ IHE	mg/L NH3-N	1.2	2.1	2.3	0.7	0.8	0.1	0.01	0.02	0.6
NH4+ Colombia[13]	mg/L NH3-N	<0.054	<0.054	<0.054	<0.054	<0.054	0.069	<0.054	<0.054	<0.054
Coliform bacteria	CFU/100mL	160	170	420	80	90	100	370	540	260
Tot. Hardness	mmol/L	3.98	2.65	5.54	1.52	1.42	2.13	0.98	1.48	3.99

[12] TDS=0.6*EC was used as an approximation. Other estimations use from 60 to 65 %. Source: https://www.lenntech.com/

[13] See Appendix E to find the report from the laboratory in Colombia, AMBIUS.

4.2.5. Water quality variation in the region

The notorious variation of EC found in the communities presented the need to analyse the degree of salinity variation in the region. The reason to establish this pattern and understand its cause is because for the water treatment selection, and future expansion of schools in the region, requires a thorough analysis of the possible worst cases and the limits to which the technology must be able to cope with.

A well inventory and a map containing the spatial location and extent of the different hydrogeological features in La Guajira was obtained from the Geological Colombian Service; SGC in Spanish (Servicio Geológico Colombiano, 2018). In the inventory, properties such as pH, water temperature, electroconductivity and coordinates, among other parameters, were reported. Using ArcGIS, the inventory of wells and the hydrogeological features were analysed spatially.

4.2.6. Spatial characteristics in the region

The expected groundwater salinity is expected to vary according to three different factors, namely, proximity to sea, hydrogeological features and depth. Statistical analyses were performed to assess the influences of the first two factors as the last one misses information.

The first step was building a contour map of the distance from the sea and overlay it on the hydrogeological layer. A map called Hydrogeological features in La Guajira, Colombia (Appendix F) presents this first step. It can be observed in Table 4-10 that there is a predominance of the class A hydrogeological features (56.6 % of the area) over the other classes. Also, the spatial location of the features are distributed geographically with the class C in the south, class A predominantly in the middle part of the region and class B in the northern section with certain portions in the south.

Distance from the sea is influenced by the coast in the western part of La Guajira and the eastern coast in Venezuela. In the northern part of the region, the maximum distance was around 35km. In the middle part of the region the distance reached 45 km. The southern section, the maximum distance was around 95 km.

Table 4-10 Area coverage per hydrogeological feature

Hydrogeological feature	Percentage of area in La Guajira
A2	7.6%
A3	16.4%
A4	32.6%
B2	1.4%
B3	0.4%
B4	19.2%
C1	1.9%
C2	20.5%

4.2.7. Salinity and the proximity to the sea

To begin with, for the proximity of the wells to the sea, it was expected that at closer distances salinity would be higher. Figure 4-6 presents a bivariate scatter plot of the wells' conductivity and the distance from the sea. At first glance, the shorter the distance between the well and the sea, the higher the conductivity measurement. However, a linear correlation factor for this plot is 0.09, which is not enough to conclude anything about the influence of the distance with the water salinity.

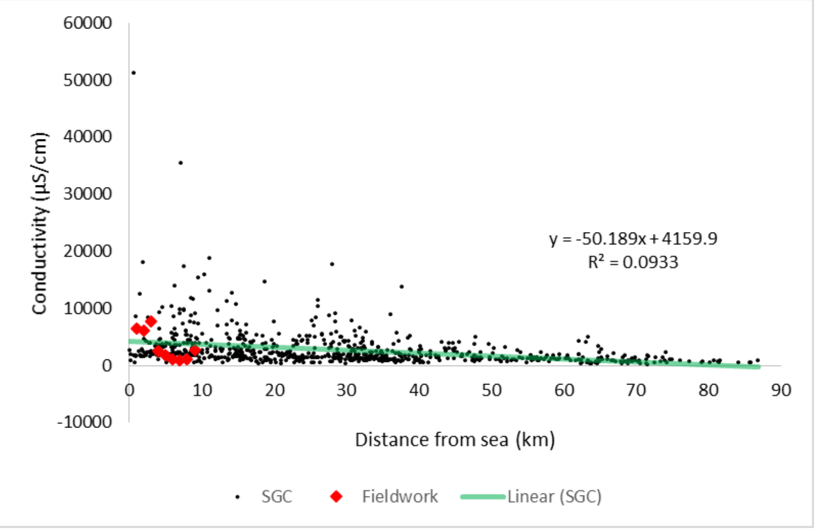


Figure 4-6 Conductivity vs. distance from the sea

To determine if there is such trend, an analysis of variance (ANOVA) was conducted. The test was performed by analysing deep wells and shallow wells combined and individually[14]. Wells were grouped according to their distance, with a 10 km range per group.

The results of the ANOVA for the different groupings are presented in Appendix G. With a 95 % confidence level, there was a significant difference of the salinity according to the distance for all the different groups. Additionally, it was observed that the salinity, measured as electrical conductivity, decreased as the distance to the sea increased.

Figure 4-7 presents box plots of the data distribution that was analysed with the ANOVA test. It can be seen in all cases that the average value of electrical conductivity decreases. It is worth to mention the odd behaviour found in the 40-50 km range, in all the different groupings. There is a slight increase in the measurements of salinity, which is not what it was expected. However, this can probably be happening due to the effects of the hydrogeological features, which will be discussed in the following section.

Finally, a comparison between the deep and shallow wells box plots in Figure 4-7, shows that values for electrical conductivity found in the latter tend to vary more, in spite of the trend of decreasing salinity. This is an indication that there may be a more pronounced influence of the superficial waters, for instance rain or unmanaged wastewaters that can influence the groundwater quality.

[14] A distinction between deep wells and shallow wells is done in the inventory by the different names in Spanish. Wells is "pozos" and shallow wells are "aljibes".

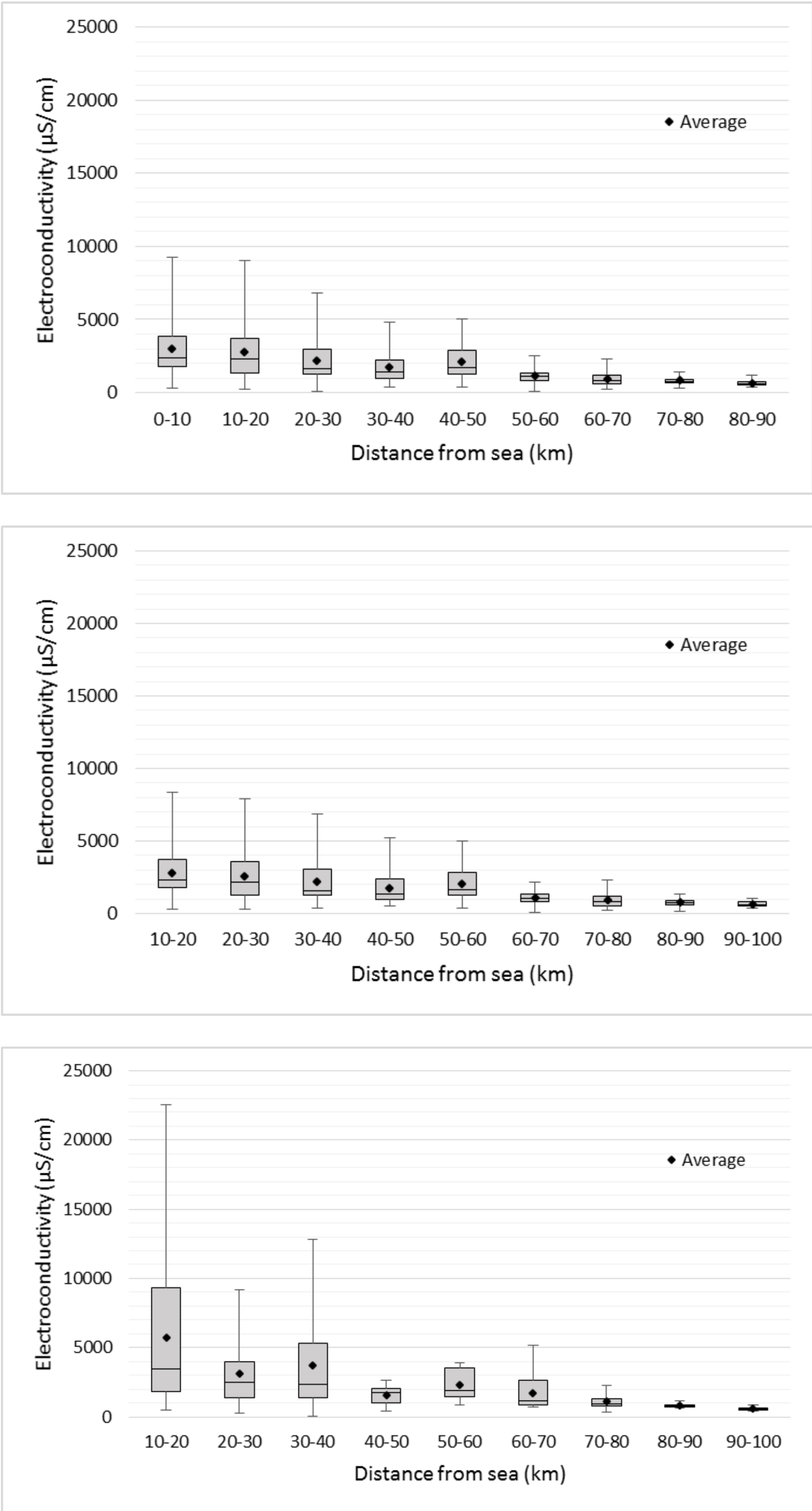


Figure 4-7 Box plots for the analysis of proximity to sea and salinity. Top: deep and shallow wells. Middle: deep wells. Bottom: shallow wells

4.2.8. Salinity and hydrogeology

For the hydrogeological features, a similar procedure was done as for the proximity to the sea analysis. The same groups, combined deep and shallow wells and individual analysis were used.

Before the ANOVA was done, the inventory of wells was geo-processed in ArcGIS so that every well was assigned its related hydrogeological feature, depending on its spatial location. Once this was finished, the groups were analysed. In Appendix H and I, all the ANOVA, the f-tests and t-tests are shown.

In all cases, with a 95 % confidence level, there was a significant difference between the hydrogeological features. However, the analysis was only done between the class A features as for class B and C, the number of wells were less than 17, compared to class A that ranged between 31 up to 719 wells.

The ANOVA results were complemented with t-Test in order to find the significant difference between the features and to know the order of salinity concentration regarding the class. A previous analysis of the variance difference was done in order to choose the correct t-Test. A summary of the results is shown in Table 4-11.

Table 4-11 Summary of t-Test for hydrogeological features

Combined deep wells and shallow wells	A2 and A3	Not significant
	A2 and A4	Significant: A4>A2
	A3 and A4	Significant: A4>A3
Deep wells	A2 and A3	Significant: A3>A2
	A2 and A4	Significant: A4>A2
	A3 and A4	Significant: A4>A3
Shallow wells	A2 and A3	Significant: A2>A3
	A2 and A4	Significant: A2>A4
	A3 and A4	Not significant

The results show an interesting and contradicting behaviour. The combined group analysis elucidates that A4 wells have higher measurements for EC. This behaviour is the same for the deep wells, where A4>A3>A2. However, the opposite occurs in the analysis of shallow wells, where A2>A3 and A2>A4.

Similar to the results in the analysis of the proximity of the sea, shallow wells tend to vary from the results of deep wells. This is an indication that probably, the effects of infiltration to the first layers of the soil have a direct consequence in the groundwater quality. As a result, the effect hydrogeological features have in the groundwater salinity cannot be concluded from these statistic results. Figure 4-8, presents box plots of this analysis and visually evidences what was obtained from the t-Tests.

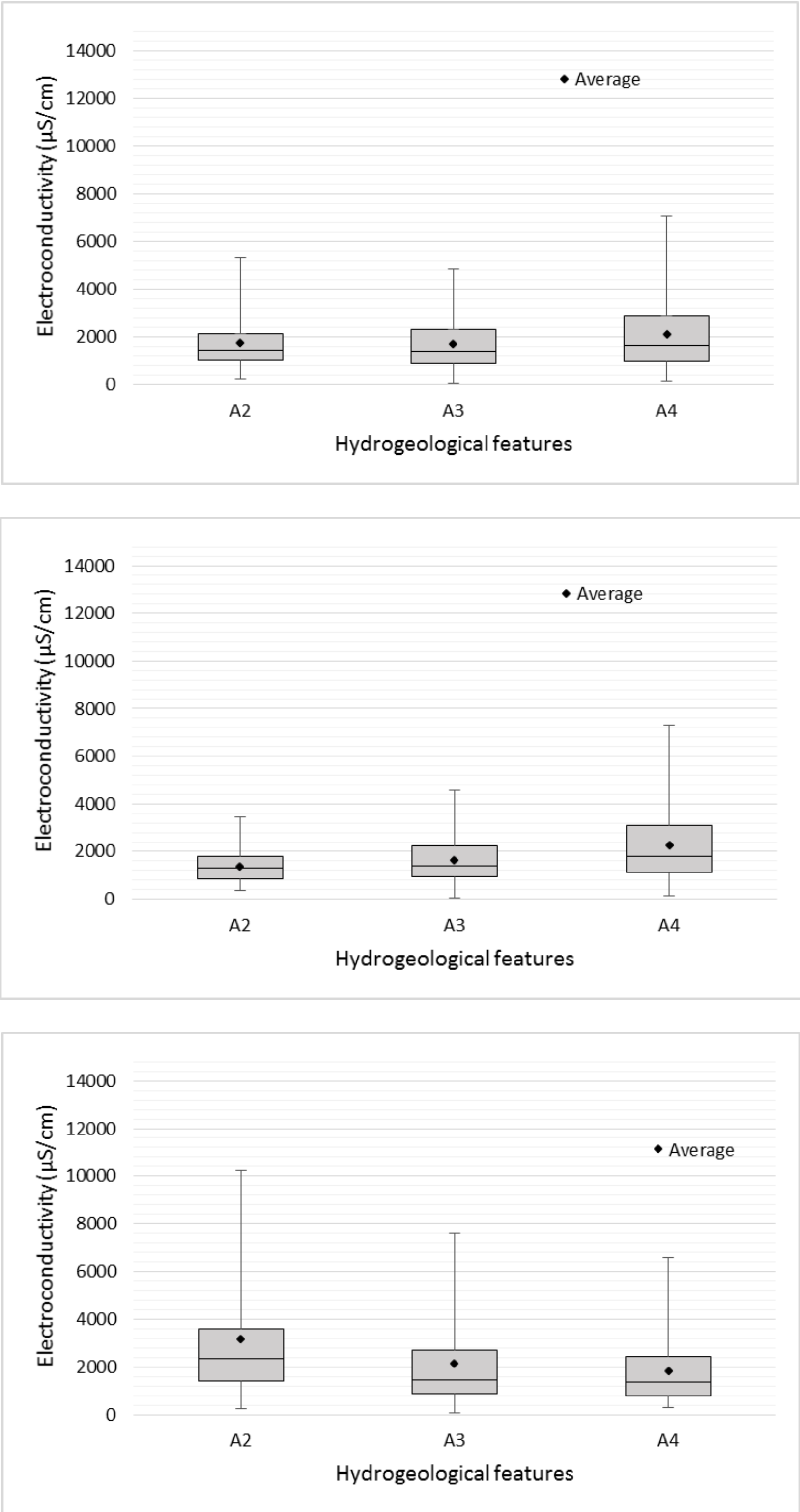


Figure 4-8 Box plots for the analysis of hydrogeological features and salinity. Top: deep and shallow wells. Middle: deep wells. Bottom: shallow wells

4.2.9. Fieldwork wells analysis

The groundwater samples collected during the fieldwork were analysed further to find evidences to solve the uncertainty of the previous analysis regarding the hydrogeological features. After assigning the hydrogeological feature and the distance from the sea to the different sampling points in ArcGIS, an analysis regarding these two factors was done. Table 4- 12 displays the data obtained.

Table 4-12 Data from sampled groundwater during fieldwork

	Conductivity (µS/cm)	Hydrogeological class	Distance from sea* (km)	Depth (m)
Chojochón	7690	A4	7.60	*
Ishasihamana	6530	A4	5.04	72
Yuntamana	6020	A4	5.34	150
Kamuchasain	2760	A3	8.98	*
Aremasain	2610	A4	17.60	20
Aujero	1825	A2	5.75	*
Cucurumaná	1159	A4	11.98	200
Paraiso	1080	A2	15.68	*
Guachaquero	910	A2	16.85	*

*Note: This distance was calculated using ArcGIS.

The distance ranged from 5.04 km to 17.6 km. According to the analysis of the SGC inventory, it should be expected that the closer to the sea the higher the salinity and the opposite the farther the point is. Additionally, regarding the hydrogeological features, A4 should have higher EC measurements than A3 and A2, in that specific order.

Regarding the proximity to the sea, a trend was seen in Figure 4-6 where as expected, shorter distances had higher EC readings. However, certain exceptions to the trend are Chojochón, Aremasain and Aujero. As for the hydrogeological features, the highest EC measurements are found in A4 and the lowest in A2. Nonetheless, intermediate values presented exceptions as the case of Cucurumaná.

The depth of wells is unknown for some locations and it is due to the poor management and control of the information in the region. This data would have been useful to compare the influence of depth and salinity.

Plotting in a Piper diagram the chemical properties of the samples was done in order to further understand the characteristics of the groundwater quality. This diagram classifies the type of water analysed based on the position in the cations triangle (bottom-left), the anions triangle (bottom-right) and central diamond. Figure 4-9 displays the diagram and classifies the points by their hydrogeological feature. It can be seen that all the cations fall in the Na-K corner. For anions, two groups are found, the Cl^- and HCO_3^-. Finally, in the centre diamond, the points are located in the bottom corner and in the right corner. The former refers to Na-HCO_3 type groundwater and the latter to Na-Cl type groundwater (seawater).

Noticing that all the hydrogeological features share the Na-Cl group is already an indication that seawater may be intruding as this region in the central diamond is typically where seawater is located. Furthermore, observing that within the same hydrogeological feature there are wide differences, as belonging to two different types of water, already evidences changes from original conditions.

According to studies from the SGC and Rodríguez and Londoño (2002), the cross sectional view of the geologic structures present two important features: the N1C and N1M (Appendix J). These features are characterized by the presence of limestone which explains the presence of calcium and carbonates. This can explain why the group of wells in the red circle in Figure 4-9 are in the bicarbonate group, as they probably still have their original characteristics.

The group in the red circle in Figure 4-9 belongs to the wells of Cucurumaná, Guachaquero and Paraíso. These wells were the farthest away from the sea from all the communities sampled (see Table 4-12). This is an additional argument to say that still, seawater intrusion has not affected the water quality in these communities as it already has in the others, which are closer to the sea.

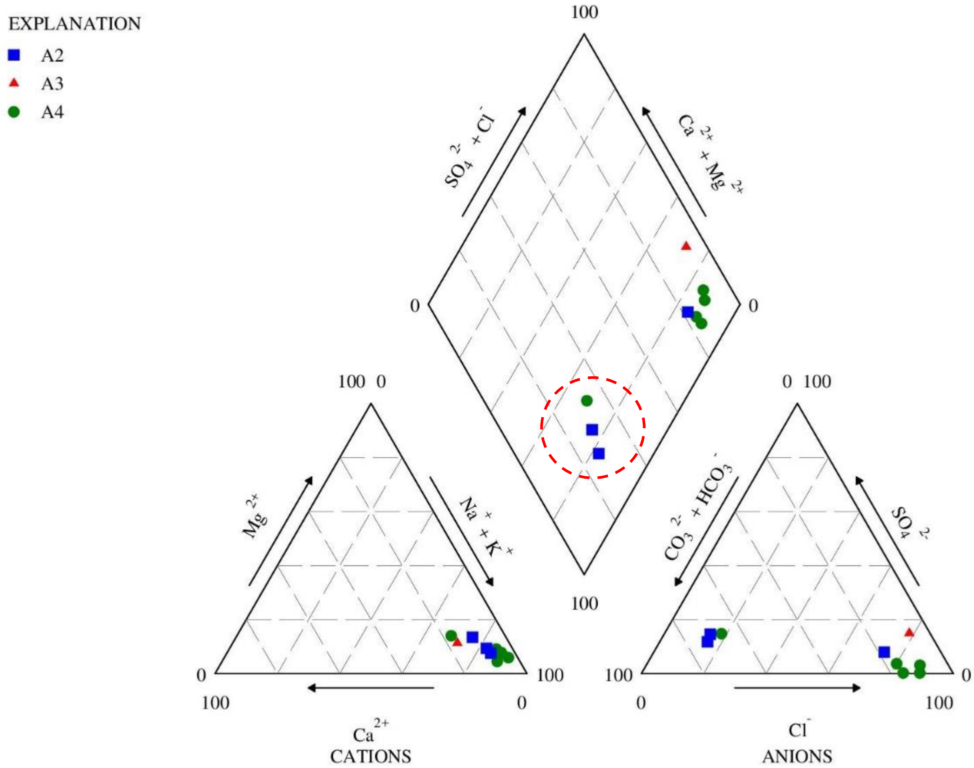


Figure 4-9 Piper diagram of the fieldwork's groundwater samples

Finally, based on the results that indicate seawater intrusion, a contour map was done by interpolating the EC readings in the wells. This map puts a boundary in 1,500 µS/cm, as the limit between freshwater and brackish water. It can be seen that at closer distances to the coast, higher EC readings were obtained (see maps in Appendix K and Appendix L).

The lack of control on the extraction of wells and the arid conditions may not contribute to seawater intrusion if it is already happening. A closer look to this issue must be done as it is not the scope of this research.

Chapter 4.2 Recap

Water sources:

Wells, jaweis, water tankers, and water bidons, bags and bottles, were the common sources reported.

Water quantity for some sources is heavily influenced by the rain seasons as jaweis and artisan wells. Unfortunately, water tankers, which are offered by the municipalities, are not regular. Their quantity is not fixed in time. Water bought in bottles, bags and containers, is not accessible to everyone, Finally, wells are the only source that is present most of the time.

The reported uses varied according to source availability. Overall, wells, jaweis and water tankers were the more used proportionally to the other sources.

Is concerning that jaweis are used for domestic consumption given the fact they are heavily contaminated.

Water quality:

No toxic compounds were found in the analysis done to the wells that were sampled.

Coliform contamination was common and relatively high in all the wells. Disinfection should be put in place by means of chlorine tablets as minimum.

Wells salinity varied between 1,000 µS/cm to 7,500 µS/cm. This range of salinity is acceptable for goats but compromises the quality of crops. For human consumption it is not acceptable above TDS content of 900 mg/L ~1,500 µS/cm (WHO, 2011).

Water quality variation:

Proximity to sea was found to be an important factor that increases EC readings, salinity. An indication that seawater intrusion is already happening was found.

Conclusions regarding hydrogeological features and their effect on water salinity cannot be drawn based on the limited results.

Reference tables and maps:

Appendix F: Map – Hydrogeological features in La Guajira, Colombia

Appendix G, H and I: ANOVA, F-test and T-test

Appendix J: Cross-section view of geologic structures

Appendix K – Map – Hydrogeological features and wells in La Guajira, Colombia

Appendix L – Map – Electrical conductivity spatial distribution in La Guajira, Colombia

4.3. Selection of water treatment technology

To select a water treatment technology for the indigenous communities in La Guajira, different people can be consulted to make an informed decision. For instance, the communities themselves have an opinion towards different treatments systems based on their own criteria and could find one technology more adequate for their needs than another. Similarly, NGOs, academia and water companies, have different opinions and their opinions could be the same as the indigenous communities or not.

As a result, the likelihood that these consulted groups have different arguments to decide upon one technology instead of another is almost certain. The reasons why they are more attracted to one alternative than other are because they have a set of criteria that enables them to differ between options, and decide which one is the best one. Additionally, these set of criteria, may have different importance among them, for instance, investment costs may be a factor that influences more the final decision than the operation and maintenance costs.

A multi-criteria decision analysis allows the decision makers to have an informed and structured decision. It includes all the criteria the different groups of actors will use to evaluate the alternatives and also, it takes into account the weight, the importance, each criteria has. Therefore, this tool was used for this specific case study and through surveys, the communities, water companies, academia and NGOs were asked to give their opinion to have the basis for the analysis.

In the first section of this chapter, the definition of the different criteria will be explained. The second section will show the actors response to the criteria weighing process in the surveys. The third section will establish the water treatment technologies to be compared for the case study and based on their characteristics, they will be scored for each criteria. Finally, by using DEFINITE software for MCDA a final ranking of the technologies will be obtained and analysed.

4.3.1. Criteria definition

The definition of the problem was a priority towards the definition of the criteria. Based on the recommendations by Enserink, et al. (2010), the procedure to clearly define the problem, objectives and criteria was followed.

The initial problem identified was the provision of water to the indigenous communities in La Guajira, shown in Figure 4-10. Other problems could have been listed to find the fundamental objective, for example: stop corruption, stop children malnutrition, preserve Colombian indigenous cultures, etc. However, as the problem definition can become broader by listing other relevant issues, a more concise definition of the problem was used: improve the livelihood of indigenous communities in La Guajira. In Figure 4-11, this new definition is put in a “means-end diagram” which helps visualize what strategies or actions can be done in order to achieve the objective of the improved livelihood of the communities.

Provide water to the indigenous communities in La Guajira

Figure 4-10 Initial problem definition

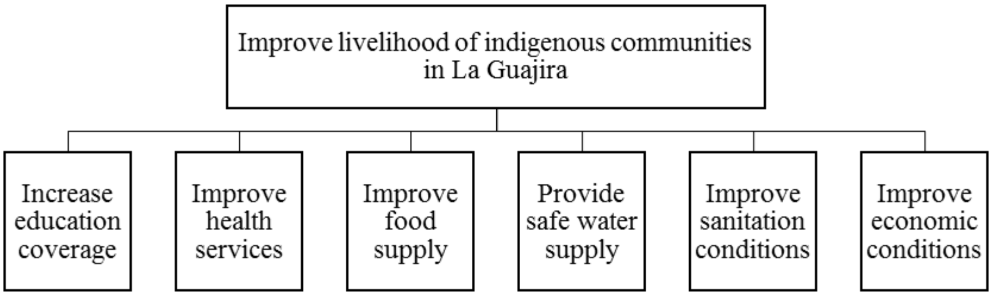


Figure 4-11 Means-end diagram

The main focus of this research is the selection of a water treatment technology to provide water to the communities in La Guajira. Therefore, a deeper analysis of this objective is done. For instance, Figure 4-12 presents that in order to accomplish this goal, either rainwater collection systems and/or brackish water treatment technologies could be used to solve the problem. The aridity in the region does not allow rainwater collection to be totally reliable. Therefore, the selection of a brackish water treatment technology is further analysed.

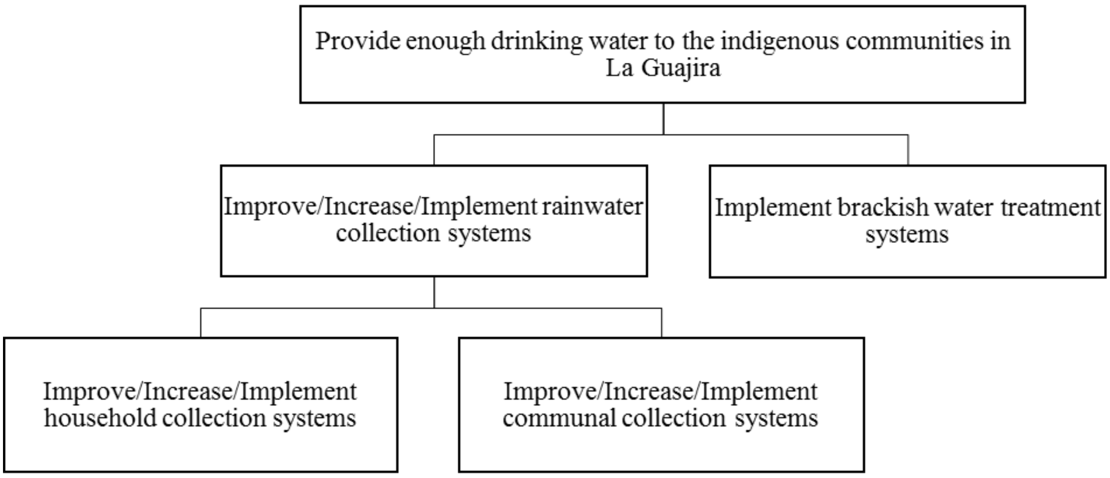


Figure 4-12 Focused means-end diagram

The implementation of a brackish water treatment system is the mean by which the objective to provide enough water to the indigenous communities in La Guajira can be achieved. The final step to obtain the set of criteria to be able to select the technology and use a MCDA is to reveal the dilemmas of this strategy.

In Table 4-13, different questions are asked to reveal different obstacles and concerns. The continuous questioning brings different concerns: investment costs, operation and maintenance costs, enough water supply, water treatment complexity, the use of consumables, environmental impacts, energy supply, and site-specific arrangements. These dilemmas can be transformed to the criteria by which a decision will be evaluated and chosen.

Table 4-13 Dilemmas and criteria

Implementation of a brackish water treatment		
Dilemmas		**Criteria**
How can a brackish water treatment be implemented without ….		
… high costs of investment?	1.	Investment costs
… elevated costs of maintenance?	2.	Operation and maintenance costs
… inadequate water to meet demand?	3.	Water production
… causing environmental impacts?	4.	Environmental impacts
… site-specific arrangements?	5.	Operation flexibility
… intensive use of consumables not available locally?	6.	Use of consumables
… the use of complex treatment schemes?	7.	Treatment complexity
… stable energy supply?	8.	Alternative energy use capability

As the criteria has been set, an ideal solution can also be stated. Figure 4-13 states for each criteria what the ideal characteristics of the technology would be.

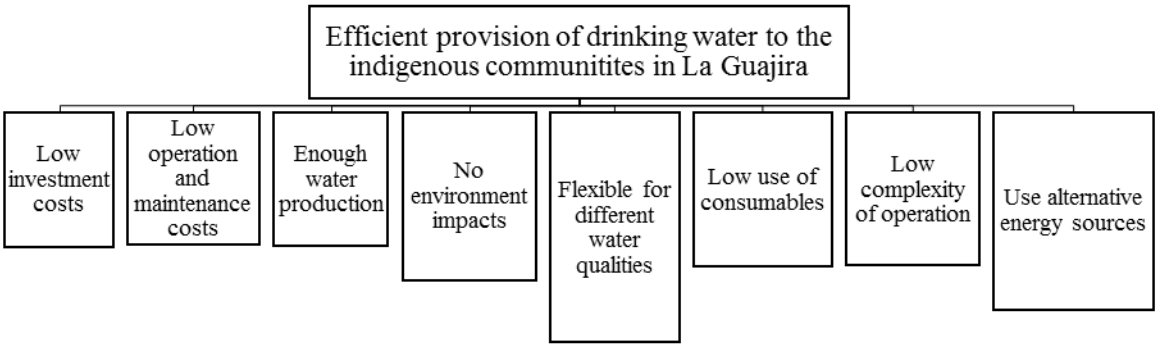


Figure 4-13 Ideal characteristics of the water treatment technology

4.3.2. Actors and criteria weighing

After the set of criteria was defined, the next step taken was to consult with different actors what weight they would assign to each criteria. To do this, an Analytical Hierarchy Process was followed, using a pair-wise comparison between the criteria (see Table 2-3) to systematically assign the weight to each one of them. This method was chosen as it is ideal when there are criteria that have conflicting opinions between groups (Zarghami and Szidarovszky, 2011). A survey was delivered to the different actors where they filled in a matrix, based on a scale, how important was one criteria compared to other. Appendix C shows the format of the survey used in this research and the methodology on how the results were obtained.

The actors that were surveyed were grouped in 4 different groups: water companies, academia, NGOs and communities. The results of this groups were averaged and then ranked. Table 4-14 presents the results of the survey and Figure 4-14 presents the ranking of the different criteria.

Table 4-14 Results from criteria analysis surveys

	Water Company[15]			Academia[16]			NGO[17]			Communities[18]			Overall		
	Weight Average (%)	Std. Dev (%)	Rank	Weight Average (%)	Std. Dev (%)	Rank	Weight Average (%)	Std. Dev (%)	Rank	Weight Average (%)	Std. Dev (%)	Rank	Weight Average (%)	Std. Dev (%)	Rank
Investment costs	8.5	4.7	7	4.9	2.9	8	4.2	2.4	8	4.7	4.5	8	5.6	4.0	8
O&M costs	10.8	6.6	5	11.5	3.6	6	9.5	4.9	6	9.4	5.6	6	10.2	5.2	7
Water production	12.9	7.6	3	15.4	11.2	2	16.2	11.0	2	7.1	5.7	7	13.2	10.0	3
Environment impacts	6.9	4.3	8	12.7	8.4	5	15.4	4.1	3	10.9	6.0	4	12.2	6.6	4
Operation flexibility	10.6	1.9	6	14.6	2.7	3	7.5	4.0	7	10.6	8.3	5	10.4	3.9	6
Use of consumables	13.9	3.5	2	10.5	5.7	7	25.2	13.4	1	34.5	4.1	1	19.1	11.2	1
Treatment complexity	11.9	7.1	4	16.6	6.2	1	10.6	3.3	5	11.1	0.7	3	11.9	6.1	5
Alternative energy use capability	24.7	11.8	1	13.8	5.8	4	11.4	5.1	4	11.8	6.7	2	17.6	10.3	2

[15] EAAAM- Colombia; Aremasain Boarding school; SEMAE, Brazil; Ghana Water Company Limited; CWSA. Saint Vincent & The Grenadines.
[16] IHE Delft professors; Univerisdad de los Andes – Modelo Agronegocios Sostenibles.
[17] Entropika and Ancla, Water Vietnam, Colernergy.
[18] Ishasihamana and Paraíso.

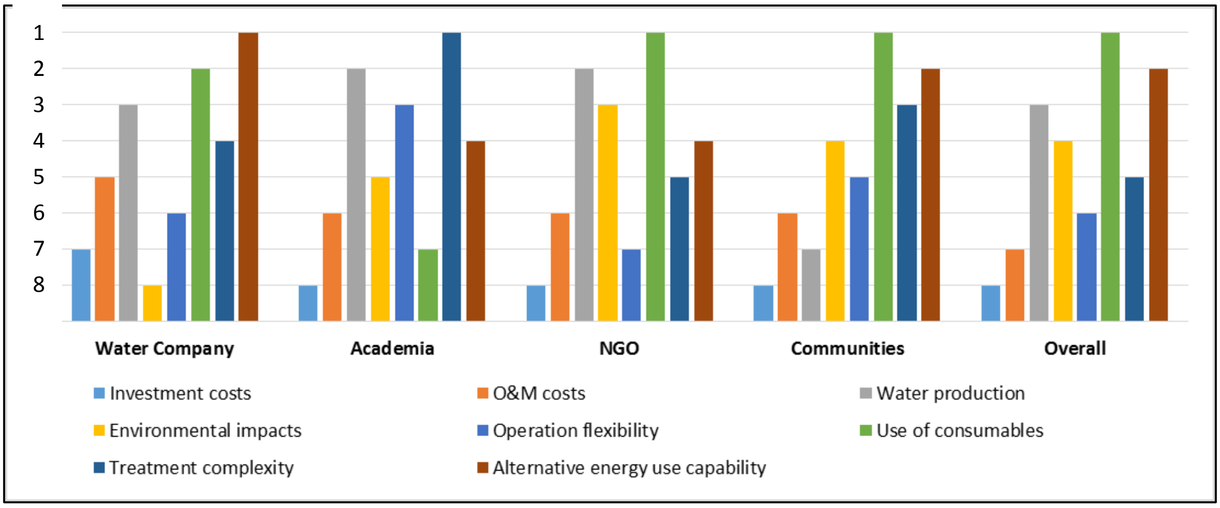


Figure 4-14 Ranking of the different criteria per groups and overall

As expected, there were similarities and differences found between the actors surveyed. For instance, water production was always ranked in the top positions; 3rd for water companies, 2nd for academia, 2nd for NGOs but exceptionally for communities it was the 7th. For investment costs, the majority of groups ranked it 7th and 8th place. For operation and maintenance costs, it was similar as for investment costs, 5th and 6th place. For the rest of the criteria, there were many differences in the ranking.

However, ranking may yield false sensations of the amount of influence a criteria might have. In other words, the rank is just an order reference but it doesn't quantify the importance given to a specific criteria. For this reason, Figure 4-15 presents the same information but with the weights.

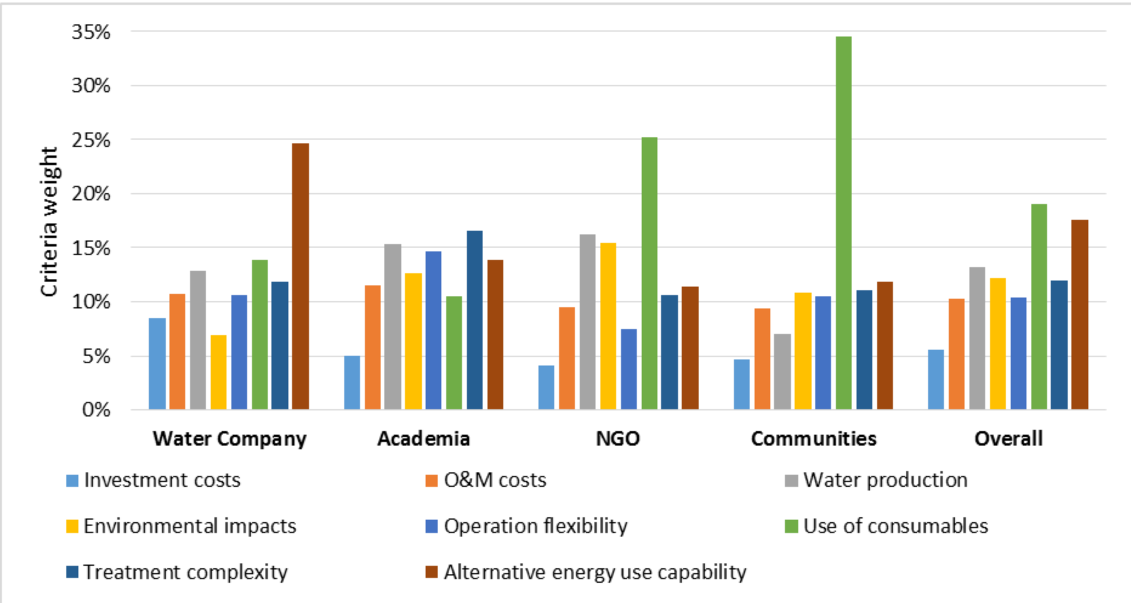


Figure 4-15 Criteria's weights according to the different groups

Figure 4-15 shows that the different groups have preferences sometimes very pronounced for one criteria. For example, water companies have a marked preference for alternative energy use capability, while NGOs and communities worry more about the use of consumables. On the other hand, the academia groups presented a more even distribution of weights.

The differences encountered in the previous analyses were expected to occur. However, when making a decision, it is difficult to determine which of the consulted groups should be considered to be more “correct” or more influent when deciding. As a consequence, Table 4-14 and Figure 4-14 and 4-15, have an extra group called “Overall”. This group averaged all the weights assigned by the different groups. No extra consideration was given to a group of consulted actors.

The Overall group presents the use consumables as the most important criteria, followed in 2nd place by alternative energy use capability and in 3rd place water production. The effect this group has on the final ranking of the technologies will be analysed in the following section.

4.3.3. Scores and standardization

To begin the MCDA analysis, the alternatives that were selected for the analysis were: solar stills, humidification-dehumidification towers, reverse osmosis, electrodialysis and mechanical vapour compression (see sections 2.2.1, 2.2.2 and 2.2.3 or the description of each technology). The reasons why these technologies were selected were because they have been used for small scale applications that could be applied in decentralized systems. These reasons are convenient based on the fact that there is no infrastructure in place in the region to supply water from a central system and that the amount of communities dispersed in the region make it impossible to create a distribution system based on a central treatment plant.

The characteristics of each technology regarding the 8 criteria defined in the previous section can be seen in Appendix M. Based on the reference to complete the aforementioned table, different scores were assigned to the technologies.

For *investment costs* the unit used was €/m^3. Based on the different sources consulted, various ranges were found. The values were then averaged to find and average for the technology so that it would represent its score. Based on the range found, the way scores were standardized was giving a maximum value to the cheapest one and the worst values to the most expensive one. For instance, MVC was the most economical and HDH the most expensive.

A similar procedure was done with *operation and maintenance costs*. In this case, electricity consumption of the technologies was considered. An exception was done with solar stills as they don’t need electric input. However, labour is intensive for this technology which increases the costs associated for its operation (Fath, et al., 2003). For the other technologies, the energy demand was then multiplied by the average cost of energy in La Guajira and then, depending on the kind of system, a factor was used to account for the rest of operation and maintenance cost (National Research Council, 2004). For instance, there were different percentages associated to the costs for membrane technologies and thermal (see sources Appendix M).

Regarding *water production*, different references were collected with the reported capacities of the technologies. Based on these information, the score was given using a qualitative (--/++) scale. A -- score was given to the technologies that did not meet the demand calculated in section 4.1.4. A score of 0 was given to technologies that met the demand but whose capacities were always bigger than needed (sub-utilization and oversize). A ++ was given to the technologies that always met the demand without oversizing. For instance, RO and ED scored better than MVC, HDH and solar stills. Additionally, as it is important to be able to supply the water needed, the standardization of this criteria was further set to have a minimum goal of having "0" as the score, in other words, meet the demand.

Environmental impacts were scored based on the brine disposal. Solar stills and HDH have better brine disposal management due to the lower concentrations they handle (Narayan, et al., 2010). On the contrary, MVC, RO and ED don't. However, the concentrations that will be handled in the region won't generate brines so concentrated. Therefore, the scale used was 0/++ where 0 meant the worst management of brine disposal and ++ the best. HDH and solar still had ++ and RO, MVC and ED had +.

The *operation flexibility* evaluated how water quality and quantity could be maintained even when changes in water quality occurred due to different groundwater wells or even when there was contamination. The scale use was --/++ where – would be for the least flexible technology and ++ for the most flexible. RO scored + as it work very well to treat both salinity and remove pathogens . It didn't get a ++ considering the fact that if salinity increases over time, operation must be modified. ED scored -- because if salinity exceeds 2000 mg/L, it is not effective and also because it requires further treatment to remove pathogens (Mathioulakis, et al., 2007). HDH and solar stills scored 0 because they cannot handle water contamination but on the other hand, salinity is not a problem. Finally, MVC scored ++ as it is both resilient to salinity and pathogens (Sharon and Reddy, 2015).

For the *use of consumables*, the scale used was --/++. For the membrane systems, the need of replacement and the cleaning chemicals needed, made their score be -. For MVC the score was 0 and for HDH, and solar stills +. The membrane systems have long replacement time period, for RO every 5-7 years and for ED 7-10 years (Eltawil, et al., 2009). MVC requires corrosion control but is better compared to the membrane systems. HDH materials as condenser, packed material, among others, are vulnerable to damage and require change in shorter periods compared to membranes (Giwa, et al., 2016). Finally, solar stills require large areas and the system maintenance requires large amount of materials (Fath, et al., 2003).

As for *treatment complexity*, the qualified skills for RO are not high but certain training must be given to the operator, which is why the score is 0. The same situation occurs with ED but a frequent cleaning is more needed which makes the operation more complex. The score given was -. For MVC, there is no need for qualified technician but a constant maintenance to the compressor makes it complex, so the score given was 0/+. For HDH, no qualified skills are needed but cleaning of the packed material is needed. The score was +. Finally solar stills don't require qualified hand and the maintenance is not frequent (Eltawil, et al., 2009). The scale used was --/++

Finally, a*lternative energy use capability* consisted on finding references that reported the ability of the technologies to be coupled with sustainable energy sources such as solar panels and/or wind turbines. In all the technologies, several studies have shown the potential they have to be coupled with alternative energy source . That is why for all technologies, the score was +. The scale used was 0/+.

The last five criteria were all standardized by maximum values having the best score.

Table 4-15 summarizes all the scores and standardization methods of the different criteria[19].

Table 4-15 Criteria scores and standardization for the technologies

	Unit	Standardization method	RO	ED	Solar Stills	HDH	MVC
Investment costs	€/m3	maximum	6.15	8.83	10.1	51.71	5.25
		score	*0.88*	*0.83*	*0.8*	*0*	*0.9*
O&M costs	€/m3	maximum	0.47	1.1	2.1	2.1	1.87
		score	*0.78*	*0.48*	*0*	*0*	*0.11*
Water Production	--/++	goal	++	++	--	0	+
		score	*1*	*1*	*0*	*0*	*0.5*
Environmental impacts	0/++	maximum	+	+	++	+	+
		score	*0.5*	*0.5*	*1*	*0.5*	*0.5*
Operation flexibility	--/++	maximum	+	--	0	0	++
		score	*0.75*	*0*	*0.5*	*0.5*	*1*
Use of consumables	--/++	maximum	-	-	+	+	0
		score	*0.25*	*0.25*	*0.75*	*0.75*	*0.5*
Treatment complexity	--/++	maximum	0	-	++	+	0/+
		score	*0.5*	*0.25*	*1*	*0.75*	*0.63*
Alternative energy use capability	0/+	maximum	+	+	+	+	+
		score	*1*	*1*	*1*	*1*	*1*

4.3.4. MCDA results and sensitivity analysis

After the criteria scoring and standardization was done, the information was uploaded to DEFINITE to run the MCDA. Figure 4-16 shows the results for each group. It can be observed that RO and solar stills were the technologies that were most of times in the first positions. For water companies, academia and NGOs, the first place was for RO followed by solar stills. Communities were the only group were solar stills were better placed than RO. For the rest of technologies, the 3rd place was mainly for MVC (academia and NGOs) while the last place was mainly for HDH (water companies, academia, NGOs).

In the group where all criteria weights were averaged, the "Overall", the technology which had the best score was RO (0.68) followed by solar stills (0.66). It is worth noting the difference is very small, which is why a sensitivity analysis was performed, as shown in Figure 4-17.

[19] See Appendix M for further information and references for the characteristics given for each criteria.

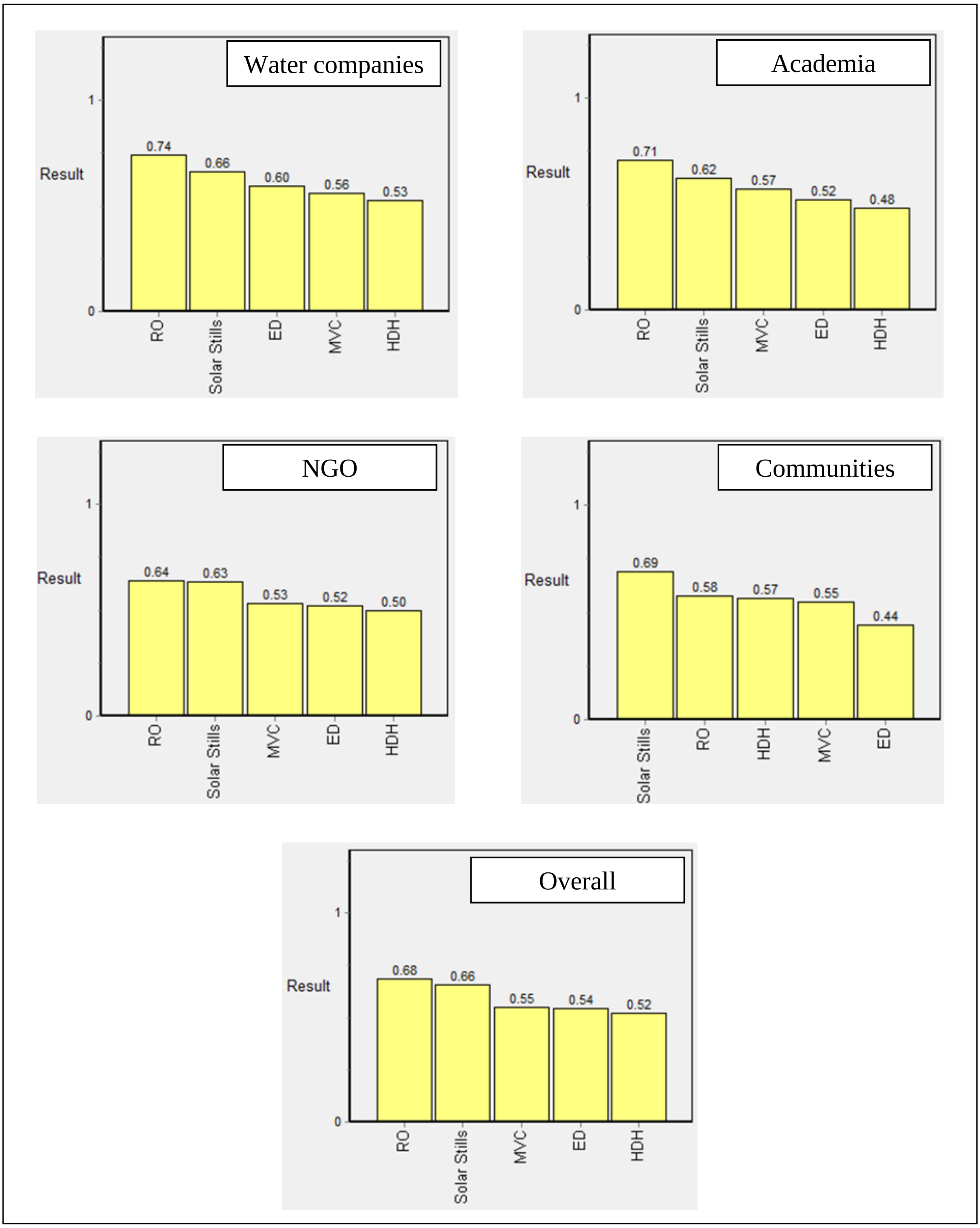


Figure 4-16 Results from MCDA analysis per group and overall

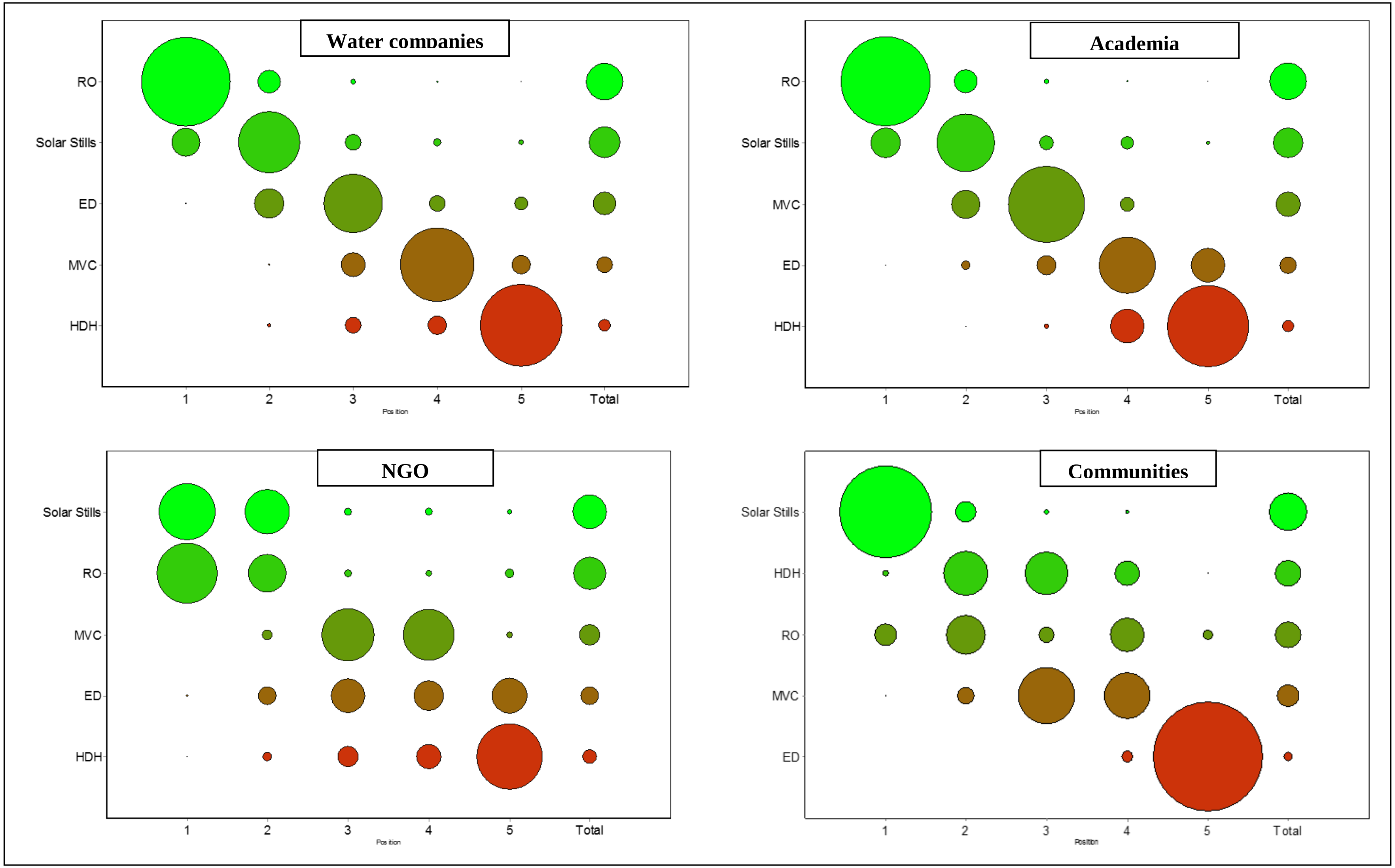


Figure 4-17 Sensitivity analysis for water companies, academia, NGO and communities

The sensitivity analysis was done giving uncertainty to the criteria's weights and the scores. For the criteria, the standard deviation of the average of the different groups was used for the uncertainty (see Table 4-12). No recommendations on how much variation should be considered were found in the literature. Therefore, a 20 % variability was used in order to have considerable sensitivity in the results.

The sensitivity analysis figures are interpreted in the following way. The x-axis refers to the position, being 1 the 1st place and 5 the 5th. In this range, circles will represent the probability a technology has to be in that position, the bigger the circle is the higher the probability. Lastly, in the x-axis the "Total" value presents, by mean of the circles sizes, the relative score one technology has compared to the others.

For water companies and the academia, RO has a clear preference compared to solar stills. Not much difference with the uncertainties in the criteria weights and technologies' scores is obtained compared to the results in Figure 4-16. On the contrary, NGOs present in the first place a slight difference between RO and solar stills, which still puts RO in the first place. 2nd place is more probable for solar stills than for RO and in the "Total", very little difference is found between these two alternatives. Finally, for communities, solar stills have a marked preference and HDH and RO compete for the 2nd place. The "Total" results puts in the 1st place solar stills and in the 2nd place HDH and RO[20].

Figure 4-18 presents the sensitivity analysis for the "Overall" group. In this case, the results obtained before present few differences with the uncertainties used to evaluate the variance. RO occupies the 1st place with a notable difference while solar stills continue in the second position. The rest of technologies did not increase their score and maintained the last positions. Clearly, RO and solar stills have the better scores.

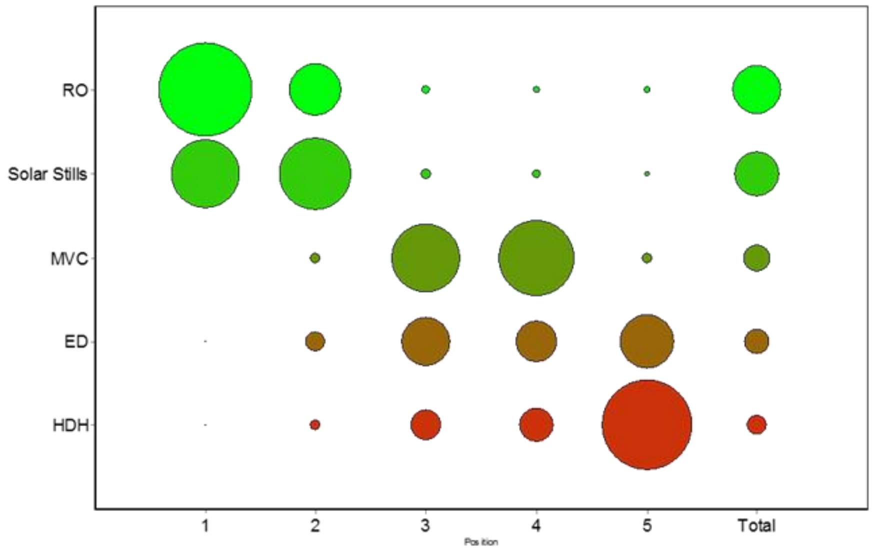


Figure 4-18 Sensitivity analysis for the "Overall" group

[20] Appendix N has the supported probabilities in a table for each group analysis in Figure 4-18.

A deeper analysis in the "Overall" group can explain why the results were that way. For instance, in favour of solar stills, the use of consumables and treatment complexity were better scored than for RO. On the other hand, O&M costs and water production were favourable for RO. However, out of these criteria, the use of consumables has the highest weight (19.1 %) while the others have similar weightw (between 10 - 13 %). This favoured the score for solar stills, as the most important criteria gave it an advantage over RO but certainly, its low performance in water production and O&M costs, disfavoured its eligibility. See Figure 4-19.

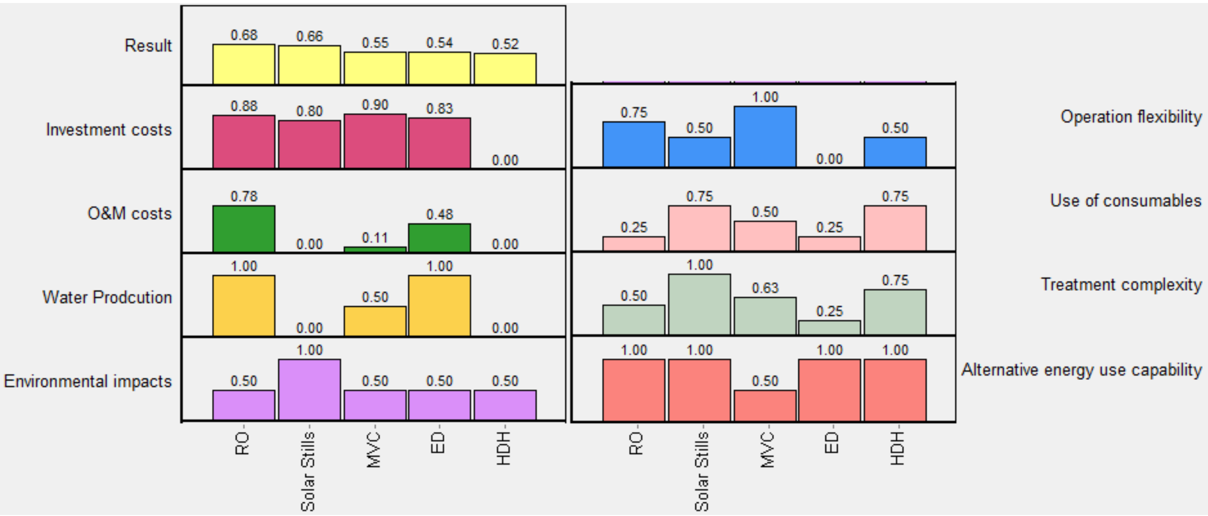


Figure 4-19 Individual criteria contribution to score for "Overall

The criteria mentioned in the previous analysis for "Overall", also played an important role on the other groups. For communities, use of consumables was the highest ranked, with 34.5 % (highest rank found for all the different surveys) and it was the reason why solar stills were in the 1st place followed by HDH in the 2nd, which generally was in the last places for the rest of consulted groups. A similar situation occurred with NGOs, where use of consumables, with 25.2 % weight (the second highest of all the surveys) brought a very close 1st and 2nd place between RO and solar stills. Certainly, this criteria was a key factor on the ranking outcome.

To give a final recommendation based on the different rankings and sensitivity analysis two factors are considered. The sensitivity analysis presented that RO and solar stills have a 1st and 2nd place clearly defined compared to the rest of technologies analysed. However, the difference in the score among these two technologies is very small. Second, the fact that solar stills require large areas for water production, for instance 1 m^2 to produce 4 L (Buros, 2000), based on the projection in section 4.1.4, 1,250 m^2 up to 5,375 m^2 (5 m^3/day to 21.5 m^3/day), would be required. This is almost one quarter to one half the area of a football field. Based on this, given that RO systems can be compact and that for the most of groups this technology was ranked in the 1st place, it is recommended that it should be used as the water treatment technology for the indigenous communities in La Guajira.

The recommendation given should also consider that as this is the first attempt to reach an informed decision, the results can be influenced by the people and groups surveyed. This is a recommendation and should be used as such. The probability of obtaining different rankings can happen if a different methodology was used. However, the results obtained in this research are useful as a basis and further improvements can be done. Lastly, the “Overall” group was used to bring an impartial average of the total groups surveyed. However, different arrangements can be studied where the different actors could be given higher weights, for instance, the communities, who will be in the end the final consumers.

Chapter 4.3 Recap

Selection of water treatment:

The MCDA carried in this chapter presented the derivation of the criteria based on the procedure recommended by (Enserink, et al., 2010). These criteria were later weighted by water companies, academia, NGOs and the communities. The procedure was based on the AHP explained in detail in Appendix C.

The use of consumables was found to be a very influential criteria on the selection of water treatment. For NGOs and communities it was the criteria with the highest weight assigned.

RO was the best scored technology for water companies, academia and NGOs. Solar stills was only better than RO in the evaluation using communities' criteria weights. In the "Overall" group, RO was better scored than solar stills for a small difference.

The sensitivity analysis clearly showed that the 1st and 2nd places were always obtained by RO and solar stills. The only exception this time were communities were HDH climbed to 2nd place.

The final recommendation is to use RO given the fact of its rank throughout the analysis and the fact that it is more compact than solar stills, which for the projections done in section 4.1.4 would require areas comparable to one-quarter to one-half of a football field.

4.4. Water treatment technology recommended design

In this section, current water treatment systems found in the fieldwork are going to be presented and an idea on the set-up in the future is presented.

4.4.1. Current water treatment schemes

During the fieldwork, two treatment plants were found and currently under operation. One was in the Ishasihamana community and the other one was in the boarding school in Aremasain. Both used reverse osmosis for the water treatment.

The treatment plant in Ishasihamana consists of three media filters in parallel followed by two microfiltration steps and finally one stage of RO with 3 vessels in parallel. There is no disinfection step after the treatment. The production capacity according to the person in charge of the operation is 15 m^3 per day and it is operated in batch. This community is connected to the electric grid which is the source of energy of this system. However, specific energy consumption is not known. No maintenance has been done since it was installed in 2013. Product water is not demineralized nor blended. Additionally, the person in charge of the operation is one member of the community who has learned empirically how to run the plant, as no capacitation was given to him.

Specific information on recovery and product quality was not available as the operator did not know it and the gauges were broken.

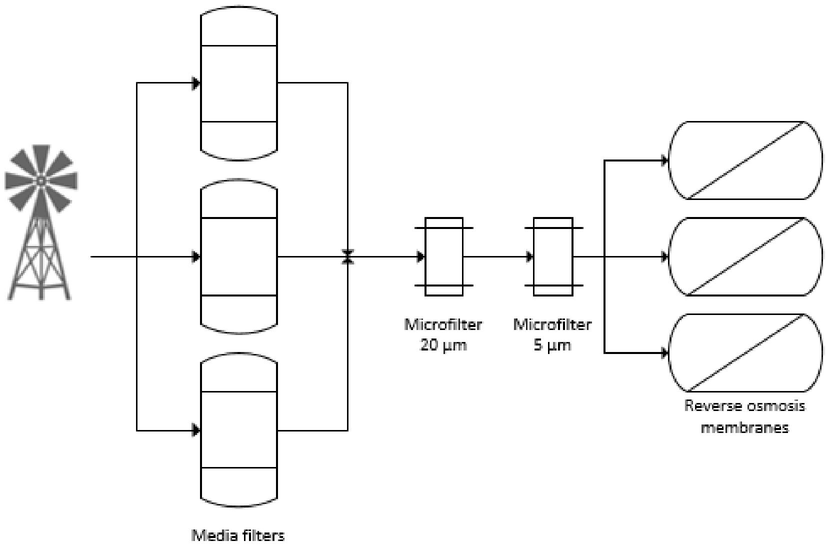


Figure 4-20 Ishasihamana treatment scheme

In Aremasain, a compact reverse osmosis system was installed in the second semester of 2017. This system contains a system in which operation of the scheme is monitored via GSM mobile card. With this, MFT and Colenergy, providers of the system, can control the operation remotely. The capacity is of 2000 L/day and it is getting the energy from solar panels and a wind turbine without using electricity from central grid. Specific energy consumption is not known. However, the power generated by the wind turbine and solar panel is 2 kW and is able to supply all the energy needed for treatment.

There is no use of chemicals in this system and there is no remineralization or blending. Up to date, there has not been a cleaning in place. The recovery was 10 % and the membranes used were SWRO 30-4040 DOW (40 inch x 4 inch).

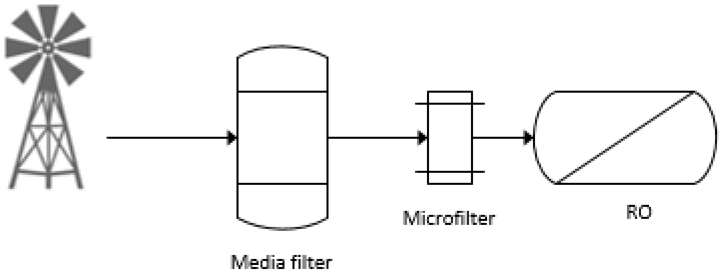


Figure 4-21 Aremasain treatment scheme

4.4.2. Recommended set-up for reverse osmosis

The projected capacities in section 4.1.4 ranged from 5 to 21.5 m^3/day. Therefore, it is recommended that modular configurations are installed based on this range. The modules will be lines that are able to produce 5 m^3/day. If more water is required, an additional line can be installed. In case there is need to scale up the capacity, it should also be considered that the media filters and microfiltration systems must be resized in some cases.

The pre-treatment system is a key factor for the life span of the RO membrane and it should be similar as to what is already placed in Ishasihamana and Aremasain. Media filtration followed by two microfiltration steps. No disinfection step is needed after the RO stage. The simplified treatment scheme is presented in Figure 4-22.

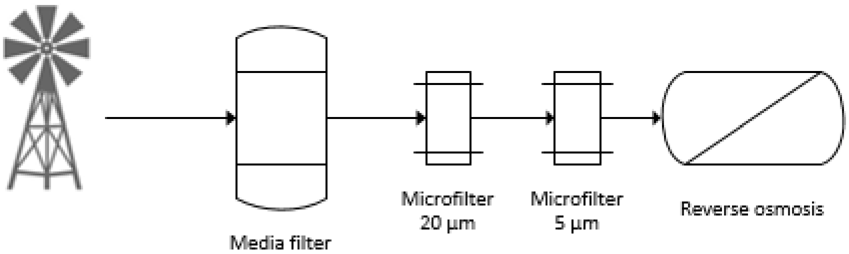


Figure 4-22 Recommended treatment scheme

In order to determine the recovery of the system, five factors must be considered. The first one is that flux should be in the range recommended by the membrane and that is recommended for brackish waters. In this case, a typical range is between 23.8 to 30.6 L/m^2/h (Hydranautics, 2001). Second, the Langelier Saturaion Index (LSI) which determines if water is aggressive or supersaturated. Third, the β factor of concentration polarization which is recommended to be below 1.2. Fourth, energy consumption. Finally, the fifth factor is scaling.

IMSDesign software was used to run a design of a treatment scheme with this characteristics. As an example, Chojochón was used, as it has the highest TDS concentration, 4558 mg/L. Different recoveries were used and the results of the different factors mentioned above are presented in Table 4-16.

Table 4-16 IMSDesign runs results

Recovery	Flux (L/m²/h)	LSI*$_{concentrate}$	β factor	Energy (kWh/m³)	Super saturation index for $Ca_3(PO_4)_2$
6 %	26.3	0.93	1.06	5.58	-0.09
10 %	26.3	0.98	1.10	3.31	-0.06
16 %	26.3	1.07	1.17	2.08	0.00
18.5 %	26.3	1.11	1.2	1.81	0.03
20 %	26.3	1.12	1.22	1.68	0.05

*LSI_{feed}=0.9

**Super saturation index = $\log([Ca^{2+}]^3[PO_4^{3-}]^2)\ /K_{sp}$. If <0, undersaturated. If >0, supersaturated.

From the results it can be seen that while recovery increases some factors improve while others not. To begin with, flux was always in the recommended range. The LSI of the concentrate increased as recovery increased, which makes scaling more likely. The β factor increased as well. The limit of 1.2 is reached when recovery is 18.5 %. Energy consumption decreases with increased recovery. Finally, the saturation index for $Ca_3(PO_4)_2$[21] passed from undersaturated to saturated when recovery is higher than 16%.

In order to select the recovery, certain trade-offs must be assumed. In this case, a recovery of 16 % could be the better one as scaling is in the limit of supersaturation and the β factor within limits recommended to avoid concentration polarization. The energy consumption with this recovery is 2.08 kWh/m³ which is common as reported by different sources (Al-Karaghouli and Kazmerski, 2013; Eltawil, et al., 2009). The LSI is always in the supersaturation side (greater than zero) from the feed which is why is not mentioned in the trade-offs.

As water quality is not the same in the different locations, in order to select the recovery for every specific location, a deeper analysis has to be done. However, as a rough estimation, considering a 10 % recovery, Table 4-17 contains the LSI values of the concentrate and the saturation indexes of other compounds calculated with PHREEQC. The risk of scaling is present in most of the wells. This requires and justifies a very robust pre-treatment and a low recovery to prolong the life of the membrane. Membrane cleaning in place should be done if possible.

[21] Saturation ratios from $CaSO_4$, $BaSO_4$, $SrSO_4$, SiO_2 and CaF_2 in the IMSDesign software are always below the limits. This is why not considered in the analysis of scaling.

Table 4-17 LSI and scaling indexes in the sampled wells

	LSI_{feed}	LSI_{conc}	Anhydrite $CaSO_4$	Aragonite $CaCO_3$	Calcite $CaCO_3$	Celestite $SrSO_4$	Chalcedony SiO_2	Dolomite $CaMg(CO_3)_2$	Gypsum $CaSO_4$	$Ca_3(PO_4)_2$
Ishasihamana	0.9	1.04	-3.57	0.63	0.77	-2.9	-0.07	2.01	-3.35	-0.28
Yuntamana	0.4	0.55	-3.73	0.16	0.3	-3.03	-0.02	1.12	-3.52	-0.74
Chojochón	0.9	0.98	-2.23	0.55	0.69	-1.64	-0.06	1.83	-2	-0.06
Aremasain	0.4	1.09	-2.66	0.31	0.45	-2.07	-0.17	0.9	-2.43	-0.08
Aujero	0.5	0.6	-2.55	0.39	0.53	-1.73	-0.1	1.25	-2.32	0.05
Cucurumaná	0.2	0.32	-2.18	0.12	0.26	-2.08	0.17	0.63	-1.95	-0.68
Guachaquero	0.7	0.82	-2.72	0.57	0.71	-2.37	0.09	1.68	-2.5	-0.02
Paraíso	0.2	0.37	-2.49	0.2	0.34	-2.02	0.15	0.95	-2.24	-0.61
Kamuchasaín	0.4	0.49	-1.7	0.24	0.38	-1.2	-0.1	0.78	-1.47	0.32

Based on the experience of Aremasain, the possibility to couple the system with solar panels and/or wind turbines and rely only on this source of energy is possible. The solar panel and wind turbine can be designed to produce more energy when necessary. In addition to be able to rely by itself, the system should be designed in this way to foresee power outages and the possibility that some communities are not connected to the electrical grid. Furthermore, if excess energy is produced, it can be used for different purposes within the community.

4.4.3. Water quality after treatment

Using IMSDesign, a system of a single vessel with one element was chosen. The membrane chosen was ESPA 2 – 4040 which has a salt rejection of 99.6 % and a maximum permeate flow of 7.2 m^3/h. Further specifications on the membrane can be seen in Appendix O.

As mentioned in the previous section, for simplicity reasons, a recovery of 10 % was chosen to elucidate the water quality of all the wells analysed. Table 4-18 presents the relevant paramenters obtained using IMSDesign. It can be seen that the permeate water quality has TDS concentrations ranging from 5 to almost 60 mg/L, which improves water drastically. However, it must be noted that concentration of important elements for health such as fluoride are below the Who guideline of at least 0.5 mg/L. Further remineralization should be considered, for instance by blending with treated disinfected raw water.

Microbiological water quality is not measured by the model but is expected that 99.99 % removal of pathogens occurs with the RO. Considering the highest coliform count around 540 CFU/ 100 mL, still some bacterial contamination would be possible in the challenging locations (5 CFU/100 mL). However, as discussed in section 4.2.4, it is possible the measurements of coliform contamination to be on the high side.

Table 4-18 Water quality after treatment

	TDS feed (mg/L)	TDS permeate (mg/L)	TDS concentrate (mg/L)	LSI conncentrate	β- factor	Energy (kWh/m^3)	SI $Ca_3(PO_4)_2$
Ishasihamana	3885	46	4324	1.04	1.1	3.09	-0.06
Yuntamana	3667	45	4091	0.79	1.1	2.98	-0.46
Chojochón	4558	57	5066	0.98	1.1	3.31	-0.06
Aremasain	1557	11.7	1732	0.56	1.1	2.33	-0.08
Aujero	1095	7.2	1238	0.6	1.1	2.22	0.05
Cucurumaná	984	6.8	1097	0.32	1.1	2.11	-0.68
Guachaquero	794	5.3	900	0.82	1.1	2.15	-0.02
Paraíso	865	5.5	979	0.37	1.1	2.22	-0.61
Kamuchasain	1627	10.4	1818	0.49	1.1	2.36	0.32

CHAPTER 5

Conclusions and recommendations

This research was able to produce information about water demand for the communities studied in La Guajira, Colombia. The results obtained from these communities can be used as a reference for future investigations.

The domestic demand found was below WHO guidelines for basic level service of water supply, as currently 27.5 lpcd are consumed compared to 40 lpcd (Howard and Bartram, 2003). It is expected that with the installation of a water treatment system, the living conditions of the indigenous communities in La Guajira improve.

Regarding water quality, two observations and results from the research are concerning. First, the use of jaweis, as a last resource, by many communities for drinking water poses health risks that put in danger the vulnerable members in the community as the coliform contamination is very high in this source. Additionally, the coliform contamination of water extracted from the wells requires that disinfection should be done. It is recommended that chlorine tablets should be given to the communities to prevent more diseases. Even if the coliform concentration found may be influenced by biofilm formation, appropriate care and maintenance of storage tanks will help reduce the risks of contamination of water and the occurrence of diseases. Second, the indication that sea water intrusion is highly likely to be occurring, has terrible consequences for the groundwater quality in the region if no measures from the government are taken. Control on the water extraction for the wells should be put in place, as well as updating the wells inventory with complete information. Aquifer recharge should be studied further in the region and recommended as a strategy to prevent the problem from aggravating.

The selection of the water technology considered a wide spectrum of inputs from groups that are familiar with water-related issues. The procedure proposed in this research allowed for a transparent and informed ranking of the technologies studied so that decision makers can argument their choices. However, the results of this research are not definite. The methodology used here can be improved by including more target groups for surveying and if needed, more criteria can be included. Additionally, different standardization for the scores of the alternatives regarding the different criteria can be selected and could be explored.

The treatment scheme proposed considers the wide variability of parameters in the region, as population size and water quality variation. It also contemplates that the set-ups to be put in place in the communities should follow a basic scheme from which scaling to larger capacities can be easily achieved. Furthermore, for monitoring and appropriate maintenance, schemes should be similar for the sake of simplicity for the people in charge of the operation and coordination.

Investigation on water quality after storage is recommended to be investigated. It has been a common problem that after an exhaustive water treatment, water is contaminated in the storage containers used by the consumers. Additionally, the degree of deterioration of groundwater quality due to sea water intrusion and the regulations that should be implemented to reduce this impact should be also analysed.

Finally, the implementation of the technology selected requires different strategies not considered in this investigation. Cooperation with the leaders of the communities is a key factor to the correct operation of the technology deployed. Financial sustainability must also be considered and the information collected on the willingness to pay for water services should be used and further studied. Engagement of all the community with the new water system must be fundamental for the long-term sustainability and to serve as a model for future application in more communities in the region.

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Appendix

Appendix A **Communities visited and coordinates**

Community	Municipality	North	West
Ahumao I	Riohacha	11°27.244	73°3.256
Ishasihamana	Manaure	11°44.881	72°24.038
Yuntamana	Manaure	11°44.532	72°24.702
Chojochón	Manaure	11°44.578	72°21.740
Aremasain	Manaure	11°29.116	72°42.896
Aujero	Riohacha	11°30.687	72°51.917
Cucuramana	Riohacha	11°28.160	72°48.752
Guachaquero	Riohacha	11°22.568	72°55.075
Paraíso	Riohacha	11°23.530	72°54.359
Kamuchasain	Riohacha	11°28.126	72°53.752

Appendix B **Surveys for locals and leaders**

40 L

Encuesta a locales

Nombre: Lionora Ipuana Epiau
Comunidad: Yuntamana

1. ¿Cuánta gente vive en su casa?
   - ○ 1
   - ○ 2
   - ○ 3
   - ○ 4
   - ☒ Otro: 6
2. ¿Dónde obtuvo el agua que utilizó hoy/ayer?
   pozo artesano (agua "mas" dulce) / agua salada de mangueras / carro tanque pero gratis
3. ¿Cómo utilizó el agua?
   - ☒ Preparar comida/ Consumo personal → pozo artesano, agua salada a veces para preparar alimentos
   - ○ ~~Limpiar el hogar~~ lavan platos → agua salada
   - ○ Higiene personal agua salada
   - ○ Agricultura No
   - ○ Otros: ________
4. ¿Para usar el agua le hizo algún tratamiento? ¿Cuál?
   - ☒ No
   - ○ Sí, filtración: ________
   - ○ Sí, desinfección: ________
   - ○ Sí, cuál? ________
5. ¿Quién se encarga de recolectar el agua en el hogar?
   Ella misma, hijo, esposo en moto y bicicleta
6. ¿Cuántos hijos tiene? ¿Cuántos son menores de 5 años?
   5 1
7. ¿Sus hijos han tenido diarrea, vómito o dolores de estomago?
   - ○ No
   - ☒ Sí, ¿Frecuencia? 2 veces al año
8. ¿Esta casa ha sido su lugar de residencia siempre?
   - ☒ Sí
   - ○ No,
9. ¿Cuál es su fuente de ingresos? ¿Cuánto?*
   cocinera para el colegio - 100.000 mensuales
10. ¿Actualmente en su hogar pagan por el uso del agua?
    - ○ Sí. ¿Cuánto? ________
    - ☒ No
11. ¿Estaría dispuesto a pagar por un servicio de agua?
    - ☒ Sí. ¿Cuánto? 5.000
    - ○ No
12. ¿En el futuro, que le gustaria poder hacer con el agua?
    - ○ Sembrar

Observaciones por el encuestado:

____

Observaciones por el encuestador:

Saneamiento: Sí, pero sin agua
Conexión de agua en la casa: No
Almacenamiento del agua Tanque 500 L
Otros: ________

2

Tiene electricidad
↳ Para confirma
Sí

Encuesta a líder de la comunidad

Nombre: Angelica Maria Coronado
Comunidad: Alumao 1
Teléfono: 321 8949175

1. ¿Cuántas personas viven en la comunidad?
   350 personas / 50 casas + niños escuela?

2. ¿Cúantos son mayores de edad? ¿Cuántos menores de 5 años?
   - Mayores de edad: 150
   - Menores de 5 años: casi 200 de 0 a 18 → 60 menores de 5

3. ¿Cúantas casas hay en la comunidad?
   50 casas

4. ¿Cúales son las fuentes de agua de la comunidad?
   Camion con agua (80-0L) - Alcaldía - semanal
   ~~[illegible]~~ Jawel - lluvia - toman varias rancherías + animales

5. ¿Existe un tratamiento para el agua que se consume?
   No

6. ¿Cuáles son las enfermedades más comunes en los niños?
   Diarrea, vomitos + gripa (todos los niños)
   A veces adultos.

7. ¿Hay algún médico del gobierno en la comunidad?
   - ☒ No - de vez en cuando - afiliados a EPS
   - ○ Sí. (Añadir en observaciones contacto si es posible).

8. ¿Esta *ranchería* ha estado siempre en este lugar?
   Si

9. ¿Ha existido migración de los integrantes de la comunidad?
   - ○ Sí. ¿Cuántos? ______
   - ☒ No

Observaciones por el encuestado:

Médico* ______

Observaciones por el encuestador:

Saneamiento: Al monte. → Algunas tasas sanitarias (gobierno) → No hay agua

Conexión de agua en la casa: Se recoge en garrafón.

¿Recolección de agua es individual o grupal? Se recoge en garrafones. Las mujeres

Otros: Pozo en contrucción y siempre agua salada.
El otro año se espera tener el pozo.

2

Appendix C **AHP procedure to find criteria weights**

Survey for criteria in the multi-criteria analysis

Name:
Community/NGO/University/Institute:

Definition of weights distribution for different criteria in a multi-criteria decision (MCDA) analysis is not an easy task. Moreover, this is not always done in an objective manner and therefore, there is no single right weight distribution. As a result, considering contributions of different groups as experts, actors, academy, etc., provides a better way to find a more suitable arrangement of the ranking of importance of the different criteria.

For the specific case of decentralized treatment of brackish water, for small, arid and isolated communities, please compare the criteria defined in Table 2 using the scores defined in Table 1. The value that you will assign in a cell is the comparison between the row and the column criteria. If the row header, in your opinion, is more important than the column header, write the score you consider the best. On the other hand, if the column header is more important than the row header, write the score as a fraction. This process will reveal many dilemmas that can guide the MCDA better.

Please see the following example.

Example: Investment costs Vs. O&M costs.

The first cell of the table is the comparison between Investment costs (row header) and O&M cost (column header).

If Investment costs is very strongly preferred over O&M costs, than in the cell the score will be 7.

If O&M costs is very strongly preferred over Investment costs, than in the cell the score will be 1/7.

Table 1

Scale	Definition	Interpretation
1	Equally preferred	Both elements in comparison have the same importance
3	Moderately preferred	A lightly higher importance of one element with respect to the other
5	Strongly preferred	A considerable higher importance of one element with respect to the other
7	Very strongly preferred	A much higher importance of one element with respect to the other
9	Extremely preferred	The maximum importance of one element with respect to the other
2, 4, 6, 8	Intermediate values	

Table 2

	Investment costs	O&M costs	Water production	Environmental impacts	Operation flexibility	Use of consumables	Treatment complexity	Alternative energy use capability
Investment costs	1							
O&M costs		1						
Water production			1					
Environmental impacts				1				
Operation flexibility					1			
Use of consumables						1		
Treatment complexity							1	
Alternative energy use capability								1

Criteria definition

Investment costs: Costs associated to the installation of a water treatment technology.

O&M costs: Costs associated to the maintenance and the operation of the water treatment.

Water production: Associated to the quantity of water a water treatment technology is able to produce.

Environmental impacts: Collateral effects with environment consequences associated to the operation, disposal of consumables, etc., in the water treatment.

Operation flexibility: Associated to the capacity of a treatment plant to operate even when water quality changes. For instance, the flexibility of a technology in different locations with different water properties.

Use of consumables: Associated to technologies that need different chemicals or consumables for the water treatment.

Treatment complexity: Related to the process of water treatment and the required skills for which the operators must be trained for.

Alternative energy use capability: The ability of a technology to be able to be powered by off-grid, sustainable energy sources.

Table 2

	Investment costs	O&M costs	Water production	Environmental impacts	Operation flexibility	Use of consumables	Treatment complexity	Alternative energy use capability
Investment costs	1	1/2	1/3	3/1	3/1	2/1	3/1	3/1
O&M costs		1	1/1	3/1	3/1	1/1	3/1	1/1
Water production			1	5/1	3/1	3/1	3/1	3/1
Environmental impacts				1	1/3	1/3	1/1	1/3
Operation flexibility					1	1/1	3/1	1/2
Use of consumables						1	2/1	1/1
Treatment complexity							1	1/3
Alternative energy use capability								1

Criteria definition

Investment costs: Costs associated to the installation of a water treatment technology.

O&M costs: Costs associated to the maintenance and the operation of the water treatment.

Water production: Associated to the quantity of water a water treatment technology is able to produce.

Environmental impacts: Collateral effects with environment consequences associated to the operation, disposal of consumables, etc., in the water treatment.

Operation flexibility: Associated to the capacity of a treatment plant to operate even when water quality changes. For instance, the flexibility of a technology in different locations with different water properties.

Use of consumables: Associated to technologies that need different chemicals or consumables for the water treatment.

Treatment complexity: Related to the process of water treatment and the required skills for which the operators must be trained for.

Alternative energy use capability: The ability of a technology to be able to be powered by off-grid, sustainable energy sources.

Water Company: Public water company – SEMAE – Mogi das Cruzes, Sao Paulo, Brasil

Ease of treatment

Table 2

	Investment costs	O&M costs	Water production	Environmental impacts	Operation flexibility	Use of consumables	Treatment complexity	Alternative energy use capability
Investment costs	1	1/5	1/9	1/5	1/7	1/9	1/9	1/9
O&M costs		1	1/3	1	1/3	3	1	1
Water production			1	3	3	5	3	3
Environmental impacts				1	1/3	1	1/3	1
Operation flexibility					1	3	1/3	1
Use of consumables						1	1/3	1
Treatment complexity							1	5
Alternative energy use capability								1

Criteria definition

Investment costs: Costs associated to the installation of a water treatment technology.

O&M costs: Costs associated to the maintenance and the operation of the water treatment.

Water production: Associated to the quantity of water a water treatment technology is able to produce.

Environmental impacts: Collateral effects with environment consequences associated to the operation, disposal of consumables, etc., in the water treatment.

Operation flexibility: Associated to the capacity of a treatment plant to operate even when water quality changes. For instance, the flexibility of a technology in different locations with different water properties.

Use of consumables: Associated to technologies that need different chemicals or consumables for the water treatment.

Treatment complexity: Related to the process of water treatment and the required skills for which the operators must be trained for.

Alternative energy use capability: The ability of a technology to be able to be powered by off-grid, sustainable energy sources.

Academia: Yness Slokar – IHE Delft

Tabla 2

	Costos de inversión	Costos de O&M	Producción de agua	Impactos ambientales	Flexibilidad en la operación	Uso de químicos	Complejidad del sistema	Capacidad de uso de energías alternativas
Costos de inversión	1	1/2	1/6	1/6	1/4	1/9	1/7	1/4
Costos de O&M		1	1/3	1/6	1/3	1/9	1/3	1/2
Producción de agua			1	1	4	1/5	3	2
Impactos ambientales				1	9	1/9	5	7
Flexibilidad en la operación					1	1/9	1/3	1
Uso de químicos						1	9	9
Complejidad del sistema							1	3
Capacidad de uso de energías alternativas								1

Definición de los diferentes criterios.

Costos de inversión: Costos asociados a la instalación de una tecnología de tratamiento de agua salobre.

Costos de O&M: Costos asociados a mantenimientos preventivos y de la operación del tratamiento de agua.

Producción de agua: Asociado a la cantidad de agua potable que una tecnología es capaz de producir.

Impactos ambientales: Efectos colaterales con impacto ambiental de la operación, asociados al manejo de la disposición del concentrado y de químicos.

Flexibilidad en la operación: Capacidad de la tecnología de operar eficientemente considerando cambios en las propiedades del agua de entrada. Adicionalmente, mide la capacidad de que una tecnología pueda ser usada en otros lugares, adaptándose a los cambios.

Uso de químicos: El uso de químicos para ciertas tecnologías puede ser obligatorio para su operación, mantenimiento o post-producción.

Complejidad del sistema: Relacionado al proceso de tratamiento de agua y a las habilidades para las cuales deben ser entrenados los operadores locales para operar el sistema.

Capacidad de uso de energías alternativas: Ciertas tecnologías pueden ser adaptadas para usarse con un sistema eléctrico central o con energías alternativas.

NGO: Entropika and Ancla

Tabla 2

	Costos de inversión	Costos de O&M	Producción de agua	Impactos ambientales	Flexibilidad en la operación	Uso de químicos	Complejidad del sistema	Capacidad de uso de energías alternativas
Costos de inversión	1							
Costos de O&M		1						
Producción de agua			1	1/7	[illegible]	1/9	1/6	1/7
Impactos ambientales				1	1/7	1/9	1	1/7
Flexibilidad en la operación					1	7	1/5	1/7
Uso de químicos						1	7	6
Complejidad del sistema							1	1
Capacidad de uso de energías alternativas								1

Definición de los diferentes criterios.

Costos de inversión: Costos asociados a la instalación de una tecnología de tratamiento de agua salobre.

Costos de O&M: Costos asociados a mantenimientos preventivos y de la operación del tratamiento de agua.

Producción de agua: Asociado a la cantidad de agua potable que una tecnología es capaz de producir.

Impactos ambientales: Efectos colaterales con impacto ambiental de la operación, asociados al manejo de la disposición del concentrado y de químicos.

Flexibilidad en la operación: Capacidad de la tecnología de operar eficientemente considerando cambios en las propiedades del agua de entrada. Adicionalmente, mide la capacidad de que una tecnología pueda ser usada en otros lugares, adaptándose a los cambios.

Uso de químicos: El uso de químicos para ciertas tecnologías puede ser obligatorio para su operación, mantenimiento o post-producción.

Complejidad del sistema: Relacionado al proceso de tratamiento de agua y a las habilidades para las cuales deben ser entrenados los operadores locales para operar el sistema.

Capacidad de uso de energías alternativas: Ciertas tecnologías pueden ser adaptadas para usarse con un sistema eléctrico central o con energías alternativas.

Community: Ishasihamana – Maria Rita Uriana

The matrix that results from the survey will be A:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} \\ 1/a_{12} & 1 & a_{23} \\ 1/a_{13} & 1/a_{23} & 1 \end{bmatrix}$$

The columns are added and later, matrix B will be equal to the division of the column sum and the element from matrix A:

$$B = \begin{bmatrix} \frac{1}{1+\frac{1}{a_{12}}+\frac{1}{a_{13}}} & \frac{a_{12}}{a_{12}+1+\frac{1}{a_{23}}} & \frac{a_{13}}{a_{13}+a_{23}+1} \\ \frac{1}{a_{12}*\left(1+\frac{1}{a_{12}}+\frac{1}{a_{13}}\right)} & \frac{1}{a_{12}+1+\frac{1}{a_{23}}} & \frac{a_{23}}{a_{13}+a_{23}+1} \\ \frac{1}{a_{13}*\left(1+\frac{1}{a_{12}}+\frac{1}{a_{13}}\right)} & \frac{1}{a_{23}*a_{12}+1+\frac{1}{a_{23}}} & \frac{1}{a_{13}+a_{23}+1} \end{bmatrix}$$

The weight each criteria will be equal to the sum of the row elements divided by the number of rows.

$$B1 = \left(\frac{1}{1+\frac{1}{a_{12}}+\frac{1}{a_{13}}} + \frac{a_{12}}{a_{12}+1+\frac{1}{a_{23}}} + \frac{a_{13}}{a_{13}+a_{23}+1}\right)/3$$

Same for B2 and B3.

Appendix D **Water usage according to source**

Drinking

Community	Jawei	Artisan Well	Well	Brackish Water Line	Water Tanker	Water Bidon/Bags	Casa Azul
Ahumao I	45%				55%		
Ishasihamana							
Yuntamana							
Chojochón	75%	12%					13%
Aujero					33%	67%	
Cucuramana			83%			17%	
Guachaquero			100%				
Paraíso	14%		57%			29%	
Kamuchasain			67%			33%	

Cooking

Community	Jawei	Artisan Well	Well	Brackish Water Line	Water Tanker	Water Bidon/Bags	Casa Azul
Ahumao I	45%				55%		
Ishasihamana							
Yuntamana							
Chojochón	43%			43%			14%
Aujero			83%		17%		
Cucuramana			100%				
Guachaquero			100%				
Paraíso			67%			33%	
Kamuchasain			100%				

Personal Hygiene

Community	Jawei	Artisan Well	Well	Brackish Water Line	Water Tanker	Water Bidon/Bags	Casa Azul
Ahumao I	50%				50%		
Ishasihamana							
Yuntamana							
Chojochón	25%			62%			13%
Aujero			100%				
Cucuramana			100%				
Guachaquero			100%				
Paraíso	16%		67%			17%	
Kamuchasain	50%		50%				

House cleaning

Community	Jawei	Artisan Well	Well	Brackish Water Line	Water Tanker	Water Bidon/Bags	Casa Azul
Ahumao I	53%				47%		
Ishasihamana	33%			56%			11%
Yuntamana							
Chojochón							
Aujero			100%				
Cucuramana			100%				
Guachaquero			100%				
Paraíso			100%				
Kamuchasain	50%		50%				

Appendix E Laboratory analysis report – AMBIUS

Pozo 2	Ishasihamana
Pozo 3	Yuntamana
Pozo 4	Chojochón
Pozo 5	Aremasain
Pozo 6	Aujero
Pozo 7	Cucurumaná
Pozo 8	Guachauqero
Pozo 9	Paraíso
Pozo 10	Kamuchasain

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RESULTADOS DE ANÁLISIS

R 41032

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Laboratorio acreditado NTC-ISO/IEC 17025
Res. No. 2016 de 2014 y 1226 de 2016

Empresa: AMBIUS SAS
Nit: 900506483 1
Dirección: CALLE 24C No 25-35 PISO 2
Solicitado por: Jaime Bermudez Gutierrez
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Orden de Servicio: 20515

Fecha Recepción: 2017-12-05
Fecha de Emisión de Resultados: 2017-12-26
Fecha de Muestreo: 2017-11-28
Muestreo a Cargo de: CLIENTE
Plan de muestreo: No Reporta
Procedimiento de muestreo: No Reporta
Número total de muestras: 3
Lugar de Muestreo: ETROPIKA GUAJIRA
Tipo de muestreo: Puntual
Tipo de Muestra: ARI( ) ARD( ) ARnD( ) AN(X) AP( ) AM( ) S( ) AX( )

Reporte de Resultados

Item	Fecha de Análisis (AAAA-MM-DD)	Parámetro	Método	Técnica	Limite de Cuantificación del método	Unidad	POZO No 2	POZO No 3	POZO No 4
							MN62480	MN62481	MN62482
1	2017-12-15	Nitrógeno amoniacal (Amonio)*	SM 4500 NH3-B, Asian Journal of Applied Sciences 2009.2, (4):363-371	Colorimétria	0,054	mg/L NH3-N	<0,054	<0,054	<0,054

ARI: Agua Residual Industrial, ARD: Agua Residual Doméstica, ARnD: Agua Residual no Doméstica, AN: Agua Superficial o Subterranea, AP: Agua Potable, S: Suelo, AM: Agua Marina, AX: Otros
* ChemiLab tiene estos parametros acreditados mediante resolución 2016 de 2014 y 1226 de 2016 del IDEAM.
** Análisis realizados por laboratorio subcontratado acreditado
(P) PICCAP
Parámetro no acreditado

OBSERVACIONES ANALITICAS

NINGUNA

Observaciones: Métodos de Análisis aplicados según el Laboratorio de Suelos IGAC y US-EPA (aplica para suelos)
Métodos de Análisis aplicados según Standard Methods for the Examination of Water and Wastewater (aplica para aguas)
Resultados validos únicamente para la(s) muestras analizadas.
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Coordinador de Reportes
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**** FIN DE ESTE REPORTE ****

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R 41033

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Número total de muestras: 3
Lugar de Muestreo: ETROPIKA GUAJIRA
Tipo de muestreo: Puntual
Tipo de Muestra: **ARI( ) ARD( ) ARnD( ) AN(X) AP( ) AM( ) S( ) AX( )**

Reporte de Resultados

Item	Fecha de Análisis (AAAA-MM-DD)	Parámetro	Método	Técnica	Límite de Cuantificación del método	Unidad	POZO No 5	POZO No 6	POZO No 7
							MN62483	MN62484	MN62485
1	2017-12-15	Nitrógeno amoniacal (Amonio)*	SM 4500 NH3-B, Asian Journal of Applied Sciences 2009.2, (4):363-371	Colorimétria	0,054	mg/L NH3-N	<0,054	<0,054	0,069

ARI: Agua Residual Industrial, ARD: Agua Residual Doméstica, ARnD: Agua Residual no Doméstica, AN: Agua Superficial o Subterranea, AP: Agua Potable, S: Suelo, AM: Agua Marina, AX: Otros
* ChemiLab tiene estos parametros acreditados mediante resolución 2016 de 2014 y 1226 de 2016 del IDEAM.
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(P) PICCAP
Parámetro no acreditado

OBSERVACIONES ANALITICAS

NINGUNA

Observaciones: Métodos de Análisis aplicados según el Laboratorio de Suelos IGAC y US-EPA (aplica para suelos)
Métodos de Análisis aplicados según Standard Methods for the Examination of Water and Wastewater (aplica para aguas)
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Empresa: AMBIUS SAS
Nit: 900506483 1
Dirección: CALLE 24C No 25-35 PISO 2
Solicitado por: Jaime Bermudez Gutierrez
Telefono: 2698305
Celular: --
E-mail: j.bermudez@ambius.com.co
Orden de Servicio: 20515

Fecha Recepción: 2017-12-05
Fecha de Emisión de Resultados: 2017-12-26
Fecha de Muestreo: 2017-11-30
Muestreo a Cargo de: CLIENTE
Plan de muestreo: No Reporta
Procedimiento de muestreo: No Reporta
Número total de muestras: 3
Lugar de Muestreo: ETROPIKA GUAJIRA
Tipo de muestreo: Puntual
Tipo de Muestra: **ARI( ) ARD( ) ARnD( ) AN(X) AP( ) AM( ) S( ) AX( )**

Reporte de Resultados

Item	Fecha de Análisis (AAAA-MM-DD)	Parámetro	Método	Técnica	Límite de Cuantificación del método	Unidad	POZO No 8	POZO No 9	POZO No 10
							MN62486	MN62487	MN62488
1	2017-12-15	Nitrógeno amoniacal (Amonio)*	SM 4500 NH3-B, Asian Journal of Applied Sciences 2009.2, (4):363-371	Colorimétria	0,054	mg/L NH3-N	<0,054	<0,054	<0,054

ARI: Agua Residual Industrial, ARD: Agua Residual Doméstica, ARnD: Agua Residual no Doméstica, AN: Agua Superficial o Subterranea, AP: Agua Potable, S: Suelo, AM: Agua Marina, AX: Otros
* ChemiLab tiene estos parametros acreditados mediante resolución 2016 de 2014 y 1226 de 2016 del IDEAM.
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(P) PICCAP
Parámetro no acreditado

OBSERVACIONES ANALITICAS

NINGUNA

Observaciones: Métodos de Análisis aplicados según el Laboratorio de Suelos IGAC y US-EPA (aplica para suelos)
Métodos de Análisis aplicados según Standard Methods for the Examination of Water and Wastewater (aplica para aguas)
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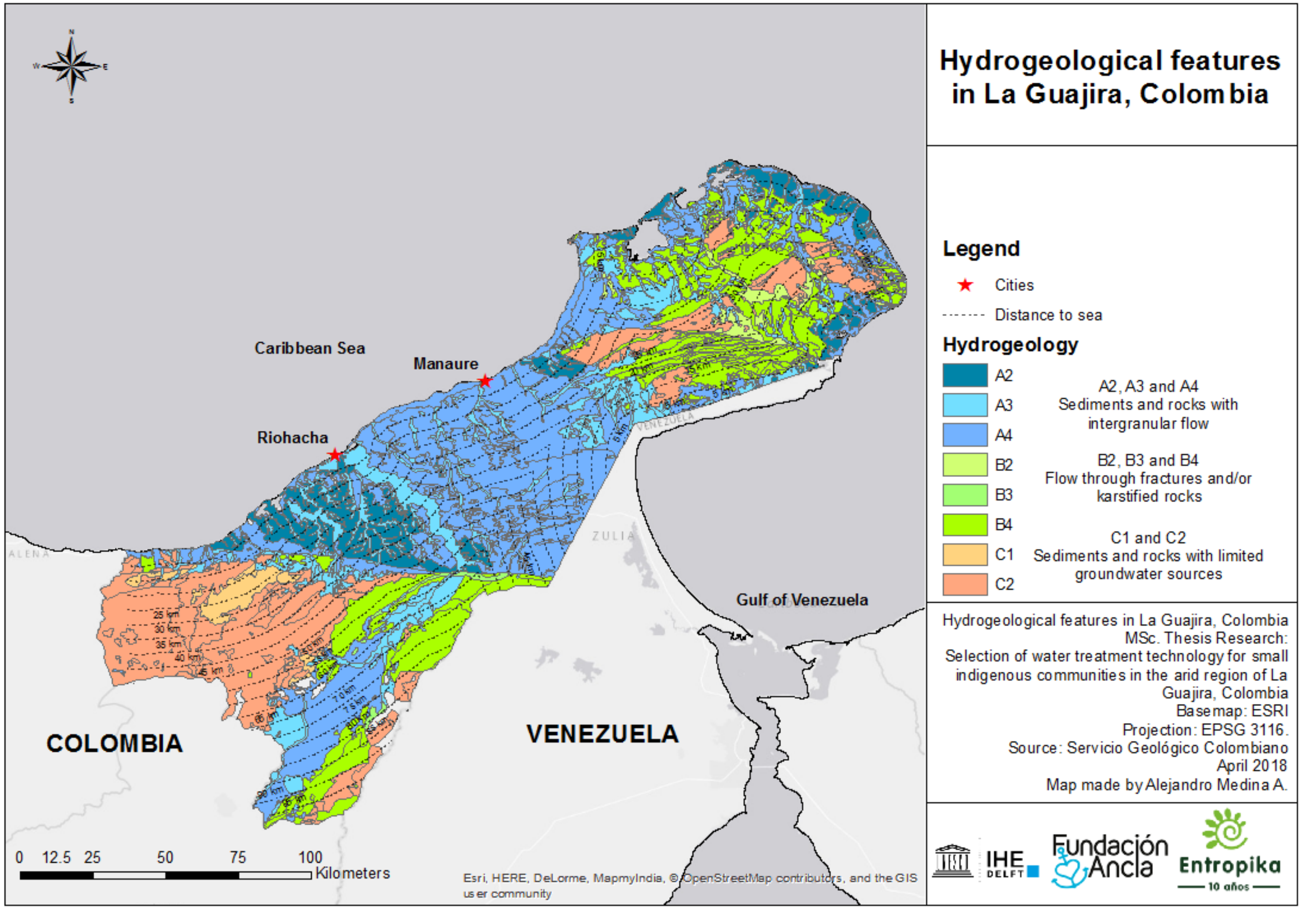
Appendix F **Map - Hydrogeological features in La Guajira, Colombia**



Appendix G **ANOVA – Proximity of sea and salinity**

Deep and shallow wells

Groups	Count	Sum	Average	Variance	Std. Deviation
0-10	202	601845	2979	3566323	1888
10-20	231	649379	2811	4013822	2003
20-30	164	362794	2212	2229636	1493
30-40	149	255180	1713	983923	992
40-50	70	147746	2111	1404837	1185
50-60	74	85887	1161	244394	494
60-70	70	64492	921	268124	518
70-80	50	41364	827	62797	251
80-90	43	26987	628	29707	172

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.34E+08	8	79210496	36.16	8.81E-51	1.95
Within Groups	2.29E+09	1044	2190288			
Total	2.92E+09	1052				

Deep wells

Groups	Count	Sum	Average	Variance	Std. Deviation
10	166	461710	2781	2499404	1581
20	134	349467	2608	3089226	1758
30	127	278029	2189	2169467	1473
40	133	235087	1768	1165596	1080
50	58	120087	2070	1439336	1200
60	55	59566	1083	159913	400
70	62	55833	901	257360	507
80	22	16383	745	94506	307
90	10	6612	661	43528	209

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.34E+08	8	41698272	23.25	5.46E-32	1.95
Within Groups	1.36E+09	758	1793183			
Total	1.69E+09	766				

Shallow wells

	Groups	Count	Sum	Average	Variance	Std. Deviation
	10	40	229257	5731	29195330	5403
	20	98	309109	3154	5526056	2351
	30	45	166847	3708	11912184	3451
	40	17	26125	1537	496730	705
	50	12	27660	2305	1304057	1142
	60	21	36458	1736	1375845	1173
	70	8	8659	1082	366738	606
	80	24	19163	798	18835	137
	90	32	19181	599	16076	127
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	7.21E+08	8	90157087	11.53	3.33E-14	1.97
Within Groups	2.25E+09	288	7819755			
Total	2.97E+09	296				

Appendix H **ANOVA - Hydrogeology and salinity**

Deep and shallow wells

Groups	Count	Sum	Average	Variance	Std. Deviation
A2	104	183909	1768	1305521	1143
A3	196	334039	1704	1178370	1086
A4	719	1529132	2127	2267714	1506

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.42E+07	2	17095475	8.72	1.76E-04	3.00
Within Groups	1.99E+09	1016	1961092			
Total	2.03E+09	1018				

Deep wells

Groups	Count	Sum	Average	Variance	Std. Deviation
A2	72	99900	1387	465992	683
A3	135	222940	1651	1055814	1028
A4	553	1242600	2247	2400300	1549

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.44E+07	2	37221112	18.79	1.09E-08	3.01
Within Groups	1.5E+09	757	1980886			
Total	1.57E+09	759				

Shallow wells

Groups	Count	Sum	Average	Variance	Std. Deviation
A2	31	99012	3194	6781883	2604
A3	65	138416	2129	2829999	1682
A4	169	308705	1827	2159885	1470

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.94E+07	2	24687363	8.65	2.29E-04	3.03
Within Groups	7.47E+08	262	2852814			
Total	7.97E+08	264				

Appendix I F-test and t-test for hydrogeology

Deep and shallow wells

F-Test Two-Sample for Variances

	A2	*A3*	*A4*	*A2*	*A4*	*A3*
Mean	1768	1704	2127	1768	2127	1704
Variance	1305521	1178370	2267714	1305521	2267714	1178370
Observations	104	196	719	104	719	196
df	103	195	718	103	718	195
F	1.11		1.74		1.92	
P(F<=f) one-tail	0.27		0.00		4.57E-08	
F Critical one-tail	1.32		1.30		1.21	

t-Test: Two-Sample Assuming Equal Variances

	A2 and A3
Pooled Variance	1222318
Hypothesized Mean Difference	0
df	298
t Stat	0.48
P(T<=t) one-tail	0.32
t Critical one-tail	1.65
P(T<=t) two-tail	0.63
t Critical two-tail	1.97

t-Test: Two-Sample Assuming Unequal Variances

	A2 and A4	*A3 and A4*
Hypothesized Mean Difference	0	0
df	160	422
t Stat	-2.86	-4.41
P(T<=t) one-tail	0.00	0.00
t Critical one-tail	1.65	1.65
P(T<=t) two-tail	0.00	0.00
t Critical two-tail	1.97	1.97

Deep wells

F-Test Two-Sample for Variances

	A3	*A2*	*A4*	*A2*	*A4*	*A3*
Mean	1651	1387	2247	1387	2247	1651
Variance	1055814	465992	2400300	465992	2400300	1055814
Observations	135	72	553	72	553	135
df	134	71	552	71	552	134
F	2.27		5.15		2.27	
P(F<=f) one-tail	0.00		0.00		0.00	
F Critical one-tail	1.42		1.37		1.26	

t-Test: Two-Sample Assuming Unequal Variances

	A2 and A3	*A2 and A4*	*A3 and A4*
Hypothesized Mean Difference	0	0	0
df	195	187	301
t Stat	-2.21	-8.26	-5.40
P(T<=t) one-tail	0.01	1.25E-14	6.74E-08
t Critical one-tail	1.65	1.65	1.65
P(T<=t) two-tail	0.03	2.51E-14	1.35E-07
t Critical two-tail	1.97	1.97	1.97

Shallow wells

F-Test Two-Sample for Variances

	A2	*A3*	*A2*	*A4*	*A3*	*A4*
Mean	3194	2129	3194	1827	2129	1827
Variance	6781883	2829999	6781883	2159885	2829999	2159885
Observations	31	65	31	169	65	169
df	30	64	30	168	64	168
F	2.40		3.14		1.31	
P(F<=f) one-tail	0.00		0.00		0.09	
F Critical one-tail	1.64		1.53		1.39	

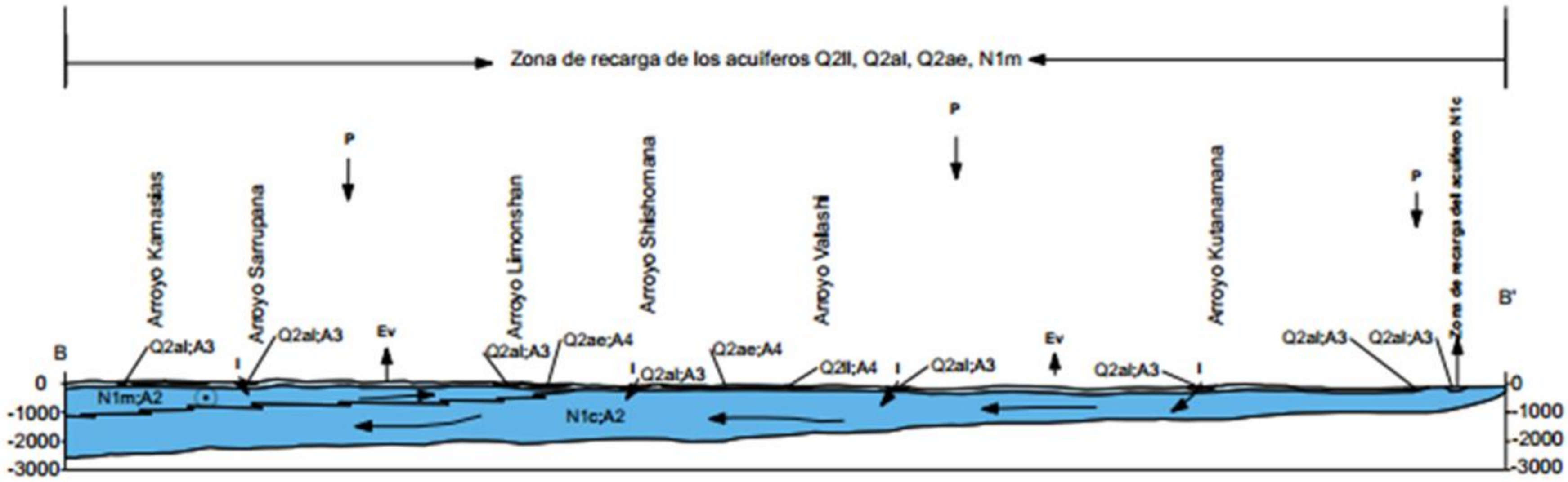
t-Test: Two-Sample Assuming Unequal Variances

	A2 and A3	*A2 and A4*
Hypothesized Mean Difference	0	0
df	42	34
t Stat	2.08	2.84
P(T<=t) one-tail	0.02	0.00
t Critical one-tail	1.68	1.69
P(T<=t) two-tail	0.04	0.01
t Critical two-tail	2.02	2.03

t-Test: Two-Sample Assuming Equal Variances

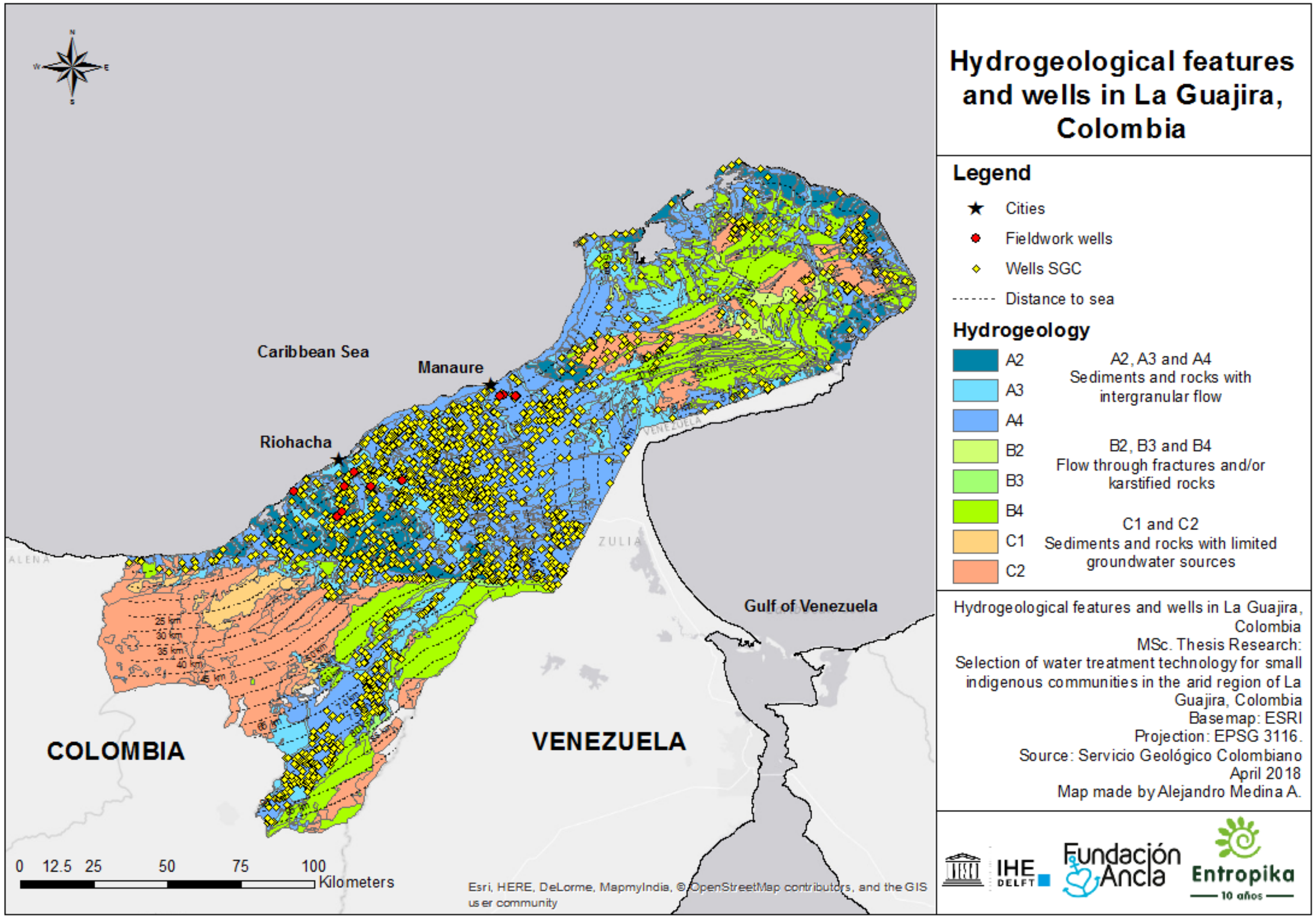
	A3 and A4
Pooled Variance	2344744
Hypothesized Mean Difference	0
df	232
t Stat	1.35
P(T<=t) one-tail	0.09
t Critical one-tail	1.65
P(T<=t) two-tail	0.18
t Critical two-tail	1.97

Appendix J **Cross-section of geologic structures in La Guajira**

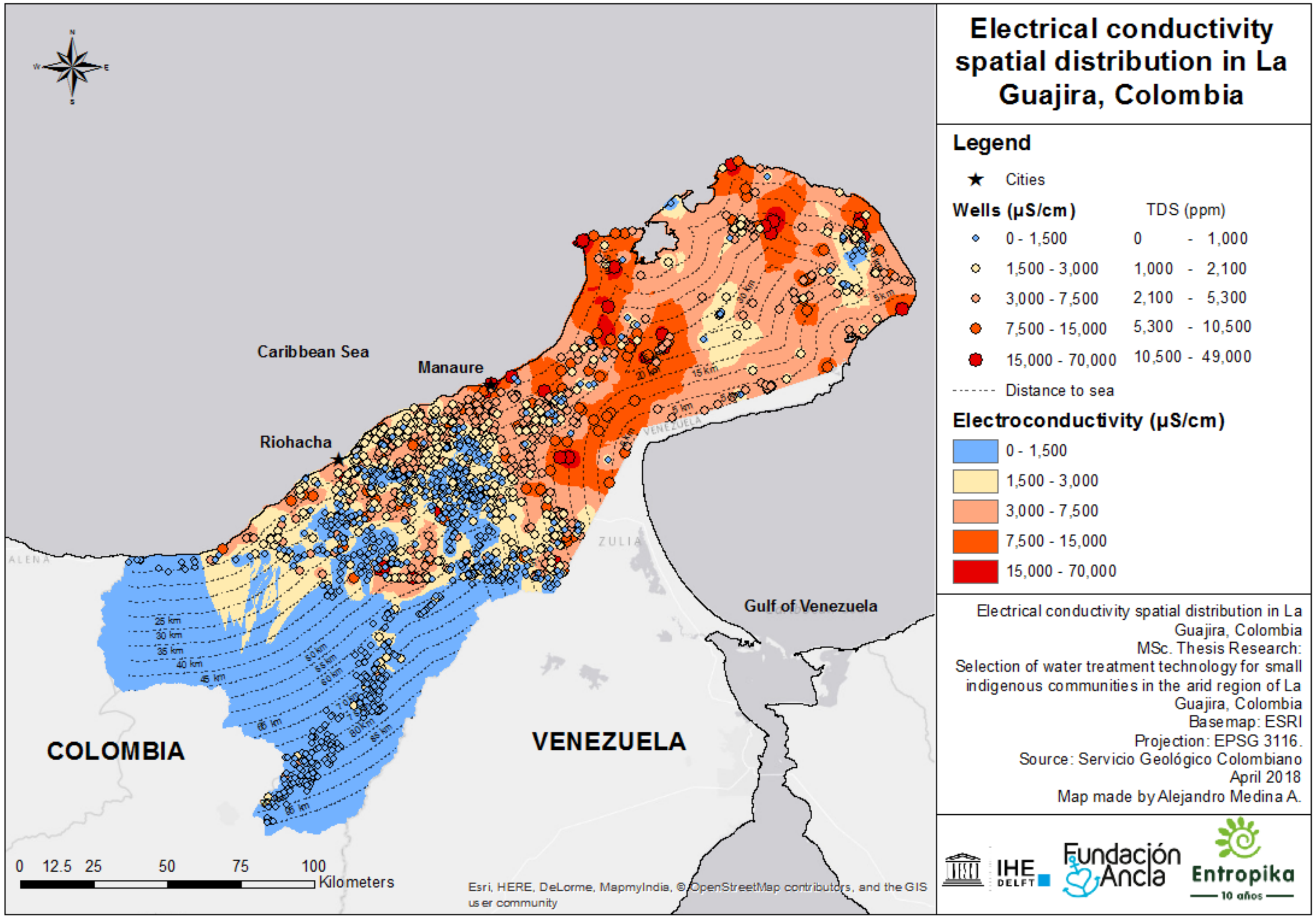


Note: Units in axis are in meters.

Appendix K **Map – Hydrogeological features and wells in La Guajira, Colombia**



Appendix L **Map – Electroconductivity spatial distribution in La Guajira, Colombia**



Appendix M Parameters for criteria in MCDA

	Investment costs	O&M costs[22]	Water production	Environmental impacts
Input	Capital cost of units.	Considers operation costs related use of consumables and to energy requirements (based on Colombian energy price). Additionally, it will add the percentage of the investment cost associated with maintenance.	Evaluates the capacity of a technology to supply the water needed. Also, it will evaluate if the water capacity exceeds too much or if it is below the water needed.	Considers the technology life cycle analysis and evaluates its environmental impacts.
Scoring	€/m3	€/m3	-,0.+	-,0.+
RO	115 m^3/day – 1.92 €/m^3 (Eltawil, et al., 2009) < 100 m^3/day - 5.25-7.35 €/m^3 RO + WP: 1000 m^3/day – 1.6 – 4.2 €/m^3. (Al-Karaghouli and Kazmerski, 2013) 12 m^3/day 5.36 – 6.64 €/m^3 (Mohamed and Papadakis, 2004)	Higher costs due to chemical and membrane replacement. BWRO 1-2.5 kWh/m^3 (Eltawil, et al., 2009). 1.5-2.5 kWh/m^3 for BWRO (Al-Karaghouli and Kazmerski, 2013) For membranes, energy + maintenance + consumables costs represent 37% of investment (Eltawil, et al., 2009).	15 m3/day 6-9 m3/day in Island of Suderoog (Eltawil, et al., 2009) <100 m3/day for RO+PV and 50-200 RO+WP (Shouman, et al., 2015). 12 m^3/day (Mohamed and Papadakis, 2004).	Brine disposal

[22] Electrical costs for membranes systems represent 43% of total O&M, while for thermal systems is 59% National Research Council (2004) Review of the Desalination and Water Purification Technology Roadmap The National Academies Press, Washington, DC.

Electricity price in the region, in average is $ 406 COP/kWh = 0.12 €/kWh (Source: https://goo.gl/W1BhWc)

Currency in Colombia is the COP. Exchange rate during the research was $3,550 COP = €1.00 (Source: https://www.oanda.com/lang/fr/currency/converter/).

	Investment costs	O&M costs[22]	Water production	Environmental impacts
ED	ED + PV 4.7-12.95 €/m^3 (Al-Karaghouli and Kazmerski, 2013)	2.64 – 5.5 kWh/m^3 (Al-Karaghouli and Kazmerski, 2013)	72-192 m3/day, ITC, Gran Canarias (Eltawil, et al., 2009)	Brine disposal.
Solar Stills	24 €/m^3 – 2.6 L/m^2/day (Fath, et al., 2003) 1.05-5.25 €/m^3 (Al-Karaghouli and Kazmerski, 2013)	No electricity when free circulation of air. On the other hand, with forced circulation, costs are still negligible. 2.10 €/m^3 (Fath, et al., 2003)	<0.1 m3/day (Shouman, et al., 2015). 1-100 m^3/day but higher capacities increase land use. For instance 1 hectare was used to produce 125 m^3/day (Goosen, et al., 2003; Sharon and Reddy, 2015)	No brine generation.
HDH	10 m^3/day – 50.92 €/m^3 (Chafik, 2004). 0.15 – 0.36 m^3/day 38 €/m^3 – 58 €/m^3 (Houcine, et al., 2006). 1 m^3/day – 5.25 €/m^3 (Yuan, et al., 2011)	31.1 kWh/m^3 (Sharon and Reddy, 2015).	10 m^3/day (Chafik, 2004). 0.15 – 0.36 m^3/day (Houcine, et al., 2006). 1 m^3/day (Yuan, et al., 2011)	Better management of less concentrated brine is achieved (Narayan, et al., 2010)
MVC	115 m^3/day – 4.05 €/m^3 500 m^3/day – 2.60 €/m^3 (Eltawil, et al., 2009) 100 – 3,000 m^3/day MVC + WP <100 m^3/day: 4.20–6.30 €/m^3 (Al-Karaghouli and Kazmerski, 2013)	7-12 kWh/m^3 (Al-Karaghouli and Kazmerski, 2013) Gran Canaria 14.4 kWh/m^3 (Ma and Lu, 2011)	<100 m3/day for MVC+WP (Shouman, et al., 2015) Gran Canaria 50 m^3/day (Ma and Lu, 2011).	Brine disposal. The impacts on the environment are low (Sharon and Reddy, 2015).

	Operation flexibility	Use of consumables	Ease of treatment	Alternative energy use capability
Input	Evaluates the ability a plant can treat different water qualities without affecting the operation, quality or quantity.	Evaluates the requirement a technology has for the use of different consumables, such a chemicals.	Evaluates the need of skilled labour requirements.	Evaluate the capacity a technology has to be ran only/mostly with renewable energy sources.
Scoring	-,0,+	-,0.+	-,0,+	-,0,+
RO	Pre-treatment is more necessary than for ED. However, compared to ED, pathogens are removed (Mathioulakis, et al., 2007). Vulnerable to feed quality water changes (Eltawil, et al., 2009).	Membranes life expectancy between 5-7 years (Eltawil, et al., 2009). Cleaning in place requires certain chemicals.	Operator is preferred to be qualified (Eltawil, et al., 2009).	Several PV, wind and combinations of energy sources have been installed. (Eltawil, et al., 2009; Mathioulakis, et al., 2007)
ED	If salinity is > 2000 ppm, RO is preferred. Further treatment for disinfection needed (Mathioulakis, et al., 2007).	Membranes with 7-10 life expectancy (Eltawil, et al., 2009). Cleaning in place requires certain chemicals.	Operator is preferred to be qualified and a frequent cleaning of membranes is required (Eltawil, et al., 2009).	Several PV, wind and combinations of energy sources have been installed. (Eltawil, et al., 2009; Mathioulakis, et al., 2007)
Solar Stills	Its operation is dependent on solar radiation. However, there is no distinction between water qualities. The risk of contamination of water is high and further treatment should be considered.	Not expensive but requires large areas (Sharon and Reddy, 2015) 4 L of water require 1 m^2 (Buros, 2000), which in turns results in large quantities of replacement parts.	No qualified technical labor is needed.	Already uses alternative energy sources. If convection of air within the still is wanted, it can be supplied by PV panels (Fath, 1998)
HDH	Easier to adapt to different water qualities (Narayan, et al., 2010).	The different parts of the system (coolers, heat exchangers, packed material, etc.) require a considerable stock of replacement parts (Giwa, et al., 2016).	No qualified technical labor needed.	Can be adapted to solar panels (Al-Sahali and Ettouney, 2008; Giwa, et al., 2016).
MVC	Highly adaptable to water quality variation (Sharon and Reddy, 2015).	The treatment needs small consumption of chemicals (Eltawil, et al., 2009).	There is continuous need of compressor maintenance (Eltawil, et al., 2009)	Several PV, wind and combinations of energy sources have been installed. (Eltawil, et al., 2009; Mathioulakis, et al., 2007)

Appendix N **Support information for the sensitivity analysis**

Water companies	1	2	3	4	5	Total
RO	0.730	0.190	0.050	0.020	0.010	4.610
Solar Stills	0.240	0.510	0.140	0.070	0.040	3.840
ED	0.020	0.250	0.480	0.140	0.110	2.930
MVC	0.000	0.020	0.200	0.620	0.160	2.080
HDH	0.000	0.030	0.130	0.160	0.680	1.510

Academia	1	2	3	4	5	Total
RO	0.730	0.200	0.040	0.020	0.010	4.620
Solar Stills	0.250	0.480	0.120	0.110	0.030	3.780
MVC	0.010	0.240	0.630	0.120	0.000	3.140
ED	0.010	0.080	0.160	0.470	0.280	2.070
HDH	0.000	0.010	0.040	0.280	0.670	1.390

NGO	1	2	3	4	5	Total
Solar Stills	0.470	0.370	0.060	0.070	0.040	4.190
RO	0.500	0.310	0.060	0.050	0.080	4.100
MVC	0.010	0.090	0.430	0.420	0.050	2.590
ED	0.020	0.150	0.280	0.250	0.290	2.330
HDH	0.010	0.080	0.170	0.200	0.540	1.820

Communities	1	2	3	4	5	Total
Solar Stills	0.760	0.170	0.040	0.030	0.000	4.660
HDH	0.050	0.370	0.360	0.210	0.010	3.240
RO	0.180	0.320	0.130	0.280	0.090	3.220
MVC	0.010	0.140	0.460	0.380	0.000	2.750
ED	0.000	0.000	0.000	0.100	0.900	1.100

Overall	1	2	3	4	5	Total
RO	0.560	0.310	0.050	0.040	0.040	4.310
Solar Stills	0.410	0.430	0.070	0.050	0.030	4.110
MVC	0.000	0.060	0.410	0.450	0.070	2.440
ED	0.010	0.120	0.290	0.250	0.320	2.220
HDH	0.010	0.070	0.180	0.210	0.540	1.830

Appendix O **IMSDesign membrane specification sheet**

Nitto | HYDRANAUTICS Nitto Group Company

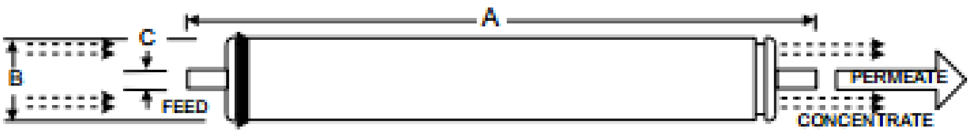
	Membrane Element	ESPA2-4040
Performance:	Permeate Flow:	1,900 gpd (7.2 m^3/d)
	Salt Rejection:	99.6% (99.4% minimum)
Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Membrane Active Area:	85 ft^2 (7.9 m^2)
Application Data*	Maximum Applied Pressure:	600 psig (4.14 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	pH Range, Continuous (Cleaning):	2-10.6 (1-12)*
	Maximum Feedwater Turbidity:	1.0 NTU
	Maximum Feedwater SDI (15 mins):	5.0
	Maximum Feed Flow:	16 GPM (3.6 m^3/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	15 psi

* The limitations shown here are for general use. For specific projects, operating at more conservative values may ensure the best performance and longest life of the membrane. See Hydranautics Technical Bulletins for more detail on operation limits, cleaning pH, and cleaning temperatures.

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

1500 PPM NaCl solution
150 psi (1.05 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
15% Permeate Recovery
6.5 - 7.0 pH Range



A, inches (mm)	B, inches (mm)	C, inches (mm)	Weight, lbs. (kg)
40.0 (1016)	3.95 (100.3)	0.75 (19.1)	8 (3.6)

Core tube extension = 1.05" (26.7 mm)

Notice: Permeate flow for individual elements may vary +25 or - 15 percent. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are enclosed in a sealed polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box. All elements are guaranteed 99.4% minimum rejection.

Hydranautics Corporate: 401 Jones Road, Oceanside, CA 92058
1-800-CPA-PURE Phone: 760-901-2500 Fax: 760-901-2578 info@Hydranautics.com

Appendix P **Photographic registration of fieldwork**

Arriving to different communities

Visit to Triple A water company in Manaure

Typical houses of the indigenous communities

Water collection and transport in wheelbarrows

In-situ testing of water parameters

Surveys to locals and leaders


Goats in the communities


Goats drinking water from small jawei


Treatment plant and operator in Ishasihamana


Treatment plant in Aremasain boarding school