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INTEGRATED STRATEGIC AND TACTICAL OPTIMIZATION OF WATER SUPPLY CHAINS

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Abstract: *This paper adopts a holistic approach to the integrated water supply chain system, considering water-related aspects including production, technology selection, distribution routes, and storage, among others. It also introduces a multi-period comprehensive mathematical model that assists decision makers in jointly optimizing a multitude of decisions pertaining to the water supply chain, ranging from strategic to tactical ones. In particular, the former address the installation of new desalination plants along with their operational capacity, capacity expansion of existing plants and infrastructure assets (storage and distribution), as well as the selection of the best-suited desalination technologies. On the other hand, tactical decisions consider issues such as the allocation of water resources among end users, production level of desalinated water at the different plants, and storage levels across various demand zones. All these decisions are being optimized in every period towards minimizing financial and environmental costs throughout the planning horizon. To illustrate the model's practical relevance and assess its validity, a case study focused on an Emirate in the United Arab Emirates (UAE). Results highlight the need for increased desalination capacity over the next 15 years to match growing demand. The study pinpoints the timings for desalination facility expansions, compensating for decreased capacity due to degradation or retirement. The study underscores the superiority of reverse osmosis technology over other desalination options.*

Keywords: *water supply chain; water desalination; mathematical optimization; capacity expansion.*

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1. Introduction

The availability of water, in terms of quantity and quality, is one of the most pressing and critical challenges in the current time, especially for countries experiencing water scarcity (Ahuja, 2009). The accelerated population growth, accentuated industrial development, swift climatic change, and ineffective water management strategies have emerged as major factors contributing to the current water crisis observed in numerous regions across the globe (Bond et al., 2019). Moreover, the quality of current conventional water sources worldwide is steadily deteriorating, largely due to human activities (Tzanakakis et al., 2020). The combination of the scarcity of freshwater resources, declining water quality, and surging water demand has prompted a growing reliance on non-conventional water resources to meet current water needs. Additionally, the substantial reduction in the cost of desalination technologies has accelerated their adoption in water stressed regions, such the Arab Gulf region, notably the United Arab Emirates (UAE), and this trend is expected to continue in the future (Mohsen et al., 2016); (Ghaffour et al., 2013).

To meet its ever-growing water demand, the UAE has diversified its sources of water to include non-conventional water sources such as desalinated water and treated wastewater alongside groundwater and surface water (Rizk & Alsharhan, 2003). Currently, the country's potable water supply heavily relies on desalination with projections indicating a steady expansion of desalination plant capacities over the next few years. As a result, the UAE currently contributes to roughly 14% of the global desalination capacity (Administration, 2023). Within the UAE, there are seventy desalination plants, with 67% situated in the emirate of Abu Dhabi, 18% in Dubai, 10% in Sharjah, and 5% in the Northern Emirates (Administration, 2023). By 2050, it is predicted that the total water production will reach approximately 12 billion cubic meters (BCM). Alongside the UAE government's efforts, which include awareness programs, subsidy reduction, aquifer-based water storage, groundwater extraction regulation, and investments in energy-efficient seawater desalination, a pressing challenge lies in the establishment of a long-term strategy for managing water resources. Such planning plays a pivotal role in ensuring efficient, equitable and sustainable utilization of the country's limited water resources for generations to come.

A water supply chain (WSC) encompasses all entities involved in the various processes of generating, storing, and distributing water to its various points of consumption. This includes water sources, water treatment facilities, storage infrastructure, and end users. An Integrated water supply chain (IWSC) system is a holistic approach which considers all sorts of water resources such as groundwater, surface water, brackish water, water desalination, wastewater treatment and reclamation, among others (Al-Nory & Graves, 2013). IWSCs are useful to map out the flow of both conventional and non-conventional water, from their sources to the end users. Recently, integrated water supply chain management (IWSCM) has been recognized as an essential and instrumental approach towards improving the efficiency and responsiveness of integrated water supply chains (Katusiime & Schütt, 2020). The main goal of the IWSCM is to meet future water demand from conventional and non-conventional water supplies, while taking into account their availability in terms of quantity and quality, through the efficient design and operations of the plants and physical assets across the supply chain.

Generally speaking, optimization techniques provide powerful means for optimizing pertinent decisions in situations where the goal is to optimize an objective function representing one or more criteria subject to a set of constraints. Optimization methods have been widely employed to address strategic, tactical, and operational challenges in water resources management. In particular, optimization techniques have proven to be a useful tool for the management of integrated water supply chains addressing critical aspects such as water allocation, technology selection, and integration of environmental concerns (Maraveas, 2023).

In reality, there exist a wide range of water desalination challenges that severely affect the efficient design and planning of WSC operations. To that end, this paper proposes a comprehensive optimization model that caters for such challenges while resembling the reality of the desalination industry via considering various technologies for water desalination, multiple supply and demand nodes, as well as realistic economic and environmental cost structures and constraints. The developed mathematical model provides water policy-makers with an effective mean to jointly optimize a multitude of strategic and tactical decisions from technical, economic, and environmental standpoints. In essence, strategic decisions deal with the installation of new desalination plants and their operational capacity, capacity expansion of existing plants and infrastructure assets (storage and distribution), and the selection of desalination technologies. On the other hand, tactical decisions address issues such as optimal allocation of water resources among end users, production level of desalinated water at the different plants, storage levels across various demand zones, and amount of CO_2 emissions. All these decisions are taken into consideration at each period of the planning horizon.

The remainder of this paper is organized as follows. A literature review closely examining related works is presented in Section 2. The proposed model is provided in Section 3 along with a detailed description of all constraints and the objective function. In Section 4, a case study is presented to illustrate the implementation of the proposed model and its results. Finally, Section 5 contains some concluding remarks and highlights promising avenues for future research.

2. Literature review

A wide range of water supply chain management decisions can be tackled with modelling and optimization toward coming up with rational decisions. Such methods may be used to handle operational, tactical, and strategic issues. Examples include finding the optimal operating parameters of a desalination process (Ali & Kairouani, 2016), determination of sustainable underground water retrieval levels (Singh, 2014), managing supply and demand variations, and feasibility of water saving technologies (Cetinkaya et al., 2008), among many others. In particular, numerous research works have been carried out to develop optimization models for the design and planning of WSCs. The design of WSC networks refers to the strategic decisions associated with the location of new facilities, such as desalination plants and storage and distribution facilities, design capacity of the new plants, selection of the desalination technologies, and expansion or closure of existing facilities. Several studies were related to the design of desalination plants and their optimal operating conditions. We limit this review to closely related studies. (Draper et al., 2003) developed an optimization model to analyse water resources operations and allocation for an integrated WSC in the state of California. They concluded that IWSC optimization models driven by economic objective functions are both possible and practical. (Saif et al., 2008) conducted an optimization study of reverse osmosis (RO) networks for wastewater treatment by formulating the system as a nonconvex mixed-integer nonlinear program (MINLP). Subsequently, a mixed-integer linear program (MILP) obtained after the convex relaxation of the MINLP is solved iteratively to supply different initial solutions for the nonconvex MINLP model.

(Kondili et al., 2010) presented a mathematical formulation for the design of water supply taking into account multiple sources and end users. (Padula et al., 2013) presented a deterministic optimization model for capacity expansion based on a MILP formulation. (Al-Nory & Graves, 2013) discussed various strategic planning aspects of desalination options and developed a decision-making methodology, which they used to solve a case study in Saudi Arabia. (Roozbahani et al., 2015) proposed a mathematical model for the allocation of water resources among stakeholders with each of them having a water demand and a water profit but the available water cannot meet their total demands. Their model can successfully be used for sustainable conflict resolution in a shared basin as it satisfies the environmental water requirement and provides equitably the same ratio of the stakeholders' highest possible profits for them. Some studies incorporated water treatment facilities as well in the context of closed loop system (Ray et al., 2010), (Liu et al., 2011), (Ghassemi et al., 2017), (Abdulbaki et al., 2017), (Koleva et al., 2017), and (Fathollahi-Fard et al., 2020).

There is also a growing interest among researchers and practitioners in integrating water and energy supply chains optimization. (Papapostolou et al., 2018) tackled this problem by considering all potential water supply sources in order to support investment planning taking into account environmental considerations. A similar problem was addressed by (Papapostolou et al., 2020) using linear programming and the results showed that reliable renewable energy and water supply can be achieved at reasonable cost and contribute positively to gas emissions.

Motivated by the lack of a generic optimization model in the existing literature that encompasses various aspects of WSCs, we propose an all-encompassing mathematical model for their effective design and planning, taking into account economic, technological, and environmental related issues. This optimization model exhibits flexibility in handling a multitude of real-world scenarios, including variations in the number of water sources, treatment technologies, water end users, and the environmental repercussions of design and planning decisions. The model's outcomes will prove invaluable to water decision-makers by aiding them in making strategic and tactical decisions that optimize the management of their IWSCs across finite, multi-period planning horizons. In addition, it is structured as a comprehensive mathematical decision-making tool that takes into account the following considerations:

Excluding the capacity of retired production units from the overall capacity of desalination plants once they have reached the end of their operational lifespan.

Accounting for the construction time of expanded facility (desalination unit, storage tanks, and pipeline) to ensure the feasibility of the capacity expansion decision and to reduce the mathematical and computational time complexities of the model.

Depicting the desalination plant as clusters of production units employing different technologies and capacities. This approach of plant representation is more practical and realistic as opposed to conceptualizing a desalination plant as a single monolithic entity.

Incorporating entropy generation as an environmental indicator in the comparison of desalination methods and the management of WSCs.

3. Integrated Water Supply Chain Model: Overview

To effectively address the complexity of the IWSC problem, this section provides a detailed descriptive explanation of the optimization model's decision variables, constraints, and objective function due to its significant size. Additional details and the complete set of mathematical formulations for the various components of the model can be provided upon request. Before introducing the proposed mathematical model, it is important to highlight the unique features that distinguish it from existing models in the literature.

3.1 Model Planning Horizon

The duration of the model's planning period accounts for the construction timelines for the expansions of the water production, storage, and transportation facilities. Stated differently, it assumes that there is an adequate timeframe at the start of the planning period for building these new facilities. More specifically, if CT^{max} is the longest construction time among all IWSC facilities, i.e., CT^{max} is the maximum of (construction time of a desalination unit using technology k ($k = 1$ to K), construction time of storage facility, construction time of pipelines), then we assume that the start of the planning period should be the beginning of year $CT^{max} + 1$ (end of year CT^{max}). Accordingly, it is assumed that any expansion decision during the time period (0 to CT^{max}) was taken into account in the previous planning cycle. Therefore, any decision to expand a desalination plant, storage facilities, and pipelines after time CT^{max} is feasible as there is sufficient time during the planning period to construct such facilities. For example, for a 20-year planning period that starts at the beginning of 2022 with a CT^{max} of 3, the first three years are not part of the effective planning horizon and all expansions required for those years to meet demand are assumed to be preplanned before 2022. This also implies that the next planning period and effective planning period should start at years 2039 and 2042, respectively. The use of the effective planning period will reduce the mathematical and computational time complexities of the model by ensuring the feasibility of the binary variables used to represent expansion decisions.

3.2 Water Sources

The two water sources considered as feed for desalination plants in the mathematical formulation of the model are sea water and brackish underground water. Fresh water sources are not included; rather, their available capacity is accounted for as input data to the model. That is, the maximum retrievable volume of fresh water is discounted from the yearly demand. The rationale behind avoiding freshwater decision variables is their very low treatment costs and environmental impact when compared to desalinated brackish or sea water. Moreover, fresh water sources are usually limited in terms of quantity and their inclusion in the model will represent an unsustainable long-term plan. Another relevant issue is the depletion of fresh underground wells which, even when recharged by rain water, may lead to degradation in the quality of water (Sherif et al., 2021); (Kayemah et al., 2021). Actually, even brackish water utilized as feed to desalination plants is also limited due to sustainability considerations.

3.3 Water Quality

The mathematical model will only consider standards deemed acceptable for domestic water use and will not take into consideration production of water with inferior quality standards. This decision is made based on the local water authority data that divided water demand to residential, industrial, commercial, governmental, and agricultural demand. In 2019, the data indicated that residential demand represented about 61% of total demand while industrial, commercial, and governmental demands were 4.75, 25.6, and 9.5% respectively. Agricultural demand represents less than 0.1% of total demand which is considered negligible. The only demand sector out of the four significant ones which can withstand lower quality standards is industrial demand. Further analysis of the data for the 4 years prior to 2019 indicated that the industrial demand fluctuated between 4 and 5% but never exceeded this value. Moreover, not all industrial users of water tolerate lower quality water standards and some require higher quality (Gracia-de-Rentería & Barberán, 2021).

3.4 Water Demand Zones

For the study under consideration, the geographical area has been segmented into distinct demand zones or municipalities. These zones are categorized into two primary groups: coastal and inland municipalities. The key distinguishing feature between them is the presence or absence of access to seawater. Furthermore, some coastal municipalities have access not only to seawater but also to brackish water, whereas others only have access to seawater. Similarly, within the inland municipalities, a differentiation is made based on the availability of brackish water within the municipality. Only inland municipalities with access to brackish water are being considered for the implementation and potential expansion of brackish water desalination plants. It is worth reiterating, as mentioned earlier, that for inland and coastal municipalities with access to freshwater resources, the maximum retrievable yearly volume is subtracted from their overall demand.

The inland municipalities that have no local water desalination plants can meet their demand by relying on neighboring coastal and inland municipalities' water production. Meanwhile, all other coastal and inland municipalities with local water production can satisfy their water requirements either through local production or by importing water from neighboring municipalities. Input water in these municipalities is retrieved either from brackish water sources in the case of inland municipalities, while coastal municipalities with no access to brackish water rely exclusively on seawater. Coastal municipalities with access to both seawater and brackish water use both sources. Subsequently, the water undergoes desalination in desalination plants and is then stored in tanks within each municipality. Water output is then extracted from these storage facilities and is either distributed to meet the municipality's internal demand or transported to fulfill the needs of neighboring municipalities.

In the model formulation, we assume that each municipality can only serve a specific group of neighbouring municipalities via pipelines. Neighboring coastal municipalities are allowed to send and receive water provided it does not exceed the capacity of the pipelines connecting them. In contrast, inland municipalities can only receive water from coastal ones and may redistribute it to other inland municipalities. Moreover, inter-municipal transportation between inland areas is restricted to flow away from the coast. Figure 1 illustrates potential water transportation routes, taking into account all the aforementioned water flow constraints. These restrictions of the direction of inter-municipal water transportation routes are crucial to reduce the model complexity and prevent the flow of water back toward the coast from inland municipalities.

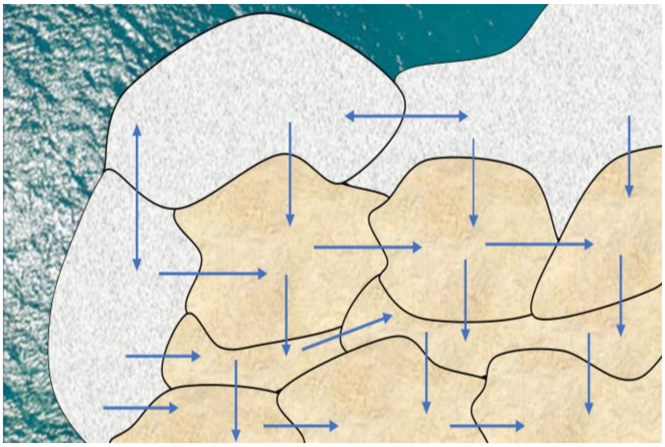

Figure. 1: A schematic diagram showing allowed water transportation routes between municipalities

Among the main outputs of the model are the optimum choices of capacity expansions including the choice of desalination technology in addition to the location and number of expansions of all facility types. It is noted that expansions in this model are defined as the installation of new desalination units, pipelines, and storage tanks, which better resembles reality.

3.5 Desalination Plant Structure

In the model formulation, desalination plants are divided into units of different technologies and capacities. Units of the same technology are clustered in sections of the plant to account for the water recovery yield and operational costs both of which are dependent on the technology. Moreover, a cluster of units utilizing the same technology would have the same water intake and post-treatment infrastructure; therefore, they have distinct water input and output from a modeling perspective. In addition, the installation of new desalination units is subject to area limitations in each plant. This approach of desalination capacity expansion is more realistic when compared to modeling desalination plants as one block. When desalination plants are first constructed, potential capacity expansions are taken into account and therefore the area within the borders of the plant is usually much larger than the area utilized. This approach was observed in the UAE's Emirate under study when analyzing the 1981-2007 data regarding the year of installation for the different desalination units in one of its plants. This information indicate that once a desalination plant is expanded, new units are installed to cater for demand increase.

3.6 Capacity Expansion

The proposed installation of desalination units is set to a discrete number of capacity level options to ensure the linearity of the model and, therefore, reduce unnecessary model complexity. Accordingly, not only will the model decide the technology to be adopted, but also the capacity of the unit utilizing the technology in question from a discrete set of options for capacity levels. Following this approach allows for model flexibility when it comes to capacity expansions to meet varying levels of demand increases in municipalities of different demand volumes, making the results more applicable and realistic. Moreover, the utilization of any operational production capacity is improved since expansions have a greater ability to meet different ranges of demand increases which improves the overall efficiency of the model results. In addition, having a discrete number of capacity levels for expansion avoids considering the capacity level as a decision variable which would introduce nonlinearities into the model as cost relations are usually nonlinear functions with relation to the capacity level. Storage and transportation facilities expansions are modeled in a manner similar to desalination units where a discrete number of capacities can be chosen from for any expansion decision throughout the planning horizon.

3.7 Environmental impact

Carbon regulation policies in many countries restrict the carbon footprint of industrial operations or implement a carbon tax system where operators are directly incentivized to reduce their carbon footprint. However, the application of this indicator in optimization modeling of water supply chains faces some issues. First, estimates of the carbon footprint of desalination plants in the literature are not consistent due to many reasons including the dependence of estimates on geographical locations (Raluy et al., 2006); (Cornejo et al., 2014). From a modeling perspective, emissions are usually included as a cost to be minimized and are therefore converted to a financial term using an estimate for the cost of carbon emissions. This becomes an issue due to the lack of empirical methodology in coming up with such estimations as it is very difficult to numerically assess damage to the environment due to greenhouse emissions in financial terms (Moore & Diaz, 2015). To avoid the use of such estimates, the mathematical model in this study restricts the total CO_2 emissions of the desalination supply chain to a value set by the decision maker based on their own environmental initiative to minimize the carbon footprint of the WSC.

One of the valuable resources that must be utilized efficiently is energy. This is especially true when energy is produced through nonrenewable resources, where both financial and environmental costs are incurred. The classical definition of thermodynamic efficiency, which assesses how efficiently the input energy is utilized in any energy-consuming process, may not be appropriate for making comparisons between various desalination technologies with different driving forces or different forms of energy as inputs. A more holistic view of efficient energy utilization is based on the concept of entropy generation or exergy destruction, which incorporates the use of the second law of thermodynamics (Sciacovelli et al., 2015)

According to the first law of thermodynamics, energy cannot be created or destroyed; instead, it can only be converted from one form to another (Iwase, 2014). A direct consequence of the first law of thermodynamics is the equivalency of heat and work as two forms of energy appearing on system's boundaries. However, according to the second law of thermodynamics, heat is inferior in quality as compared to work since the transfer of heat into useful work implies a loss in work. Alternatively, the concept of exergy was formulated to capture the inherent lost work in all real processes. Exergy is defined as the amount of useful energy that can be extracted from an available energy resource. Unlike energy, exergy is destroyed in real processes (Bejan, 2002). Physically, exergy destruction or entropy generation are the result of inevitable frictional losses and irreversibility within any ongoing processes. Exergy is conserved only in ideal processes, i.e., those (hypothetical) processes which are free of frictional losses and irreversibility. According to the second law of thermodynamics the exergy destruction in any real process is directly proportional to the entropy generation or the lost work. Thus, exergy destruction, entropy generation, or lost work can be used interchangeably to indicate the same concept.

For water desalination processes, exergy destruction is measured in terms of units of energy per unit volume of produced water, Therefore, it can be converted to a financial cost that can be incorporated into the objective function. The inclusion of entropy generation as a cost can be perceived as a tax on the inefficient use of energy, with the ultimate goal of which is improving the sustainability of the overall water supply chain (Bejan, 2002); (Palamutcu, 2015)

4. Model Assumptions, Notations, and Data Inputs

The proposed mathematical model is based on the following assumptions:

- Seawater is an unlimited water resource.
- The salinity of seawater remains constant over time and not influenced by brine disposal (Ibrahim & Eltahir, 2019). Therefore, desalination units utilized for seawater desalination have the same cost parameters over the whole planning horizon and do not require any adjustments to desalinate water with higher salinity.
- A percentage of desalination capacity is lost due to degradation and maintenance closures.
- Only certain sets of municipalities can exchange water based on availability of water sources and their geographical location.
- All water demand requires the same water quality consistent with standards for potable water.
- Operation of storage facilities involves no carbon emissions.
- Storage tanks and water pipelines have an unlimited lifetime.

- All current desalination units must be decommissioned at the end of their estimated lifetime. However, costs associated with decommissioning of units are not considered since they are inevitable costs that cannot be altered and not affected by the model decisions.
- Sections of desalination plants which treat different feed water types are considered as separate plants. For example, if a desalination plant includes units treating brackish water and others treating sea water, the section treating brackish water will be considered as a separate plant.
- Water produced using the same technology has the same cost across different municipalities since desalination units are considered to be of similar age. The only factors affecting the cost of water production are feed water type and desalination technology used.
- Operational costs of desalination units, storage tanks, and pipelines are only dependent on the amount of water desalinated, stored, or transported and not the capacity of the unit, tank, or pipeline.
- Capital costs of expansions with capacities beyond the largest capacity available for the expansion of any facility are assumed to be linearly related to the capacity (no accounting for economies of scale where a larger unit size leads to a decrease in the capital cost per unit capacity). For example, if the largest desalination unit size was 5 million imperial gallons per day (MIGD) and an expansion of 10 MIGD is suggested, then two 5-MIGD units would be installed, and the total capital costs would be 2 multiples of the capital cost of a 5 MIGD unit.
- Whenever a capacity expansion decision is made at time period t, the facility becomes operational at that same time. The decision maker is expected to factor in the time needed for construction while implementing the model's results. For further details, readers can refer to the model's feature related to the planning horizon.

The mathematical model utilizes an extensive set of notations pertaining to its parameters and decision variables.

4.1 Model Parameters

The input parameters needed for formulating the model relate to the following categories.

- Capacity and operation parameters of water desalination units
- Water desalination cost and yield parameters
- Water transportation parameters
- Water storage parameters
- Entropy generation parameters
- Carbon emissions parameters

4.2 Decision variables

The decision variables for the model are associated with strategic capacity expansions of WSC facilities, tactical operations, and logical constraints. They are categorized as follows:

- Set of binary and continuous variables related to the capacity expansion of water desalination units (binary expansion decision variables, number of new desalination units in coastal and inland municipalities, and water production capacity).
- Set of binary and continuous variables associated with the capacity expansion of storage facilities (binary expansion decision variables, number of new storage tanks in coastal and inland municipalities, and water storage capacity).
- Set of continuous variables that represent the capacity expansion of the water transportation pipelines (expansion level of water transport capacity between any two municipalities).
- Set of continuous variables related to the operation of water desalination plants (water output and input in coastal and inland plants).
- Set of continuous variables to indicate the volume of water transported between two municipalities.
- Set of continuous variables to denote the volume of water stored in coastal and inland municipalities.
- Set of continuous variables to represent the amount of carbon emissions generated by the desalination plants and transportation activities.

The purpose of the proposed model is to aid decision-makers in making strategic and tactical decisions aimed at reducing both the overall financial expenses and environmental footprint of the WSC over a predetermined planning timeframe. To that end, the model necessitates input data that encompasses the current state of the WSC. This should encompass projections for water demand in each region over the chosen planning horizon, as well as exhaustive details regarding the capacity and location of every plant. Additionally, it should include information concerning the environmental data and financial costs associated with all components of the WSC, such as desalination plants, storage tanks, and pipelines. Furthermore, it is essential to provide a breakdown of the desalination units within each plant, including their respective capacities and operating costs. Lastly, data pertaining to potential expansions of the aforementioned WSC facilities are essential. This includes the available technologies for expanding capacity, along with estimations of the associated financial expenditures and environmental ramifications for each option.

5. Overview of the Model Constraints and Objective Function

This section provides a comprehensive overview of the IWSCM model, including its constraints and objective function.

5.1 Model constraints

5.1.1 Strategic constraints related to the capacity expansion of water desalination units

This set includes four distinct types of constraints. The first type of constraints ensures that, in the absence of expansion decisions for desalination plants in either coastal or inland municipalities during any given time period, the number of new desalination plants will be zero for that period. The second type of constraints stipulates that any new desalination plant will adopt only one type of desalination technology. The third type of constraints restricts the number of desalination units that can be installed within any given desalination plant due to space limitations. The last type of equations determines the water production capacity for any given period within the planning horizon for facilities located in both coastal and inland municipalities depending on the adopted desalination technology and feed water. The production capacity level at any time period is computed as the sum the initial production capacity levels of the existing desalination units who are still operational and the capacity of the newly installed unit before that time period. In addition, both capacity levels for existing and newly installed units are discounted to account for aging.

5.1.2 Strategic constraints related to capacity expansion of storage facilities

The first type of capacity expansion of storage facilities constraints determines the number of new storage tanks to be installed in coastal and inland. It also ensures that new storage facilities are installed only when an expansion decision is made. The second type constraints updates the capacities of storage facilities in both coastal and inland municipalities, to include water storage capacity expansions taking place in the same period.

5.1.3 Strategic constraints related to the capacity expansion of water pipelines

The first category of constraints ensures that expansions of the capacity for water transportation between a coastal municipality and an inland municipalities, between coastal municipalities, and between inland municipalities, will not be allocated unless transportation capacity expansion decisions have been made. The second type of constraints assures that the capacity expansion of water transportation between desalination plants and storage facilities in coastal and inland municipalities with desalination plants occurs only after an expansion decision has been made. The third type of constraints calculates the available capacity of transportation between coastal/inland, coastal/coastal, and inland/inland municipalities including expansions. The last type of constraints serves the same purpose as the previous set of constraints for water transportation between desalination plants and storage facilities within all coastal municipalities and inland municipalities with desalination plants.

5.1.4 Constraints related to the operation of water desalination plants

There are five types of constraints related to the operation of water desalination plants. The first type of constraints restricts the water input of desalination plants in coastal municipalities or any inland municipalities with desalination plants treating brackish water to the available desalination capacity. The second type of constraints ensures an efficient utilization of the technology adopted in any plant. The third type of constraints calculates the water output from desalination plants as the product of the water input and the water recovery yield of different technologies. The fourth type of constraints restricts the total water output from a desalination plant to be less than or equal to the transport capacity of the pipeline connecting the plant to the storage facility. The fifth type of constraints limits the intake of brackish water input at all desalination plants in coastal and inland municipalities, which have access to brackish water sources, as a result of sustainability concerns.

5.1.5 Constraints related to water transportation

This type of constraints guarantees that the volume of water being transported between neighbouring municipalities remains within the pipeline capacity at any time period.

5.1.6 Constraints related to the operation of water storage facilities

The first type of constraints defines and updates water storage levels at the end of the time period for both coastal and inland municipalities. The updated storage level is determined by combining the storage level from the preceding time period with the net inflow/outflow of water to and from storage facilities during the year. The second type of constraints ensures the balance between water inflows and outflows for storage facilities in inland municipalities with desalination plants treating brackish water at any year of the planning horizon. For both coastal and inland municipalities that do not have any desalination plants, their storage balances do not include the output of desalination plants. The third type of constraints guarantees that the water storage level remains within the available water storage capacity of the municipality. Conceptually, it is assumed that the maximum storage level is reached when there is no water outflow from the municipality. In such case, the maximum water storage level at any year equals to the volume of water carried out from the previous period, combined with the water inflow from the municipality's desalination plants and neighbouring municipalities.

5.1.7 Constraints associated with Carbon emissions

In the first set of constraints, the equivalent carbon emissions of water desalination plants produced by coastal and inland municipalities and water transportation between neighbouring municipalities belonging to the sets of allowable connections are calculated. The second type of constraints limits the total carbon emissions from the desalination processes and transportation activities in each year to a maximum amount determined by the water authorities and aligned with their voluntary environmental commitments.

6. Objective function

The objective function of the mathematical model includes the costs related to water desalination, storage, and transportation in addition to the estimated cost of entropy generation associated with the desalination process, and total carbon taxes. The water desalination costs comprise the operational and capital costs associated with water desalination for plants located in coastal and inland municipalities. The Operational costs are contingent upon the water output and the costs per unit water produced. On the other hand, the capital costs are a function of the selected capacity for prospective units and the corresponding capital costs associated with these capacities. The calculation of the entropy generation costs for a desalination plant takes into account the plant's water output, the unit entropy generation associated with the use of the desalination technology, as well as the unit cost per unit entropy generation. The operational costs of transporting water between neighbouring municipalities depend on the volume of water transported in a given year, the unit cost per unit volume of water transported, and the distance between the municipalities.

The capital costs associated with water transportation between adjacent municipalities are computed based on the capacity of the proposed expansions and their respective costs. It is assumed that the operational costs for water storage tanks in coastal and inland municipalities depend on the water storage capacity. On the other hand, the calculation of the capital costs for expanding storage facilities in both coastal and inland municipalities takes into account the number of new facilities to be introduced and the capital costs of facilities of such capacity within any coastal and inland.

Each of the above costs is discounted to compute its cumulative discounted costs of throughout the entire planning horizon. Finally, the objective function to be minimized in the IWSC optimization model is the sum of all cumulative discounted costs.

7. Case Study Results

In this section, we provide an overview of the main findings of the application of the developed mathematical model within one of the Emirates in the UAE. The specific Emirate under study is divided into 9 municipalities, which are not all interconnected geographically. The data necessary for the study was sourced from either the Emirate's water authority or collected from existing literature. It is important to mention that only five out of the nine municipalities receive their water services from the local water authority. Therefore, only the data pertaining to these municipalities has been made available for this study. The remaining municipalities are served by a federal water authority, and their data has not been supplied.

The total production in the Emirate under study amounted to approximately 90,000 million imperial gallons in the year 2020 with desalinated water amounting for 94% of this production. Notably, the reliance on desalinated water increased from approximately 88% to 93% between 2015 and 2019 (Administration, 2023). The remainder of the water production within the Emirate's municipalities is sourced from freshwater wells. However, dependence on those sources has significantly decreased from 11.3% in 2015 to 5.7% in 2020. The Data obtained from the local water authority regarding current desalination plants within the Emirate is presented in Table 1 (Administration, 2023). Moreover, Tables 2 presents a breakdown of the water sources in the coastal and inland municipalities.

Table 1. Current coastal desalination plants in the Emirate

Plant	Production capacity (MIGD)	Number of Desalination units	Desalination technology
Lay	53.00	10	Thermal (9), SWRO (1)
Rah	5.00	5	BWRO
Ham	13.50	8	SWRO
Kal	7.00	3	SWRO, MED, BWRO
Kho	5.4	2	SWRO

Table 2. Water sources of the municipalities included in the analysis

Coastal municipalities		Inland municipalities	
Sea water only	Sea and brackish water	Brackish water only	No feed water
Kho	Lay, Rah, Ham Kal	Mal Mad	Dha

The developed model was implemented within GAMS environment and solved using CPLEX solver. The model comprised 12,961 variables, where 6,300 of them were discrete variables. Additionally, there were 11,116 constraints in the model. The computational setup involved a 16 GB RAM PC and an Intel Core i10310U processer with a clock speed of 1.7 GHz. The results were rigorously validated using Excel to ensure that the model's constraints were satisfied. For instance, the second type of constraints related to the operations of water storage facilities was validated to ensure the balance between water inflows and outflows in both coastal and inland municipalities with desalination plants treating sea water and brackish water, respectively, at any year of the planning horizon. Figure 2 illustrates the recommended water inflow, outflow, and water storage levels for one of these municipalities based on the obtained results.

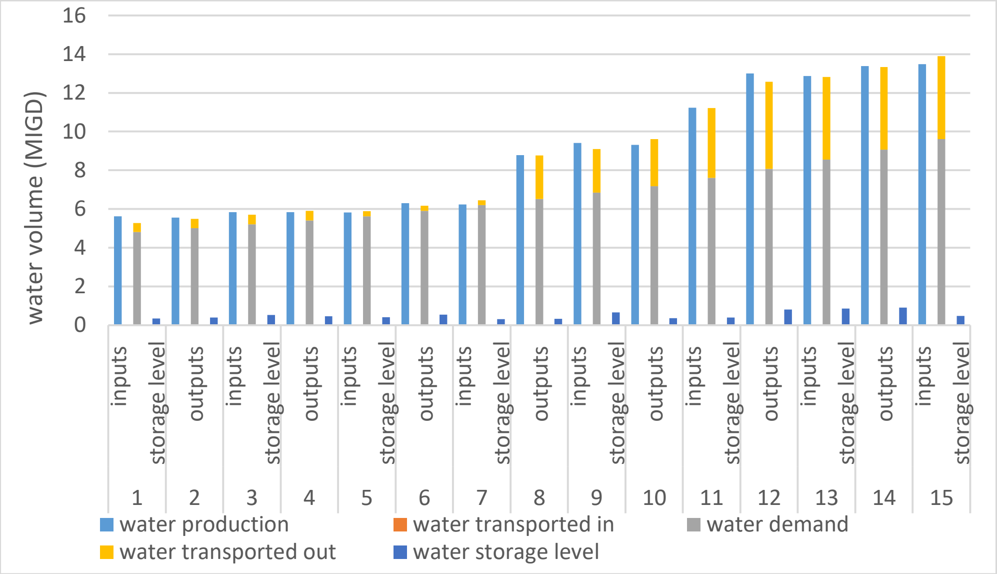

Figure. 2: Water inflows vs. outflows and storage levels results within one of the municipalities

Figure 3 displays the capacity of water production in the primary and largest coastal municipality of the Emirate, computed from the last type of equations related to the capacity expansion of water desalination units. As evident from the same Figure, the water production capacity needs to undergo an increase over the planning horizon to cater for the growing demand. Moreover, expansions were deemed essential due to reductions in capacity caused by the ongoing deterioration of existing facilities and the retirement of units that have reached the end of their operational lifespan. Additionally, in the first year, the demand exceeded the current capacity, necessitating a production capacity expansion of 16.8 MIGD (involving the addition of 3 new units).

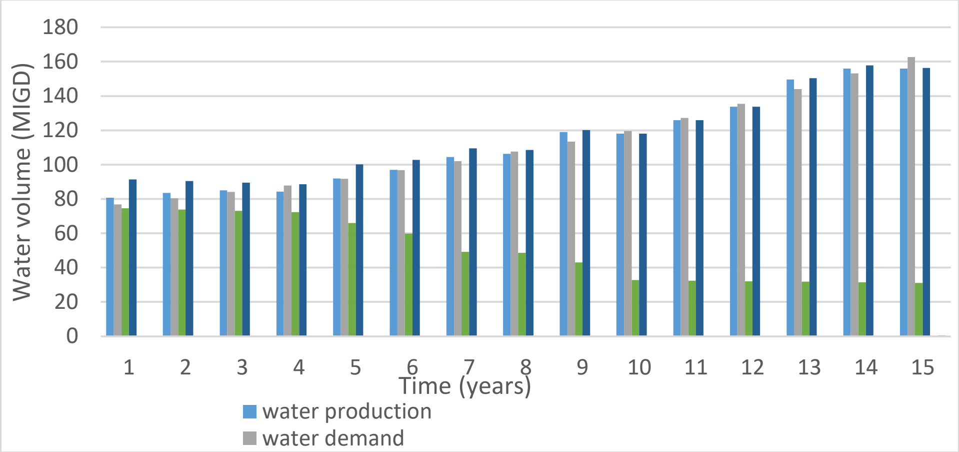

Figure. 3: Water production, demand, and production capacity in the main coastal municipality

Based on the results obtained, the "Lay" plant, as shown in Table 1, initially comprising nine thermal units (MSF and MED) and one RO unit, must undergo expansions at various points throughout the planning horizon to compensate for the reduction in capacity resulting from the older MSF units reaching their designated operational lifetime. The expansion decisions outlined in Table 3, satisfying the strategic constraints related to the capacity expansion of water desalination units, all involve the utilization of RO technology. Additionally, the model has chosen to employ the maximum unit capacity available, which is 9 MIGD production capacity.

Table 3. Expansion of capacity results in water desalination plant in "Lay" plant

Plant	Technology	Year	Production capacity (MIGD)	Number of new units
Lay	RO	5	9	1
		6	9	1
		7	9	2
		9	9	1
		10	9	1

Three distinct expansions are required in the "Mad" inland plant to increase its BWRO capacity. Notably, only one of these three expansions featured the highest capacity among the model's available options. This highlights the significance of granting flexibility to the model, enabling expansions of varying capacities.

It should be noted that not all allowed transportation routes were utilized by the model. For example, the model included the transportation of 0.4 MIGD from the coastal municipality "Sha" to the inland municipality "Dha" in the final year of the planning horizon. Meanwhile, the coastal "Kal" municipality served one neighbouring coastal municipality and one neighbouring inland municipality. The suggested water volumes for transportation to the inland municipality "Mal" fluctuate between 0.25 and 0.5 MIGD throughout the planning horizon. On the other hand, transportation from the same coastal municipality began at 2 MIGD in year 8 and eventually reached approximately 4 MIGD in the last year of the planning horizon. It is also recommended that the storage facilities in coastal municipalities would gradually expand their capacities year by year, primarily in response to the growth in their production capabilities.

The overall cost of the strategic and tactical decisions suggested by the mathematical model amounts to 12.47 billion dirhams throughout the planning horizon. As depicted in Figure 4, the principal cost drivers are the capital and operational costs associated with desalination, which make up approximately 97% of the total cost.

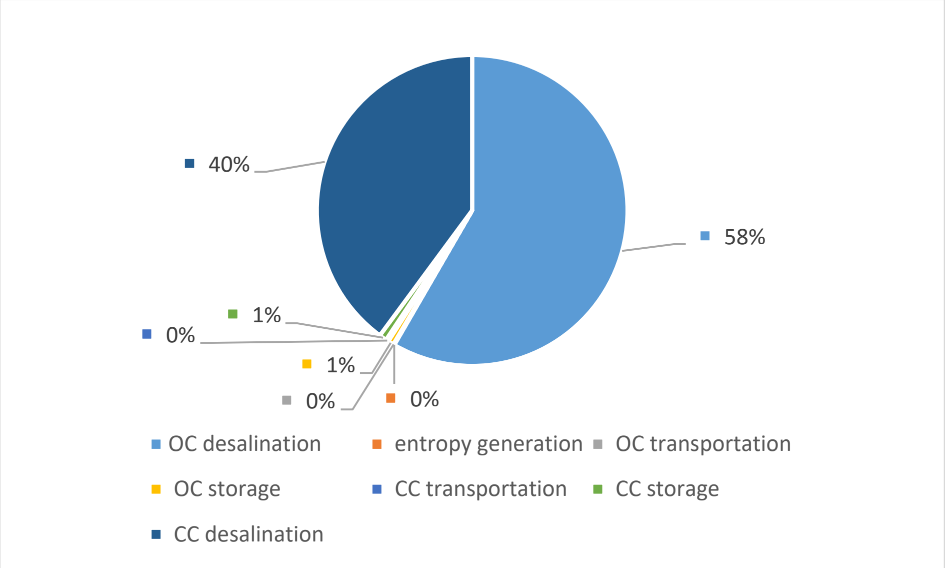

Figure. 4: A breakdown of all cost drivers as a percentage of the overall cost

The cumulative carbon emissions throughout the planning horizon, including emissions from desalination, transportation between municipalities, transportation between desalination plants, and storage facilities, amounted to approximately 8.62 billion kilograms of carbon dioxide equivalent. Particularly, roughly 75% of this carbon footprint is attributed to desalination, with the remaining portion stemming from transportation.

We further conducted a sensitivity analysis of how the estimated demands affect the decisions made by the model. To achieve this, we multiplied the demand by a factor to assess its impact on both the expansion of various facilities under consideration and the overall costs throughout the planning horizon. As anticipated, it is found out that an increase in the demand positively influenced the frequency of expansions across all facilities. Furthermore, given that expansions result in higher capacities, it is naturally followed that costs would rise as the demand increases.

Finally, in order to determine the minimum total carbon emissions generated by all water facilities, we solved the optimization problem with total carbon emissions as the objective function, as opposed to total financial costs. The results revealed a reduction in total carbon emissions to 6.34 billion kg. Subsequently, we reverted back to making total financial costs as the objective function and imposed different carbon emission caps ranging from 6.35 billion kg to 8.4 million kg to examine the ramifications of this new constraint on the results. Overall, the total capacity for expanding sea and brackish water desalination remained consistent across all scenarios. However, the expansion choices varied in terms of their reliance on brackish versus seawater. Furthermore, the selection of technologies for both sea and brackish water desalination differed among the scenarios. Lastly, it is worth noting that the total financial costs decreased as the constrained carbon cap increased.

8. Conclusion and Future work

This paper adopts a comprehensive approach to the management of integrated water resources, presenting a detailed multi-period mathematical model. This model is developed to assist decision-makers in simultaneously optimizing a broad spectrum of strategic and tactical decisions. The model's results have yielded significant insights and recommendations for enhancing the operation and expansion of the water supply chain over the planning period. These recommendations cover multiple facets, such as optimizing water production capabilities, strategically timing and locating expansions in production, transportation, and storage capacities. Moreover, insights from the sensitivity analysis and additional observations provide valuable guidance for future water production strategies. Notably, the analysis highlights RO as the preferred technology for seawater desalination.

Suggestions for potential future work include the integration of the power generation into the proposed model, which has the potential to significantly improve the overall efficiency of both water and power productions. This integration would also open up opportunities for analysing various configurations that combine power and water production facilities. For instance, utilizing membrane desalination technologies requires electric energy as a source. Meanwhile, nuclear energy is considered to be a clean energy source; however, it is generally less flexible when compared to fossil fuel power production. Utilizing excess power production during demand down times to produce and store desalinated water for future use could positively affect the feasibility of nuclear power production. Additionally, hydrological assessments of underground water levels and sustainable abstraction levels could be included to determine their sustainable rates in a more precise manner. Another promising avenue for future research involves exploring the role and potential applications of the Internet-of-Things (IoT), big data analytics, machine learning, and artificial intelligence in the management of water supply chains.

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