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AN OPTIMIZATION MODEL FOR TREATMENT AND ALLOCATION OF WATER RESOURCES

by
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AN ABSTRACT OF THE THESIS OF

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Increasing population, diminishing supplies, and climate changes may cause difficulty in meeting water demands. Scarcity in water resources is a major concern for water resources planners all over the world. Water requirements are exceeding the availability of fresh water resources, so desalination and water reuse are becoming increasingly popular in sustainable water management.

The objective of this thesis is to introduce an optimization-based decision support system for the treatment and allocation of water resources. The developed approach targets the minimization of the overall economic cost of the water treatment and distribution system, as well as the associated environmental cost of the employed treatment processes, transportation, construction and maintenance, etc… The system considers the available sources of water, the locations of treatment plants and applicable technologies, and the demand for water and provides an optimal solution on the volume of water from each source to be transported to each plant and treated by an appropriate technology in order to satisfy certain demand at the lowest possible overall economic and environmental cost. We propose an integer program as a mathematical formulation of the problem addressed. To achieve this formulation, we gather data on economic and environmental costs of different water treatment options from a variety of sources, and model the cost functions based on the gathered data.

We also propose an alternate decision support system based on multi-criteria decision analysis to incorporate the qualitative criteria (such as social criteria) that may affect the decision maker's choice in addition to quantitative criteria. This allows the comparison among all possible treatment alternatives, and considers the key criteria involved in the selection of alternatives, giving each criterion a weight based on its importance in the decision.

The use of the proposed decision tools, instead of intuitive judgments, could assist in improving the quality of the decision by making it more explicit, rational and efficient.

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CHAPTER 1

INTRODUCTION

Water is an essential resource to all forms of human activities; whether it is for basic uses of drinking and sanitation, or agriculture, industry, and other forms of demand. The scarcity of fresh water sources in different regions all over the world is becoming more critical with every day due to different factors that include but are not limited to: climate change, increasing consumption with population growth, and limited resources.

The amount of water on Earth is almost 2 billion km^3. Of this volume, about 3% is fresh water. About 2.5% (24 million km^3) is in the form of ice and permanent snow cover in mountainous regions, the Antarctic, and Arctic regions. The remaining 0.5% (10,217,120 km^3) is present in the form of underground aquifers, natural lakes and rivers, rainfall, and man-made storage facilities water (Fry and Haden, 2005).

The UN defines different water statuses based on the local water availability (m^3/person/year). The status is *adequate* when the water availability is 1700-4000 m^3/person/year. When the local water availability lies between 1000 and 1700 m^3/person/year, the status is *water stress*. *Water scarcity* is when the amount falls within the range of 500-1000 m^3/person/year (Fry and Haden, 2005). Water scarcity already affects almost every continent and more than 40% of the world population. The Middle East and North Africa are the most water scarce regions in the world. These areas contribute to about 6.3% of the world's population, but receive only 1.4% of Earth's renewable fresh water (Miller, 2003). The forecast is that by 2025, 1.8 billion people will be living in regions with absolute water scarcity, and two-thirds of the people in the world could be living under water stressed conditions (Fry and Haden, 2005).

The problem that we address in this thesis can be summarized as follows: given the available sources of water, the locations of treatment plants and applicable technologies, and the demand for water; we need to determine the optimal amount of water from each source to be transported to each plant and treated by an appropriate technology in order to satisfy certain demand at the lowest possible overall economic cost (in $ terms) and environmental cost (in terms of carbon footprint expressed in kg CO_2e).

The construction of a mathematical optimization model for water resource treatment and allocation for a certain area requires the knowledge of the available water treatment alternatives and technologies, the costs associated with these alternatives (whether economic, social, environmental,…), and their applicability to that specific area.

In this paper we propose an integer program as a mathematical formulation of the problem addressed. The objective of the linear program is to minimize the overall economic and environmental cost of the water treatment and distribution system, subject to technical constraints. To achieve this formulation, we gather data on economic and environmental costs of different water treatment options from a variety of sources, and model the cost functions based on the gathered data. The result is a decision support system (DSS) that can aid decision makers in the optimal design of water treatment and distribution systems while keeping the environmental damage under control.

The optimization-based DSS only takes into account the quantitative criteria affecting the decision. To incorporate the qualitative criteria that may affect the decision maker's choice, we propose an alternate DSS based on multi-criteria decision analysis (MCDA). This system allows the comparison among all possible treatment alternatives, and considers the key factors (criteria) involved in the selection of alternatives. The resulting system supports decision making by incorporating the investor's priorities of the different options available into the final outcome.

The outline of this paper is as follows. In Chapter II we provide a review of literature available on the proposed subject and identify our contribution in the field. Chapter III gives a detailed statement of the problem studied, explaining in detail the different aspects to be considered. An overview of applicable water treatment technologies is presented in Chapter IV. Recommended quality guidelines for different water uses are stated in Chapter V and followed by a comprehensive cost data collection in Chapter VI. The devised mathematical model is presented in Chapter VII, along with a case study application to the presented optimization model. Chapter VIII presents the DSS based on MCDA and the decision outcome, and we conclude our study in Chapter IX.

CHAPTER 2

LITERATURE REVIEW

While there have been several studies that aim to select the optimal water treatment strategies under a given set of criteria by developing various DSSs, they have not included all the treatment options we will consider nor have they given the environmental impact of carbon footprint such a priority. Before diving into the subject, we present the work done by others in this field. A summary of the reviewed literature is presented in Table 1.

Method	***Application***	***Reference***
DSS based on Multi Criteria Decision Analysis	OMP treatment system selection	Sudhakaran et al. (2013)
	Desalination technology selection	Afify (2010)
DSS based on Multi Criteria using ELECTRE	Selection of location for water supply system project	Morais and Almeida (2007)
DSS based on LP Optimization	Evaluation of wastewater treatment schemes	Joksimovic et al. (2006)
	Design of water desalination and distribution networks	Atilhan et al. (2012)
DSS based on Fuzzy-AHP and TOPSIS	Desalination technology selection	Ghassemi and Danesh (2013)
Environmental DSS based on Cost-Benefit Analysis	Assessment of waste water treatment plant design	Molinos-Senante et al. (2012)

Table 1: Literature Review Summary

Sudhakaran et al. (2013) created a decision support system (DSS) based on multi-criteria analysis (MCA) to compare processes for organic micropollutant

(OMP) removal under various criteria. A survey among two groups of participants including academics and industry representatives was conducted to assign weights for the following criteria: treatability, costs, technical considerations, sustainability and time. The proposed DSS can be used as a screening tool for experimental planning or a feasibility study preceding the main treatment system selection and design. It can also be considered as an aid in assessing a multi-barrier approach to remove OMPs (Sudhakaran et al., 2013).

Joksimovic et al. (2006) developed a simulation model to be used in combination with an integrated optimization engine. The focus was on the evaluation of performance and cost of a number of treatment alternatives to select the most appropriate ones. The simulation model includes a default knowledge base, as well as separate computational modules for wastewater treatment schemes and the reclaimed water distribution system. The least-cost sizing of the distribution system facilities is ensured by incorporating a linear programming (LP) algorithm, which uses the information on standard pipe sizes and pumping station costs contained in the model knowledge base. The DSS provides a framework for evaluation and optimization of treatment and distribution aspects of water reuse, and can be used to achieve the project aim of the development of the design principles for water reuse systems (Joksimovic et al., 2006).

Chung et al. (2008) presented a general water supply planning tool, useful for decision makers to plan water management strategies, that is comprised of modular components including water sources, users, recharge facilities, and water and wastewater treatment plants. Model components include detailed domestic indoor and outdoor usage, industrial, agricultural, and environmental demands, multiple supplies, conveyance between sources and demand centers, and surface and groundwater storage. Water quality was modeled through the system including water and wastewater treatment plants. They concluded that the resulting decisions were made based on engineering judgment; and that these modules should be linked with optimization routines for better more reliable results (Chung et al., 2008).

Ghassemi and Danesh (2013) developed an integrated two-step model based on the fuzzy-AHP and TOPSIS methods for the selection of the optimum desalination technology. The fuzzy-AHP was used to analyze the structure of the selection process and to determine the weights of the various environmental, technical and economic criteria and sub-criteria, and the TOPSIS method was used to calculate the final ranking of the technologies. Their results showed that membrane-based technologies (ED and RO) have priority over the distillation technologies. The sensitivity analysis indicated that changes made in the criteria weights do not affect the final output of the model Ghassemi and Danesh (2013).

Afify (2010) also made a comparison among all the possible desalination alternatives for Egypt, considering key factors involved in the selection such as the use of desalinated water, source of feed water, desalination technology, locations of the plants, and their capacities using Multi-criteria Decision Analysis (MCDA). Values for each criterion corresponding to the different desalination alternatives were first standardized to obtain standardized scores. Then the alternatives were ranked based on the weighted sum of the standardized scores. He found that alternatives of any plant size are more prioritized than smaller plants using the same technology because of the double costs reduction. It was also found that rankings are sensitive to changes in the weights (Afify, 2010).

Morais and Almeida (2007) dealt with the allocation of resources for water supply applying the ELECTRE method (a multi-criteria decision-aid support tool that allows comparison among alternatives in pairs) in order to choose the city in which a water supply system project will be implemented, by integrating weighted qualitative judgment criteria that are usually conflicting. Different factors (economic, environmental, social, and political) were considered in evaluating the alternatives. Weights were assigned to each criterion reflecting the preferences of the decision makers. They concluded that use of this method, instead of intuitive judgments, assisted in improving the quality of the decision by making it more explicit, rational and efficient (Morais and Almeida, 2007).

Atilhan et al. (2012) developed an optimization-based approach for the design of water desalination and distribution networks to satisfy the demands of the various water-consuming sectors. This approach accounts for fluctuations in water demand, and considers the available energy sources tied to desalination. Two objectives were considered: economic potential and resource conservation. They applied the approach to a case study dealing with the management of water resources in the State of Qatar. As a result, the total monthly stored fresh water was calculated, and the existing fresh water was stored and reached full storage capacity after the first month (Atilhan et al., 2012).

Molinos-Senante et al. (2012) developed a pioneer approach for implementing efficient and effective policies and strategies for wastewater treatment since it integrated not only the traditional methodology for the economic assessment but also environmental benefits from wastewater treatment were included by using an environmental decision support system (EDSS). A useful economic feasibility indicator was obtained for each technology including internal and external costs as well as a benefits indicator associated with the environmental damage avoided. Their study assessed nine different technologies set-up for the secondary or main treatment step in small wastewater treatment plants (WWTPs). They concluded that the developed EDSS is useful for the development of feasibility studies for wastewater management projects, justifying the implementation of technologies aimed to increase the level of environmental protection (Molinos-Senante et al., 2012).

After presenting the work done in the field of developing DSSs for water treatment systems, it is easier to outline the contribution of our study. The value of the model we present in this paper lies in the variety of treatment options available to the decision maker, and in the environmental damage limitation that he/she can impose. Thus, the model provides the decision maker an optimal distribution of water sources to be treated by the appropriate technology to satisfy different demands at a minimum economic cost and a limited environmental damage.

CHAPTER 3

PROBLEM STATEMENT

Aside from the size of the population, other factors influence water use in a specific region. The type of the community (agricultural, industrial, residential), level of development of the economy (ability to finance water development and treatment plans), and local climate greatly affect the amount of water consumption (Miller, 2003). Thus, the uses of water are classified into three main categories: (1) Domestic, (2) Agricultural, and (3) Industrial.

To satisfy increasing demands, all possible water sources are studied. In addition to the fresh water available as surface water (rivers and lakes) and groundwater (aquifers and wells), we consider non-traditional sources of water such as seawater and wastewater.

Some of these sources (mainly seawater) need to undergo desalination to become adequate for use, others need to go through some treatment processes in order to become acceptable for use, and some might even need both. This depends on the quality of the available feed water, and the quality of the required water depending on the different uses.

In any given area, there are some available water sources, and a certain demand from the community. The goal is to select the water sources that are to be used to satisfy the local demand, and the plant in which they are to be treated by a specific technology, based on a set of selection criteria as described below. The primary objective is to minimize the overall cost of this system, in both its economic and environmental forms. A general sketch of our problem is shown in Figure 1.

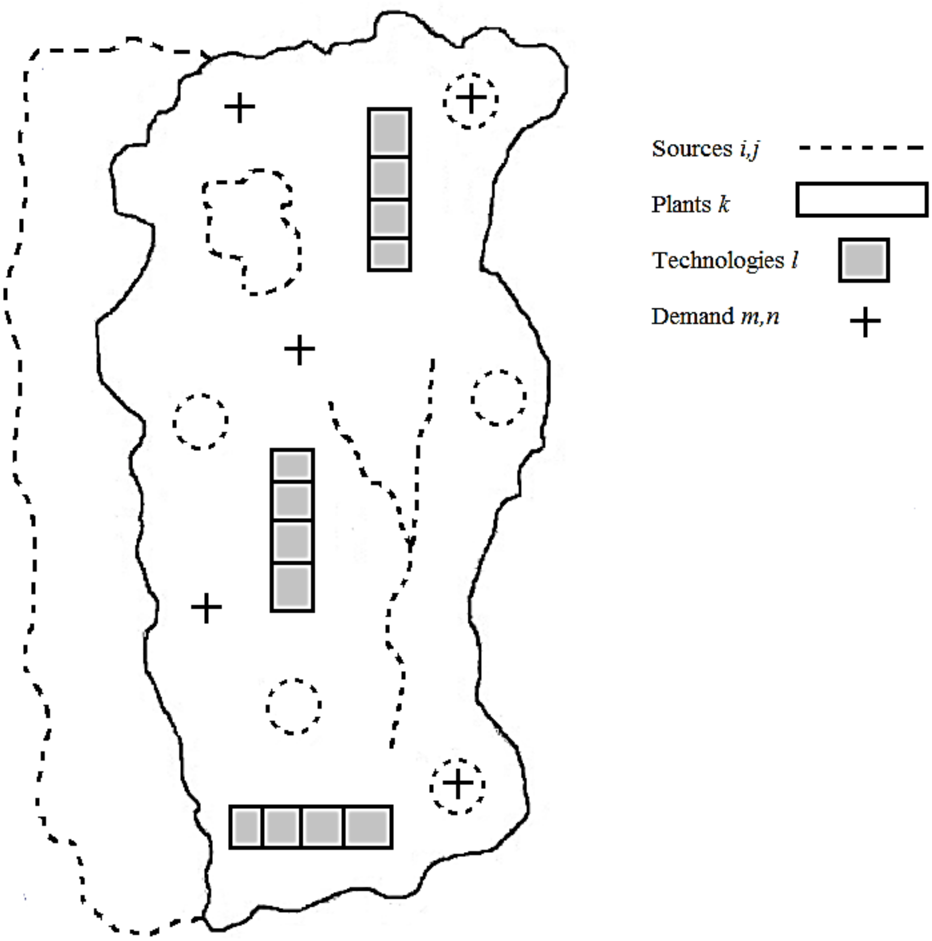

Figure 1: Problem Sketch

After identifying the alternative water sources and associated treatment technologies, and considering the expected uses of this resource, we define the criteria for decision making. These criteria were formulated and specified after conducting a detailed literature review on the subject, and bearing in mind the goal to minimize the economic and environmental cost of the project.

3.1 Economic Criteria

This category measures the net cost (in $ terms) of the project. It includes the cost of initial design and construction of the water treatment plants and transportation systems, the cost of operation and maintenance, in addition to the cost of transporting the water. The criteria are as follows:

a. Capital cost: equipment, installation, construction
b. Operating cost: energy requirements, service and maintenance, supplies and parts, labor, pre-treatment of feed water and post-treatment of output water
c. Land Requirement
d. Pumping and transportation: source nodes to treatment plants, and treatment plants to demand nodes

3.2 Technical Criteria

No one process is necessarily “the optimum”. A variety of factors come into attention when selecting the appropriate process for a particular situation. These factors include the quality of the source water, the desired quantity and quality of the water produced, pretreatment, and chemical requirements. The criteria are as follows:

a. Feed water quality: degree of salinity, TDS, pH, hardness, toxicity, microbial content, and chemical content
b. Required water quality based on end use: guidelines/recommendations for drinking water, irrigation water, and water for industrial use

c. Brine and waste management: both end products should be disposed off in an environment-friendly and economic manner in compliance with national standards and internationally accepted environmental quality criteria
d. Water recovery rate: amount of output water relative to the input water flow

3.3 Environmental Criteria

During the construction and operation of the proposed system, there are several factors contributing to environmental damage, most notably the greenhouse gas emissions and the waste produced. Other factors include noise pollution, pollution due to possible leakage, and so on. This category measures the environmental cost of the project. The criteria are as follows:

a. Carbon footprint: an estimate of the amount of greenhouse gases (GHGs) expressed as carbon dioxide equivalents (CO_2e) released into the environment as a result of this system over some period of time.

3.4 Social Criteria

Every project has a social component; and even though it is difficult to quantify, it must not be neglected. The proposed system has a number of effects on the society. While it may benefit people to have cleaner water, some may not be able to afford it, and others may reject it for personal beliefs. The social criteria are as follows:

a. Sanitation and health benefits: improvement in the local population’s quality of life corresponding to less water borne diseases, and more personal hygiene

b. Job creation: implementation of water treatment projects employs many people; this job creation is beneficial to the society and contributes to improvement in the quality of life
c. Cultural and religious issues: local population’s acceptability/tolerance to the drinking or use of treated wastewater; unwillingness is partly based on the fear of risks involved and related to the potential effects of contaminants on human health

CHAPTER 4

TREATMENT TECHNOLOGIES

Before being ready for human use, water from different sources must undergo some processes in order to become safe and sanitary. Such processes may include desalination or just some cleaning treatment depending on the quality of the feed water.

4.1 Desalination Technologies

Desalination is a process that removes dissolved minerals (including but not limited to salt) from seawater, brackish water, or treated wastewater. All desalination processes involve three liquid streams: the saline feed water (brackish water or seawater), the low-salinity product water, and a very saline concentrate (known as brine or reject water). A number of technologies have been developed for desalination. These can be divided into two main categories (thermal and membrane) based on the principle used.

4.1.1 Thermal Processes

Thermal processes employ distillation, which is a phase separation method where saline water is heated to produce water vapor, which is then condensed to produce freshwater. There are various distillation processes used to produce potable water, including MSF, MED, and VC.

The Multi-stage Flash (MSF) Distillation process is based on the concept of flashing. The saline water is repeatedly heated and evaporated, and then the steam is condensed to produce the fresh water. The process is as follows. The seawater is heated in the brine heater by low pressure steam supplied from a power plant. The heated seawater enters into the evaporator flash chambers. Evaporation takes place gradually when water vapor is produced with the successive reduction of pressure applied to the heated water. The flashed water vapor is then condensed and cooled (Miller, 2003, Khawaji et al., 2008).

Multiple-effect Distillation (MED) is similar to MSF in that it involves the evaporation and condensation of saline water. In MED vapor from each stage is condensed in the next stage and the heat from this vapor is used to drive more evaporation. The process is as follows. Saline water is sprayed on the outside of tubes causing the vapor inside these tubes to condense. The heat from the vapor causes the saline water to boil and generate the steam to be condensed at the next stage (Miller, 2003, Khawaji et al., 2008).

Compared to MSF distillation, MED is thermally more efficient and can operate at lower temperatures.

In Vapor Compression (VC) Distillation processes, the evaporation is driven by heat supplied from the compression of vapor. The vapor is either compressed mechanically (with a mechanical compressor) or thermally (with a steam ejector). Low temperature VC distillation is simple and generally used for small-scale desalination units (Miller, 2003, Khawaji et al., 2008).

4.1.2 Membrane Processes

Membrane processes employ pressure to move saline water across a semi-permeable membrane in order to obtain fresh water on the other side of the membrane.

In Reverse Osmosis (RO) processes, water is extracted from the saline water by passing it through a membrane in the reverse direction to the natural flow across the membrane by applying to it a pressure larger than the osmotic pressure of the saline water. The pressure contributes to most of the energy required for RO, and it is directly related to the level of salinity of the feed water. For this reason RO desalination processes are more popular with brackish water than seawater (Miller, 2003, Khawaji et al., 2008, Greenlee et al., 2009).

Unlike RO and distillation processes, Electrodialysis (ED) makes use of a current source to separate the water from the dissolved salts. The saline water passes through several channels separated by alternating anion and cation selective membranes (Miller, 2003). This technology is commercially used for brackish water applications only.

4.2 Water Treatment Technologies

For water to be potable, it needs to be treated pathogens, microbes, and other dangerous chemicals.

4.2.1 Conventional Treatment

Almost all water treatment plants employ conventional pretreatment systems to prepare the feed water and reduce its turbidity. This includes processes such as acid addition, coagulant/flocculant addition, and filtration. Adding acids such as sulfuric acid and hydrochloric acid reduces the pH of the feed water and this increases the solubility of calcium carbonate which a common precipitate in feed waters. Coagulants (small, positively charged molecules) allow suspended solids to group together in flocs. Flocculation and sedimentation are often used with coagulation before filtration. These processes are common methods of particle removal in water treatment. Granular filtration uses several materials as layers (such as sand and gravel) of the filter to make use of their different sizes (Greenlee et al., 2009).

4.2.2 Membrane Treatment

A newer trend in pretreatment systems employs membranes (microfiltration MF, ultrafiltration UF, and nanofiltration NF). The filtration process involves passing liquids through a membrane that has a minimum pore size. Suspended and dissolved particles that are larger than the membrane pore size are blocked by the membrane while the water and smaller particles pass through. Filtration membranes and processes are subdivided by pore size ranges. The various categories, from largest to smallest pore size, include: microfiltration (0.01-1μm), ultrafiltration (0.001-0.01μm), nanofiltration (0.0001-0.001μm), and reverse osmosis (<0.0001μm). As membrane pore size decreases, the energy required to push the water solution through the membrane increases. Both MF and UF processes require low trans-membrane pressure (compared to RO and NF) to operate, and both are now used as a pretreatment to desalination technologies such as RO, NF, and ED, but cannot remove salt themselves. UF membranes are perhaps the best; they have smaller pore sizes than MF membranes, and higher flux than NF membranes. MF membranes are suitable for removing larger particulate matter, while NF membranes are good for removing dissolved contaminants as well as particulate matter. The type of membrane used depends on the required contaminant removal (Greenlee et al., 2009).

4.2.3 Disinfection

There are several different disinfectants, which either kill or deactivate pathogenic microorganisms. All disinfectants have benefits and drawbacks and can be used for water disinfection depending on the circumstances. There are two kinds of disinfection: primary disinfection achieves the desired level of microorganism kill or inactivation, while secondary disinfection maintains a disinfectant residual in the finished water that prevents the regrowth of microorganisms. Examples of disinfection methods are chlorination, oxidation, UV treatment, and ozonation.

Chlorine is one of the most well-known disinfectants worldwide. The amount of chlorine needed for disinfection is related to the turbidity of the water, its pH, temperature, and concentrations of ammonia, hydrogen sulfide, Fe, and Mn. Chlorine is very effective for removing almost all microbial pathogens and is appropriate as both a primary and secondary disinfectant. It also acts as an oxidant and can remove or assist in the removal or chemical conversion of some chemicals (Gadgil, 1998).

Ozone is a good oxidant and widely used disinfectant (after chlorine). However, it requires high cost and excessive care in not releasing excess ozone into the air (Gadgil, 1998).

Ultraviolet light has a germicidal effect because it damages the DNA of micro-organisms. It is most effective at a wavelength of 260 nm. UV treatment has high energy efficiency when compared to pasteurization. It also has an advantage over chemical disinfection in that it leaves no taste or odor to the treated water and no health risks from overdosing (Gadgil, 1998).

4.2.4 Water Softening

For hard water (water containing large amounts of certain salts such as calcium and magnesium), a water softening process is used to remove the hardness. One common process is ion exchange. It is useful for demineralizing water to improve its purity. Ion exchangers are organic or inorganic solids that exchange one type of ion immobilized in the solid for another type of ion in the solution (for example Na^+ ions in the solution can be replaced with H^+ in a cation exchanger) (Miller, 2003).

4.3 Wastewater Treatment

Wastewater is generated when water combines with wastes from domestic, commercial, and industrial facilities. It contains high levels of organic materials, pathogenic microorganisms, and toxic compounds. Recycled water has the advantage of being a constant, reliable water resource, and reduces the amount of water extracted from the environment. Treatment of wastewater is carried out in three or four stages depending on the end-use. The first stage, preliminary treatment, prepares the wastewater for further treatment by employing physical processes to remove large solids, abrasive grit, odors, oil, and grease. These physical processes include coarse screening, comminution, flotation, equalization, flow equalization, and neutralization. The second stage, primary treatment, removes suspended solids and organic matter by physical operations such as fine screening and sedimentation. It produces a liquid that can be treated biologically in the next stage, and sludge that should be treated before being disposed. The third stage, secondary treatment, employs biological processes to convert the dissolved organic matter into flocculent settleable organic and inorganic solids. Such biological processes include activated sludge (AS) process, trickling filtration, oxidation, rotating biological contactor, sequencing batch reactor (SBR), and membrane bioreactor (MBR). The fourth stage, tertiary treatment, purifies the water by removing nitrogen, phosphorus, metals, biodegradable organics, bacteria, and viruses. This is achieved by several processes such as disinfection (by chlorine, UV…), evaporation, filtration (by reverse osmosis, nanofilters…), ion exchange, and chemical precipitation (Lakshmana Prabu et al., 2011).

CHAPTER 5

WATER QUALITY GUIDELINES

The primary purpose of the guidelines for water quality is the protection of public health. Water is essential to sustain life, and a satisfactory (adequate, safe and accessible) supply that must be available to all. Improving access to safe water can result in tangible benefits to health. Every effort should be made to achieve a water quality as safe as possible.

5.1 Drinking Water Quality Guidelines

The "Guidelines for Drinking-water Quality", a book regularly published by the World Health Organization (WHO), explains the requirements to ensure drinking-water safety, including minimum procedures and specific guideline values, and how those requirements are intended to be used (World Health Organization, 2008). The guidelines describe a quality of water that is acceptable for lifelong consumption. Safe drinking-water is suitable for all usual domestic purposes, including personal hygiene.

The ability to achieve a guideline value within a drinking-water supply depends on a number of factors, including: the concentration of the chemical in the raw water; control measures employed throughout the drinking-water system; nature of the raw water (groundwater or surface water, presence of natural background and other components); and treatment processes already installed (World Health Organization, 2008).

For the purpose of this thesis, we will not consider all the WHO guidelines, but limit our study to only the few most important factors in drinking water quality which include total dissolved solids (TDS), pH, and hardness. The values for these factors are shown in Table 2.

TDS is the term used to describe the inorganic salts and small amounts of organic matter present in solution in water. The principal constituents are usually calcium, magnesium, sodium, and potassium cations and carbonate, hydrogen carbonate, chloride, sulfate, and nitrate anions. Their presence in water may affect its taste as well as produce technical side-effects such as increasing hardness of the water (World Health Organization, 2008).

The pH value of a water source is a measure of its acidity or alkalinity. Pure water would have a pH of 7.0, but water sources and precipitation tends to be slightly acidic, due to contaminants that are in the water. Chemical pollution, from industrial operations, individuals and communities, can cause a water body to become acidic (World Health Organization, 2008).

Water hardness is the traditional measure of the capacity of water to react with soap, hard water requiring considerably more soap to produce lather. Hard water often produces a noticeable deposit of precipitate (e.g. insoluble metals, soaps or salts) in containers. Hardness is most commonly expressed as milligrams of calcium carbonate equivalent per liter (World Health Organization, 2008).

5.2 Agricultural Water Quality Guidelines

The agricultural use classification defines waters that are suitable for irrigation of crops, consumption by livestock, support of vegetation for range grazing, and other uses in support of farming and ranching and protects livestock and crops from injury due to irrigation and other exposures. The quality of water is not only important in determining the productivity of plants and animals, but also in its impact on the health of the human population consuming these products.

While there are water quality requirements for all aspects of agriculture (water for farm uses, water for preparing produce and milk, water for livestock, water for irrigation), we will focus on those specified for irrigation. Guideline values are shown in Table 2.

Salinity is a measure of the total amount of salt in the water. Electrical conductivity or Total Dissolved Solids tests are two means of measuring salinity. The properties of the soil, the ground water and the landscape interact with the salinity of the irrigation water to either increase or decrease the salinity hazard (National Research Council et al., 1972).

Some dissolved solids are worse than others, and the amount of elements in relationship to each other is also important. The relative proportion of sodium cations to other cations can give rise to soil permeability problems. The Sodium Absorption Ratio (SAR) describes the amount of excess sodium in relationship to calcium and magnesium. The TDS should be used together with SAR or with the amount of sodium cations (measured in mg/L) in the irrigation water (National Research Council et al., 1972).

The pH of normal irrigation water has little or no direct significance.

5.3 Industrial Water Quality Guidelines

Water quality requirements differ widely for the broad variety of industrial uses but modern water treatment technology is capable of treating almost any raw water and rendering it suitable for use in any industry. The closer the composition of the available water to the particular composition required, the more desirable that water is; and conversely the more such compositions differ, the more timely and expensive it is to modify the available water for particular use. Guideline values for the most important factors are shown in Table 2.

Water Use	***Guideline Values***			
	TDS (mg/L)	pH	Hardness (mg/L)	Sodium, Na (mg/L)
Domestic Use	≤ 500	≥ 6.5 ≤ 8.5	≥ 50 ≤ 100	NA
Agricultural Use	≤ 1000	≥ 4.5 ≤ 9.0	NA	≤ 70
Industrial Use	≤ 700	≥ 7.0 ≤ 9.0	NA	NA

Table 2: Guidelines for Water Quality

Dissolved solids can produce hard water, and high amounts of dissolved solids can corrode water pipes, form deposits and films, and cause scaling. Water with a pH that is less than 6.5 can leach metal ions, including iron, manganese, copper, lead and zinc from plumbing fixtures and pipes. Other guidelines include the hardness of the water, the turbidity and color, and the presence of solids, floating materials, and deposits. The hardness of or the mineral compounds contained in the water should not appreciably impair the usefulness of the water as a source of industrial water supply. There should also be no turbidity or color in amounts or characteristics that cannot be reduced to acceptable concentrations by conventional water treatment processes. Moreover, there should be no distinctly visible solids, scum, foam, oily slick, or the formation of slimes, bottom deposits or sludge banks of such size or character as may impair the use of the water in any industry (National Research Council et al., 1972).

CHAPTER 6

COSTS

The capital and operating water costs are primary parameters used by decision makers to select the appropriate water treatment technology for a project. Cost data reported is commonly not consistent for different technologies or similar-sized facilities, because they are site-specific. In fact, the cost of treatment with different processes depends on many parameters. In this thesis, we will show the different costs reported by various studies, and then use the numbers we find to be most appropriate to our application.

Capital cost, often referred as CAPEX or Capital Expenditure, includes all expenditures associated with the implementation of a given water treatment project from the time of its conception, through design, permitting, financing, construction, commissioning and acceptance testing for normal operation. Land cost depends on the contract agreement and may vary from zero to an agreed sum depending on the site characteristics.

Operating costs, also referred to as OPEX or Operating Expenditure, are site-specific and consist of fixed costs and variable costs. Fixed costs include insurance and amortization costs. The primary variable operating costs include the cost of labor, energy, consumables (chemicals, parts replacement, pump replacement…), and maintenance.

The parameters that affect the total investment and operational costs of water treatment plants are the major factors considered in selection of an appropriate technology. The estimated cost of treatment with different processes depends mainly on the following parameters:

i. Energy consumption and type of energy available (conventional energy sources, renewable energy sources, hybrid systems).
ii. Process configuration, plant capacity and its component design. The investment cost of different water treatment technologies varies widely due to use of different equipment, different energy requirements, different chemicals required, pretreatment needed…
iii. Feed water quality, temperature, intake arrangement and required product water quality.
iv. Reject discharge type and disposal methods.
v. Materials, equipment, chemicals and other consumables.
vi. O&M, equipment replacement, skilled labor costs and training requirements.

Based on these parameters, we will discuss in more detail the different costs associated with the different water treatment processes described earlier.

6.1 Pumping and Transportation Costs

Cost of groundwater pumping is a function of pump efficiency, lift (depth to groundwater), and cost of the type of energy expended. Groundwater unit volume cost increases with depth to groundwater, as more energy is required for pumping and deeper wells might be needed. These costs usually range between \$0.01 and \$0.20/m3, depending on the country and the aquifer (Plappally and Lienhard, 2012, Llamas and Martínez-Santos, 2005).

The cost of transporting surface water is mainly dependent on distance, elevation difference, soil conditions, labor costs, electricity costs, and spare parts costs. The variation of pumping uphill and flow due to gravity are other aspects that can influence the variation in the cost of water. It is therefore difficult to compare pipeline construction costs from one location to another. There is also significant influence of the mode of transport on the cost of water supplied. Trucks could be used to transport water, but such an option would have large operational costs and energy requirements, and would generate large amounts of greenhouse gases. Another alternative would be to use canals, which are open channels cut through the land. However, a canal needs to follow the contours of the land. This means it tends to be much longer than a direct pipeline. Pipelines are preferred over canals because they minimize the amount of water lost to seeping and evaporation since the transported water is not exposed to sunlight or air. Pipelines also maintain the transported water quality (Plappally and Lienhard, 2012).

In their study of the water life cycle cost, Plappally and Lienhard (2012) found the ground and surface water extraction costs in Western countries and Australia to be similar. These results are summarized in Table 3.

Location	***Process***	***Cost (\$/m^3)***
Europe and USA	Ground/surface water production without distribution	0.40-0.75
Western Australia	Ground/surface water production with distribution	0.45-0.61

Table 3: Ground and Surface Water Extraction Costs

Zhou and Tol (2005) estimated the costs for transferring water from the Nile to Gaza. They found that transporting 10^8 m^3 of water per year over a distance of 200 km would cost 0.214$/m^3. Of this, 0.04$/m^3 were for the purchase of Egyptian water, and 0.052$/m^3 for lifting the water some 100 m. Thus, it cost 0.061$/m^3 per 100 km to transport water. If the transfer scheme were to be extended to 5x10^8 m^3 of water per year, total costs would fall to 0.198$/m^3 and consequently the transport costs to 0.053$/m^3 per 100 km (Zhou and Tol, 2005, Plappally and Lienhard, 2012).

In their study to estimate unit production costs for long-distance piping to supply water to some regions of Egypt, Lamei et al. (2008) performed a multiple linear regression on collected data about different long-distance water piping projects in Egypt to correlate unit capital and unit production costs with length (distance of transfer) and volumetric capacity of the pipelines. The following two relationships were obtained:

$$C_c = 49 + 18.5L - 0.04Q_w \qquad \text{and} \qquad C_p = 0.04 + 0.01L - 10^{-5}Q_w$$

Where C_c is the unit capital cost in \$/m^3/d; C_p is the unit production cost in \$/m^3; L is the length in km; and Q_w is the capacity in m^3/d (Lamei et al., 2008).

6.2 Water Desalination Processes Costs

Desalination capacity has rapidly increased in the last decade because of the increase in water demand and a significant reduction in desalination cost as a result of significant technological advances, especially in the RO process. The reduction in RO treatment cost has been favored by the growth rate, plant capacity, competition with other technologies, and the vast improvements in RO systems (better process designs, membranes and materials, and lower energy consumption). There is variability in the cost for water desalination because the water cost depends upon many factors, most important of which are the desalination method, the level of feed water salinity, the energy source, the capacity of the desalting plant, and other site related factors.

Thermal methods are more expensive because of the large quantities of fuel required to vaporize salt water. In general, thermal energy contributes to half the cost of the thermal desalination process. Systems that use thermal methods have usually large production capacity. In a water desalination cost literature review done by Karagiannis and Soldatos (2008), they summarized thermal process costs as shown in Table 4.

Desalination Method	***Plant Size (m^3/day)***	***Cost (\$/m^3)***
MED	≤ 100	2.50-10.00
	12,000-55,000	0.95-1.95
	> 91,000	0.52-1.01
MSF	23,000-528,000	0.52-1.75
VC	1,000-1,200	2.01-2.66

Table 4: Thermal Desalination Methods and Cost of Water Produced

On the other hand, membrane methods, mainly RO, can desalt brackish water somewhat more economically, and have replaced thermal methods for the desalination of brackish water. However, because of the high cost of membrane replacement, membrane methods are less suitable for desalinating seawater. Membrane process costs collected by Karagiannis and Soldatos (2008) are shown in Table 5.

Type of Feed water	***Desalination Method***	***Plant Size (m^3/day)***	***Cost (\$/m^3)***
Brackish	RO	≤ 20	5.62-12.90
		20-1,200	0.77-1.32
		5,000-60,000	0.26-0.54
	ED	-	0.60
Seawater	RO	≤ 100	1.50-18.75
		250-1,000	1.25-3.92
		1,000-5,000	0.70-1.72
		12,000-60,000	0.47-1.62
		100,000-320,000	0.45-0.66

Table 5: Membrane Desalination Methods and Cost of Water Produced

Wittholz et al. (2008) created a cost database for the different desalination technologies. The data collected included information about the plants including location, the technology being used, plant capacity, operating life, availability and the type of water being treated. Cost data collected included the capital cost, fixed cost, annual operating cost and unit product cost. The capital cost includes the plant and land costs, civil works and amortization. The operating cost per m^3 of water produced included the cost of chemicals for pre and post water treatment, energy requirement (including electricity and steam), spares and maintenance, and labor. Plant data was collected spanning the period from 1970 to 2005.

Loutatidou et al. (2014) collected cost data from 950 RO desalination plants contracted in the Gulf Cooperation Council (GCC) countries and in five southern European countries. Parameters potentially affecting the direct capital costs of brackish water RO (BWRO) and seawater RO (SWRO) desalination plants included plant capacity, location, award year, feed salinity, and the cumulative installed capacity within a region. They used multiple linear regression and developed a model to estimate the direct CAPEX of RO desalination plants to be located either in the GCC countries or southern Europe. They found that the capacity of an SWRO or BWRO desalination plant is the most important statistical parameter influencing the CAPEX of the plant, and concluded that the strong linearity of capital cost and annual capacity confirm that the capital cost of RO plants follows the pattern of scale-economy.

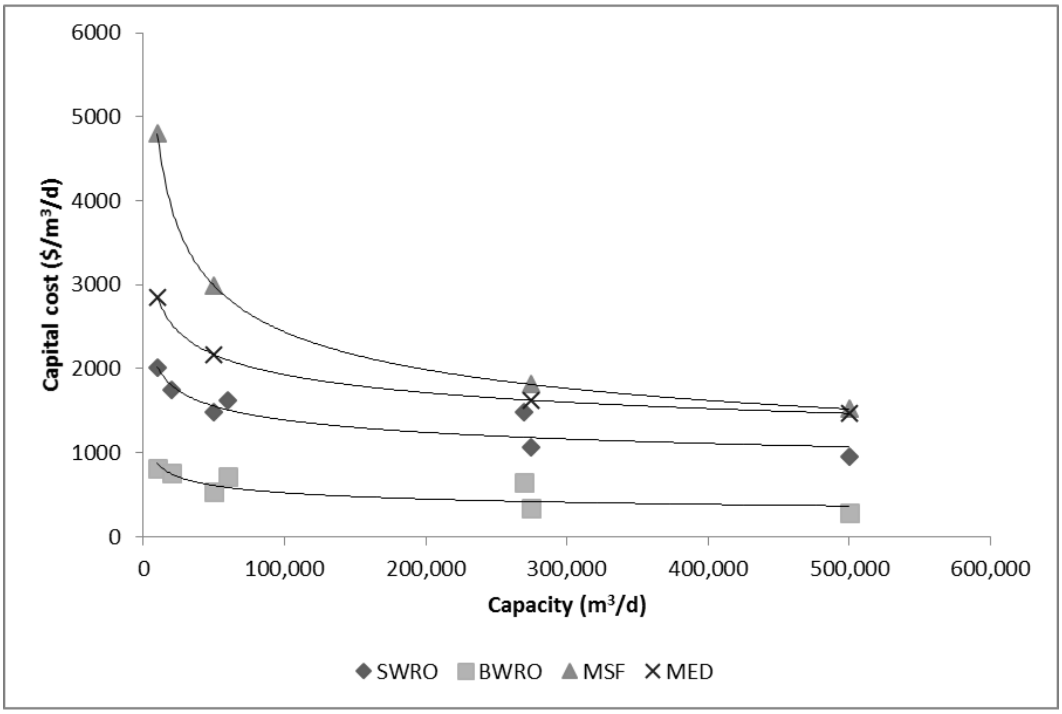

Figure 2: Investment Cost for Different Desalination Processes

Figures 2 and 3 show the cost curves constructed as part of the data collection phase of this thesis. The data used in forming these cost curves and functions was obtained from Wittholz et al. (2008) and Loutatidou et al. (2014) for investment and operating costs function of the plant capacity C (m^3/d). There was no sufficient information available for ED and VC, so they were excluded. The shape of the curves indicates that the system cost follows the pattern of economies of scale; i.e. the system cost decreases as the capacity used increases.

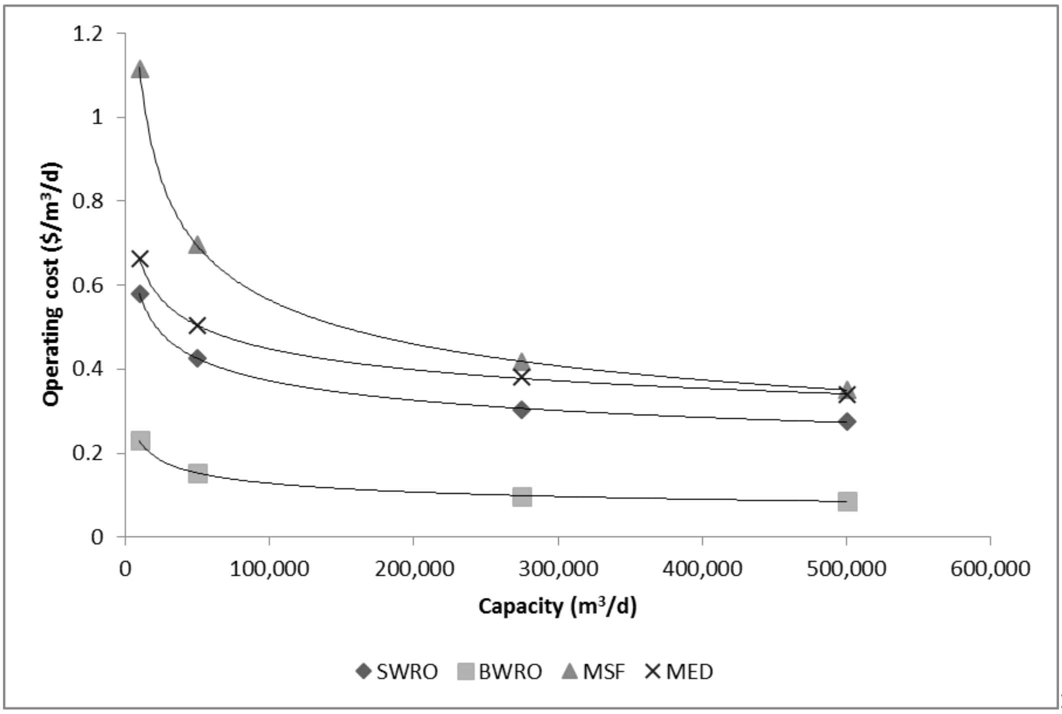

Figure 3: Operating Cost for Different Desalination Processes

Desalination Process	***Capital Cost ($/m³/d)***	R^2	***Operating Cost ($/m³/d)***	R^2
MSF	$8995.2C^{-0.162}$	0.7994	$3.4241C^{-0.193}$	0.9997
MED	$6756.5C^{-0.222}$	0.6479	$2.4051C^{-0.255}$	0.9993
SWRO	$72029C^{-0.294}$	1	$17.214C^{-0.297}$	1
BWRO	$13584C^{-0.17}$	1	$3.1725C^{-0.17}$	0.9996

Table 6: Capital and Operating Cost Functions for Desalination Processes

Table 6 includes the cost functions and the R^2 values. The high R^2 values validate the choice of representing the cost functions in the form of AC^n.

6.3 Wastewater Treatment Processes Costs

Factors that influence the investment cost of wastewater treatment plants (WWTP) include plant capacity, design criteria, treatment process, land cost, location of construction and weather conditions, as well as competition among bidders and suppliers and stability of the local and national economic conditions. The investment cost includes: construction costs, contingencies, engineering, overhead expenses, industrial profit, and VAT. The O&M cost of WWTPs includes: labor, materials, chemicals, repairs, and energy.

A cost function modeling approach was applied by Gonzalez-Serrano et al. (2005) to analyze the effectiveness and cost of WWTP options for various uses of reclaimed water in seasonally stressed regions. They obtained two cost estimations: one for investment costs I, and another for operational and maintenance costs C. They formulated the investment cost function as $I = AQ^n$ where I is total cost of investment (€), Q is flow rate (m^3/h), A, and n are constant parameters. The O&M costs were calculated using the equation $C = -\alpha lnQ + \beta$ where C is total cost of operation and maintenance (€/m^3), Q is also flow rate (m^3/h), α, and β are constant parameters.

The main limitation for the model proposed by Gonzalez-Serrano et al. (2005) is that it only provides information about the influence of the size of plant on the cost. To overcome this weakness, Hernandez-Sancho et al. (2011) proposed a new formulation for the operating cost function. The modified O&M cost function is

$C = AV^b e^{(\sum \alpha_i x_i)}$ or in logarithmic terms $lnC = lnA + blnV + \sum \alpha_i x_i$ where A, b and α_i are parameters, C is total cost per year, V is volume of wastewater treated per year; and the x_i are different kinds of variables representative of the treatment processes such as the age of the facility, and the efficiency removal (%) of the following contaminants removed: suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), nitrogen (N) and phosphorus (P).

Technology		***Cost Function***
Suspended Growth Processes	EA	$C = 169.4844V^{0.4540}e^{(0.0009A+0.6086SS)}$
	AS	$C = 2.1165V^{0.7128}e^{(0.0174A+1.5122SS+0.0372BOD)}$
	NR	$C = 2.518V^{0.7153}e^{(0.007A+1.455COD+0.258N+0.243P)}$
Attached Growth Processes	BB	$C = 17.3617V^{0.5771}e^{(0.1006A+0.6932COD)}$
	PB	$C = 1510.84V^{0.2596}e^{(0.0171SS)}$
	BD	$C = 28.9522V^{0.4493}e^{(2.3771SS)}$
Tertiary Treatment	TT	$C = 3.7732V^{0.7223}e^{(0.6721COD+0.1958N+0.7603P)}$

Table 7: Cost Functions for Each WWT Technology

WWT systems were classified into two major categories, depending on the way in which microorganisms grow: suspended in the liquid under treatment or attached to a solid support. Extended aeration without nutrient removal (EA), activated sludge without nutrient removal (AS) and activated sludge with nutrient removal (NR) are the three types of suspension growth technologies more widely used. Concerning the attached growth processes, other three technologies considered were: Bacterial beds (BB), peat beds (PB) and biodisk (BD). WWTPs with tertiary treatment (TT) were been included in a third group since in these plants only costs associated with this stage of the process were considered. The cost functions and their determination coefficients are shown in Table 7. C is total cost (€/year), V is total wastewater treated volume (m^3/year), A is the WWTP age (years), SS is suspended solid removal efficiency (%), COD is chemical oxygen demand removal efficiency (%), BOD is biological oxygen demand removal efficiency (%), N is nitrogen removal efficiency (%), and P is phosphorous removal efficiency (%) (Hernandez-Sancho et al., 2011).

According to NRC (2012), the factors that affect the costs of a wastewater treatment program include the location of the facility, treatment infrastructure, plant influent water quality, customer use requirements, transmission and pumping, timing and storage needs, energy requirements, concentrate disposal, and financing costs. In most cases, non-potable uses of reclaimed water (e.g., irrigation, industrial) require a quality of water that is not much different than what a typical secondary or advanced wastewater treatment plant would produce. Potable reuse projects require substantially more treatment, and therefore require larger investments than non-potable projects. The reported costs by NRC (2012) are shown in Table 8.

Use of Reclaimed Water	***Capital Cost ($/m^3/year)***	***O & M Cost ($/m^3)***
Potable	1029.02 – 8179.42	81.79–627.97
Non-potable	300.79 – 4947.23	13.19 – 311.35

Table 8: Capital and Operational Costs for Potable and Non-potable Water Reuse

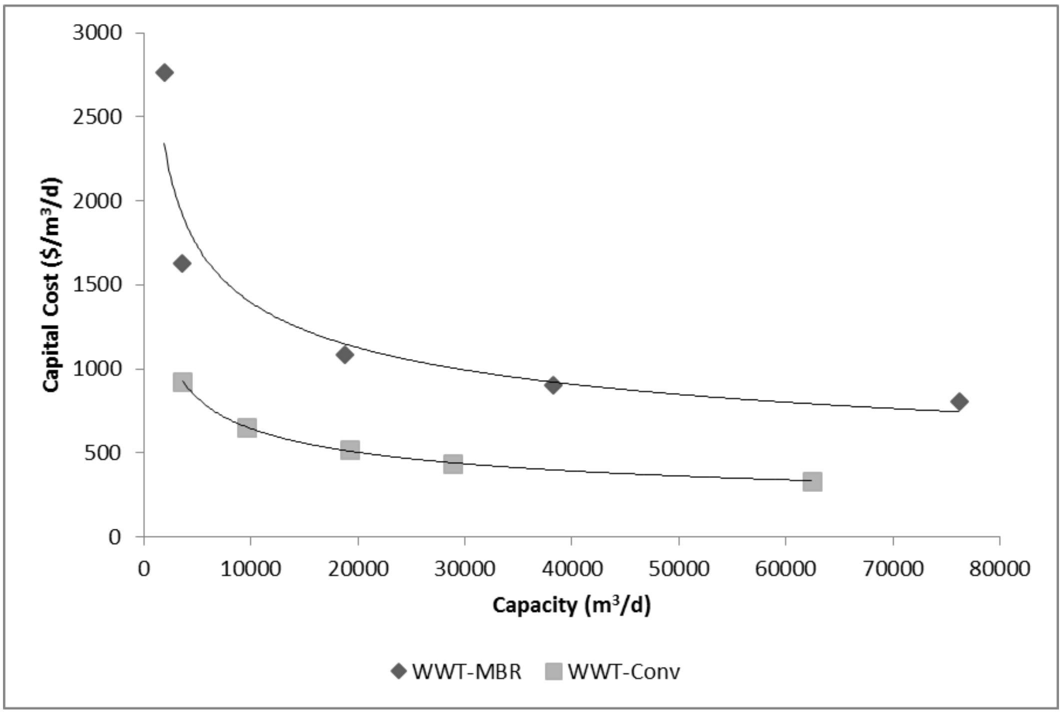

Figure 4: Investment Cost for Different Wastewater Treatment Processes

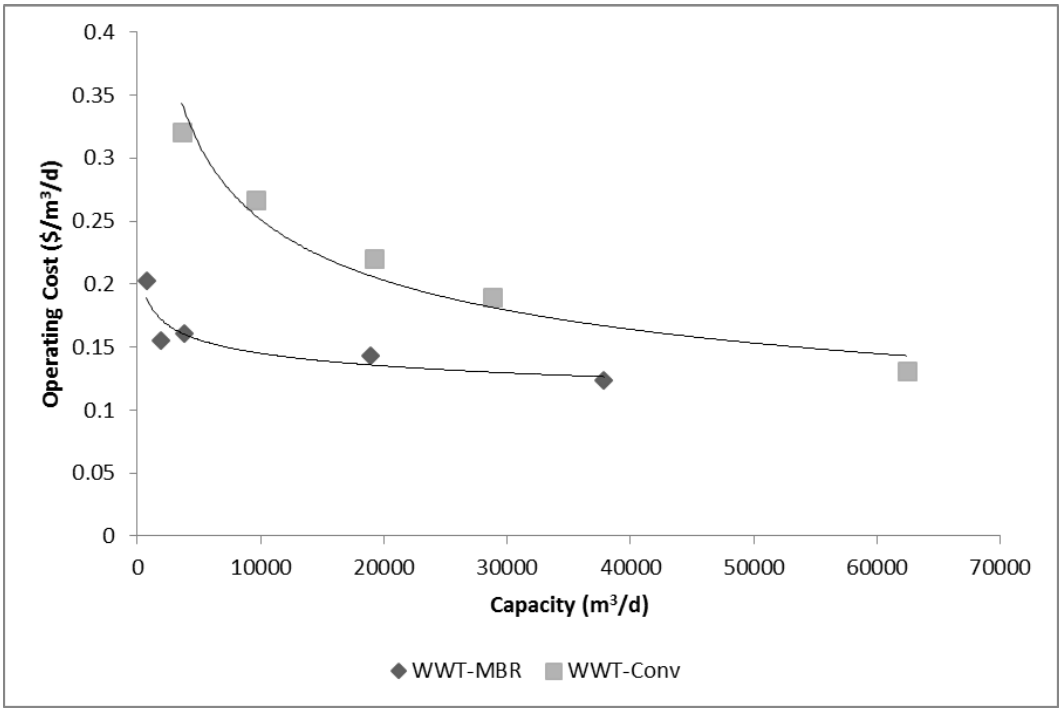

Figure 5: Operating Cost for Different Wastewater Treatment Processes

Figures 4 and 5 show the cost curves constructed as part of the data collection phase of this thesis. The data used in forming the WWT-MBR cost curve and function was obtained from Côté et al. (2004), Brepols et al. (2009), Adham and DeCarolis (2004), and DeCarolis et al. (2007) for investment and operating costs function of the plant capacity C (m^3/d). The data used in forming the WWT-Conv cost curve and function was obtained from Gonzalez-Serrano et al. (2005). The shape of the curves indicates that the system cost follows the pattern of economies of scale.

Wastewater Treatment Process	***Capital Cost ($/m³/d)***	R^2	***Operating Cost ($/m³/d)***	R^2
WWT-Conv	$17599C^{-0.359}$	0.9986	$4.2652C^{-0.307}$	0.9543
WWT-MBR	$24313C^{-0.31}$	0.9336	$0.375C^{-0.103}$	0.8541

Table 9: Capital and Operating Cost Functions for Wastewater Treatment Processes

Table 9 includes the corresponding cost functions and the R^2 values. The high R^2 values validate the choice of representing the cost functions in the form of AC^n.

6.4 Other Water Treatment Processes Costs

The membrane processes of most significance in water treatment are reverse osmosis (RO), ultrafiltration (UF), microfiltration (MF) and nanofiltration (NF). As mentioned in previous sections, the most common application of RO is desalination of brackish water and seawater. A detailed cost description for RO was also provided earlier.

Capital costs for NF systems vary from $0.8 to $4/gpd ($210.53 - $1052.63/$m^3$ per day), depending on various factors including size, materials of construction and site location. Operating costs are assumed similar to BWRO, approximately \$0.70/kgal (\$2.66/m^3). Moderate reductions in energy costs can be obtained by implementing energy recovery subsystems (CSM, 2009).

Polymeric MF/UF membranes are relatively inexpensive. Capital cost for polymeric UF systems vary based on the size of the plant and feed water quality. Approximate capital costs will be near \$1 - \$2/gpd (\$0263.16 - \$526.32/m^3 per day) and O&M costs approximately \$1 to \$2/kgal (\$3.8 to \$7.6/m^3) (CSM, 2009).

Membrane filtration systems' capital costs, on a basis of dollars per volume of installed treatment capacity, do not escalate rapidly as plant size decreases. This factor makes membranes quite attractive for small systems. In addition, for groundwater sources that do not need pretreatment, membrane technologies are relatively simple to install, and the systems require little more than a feed pump, a cleaning pump, the membrane modules, and some holding tanks.

Another popular treatment process is disinfection. There are different ways to achieve disinfection, but we will mainly focus on disinfection by chlorination and by UV radiation.

UV radiation disinfection is a popular form of primary disinfection because of its ease of use, no need of chemicals, and no formation of disinfection byproduct. EPA estimated capital costs are \$0.13/gpd (\$34.21/m^3 per day). For chlorination, capital costs can be near to \$0.01/gpd (\$2.63/m^3 per day), O&M costs can be approximately \$0.05/kgal (\$0.19/m^3) (CSM, 2009).

Chen et al. (2008) explored the current and long-term effects of Delta export water quality on drinking water treatment cost and public health risk from disinfection byproduct (DBP) formation. Costs for each treatment technology include capital and O&M costs. The capital cost includes construction components such as excavation and site work, equipment, concrete and steel, labor, pipe and valves, power supply access and instrumentation, and housing. These costs are expressed as annualized capital costs, assuming a 5% interest rate and 20 years of operation. O&M costs include building-related energy, process energy, maintenance materials, and labor. The annualized capital cost and annual O&M cost were summed to obtain the total annualized cost.

Size of System (m^3/day)	3,785 – 26,495	26,495 – 287,660	287,660 – 1,968,200
Total annualized cost (\$/m^3)	0.017 – 0.085	0.008 – 0.018	0.005 – 0.010
Annual Capital Cost (\$/m^3)	0.012 – 0.063	0.006 – 0.008	0.003 – 0.004
Annual O&M cost (\$/m^3)	0.005 – 0.022	0.002 – 0.010	0.002 – 0.006

Table 10: Cost of UV Disinfection for Different System Sizes

Estimated total annualized and annual O&M costs of UV disinfection for three system sizes appear in Table 10. These costs were estimated by assuming a UV dose of 40 mJ/cm2. An uninterrupted power supply (UPS) system was considered. Low and medium pressure lamps were assumed to be replaced annually and every six months, respectively. Although this technology is potentially cost-effective, UV disinfection uses large amounts of electricity and requires regular lamp cleaning, which can be expensive (Chen et al., 2008).

6.5 Environmental Costs

Life Cycle Assessment (LCA) is a tool that can be used to generate information on the environmental impacts of water treatment systems. LCA enables the calculation of the environmental burdens in a systematic and scientific way by regarding all the inputs and outputs of a water supply system. Here, the environmental damage is limited to the carbon footprint associated with each treatment system referred to as the global warming potential (GWP) and expressed in kilograms carbon dioxide equivalents (kg CO_2e). The most important substances accounted for in GWP are $C0_2$, CH_4, N_2O, and the halogenated hydrocarbons.

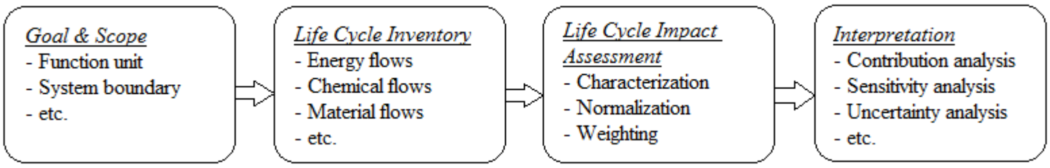

Figure 6: LCA Methodology

LCA has four phases as seen in Figure 6. The goal and scope definition attempts to set the function unit and system boundary. The function unit describes the primary purpose of a system and enables different systems to be treated as functionally equivalent. In water treatment LCA studies, the functional unit is often defined as 1 m3 of produced water. Boundary selection determines the processes and activities included in an LCA study. Life cycle inventory (LCI) analysis is a methodology for estimating the consumption of resources, the quantities of waste flows and emissions caused by, or otherwise attributable to, a product's life cycle. Life cycle impact assessment (LCIA) usually includes the mandatory step of characterization, and optional steps of normalization and weighting. The characterization step evaluates impact in terms of several impact categories (such as climate change, toxicological stress, water use, land use, etc.). After the impact assessment, the interpretation guides decision makers by providing a better understanding of uncertainties and assumptions (Zhou et al., 2014).

The goal of the study done by Tarnacki et al. (2012) is the environmental assessment of the RO desalination process for seawater and brackish water. The functional unit for the performed study has been defined as 1 m^3 of desalted water. In this study the construction and dismantling phase and the related impact have been neglected due to their minor influence into the total result. For the operational phase all mass and energy in- and output flows have been considered, as well as their transport to the plant and to the disposal after use. The feed water studied was seawater from the Mediterranean Sea with a salt content of 3.8%, as well as brackish water with a salt content of 2%. The values for GWP were found to be 0.624 kg CO_2e for brackish water RO, and 1.81 kg CO_2e for seawater RO (Tarnacki et al., 2012).

Raluy et al. (2006) used LCA to analyze and compare the most important commercial desalination technologies (MSF, MED and RO), encompassing more than 90% of desalinated water in the world; to provide a good idea of the technology that provokes a lower global impact. The considered functional unit for the LCA analysis is the production of 45,500 m^3/day of potable water, with 8,000 hours of operation per year. Contrary to Tarnacki et al. (2012), the system boundaries include: desalination plant components, installation construction materials and their transformation processes, operation and maintenance phases, and, finally, the disassembly at the end of its useful life.

The LCA study shows that the carbon dioxide emissions measured in kg CO_2/m^3 desalted water were 23.41 kg CO_2/m^3 for MSF, 18.05 kg CO_2/m^3 for MED, and 1.78 kg CO_2/m^3 for RO. It was also noticed that in all desalination technologies, the materials have little weight in the analysis, so the environmental load associated with the operation stage is much higher (88.6–99%) than that associated with assembly and final plant disposal (1-11.4%), due to the high energy consumption that desalination requires. Also, the RO plant has an associated environmental load which is significantly lower than the thermal desalting processes (MSF and MED) (Raluy et al., 2006).

However, when thermal desalination is integrated with other productive processes taking advantage of the residual heat, the environmental loads of thermal desalination technologies is highly reduced, obtaining similar loads to that of RO. In this way, very important energy saving can be achieved, because the consumption of any fuel could be avoided. When thermal desalination plants are driven by waste heat, it produces a decrease of 77% for MSF emissions and 84% for MED emissions, on average. The carbon dioxide emissions measured in kg CO_2/m^3 desalted water become 1.98 kg CO_2/m^3 for MSF, and 1.11 kg CO_2/m^3 for MED (Raluy et al., 2006).

Furthermore, Amores et al. (2013) used the LCA methodology to carry out an environmental analysis of every stage of the urban water cycle in Tarragona, a Mediterranean city of Spain. These stages are (1) water abstraction: extraction of water resources directly from the environment by pumping, (2) potable water treatment: conditioning the water before it reaches the distribution network by sieving, settling and filtering, pre-oxidation, physical and chemical treatment, decantation, chemical disinfection by activated carbon treatment and post-chlorination, (3) intermediate pumping and distribution network: water is supplied from the WTP to the population through the distribution network, (4) sewage collection: wastewater collection and its passage through the sewage network to the WWTP, and (5) wastewater treatment: pre-treatment, primary treatment (primary decanter), secondary treatment (biologic reactor, secondary reactor) and tertiary treatment (sand filtration, UV treatment, chlorination). The Functional Unit used is 1 m^3 of potable water supplied to the consumers in the Spanish Mediterranean area. All the processes, from water abstraction to final treatment are included within the system boundaries. The infrastructure of the treatment plants' processes and products was not taken into account, however, the infrastructure of the distribution network and sewage collection has been considered. The results for GWP impact category are summarized in Table 11 (Amores et al., 2013).

Stage	***Water Ab-strac-tion***	***Potable water treat-ment plant***	***Inter-mediate pump-ing***	***Distri-bution Net-work***	***Sewer-age***	***Wastewa ter treat-ment Plant***	***Total***
GWP (kg CO_2-Eq/m^3)	0.1770	0.1010	0.1540	0.3040	0.0089	0.1190	0.8639
Percent (%)	20.5	11.7	17.8	35.2	1.0	13.8	100

Table 11: GWP for the steps considered in the urban water cycle

Pasqualino et al. (2011) conducted a research to assess the environmental impact of the stages of operation of a Spanish Mediterranean WWTP to identify the stages with the highest environmental impact. The environmental assessment method applied in this study is LCA. The functional unit was defined as 1 m^3 of wastewater entering the WWTP. The system boundaries considered included all the processes involved from wastewater collection to final disposal or reuse, and excluded the construction and dismantling of the plant.

They found that the environmental impact of the secondary treatment is mainly caused by the aerobic reactor, which is responsible for 68.75% of the electricity consumed at the plant and uses high amounts of liquid oxygen. It was also noted that the tertiary treatment makes about a 1.1% to 3.2% contribution to the total impact. This means that the addition of a tertiary treatment to a WWTP does not significantly increase the environmental impact of the whole plant for the amount of wastewater treated. Moreover, any increase is compensated for by the fact that the reclaimed water can replace potable water for non-potable uses. Results are summarized in Table 12 (Pasqualino et al., 2011).

Environmental Impact Category	***Primary Treatment***	***Secondary Treatment***	***Sludge Line***	***Tertiary Treatment***	***Total***
GWP (kg CO_2e)	0.1550	0.5040	0.1700	0.0174	0.8464

Table 12: GWP for tertiary treatment WWTP

Bonton et al. (2012) performed a detailed comparative LCA of a nanofiltration system (NF) and an enhanced conventional system (CONV-GAC), producing treated water of equal quality from the same raw surface freshwater. Three life cycle phases were considered for each system: Construction of the water treatment plant (including transport and materials, excluding equipment for building), operation of the water treatment plant (including electricity, consumables and waste), decommissioning of the water treatment plant (including decommissioning, sorting, recycling, end-of-life). For the NF system, the GWP was measured to be 0.473 kg CO_2e/m^3 using coal energy, whereas for the CONV-GAC system, the GWP was measured to be 0.79 kg CO_2e/m^3.

In their study, Stokes and Horvath (2009) focused on the material and energy consumption associated with water provision systems and related air emissions using typical U.S. conditions. The following processes were evaluated: desalinating seawater with conventional pretreatment (DC), desalinating seawater with pretreatment by micro- and ultrafiltration (MF/UF) membranes (DM), desalinating brackish groundwater (DBG), and recycling wastewater for non-potable use in irrigation, commercial and industrial applications (REC). Seawater desalination was analyzed with two different pretreatment processes to evaluate the advantages of emerging membrane pretreatment processes versus more conventional processes. The Water-Energy Sustainability Tool (WEST) was used to evaluate the construction, operation, and maintenance of water systems and compare the direct and indirect energy and environmental effects of alternative water sources in terms of material production (concrete, pipe, and chemicals), material delivery, construction and maintenance equipment use, energy production (electricity and fuel),and sludge disposal. The functional unit considered in the analysis is one cubic meter (m^3). A summary of results obtained is shown in Table 13 (Stokes and Horvath, 2009).

Water Source	Desalinated Ocean Water, Conventional Pretreatment (DC)	Desalinated Ocean Water, Membrane Pretreatment (DM)	Desalinated Brackish Groundwater (DBG)	Recycled Water (REC)

GWP (kg CO_2e/m^3)	2.465	2.395	1.628	1.023

Table 13: LCA results of GWP for different processes

Hospido et al. (2012) aimed to increase the knowledge related to the environmental performance of MBRs by evaluating different configurations and discussing the possible correlation between operational conditions and environmental profiles. Four MBRs were studied: (1) MBR-A which corresponds to an activated sludge reactor coupled with a hollow fiber membrane, (2) MBR-B which is based on three connected tanks: one anoxic, one aerobic, and the hollow fiber membrane unit, (3) MBR-C which is based on one anaerobic tank, two anoxic tanks, one aerobic tank, and the hollow fiber membrane compartment, and (4) MBR-D which consists of a bioreactor followed by a hybrid aerobic reactor. A functional unit of 1 m^3 of permeate produced was chosen. The system under study starts with the incoming water and includes the reactor operation, the background processes associated to the energy and chemicals used, as well as the discharge of the treated water. Sludge treatment and its disposal as soil amendment has also been included in the system boundary. The environmental impact of the construction stage of the WWTPs is usually neglected as it is considered insignificant when being compared with the impact caused by the operation phase.

Emissions generated by energy production influenced the GWP impact category, in particular due to the CO_2 emitted from fossil fuels. Being the reactor with higher electricity demand, MBR-A reported worse on this impact category (5.4 kg CO_2e/m^3), followed by MBR-B (2.2 kg CO_2e/m^3), MBR-C (1.6 kg CO_2e/m^3), and finally MBR-D (1.35 kg CO_2e/m^3) (Hospido et al., 2012).

CHAPTER 7

MODEL FORMULATION

In this chapter we present our model and assumptions. We consider a geographic area that has a known, deterministic, and static demand for water for a specific use (demand for water quality type m) at a specific location within the considered geography (demand node n). To satisfy this demand, we assume that there exist various water sources (source node i) of different types (source water type j) in the same area considered.

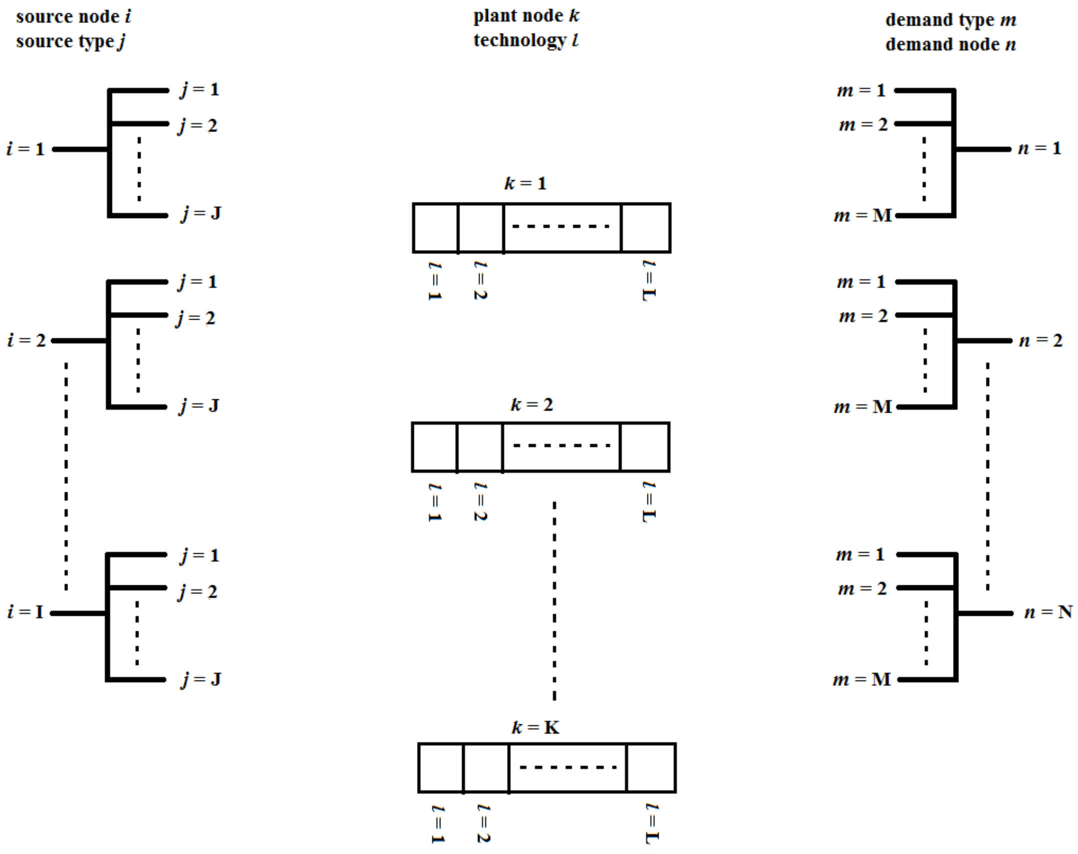

Figure 7: Model Diagram

In order to map the various source nodes and their different types to the various demand nodes and their corresponding requirements, we must select the volume of water to be taken from each source and used to satisfy a certain demand after being treated in a certain plant by the suitable treatment technology. The choice of plant (plant node k) and the associated treatment processes (treatment technology l) are considered from a given set of alternatives which are known in advance. Figure 7 gives a clearer idea of how the problem can be seen.

7.1 Mathematical Formulation

In the model we consider the following notation for decision variables and parameters:

Decision Variables

a_{ijklmn}	Binary variable that is 1 when water from source node i of type j is transported to plant k and treated with technology l to satisfy demand type m at demand node n ($V_{ijklmn} > 0$); and 0 otherwise.
V_{ijklmn}	Volume of water taken from source node i of type j and transported to plant k and treated with technology l to satisfy demand type m at demand node n. (m^3/d)

Parameters

T^c_{ijk}	Investment cost of transporting water from source node i of type j to plant k.
C_{jklm}	Investment cost which includes cost of equipment, installation and construction.
T^c_{kmn}	Investment cost of transporting water of type m from plant k to demand

node n.

T_{ijk}^{o} Operating cost of transporting water from source node i of type j to plant k.

O_{jklm} Operating cost which includes cost for energy requirements, service and maintenance, supplies and parts, and labour.

T_{kmn}^{o} Operating cost of transporting water of type m from plant k to demand node n.

L_l Cost of transporting water, brine or other material removed by technology l and disposing it off in the appropriate manner.

CF_l Carbon footprint cost for technology l.

$CF_{T,ijk}$ Carbon footprint cost for transporting water from source node i of type j to plant k.

$CF_{T,kmn}$ Carbon footprint cost for transporting of type m from plant k to demand node n.

CF_{max} Carbon footprint upper limit for whole system.

d_l Fraction of water lost during treatment.

d_T Fraction of water lost during transportation.

S_{ij} Supply of water of type j available at node i.

D_{mn} Demand of water of type m required at node n.

TDS_l Estimated TDS value of water treated by technology l.

TDS_{mH} Guideline TDS value of water for demand type m.

pH_l Estimated pH of water treated by technology l.

pH_{mH} Upper guideline pH value of water for demand type m.

pH_{mL} Lower guideline pH value of water for demand type m.

hd_l Estimated hardness of water treated by technology l.

hd_{mH} Upper guideline hardness value of water for demand type m (domestic use).

hd_{mL} Lower guideline hardness value of water for demand type m (domestic use).

Na_l Estimated Sodium value of water treated by technology l.

Na_{mH} Guideline Sodium value of water for demand type m (agricultural use).

The general form of the objective function considers the minimization of the overall cost of the system as stated below.

Minimize

Total cost (Z) = Investment cost (I) + Operating cost (O) + Environmental cost (E)

$$Z = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{V_{ijklmn}(I^V + O^V + E^V) + a_{ijklmn}(I^F + O^F + E^F)\right\}$$

I = Transportation investment cost (i→k) + Treatment Process investment cost + Transportation investment cost (k→n)

$$I = T_{ijk}^{c} + C_{jklm} + T_{kmn}^{c}$$

O = Transportation operating cost (i→k) + Treatment Process operating cost + Unwanted material disposal cost + Transportation operating cost (k→n)

$$O = T_{ijk}^{o} + (1 - d_T)O_{jklm} + (1 - d_T)d_l L_l + (1 - d_T)(1 - d_l)T_{kmn}^{o}$$

E = Cost of carbon from transportation (i→k) + cost of carbon from treatment + Cost of carbon from transportation (k→n)

$$E = CF_{T,ijk} + (1 - d_T)^2(1 - d_l)CF_l + (1 - d_T)(1 - d_l)CF_{T,kmn}$$

Subject to

(1) $$V_{ijklmn} \leq Ma_{ijklmn} \qquad \forall\, i,j,k,l,m,n$$

Constraint (1) is specific to the part of the objective function relating to the fixed cost. It uses a binary variable that indicates when the fixed cost is incurred, and a sufficiently large number M to create redundancy. So a_{ijklmn} is 1 only when $V_{ijklmn} > 0$, and 0 otherwise.

(2) $$\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N} V_{ijklmn} \leq S_{ij} \qquad \forall\, i,j$$

(3) $$(1-d_T)^2 \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} (1-d_l)V_{ijklmn} = D_{mn} \qquad \forall\, m,n$$

The basic constraints in the model are those related to satisfying supply and demand. On one hand, constraint (2), the volume of water taken must be less than or equal to the supply available from the sources considered (S_{ij}). On the other hand, constraint (3), the volume of water taken less the losses due to transportation and the technology-specific losses must be equal to the demand required (D_{mn}).

(4) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{n=1}^{N} (TDS_l - TDS_{mH})(1-d_l)V_{ijklmn} \leq 0 \qquad \forall\, m$$

(5) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{n=1}^{N} (pH_l - pH_{mH})(1-d_l)V_{ijklmn} \leq 0 \qquad \forall\, m$$

(6) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{n=1}^{N} (pH_l - pH_{mL})(1-d_l)V_{ijklmn} \geq 0 \qquad \forall\, m$$

(7) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{n=1}^{N} (hd_l - hd_{mH})(1-d_l)V_{ijklmn} \leq 0 \qquad \forall\, m$$

(8) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{n=1}^{N}(hd_l - hd_{mL})(1-d_l)V_{ijklmn} \geq 0 \qquad \forall\, m$$

(9) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{n=1}^{N}(Na_l - Na_{mH})(1-d_l)V_{ijklmn} \leq 0 \qquad \forall\, m$$

Constraints (4)-(9) ensure that the water quality guidelines specific to each kind of use are applied. This is done by making sure that the value of TDS, pH, hardness, and Na present in the amount of water treated to satisfy specific demand type m is within the limits (upper and lower) specified by the guidelines for that particular use.

(10) $$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N}(1-d_l)CF_l V_{ijklmn} \leq CF_{max}$$

Constraint (10) is added to ensure that even while the carbon footprint is minimized in the objective function; it should also remain less than a certain specified ceiling value in order to limit the environmental damage of the system.

7.2 Solution Methodology

First we note that the mathematical model presented above is a general model that can be applied to any set of given data. However, since in our case the developed cost functions are nonlinear of the form AX^n, where X is the water capacity variable (m^3/d), A and n are constants; the model presented above is a nonlinear integer program which is usually difficult to solve. We could use specialized nonlinear solvers but it would still be difficult to find an optimal solution. Our solution methodology is based on transforming these non-linear functions into step-wise linear cost functions across p intervals. This is done by introducing the following decision variables and constraints.

a^{p}_{ijklmn} Binary variable that is 1 when water from source node i of type j is transported to plant k and treated with technology l to satisfy demand type m at demand node n for volume range p ($V^{p}_{ijklmn} > 0$); and 0 otherwise.

V^{p}_{ijklmn} Volume of water taken from source node i of type j and transported to plant k and treated with technology l to satisfy demand type m at demand node n for volume range p. (m^3/d)

w^{p}_{ijklmn} Binary variable that is 1 when V^{p}_{ijklmn} is equal to a certain maximum value; and 0 otherwise.

(a) $$a_{ijklmn} = a^{1}_{ijklmn} \qquad \forall\, i,j,k,l,m,n$$

(b) $$V_{ijklmn} = \sum_{p=1}^{P} V^{p}_{ijklmn} \qquad \forall\, i,j,k,l,m,n$$

(c) $$0 \le V^{p+1}_{ijklmn} \le V^{p+1}_{H} w^{p}_{ijklmn} \qquad \begin{cases} \forall\, i,j,k,l,m,n \\ p = 1,\dots,P-1 \end{cases}$$

(d) $$0 \le w^{p}_{ijklmn} \le \frac{V^{p}_{ijklmn}}{V^{p}_{H}} \qquad \begin{cases} \forall\, i,j,k,l,m,n \\ p = 1,\dots,P-1 \end{cases}$$

$$a_{ijklmn}, a^{p}_{ijklmn}, w^{p}_{ijklmn} \in \{0,1\};\ 0 \le V^{p}_{ijklmn} \le V^{p}_{H};\ V^{p}_{ijklmn} \ge 0$$

Constraints (c) and (d) are set as part of linearizing the non-linear cost functions. They make sure that the volume variables satisfy the lower ranges before moving to the higher ranges. If $V^{p}_{ijklmn} < V^{p}_{H}$ then V^{p+1}_{ijklmn}should be 0. This condition is ensured by these two constraints since if $V^{p}_{ijklmn} < V^{p}_{H}$ then $w^{p}_{ijklmn} = 0$ and consequently $V^{p+1}_{ijklmn} = 0$.

Despite having avoided the difficulty of solving a nonlinear program, this approach adds some complexity to our model in terms of the increase in the number of decision variables and the associated constraints that are added to achieve our purpose. In particular, the number of decision variables for the nonlinear problem is the product $2ijklmn$. For the linearized problem, the number of decision variables becomes $ijklmn(3p-1)$. So even though increasing p gives a more accurate approximation to the nonlinear function, but it also adds complexity to our linear problem. Another compromise made to achieve a simpler solution method is the margin of error that occurs as a result of the linearization process. The more intervals we consider, the closer we get to the real solution of the nonlinear problem. However this is at the expense of having a much larger amount of decision variables as mentioned earlier.

7.3 Case Study

In this section, we evaluate our DSS and apply it to the case presented in section 7.3.1. We present estimates of the parameters needed for the optimization model presented in section 7.1, and then discuss the results obtained after running the program on the Excel premium software.

7.3.1 Background and Data

A small sized coastal city located 5 km away from the sea with a total population of 250,000 inhabitants requires 0.2 m^3/day per capita of potable water, 0.15 m^3/day per capita irrigation water, and 0.1 m^3/day per capita industrial water. This population generates 0.175 m^3/day per capita wastewater. 20 km away from the city, there is a brackish water well that can supply up to 25,000 m^3/day. A river running 30 km away from the city can provide up to 70,000 m^3/day. We consider the availability of four treatment plants, each located at a 5 km distance from the city. Two of these plants are run by conventional energy source, and the other two are located next to power generating facilities so they can make use of the residual thermal energy provided from these power plants.

According to the information presented above, we will consider the following indices. For the sources, we will consider the city (i=1) which provides wastewater (j=4), the sea (i=2) providing seawater (j=1), the brackish water well (i=3) providing brackish water (j=2), and the river (i=4) providing the river water (j=3). Accordingly, the supply available is S_{14} = 43,750 m^3/day, S_{21} = 150,000 m^3/day, S_{32} = 25,000 m^3/day, and S_{43} = 70,000 m^3/day. These sources will be used to satisfy the city's demand (n=1) of potable water (m=1), irrigation water (m=2), and industrial water (m=3). The demand required is D_{11} = 50,000 m^3/day, D_{21} = 37,500 m^3/day, and D_{31} = 25,000 m^3/day.

Four treatment plants will be considered: PA (k=1) and PC (k=3) are run by conventional energy, while PB (k=2) and PD (k=4) are run by residual energy. Each plant can support seven treatment processes: MSF desalination (l=1), MED desalination (l=2), SWRO desalination (l=3), BWRO desalination (l=4), River Filtration (l=5), Conventional WWT (l=6), and WWT with MBR (l=7).

We will linearize the cost functions across nine intervals. The first volume interval (p=1) covers the range 1-5,000 m^3/day, the second interval (p=2) covers the range 5,000-10,000 m^3/day, the third interval (p=3) covers the range 10,000-15,000 m^3/day, the fourth interval (p=4) covers the range 15,000-20,000 m^3/day, the fifth interval (p=5) covers the range 20,000-30,000 m^3/day, the sixth interval (p=6) covers the range 30,000-40,000 m^3/day, the seventh interval (p=7) covers the range 40,000-

50,000 m^3/day, the eighth interval (p=8) covers the range 50,000-100,000 m^3/day, and finally the ninth interval (p=9) covers the range 100,000-500,000 m^3/day. The linearization method used is step-wise linearization, where the cost function across each interval takes a constant value. The linear cost functions for the investment and operating costs to be used in this case are shown in Table 14 and Table 15 respectively.

p	***MSF***	***MED***	***SWRO***	***BWRO***	***RF***	***WWT-Conv***	***WWT-MBR***
1	7219.60	3592.34	2532.47	1189.54	250.56	1060.79	2150.19
2	5226.84	2980.35	2119.59	932.09	250.56	715.06	1529.57
3	4497.96	2732.45	1951.24	832.16	250.56	595.25	1305.56
4	4074.31	2580.54	1847.73	772.27	250.56	527.52	1176.24
5	3668.71	2428.72	1743.99	713.48	250.56	464.12	1053.12
6	3323.16	2293.70	1651.47	662.12	250.56	411.31	948.81
7	3086.48	2197.77	1585.59	626.19	250.56	375.82	877.69
8	2656.07	2014.96	1459.66	559.06	250.56	312.85	749.15
9	1766.99	1591.90	1166.05	410.96	250.56	190.20	487.45

Table 14: Linear Investment Cost Function Values

The carbon footprint values for each treatment technology to be used in this case are summarized in Table 16. We will consider a cost of 2 \$/kg CO_2e.

p	***MSF***	***MED***	***SWRO***	***BWRO***	***RF***	***WWT-Conv***	***WWT-MBR***
1	1.68536	0.83898	0.75639	0.32708	0.23025	0.38616	0.16751
2	1.21615	0.69605	0.61187	0.24717	0.23025	0.27561	0.14959

3	1.04496	0.63816	0.55443	0.21698	0.23025	0.23561	0.14192
4	0.94558	0.60268	0.51957	0.19914	0.23025	0.21248	0.13709
5	0.85054	0.56722	0.48500	0.18183	0.23025	0.19045	0.13214
6	0.76965	0.53569	0.45451	0.16688	0.23025	0.17176	0.12764
7	0.71430	0.51328	0.43299	0.15652	0.23025	0.15900	0.12438
8	0.61375	0.47059	0.39234	0.13740	0.23025	0.13592	0.11800
9	0.40661	0.37178	0.30024	0.09649	0.23025	0.08881	0.10230

Table 15: Linear Operating Cost Function Values

Process	***GWP (kg CO_2e/m^3)***
Transportation	0.635
MSF	23.41 with conventional energy source 1.98 with residual energy
MED	18.05 with conventional energy source 1.11 with residual energy
SWRO	1.81
BWRO	0.624
Filtration	0.79
WWT-Conv	0.829
WWT-MBR	1.35

Table 16: GWP for Processes Used in the Case Study

The losses taken into account in this case are 6% loss in transportation, 50% loss in SWRO desalination, 75% loss in BWRO desalination, 80% loss in MSF and MED desalination, and no losses for WWT processes and filtration.

7.3.2 Results and Discussion

For the data presented in section 7.3.1, we run the linear optimization model using Excel premium solver. The problem formulated contains a total of 8,736 decision variables and 8,408 constraints excluding the variable lower and upper bound restrictions.

The total cost of the system is $60,737,757. The optimal mapping of sources to the corresponding treatment processes to meet the required demand is as follows:

- Treat 56,587 m^3/day of river water by filtration at plant PD to satisfy the potable water demand.
- Treat 42,440 m^3/day of wastewater by conventional WWT at plant PD to satisfy irrigation water demand.
- Treat 19,840 m^3/day of well water by BWRO at plant PD, and 13,413 m^3/day of river water by filtration at plant PD to satisfy industrial water demand.

It is important to note that this is one of several optimal solutions since there is no difference between plants PA and PC, and plants PB and PD. So if the choice was to treat water at PC instead of PA, or at plant PB instead of PD, the solution would also be optimal since both plants are at the same distance from the source nodes and demand nodes, and both plants offers the same treatment processes run by conventional energy.

Naturally, the model first selects river water filtration treatment since it is the least expensive of the available processes and has minimum loss, provided there is enough river water to be treated. Usually there is a limited amount of river water available as compared to the unlimited amount of seawater that may be used for desalination treatment. The model also used the available wastewater treated by conventional WWT to satisfy agricultural and irrigation demands. Concerning the WWT processes, the model finds the conventional WWT optimal compared to WWT with MBR. The difference between the two processes is that WWT with MBR is more expensive than conventional WWT in the investment phase, but less expensive in the operating phase. In the case of a much higher flow rate, the optimal solution may vary to include WWT with MBR in order to satisfy the required demand.

Once the available amount of river water and wastewater is used up, the model then refers to brackish water since its treatment is less expensive compared to seawater desalination to satisfy the remaining demand. It selects a combination of conventional WWT, RF, and BWRO processes in such a way as to satisfy the model constraints while minimizing the cost.

7.3.3 Sensitivity Analysis

In this section, we investigate the effects of changing the volume of water (in terms of supply available and demand required) on the optimal solution.

Since the volume of water flowing through the system depends on the population being served, we will study the effect of the demand volume on the total system cost and optimal combination of treatment processes by increasing the population size.

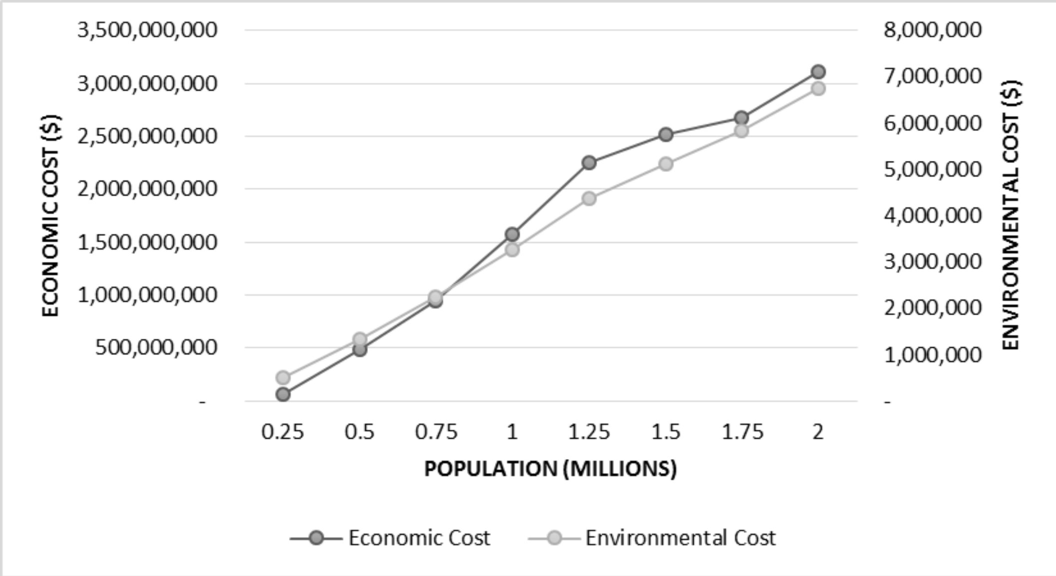

Figure 8: (Case Study) Variation of Economic and Environmental Cost

Figure 8 shows the variation of the economic cost (investment and operating) and the environmental cost as a function of the population size. Naturally both costs increase as the population size increases. The increase in environmental cost is almost linear, while the economic cost curve has changes in slope. This may be due to a change in the selection of processes in the optimal solution causing an increase in the system cost.

Figure 9-11 shows how the optimal selection of processes changes as the demand volume increases for potable use, agricultural use, and industrial use. There are several observations that can be made from these charts. The first is that the dominant treatment process is river water filtration. The most obvious reason for this dominance is the low cost of this technology compared to the rest. In addition to river water filtration, brackish water desalination is always part of the optimal solution because of its moderate cost.

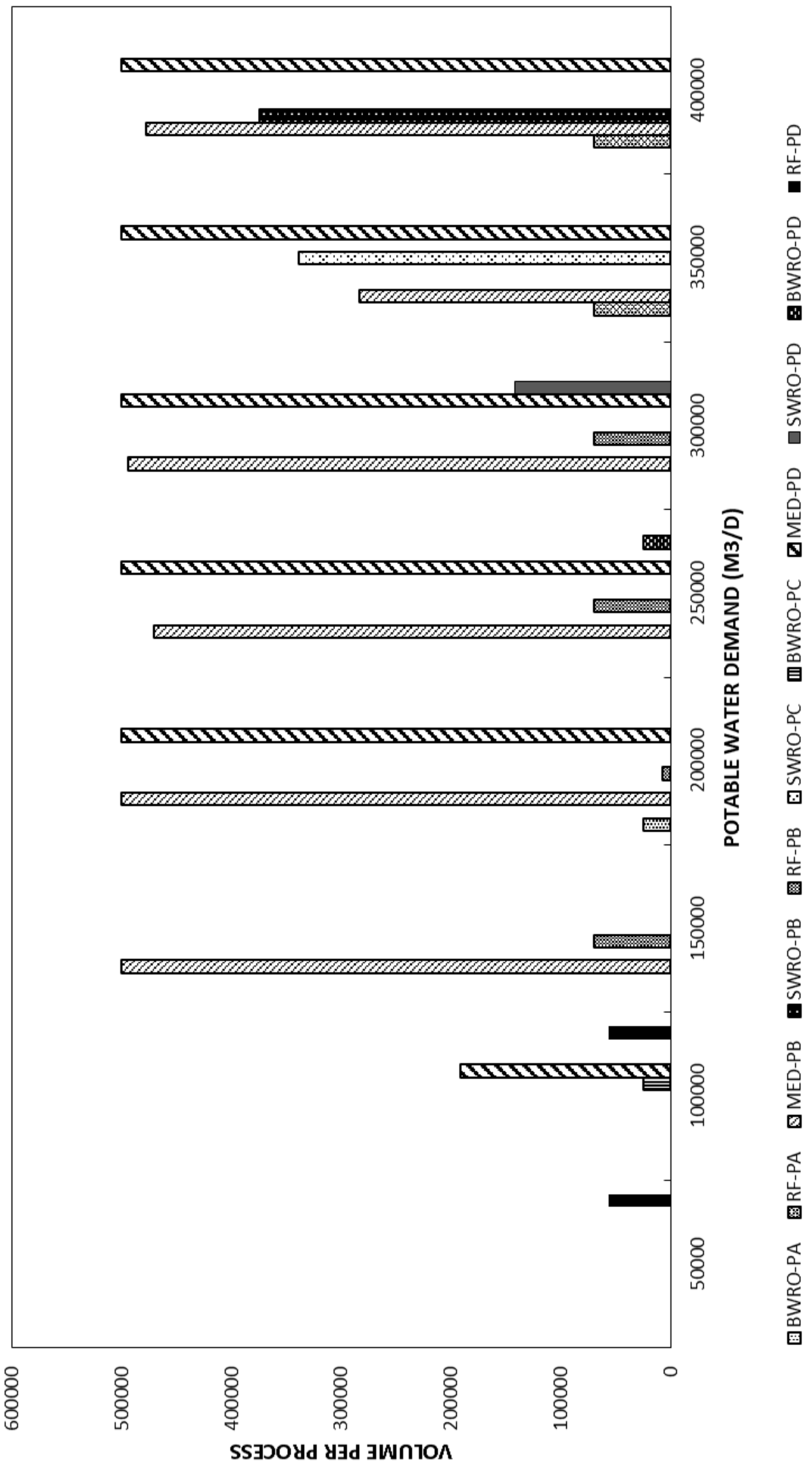

Figure 9: (Case Study) Distribution of Processes for Potable Water Demand

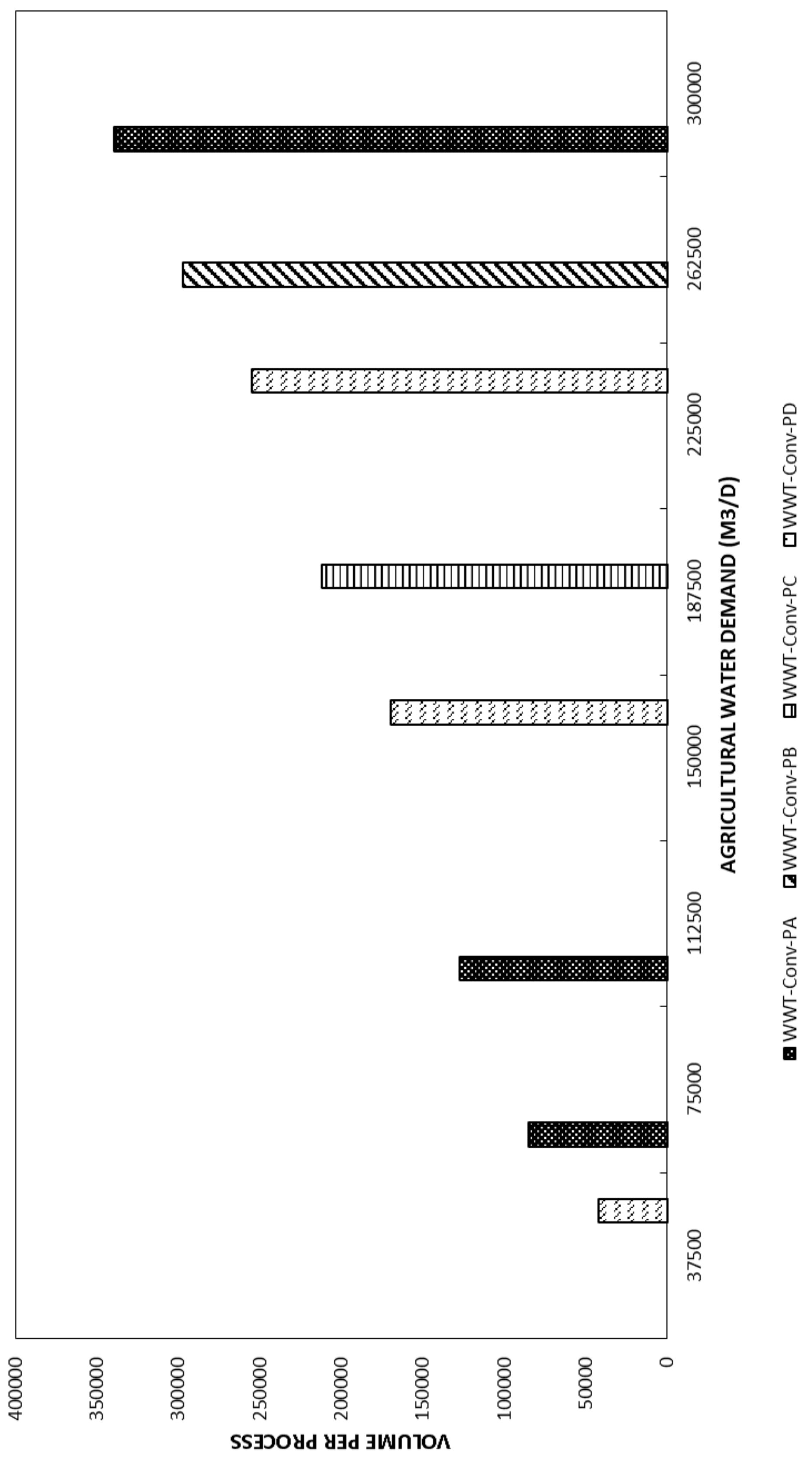

Figure 10: (Case Study) Distribution of Processes for Agricultural Water Demand

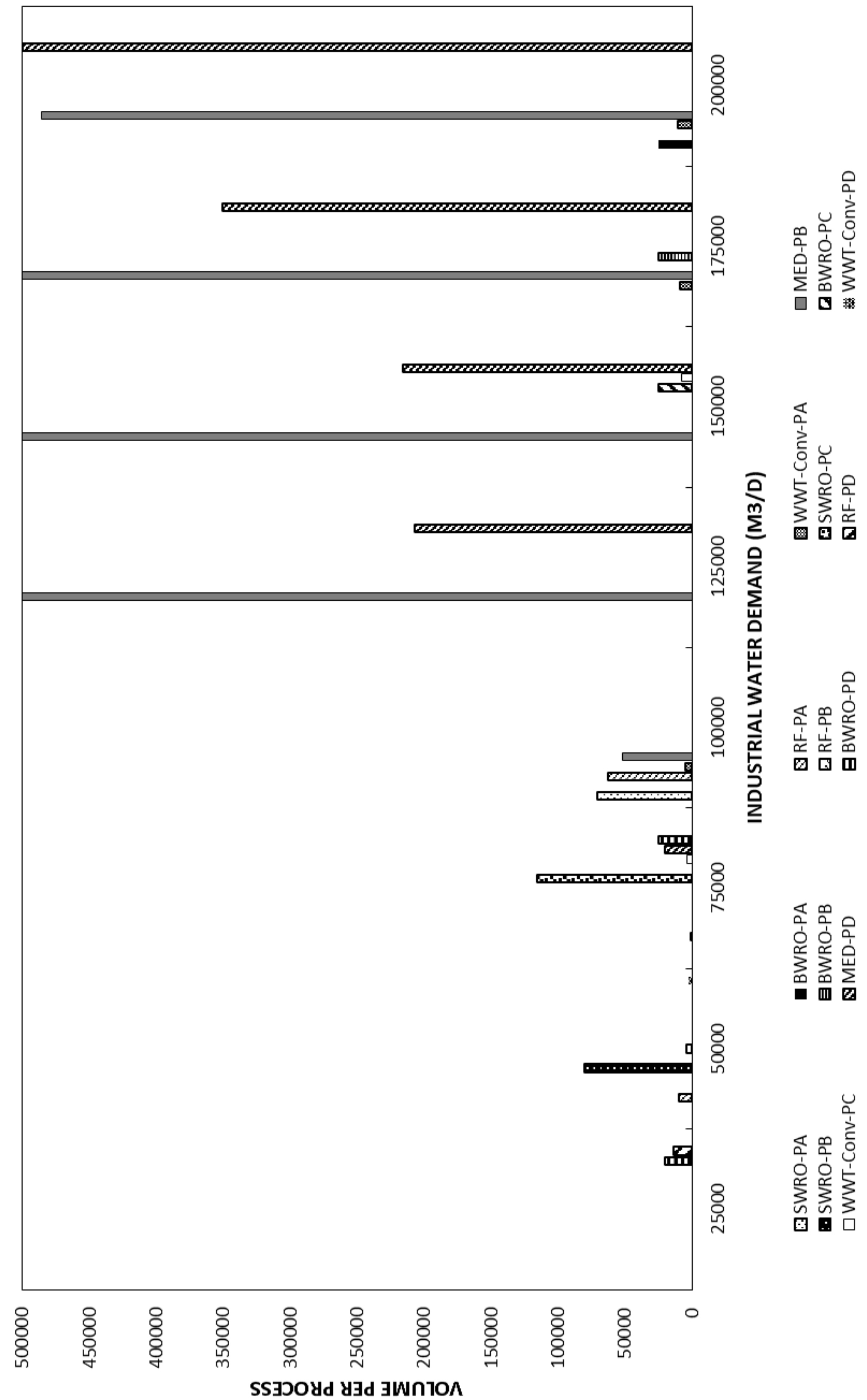

Figure 11: (Case Study) Distribution of Processes for Industrial Water Demand

Other observations that can be made are concerning the seawater desalination and the WWT. When the demand for water can no longer be met by river water, well water, or treated wastewater, the difference is made up by desalination of seawater. The processes used are SWRO and MED driven by residual energy. The model selects a combination of SWRO and MED desalination processes in such a way as to satisfy the model constraints while minimizing the cost. MED driven by residual energy is less expensive than SWRO and has a lower carbon footprint, but SWRO has a higher recovery rate (SWRO recovery is 50% while MED recovery rate is only 20%). This selection is supported by the proximity of the sea and the unlimited amount of seawater available.

With regard to WWT, conventional WWT was always part of the optimal solution while WWT with MBR was not part of it even at large demand capacity. This may be due to the large investment cost of WWT with MBR having a higher effect on the optimal solution than its low operating cost when compared to conventional WWT.

Finally, it is important to mention that sensitivity analysis was also conducted on the distance between the brackish water well and the treatment plants. The results indicated that despite the location of the water well being farther away, it remains optimal to get part of the water demand from the treated brackish water because of its relatively lower cost even as the well is located farther away. This result also shows that there is no dependence between the demand volume and the location of the water well.

CHAPTER 8

MULTI-CRITERIA DECISION ANALYSIS

The integer program presented in Chapter 7 is an efficient tool to help decision makers select the least cost alternative from a set of options. The focus was to minimize the economic cost (investment, operation, and maintenance) of the water treatment and allocation system, as well as the environmental cost (carbon footprint in dollar per kg CO_2e produced). However the optimization model did not take into account other criteria affecting the decision process.

In this chapter, we use Multi-Criteria Decision Analysis (MCDA) to develop a decision support system that takes into consideration a set of criteria affecting the decision process. MCDA is an approach suitable for addressing complex problems with uncertainty, conflicting objectives, different forms of data, and multiple interests and perspectives. MCDA allows the comparison of quantitative criteria (such as cost) as well as qualitative non-monetary, non-metric criteria.

In general, a MCDA problem involves m alternatives, evaluated on n criteria each given a weight w_j. The performance of criteria j on alternative i is labeled x_{ij}. The decision making process usually includes the following stages. First, the set of alternatives to be evaluated are formulated, and the criteria on which the chosen alternatives are to be evaluated are selected. Second, criteria weights are determined to show the relative importance of criteria in MCDA. Once these are ready, the alternatives are scored against the criteria in a performance matrix. Since scores with different measurement scales cannot be compared to each other directly, the scores are standardized to a dimensionless value between 1 and 10 (1 being lowest, 10 being highest) before the overall score for each alternative can be calculated. Finally, the alternatives are ranked based on their overall score to get the result (Wang et al., 2009, Sudhakaran et al., 2013).

8.1 Alternatives and Criteria Selection

The alternatives considered in the decision process are listed in Table 17. For convenience and ease of work, some alternatives are discarded due to technical constraints or limitations of a specific method to a certain feed water quality or output water quality.

The criteria used to evaluate the alternatives presented above are divided into four general categories: economic, environmental, technical, and social criteria.

8.1.1 Economic Criteria

Total Cost (C1a): This includes the investment cost and the operation and maintenance cost. The investment cost compromises of all costs relating to purchase of equipment, installation, and construction. The operation and maintenance cost includes costs related to energy requirements, service and maintenance, supplies and parts, employee wages, pre-treatment of feed water and post-treatment of output water. The unit costs are expressed in $\$/m^3/d$. In order to standardize these costs, a value of 1 is given to the alternative with the highest total cost, and a value of 10 is given to the alternative with the lowest total cost. Costs in between are assigned corresponding values.

Area Footprint (C1b): This refers to the amount of land space occupied for running treatment process. In this criterion, MBR receives a higher standardization value than conventional WWT systems because of less land usage, while for desalination processes RO scores highest followed by MED and MSF.

Alternative	***Description***
A1	MSF desalination of seawater for potable use
A2	MSF desalination of seawater for agricultural use
A3	MSF desalination of seawater for industrial use
A4	MED desalination of seawater for potable use
A5	MED desalination of seawater for agricultural use
A6	MED desalination of seawater for industrial use
A7	SWRO desalination of seawater for potable use
A8	SWRO desalination of seawater for agricultural use
A9	SWRO desalination of seawater for industrial use
A10	BWRO desalination of brackish water for potable use
A11	BWRO desalination of brackish water for agricultural use
A12	BWRO desalination of brackish water for industrial use
A13	River water filtration for potable use
A14	River water filtration for agricultural use
A15	River water filtration for industrial use
A16	Conventional activated sludge WWT for agricultural use
A17	Conventional activated sludge WWT for industrial use
A18	MBR WWT for agricultural use
A19	MBR WWT for industrial use

Table 17: List of Possible Feasible Alternatives

8.1.2 Environmental Criteria

Carbon Footprint (C2): This is defined as the total of the GHGs produced from construction and operational emissions. This is a major environmental concern due to its negative impact on climate change. Carbon footprint is expressed in kg CO_2e/m^3. Processes with lower carbon footprint receive a higher standardization value then processes with higher carbon footprint.

8.1.3 Technical Criteria

Water recovery rate (C3a): This is defined as the ratio of the output water volume to the input water volume. In this criterion, thermal desalination processes score lowest because of their high recovery rate followed by BWRO, SWRO, and finally filtration and WWT processes which receive the highest score.

Availability of alternate energy sources (C3b): Energy use refers to the power consumption required to run the treatment processes. Some processes such as the thermal desalination processes are far more energy intensive than other processes. However, when run by residual thermal energy from a nearby electricity plant, they become more preferable over other processes because they have a lower cost and lower associated carbon footprint. For this reason, thermal desalination processes score highest in this criterion.

8.1.4 Social Criteria

Sanitation and employment benefits (C4): With the implementation of these projects, there will be an improvement in the sanitation and hygiene conditions of the population, and consequently a better quality of life. Moreover, these processes ensure that wastewater is being treated and reused instead of being dumped. Thus there is less worry from diseases associated with improper waste disposal. Moreover, implementation of water treatment projects employs many people during its life cycle, in the construction phase as well as the operational phase. This job creation is beneficial to the society and contributes to improvement in the quality of life.

8.2 Evaluation Matrix

After identifying the alternatives (m=19) and evaluation criteria (n=6), the evaluation matrix is constructed (Table 18). The evaluation matrix shows the x_{ij} values i.e. the performance of alternative i on criterion j.

	C1a	***C1b***	***C2***	***C3a***	***C3b***	***C4***
A1	2	1	1	1	10	5
A2	2	1	1	1	10	5
A3	2	1	1	1	10	5
A4	5	2	3	1	10	5
A5	5	2	3	1	10	5
A6	5	2	3	1	10	5
A7	7	8	5	5	5	5
A8	7	8	5	5	5	5
A9	7	8	5	5	5	5
A10	9	8	9	2	5	5
A11	9	8	9	2	5	5
A12	9	8	9	2	5	5
A13	10	7	8	9	5	5
A14	10	7	8	9	5	5
A15	10	7	8	9	5	5
A16	7	2	7	10	5	10
A17	7	2	7	10	5	10
A18	6	9	6	10	5	10
A19	6	9	6	10	5	10

Table 18: Evaluation Matrix for Different Alternatives

8.3 Assessment of Alternatives

MCDA is used to compare among the different alternatives listed in Table 17. The weighted sum method (WSM) is the most commonly used method in MCDA. The score of an alternative is calculated as $S_i = \sum_{j=1}^{n} w_j x_{ij}$ where w_j is the weight of criterion j and x_{ij} is the score of alternative i on criterion j (Wang et al., 2009). The alternatives are then ranked based on the resulting scores; the best alternative is the one whose score is the maximum.

Criterion		Method (1) weight	Method (2-a) weight	Method (2-b) weight
C1a	Investment cost	1/6 ≅ 0.167	0.5	0.65
C1b	Area footprint	1/6 ≅ 0.167	0.1	0.15
C2	Carbon footprint	1/6 ≅ 0.167	0.15	0.05
C3a	Water recovery rate	1/6 ≅ 0.167	0.05	0.05
C3b	Availability of alternate energy sources	1/6 ≅ 0.167	0.05	0.05
C4	Sanitation and employment benefits	1/6 ≅ 0.167	0.15	0.05

Table 19: Criteria Weights Using Methods (1) and (2)

Concerning the weights assignment, there are usually two common methods: (1) equal weights method, and (2) rank-order weighting method. Method (1) assigns equal weights to all the criteria. However it ignores the relative importance among the criteria. Thus method (2) is used when it is necessary to show importance in the criteria. The weighting in method (2) can be subjective depending on the preference of the decision maker, or objective obtained by mathematical methods based on analysis of the initial data (Wang et al., 2009). Table 19 shows the weights assigned to each criterion for both methods (1) and (2). For method (2), we consider specialist opinions in light of two views. Method (2-a) emphasizes environmental and social criteria, while method (2-b) gives minimal regard to environmental and social concerns.

8.4 Ranking Alternatives and Results

In this section we show the results of MCDA using the Logical Decisions software. We will consider three goals based on the type of water demand. So for the potable water demand, the alternatives to be evaluated are A1, A4, A7, A10, and A13. For the agricultural water demand, the alternatives evaluated are A2, A5, A8, A11, A14, A16, and A18. And finally for the industrial water demand, the alternatives evaluated are A3, A6, A9, A12, A15, A17, and A19. All these alternatives are evaluated according to the criteria presented in section 8.1, and their scores calculated using the WSM.

Figure 12 shows the ranking of alternatives for potable water production when the criteria are assigned weights by methods (1), (2a), and (2b) respectively. For method (1), alternative A13 ranks highest with a score 7.333, and A10 ranks second highest with a score of 6.333, followed by alternatives A7, A4, and finally A1. Similar to method (1) results, alternatives A13 and A10 rank highest for weighting methods (2a) and (2b) in potable water production, followed by alternatives A7, A4, and finally A1.

Figure 13 shows the ranking of alternatives for agricultural water production when the criteria are assigned weights by methods (1), (2a), and (2b) respectively. We notice that for method (1) WWT with MBR has the highest score, followed by river water filtration. The desalination processes rank lowest for their higher costs and lower social benefits.

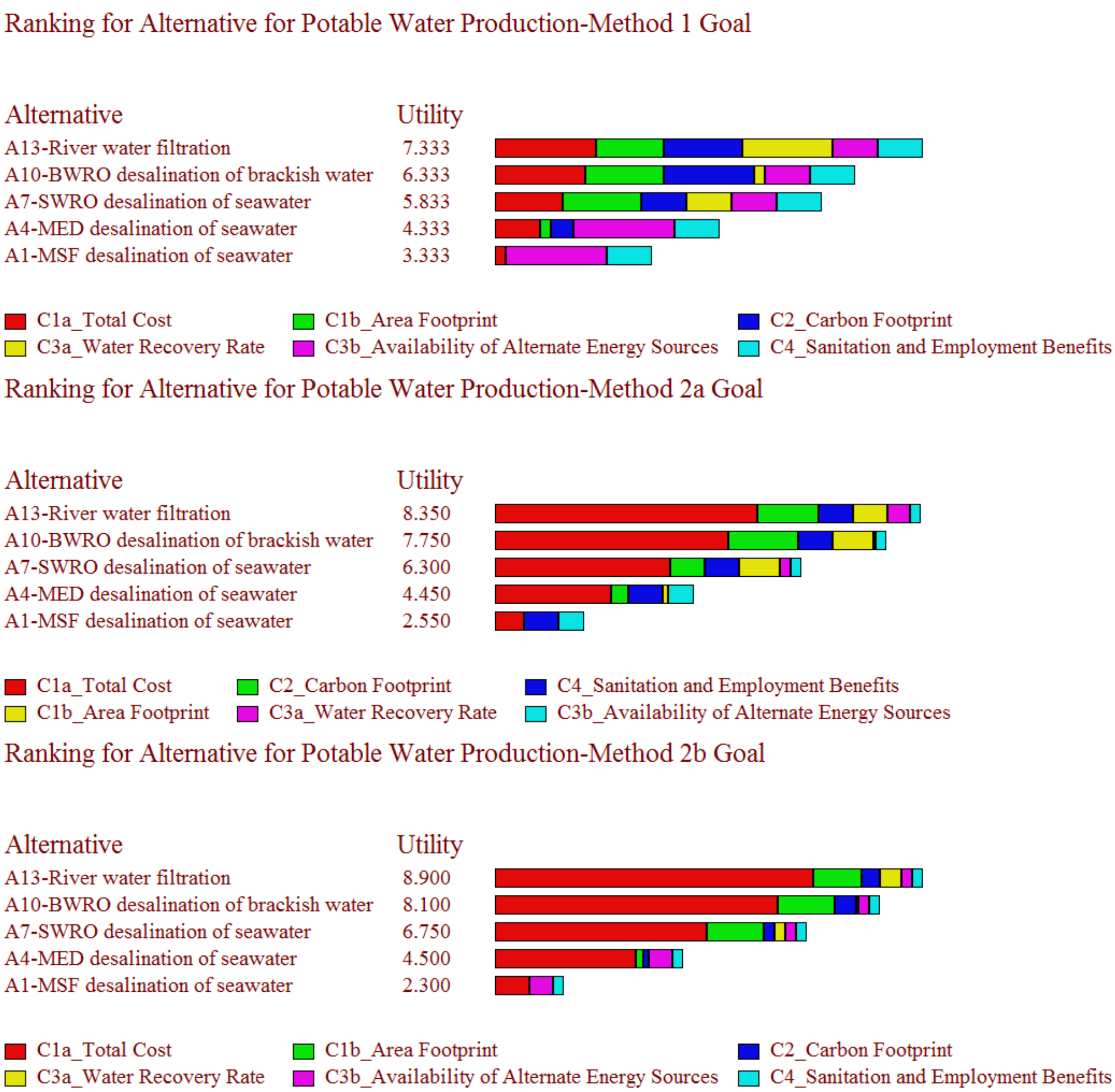

Figure 12: Ranking of Alternatives for Potable Water Use

For both methods (2a) and (2b), alternatives A14 with river water filtration and A11 with BWRO are at the top of the list. When environmental and social concerns are given more importance (2a), WWT with MBR comes next, followed by conventional WWT, and the remaining desalination options. For method (2-b), WWT with MBR is followed by SWRO rather than conventional WWT because of its better performance on criterion C1b.

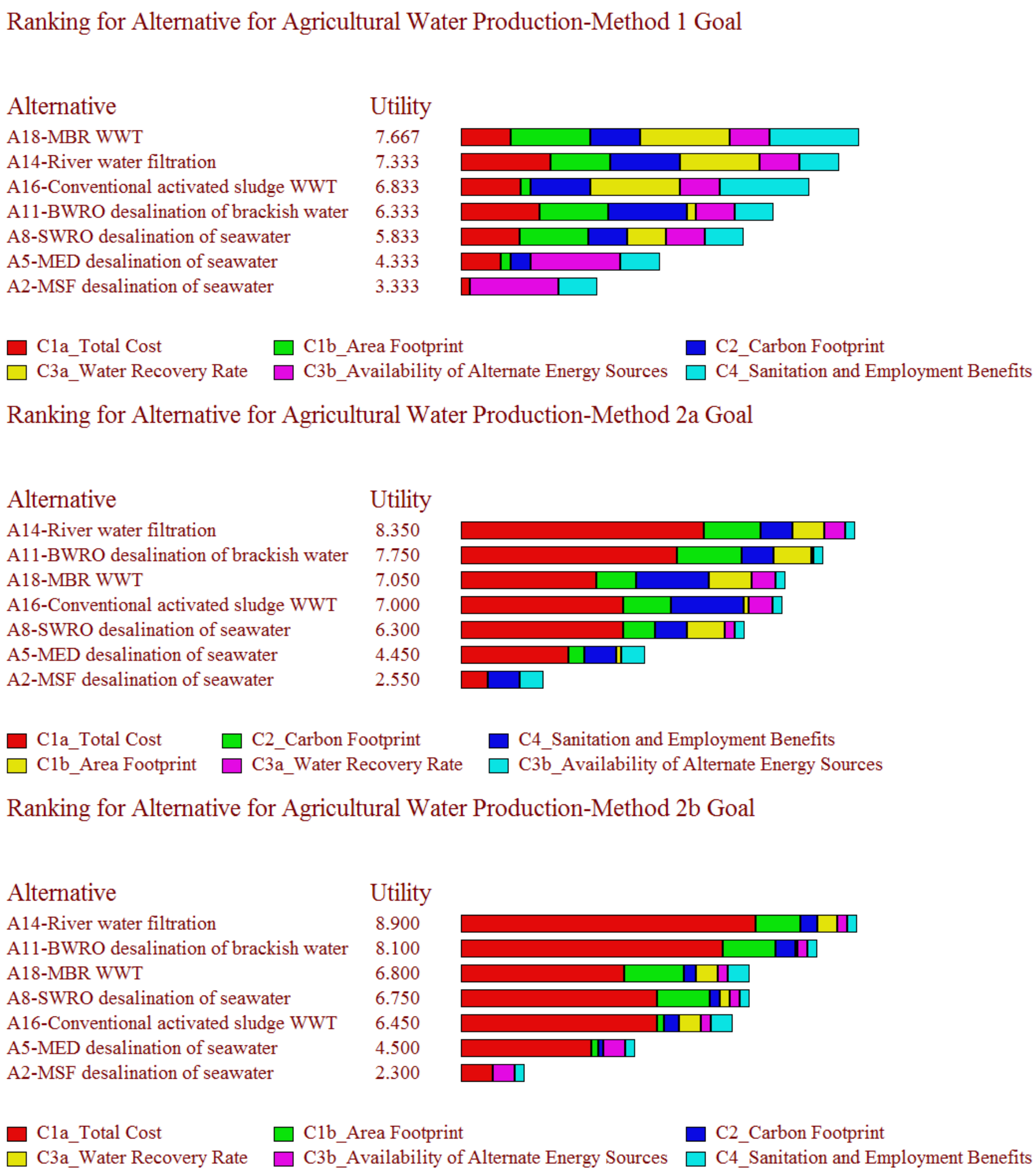

Figure 13: Ranking of Alternatives for Agricultural Water Use

Figure 14 shows the ranking of alternatives for industrial water production when the criteria are assigned weights by methods (1), (2a), and (2b) respectively. The ranking of alternatives and analysis is identical to the goal of agricultural water production.

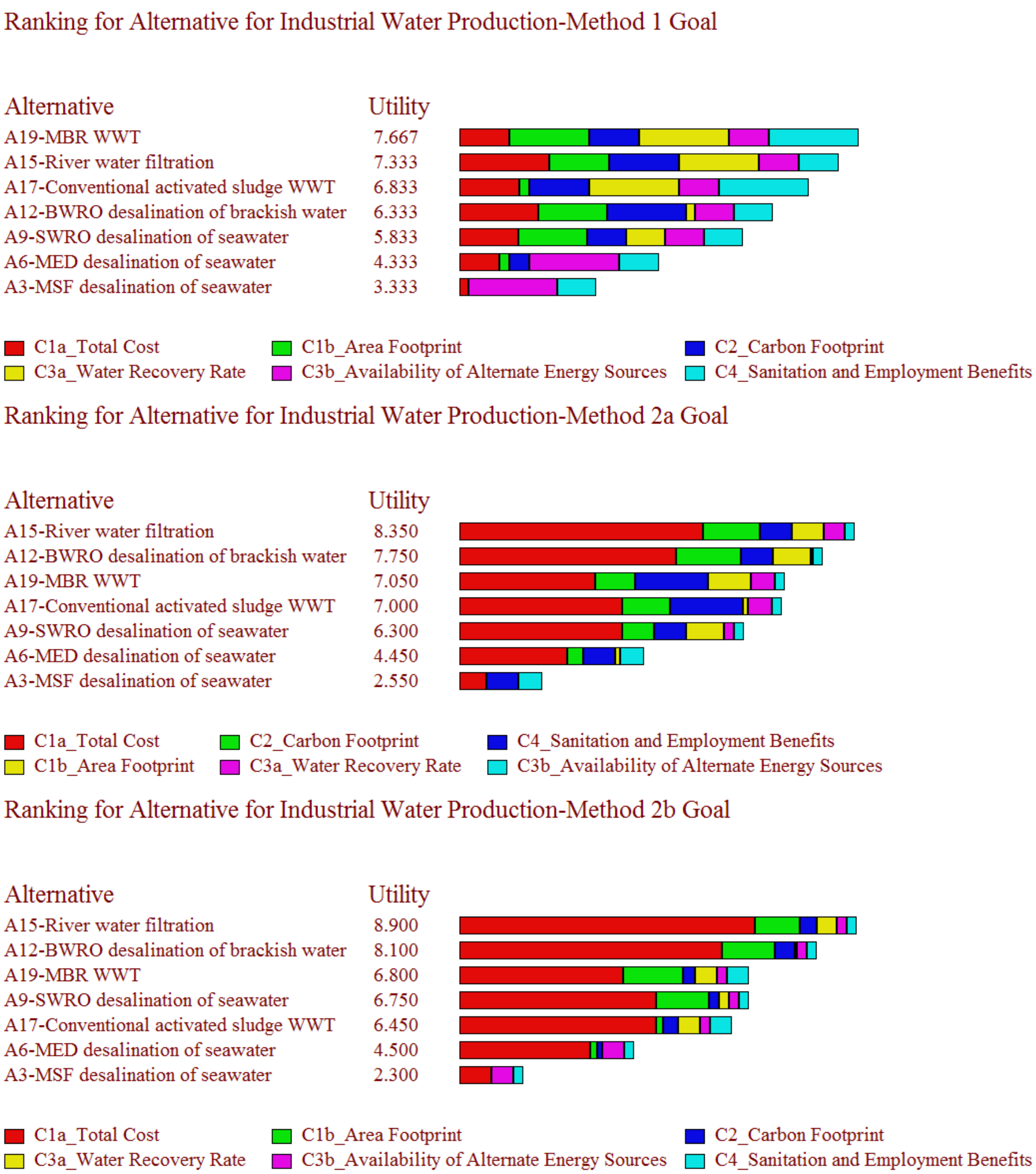

Figure 14: Ranking of Alternatives for Industrial Water Use

8.5 Sensitivity Analysis

In decision making the weights assigned to the decision criteria attempt to represent the genuine importance of the criteria. When criteria cannot be expressed in quantitative terms (such as cost, weight, volume, etc.), then it is difficult to represent accurately the importance of these criteria. In a situation like this, the decision making process can be improved considerably by identifying the critical criteria and then re-evaluate more accurately the weights of these criteria. The intuitive belief is that the criterion with the highest weight is the most critical one. This may not always be true and in some instances the criterion with the lowest weight may be the most critical one. The decision maker can make better decisions if he/she can determine how critical each criterion is. In other words, how sensitive the actual ranking of the alternatives is to changes on the current weights of the decision criteria. We determine how critical each criterion is, by performing a sensitivity analysis on the weights of the criteria. This sensitivity analysis approach determines what is the smallest change in the current weights of the criteria, which can alter the existing ranking of the alternatives.

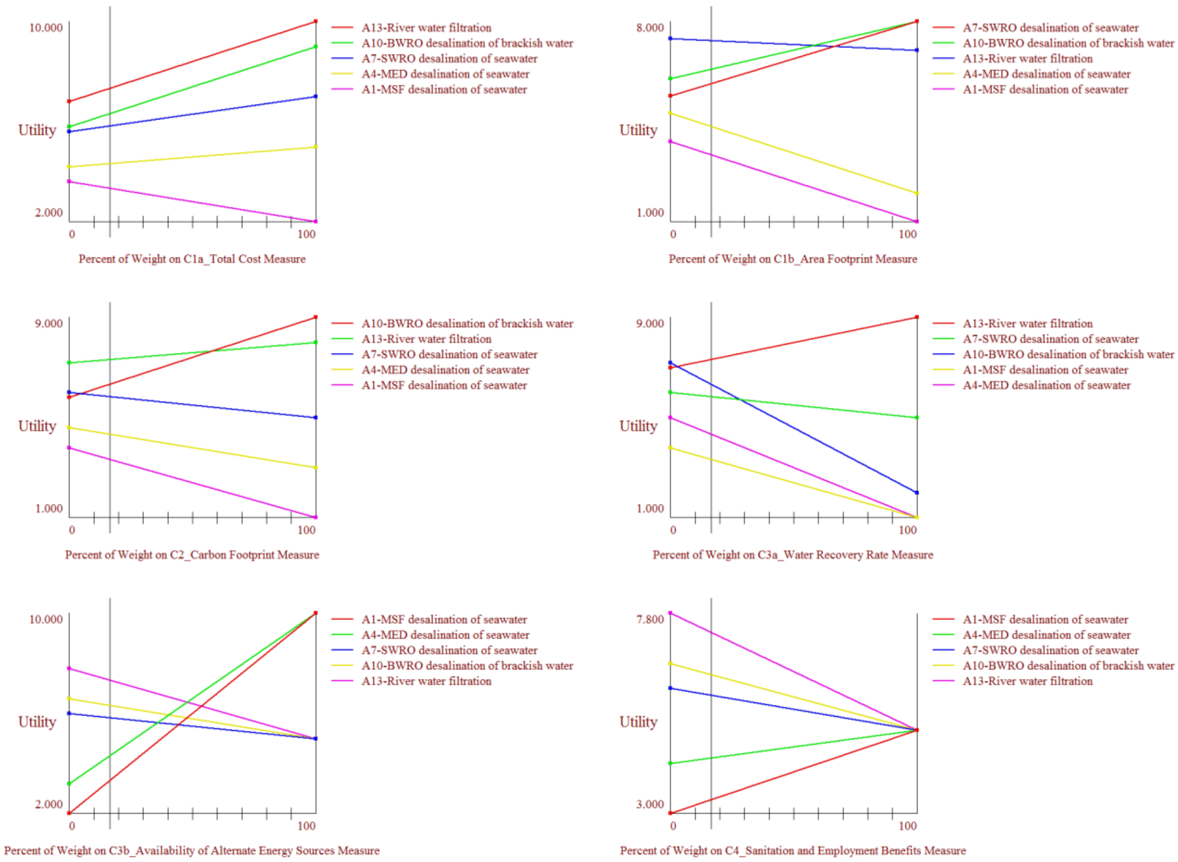

Figure 15: Effect of Weights on Potable Water Production-Method 1 Goal

Figure 15 shows how the ranking of alternatives for the goal of potable water production using method 1 changes as the weight of each criterion is changed. We notice that the ranking of alternatives does not change if any of the weights is decreased, but it changes if some weights are increased. The ranking is insensitive to changes in the importance of total cost. For the remaining criteria, the ranking is stable while the weights are varied within a reasonable range from the base case assumptions.

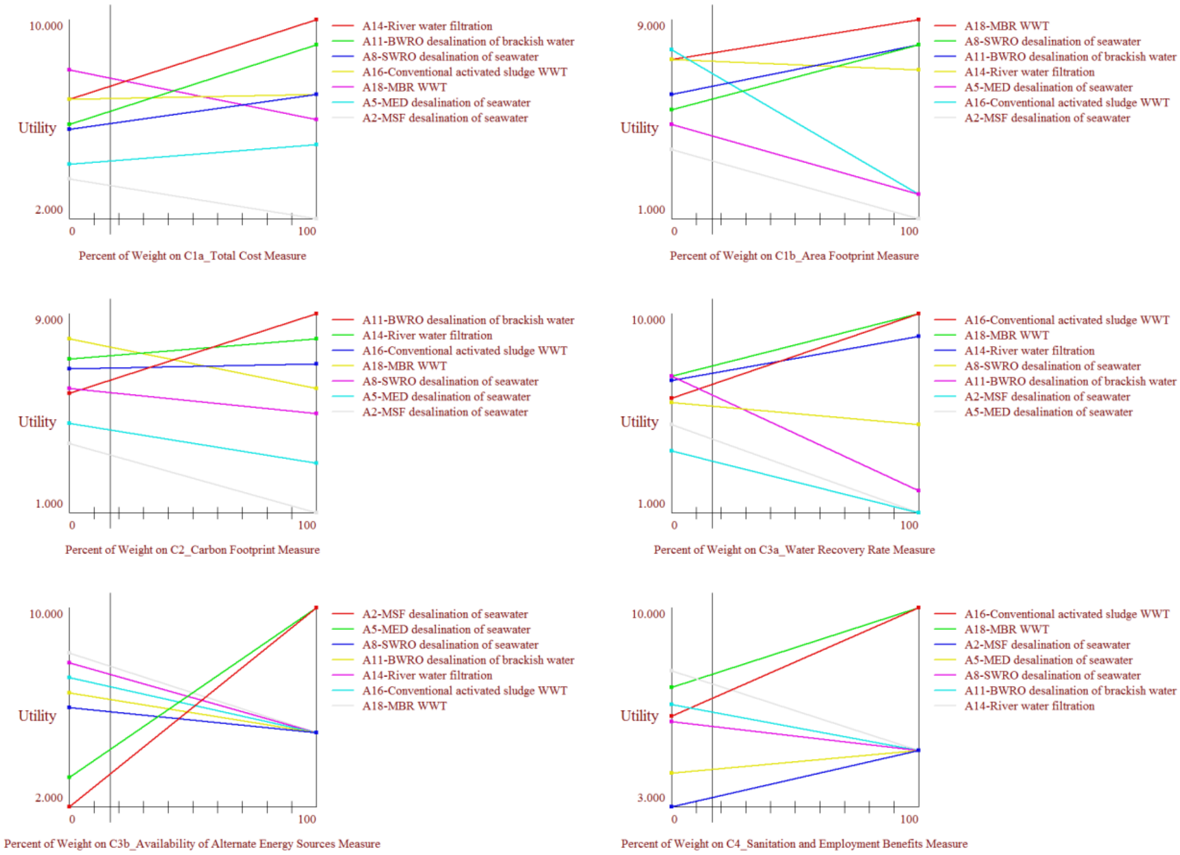

Figure 16: Effect of Weights on Agricultural Water Production-Method 1 Goal

Figure 16 shows how the ranking of alternatives for the goal of agricultural water production using method 1 changes as the weight of each criterion is changed. As the weight of criterion C1a increases, the ranking of alternatives changes so alternatives A14 and A11 become dominant over A18. Changing the weight of C1b within a reasonable range doesn't alter the rankings. The same applies for criteria C3a and C3b. Concerning criterion C2, alternatives A14, A11, A16 become more favored as the weight is increased. Alternatives A16 and A18 are dominant for variation in weight of C4.

The same analysis applies for the ranking of alternatives for the goal of industrial water production using method 1 changes as the weight of each criterion is changed.

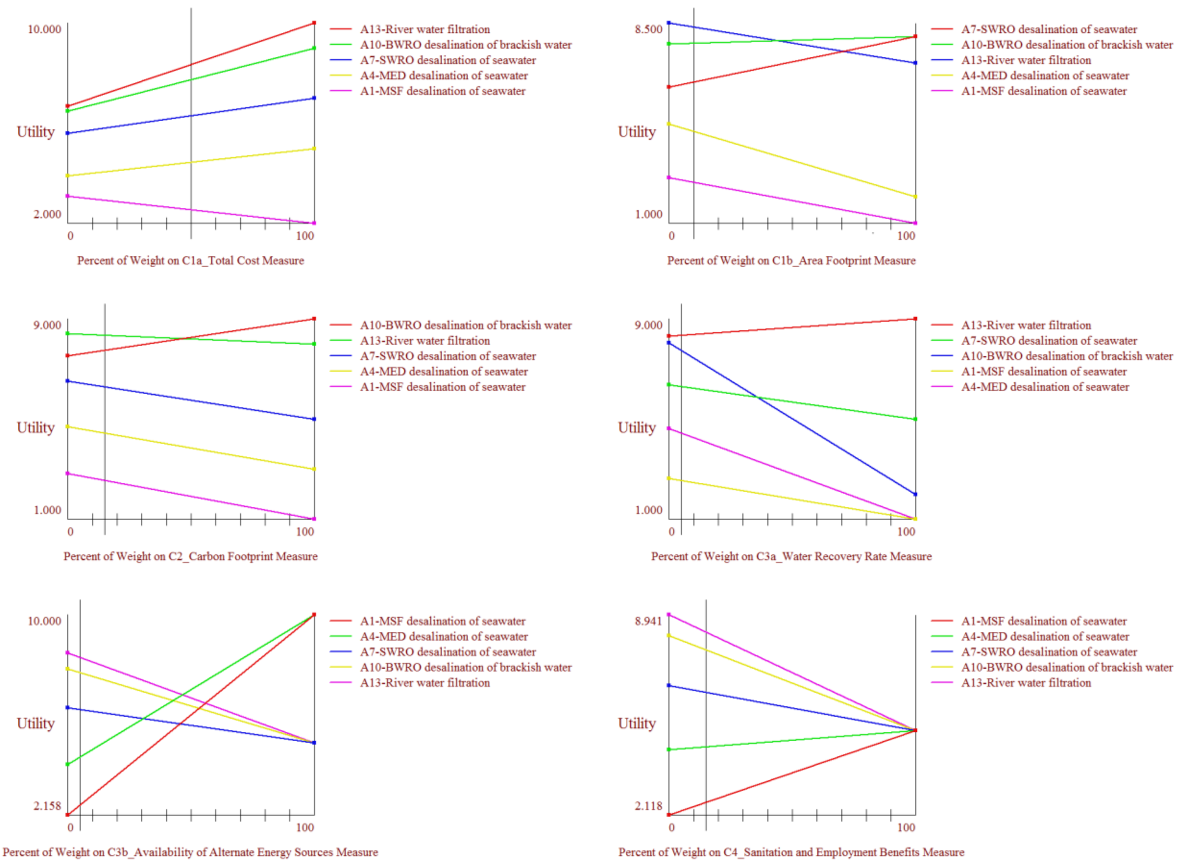

Figure 17: Effect of Weights on Potable Water Production-Method 2a Goal

Figure 17 shows how the ranking of alternatives for the goal of potable water production using method 2a changes as the weight of each criterion is changed. The observation made is that the ranking of alternatives does not change when the criteria weights are varied within a reasonable range. This indicates the validity of the base case weights in representing the importance of each criterion.

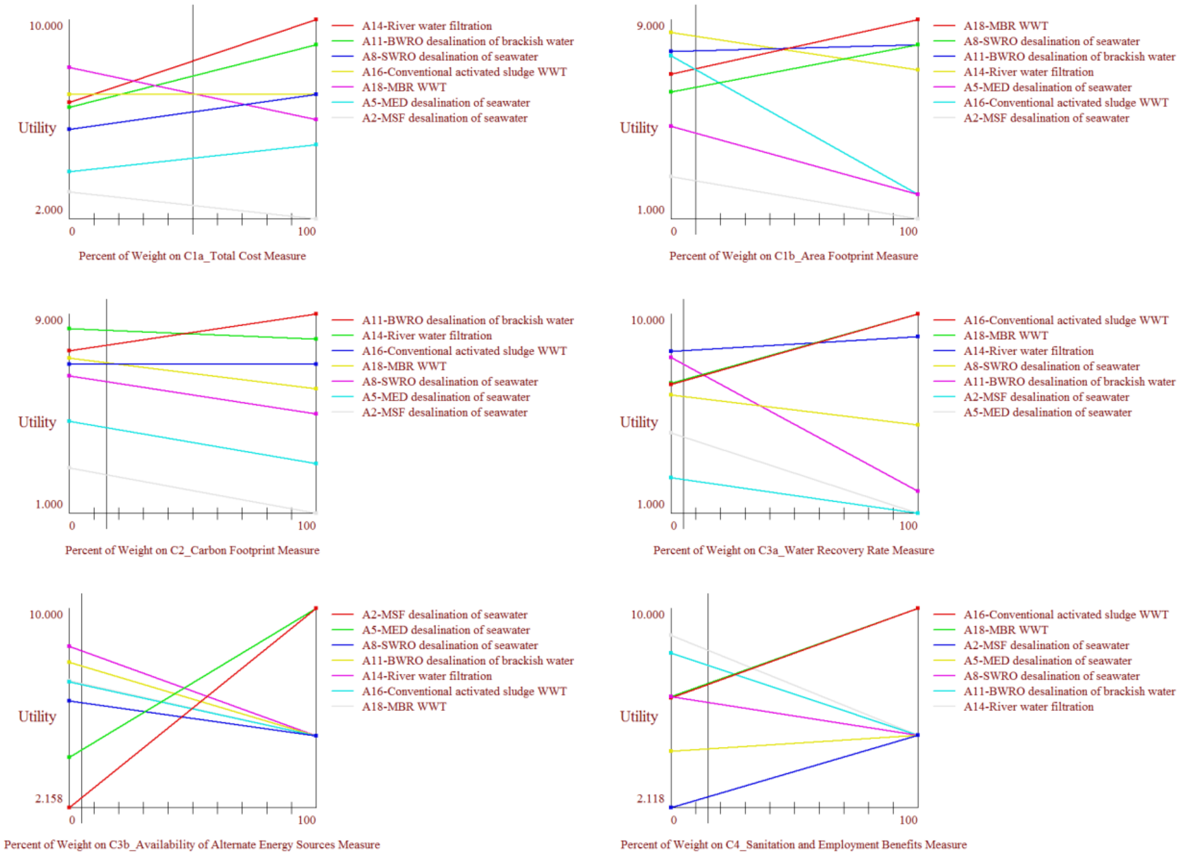

Figure 18: Effect of Weights on Agricultural Water Production-Method 2a Goal

Figure 18 shows how the ranking of alternatives for the goal of agricultural water production using method 2a changes as the weight of each criterion is changed. Varying the weight of C1a shows how alternative A18 becomes less favored while A8 becomes more favored as the weight is increased. However alternatives A14 and A11 remain top ranking. Concerning weight of C1b, the ranking does not change as weight is increased except that alternative A16 becomes less favored. Increasing the weight of C2 within a reasonable range shows how alternatives A16 and A18 switch ranks. For criteria C3a and C4, alternatives A16 and A18 take place of A11 and A14 as the weight increases. And finally the ranking does not change for variation of weight of C3b within a reasonable range.

Figure 19 shows how the ranking of alternatives for the goal of potable water production using method 2b changes as the weight of each criterion is changed. Similar to Figure 17, the observation made is that the ranking of alternatives does not change when the criteria weights are varied within a reasonable range which indicates the validity of the base case weights in representing the importance of each criterion.

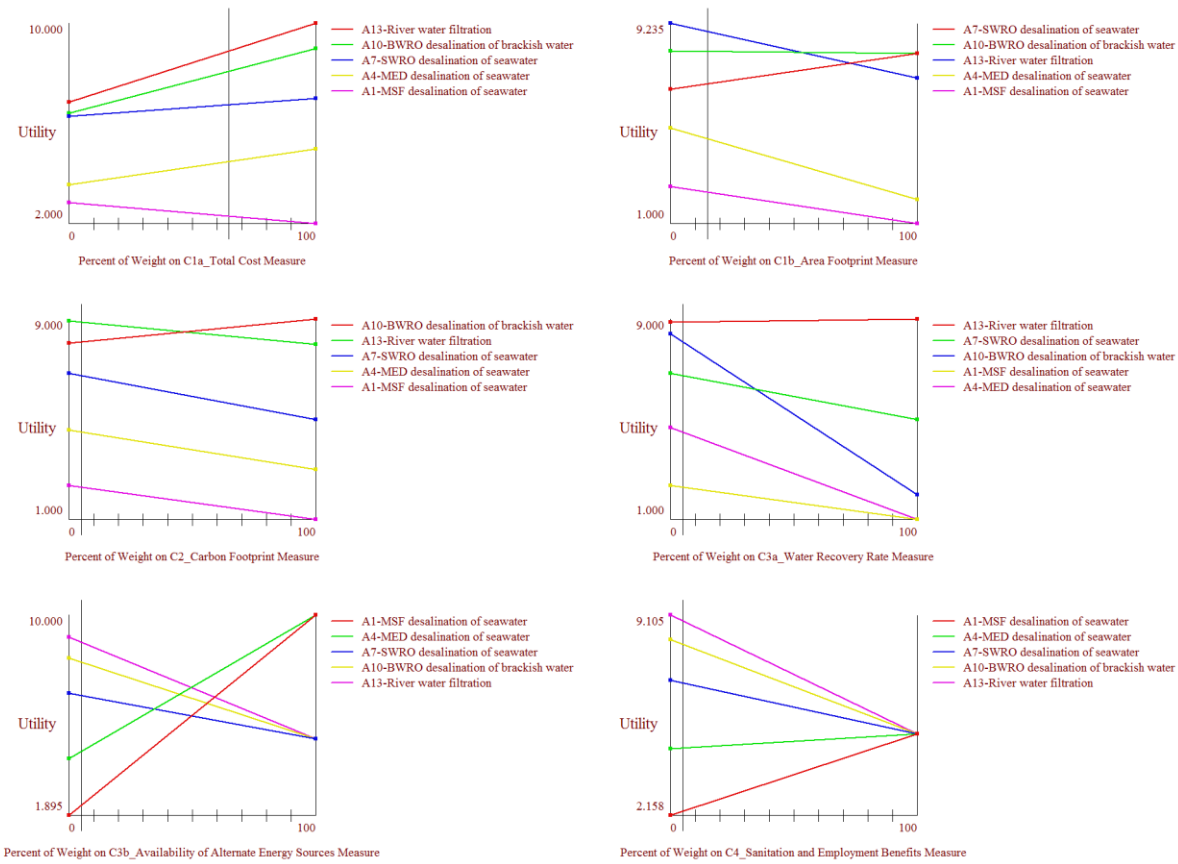

Figure 19: Effect of Weights on Potable Water Production-Method 2b Goal

Figure 20 shows how the ranking of alternatives for the goal of agricultural water production using method 2b changes as the weight of each criterion is changed.

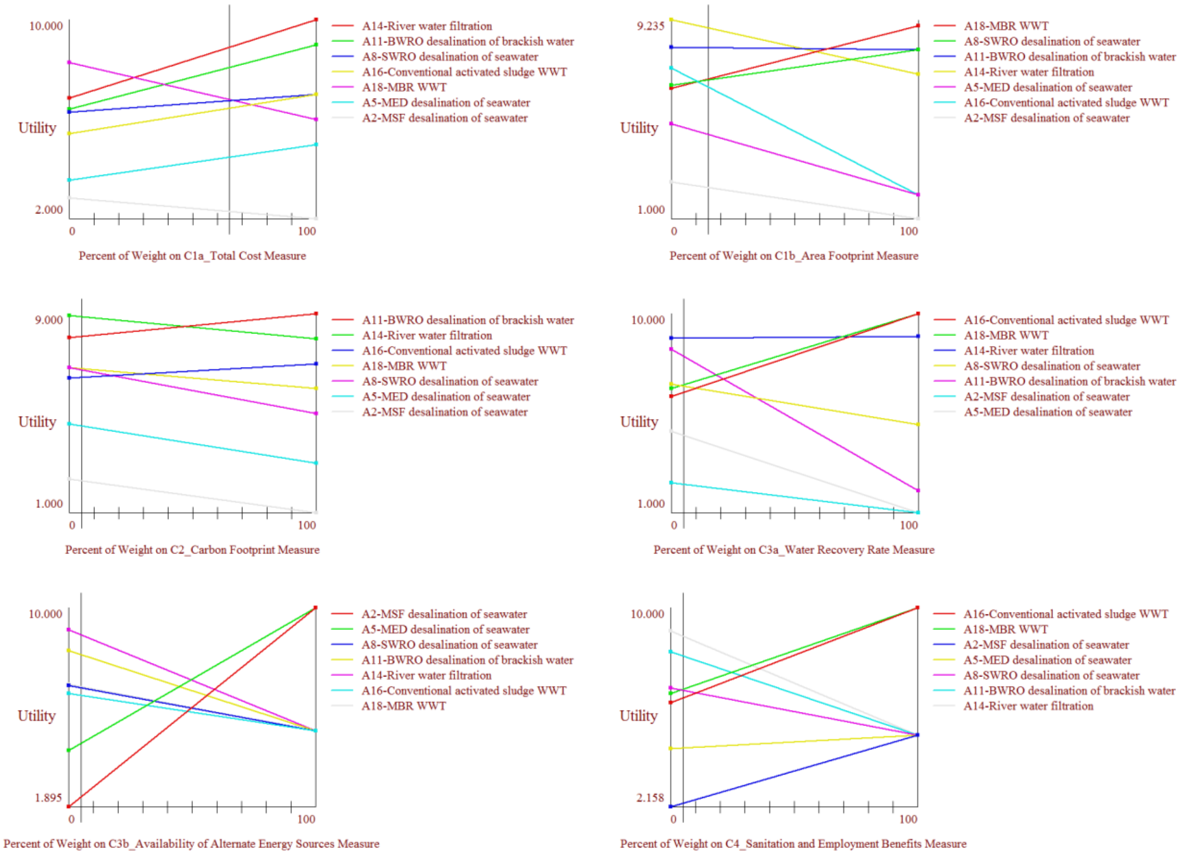

Figure 20: Effect of Weights on Agricultural Water Production-Method 2b Goal

The ranking does not change as weight of C1a increased except that alternative A18 becomes less favored. The ranking does not vary as the weights for criteria C1b and C3b are increased within reasonable ranges. Criterion C2 weight affects the ranking, as it is increased alternatives A11 and A14 remain dominant but switch at some point. The following alternatives A18, A8, and A16 also switch as the weight increases slightly. This shows that the base weight is not a well representation of the importance of criterion C2. For C3a the ranking does not change much except that alternative A11 becomes less favored with increase in weight. Finally, increasing the weight of C4 shows how the score of alternatives A16 and A18 rises while the score of the remaining alternatives drops.

8.6 Pareto Analysis

In this section, we construct the Pareto curves for the most important criteria (C1a, C2, and C4) to show which alternatives are the best in satisfying these criteria. Since this approach does not depend on the weights of the criteria, the analysis is identical for methods 1, 2a, and 2b.

Figure 21 shows the Pareto points for the goal of potable water production using. Comparing criteria C2 and C1a shows that all the points belong to the curve, but there remains the choice of which of alternatives A10 and A13 to choose. A10 performs better on C2 while A13 performs better on C1a. Comparing criteria C4 and C1a shows that all alternatives perform equally on C4, but alternative A13 performs best on C1a. Comparing criteria C4 and C2 shows that while all alternatives perform equally on C4, alternative A10 performs better on criterion C2.

Figure 22 shows the Pareto points for the goal of agricultural water production. Comparing criteria C2 and C1a shows a positive correlation between the alternatives, with the best alternatives being A11 and A14 as they perform highest on both criteria. Comparing criteria C4 and C1a shows that all alternatives other than WWT perform equally on C4, while alternatives A16 and A18 perform best on C4. However, alternative A14 performs best on C1a. Comparing criteria C4 and C2 exhibits similar performance as comparing criteria C4 and C1a except that alternative A11 performs best on C2.

The same Pareto curves and analysis apply for the goal of industrial water production.

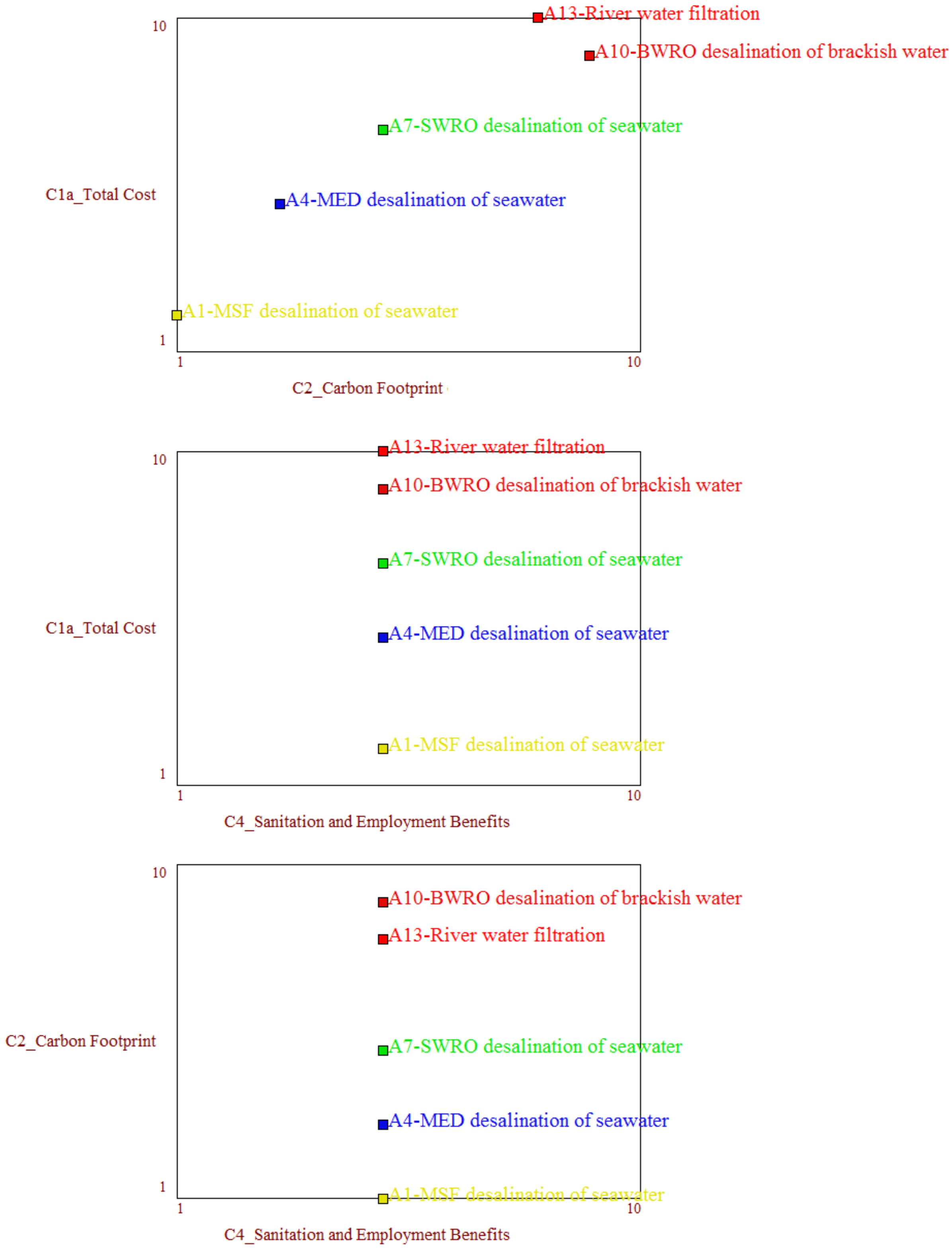

Figure 21: Pareto Curves for Potable Water Production Goal

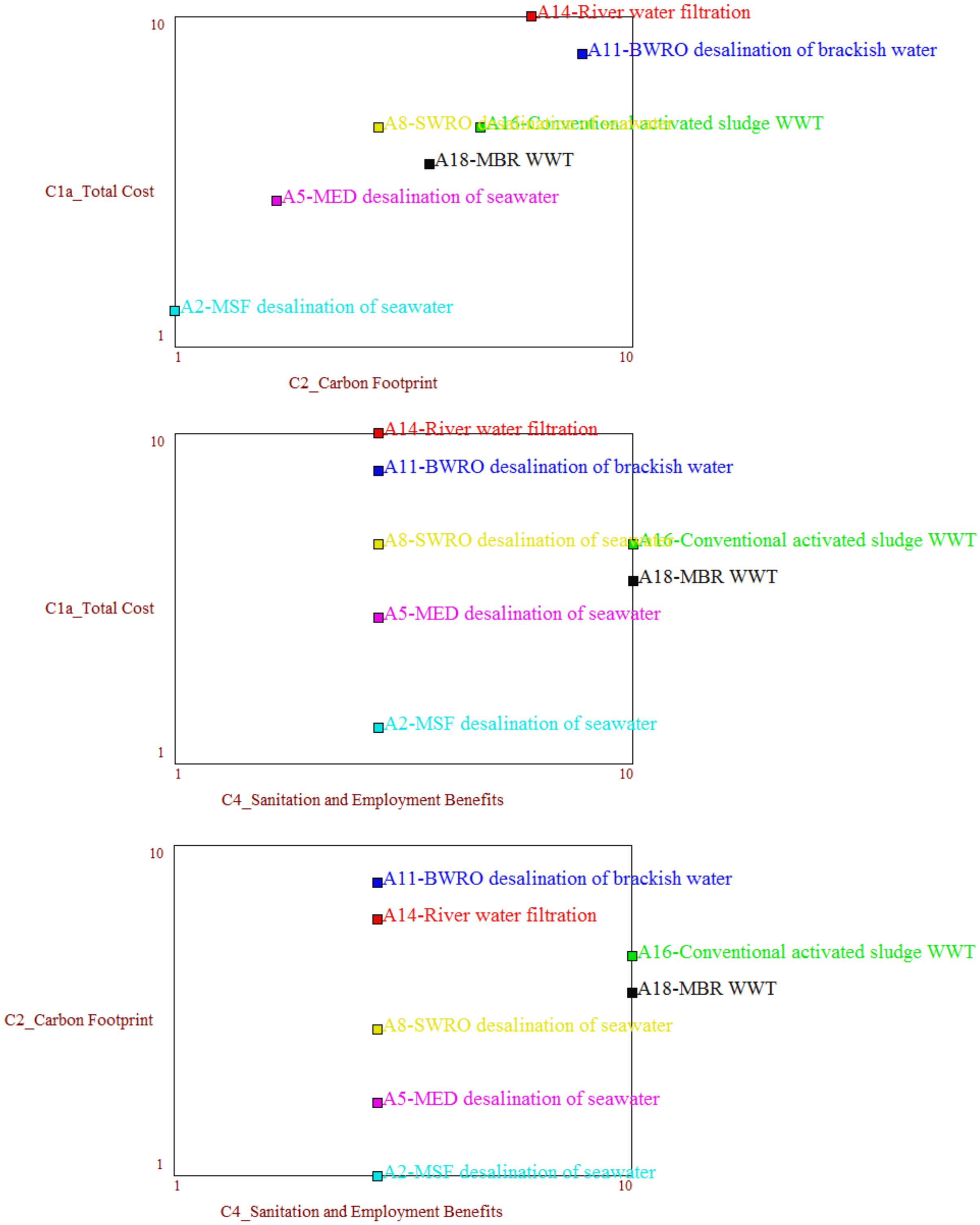

Figure 22: Pareto Curves for Agricultural Water Production Goal

CHAPTER 9

CONCLUSION

In this thesis, an integer programming optimization model was developed as a DSS to evaluate and select the optimum combination of water source and treatment process to meet different kinds of demand. The evaluation was based on economic, technical, and environmental criteria. The developed mathematical model is a general model, and can be fitted for all types of cost functions. In our case, the cost data collected produced nonlinear cost functions, so a method for overcoming the difficulty of solving a nonlinear problem was introduced. This method consisted of linearizing the cost functions by using stepwise linearization across several intervals. Even though this linearization process provides a way around the difficulty of solving a nonlinear problem, it comes with a price in the form of added decision variables and constraints. Moreover, the optimal solution of the linear problem varies from the real solution that would have been obtained if the nonlinear model was solved.

The optimization model formulated was applied to a case study, the results were analyzed, and sensitivity analysis was conducted to study the effect of demand and supply volumes (which are a direct result of variation in the population) on the optimal solution. The results show that filtration, brackish water RO, and conventional WWT are the first choices selected as an optimal solution. When the demand increases, more water is made available through desalination by sea water RO and MED.

This optimization-based DSS can be used for water resources planning in general. However, every region on its own has a specific set of constraints that should be taken into account. So in order to be used, some additional case-specific constraints may be needed. These may be related to the type of terrain, the area available for such a project, the type of funding, etc.

An alternate DSS based on MCDA was also proposed to incorporate the qualitative criteria (social criteria) that may affect the decision maker's choice in addition to quantitative criteria. This allows the comparison among all possible treatment alternatives, and considers the key criteria involved in the selection of alternatives. It also allows incorporating the decision maker's priorities of the different options available into the final outcome.

Comparing the two models, it was noticed that river water filtration was the common choice for its relatively low cost, carbon footprint, and high recovery rate. This was followed by BWRO desalination. However, when economic factors such as the area footprint and social factors such as sanitation benefits were given higher importance in the decision process, the MBR wastewater treatment process appeared at the highest rank with MCDA, while it was never part of the solution with IP optimization.

The use of the models proposed in this thesis is appropriate to aid decision makers in selecting the project to be implemented, providing the combination with the least total economic and environmental cost. The use such decision support tools, instead of intuitive judgments, could assist in improving the quality of the decision by making it more explicit, rational and efficient.

REFERENCES

Adham, S. and DeCarolis, J. F. (2004) *Optimization of Various MBR Systems for Water Reclamation, Phase III*: The City of San Diego Water Department.

Afify, A. (2010) 'Prioritizing desalination strategies using multi-criteria decision analysis', *Desalination,* 250(3), pp. 928-935.

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A. and Castells, F. (2013) 'Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach', *Journal of Cleaner Production,* 43(0), pp. 84-92.

Atilhan, S., Mahfouz, A., Batchelor, B., Linke, P., Abdel-Wahab, A., Nápoles-Rivera, F., Jiménez-Gutiérrez, A. and El-Halwagi, M. (2012) 'A systems-integration approach to the optimization of macroscopic water desalination and distribution networks: a general framework applied to Qatar’s water resources', *Clean Technologies and Environmental Policy,* 14(2), pp. 161-171.

Bonton, A., Bouchard, C., Barbeau, B. and Jedrzejak, S. (2012) 'Comparative life cycle assessment of water treatment plants', *Desalination,* 284(0), pp. 42-54.

Brepols, C., Schäfer, H. and Engelhardt, N. 'Economic Aspects of Large Scale Membrane Bioreactors'. *Workshop "Membrane Technologies for Alternative Water Resources"*, Thessaloniki, Greece, 29-30.

Chen, W.-H., Haunschild, K. and Lund, J. R. (2008) *Appendix H: Delta Drinking Water Quality and Treatment Costs*: Public Policy Institute of California. Available at: http://www.ppic.org/content/pubs/other/708EHR_appendixH.pdf.

Chung, G., Lansey, K., Blowers, P., Brooks, P., Ela, W., Stewart, S. and Wilson, P. (2008) 'A general water supply planning model: Evaluation of decentralized treatment', *Environmental Modelling & Software,* 23(7), pp. 893-905.

Côté, P., Masini, M. and Mourato, D. (2004) 'Comparison of membrane options for water reuse and reclamation', *Desalination,* 167(0), pp. 1-11.

CSM, C. S. o. M. (2009) *Technical Assessment Of Produced Water Treatment Technologies* [Research Project] (07122-12. Available at: http://aqwatec.mines.edu/produced_water/treat/docs/Tech_Assessment_PW_Treatment_Tech.pdf.

DeCarolis, J. F., Hirani, Z. M. and Adham, S. (2007) *Evaluation of Newly Developed Membrane Bioreactor Systems for Water Reclamation*: MWH Americas Inc.

Fry, A. and Haden, E. (2005) *Facts and Trends. Water.* Geneva.

Gadgil, A. (1998) 'Drinking Water in Developing Countries', *Annual Review of Energy and the Environment,* 23(1), pp. 253-286.

Ghassemi, S. A. and Danesh, S. (2013) 'A hybrid fuzzy multi-criteria decision making approach for desalination process selection', *Desalination,* 313(0), pp. 44-50.

Gonzalez-Serrano, E., Rodriguez-Mirasol, J., Cordero, T., Koussis, A. D. and Rodriguez, J. J. (2005) 'Cost of reclaimed municipal wastewater for applications in seasonally stressed semi-arid regions', *Journal of Water Supply: Research & Technology-AQUA,* 54(6), pp. 355-370.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B. and Moulin, P. (2009) 'Reverse osmosis desalination: Water sources, technology, and today's challenges', *Water Research,* 43(9), pp. 2317-2348.

Hernandez-Sancho, F., Molinos-Senante, M. and Sala-Garrido, R. (2011) 'Cost modelling for wastewater treatment processes', *Desalination,* 268(1–3), pp. 1-5.

Hospido, A., Sanchez, I., Rodriguez-Garcia, G., Iglesias, A., Buntner, D., Reif, R., Moreira, M. T. and Feijoo, G. (2012) 'Are all membrane reactors equal from an environmental point of view?', *Desalination,* 285(0), pp. 263-270.

Joksimovic, D., Kubik, J., Hlavinek, P., Savic, D. and Walters, G. (2006) 'Development of an integrated simulation model for treatment and distribution of reclaimed water', *Desalination,* 188(1–3), pp. 9-20.

Karagiannis, I. C. and Soldatos, P. G. (2008) 'Water desalination cost literature: review and assessment', *Desalination,* 223(1–3), pp. 448-456.

Khawaji, A. D., Kutubkhanah, I. K. and Wie, J.-M. (2008) 'Advances in seawater desalination technologies', *Desalination,* 221(1–3), pp. 47-69.

Lakshmana Prabu, S., Suriyaprakash, T. and Ashok Kumar, J. (2011) 'Wastewater treatment technologies: A review', *Pharma Times,* 43(5).

Lamei, A., van der Zaag, P. and von Münch, E. (2008) 'Basic cost equations to estimate unit production costs for RO desalination and long-distance piping to supply water to tourism-dominated arid coastal regions of Egypt', *Desalination,* 225(1–3), pp. 1-12.

Llamas, M. and Martínez-Santos, P. (2005) 'Intensive Groundwater Use: Silent Revolution and Potential Source of Social Conflicts', *Journal of Water Resources Planning and Management,* 131(5), pp. 337-341.

Loutatidou, S., Chalermthai, B., Marpu, P. R. and Arafat, H. A. (2014) 'Capital cost estimation of RO plants: GCC countries versus southern Europe', *Desalination,* 347, pp. 103-111.

Miller, J. E. (2003) *Review of Water Resources and Desalination Technologies*, Sandia National Laboratories: Materials Chemistry Department (SAND 2003-0800. Available at: www.semide.net/media_server/files/a/p/MillerSAND2003_0800.pdf.

Molinos-Senante, M., Garrido-Baserba, M., Reif, R., Hernández-Sancho, F. and Poch, M. (2012) 'Assessment of wastewater treatment plant design for small communities: Environmental and economic aspects', *Science of The Total Environment,* 427–428(0), pp. 11-18.

Morais, D. C. and Almeida, A. T. (2007) 'Water supply system decision making using multicriteria analysis', *Water SA,* 32(2), pp. 229-236.

National Research Council, U. S., Committee on Water Quality Criteria, U. S. and Criteria, N. T. A. C. o. W. Q. (1972) *Water quality criteria, 1972: A Report of the Committee on Water Quality Criteria.* Washington, D.C.: Environmental Protection Agency.

NRC, N. R. C. (2012) *Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater.* Washington, DC: The National Academies Press.

Pasqualino, J. C., Meneses, M. and Castells, F. (2011) 'Life Cycle Assessment of Urban Wastewater Reclamation and Reuse Alternatives', *Journal of Industrial Ecology,* 15(1), pp. 49-63.

Plappally, A. K. and Lienhard, J. H. (2012) 'Costs for water supply, treatment, end-use and reclamation', *Desalination and Water Treatment,* 51(1-3), pp. 200-232.

Raluy, G., Serra, L. and Uche, J. (2006) 'Life cycle assessment of MSF, MED and RO desalination technologies', *Energy,* 31(13), pp. 2361-2372.

Stokes, J. R. and Horvath, A. (2009) 'Energy and Air Emission Effects of Water Supply', *Environmental Science & Technology,* 43(8), pp. 2680-2687.

Sudhakaran, S., Lattemann, S. and Amy, G. L. (2013) 'Appropriate drinking water treatment processes for organic micropollutants removal based on experimental and model studies — A multi-criteria analysis study', *Science of The Total Environment,* 442(0), pp. 478-488.

Tarnacki, K., Meneses, M., Melin, T., van Medevoort, J. and Jansen, A. (2012) 'Environmental assessment of desalination processes: Reverse osmosis and Memstill®', *Desalination*, 296(0), pp. 69-80.

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F. and Zhao, J.-H. (2009) 'Review on multi-criteria decision analysis aid in sustainable energy decision-making', *Renewable and Sustainable Energy Reviews*, 13(9), pp. 2263-2278.

Wittholz, M. K., O'Neill, B. K., Colby, C. B. and Lewis, D. (2008) 'Estimating the cost of desalination plants using a cost database', *Desalination*, 229(1-3), pp. 10-20.

World Health Organization, W. (2008) *Guidelines for Drinking-Water Quality*. 3 edn.

Zhou, J., Chang, V. W. and Fane, A. G. (2014) 'Life Cycle Assessment for desalination: a review on methodology feasibility and reliability', *Water Res*, 61, pp. 210-23.

Zhou, Y. and Tol, R. S. J. (2005) 'Evaluating the costs of desalination and water transport', *Water Resources Research*, 41(3), pp. W03003.