

Cost and Sustainability Optimization of Desalinated Water Supply Chains

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ABSTRACT

The growing demand for freshwater coupled with the decline in traditional water sources is driving the increased consumption of desalinated water. This paper introduces a comprehensive mathematical model that seeks to jointly optimize a multitude of strategic and tactical decisions within desalinated water systems while accounting for environmental alongside economic considerations. These decisions include the installation of new desalination plants, replacement of obsolete units, selection of desalination technologies, and the expansion of existing facilities as well as the location of new ones. Additionally, the model determines annual production levels in each plant, allocates water to various demand zones, and manages water levels in storage tanks. In order to validate the model, a realistic case study drawn from the United Arab Emirates is utilized. It is found that the operational cost components of desalination, transportation pipelines, and storage facilities are more significant than their capital cost counterparts. In addition, all replaced and new units employed Reverse Osmosis technology, which is in line with the emerging trend worldwide. Finally, the effect of increasing the capacity of new units and varying the carbon emissions tax on the relevant decisions as well as the overall cost is studied as part of the sensitivity analysis.

Keywords: *cost, environmental impact, mathematical modelling, water desalination, water supply chain (WSC)*

1. INTRODUCTION

The scarcity of conventional freshwater, coupled with the growing demand for water, has brought up the need for the use of treated non-conventional water sources, such as seawater, brackish water, and wastewater. A commonly used method for utilizing seawater or brackish water is water desalination, which is a process that treats high-salinity feedwater to produce freshwater. The global desalination capacity was estimated at 130 million cubic meters per day (m^3/day) in 2024, with projections indicating it will exceed 200 million m^3/day by 2030 (GWI, 2020). Meanwhile, the cost of desalinated water is expected to decrease by half.

Among the countries with the largest installed capacities, Saudi Arabia leads with 14.58 million m^3/day , followed by the United States with 11.90 million m^3/day , and the United Arab Emirates (UAE) with 9.47 million m^3/day (Rios-Arriola *et al.*, 2022). Collectively, Middle Eastern countries account for 39% of the world's total desalination capacity (Mahmoudi *et al.*, 2023) while also having the highest consumption of desalinated water, representing 53% of global consumption (Almasmoudi and Jamoussi, 2024). In recent years, the UAE has significantly accelerated large-scale desalination initiatives. With over 70 desalination plants, the country contributes 14% of the total worldwide desalination capacity, and further expansion plans are underway.

Examining the water desalination process from a supply chain (SC) perspective provides a holistic view to the various strategic, tactical and operational aspects that need to be taken into consideration. In essence, a desalinated water supply chain (WSC) consists of multiple stages, which include the water source, desalination plants, storage tanks, and the demand zones that need to be satisfied, in addition to a network of pipelines connecting the different stages of the WSC. Mathematical modelling approach can be utilized to efficiently address various challenges encountered across the supply chains, and collectively optimize strategic, tactical, and operational decisions involved (Ali and Nakade, 2015).

The selection of the most-suited desalination technology for newly installed plants is of paramount importance, where such technology is broadly divided into thermal and membrane desalination. In principle, thermal desalination requires the use of heat to vaporize saline water feed and produce freshwater. Alternatively, membrane desalination utilizes semi-permeable membranes which block salt particles, present in the feedwater, from passing through when pressure is applied on the saline feedwater. Given their proven-efficiency and increasing popularity in the Gulf region, this work considers three different technologies, two of which are thermal-based: Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation

(MED), while the third one is membrane-based: Reverse Osmosis (RO). While RO has the advantage of requiring less energy to operate, it offers lesser capacity compared to MSF and MED, which is why larger plants typically rely on thermal technologies as they exploit the economies of scale (Al-Nory *et al.*, 2014; Bhojwani *et al.*, 2019). While the reliance on MSF peaked during the eighties as it accounted for slightly over 90% of the desalinated water market share, RO technology has then become very popular where it now accounts for 69% of the global desalinated water production versus roughly 20% for MSF (Jones *et al.*, 2019). Nevertheless, despite the decline in reliance on MSF globally, it continues to be an important desalination technology in the Gulf region where it still dominates (Nair and Kumar, 2013). MED is known for being the oldest desalination technique with its adoption declining over the years leading to several improvements and coupling with other technologies such as thermal vapor. This triggered a resurgence of the MED technology largely in the Middle East where it now account for 8% of the global market share (Nair and Kumar, 2013). The three desalination techniques differ in their water intake, salinity level of the produced water, energy consumption levels, production rate, as well as cost and environmental implications necessitating the incorporation of technology selection as a crucial and an inherent consideration in the optimization of desalinated WSCs.

Despite water desalination being fruitful for over 60 years, harmful by-products of this process, such as Greenhouse Gases (GHGs) and brine, have been taking a toll on the environment. In fact, it is known that the various desalination processes have multiple environmental impacts that are associated with each stage of the process (intake, pre-treatment, desalination, and outfall). Due to their high energy consumption and reliance on non-renewable fossil fuels, desalination plants significantly contribute to air pollution by emitting CO₂, NO_x, SO_x, and particulate matter. As mentioned above, desalination technologies exhibit significant variations in energy consumption, and consequently, their associated carbon emissions. RO technology generally has a lower energy footprint, whereas MSF and MED rely on thermal energy, leading to higher emissions. In alignment with global trends, a growing shift toward RO technology has been observed, primarily driven by its lower energy intensity and potential for integration with renewable energy sources. In addition, the sources of water also affect the environmental performance of desalination technologies. A study analyzing 20 desalination plants utilizing a combination of seawater reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) systems, with a total capacity of 1.736 million cubic meters per day (MCM/day), found that their carbon footprint was equivalent to 1.9 kg CO₂ per cubic meter of water produced (Heihsel *et al.*, 2019). Therefore, it is crucial to develop a comprehensive strategy that meets the growing demand for freshwater while minimizing the environmental impact of WSC in a sustainable manner.

This paper aims to develop a decision support tool that assists policy makers in minimizing total cost and environmental impact associated with desalinated WSCs. To that end, a mathematical model that divides the region under study into several coastal and inland demand zones is developed while satisfying practical technological and

operational constraints. The minimization of environmental impact will mainly focus on the reduction of CO₂ emissions due to production and distribution activities as well as brine disposal. In principle, decisions to be optimized via the multi-period model include whether to construct new desalination plants or expand existing ones given the present and forecasted increase in demand for water in different zones. If a new plant is to be installed, its corresponding location, capacity, and operational desalination technology shall also be determined by the model. Furthermore, the model establishes the need to install storage tank(s) at different locations, and the capacity of these tanks. Moreover, the capacity of pipelines connecting the different stages of the supply chain will be optimized as needed. In addition, the considered tactical decisions include water production level at each plant, storage level at each demand zone, the amount of released CO₂ and brine as well as the allocation of water among the demand zones every year throughout the planning horizon.

In essence, this study aims to investigate the following key research questions:

1. How can mathematical modelling be effectively applied to enhance cost efficiency and sustainability in desalinated WSCs, particularly in water-scarce regions?
2. What are the economic and environmental trade-offs of different desalination technologies in large-scale WSC optimization?
3. How does carbon taxation influence strategic and tactical decisions related to desalination plant expansion and technology selection?
4. What is the impact of water transportation and storage infrastructure on minimizing the total cost and carbon footprint of desalinated WSCs?

The remainder of this paper is organized as follows. Section 2 surveys single and multi-objective WSC optimization models existent in the literature. Section 3 provides the attributes, assumptions, and detailed formulation of the proposed mathematical model. Section 4 illustrates the practical relevance of the model developed herein via a case study drawn from the desalination industry and presents a discussion of the main results. Finally, Section 5 highlights some concluding remarks along with promising avenues for future research. The full notation used in the development of the mathematical model is provided in Appendix A.

2. LITERATURE REVIEW

Several studies addressed the complexities associated with efficiently managing water resources to keep up with the increasing demand whilst accounting for a multitude of technical, economic, environmental and country specific concerns. While optimization techniques and mathematical programming have been amply utilized in this field, other approaches seeking to handle various issues encountered in WSC have also been embraced by several researchers, such as conceptual frameworks (Balfaqih *et al.*, 2016), multi-criteria decision making (Kotb *et al.*, 2024), simulation (Ibrahim and Eltahir, 2019), and life cycle assessment (Shahabi, 2015). It is noted, however, that the mathematical modeling technique provides a multifaceted decision support tool allowing policymakers to jointly optimize interrelated

decisions while accounting for different sustainability factors (Mujkic *et al.*, 2018; Tundys, 2018). To that end, this section discusses and categorizes the mathematical models associated with desalinated WSCs found in the literature and differentiates them from the model provided in this work.

2.1 Single Objective WSC Optimization Models

A stream of researchers addressed the optimization of various aspects of desalinated WSCs via formulating the problem as a mathematical model aiming to optimize a single objective function while considering a multitude of technological and operational constraints. For instance, Chung *et al.* (2008) presented a comprehensive mathematical model that involves water supply and demand zones along with recharge facilities and wastewater treatment plants. The model seeks to minimize the total cost comprised of construction, expansion, operating and maintenance of transportation and treatment systems, as well as a penalty that is incurred in case of water shortage. The model investigates how the topography of the plant's location impacts the overall cost of the WSC network. The authors recommended the construction of a small, decentralized wastewater treatment system for widely dispersed communities or ones that are situated on steep ground where pumping cost is relatively high. However, it is difficult to implement their model in countries such as the UAE where people are mostly centered in cities with flat topography, which implies lower water pumping cost. In another work, Ray *et al.* (2010) proposed an integrated optimization model, which aims to minimize the cost associated with WSC network structure as well as wastewater disposal and reuse options in the city of Beirut, Lebanon. In their work, they incorporated the whole water cycle consisting of supply, demand disposal, and reuse. Al-Nory and Graves (2013) conducted an analysis of the desalinated water industry and modeled it from a SC standpoint. The objective of the model is to minimize the total investment and operational costs associated with the WSC. The proposed model was tested using actual data in Saudi Arabia, and solved to optimality using an off-the-shelf solver called Gurobi. It is important to note that this model is limited compared to other models as it fails to capture operational details and environmental impact of the WSC. Abdulbaki *et al.* (2017) proposed a MILP model that seeks to minimize the total cost and environmental impacts associated with the treatment and distribution of water. The model encompasses multiple water sources including seawater, surface, ground, and wastewater, as well as multiple demand zones including irrigation, drinking, and industry use. It seeks to specify the amount of water supplied from each source to each treatment plant, and also determine the technology employed in treating the water such that it is suitable for the distinct uses. The environmental impact of the plant was represented by brine disposal cost and social cost of emitted CO₂. The sensitivity analysis showed that increasing population beyond the capacity of conventional water resources creates the need for seawater desalination using RO technology.

In another work, Kondili *et al.* (2010) addressed the problem of water shortage in areas with limited water resources and provided a mathematical model that optimizes the allocation of water among competing end-users while incorporating multiple water sources with varying supply

costs. The water sources considered in the model include RO desalination, ground reservoirs, dams, purchased water transferred by ships, and own water resources. The authors tailored the model to reflect technical and environmental features of some of the Greek Aegean islands, but the water distribution cost was not accounted for. A closely related work is that of Liu *et al.* (2011) in which the authors presented a mixed integer linear programming (MILP) model tackling the optimization of integrated water resources in two Greek islands as a case study. The considered water sources include desalinated seawater, wastewater and reclaimed water. The model seeks to jointly optimize the location as well as the capacity of desalination, wastewater treatment and water reclamation plants, pipelines distribution network, as well as number and types of the pumps and storage tanks for all water sources. The objective is to minimize the annualized total capital and operating costs while also accounting for specific water quality demand per geographical region within the islands. Koleva *et al.* (2017) developed a mixed integer nonlinear programming (MINLP) model for efficient water treatment design such that water net cost is minimized. Furthermore, a partially linearized MINLP and a mixed integer linear fractional programming (MILFP) models were devised. The two models were tested on seawater desalination and surface water treatment case studies to produce drinking water. While both models provided results that conformed to industrial practices, the MILFP model was more efficient in finding the optimal solution. More recently, Kizhisseri *et al.* (2022) devised a multi period MILP model for the optimization of water supply in arid and semi regions which incorporates both economic and environmental measures along with three demand types for water quality (potable, non-potable, and irrigation). Such demand is satisfied by various water sources including desalinated water, wastewater and groundwater, and the objective is to determine the optimal production, expansion and distribution of water supply sources that minimize the overall cost while meeting CO₂ emissions targets, groundwater extraction limits as well as brine disposal limits. The devised model was applied to the Emirate of Abu Dhabi and solved using CPLEX optimizer. While this latter work closely relates to the work presented herein, capacity reduction via retiring desalination plants/units reaching the end of their lifetime and the expansion of distribution pipelines over the planning horizon to satisfy increasing demand are not considered.

Similarly, a multi period MILP model seeking to minimize costs related to desalination operations, water transportation, greenhouse gas emissions, and brine disposal, was developed by Saif and Almansoori (2014). This model incorporates several strategic and tactical decisions, taking into consideration both Multi-Stage Flash Distillation (MSF) and RO technologies. Despite the fact that the model is comprehensive, it only considers MSF and RO technologies even though there are other technologies, such as Multi-Effect Distillation (MED), that the model does not incorporate. In a related study, Saif and Almansoori (2016) addressed the location and capacity expansion decisions of several desalination plants on a yearly basis over a finite planning horizon and formulated the problem as a multi-period MILP model that aims to minimize the Net Present Value (NPV) of the WSC. The proposed model was implemented in the city of Abu Dhabi in the UAE while

examining three different scenarios to determine the most economical way of handling GHGs emissions. The three scenarios were: minimizing the carbon tax cost, integrating green energy sources (nuclear or solar), or deploying carbon capture facilities.

2.2 Multi Objective WSC Optimization Models

The previous works presented WSC optimization models having a single objective function where the problem was tackled merely from an economic perspective, with some works incorporating environmental aspects via a proper conversion factor (e.g. carbon tax multiplier) into the objective function. Another stream of researchers embraced a more holistic approach and proposed multi-objective WSC models that account for other pillars of sustainability in the form of separate, and possibly conflicting, objectives. Considering an urban setting, Han *et al.* (2008) developed a multi-objective linear programming model that establishes the optimal allocation of multi-sourced water among multiusers while considering both conventional and non-conventional water sources. The various water sources include groundwater, rainwater, reclaimed water, and desalinated seawater, while the demand arises from residential, industrial, agricultural and ecological sectors. The allocation model comprises three objectives: net benefit maximization, sewage drainage minimization, and greenbelt area maximization. In a related work, Han *et al.* (2011) also addressed water resource allocation problem in Dalian City, China, and proposed a multi-objective linear program utilizing interval parameters along with an interactive compromising algorithm. Considering multiple sources and multi-user water quality requirements, the model attains the maximum synthesis between economic, societal and environmental objectives. The authors concluded that the proportion of reused water to total water consumption is gradually increasing while that of the agricultural water to total water consumption is gradually decreasing. Similarly, Al-Zahrani *et al.* (2016) devised a multi-objective model for water resources management in the city of Riyadh, Saudi Arabia, while considering three sources: groundwater, desalinated water and treated wastewater, and three user sectors: domestic, agricultural, and industrial. To account for uncertainties, random realizations were generated using mean values of the forecasted water supply and demand for every year of the planning horizon. The model seeks to strike a balance between 10 different objectives for which the approach of goal programming was adopted to attain a compromise solution that aligns with the preset priority for each objective. Nevertheless, these three research works address the water allocation problem while overlooking other pressing issues pertaining to desalinated WSCs. Koleva (2018) presented a MILP model that optimizes the WSC design at regional and national levels wherein decisions pertaining to the installation of new plants and expansion of already existing ones are considered. This model offers a holistic look at the WSC problem as it encompasses environmental, regulatory, technical and economic aspects along with the cost-reliability tradeoffs. Following a one-way sensitivity analysis, the authors deduced that a WSC is more adversely affected by demand volatility than diminished rainfall.

2.3 Research Gaps Identification and Positioning

As inferred from the above review of the relevant literature, there is a shortage of comprehensive long-term WSC optimization models that capture all practical, technological and environmental aspects characterizing the water desalination industry. To that end, this work provides a mathematical model that jointly optimizes a multitude of strategic and tactical WSC related decisions from both economic and environmental standpoints while meeting the time-varying demand of different end-users. The proposed model is of a multi-period nature and will be solved over a realistic planning horizon of 15 to 25 years long. This better captures the dynamic nature of variables related to new plant location and the associated capacity, desalination technology, capacity expansion of existing plants; size, number, and location of storage tanks; construction and expansion of the pipeline network, and the source to demand zone allocation strategy (i.e. demand fulfilment plan). It is noted that the cost associated with the aforementioned decision variables will be estimated from relevant literature and available expertise at domestic electricity and water authorities. Moreover, environmental impact will be incorporated into the model as part of the selected technology for new plants, operation of existing plants, and transportation of freshwater within the WSC such that GHGs emissions and discharged brine are minimized. In addition, the impact of discharged brine will be mitigated by diluting it with seawater before disposing it back into the sea. **Table 1** below categorizes the relevant literature embracing the mathematical modeling approach based on several dimensions and provides a better positioning of the model presented in this work as compared to the existing ones. The "desalination units" column represents the modeling of a desalination plant as a collection of individual units, each potentially utilizing different technologies. The "multiple desalination technologies" column indicates cases where multiple desalination technologies are implemented within the same plant. The "desalination unit retirement" column refers to the decommissioning of desalination units upon reaching the end of their operational lifespan. Lastly, the "effective planning horizon" column accounts for the construction and expansion timelines of new and existing facilities (plants, units, storage tanks, and pipelines), ensuring a more realistic representation of the desalination supply chain. In addition, **Table 1** highlights several unique features and practical considerations incorporated into the integrated model proposed in this paper, including:

- Reducing the mathematical and time-related complexity by discounting the longest construction lead-time among all facilities from the planning horizon. This adjustment eliminates the need for binary variables that verify the feasibility of construction and expansion decisions, thereby streamlining the optimization process.
- Segmenting desalination plants into individual units that degrade over time and cease operation independently at predetermined intervals, providing a more realistic representation of the desalination industry.

- Enabling multi-technology integration within a single plant, allowing RO, MSF, and MED technologies to coexist.
- Allowing the expansion of storage and pipeline capacities via installing new tanks and pipelines with no restriction on the number of expansions.
- Optimizing production capacity expansion by incorporating both the replacement of retiring desalination units and the installation of new units in newly constructed desalination plants.

Table 1 A classification of modeling-oriented literature on WSC optimization

Publication	Sustainability dimension			Objective function		Decisions considered							Application/ Case study
	Economic	Environmental	Social	Single	Multiple	Capacity expansion	Desalination unit retirement	Technology selection	Source-user allocation	Effective planning horizon	Desalination Units	Multiple desalination technologies	
Chung <i>et al.</i> (2008)	✓	✓		✓		✓			✓				Sothorn Arizona, USA
Han <i>et al.</i> (2008)	✓	✓	✓		✓				✓				Dalian City, China
Ray <i>et al.</i> (2010)	✓	✓		✓					✓				Beirut, Lebanon
Kondili <i>et al.</i> (2010)	✓	✓		✓					✓				Greek islands
Liu <i>et al.</i> (2011)	✓	✓		✓		✓			✓				Greek islands
Han <i>et al.</i> (2011)	✓	✓	✓		✓				✓				Dalian City, China
Al-Nory and Graves (2013)	✓			✓		✓			✓				Saudi Arabia
Al-Nory <i>et al.</i> (2014)	✓	✓		✓		✓			✓				Saudi Arabia
Saif and Almansoori (2014)	✓			✓									Regional scale
Saif and Almansoori (2016)	✓	✓		✓		✓		✓	✓				Abu Dhabi, UAE
Al-Zahrani <i>et al.</i> (2016)	✓	✓	✓		✓				✓				Riyadh, Saudi Arabia
Abdulbaki <i>et al.</i> (2017)	✓	✓		✓				✓	✓				Unspecified
Koleva <i>et al.</i> (2017)	✓			✓				✓					Multiple cases
Koleva (2018)	✓	✓	✓		✓	✓		✓	✓				Australia
Kizhisseri <i>et al.</i> (2022)	✓	✓		✓		✓		✓	✓				Abu Dhabi, UAE
Current study	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	Sharjah, UAE

3. MATHEMATICAL FORMULATION OF THE WSC MODEL

In this section, the description of the proposed WSC model is presented along with the formulation of the mathematical model and the stipulated assumptions. In principle, this model represents a tool that aids the concerned authorities into making strategic and tactical decisions that jointly minimize the cost and environmental impact of the WSC while meeting a set of operational constraints over a pre-specified planning horizon. As such, water demand forecast of each demand zone, production capacity of existing desalination units, water storage capacity of each demand zone, water pipeline capacity between different nodes within the WSC, among other technical parameters must be fed into the model. In addition, environmental and

financial costs associated with the different components of the WSC including new and existing plants, storage tanks, and pipelines must be provided before running the model.

3.1 Main Attributes of the WSC Model

The major attributes that distinguish the proposed model from the models found literature are further explained in this section.

3.1.1 Planning Horizon

Since there is a lead time associated with the construction or expansion of new and existing facilities (i.e., plants, units, storage tanks, and pipelines), the model has to cater for these lead times such that these facilities are constructed and operational in time. Hence, it is assumed that the longest time it takes to install a facility is available before running the model such that the lead time of all facilities is accounted for. As such, let CT^{max} represent the longest lead

time needed among all facilities. Accordingly, any decision that needs to be executed between year 0 and year CT^{max} is assumed to have been accounted for in the previous plan. Therefore, effective planning starts at year $CT^{max} + 1$. For instance, if $CT^{max} = 5$ years, then effective planning will start at year 6. Also, if the current plan starts in 2022 with a horizon of 20 years, then effective planning will start in 2027 as the first 5 years will not be part of the effective planning period. Distinguishing planning period and effective planning period is important in reducing the mathematical and time-related complexity within the model as this allows for the binary variables that ensure the feasibility of the construction or expansion decisions to be dropped.

3.1.2 Water Demand Zones

The region under study has been divided into several demand zones, which are classified into coastal and inland zones based on their locations relative to the coast. Moreover, only coastal zones have desalination plants since seawater represents the only available water input to the desalination plants. Hence, water production in coastal demand zones must cover both coastal and inland zones. In coastal zones, seawater is desalinated at desalination plants and stored in storage tanks. Subsequently, water is distributed to meet the demand of the demand zone itself or the demand of neighbouring demand zones. Water can be transported only to adjacent demand zones and only in the direction away from the coast. All demand zones have storage tanks to hold produced and received water. Hence, as inland zones receive water from adjacent demand zones (coastal and inland), water is stored in inland storage tanks. In addition, water can be retrieved from storage tanks to meet the demand of the inland zone itself or that of neighbouring inland zones.

3.1.3 Desalination Plant Structure

Hereafter, it is assumed that each plant consists of several desalination units that may vary in capacity and adopted technology. Hence, a desalination unit can be either an RO, MSF, or MED unit with a specific capacity. Within each plant, units of the same technology are clustered and placed in separate parts of the plant, and each set of units has a separate water input and output to account for the water recovery yield of each technology. Such a plant design structure has been observed in local desalination plants in the UAE. In addition, units within plants are shut down at the end of their lifetime, which presents the model with the opportunity to replace them with new units whenever the need for additional desalination capacity arises.

3.1.4 Capacity Expansion

In the proposed model, plants, storage capacity, and pipelines are subject to expansions to meet the increasing demands over the planning horizon. Capacity expansion of existing plants is regarded as addition of new desalination units to replace retiring units, such that the number of new units is always less than or equal to retired units. On the other hand, new plants can be added to pre-specified locations with preset capacities. As such, new plants also consist of multiple same-size units that can be installed at multiple times as the need arises. Moreover, wherever more storage or transportation capacity is needed, new storage tanks and

pipelines beside the existing ones are going to be installed. Note that the throughput of each unit is determined by the model on a yearly basis which means that not all units will operate at full capacity, unless deemed necessary by the model, while taking into account storage and transportation costs.

3.1.5 CO₂ and Brine Disposal

Carbon emissions associated with the process of desalination and water transportation, along with brine disposal represent the most undesirable by products of desalinated WSCs. To incentivise the reduction of carbon emissions, carbon regulation authorities may opt to implement a tax system, among other regulatory policies. Life Cycle Assessment (LCA) is one of the commonly used methods to estimate the CO₂ emissions, despite the fact that LCA estimates may not be reliable as they can be based on old desalination plants (Zhou *et al.*, 2014). Moreover, CO₂ emissions vary based on the location of the plant and the type of fuel used to run the plant (Elsaid *et al.*, 2020). This is apparent in the review conducted by Cornejo *et al.* (2014) as emission ranges were 0.3 to 34.7 kg CO₂-eq/m³ for MSF, 0.3 to 26.9 kg CO₂-eq/m³ for MED, and 0.4 to 6.7 kg CO₂-eq/m³ for RO plants. Furthermore, according to Liu *et al.* (2015), the operation and maintenance of desalination plants accounts for 90% of the CO₂ emitted throughout the lifecycle of desalination plants. As such the mass of CO₂ emitted during the production of one cubic meter of freshwater in desalination plants, in the UAE, using MSF, MED, and RO was estimated to be 2.716 kg, 1.164 kg, and 2.238 kg, respectively (Liu *et al.*, 2015). These values are equivalent to 12350, 5292, and 10170 $\left(\frac{kg\ CO_2-e}{MIG}\right)$, respectively. Furthermore, the CO₂ emissions due to water transportation for 1 km represents 0.635 kg CO₂-eq/m³ or 2890 $\left(\frac{kg\ CO_2-e}{km.MIG}\right)$ (Abdulbaki *et al.*, 2017). Moreover, the carbon tax assumed in this model is 1 $\left(\frac{\$}{ton}\right)$ or 0.000000003675 $\left(\frac{million\ AED}{kg\ CO_2-e}\right)$. Considering that carbon tax varies significantly from one country to another, the effect of increasing carbon tax is going to be further assessed in the sensitivity analysis section of this paper.

The other major undesired output of desalination is brine. Brine discharged by desalination plants has a salinity level of more than 55,000 mg/L (Soliman *et al.*, 2021). To deal with the discharged brine, several techniques have been developed including surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application. Surface water discharge is the most commonly used technique in the world as more than 90% of seawater desalination plants dispose brine into nearby saline water bodies (Panagopoulos *et al.*, 2019). Brine disposal cost is 0.03 $\left(\frac{\$}{m^3\ brine}\right)$, which is equivalent to 0.0005012 $\left(\frac{million\ AED}{MIG\ brine}\right)$.

3.1.6 Model Assumptions

The following assumptions were considered in formulating the proposed mathematical model:

1. Seawater as the sole feedwater source: The model exclusively considers seawater desalination, as it is the predominant method in the UAE due to the country's extensive coastline (Saif and Almansoori, 2014).

2. Consistent water quality: As noted in most cited studies, desalination plants are designed to maintain stable water quality, which simplifies cost estimation and operational planning.
3. Durability of pipelines and storage facilities: Unlike desalination units, which experience wear and tear due to high-pressure operations, pipelines and storage facilities are designed for long-term use with minimal maintenance. Therefore, they are assumed not to degrade over time and are never retired.
4. Degradation of desalination unit capacity: The water production capacity of each desalination unit declines over time (Koutsou *et al.*, 2020).
5. Sufficient unit lifetime for replacement: All desalination units have a remaining lifespan longer than the time required for replacement (τ), ensuring replacement can occur smoothly within the planning horizon.
6. Sources of carbon emissions: Carbon emissions in the model are attributed solely to desalination processes and water transportation, as these two activities are the primary contributors to emissions within the desalination supply chain.
7. Standard lifespan of new desalination units: New desalination units are assumed to have a lifespan of 30 years, in line with industry standards.
8. Adequate pumping station capacity: The model assumes that the pumping stations have sufficient capacity to accommodate any changes in desalinated water volumes, avoiding additional complexities related to pump upgrades.
9. Capital cost occurrence: Capital costs are incurred at the end of the construction period, consistent with standard accounting practices, where expenditures are recorded upon project completion.

Notation adopted in the model development is provided in Appendix A, as the mathematical model is comprehensive.

3.2 Model Constraints

This section provides the formulation of the constraints and objective function of the model.

Strategic constraints related to installation of new plants and replacement of retiring units.

Equations for the calculation of plants capacities:

Equation (1) determines the number of operating units that should be replaced with new units using technology k' at time t . Equation (2) represents the total capacity of operating units which have not yet been replaced ($t \leq \tau$). The first term in equation (3) represents the total capacity of units that have not yet been replaced, while the second term represents the cumulative capacity of the replaced units. Equations (4) determines the capacities of the new plants at time t .

$$RU_{pjkt} = \sum_{k'=1}^K \sum_{u=1}^{U_{pj k' 0}} y_{upjk'k(t-\tau)}^r \quad \text{for } j \in JP, p = 1, \dots, P_j, k, k' = 1, \dots, K, \text{ and } t = \tau + 1, \tau + 2, \dots, T. \quad (1)$$

$$C_{pjkt} = \sum_{u=1}^{U_{pj k 0}} Z_{upjkt} * C_{upjk0} * \rho_k^t \quad \text{for } j \in JP, p = 1, \dots, P_j, k = 1, \dots, K, \text{ and } t = 1, \dots, \tau \quad (2)$$

where C_{pjkt} is the capacity of an existing plant p in demand zone j using technology k at time t .

$$C_{pjkt} = \sum_{u=1}^{U_{pj k 0}} Z_{upjkt} * C_{upjk0} * \rho_k^t + \sum_{t'=\tau+1}^t CP_k * \rho_k^{t-t'} * RU_{pjkt'} \quad \text{for } j \in JP, p = 1, \dots, P_j, k = 1, \dots, K, \text{ and } t = \tau + 1, \tau + 2, \dots, T \quad (3)$$

$$C_{jkt}^n = \sum_{t'=1}^t \rho_k^{t-t'} * CP_k * NU_{jkt'} \quad \text{for } j \in PL, k = 1, \dots, K, \text{ and } t = 1, \dots, T \quad (4)$$

where C_{jkt}^n is the capacity of a new plant in demand zone $j \in PL$ using technology k at time t .

Constraints related to the installation of new plants:

Equation (5) restricts the number of new desalination plants to be installed in demand zone $j \in PL$ over the planning horizon to one plant. On the other hand, equation (6) limits the number of new plants over the planning horizon to np^{max} . Equation (7) guarantees that the installations of a new plant and the first desalination unit(s) take place during the same year. Equation (8) ensures that expansion of the desalination capacity of a new plant in demand zone $j \in PL$ is carried out at time t through the installation of new desalination unit(s) only when the new plant is set up during the same year or in one of the previous years. Equation (9) sets the number of new desalination units equal to zero in case a decision is not made to install new unit(s) in demand zone $j \in PL$ at year t , while equation (10) ensures that the number of new units is never less than y_{jkt}^{nu} at year t . Equation (11) limits the addition of new desalination units at any time period to one technology for said year. Equation (12) restricts the number of desalination units in a new plant in demand zone $j \in PL$ to the maximum number of allowed units given the provided space for the new plant.

$$\sum_{t=1}^T y_{jt}^{np} \leq 1 \quad j \in PL \quad (5)$$

$$\sum_{t=1}^T \sum_{j \in PL(j)} y_{jt}^{np} \leq np^{max} \quad (6)$$

$$\sum_{k=1}^K y_{jkt}^{nu} \geq y_{jt}^{np} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (7)$$

$$\sum_{k=1}^K y_{jkt}^{nu} \leq \sum_{t'=1}^t y_{jt'}^{np} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (8)$$

$$NU_{jkt} \leq y_{jkt}^{nu} * \beta \quad \text{for } j \in PL, k = 1, \dots, K, \text{ and } t = 1, \dots, T \quad (9)$$

where β is a given large real number.

$$NU_{jkt} \geq y_{jkt}^{nu} \quad \text{for } j \in PL, k = 1, \dots, K, \text{ and } t = 1, \dots, T \quad (10)$$

$$\sum_{k=1}^K y_{jkt}^{nu} \leq 1 \quad \text{for } j \in PL, \text{ and } t = 1, \dots, T \quad (11)$$

$$\sum_{t'=1}^t \sum_{k=1}^K NU_{jkt'} \leq U_j^{max} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (12)$$

Constraints related to the replacement of retiring desalination units:

Equation (13) ensures that an existing unit is replaced only after its retirement. Equation (14) limits additions of replacement desalination units at any time period to one technology for that year. Equation (15) ensures that there will be only one replacement of a retired unit over the planning horizon.

$$y_{upjkk't}^r \leq 1 - Z_{upjkt} \quad \text{for } u = 1, 2, \dots, U_{pjk0}, j \in JP, \\ p = 1, \dots, P_j, k, k' = 1, 2, \dots, K, \text{ and } t = 1, \dots, T \quad (13)$$

$$\sum_{k'=1}^K y_{upjkk't}^r \leq 1 \quad \text{for } u = 1, 2, \dots, U_{pjk0}, j \in JP, p = \\ 1, \dots, P_j, k = 1, 2, \dots, K, \text{ and } t = 1, \dots, T \quad (14)$$

$$\sum_{t=\tau+1}^T y_{upjkk't}^r \leq 1 \quad \text{for } u = 1, 2, \dots, U_{pjk0}, j \in JP, p = \\ 1, \dots, P_j, \text{ and } k, k' = 1, 2, \dots, K \quad (15)$$

Strategic constraints related to the expansion of water storage capacities

Equations (16) and (17) define the number of new storage tanks to be installed in coastal and inland demand zones, respectively. In case capacity expansion is not undertaken in storage facility of demand zone j (or d) at year t , then $NS_{jt} = 0$ ($NS_{dt} = 0$).

$$NS_{jt} \leq y_{jt}^s * \beta \quad \text{for } j = 1, \dots, J \text{ and } t = 1, \dots, T \quad (16)$$

$$NS_{dt} \leq y_{dt}^s * \beta \quad \text{for } d = 1, \dots, D \text{ and } t = 1, \dots, T \quad (17)$$

Equations (18) and (19) account for expansions in water storage capacities of coastal and inland demand zones, respectively.

$$WSC_{jt} = \sum_{t'=1}^t NS_{jt'} * SC + WSC_{j0} \quad \forall j, t \quad (18)$$

$$WSC_{dt} = \sum_{t'=1}^t NS_{dt'} * SC + WSC_{d0} \quad \forall d, t \quad (19)$$

Strategic constraints related to the transportation of water through pipelines

Equations (20) to (24) define the amount of expansions for the water transport capacities between coastal/coastal, coastal/inland, inland/inland demand zones, existing plants and storage facilities, and new plants and storage facilities, respectively. Unlike the equations for the desalination unit and storage capacity expansions, the magnitude of the expansion for the water transport capacity is not a model parameter but rather a decision variable.

$$NL_{jj't} \leq y_{jj't}^l * \beta \quad \text{for } j = 1, \dots, J, j' \in A(j, j'), \\ \text{and } t = 1, \dots, T \quad (20)$$

$$NL_{jdt} \leq y_{jdt}^l * \beta \quad \text{for } j = 1, \dots, J, d \in A(j, d), \\ \text{and } t = 1, \dots, T \quad (21)$$

$$NL_{dd't} \leq y_{dd't}^l * \beta \quad \text{for } d = 1, \dots, D, d' \in A(d, d'), \\ \text{and } t = 1, \dots, T \quad (22)$$

$$NL_{pjt} \leq y_{pjt}^l * \beta \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = \\ 1, \dots, T \quad (23)$$

$$NL_{jt}^{nl} \leq y_{jt}^{nl} * \beta \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (24)$$

Equations (25) to (27) state the available capacity for water transportation between coastal/coastal, coastal/inland, and inland/inland demand zones. Meanwhile, equations (28) and (29) serve the same function for water transportation between existing and new desalination plants and storage facilities in same demand zones, respectively.

$$CL_{jj't} = CL_{jj'(t-1)} + NL_{jj't} \quad \forall j, t \text{ and } j' \in A(j, j') \quad (25)$$

$$CL_{jdt} = CL_{jd(t-1)} + NL_{jdt} \quad \forall j, t \text{ and } d \in A(j, d) \quad (26)$$

$$CL_{dd't} = CL_{dd'(t-1)} + NL_{dd't} \quad \forall d, t \text{ and } d' \in A(d, d') \\ (27)$$

$$CL_{pjt} = CL_{pj(t-1)} + NL_{pjt} \quad \forall p, t \text{ and } j \in JP \quad (28)$$

$$CL_{jt}^{nl} = CL_{j(t-1)}^{nl} + NL_{jt}^{nl} \quad \forall t \text{ and } j \in PL \text{ with } CL_{j0}^{nl} = 0 \\ (29)$$

Tactical constraints related to water production in existing and new plants

Equations (30) and (31) restrict the water input of different technologies within the existing and new desalination plants to their respective capacities, where γ_{pjk} and γ_{jk}^n are capacity utilization factors for existing and new plants, respectively. Each factor ensures that water input to plant p in coastal zone j using technology k is higher than a threshold value. Also, equations (32) and (33) ensure that water input to plant p in coastal zone j using technology k is below the maximum capacity.

$$W_{pjkt}^i \geq \gamma_{pjk} * C_{pjkt} \quad \text{for } j \in JP, p = 1, \dots, P_j, k = \\ 1, \dots, K, \text{ and } t = 1, \dots, T \quad (30)$$

$$W_{jkt}^{i,n} \geq \gamma_{jk}^n * C_{jkt} \quad \text{for } j \in PL, k = 1, \dots, K, \text{ and } t = \\ 1, \dots, T \quad (31)$$

$$W_{pjkt}^i \leq C_{pjkt} \quad \text{for } j \in JP, p = 1, \dots, P_j, k = \\ 1, \dots, K, \text{ and } t = 1, \dots, T \quad (32)$$

$$W_{jkt}^{i,n} \leq C_{jkt} \quad \text{for } j \in PL, k = 1, \dots, K, \text{ and } t = 1, \dots, T \\ (33)$$

Moreover, the water output of the desalination units using technology k within the existing and new desalination plants depends on the water yield ratio of each technology as shown in Equations (34) and (35), respectively.

$$W_{pjkt}^o = YD_k * W_{pjkt}^i \quad \text{for } j \in JP, p = 1, \dots, P_j, k = \\ 1, \dots, K, \text{ and } t = 1, \dots, T \quad (34)$$

$$W_{jkt}^{o,n} = YD_k * W_{jkt}^{i,n} \quad \text{for } j \in PL, k = 1, \dots, K, \text{ and } t = \\ 1, \dots, T \quad (35)$$

Similarly, the amount of brine produced can be expressed as a function of the desalination unit yield and water input as shown in equations (36) and (37).

$$B_{pjkt} = (1 - YD_k) * W_{pjkt}^i \quad \text{for } j \in JP, p = 1, \dots, P_j, k = \\ 1, \dots, K, \text{ and } t = 1, \dots, T \quad (36)$$

$$B_{jkt}^n = (1 - YD_k) * W_{jkt}^{i,n} \quad \text{for } j \in PL, k = \\ 1, \dots, K, \text{ and } t = 1, \dots, T \quad (37)$$

As the total water output from desalination plant p in demand zone j is transported through pipeline to the storage

tanks in the same zone, it should be smaller or equal to the transport capacity of the pipeline connecting plant p to the storage facility. Such constraints can be stated mathematically as:

$$W_{pjt}^o \leq CL_{pjt} \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (38)$$

$$W_{jt}^{o,n} \leq CL_{jt}^{n,l} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (39)$$

Tactical constraints related to water storage

Equation (40) represents the water balance equation in the storage facility of demand zone $j \in (JP \cap PL)$ at the end of year t . The third term on the left-hand-side of equation (40) is the amount of water transferred from the new desalination plant to the storage facility in demand zone j at year t . Likewise, equation (41) is the water inflow and outflow balance for demand zones with desalination plants but not in the set of potential locations for a new plant. Equations (42) and (43) balance the water inflow and outflow in the demand zones $\overline{JP} \setminus (\overline{JP} \cap PL)$ and $(\overline{JP} \cap PL)$, respectively.

$$W_{j(t-1)}^{v,s} + \sum_{p=1}^{P_j} W_{pjt}^o + W_{jt}^{o,n} + \sum_{j' \in A(j',j)} W_{j'jt}^l - \sum_{j \in A(j,j')} W_{jj't}^l - \sum_{d \in A(j,d)} W_{jdt}^l - W_{jt}^{v,s} = WD_{jt} \quad \text{for } j \in (JP \cap PL) \text{ and } t = 1, \dots, T \quad (40)$$

where $(JP \cap PL)$ is the set of demand zones with desalination plants and are also considered as potential locations for a new plant.

$$W_{j(t-1)}^{v,s} + \sum_{p=1}^{P_j} W_{pjt}^o + \sum_{j' \in A(j',j)} W_{j'jt}^l - \sum_{j \in A(j,j')} W_{jj't}^l - \sum_{d \in A(j,d)} W_{jdt}^l - W_{jt}^{v,s} = WD_{jt} \quad \text{for } j \in JP \setminus (JP \cap PL) \text{ and } t = 1, \dots, T \quad (41)$$

where $JP \setminus (JP \cap PL)$ is the set of coastal demand zones with desalination plants that are not considered as potential locations for a new plant.

$$W_{j(t-1)}^{v,s} + \sum_{j' \in A(j',j)} W_{j'jt}^l - \sum_{j \in A(j,j')} W_{jj't}^l - \sum_{d \in A(j,d)} W_{jdt}^l - W_{jt}^{v,s} = WD_{jt} \quad \text{for } j \in \overline{JP} \setminus (\overline{JP} \cap PL) \text{ and } t = 1, \dots, T \quad (42)$$

where \overline{JP} is the complement set of JP , that is the set of demand zones with no desalination plants, and $\overline{JP} \setminus (\overline{JP} \cap PL)$ is set of demand zones with no desalination plant and are not considered as potential locations for a new plant.

$$W_{j(t-1)}^{v,s} + W_{jt}^{o,n} + \sum_{j' \in A(j',j)} W_{j'jt}^l - \sum_{j \in A(j,j')} W_{jj't}^l - \sum_{d \in A(j,d)} W_{jdt}^l - W_{jt}^{v,s} = WD_{jt} \quad \text{for } j \in \overline{JP} \cap PL \text{ and } t = 1, \dots, T \quad (43)$$

where $(\overline{JP} \cap PL)$ is the set of demand zones with no desalination plants but are considered as potential locations for a new plant. Equation (44) represents the water flow balance equation for inland demand zones.

$$W_{d(t-1)}^{v,s} + \sum_{j \in A(j,d)} W_{jdt}^l + \sum_{d' \in A(d',d)} W_{d'dt}^l - \sum_{d' \in A(d,d')} W_{dd't}^l - W_{dt}^{v,s} = WD_{dt} \quad d = 1, \dots, D \text{ and } t = 1, \dots, T \quad (44)$$

The maximum level of water that can be reached in storage facility $j \in (JP \cap PL)$ is when the water outflow is zero. Following a conservative approach, the water storage capacity should be designed to store such amount of water, which is ensured by the following equation:

$$W_{j(t-1)}^{v,s} + \sum_{p=1}^{P_j} W_{pjt}^o + W_{jt}^{o,n} + \sum_{j' \in A(j',j)} W_{j'jt}^l \leq WSC_{jt} \quad \text{for } j \in (JP \cap PL) \text{ and } t = 1, \dots, T \quad (45)$$

Similarly, the storage facilities in the remaining demand zones should be capable of storing their maximum water levels. Equations (46) to (49) guarantee that such conditions are met.

$$W_{j(t-1)}^{v,s} + \sum_{p=1}^{P_j} W_{pjt}^o + \sum_{j' \in A(j',j)} W_{j'jt}^l \leq WSC_{jt} \quad \text{for } j \in JP \setminus (JP \cap PL(j)) \text{ and } t = 1, \dots, T \quad (46)$$

$$W_{j(t-1)}^{v,s} + \sum_{j' \in A(j',j)} W_{j'jt}^l \leq WSC_{jt} \quad \text{for } j \in \overline{JP} \setminus (\overline{JP} \cap PL) \text{ and } t = 1, \dots, T \quad (47)$$

$$W_{j(t-1)}^{v,s} + W_{jt}^{o,n} + \sum_{j' \in A(j',j)} W_{j'jt}^l \leq WSC_{jt} \quad \text{for } j \in \overline{JP} \cap PL \text{ and } t = 1, \dots, T \quad (48)$$

$$W_{d(t-1)}^{v,s} + \sum_{j \in A(j,d)} W_{jdt}^l + \sum_{d' \in A(d',d)} W_{d'dt}^l \leq WSC_{dt} \quad \forall d, t \quad (49)$$

Tactical constraints related to water transport through pipelines

Equation (50) limits the volume of water transported between coastal demand zones j and j' at time t to the capacity of the pipelines connecting these zones. Similarly, equation (51) limits the volume of water transported from coastal demand zone j to internal zone d to the capacity of that pipeline at time t . Moreover, equation (52) limits the volume of water transported between inland demand zones d and d' to the capacity of that pipeline at time t .

$$W_{jj't}^l \leq CL_{jj't} \quad \text{for } j = 1, \dots, J, j' \in A(j, j'), \text{ and } t = 1, \dots, T \quad (50)$$

$$W_{jdt}^l \leq CL_{jdt} \quad \text{for } j = 1, \dots, J, d \in A(j, d), \text{ and } t = 1, \dots, T \quad (51)$$

$$W_{dd't}^l \leq CL_{dd't} \quad \text{for } d = 1, \dots, D, d' \in A(d, d'), \text{ and } t = 1, \dots, T \quad (52)$$

3.3 Formulation of the Model's Objective Function

This section presents the formulation of the model's objective function, which consists of the various operational and capital costs associated with existing and new plants, storage tanks, and pipelines, as well as the CO₂ emissions and brine dilution related costs.

Operational and capital costs of water desalination plants

Equations (53) and (54) define the operational and the capital costs of existing desalination plants. Operational costs are functions of the water output and the costs per unit water produced. On the other hand, capital costs are

functions of the number of new units as replacement to retiring units. Similarly, equations (55) to (57) give the operational and capital costs of a new plant and desalination units.

$$OC_{pjt} = \sum_{k=1}^K W_{pjkt}^o * OPC_k \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (53)$$

$$CC_{pjt} = \sum_{k=1}^K RU_{pjkt} * CI_k^r \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (54)$$

$$OC_{jt}^{np} = \sum_{k=1}^K W_{jkt}^{o,n} * OPC_k \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (55)$$

$$CC_{jt}^{np} = y_{jt}^{np} * CI^{np} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (56)$$

$$CC_{jt}^{nu} = \sum_{k=1}^K NU_{jkt} * CI_k^{nu} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (57)$$

The total discounted operating costs over the planning horizon for producing water in all coastal demand zones with desalination plants is given by:

$$TDOC = \sum_{t=1}^T \alpha^t \left[\sum_{j \in JP} \sum_{p=1}^{P_j} OC_{pjt} + \sum_{j \in PL} OC_{jt}^{np} \right] \quad (58)$$

where $\alpha = 1/(1+r)$ and r is the interest (discount) rate. The total discounted capital costs (TDC) over the planning horizon for existing and new plants is given by:

$$TDC = \sum_{t=1}^T \alpha^t \left[\sum_{j \in JP} \sum_{p=1}^{P_j} (CC_{pjt}) + \sum_{j \in PL} (CC_{jt}^{nu} + CC_{jt}^{np}) \right] \quad (59)$$

Operational and capital costs of water storage and transportation

The operational costs of water transportation are functions of the amount of water transported at any given year, the unit cost per water transported, and the distance between demand zones as presented by equations (60) to (64) for coastal/coastal, coastal/inland, inland/inland, existing desalination plant/storage facility, and new desalination plant/storage facility transportation, respectively.

$$OC_{jj't}^l = DS_{jj'} * W_{jj't}^l * OPC^l \quad \text{for } j = 1, \dots, J, j' \in A(j, j'), \text{ and } t = 1, \dots, T \quad (60)$$

$$OC_{jdt}^l = DS_{jd} * W_{jdt}^l * OPC^l \quad \text{for } j = 1, \dots, J, d \in A(j, d), \text{ and } t = 1, \dots, T \quad (61)$$

$$OC_{dd't}^l = DS_{dd'} * W_{dd't}^l * OPC^l \quad \text{for } d = 1, \dots, D, d' \in A(d, d'), \text{ and } t = 1, \dots, T \quad (62)$$

$$OC_{pjt}^l = DS_{pj} * W_{pjt}^o * OPC^l \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (63)$$

$$OC_{jt}^{ln} = DS_j^n * W_{jt}^{o,n} * OPC^l \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (64)$$

The total discounted operating costs for transporting water through all pipelines over the planning horizon is given by:

$$TDOC^l = \sum_{t=1}^T \alpha^t \left[\sum_{j=1}^J \sum_{j' \in A(j, j')} OC_{jj't}^l + \sum_{j=1}^J \sum_{d \in A(j, d)} OC_{jdt}^l + \sum_{d=1}^D \sum_{d' \in A(d, d')} OC_{dd't}^l + \sum_{p=1}^P \sum_{j \in JP} OC_{pjt}^l + \sum_{j \in PL} OC_{jt}^{ln} \right] \quad (65)$$

The operational costs for water storage facilities in coastal and inland demand zones are given by equations (66) and (67). It is assumed that operational storage cost is charged against the available water storage capacity at year t .

$$OC_{jt}^s = WSC_{jt} * OPC^s \quad \text{for } j = 1, \dots, J \text{ and } t = 1, \dots, T \quad (66)$$

$$OC_{dt}^s = WSC_{dt} * OPC^s \quad \text{for } d = 1, \dots, D \text{ and } t = 1, \dots, T \quad (67)$$

The total discounted operating costs for storing water in all storage facilities over the planning horizon is given by:

$$TDOC^s = \sum_{t=1}^T \alpha^t \left[\sum_{j=1}^J OC_{jt}^s + \sum_{d=1}^D OC_{dt}^s \right] \quad (68)$$

Furthermore, the variable capital costs of water transportation and storage are functions of the capacity of the proposed expansions and their costs (equations 69 to 75).

$$VCC_{jj't}^l = DS_{jj'} * NL_{jj't} * VCI^l \quad \text{for } j = 1, \dots, J, j' \in A(j, j'), \text{ and } t = 1, \dots, T \quad (69)$$

$$VCC_{jdt}^l = DS_{jd} * NL_{jdt} * VCI^l \quad \text{for } j = 1, \dots, J, d \in A(j, d), \text{ and } t = 1, \dots, T \quad (70)$$

$$VCC_{dd't}^l = DS_{dd'} * NL_{dd't} * VCI^l \quad \text{for } d = 1, \dots, D, d' \in A(d, d'), \text{ and } t = 1, \dots, T \quad (71)$$

$$VCC_{pjt}^l = DS_{pj} * NL_{pjt} * VCI^l \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (72)$$

$$VCC_{jt}^{ln} = DS_j^n * NL_{jt}^{ln} * VCI^l \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (73)$$

$$VCC_{jt}^s = NS_{jt} * VCI^s \quad \text{for } j = 1, \dots, J \text{ and } t = 1, \dots, T \quad (74)$$

$$VCC_{dt}^s = NS_{dt} * VCI^s \quad \text{for } d = 1, \dots, D \text{ and } t = 1, \dots, T \quad (75)$$

Equations (76) to (82) calculate the fixed capital costs of water transportation and storage whenever pipeline and water tanks capacity expansions take place.

$$FCC_{jj't}^l = y_{jj't}^l * FCI^l \quad \text{for } j = 1, \dots, J, j' \in A(j, j'), \text{ and } t = 1, \dots, T \quad (76)$$

$$FCC_{jdt}^l = y_{jdt}^l * FCI^l \quad \text{for } j = 1, \dots, J, d \in A(j, d), \text{ and } t = 1, \dots, T \quad (77)$$

$$FCC_{dd't}^l = y_{dd't}^l * FCI^l \quad \text{for } d = 1, \dots, D, d' \in A(d, d'), \text{ and } t = 1, \dots, T \quad (78)$$

$$FCC_{pjt}^l = y_{pjt}^l * FCI^l \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (79)$$

$$FCC_{jt}^{l,n} = y_{jt}^{l,n} * FCI^l \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (80)$$

$$FCC_{jt}^s = y_{jt}^s * FCI^s \quad \text{for } j = 1, \dots, J \text{ and } t = 1, \dots, T \quad (81)$$

$$FCC_{dt}^s = y_{dt}^s * FCI^s \quad \text{for } d = 1, \dots, D \text{ and } t = 1, \dots, T \quad (82)$$

The total discounted capital costs over the planning horizon for water transportation is given by:

$$TDCC^l = \sum_{t=1}^T \alpha^t \left[\sum_{j=1}^J \sum_{j' \in A(j, j')} (VCC_{jj't}^l + FCC_{jj't}^l) + \sum_{d=1}^D \sum_{d' \in A(d, d')} (VCC_{dd't}^l + FCC_{dd't}^l) + \sum_{j \in JP} (VCC_{pjt}^l + FCC_{pjt}^l) + \sum_{j \in PL} (VCC_{jt}^{l,n} + FCC_{jt}^{l,n}) \right] \quad (83)$$

The total discounted capital costs over the planning horizon for water storage is given by:

$$TDCC^s = \sum_{t=1}^T \alpha^t \left[\sum_{j=1}^J (VCC_{jt}^s + FCC_{jt}^s) + \sum_{d=1}^D (VCC_{dt}^s + FCC_{dt}^s) \right] \quad (84)$$

Total carbon emissions and brine disposal costs

Carbon emissions resulting from the production of desalinated water in existing and new plants are defined based on the water output and amount of carbon emissions per unit of water desalinated as presented by equations (85) and (86), respectively. Likewise, carbon emissions due to the transportation of water between demand zones and between desalination plants and storage facilities depend on the water transported by pipelines, carbon emissions per unit of water transported, and length of the pipelines as given by equations (87) to (91).

$$E_{pjt} = \sum_{k=1}^K CO2_k * W_{pjk}^o \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (85)$$

$$E_{jt}^n = \sum_{k=1}^K CO2_k * W_{jkt}^{o,n} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (86)$$

$$E_{jj't}^l = CO2^l * DS_{jj'} * W_{jj't}^l \quad \text{for } j = 1, \dots, J, j' \in A(j, j'), \text{ and } t = 1, \dots, T \quad (87)$$

$$E_{jdt}^l = CO2^l * DS_{jd} * W_{jdt}^l \quad \text{for } j = 1, \dots, J, d \in A(j, d), \text{ and } t = 1, \dots, T \quad (88)$$

$$E_{dd't}^l = CO2^l * DS_{dd'} * W_{dd't}^l \quad \text{for } d = 1, \dots, D, d' \in A(d, d'), \text{ and } t = 1, \dots, T \quad (89)$$

$$E_{pjt}^l = CO2^l * DS_{pj} * W_{pjt}^o \quad \text{for } j \in JP, p = 1, \dots, P_j, \text{ and } t = 1, \dots, T \quad (90)$$

$$E_{jt}^{l,n} = CO2^l * DS_j^n * W_{jt}^{o,n} \quad \text{for } j \in PL \text{ and } t = 1, \dots, T \quad (91)$$

The total CO₂ emissions generated by desalination and transportation operations, CE_t , is given by:

$$CE_t = \sum_{j \in JP} \sum_{p=1}^{P_j} E_{pjt} + \sum_{j \in PL} E_{jt}^n + \sum_{j=1}^J \sum_{j' \in A(j, j')} E_{jj't}^l + \sum_{j=1}^J \sum_{d \in A(j, d)} E_{jdt}^l + \sum_{d=1}^D \sum_{d' \in A(d, d')} E_{dd't}^l + \sum_{j \in JP} \sum_{p=1}^{P_j} E_{pjt}^l + \sum_{j \in PL} E_{jt}^{l,n} \quad (92)$$

As previously mentioned, carbon tax is one of the widely adopted regulatory policies that can effectively be implemented to mitigate carbon emissions. The tax rate (tx) also serves as a policy control mechanism, influencing the selection of desalination technologies by incentivizing lower-emission alternatives. Furthermore, given that carbon tax has not been formally embraced in the UAE as part of its carbon regulation policies, the proposed model facilitates conducting sensitivity analysis through varying tx . This allows policymakers to assess how different tax levels impact the overall costs of their WSCs.

After calculating the total carbon emissions generated from production and transportation operations in each period t , the carbon tax rate tx is applied to determine the corresponding monetary cost. Since these emissions and their associated costs occur over a multi-year planning horizon, the discount factor α is incorporated to reflect the time value of money. By summing the discounted emission costs across all periods, the total discounted carbon emission cost is given by:

$$TDCE = \sum_{t=1}^T \alpha^t tx CE_t \quad (93)$$

The amount of brine disposed by all desalination plants is defined as:

$$BQ_t = \sum_{j \in JP} \sum_{p=1}^{P_j} \sum_{k=1}^K B_{pjk} + \sum_{j \in PL} \sum_{k=1}^K B_{jkt}^n \quad (94)$$

Therefore, the total discounted brine disposal cost is:

$$TDBD = \sum_{t=1}^T \alpha^t CB BQ_t \quad (95)$$

Model objective function

The objective of the model is to minimize the total discounted costs of the water supply chain over the entire planning horizon. The components of the objective function include all the above presented discounted costs. Thus, the model's objective function can be mathematically stated as:

$$\text{Min } TC = TDOC + TDCC + TDOC^l + TDOC^s + TDCC^l + TDCC^s + TDCE + TDBD \quad (96)$$

4. CASE STUDY AND RESULTS

In this section, the practical relevance of the mathematical model proposed in Section 3 will be illustrated via synthesizing a coherent plan to meet the increase in the demand for freshwater in the Emirate of Sharjah. The Emirate of Sharjah has a total of nine demand zones, out of which only six receive their freshwater needs from Sharjah

Electricity and Water authority (SEWA). These demand zones are Sharjah city, Khor Fakkan, Kalba, Al Dhaid, Mileha, and Al Madam. The former three zones are coastal while the latter three demand zones are internal. As such, only data associated with these six demand zones was provided by SEWA. The other three demand zones are served by federal water authority, and their data was not made accessible. The provided data encompass the water demand in the Emirate of Sharjah until 2020. However, it

was indicated that the demand increases at a rate of 3.92% yearly, which was used to forecast the water demand in the six demand zones until 2038 as shown in **Table 2**. Moreover, **Table 3** presents data related to desalination plants within the Emirate of Sharjah. It is also important to mention that studies found in literature were used to collect some of the data, which the local water authority could not provide. **Figure 1** displays the locations of desalination plant within the Emirates of Sharjah.

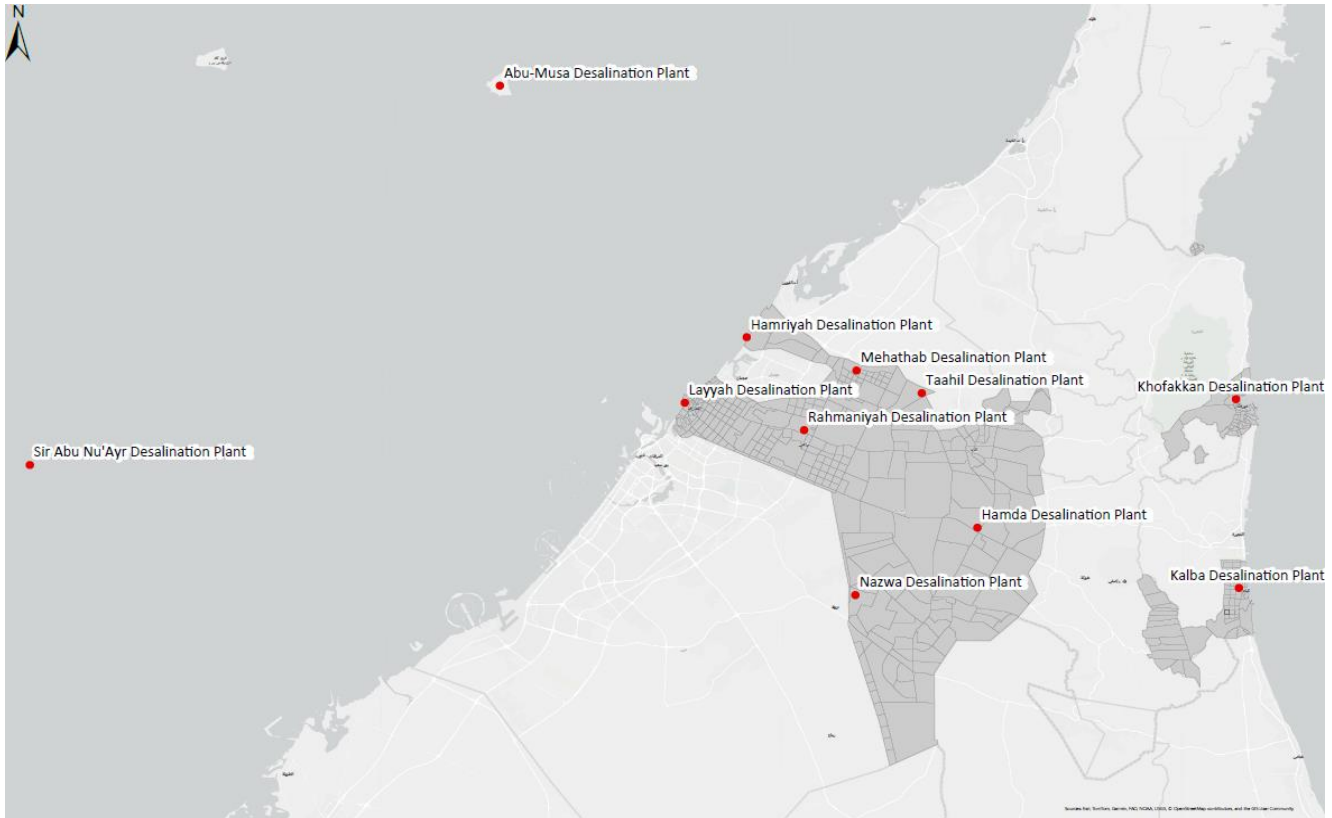


Figure 1 Sharjah desalination plants location

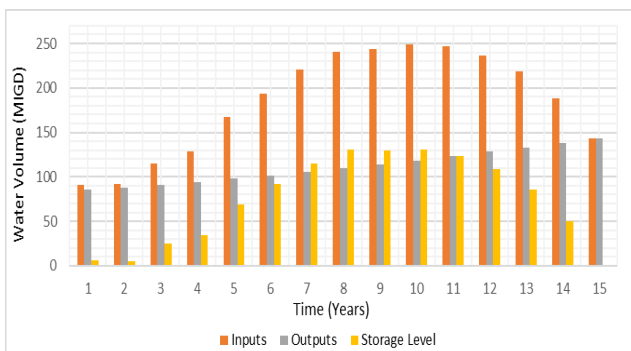


Figure 2 Total input, total output, and storage level over the horizon in the city of Sharjah

In order to implement the case study, the mathematical model was coded in GAMS and solved using CPLEX solver. The code has 108 blocks of equations that encapsulate 85,855 equations. The code also has 85 blocks of variables including 85,749 continuous variables and 80,385 integer-binary variables. It took the solver 48703.98 seconds, which is equivalent to 13.5 hours, to find the optimal solution. Upon

extracting the results from the solver, MS Excel was used to manually validate the results against the equations in the model. For example, equations (40) through (44) represent water balance equations of different demand zones. As such, input streams include initial water level in the demand zone, water production in the demand zone itself, and water transported in from neighbouring demand zones. Output streams, on the other hand, include water demand of the zone itself and water transported out to neighbouring demand zones. This water balance is illustrated for the city of Sharjah in **Figure 2**, where the difference between the sum of input streams and sum of output streams at any year must be equal to the water level in that demand zone at the end of the same year.

Table 4 shows the year in which existing desalination units are going to retire. With a planning horizon of 15 years, only units 1 to 8 are going to retire. As such, a maximum of eight units shall be replaced over the studied horizon. This is validated by the solution obtained as a total of seven units are replaced as illustrated in **Table 5**.

Table 2 Water demand (MIGD) forecasts in the demand zones of the Emirate of Sharjah until 2038

Year	Demand Zone					
	Sharjah	Kalba	Khor Fakkan	Madam	Mleiha	Dhaid
2023	80.76	4.61	3.84	0.95	0.31	1.73
2024	83.92	4.79	3.99	0.98	0.32	1.79
2025	87.21	4.98	4.14	1.02	0.34	1.86
2026	90.63	5.18	4.31	1.06	0.35	1.94
2027	94.19	5.38	4.48	1.10	0.36	2.01
2028	97.88	5.59	4.65	1.15	0.38	2.09
2029	101.71	5.81	4.83	1.19	0.39	2.17
2030	105.70	6.04	5.02	1.24	0.41	2.26
2031	109.85	6.27	5.22	1.29	0.42	2.35
2032	114.15	6.52	5.43	1.34	0.44	2.44
2033	118.63	6.78	5.64	1.39	0.46	2.53
2034	123.28	7.04	5.86	1.44	0.48	2.63
2035	128.11	7.32	6.09	1.50	0.49	2.74
2036	133.13	7.60	6.33	1.56	0.51	2.84
2037	138.35	7.90	6.58	1.62	0.53	2.96
2038	143.77	8.21	6.83	1.68	0.56	3.07

Table 3 Desalination plants in the Emirate of Sharjah

Plant	Installed Capacity (MIGD)	Available Capacity (MIGD)	Number of Units (maximum)	Desalination Technology
Layyah	59.00	53.00	10	Thermal (9), SWRO (1)
New Hamriyah	20.00	13.50	8	SWRO
Rahmaniya	5.50	5.00	5	BWRO
Kalba	7.20	6.20	3	SWRO, MED, BWRO
Khor Fakkan	5.00	4.40	2	SWRO

Figure 3 illustrates how water production in Sharjah decreases over time due to the degradation of all existing and replaced units. To make up for the drop in production and satisfy the increasing demand, starting year 3, Sharjah municipality starts receiving water from Kalba. In year 4, there is a relatively sharper drop in production due to units 1 and 2 going out of service as shown in **Table 4**. In year 5, there is no reduction in production as two units are installed, and unit 5 is retired (**Tables 4 and 5**). Even though water level in the beginning of year 5 (34.7 MIG) and production in year 5 (66 MIG) add up to 100.7 MIG, which is sufficient to cover the demand (97.8 MIG) in that year, a relatively large amount of water (66.7 MIG) is transported into Sharjah. This increase in water transferred is coming from Khor Fakkan. Also, the amount of water stored increases sharply year after year until year 11, where stored water starts to be depleted. Furthermore, in year 6, units 3 and 4 are retired, and one unit is installed. Year 7 witnesses an increase in production as no units are retired, and two units are installed. In year 9, units 6 and 7 are retired, which causes water production to drop further, and in year 10, production increases as two units are installed. Kalba and Khor Fakkan represent the two coastal zones where there is room to host new plants. As such, production levels in Kalba and Khor Fakkan must cover the increase in demand in both coastal and inland zones. Sharjah city cannot host new plants, as its shoreline is saturated, but can only host new units in replacement of retired ones. As demand for water increases in Kalba and Khor Fakkan, water is produced in existing and

new plants. As illustrated in **Figures 4 and 5**, production of water decreases steadily over the horizon due to degradation of existing units, but it never drops sharply, as Kalba and Khor Fakkan plants operate longer than the studied horizon. Nevertheless, the need for new plants to be installed arises in year 3, where seven new units are installed in Kalba (**Table 6**). Additional new units are installed in years 4 (three units), 5 (four units), and 6 (one unit). On the other hand, in Khor Fakkan, a new plant with nine units is installed year 5 and an extra unit is installed in year 6. Hence, a total of 15 and 10 new units are installed in Kalba and Khor Fakkan, respectively, over the horizon which is the maximum number of units allowed in Kalba and Khor Fakkan.

Table 4 Retirement year of desalination plants

Zone	Plant	Unit	Technology	Retirement Year
Sharjah	Layyah	1-2	MSF	4
Sharjah	Layyah	3-4	MSF	6
Sharjah	Layyah	5	MED	5
Sharjah	Layyah	6-7	MED	9
Sharjah	Layyah	8	MED	14
Sharjah	Layyah	9	MED	15
Sharjah	Layyah	10	RO	15
Sharjah	New Hamriyah	11-18	RO	>15
Sharjah	Rahmaniya	19-23	RO	>15
Kalba	Kalba Plant	24 and 26	RO	>15
Kalba	Kalba Plant	25	MED	>15
Khor Fakkan	Khor Fakkan Plant	27-28	RO	>15

Table 5 Replacement of retiring units at the optimal solution

Plant	Time	No. Replaced Units	Technology
Layyah	5	2	RO
Layyah	6	1	RO
Layyah	7	2	RO
Layyah	10	2	RO

Since the capacity of existing plants is decreasing over time, pipelines between plants and storage facilities are never expanded. However, pipelines between demand zones are selectively expanded to satisfy the demand of receiving zones. **Figure 6** compares the amount of water transported from Kalba and Khor Fakkan to Sharjah with the capacity of pipelines between each of Kalba and Khor Fakkan and Sharjah throughout the horizon. **Figure 6** also shows that the amount of water transported is never greater than the pipeline capacity, which supports the validity of the model. It is worth noting that the first time pipelines are installed between two demand zones happens to be the first time water is transported between these two demand zones. For example, a pipeline is first installed between Kalba and Sharjah in year

3, which is when water is first transported from Kalba to Sharjah.

Table 6 Instalment of new units in new plants at the optimal solution

Plant	Time	No. New Units	Technology
Kalba – newplant1	3	7	RO
Kalba – newplant1	4	3	RO
Kalba – newplant1	5	4	RO
Kalba – newplant1	6	1	RO
Khor Fakkan – newplant2	5	9	RO
Khor Fakkan – newplant2	6	1	RO

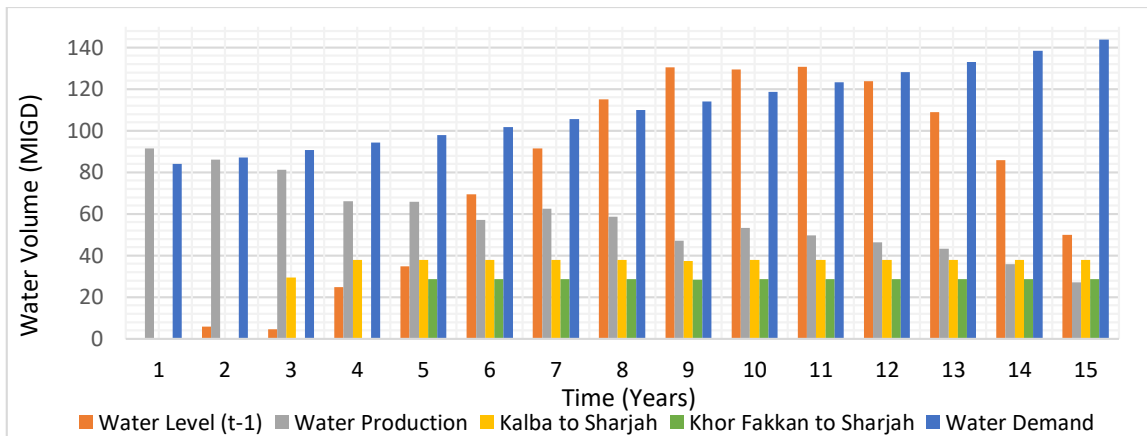


Figure 3 Water Inputs and water demand in the municipality of Sharjah

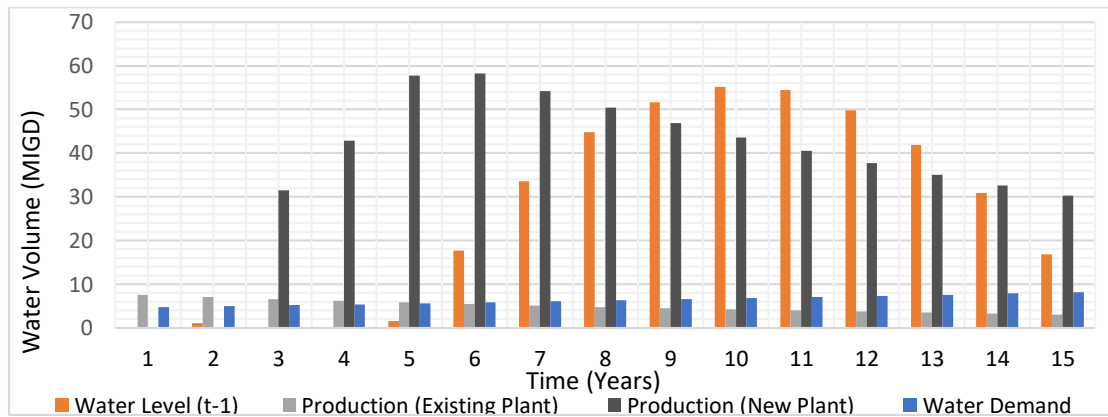


Figure 4 Water Inputs and water demand in the municipality of Kalba

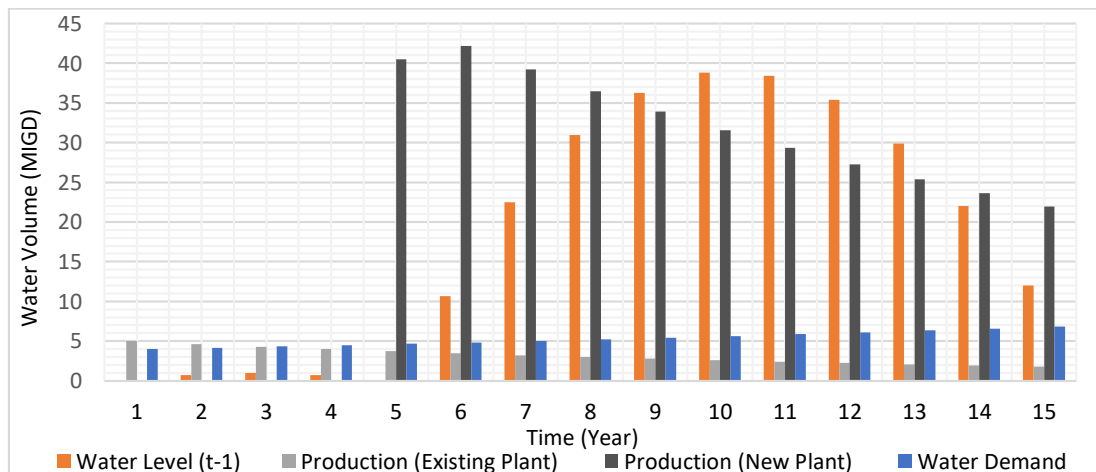


Figure 1 Water Inputs and water demand in the municipality of Khor Fakkan

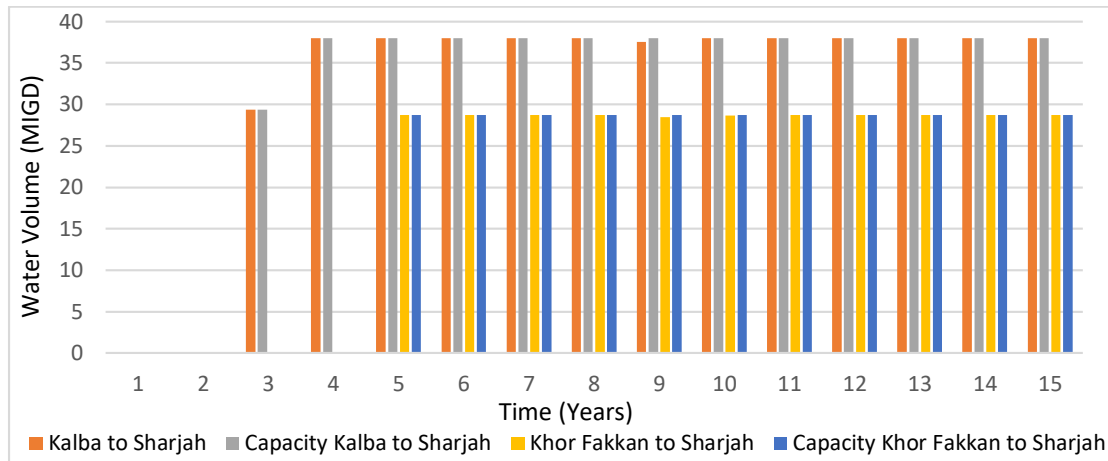


Figure 6 Amount transported vs pipeline capacity over the planning horizon in Sharjah

The minimum total cost of the model, over the full planning horizon, was found to be AED17.637 billion. As illustrated in Figure 7, the operating cost components of desalination (48.56%), transportation (8.98%), and storage (4.04%) are far more significant than their capital cost components. Furthermore, desalination costs are the most significant costs in the model as they add up to 78.35%.

Carbon emissions have two sources as indicated earlier: water transportation and water desalination. Transportation of water accounts for 94% of total emissions. This result is directly related to the selected carbon emission coefficients of desalination technologies and water transportation in pipelines. The mass of emissions due to desalination is equivalent to 12350, 5292, and 10170 ($\frac{kg\ CO_2-e}{MIG}$) for MSF, MED, and RO, respectively (Liu et al., 2015). In addition, the mass of emissions due to water transportation is 2890 ($\frac{kg\ CO_2-e}{km.MIG}$) (Abdulbaki et al., 2017). As such, these are the values which were selected to test the mathematical model, and choosing other values could change the contribution of each source of carbon emissions.

In addition, a sensitivity analysis was conducted to understand the impact of increasing the capacity of new and replacement units. Compared to the base scenario, the capacity of new units was increased from 10 MIGD to 20 MIGD, which yielded a reduction in the total cost due to the fact that only one plant was installed. Hence, fewer pipelines

were installed, which reflected a reduction in the transportation capital cost.

Furthermore, carbon tax rates tend to be higher in countries that place more emphasis on sustainability. As such, the impact of increasing the carbon tax rate iteratively from the base value of 1 ($\frac{\$}{ton\ CO_2-e}$) to 100 ($\frac{\$}{ton\ CO_2-e}$) is analysed. While there were slight changes in the number of new storage tanks and pipelines that were installed at different tax rates, it was noticed that increasing the carbon emissions tax mainly had a significant impact on carbon emissions cost without significant impact on the overall decisions within the model, where a breakdown of the total cost for each of the tax values is depicted in Table 7.

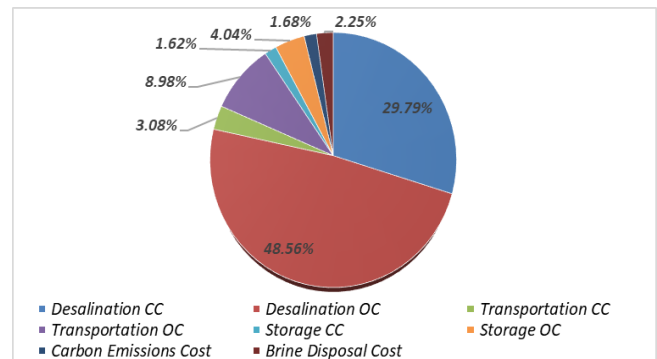


Figure 7 Cost breakdown of the minimum overall cost of the model

Table 7 Variation in the cost components (million AED) for different tax rates

Component	Carbon tax							
	\$1	\$1.5	\$5	\$20	\$40	\$60	\$80	\$100
Desalination CC	5254	5234	5209	5234	5234	5234	5254	5254
Desalination OC	8565	8628	8618	8629	8629	8629	8565	8565
Transportation CC	543	532	555	530	531	531	543	543
Transportation OC	1583	1601	1626	1599	1599	1599	1583	1583
Storage CC	286	317	319	317	317	317	286	286
Storage OC	712	791	783	792	792	791	712	712
Carbon Emissions Cost	296	449	1520	5987	11975	23939	47407	94809
Brine Disposal Cost	396	399	399	399	399	399	396	396
Total	17637	17952	19030	23489	29476	41439	64747	112149

5. CONCLUSION AND FUTURE WORK

The aim of this research was to develop a mathematical model that jointly minimizes the total cost and the negative environmental impact associated with water desalination, transportation, and storage while meeting the demand increase for desalinated water in the region of interest. To that end, several interrelated strategic and tactical decisions need to jointly be optimized while considering a set of technological and operational constraints. From an economic perspective, the model seeks to minimize the total cost over the planning horizon. These costs comprise the capital and operational costs of desalination units, pipelines, and storage tanks, as well as carbon emissions and brine disposal costs. Moreover, from an environmental standpoint, the model seeks to minimize the carbon footprint generated due to the desalination and transportation of water.

After a thorough analysis of the mathematical models found in literature, the model provided in this paper is distinct for splitting desalination plants into units, while allowing for units to be replaced and new units to be added. The model also allows units of one plant to feature more than one desalination technology, while segregating different desalination technologies in terms of degradation rate, costs, and yield. This model provided in this work is a useful tool for decision makers to evaluate their WSC readiness to cater to the increasing demand for freshwater, as it can be modified to contain multiple scenarios, to ensure the sustainability of water supply for future generations.

One possible extension to this work is to accommodate promising technologies in the model, such as Membrane Distillation, as they become more relevant. The model can also be extended to consider brackish feedwater, along with seawater, which would allow for more desalination technologies that are suitable for dilute systems, such as Electrodialysis, to be considered. Also, the degradation rate of the units was assumed constant throughout the planning horizon. However, it may be more realistic to allow the degradation rate to increase with time due to fouling, especially in RO units. Furthermore, compared to seawater, brine has higher concentrations of valuable metals, which can be extracted from the effluent stream (Loganathan *et al.*, 2017).

ACKNOWLEDGMENT

The authors sincerely appreciate the invaluable support provided by the Sharjah Electricity and Water Authority (SEWA). Their generous assistance in supplying essential information and comprehensive data was instrumental in facilitating various phases of this research. The collaboration and insights shared by SEWA significantly contributed to the accuracy and depth of the conducted analysis, enabling the authors to achieve a more thorough and well-informed study. We extend our deepest gratitude for their commitment and willingness to support academic research, which has greatly enhanced the quality and impact of this work. The authors are also indebted to the anonymous reviewers for their insightful comments which greatly enhanced the manuscript's content and quality.

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APPENDIX A: MODEL NOTATIONS

Following are the lists of indices, sets, parameters, and decision variables used in the formulation of the mathematical model presented earlier.

A.1 Indices and sets

- j : coastal demand zones, $j = 1, 2, \dots, J$.
- d : inland demand zones, $d = 1, 2, \dots, D$.
- t : time periods in the planning horizon, $t = 1, 2, \dots, T$.
- p : desalination plant in demand zone j , $p = 1, 2, \dots, P_j$.
- u : desalination units within a plant.
- s : storage facilities.
- l : pipelines.
- k : available desalination technologies, $k = 1, 2, \dots, K$.
- v : water level in storage tanks.
- $A(j, j')$: set of coastal zones j' which can be served by coastal zone j , where $A(j, j') \subset \{1, 2, \dots, J\}$.
- $A(j, d)$: set of inland zones d which can be served by coastal zone j , where $A(j, d) \subset \{1, 2, \dots, D\}$.
- $A(d, d')$: set of inland zones which can be served by inland zone d , where $A(d, d') \subset \{1, 2, \dots, D\}$.
- PL : set of potential locations for a new plant, where $PL \subset \{1, 2, \dots, J\}$.
- JP : set of coastal zones with desalination plants, where $JP \subset \{1, 2, \dots, J\}$.

A.2 Model Parameters

- CT^{max} : maximum lead time for the construction or expansion of new or existing facilities.
 τ : duration it takes to dismantle and replace a desalination unit of any technology k .
 C_{upjkt} : capacity of an existing unit u in plant p of demand zone j using technology k at time t .
 C_{upjk0} : capacity of an existing unit u in plant p of demand zone j using technology k at time 0.
 $\bar{\rho}_k$: capacity degradation rate, i.e., reduction in the water production capacity of a desalination unit after one year of operation due to unit aging.
 Let $\rho_k: 1 - \bar{\rho}_k$, then the desalination unit capacity in plant p of demand zone j using technology k at time t can be expressed as follows:
 $C_{upjkt} = C_{upjk0} * \rho_k^t \quad \forall u, p, j, k, t$.
 P_{j0} : number of desalination plants in demand zone j at time 0. Note that P_{j0} is set to zero for demand zone j with no desalination plants.
 U_{pjko} : number of units in plant p of demand zone j using technology k at time 0.
 R_{upjk0} : remaining lifetime of an existing unit u in plant p of demand zone j using technology k at time 0.
 U_j^{max} : maximum allowed number of units in a new desalination plant of demand zone j due to space limitation.
 np^{max} : maximum number of new desalination plants to be installed over the planning horizon.
 Z_{upjkt} : 0 or 1 indicator showing whether unit u in an existing plant p of demand zone j using technology k is operational at time t .
 $Z_{upjkt} = \begin{cases} 1 & \text{if } t \leq R_{upjk0} \\ 0 & \text{if } t > R_{upjk0} \end{cases}$
 CP_k : water production capacity in million imperial gallons per day (MIGD) of a new unit using technology k .

Water desalination cost and yield:

- CI^{np} : capital cost of installing a desalination plant, excluding the capital costs for installing new desalination units. This includes costs of land acquisition, construction of intake infrastructure, which is the set of pumps and pipelines that draw feed water into the desalination unit. This cost also accounts for installing pre-treatment facilities, where large and small particles, like sand and bacteria, respectively, are filtered out of the feed water. The capital cost also includes the cost of installing brine dilution facilities, and outfall infrastructure in addition to engineering and project management costs.
 CI_k^{nu} : capital cost of installing a new desalination unit using technology k with production capacity CP_k . This consists of material, construction, energy, labour, and maintenance costs, as well as membrane replacement cost in case of RO units (Papapetrou *et al.*, 2017).
 CI_k^r : capital cost of replacing a retiring desalination unit by a new one using technology k . This is different from FCI_k^{nu} as it includes the cost of dismantling the components of the retiring unit.
 OPC_k : operational costs per MIG of water produced by an existing plant using technology k .
 YD_k : water yield ratio of technology k .

Water transportation:

- $CL_{jj'0}$: water transport capacity in MIGD between demand zone j and j' at time 0.
 CL_{jd0} : water transport capacity in MIGD between demand zone j and d at time 0.
 $CL_{dd'0}$: water transport capacity in MIGD between inland demand zones d and d' at time 0.
 CL_{pj0} : water transport capacity in MIGD between desalination plant p and storage facilities available in its demand zone j at time 0.
 DS_{jd} : distance between coastal/inland demand zones j and d in km.
 $DS_{jj'}$: distance between coastal demand zones j and j' in km.
 $DS_{dd'}$: distance between inland demand zones d and d' in km.
 DS_{pj} : distance between desalination plant p and the storage facility in demand zone j in km.
 DS_j^n : distance between a new plant and the storage facility in demand zone $j \subset PL$ in km.
 OPC^l : operational cost of transporting one MIG of water over one km of pipeline.
 VCI^l : variable capital cost of proposed capacity expansion per MIG of water over one km of pipeline.
 FCI^l : fixed capital cost for the expansion of the pipeline transportation capacity.

Water storage:

- WSC_{j0} : water storage capacity in MIGD of demand zone j at year 0.
 WSC_{d0} : water storage capacity in MIGD of demand zone d at year 0.
 $W_{j0}^{v,s}$: water storage level in demand zone j at the beginning of the planning horizon.
 $W_{d0}^{v,s}$: water storage level in demand zone d at the beginning of the planning horizon.
 SC : storage capacity of proposed tanks.
 VCI^s : variable capital cost for the expansion of the storage facility capacity.

FCI^s : fixed capital cost for the expansion of the storage facility capacity.
 OPC^s : operational cost of storing one MIG of water.

Carbon emissions:

$CO2_k$: amount of CO₂ emitted by one MIG of water produced using technology k $\left(\frac{kg\ CO2-e}{MIG}\right)$.
 $CO2^l$: amount of CO₂ emitted by one MIG of water transported through pipeline $\left(\frac{kg\ CO2-e}{MIG}\right)$.
 tx : tax rate charged to each kg of CO₂ emitted by every process within the WSC $\left(\frac{\$}{kg\ CO2-e}\right)$.

Demand:

WD_{jt} : water demand in MIGD in zone j at time t .
 WD_{dt} : water demand in MIGD in zone d at time t .

Brine disposal

CB : brine disposal cost $\left(\frac{\$}{MIG\ brine}\right)$. This is the cost of diluting one MIG of brine with seawater such that it is safe to release back into the sea.

$1 - YD_k$: fraction of disposed brine in desalination unit using technology k $\left(\frac{MIG\ brine}{MIG\ water\ feed}\right)$.

A.3 Decision Variables

Note that it is assumed hereafter that whenever a binary variable related the installation of new plants or to the expansions of existing infrastructure assets is equal to 1, it indicates that the related facility starts to be operational at time t (instead of starting construction at time t). Hence, the decision maker should account for the construction lead time of the facility in question to specify the time at which construction should start.

A.3.1 Strategic Decision Variables Related to Installation of New Plants and Replacement of Retiring Units.

The strategic decision variables that establish the location and capacity size for a new plant and the desalination technology for replaced and new desalination units are:

y_{jt}^{np} : a binary variable, which is equal to 1 if a new desalination plant is installed in demand zone $j \subset PL$ at year t .
 y_{jkt}^{nu} : a binary variable, which is equal to 1 if a new desalination unit is installed in a new plant in demand zone $j \subset PL$ using technology k at year t .
 $y_{upjkk't}^r$: binary variable that takes 1 when unit u in plant p of demand zone j using technology k is replaced by a new unit using technology k' at time t .
 NU_{jkt} : integer variable that denotes the number of desalination units to be installed in a new plant in demand zone $j \subset PL$ using technology k at year t .
 RU_{pjkt} : number of replaced units in plant p of demand zone j that start to be operational using technology k as at time t (the decision to replace these units was taken at time $t - \tau$).

A.3.2 Strategic Decision Variables Related to the Expansions of Water Storage Capacities

The following are the strategic decision variables associated with the expansions of water storage capacity.

y_{jt}^s : binary variable that takes 1 if storage capacity is expanded in zone j at year t .
 y_{dt}^s : binary variable that takes 1 if storage capacity is expanded in zone d at year t .
 NS_{jt} : integer variable that represents the number of new storage tanks in demand zone j at year t .
 NS_{dt} : integer variable that gives the number of new storage tanks in demand zone d at year t .
 WSC_{jt} : water storage capacity of coastal demand zone j at year t .
 WSC_{dt} : water storage capacity of inland demand zone d at year t .

A.3.3 Strategic Decision Variables Related to Transportation of Water Through Pipelines

The strategic decision variables associated with the distribution of water through pipelines are:

$y_{jj't}^l$: binary variable for the decision to expand transport capacity between demand zones j and j' at time t .
 y_{jdt}^l : binary variable for the decision to expand transport capacity between demand zones j and d at time t .
 $y_{dd't}^l$: binary variable for decision to expand transportation capacity between inland demand zones d and d' at year t .
 y_{pjt}^l : binary variable for the decision to expand transportation capacity between existing desalination plant p and the storage facility in its demand zone j at time t .
 y_{jt}^{nl} : binary variable for the decision to expand transportation capacity between a new desalination plant and the storage facility in demand zone j at time t .
 $NL_{jj't}$: amount of expansion of the water transport capacity between demand zone j and j' at time t for $j = 1, \dots, J$, $j' \in A(j, j')$, and $t = 1, \dots, T$.
 NL_{jdt} : amount of expansion of the water transport capacity between demand zone j and d at time t for $j = 1, \dots, J$, $d \in A(j, d)$, and $t = 1, \dots, T$.

- $NL_{dd't}$: amount of expansion of the water transport capacity between demand zones d and d' at time t for $d = 1, \dots, D, d' \in A(d, d')$, and $t = 1, \dots, T$.
- NL_{pjt} : amount of expansion of the water transport capacity between existing desalination plant p and the storage facility in demand zone j at time t for $j \in JP$ and $t = 1, \dots, T$.
- NL_{jt}^{nl} : amount of expansion of the water transport capacity between a new desalination plant and the storage facility in demand zone j at time t for $j \in PL$ and $t = 1, \dots, T$.
- $CL_{jj't}$: water transportation capacity between coastal demand zones j and j' at year t for $j = 1, \dots, J, j' \in A(j, j')$, and $t = 1, \dots, T$.
- CL_{jdt} : water transportation capacity between coastal and inland demand zones j and d at year t for $j = 1, \dots, J, d \in A(j, d)$, and $t = 1, \dots, T$.
- $CL_{dd't}$: water transportation capacity between inland demand zones d and d' at year t for $d = 1, \dots, D, d' \in A(d, d')$, and $t = 1, \dots, T$.
- CL_{pjt} : water transportation capacity between existing desalination plant p and the storage facility in demand zone j at time t for $j \in JP$ and $t = 1, \dots, T$.
- CL_{jt}^{nl} : water transportation capacity between a new desalination plant and the storage facility in demand zone j at time t for $j \in PL$ and $t = 1, \dots, T$.

A.3.4 Tactical Decision Variables Related to Water Production in Existing and New Plants

The decisions related to the operations of existing and new desalination plants include the amount of treated seawater and amount of water produced in each year of the planning horizon.

- W_{pjkt}^i : water input of existing plant p in demand zone j using technology k at time t .
- $W_{jkt}^{i,n}$: water input of a new plant in demand zone j using technology k at time t .
- W_{pjkt}^o : water output from existing plant p in demand zone j using technology k at time t .
- $W_{jkt}^{o,n}$: water output from a new plant in demand zone j using technology k at time t .
- W_{pjt}^o : total water output from plant p in demand zone j at time t , which is given by:
- $$W_{pjt}^o = \sum_{k=1}^K W_{pjkt}^o.$$
- $W_{jt}^{o,n}$: total water output from a new plant in zone j at time t , which is given by:
- $$W_{jt}^{o,n} = \sum_{k=1}^K W_{jkt}^{o,n}.$$
- B_{pjkt} : amount of brine produced by plant p in zone j using technology k at time t .
- B_{jkt}^n : amount of brine produced by a new plant in zone j using technology k at time t .

A.3.5 Tactical Decision Variables Related to Water Storage

The tactical decisions associated with the operations of the water tanks are the amount of water left by the end of the year in the storage facilities in coastal and inland demand zones. More specifically, they are defined as follows:

- $W_{jt}^{v,s}$: water level of storage tanks in coastal demand zone j at the end of year t .
- $W_{dt}^{v,s}$: water level of storage tanks in inland demand zone d at the end of year t .

A.3.6 Tactical Decision Variables Related to Water Transport through Pipelines

Tactical decisions related to the operation of pipelines consist of the decisions that determine the amount of water to be transported between the demand zones.

- $W_{jj't}^l$: water transported between coastal demand zones j and j' at year t for $j = 1, \dots, J, j' \in A(j, j')$, and $t = 1, \dots, T$.
- W_{jdt}^l : water transported between coastal and inland demand zones j and d at year t for $j = 1, \dots, J$ and $d \in A(j, d)$, and $t = 1, \dots, T$.
- $W_{dd't}^l$: water transported between inland demand zones d and d' at year t for $d = 1, 2, \dots, D$ and $d' \in A(d, d')$, and $t = 1, \dots, T$.

A.4 Formulation of the Model Objective Function

This section presents the formulation of the model objective function, which consists of the various operational and capital costs associated with existing and new plants, storage tanks, and pipelines, as well as the CO₂ emission and brine dilution costs.

A.4.1 Operational and Capital Costs of Water Desalination Plants

The capital and operational costs of new and existing desalination plants are formulated next. Moreover, the total discounted capital and operating costs of all desalination plants over the planning horizon are presented.

Let:

- OC_{pjt} : operating cost of plant p of demand zone j at year t .
- CC_{pjt} : capital cost for the replacement of retiring units in plant p of demand zone j at time t .
- OC_{jt}^{np} : operating cost of a new plant of demand zone j at year t .

- CC_{jt}^{np} : capital cost of a new plant of demand zone j at time t , excluding the capital cost for installing new desalination units.
 CC_{jt}^{nu} : capital cost of a new desalination unit in a new plant.

A.4.2 Operational and Capital Costs of Water Transportation and Storage.

The operating and capital costs of transporting and storing water, as well as installing new pipelines and storage tanks, are discussed next. The following are the related cost components.

- $OC_{jj't}^l$: operating costs of water transported between demand zone j and j' at year t .
 $OC_{jd't}^l$: operating costs of water transported between demand zones j and d' at year t .
 $OC_{dd't}^l$: operating costs of water transported between demand zones d and d' at year t .
 OC_{pjt}^l : operating costs of water transported between desalination plant p and storage facility in demand zone j at time t .
 $OC_{jt}^{l,n}$: operating costs of water transported between a new desalination plant and storage facility in demand zone j at time t .
 $VCC_{jd't}^l$: variable capital costs for the expansion of the capacity of the pipelines between demand zones j and d' at year t .
 $VCC_{jj't}^l$: variable capital costs for the expansion of the capacity of the pipelines between demand zones j and j' at year t .
 $VCC_{dd't}^l$: variable capital costs for the expansion of the capacity of the pipelines between demand zones d and d' at year t .
 VCC_{pjt}^l : variable capital costs for the expansion of the capacity of the pipelines between desalination plant p and storage facility in demand zone j at time t .
 $VCC_{jt}^{l,n}$: variable capital costs for the expansion of the capacity of the pipelines between a new desalination plant and storage facility in demand zone j at time t .
 $FCC_{jd't}^l$: fixed capital costs for the expansion of the capacity of the pipelines between demand zones j and d' at year t .
 $FCC_{jj't}^l$: fixed capital costs for the expansion of the capacity of the pipelines between demand zones j and j' at year t .
 $FCC_{dd't}^l$: fixed capital costs for the expansion of the capacity of the pipelines between demand zones d and d' at year t .
 FCC_{pjt}^l : fixed capital costs for the expansion of the capacity of the pipelines between desalination plant p and storage facility in demand zone j at time t .
 $FCC_{jt}^{l,n}$: fixed capital costs for the expansion of the capacity of the pipelines between a new desalination plant and storage facility in demand zone j at time t .
 OC_{jt}^s : operating costs of storage tank in demand zone j at year t .
 OC_{dt}^s : operating costs of storage tank in demand zone d at year t .
 VCC_{jt}^s : variable capital costs of new storage tanks in demand zone j at year t .
 VCC_{dt}^s : variable capital costs of new storage tanks in demand zone d at year t .
 FCC_{jt}^s : fixed capital costs of new storage tanks in demand zone j at year t .
 FCC_{dt}^s : fixed capital costs of new storage tanks in demand zone d at year t .

A.4.3 Total Carbon Emissions and Brines Disposal Costs

The total discounted costs resulting from CO₂ emission and diluting brine over the planning horizon are provided next.

- E_{pjt} : amount of CO₂ emitted by plant p of demand zone j during year t .
 E_{jt}^n : amount of CO₂ emitted by a new plant of demand zone j during year t .
 $E_{jd't}^l$: amount of CO₂ emitted by transporting water between demand zones j and d' during year t .
 $E_{jj't}^l$: amount of CO₂ emitted by transporting water between demand zones j and j' during year t .
 $E_{dd't}^l$: amount of CO₂ emitted by transporting water between zones d and d' during year t .
 E_{pjt}^l : amount of carbon emitted by transporting water between desalination plant p and storage facility in demand zone j during time t .
 $E_{jt}^{l,n}$: amount of carbon emitted by transporting water between a new plant and storage facility in demand zone j during time t .
 BQ_t : total brine disposal quantity during year t .

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