A SYSTEMS-INTEGRATION APPROACH TO THE OPTIMAL DESIGN AND OPERATION OF MACROSCOPIC WATER DESALINATION AND SUPPLY NETWORKS

A Dissertation

by

SELMA ATILHAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2011

Major Subject: Chemical Engineering

A Systems-Integration Approach to the Optimal Design and Operation of Macroscopic
Water Desalination and Supply Networks

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ABSTRACT

A Systems-Integration Approach to the Optimal Design and Operation of Macroscopic
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With the escalating levels of water demand, there is a need for expansion in the capacity of water desalination infrastructure and for better management and distribution of water resources. This dissertation introduces a systems approach to the optimization of macroscopic water desalination and distribution networks to tackle three problems:
1. Optimal design of desalination and allocation networks for a given demand,2. Optimal operation of an existing infrastructure of water desalination, distribution, and storage, 3.Optimal planning for expanding the capacity of desalination plants to meet an increasing water demand over a time horizon.

A source-interception-sink representation was developed to embed potential configurations of interest. Mathematical programming was used to model the problem by studying different objective functions while accounting for constraints the supply, demand, mass conservation, technical performance, and economic aspects. Such approach determines the type of technologies to be selected, the location and capacity of the desalination plants, and the distribution of the desalinated water from sources to destinations. For the operation and planning problems, the planning horizon was discretized into periods and a multi-period optimization approach was adopted with decisions made for each period. Short- and long-term water storage options (e.g., in storage tanks, aquifers) were included in the optimization approach. Water recycle/reuse was enhanced via the use of treated water and its utilization was improved by minimizing the losses observed in discharged water resulting from the linkage of power plants and thermal desalination plants and the lack of integration between water production and consumption. Several case studies were solved to demonstrate the applicability of the devised approaches.

DEDICATION

To my excellent husband, Mert

&

Our families

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I can hardly thank my advisor and the committee chair Dr.El-Halwagi enough. He truly has been my role model and guided me in the right track of research and life too. He sets very high expectations for his students, then he encourages and guides them to meet or exceed those standards. His teaching continuously inspired me to work hard.

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NOMENCLATURE

$G_{i,t}^{Desalinated}$	Desalinated-water flow from source i
$G_{i,d,t}^{discharge}$	Excess water flow from source i to sea
$G_{k,d,t}^{discharge}$	Excess water flow from sinkA k to sea
$G_{i,t}^{Groundwater}$	Groundwater flow rate that enters source i
$G_{i,t}^{brine}$	Rejected brine flow from source i
$G_{k,p,t}^{aquifer}$	Remaining unused water flow from sinkA k to ground p
$G_{i,t}^{Seawater}$	Seawater flow rate that enters source i
$G_{l,k,t}^{SinkA}$	Treated sewage water flow rate from WWTP (interceptor) l to sinkA k
$G_{i,n,t}^{mainA}$	Usable water flow rate from source i to agricultural main n
$G_{i,m,t}^{mainD}$	Usable water flow rate from source i to domestic main m
$G_{i,k,t}^{SinkA}$	Usable water flow rate from source i to agricultural sink (sinkA) k
$G_{i,j,t}^{source}$	Usable water flow rate from source i to domestic sink (sinkD) j
$G_{i,s,t}^{storage}$	Usable water flow rate from source i to storage s
$G_{s,j,t}^{storage}$	Usable water flow rate from storage s to sinkD j
$G_{j,k,t}^{SinkA}$	Usable water flow rate from sinkD j to sinkA k
$G_{j,l,t}^{SinkD}$	Usable water flow rate from sinkD j to WWTP (interceptor) l

$G_{i,t}^{lossSource}$	Water flow rate lost from source i
$G_{j,t}^{lossSinkD}$	Water flow rate lost from sinkD j
$G_{l}^{lossInterceptor}$	Water flow rate lost from interceptor l
$G_{k,t}^{lossSinkA}$	Water flow rate lost from sinkA k
$Power_{i,t}$	Power produced from the power plant tied to the ith desalination plant
$Q_{j,t}$	Usable water flow rate entering sinkD j
$Storage_{s,t}$	Amount of water stored in tank s at the end of period t
$W_{l,t}$	Usable water flow rate from interceptor l
$Y_{k,t}$	Usable water flow rate entering sinkA k

Subscripts

i	Number of desalination plant
j	Number of SinkD
k	Number of SinkA
l	Number of Interceptor
m	Number of domestic main
n	Number of agricultural main
p	Number of ground
s	Number of storage
t	time

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CHAPTER I

INTRODUCTION

CURRENT SITUATION ON THE WATER SITUATION AND OVERVIEW OF THE RESOURCES IN THE WORLD

Water is vital for life not only for drinking, cooking and cleaning, but also for growing food, producing fuel and supporting ecosystems. However, it is a known and proven fact that access to water is not easy to all humankind. Every one individual out of three endures some form of water scarcity all around the world since one-quarter of the world's population lives in areas where water is physically scarce. Approximately over one billion people live where water is economically scarce or places where people lack of infrastructure to utilize water effectively and make this water available. Moreover, in some places of the world, due to the uncontrolled increase in population, deteriorated water quality led to water scarcity as well. Thus, providing the large volume of water required for industrial, agricultural, recreational, and potable applications in many arid and semi-arid areas is extremely difficult (Al-Zubari 2003; Khouri 2003; Dawoud 2007; Mathioulakis et al. 2007).

In order to overcome these problems, government agencies, local, regional and international bodies have been developing programs on searching for ‘‘new’’ water sources and at the same time limiting quantity of water demand in order to integrate the current resources along with the population growth and industry expansion. One

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This dissertation follows the style of Clean Technologies and Environmental Policy.

example is the “Water for Life” program declared by The United Nations. For sustainable development of the entire humanity, The United Nations declared 2005–2015 the ‘‘Water for Life’’. The main purpose of this movement is to decrease the number of people those are suffering from water scarcity. It is aimed to decrease the figures by half the proportion of people without access to safe drinking water, to stop unsustainable exploitation of water resources, to aim to develop integrated water resource management and water efficiency plans, and to halve the proportion of people who do not have access to basic sanitation (UNDP 2006).

WATER SCARCITY

Excessive population growth and economic development are driving significant increases in industrial and agricultural water demand. Agriculture accounts for more than two-thirds of global water use, including as much as 90% in developing countries (UNESCAP 2007). Freshwater consumption worldwide has more than doubled since World War II and is expected to rise another 25% by 2030. Much of the growth is the result of expected increases in the world population from 6.6 billion currently to about 8 billion by 2030 and over 9 billion by 2050. Domestic water withdrawal per capita in Asia and the Pacific is nearly 49 cubic meters per year, which places the region ahead of Africa, at 31, but behind Latin America and the Caribbean, at 98. North America has the highest level of domestic water use per capita at 221, while Europe is a more efficient user of water, at 86 cubic meters per capita.

The Asian and Pacific region uses the largest proportion of its water nearly 79 % of its total withdrawal for agriculture. This is followed by industrial use, at about 13 %, and domestic purposes, at 8 %. Of the 32 developing countries in Asia and the Pacific for which data are available, 29 withdraw more than 50 % of their water for agriculture. In 16 of these countries, more than 90 % of the water withdrawn is used in the agricultural sector (UNESCAP 2007).

In the other developing regions of the world, agriculture also consumes the largest share of water withdrawn. In Africa, agricultural consumption comprises 84 % of total water consumption, whereas in Latin America and the Caribbean this share is about 71 %. Both these regions differ from Asia and the Pacific in that they consume more water for domestic purposes than for industry. In North America and Europe, the largest share of water is used for industry, followed by agriculture and domestic purposes (UNESCAP 2007).

20 % of the people in the developing world lack of access to sufficient clean water, while average water use in Europe and the United States of America ranges between 200 and 600 liters/day per person. A recent report by the United Nations Development Program shows that people in the slums of developing countries typically pay 5 – 10 times more per unit of water than do people with access to piped water (UNDP 2006).

If all the freshwater on the planet were divided equally among the global population, there would be 5000 to 6000 m^3 of water available for everyone, every year.

As experts consider that people experience scarcity below a threshold of 1700 m^3/person, this global calculation gives an impression of abundance.

However, the world's freshwater resources are distributed unevenly, as is the world's population. The areas of most severe physical water scarcity are those where high population densities converge with low availability of freshwater. Many countries are already well below the threshold value. Especially GCC countries in the Middle East, is an extreme case with less than 200 m^3/person per year (Al-Zubari 2003; Khouri 2003; Dawoud 2005; Mathioulakis et al. 2007).

There will be four main drivers of increasing water scarcity during the coming decades. First, there is the inevitable growth in population. Second, the world is expected to become increasingly developed; thus, focusing the demand for water among an ever more concentrated population. Asian cities alone are expected to grow by 1 billion people in the next 20 years. Third, per-capita consumption will as well rise; consequently the amount of domestic water that each person uses is expected to rise due to the fact that the world becomes more developed. Fourth, while these factors will increase the demand for water (Cosgrove 2003; Nairn 2003; Atkinson 2005; Voutchkov 2005; Dawoud 2007; Raouf 2009). While the magnitude of this change is still subject to uncertainty and will vary from one region to another, it is recognized that semi-arid regions will probably see an increase in the variability of precipitations, leading to more frequent periods of drought (UNDP 2006).

In cities, municipal wastewater comprises between 75% and 80% of consumed water in most cities, remains as one of the most reliable source; since through suitable treatment, reclaimed wastewater can meet various water quality requirements for potential wastewater reuse and recycle (UNDP 2006; Wang and Smith 1994; Dunn and El-Halwagi 2003; Rizk and Alsharhan 2003). On the other hand, this recycled water can be used in numerous applications to satisfy many water demands such as landscape irrigation, agricultural use, industrial processes, etc. Such treatment typically involves four steps: primary, secondary, tertiary or advanced, and disinfection. Amongst the many existing treatment options, membrane filtration technologies are proven and reliable method of providing high-quality, cost-effective water. Membrane technologies have immediate applications to treatment of fresh, brackish, and seawaters, as well as wastewater recovery via innovative module design and engineering, microfiltration and ultrafiltrations, which made this technology viable for removal of microorganisms (Mezher et al. 2011; Hajeeh 2010; Committee on Advancing Desalination Technology 2008; Raluy et al. 2006). For this purpose, membrane bioreactors are being developed for municipal and industrial water recycling. The use of membrane technologies for aqueous separations has become very popular over the past 20 years and such technologies are used to remove contaminants from industrial wastewaters as well. It is also observed that membranes are also used in desalination plants as well in industrial scale, moreover, due to the improvements in membrane materials and manufacturing technology, membrane technology can be applied in treatment of waters of varying high quantities and improved quality. Therefore, membrane technologies are emerging as treatment of choice for communities, as such technologies become better understood and widely available (Gasson and Allison 2006). Details of water production via desalination will be discussed later.

WATER CONSUMPTION AND FRESH WATER PRODUCTION IN THE GCC REGION AND QATAR

The availability of fresh water resources is becoming a major concern in several parts of the world; particularly in the vulnerable area Middle East, which is one of the world's most arid regions. In contrast to the abundant energy resources, water is an extremely scarce resource in the Gulf Cooperation Council (GCC) countries (Atilhan et al. 2011b). The GCC countries have become one of the biggest global energy hubs in recent decades and this has led to rapid increase in the local population (Wittholz et al. 2008). Furthermore, the growing levels of major industrial activities in the GCC countries are posing an additional load on the already scarce water resources. Indeed, recent studies point to the prediction that over the next decade, the GCC countries will be among the world's highest per-capita users of water (McKenna et al. 2010). Industrial water demand is likely to escalate faster than the economic growth in these countries. As a result of the excessive use of limited groundwater resources in recent years with the increasing population, larger seawater-desalination plants will have to be added (Atilhan et al. 2010c). Also, recycle/reuse activities must be enhanced. Currently about 3% of the world's total water requirements are met by desalination, and given the World Water

Council's prediction of water shortages by 2025 there exists potential for increased use of this energy-intensive process. Because of the high-energy usage of the desalination plants, the long-run sustainability of the infrastructure is questionable(Cosgrove 2003).

Qatar is an excellent example of the growing water challenges in the GCC. Qatar's population has increased with a massive 9 % annual rate since 2002. A major challenge is to provide sufficient and sustainable water distribution networks for the State of Qatar (Al Malki 2009; Wittholz et al. 2008). The increase in water demand has been largely induced by the huge economic boom from a natural gas based economy. The proved world total natural gas reserves are estimated to be 185.8×10^{12} m^3 in 2010, which is a remarkable increment of 9.956×10^{12} m^3 when compared with 2009 data (Worldwide Look at Reserves and Production 2009). The analysis by countries shows that Qatar, with 25.28×10^{12} m^3 proved reserves, has the world's third largest reservoirs, equivalent to almost 14 % of the total reserves of the world's natural gas. In 2008, Qatar produced 75.9×10^{9} m^3 of natural gas, which is more than 5 times the amount produced in 1995; nevertheless, this quantity will increase remarkably in the next years (Energy Information Administration 2010). The majority of Qatar's natural gas is located in the massive offshore North Field, the world's largest nonassociated natural gas field. Increasing Qatar's natural gas production will lead to large-scale projects such as new liquefied natural gas infrastructure, natural gas exports through the pipeline, large-scale gas-to-liquids projects, and the promotion of downstream industries that utilize natural gas as feedstock (Atilhan et al. 2010a). These activities in natural gas processing have dramatically increased the need of fresh water supply to its industrial and urban areas in the State of Qatar(Atilhan et al. 2010d). For this purpose, currently there are five desalination plants in Qatar with a total production capacity of 217 MIGD (986,000 m^3/day). There are two desalination plants that are being constructed with a combined capacity of 108 MIGD (491,000 m^3/day). On the other hand, the northern groundwater aquifer is the major source of groundwater in Qatar, estimated to contain 550,000 MIG (2,500 million m^3) of freshwater, which is mostly used for agriculture. Desalinated water is the primary source of the total water produced, and Qatar is almost dependent exclusively on the desalinated water based on these figures. In this situation, transmitting the desalinated water to industrial and urban areas becomes an important issue. For this purpose 5,400 km of transmission and distribution lines have been constructed so far in Qatar and currently 290 MIG of storage capacities exists that corresponds to 1.5-day usage capacity. There are 22 water-pumping stations installed in the water distribution network to provide transmission of the desalinated water. Since 2000, the average annual percentage increase in supply has been 10.3 %, and the average annual percentage increase in demand has been 9.9 %. These figures are expected to remain for the next decade. Thus, there will be additional desalination plants, and need of improved and optimized water distribution network will rise significantly (Al Malki 2009).

DESALINATED WATER PRODUCTION

With the increasing world population and escalating demands for fresh water, there is a tremendous need for developing comprehensive and integrated strategies for water management. At present, the world is facing a water crisis and the all signs indicate that there is a high potential for this crisis to get worse. Furthermore, the water resources are decreasing by increasing the global warming and pollution and uncontrolled population growth (Johnson et al. 2001). Although water is perceived to be an abundant resource, only 2.53 % of it is fresh water and the rest is saline water constituting oceans and seas. One of the strategies for tapping into the saline water resources and utilizing them to solve the global water problem is through desalination and distribution of desalinated water. The need of the desalinated water is increasing very rapidly with the decrease in the fresh water resources and the increase in the industrial activities and population in the world (UN 2003; Atilhan et al. 2011a).

The removal of salt from seawater by means of evaporation has been applied for a long-time, dating back in the days when salt was more valuable product than water (Cooley et al. 2006). Advanced technologies that imitate the usual processes of evaporation or osmosis have only been developed in modern times. In 1928, the first desalination facility was established in the island of Curacao in the Netherlands Antilles, which was followed by a major seawater desalination plant in Saudi Arabia in 10 years after (Cooley et al. 2006; Committee on Advancing Desalination Technology 2008). However, major development in desalination technologies has started during World War II so as to provide fresh drinking water to military establishments in arid areas. Later, beginning in the 1950's Office of Saline Water (OSW) and mid 1970's Office of Water Research and Technology (OWRT) started research and development of the different desalting technologies (Committee on Advancing Desalination Technology 2008; Buros 2000). Early research projects were focused on the thermal processes and significant work was completed on heat and corrosion resistant construction materials and better heat transfer performance surfaces, which lead large desalination systems in the Middle East (Committee on Advancing Desalination Technology 2008). The multi-effect distillation (MED) process has been used for this purpose; however, the multistage flash (MSF) process continually displaced the MED process due to a higher resistance against scaling. A revived interest in MED can be observed since the 1980s due to a lower operating temperature and energy demand of the process (Buros 2000). Meanwhile, alternative desalination technologies have started to be investigated and in early 1960s, the first membrane for desalination was developed by Loeb and Sourirajan, which consisted of cellulose acetate polymer (Wilf and Klinko 2001). Moreover, during the same period, electro dialysis (ED) process, which moves salts selectively through a membrane driven by an electrical potential, was developed as the first cost-effective way to desalt brackish water and spurred a considerable interest in using desalting technologies for municipal water supply, especially in the United States.

Other important development was commercialization of reverse osmosis (RO) technology, which is a pressure-driven membrane process that is used in water purification (Buros 2000). This technology succeeded by the development of a more robust composite aromatic polyamide spiral wound membrane in the 1980s (Wilf and

Klinko 2001). In present day, composite aromatic polyamide membranes in spiral wound configuration are exclusively in modern RO plants. While cellulose acetate seawater membranes had a specific salt rejection percentage of 98.8 % in the 1970s, the latest polyamide seawater membranes have salt rejection percentage of 99.8%. Moreover, while cellulose acetate seawater membranes had a specific permeate flux of 0.5 L/(m^2*h*bar) latest polyamide seawater membranes have a specific flux of more than 1.2 L/(m^2*h*bar). Due to the improvement in salt rejection percentage and the improvement in specific flux, significant reduction of the specific energy demand of the RO process has been observed (Wilf and Klinko 2001). Other than these RO, MSF and MED technologies, new alternative hybrid technologies are developed such as RO/MSF desalination process, PV-RO desalination process and solar hybrid systems (Manolakos et al. 2008; Helal et al. 2003; Childs et al. 1999).

Nowadays, due to desalination technologies are improved, desalinated water production cost have decreased. Desalinated water cost depends on location of the desalination plants, energy usage, transportation and other costs. Desalinated water production and energy costs are aimed around \$0.5 per m^3 of water and \$0.02 per kWh (Awerbuch 2002). Techno-economic analysis of different desalination techniques is also studied and compared to select the best technology (Manolakos et al. 2008; Borsani and Rebagliati 2005; Fiorenza et al. 2003).

Desalinated water need and production in the Gulf region

In the last couple of decades, due to the tremendous booming economy in the Gulf Corporation Countries (GCC), population of GCC States has been on the rise on a constant base(Al-Zubari 2003; Bushnak 1990; Alawadhi 1999). Oil and gas related economy and related side businesses have brought many foreigners to migrate to GCC countries at all levels on the labor spectrum (Dawoud 2007). Rapid population growth resulted in dense populations concentrated in cities and such increase has brought its own problems related with basic human needs such as public service infrastructure. As being the most important necessity of human being, water is one of the biggest problems of our time in the GCC region (Ismail et al. 2003; Mishra 2009; Salem 2009). This brings the questions about the ability of the GCC countries to cope with high rate of water demand increase resulted by the enormous population growth. Water demand increase does not only pose hurdles in the cities, but also it remains as a major problem in the industrial areas as well. The growing levels of major industrial activities (mostly related with oil and gas industry) in the GCC countries are posing an additional load on water consumption(Al-Zubari 2003; Khouri 2003; Nairn 2003; Rizk and Alsharhan 2003; Dawoud 2005; Lattemann et al. 2010). Indeed, recent studies point to the prediction that over the next decade, the GCC countries will be among the world’s highest water users per-capita (McKenna et al. 2010). In order to meet such needs, utilization of current recourses through integrated water networks is as important as utilizing oil and gas reservoirs for the region (Dajnak and Lockwood 2000; Virk et al. 2001; GarcÌa-RodrÌguez 2002; Kim et al. 2002).

In terms of sea areas, the largest number of seawater desalination plants can be found in the Gulf with a total desalination capacity of approximately 12.1Mm^3/day – or a little less than half (44%)1 of the worldwide daily production. The main producer in the Gulf (and worldwide) is Saudi Arabia with 25% of the worldwide seawater desalination capacity, of which 11% are located on the Gulf shore and 12% on the Red Sea coast (2% unaccounted for), followed by the United Arab Emirates (23%) and Kuwait (6%). Thermal desalination processes dominate in the Gulf region (about 94% of all production), as water and electricity are often generated by large cogeneration plants that use low value steam and electricity from power plants as a heat source for desalination. Most of the water (81%) in the Gulf is produced by the MSF distillation process. Minor processes are MED distillation and RO, which account for 13% and 6% of the production, respectively (Lattemann et al. 2010).

Environmental impact of the seawater desalination

In present day, implementation of large desalination facilities is no longer limited to a few arid countries but oil-rich countries of the Middle East as well. Along with the increased fresh water need and fresh water production activity via desalination plant, several environmental problems has risen such as emissions of greenhouse gases and air pollutants, the concentrate and chemical discharges into the sea, the use of large quantities of seawater for cooling purposes and as feed water. Such problems cause the impingement and entrainment of marine organisms, and construction-related impacts on the coastal and near-shore habitats.

a)Feed water intake problem to the sources

Desalination plants accept feed water from different sources. However, seawater usage as feed water is the most common intake option. Seawater is an open intake source and the use of such open intakes is observed effect marine life habitat and to result in losses of marine organisms when these collide with intake screens while they are being taken into the plant with the source water. Moreover, water intake is drawn from the locations close to seabed. This orientation causes disturbance of the seabed during water withdrawal that may result in the suspension of sediments, nutrients or pollutants. Thus, water quality is affected. Therefore, several alternatives have been considered and beach-well intakes and infiltration galleries have been considered (Peters and Pinto 2008).

b)Brine reject, energy consumption and green house gas emissions

As a result of desalination process, regardless of the technology, brine reject is produced as undesired by product at large quantities in high concentrations. Concentration of the waste brine reject stream varies according to he feed water intake depending on the seawater concentration. This waste product leaves the process at elevated temperatures more than 7-15^{o}C hotter than the feed water temperature (Sommariva et al. 2004). Moreover, this stream also contains corrosion inhibitors, residues of pretreatment and cleaning chemicals and heavy metals due to corrosion.

In order to prevent biofouling, scaling, foaming, and corrosion in thermal plants and biofouling, suspended solids, and scale deposits in membrane plants, chemical treatment is performed in desalination plants. However, undesired and environmentally toxic and hazardous the chemical wastes and byproducts are discharged into the sea along with the brine reject. On the other hand, brine reject also causes increase in the salinity and decrease in the pH of the seawater. This is extremely hazardous for the marine life which causes carbonic acid production in the sea and that has severe effect on the shelves and bones of delicate marine organisms. As a summary, desalination plant discharge contain various contaminants that have potential synergistic effects on marine life, such as for example increase in temperature and salinity, which are well documented in open literature (Taylor 2006). In the recent years in order to tackle the brine reject problem and excessive CO_2 releases; research projects are ongoing around the world. A novel approach to CO_2 mineralization and reject brine management by chemical reaction has been developed and the process developed consisted of reacting CO_2 gas with desalination brine and added ammonia to precipitate CO_2 as bicarbonate and the ammonium chloride produced was successfully decomposed into ammonia gas and calcium chloride by addition of calcium oxide.

On the other hand, in terms of energy consumption, desalination process is remarkable energy expensive process and it consumes significant amounts of energy. Such energy intensive process bring about some environmental concerns, both directly and indirectly; namely the hazardous gas emissions. Since the energy requirement of these plants are totally dependent on the fossil based oil and gas resource, emissions of greenhouse gases in the form of mainly CO_2 and other pollutants as NO_x, SO_x. Fine particulate matter and other air pollutants that are produced as well when fossil fuels are used for electricity/steam generation (Bleninger and Jirka 2008; Morton et al. 1997; Al-

Mutaz 1991). When existing power plant capacities are increased or new plants constructed in order to provide additional electricity for desalination, these indirect impacts will likely be intensified.

CHAPTER II

LITERATURE REVIEW

PROCESS INTEGRATION

Process integration is a holistic method to process design and operation which emphasizes the unity of the process (El-Halwagi 1997). Over the past three decades, process integration design tools have been developed in order to achieve process productivity, improvement, conservation and enhancement in mass and energy resources. Furthermore, reductions in the operating and capital costs of chemical processes are achievable through such tools. Utilization of such powerful engineering tools have been implemented mostly in the fields of resource conservation, pollution prevention and energy management (Dunn and El-Halwagi 2003). Process integration (PI) includes a several methods and algorithms that enables engineers to oversee entire processes in bigger scale, rather than focusing on individual unit operations. Such techniques include hierarchical design methods, knowledge-based systems, numerical and graphical techniques and widely applicable pinch analysis techniques (Rossiter 2004).

As the technical and mathematical background of the field of PI has emerged, more of its applications have been observed that deals mostly with engineering supply and demand problems. Therefore, software tools made available, which deals with utilization of mathematical background of such tools and their associated algorithms.

Thus, applications of such software have become increasingly versatile, making the technology more accessible to the engineering community as a whole.

In the early stages, such tools has been develop to deal with classical engineering problems, however, with the advancement in PI technologies made it possible to apply such tools in broader perspective such as the optimization of new plant designs, improvements to existing facilities and design of more efficient system components and equipment as well (Rossiter 2004). Nevertheless, in order to develop totally economically favorable, attractive and integrated process designs, complex nature of advanced processes shall be well projected, structured and managed within the allowable constraints of the PI tools in a timely fashioned (Rossiter 2004).

PI is mainly applied in two widely used ways, categorized as mass integration and energy integration. Mass integration mainly deals with separation trains, optimizing source and sink distribution within the processes via re-routing of species and streams throughout the process. From this perspective, mass integration based PI tools are quite powerful to address the root causes of the environmental and mass processing problems at the heart of the process and they have been developed and applied to identify global insights, synthesize strategies. Furthermore, such tools delivers a systematic methodology that provides a fundamental understanding of the global flow of mass within the process and employs this understanding in identifying performance targets and optimizing the allocation, separation, and generation of streams and species (El-Halwagi and Spriggs 1998). Several mass integration approaches such as segregation, mixing, recycle, reuse, material substitution, process modifications through reaction alteration among others are being practiced in industrial scale processes in order to reach the desired mass allowable targets while minimizing the generation of waste discharge and the consumption of fresh resources. In this manner, several works have been published in open literature on mass integration strategies is the synthesis of pollutant-removing separation networks such as mass-exchange networks (El-Halwagi and Manousiouthakis 1989; Fraser and Hallale 2000; Foo et al. 2004), reactive mass-exchange networks (El-Halwagi and Srinivas 1992), reverse osmosis networks (El-Halwagi 1992).

Mass integration tools are used mostly within the environmental context and it is a powerful tool ton intercept some certain components in the process in order to keep the concentration levels within the allowable limits. Development of such methodologies for waste reduction has been driven by the desire to improve industrial competitiveness, which is shaped by more stringent environmental regulations to keep up with. At first glance, in order to achieve these goals, recycling and re-utilizing the process wastes are the first options to consider, thus, effective utilization of these tools and their details have been well studies and documented for mainly waste reduction tasks; the industrial goal was to identify a recovery system that would effectively allow the recycle and reuse of certain wastes (Bagajewicz 2000). To achieve such, variety of several process system configurations and operating conditions have to be postulated, screened and mapped based on their overall economic impact for the operating cost, capital investment etc. Since therefore, significant research has been conducted and progress has been made not only towards developing systematic design methodologies, but also identifying a system that accomplishes the waste reduction task via most cost-effective approaches. Most recently, system approach methods have been the primary focus in order to develop systematic design methodologies for identifying cost-effective mass integration and management systems from environmental management point of view and end of the pipe generic solutions has been presented as such (Dunn and El-Halwagi 2003).

Despite, it is not the main focus of this work, it is worth mentioning heat integration has influenced some of the application in mass integration and mass integration networks. Some preceding heat integration work to mass integration, some of the fundamental ideas from the thermodynamic analysis of heat exchanger networks have been used to create a new area of mass exchange networks by El-Halwagi and Manousiouthakis (El-Halwagi and Manousiouthakis 1989). This is followed by Wang and Smith and they and focused more on the extension of the same idea towards the water networks (Wang and Smith 1994) in which the design objective in water-using networks is to minimize the water consumption by maximizing the re-use of water. Further reductions in water use can also be obtained by adopting new technologies and improving processes with new equipment that deals with partial treatment of the wastewater, which known as regeneration, and allowing further re-use or recycling of water in relatively straightforward way.

At first glance, this approach might seem straightforward and easily applicable, however, this approach rapidly runs into problems since it has some difficulties while dealing with more than one contaminants at the same time rather than a singe component (Wang and Smith 1994). Moreover, introducing multi- sources and sinks with its own constraints makes the problem even more difficult to handle; thus, the simplistic extension of the energy integration approach to the water minimization problem rapidly runs into problems (Smith 2000).

Yet, it is still quite possible to re-formulate the problem via using mathematical linear and non-linear programming (depending on the case) and combine this with a conceptual approach that allows all of the complexities of water system design to be considered such as multiple contaminants and water sources, flowrate constraints, forbidden matches, water costs, effluent treatment costs and piping costs (Doyle and Smith 1997).

DESALINATION TECHNOLOGIES

Desalination is a commercialized process that removes salts and other dissolved solids from seawater or brackish water. Brackish water is saltier than fresh water, but not as salty as seawater, and it usually has a salt concentration between 5 to 20 parts per thousand (ppt) whereas seawater generally has greater than 20 ppt. Brackish waters are found in aquifers, inland wells and bays where fresh water mixes with salt water (LBG Guyton Associates 2003; Kalaswad et al. 2004; California Coastal Commission 2004; Sandia National Laboratories and Bureau of Reclamation 2003). Since brackish water is less salty, obviously it is less expensive to desalinate. However, other factors such as availability, demand, economics, transportation, energy resources and environmental impacts are the factors that vary the cost up and down and these are the factors those are considered prior to the decision on the selection of the desalination projects.

Other than the type of the feed water, the kind of the technology that is used is the other factor that has more than one alternative in desalination. There are some methods of treatment in use today and such methods are categorized into two types as thermal methods and membrane approach. Simply speaking, in thermal methods, heat is applied at elevated pressures is applied to the feed water in order to bring it to a boiling point rapidly and produce steam, which then condenses and produces freshwater. On the other hand, for membrane approach, there are two kinds of desalination; one uses an electrical current to attract the salt molecules through a membrane, whereas in other method high pressure is applied to force water through the membrane (Buros 2000; Gleick 2000). Below, more detailed descriptions of the above methods for both categories are given.

Multistage flash desalination (MSF)

Multistage flash distillation (MSF) is commonly used thermal desalination process that produces pure water via boiling and then condensing saline water. In this process, saline water is passed through series of tubes and preheated prior to the actual heating unit. Later, in the heating chamber, pre heated feed stream is heated by using any form of thermal energy (Hajeeh 2010). This stage is followed by sudden reduction of the pressure, which causes sudden boiling or in other words flashing of the saline water and forming vapors during the boiling. Produced vapor condenses on the tubes that carrying input saline water at lower temperatures, and thus the distillate is collected accordingly. Since this process has low efficiency, several stages is used for generating steam from unconverted saline water through maintaining the pressure at each stage. The unconverted remaining saline water is introduced following stages kept at even lower pressures, and the process continues until the saline water is cooled down and discharged. By using such sequences, it is observed that MSF plants may contain between stages ranging between 4 to 40. However, commonly MSF processes consist of 18 to 25 stages on the average (Cooley et al. 2006; Buros 2000). MSF has proven to be the most reliable and consistent thermal desalination technology and it was widely used and dominated the thermal desalination market till mid 1990s. Nevertheless, along with the advancements in modern technologies, such as Reverse Osmosis (RO), the popularity of MSF has declined on a downward trend and currently their share in desalination market remains approximately 25% worldwide capacity share. Recent studies have showed us that, within last couple of years between 2008 and 2009, a decrease in the number of contracted MSF plants was evidenced and reported, moreover, the overall trend is reducing due to the emerging of RO and MED, except in the Gulf region where fossil based fuel is still the dominating source of energy and plentiful in the region (Mezher et al. 2011; Hajeeh 2010).

Multi-effect distillation (MED)

Multi-effect distillation (MED) works with the similar principle of MSF that was explained previously. An MED unit is consists of several consecutive cells (or effects) maintained at decreasing levels of pressure and temperature from the first (hot) cell to the last one (cold). Each cell mainly consists of a horizontal tubes bundle and the top of the bundle is either sprayed or distributed with the seawater make-up that then flows down from tube to tube by gravity. This this permits the seawater feed to undergo onto the surface of evaporator tubes in a thin film to promote rapid boiling and evaporation; multiple boiling without supplying additional heat after the first effect (Al-Subaie 2007; Alawadhi 1999). The tubes are heated by steam from a boiler or other source, which is condensed on the inside of the tubes and the condensate from the boiler steam is recycled to the boiler for reuse (Karagiannis and Soldatos 2008; Dawoud 2005).

With the introduction of a compression technology in MED plants, the performance has been radically improved to gain output ratio of 15, where maximum temperature is now limited to 80°C and maintained a good gain output ratio of 12 kg distillate/kg of steam. Electric compressors or thermo-compressors are utilized for compression, which utilize motive steam. Recently, such units are typically called as mechanical vapor compressors (MVC), and thus, plants are referred to as thermo compression distillers (TCD). Similar to MSF, MED processes produce very low TDS production >50 mg/l, which in the interest of industries. Both MSF and MED are independent of the feed quality, whereas the reverse osmosis technology is highly depended on (Hajeeh 2010; Al-Subaie 2007). Through substantial growth in unit capacities more than 7 MIGD (32,000 m3/d), MED technology is currently compared and it is favored over the MSF technology.

Reverse Osmosis (RO)

In RO process, suspended solids are pretreated and removed from the feed water stream. This is done through cartridge filters, multimedia filters and to micro or ultra filtrations. While doing that pH of the feed is adjusted and it is chemically pretreated depending on the type of membrane used. Later, pretreated feed is pressurized up to the desired value, which is calculated depending on its salt content, and it is passed through the RO membrane. Total desalination is not achieved after passing the pretreated feed through the RO membrane as some portion of the feed stream is rejected as brine, whose mechanical energy is used in energy recovery systems before being returned to sea, achieving a significant energy saving. This process has reported efficiencies up to 40% when seawater is used as feed water and 75% when brackish is used (Hajeeh 2010; Raluy et al. 2006; Al-Subaie 2007).

CHAPTER III

A SYSTEMS INTEGRATION APPROACH TO THE DESIGN OF REGIONAL WATER DESALINATION AND SUPPLY NETWORKS

INTRODUCTION

With the increasing world population and escalating demands for fresh water, there is a tremendous need for developing comprehensive and integrated strategies for water management. At present, the world is facing a water crisis and the all signs indicate that there is a high potential for this crisis to get worse. Furthermore, the water resources are decreasing by increasing the global warming and pollution and uncontrolled population growth(Johnson et al. 2001). Although water is perceived to be an abundant resource, only 2.53 percentage of it is fresh water and the rest is saline water constituting oceans and seas. One of the strategies for tapping into the saline water resources and utilizing them to solve the global water problem is through desalination and distribution of desalinated water. The need of the desalinated water is increasing very rapidly with the decrease in the fresh-water resources and the increase in the industrial activities and population in the world(UN 2003).

A seawater desalination process produces fresh water with low concentrated dissolved salts and concentrated brine. This desalination process needs energy and utilizes different technologies. These technologies are based on thermal distillation, membrane separation, electrodialysis, etc(El-Dessouky and Ettouney 2002). Reverse osmosis (RO), multi effect distillation (MED) and multi stage flash distillation (MSF) are the most commonly used technologies for the desalination process. Other than these RO, MSF and MED technologies, new alternative hybrid technologies are developed such as RO/MSF desalination process, PV-RO desalination process and solar hybrid systems (Manolakos et al. 2008; Helal et al. 2003; Childs et al. 1999).

Nowadays, due to desalination technologies are improved, desalinated water production cost have decreased. Desalinated water cost depends on location of the desalination plants, energy usage, transportation and other costs. Desalinated water production and energy costs are aimed around \$0.5 per m^3 of water and \$0.02 per kWh(Awerbuch 2002). Techno-economic analysis of different desalination techniques is also studied and compared to select the best technology (Manolakos et al. 2008; Borsani and Rebagliati 2005; Fiorenza et al. 2003).

This work introduces a systems integration approach that can be used as the basis for developing design and planning decisions for desalination and distribution networks on a macroscopic scale (region, country, etc.). A source-interception-sink representation is developed to account for the potential configurations of interest. The design problem is formulated as an optimization problem subject to the supply, demand, mass conservation, technical performance, and economic constraints. The formulated optimization problem is solved using the computer-aided tool LINGO(Schrage 2006a) to determine the selection, design, capacity, and location of the desalination technologies and how the various desalination plants are best integrated via a distribution network to serve a region.

PROBLEM STATEMENT

Given a number of water sources (e.g., seawater, underground water) of given qualities, a number of existing desalination plants with known capacities and performance, and a number of water users (sinks) of certain requirements (flow rate and salinity). The future usage of water exceeds current supply. It is required to install a number of new desalination plants to close the gap. The design decisions will be included:

- Location of the new plants
- Capacity of the new plants
- Performance of the new plants
- Allocation of water from new and existing plants to water users

Formally, the problem may be stated as follows:

Given are

- A set of water sources = {i|i=1, 2....., N_{Source}}. Each source has a maximum allowable withdrawal flow rate, i=Q_i , and composition of the cth component, $y_{i,c}$
- A set of water users (sinks) = {j|j=1, 2....., N_{Sink}}.

  the required flow rate to each sink, j=G_j, is bounded by the following constraint:

  $G_j^{\min} \le G_j \le G_j^{\max}$

  Composition of each sink, j, are given by:

  $Z_{j,c}^{\min} \le Z_{j,c} \le Z_{j,c}^{\max}$

- A set of interception plants (desalination plants) ={k|k=1, 2....., N_{int}}.

the required flow rate to each interception, k=Q_k, is bounded by the following constraint:

$$Q_k^{\min} \leq Q_k \leq Q_k^{\max}$$

Composition of each interception, k, are given by:

$$y_{k,c}^{\min} \leq y_{k,c} \leq y_{k,c}^{\max}$$

MATHEMATICAL FORMULATION

In this water management problem, source-interception-sink representation shown in Fig. 1 is used to implant all potential configuration of interest. Each source split into the fractions of unknown flow rate which is to be optimized. Those fractions are allocated to the interceptors called desalination plant. The flow rate of each allocated stream is to be optimized (Gabriel and El-Halwagi 2005b; Lovelady and El-Halwagi 2009; Grooms et al. 2005; Frederico B. Gabriel 2005).

Software of LINGO version 10.1 by LINDO Systems Inc. is used for this work. The nonlinear program (NLP) is formulated to solve water management problem. Global Solver of the software LINGO version 10.1 (Schrage 2006a) is used to solve the problem. The optimization problem is solved with 32 variables (22 nonlinear and 10 linear) and 37 constraints (6 nonlinear and 21 linear) in 30 sec.

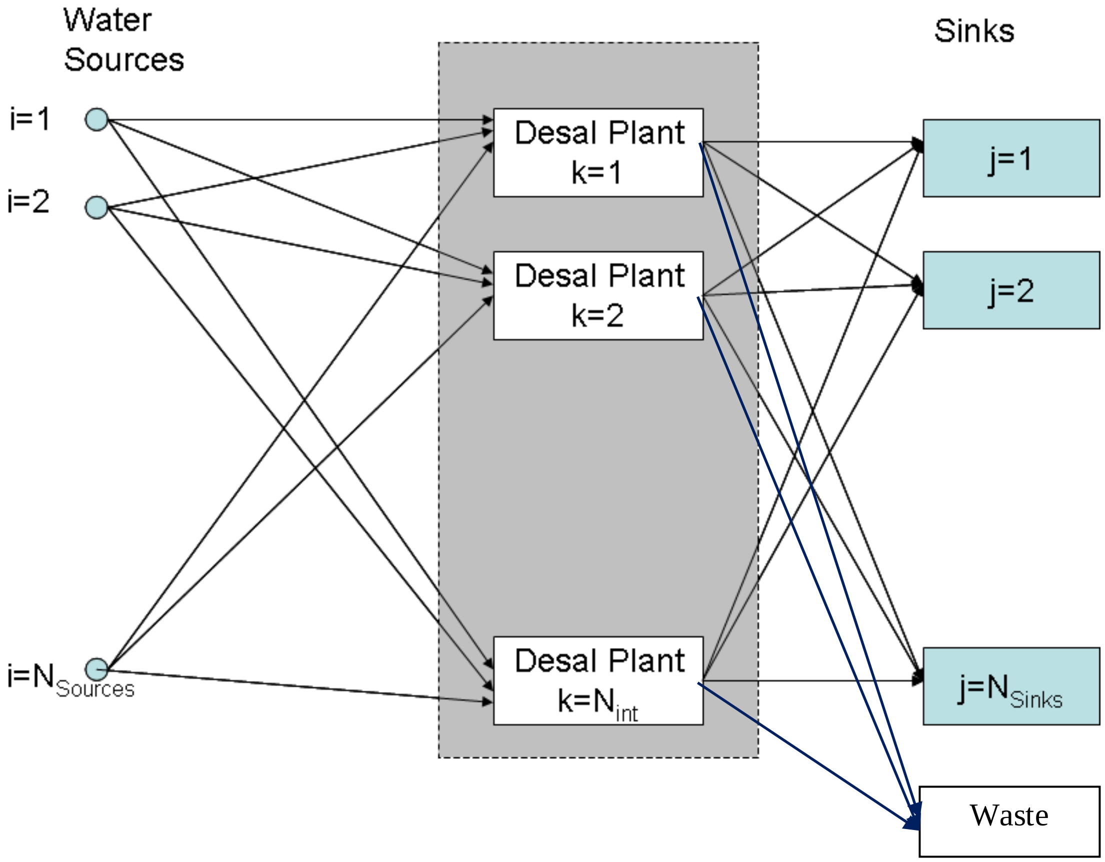

Fig.1 Structural representation of the problem

The objective is to meet the requirements for the sinks at minimum cost while satisfying constraints for the sinks:

1. Minimize total cost = Annualized Fixed Cost of Desalination Plants + Operational Cost of Desalinated Water + Desalinated Water Piping and Pumping Cost + Brine Discharge Cost

a) Annualized Fixed Cost of Desalination plants =

$$\sum_{i=1}^{N_{sources}} \text{Annualized fixed cost function} \left(\frac{\$}{\text{time}}\right)$$

b) Annualized Operational Cost of Desalinated Water=

$$\sum_{k=1}^{N_{\text{int}}} \text{Desalinated water operational cost}\left(\frac{\$}{\text{unit mass}}\right) * \text{Desalinated water flow rate}\left(\frac{\text{mass}}{\text{time}}\right)$$

c) Desalinated Water Piping and Pumping Cost =

$$\sum_{k=1}^{N_{\text{int}}} \text{The cost of pumping and piping}_{\text{k}}\left(\frac{\$}{\text{mass * distance}}\right) * \text{Desalinated water flowrate}_{\text{k},j}\left(\frac{mass}{time}\right)$$
$$* \text{ distance between plants and users}_{\text{k,j}}\text{(distance)}$$

d) Brine Discharge Cost =

$$\sum_{b=1}^{N_{brine}} \text{Brine discharge transportation cost}\left(\frac{\$}{\text{unit mass}}\right) * \text{Brine discharge flow rate}\left(\frac{\text{mass}}{\text{time}}\right)$$

2. Material balance for the each source with the split fractions assigned to interceptors (Fig. 2):

$$Q_i = \sum_{k=1}^{N_{\text{int}}} Q_{i,k}$$

3. Material balance for the each source with the split fractions assigned to interceptors at the inlet of the kth interceptor (Fig.3)

$$Q_k = \sum_{i=1}^{N_{sources}} Q_{i,k}$$

4. Component material balance around the inlet to interceptor k

$$Q_k * y_{k,c}^{\text{int},in} = \sum_{i=1}^{N_{source}} Q_{i,k} * y_{i,c}$$

where k=1, 2,....$N_{\text{interception}}$, i=1, 2,..... N_{source} and c=1, 2,....$N_{\text{component}}$

5. Material balance for outlet of the kth interceptor (Fig.4)

$$Q_k = \sum_{j=1}^{N_{\sin ks}} Q_{k,j}^{permeate} + \sum_{b=1}^{N_{brine}} Q_{k,b}^{reject}$$

6. Sink balances (Fig.5)

$$G_j = \sum_{k=1}^{N_{\text{int}}} Q_{k,j}$$

where k=1, 2,....$N_{interception}$ and j=1, 2,....N_{sink}

$$G_j * Z_{j,c} = \sum_{k=1}^{N_{\text{int}}} Q_{k,j}^{permeate} * y_{k,c}^{permeate}$$

7. Material and component balances around brine discharge

$$Q_b^{brine} * y_{b,c}^{brine} = \sum_{k=1}^{N_{\text{int}}} Q_{k,b}^{reject} * y_{k,c}^{reject}$$

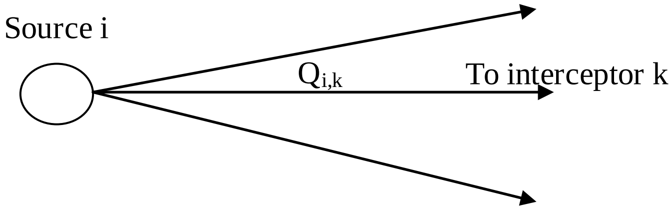

Fig.2 Splitting of sources

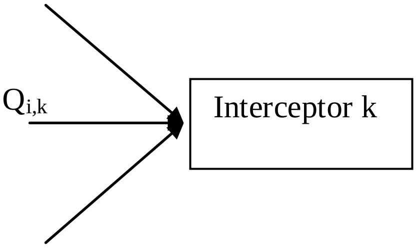

Fig.3 Mixing at split fractions at inlets of interceptors

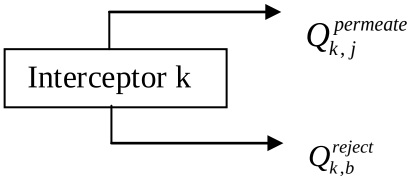

Fig.4 Splitting of permeate and reject streams from interceptors

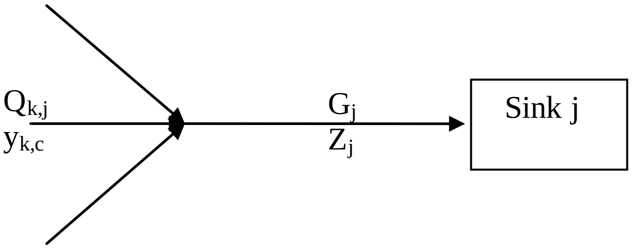

Fig.5 Mixing of split fractions from the interceptors and assignment to sinks

CASE STUDY

Consider three sources of water (A, B, C) and two sinks (city I and city II). The following tables provide information on the sources and sinks. Tables 1 and 2 show flow rate and salinity constraints for sinks and sorces.

Table 1 Flow rate and salinity constraints for sinks

Sink	Minimum Water Need, m^3/day	Maximum Allowable Salt Content, ppm
I	250,000	400
II	180,000	200

Table 2 Flow rate and salinity constraints for sources

Source	Maximum Allowable Withdrawal Rate, m^3/day	Salt Content, ppm
A	400,000	45,000
B	360,000	20,000
C	50,000	5,000

Figure 6 provides a schematic representation of the map. Table 3 gives the distances between the sources and sinks.

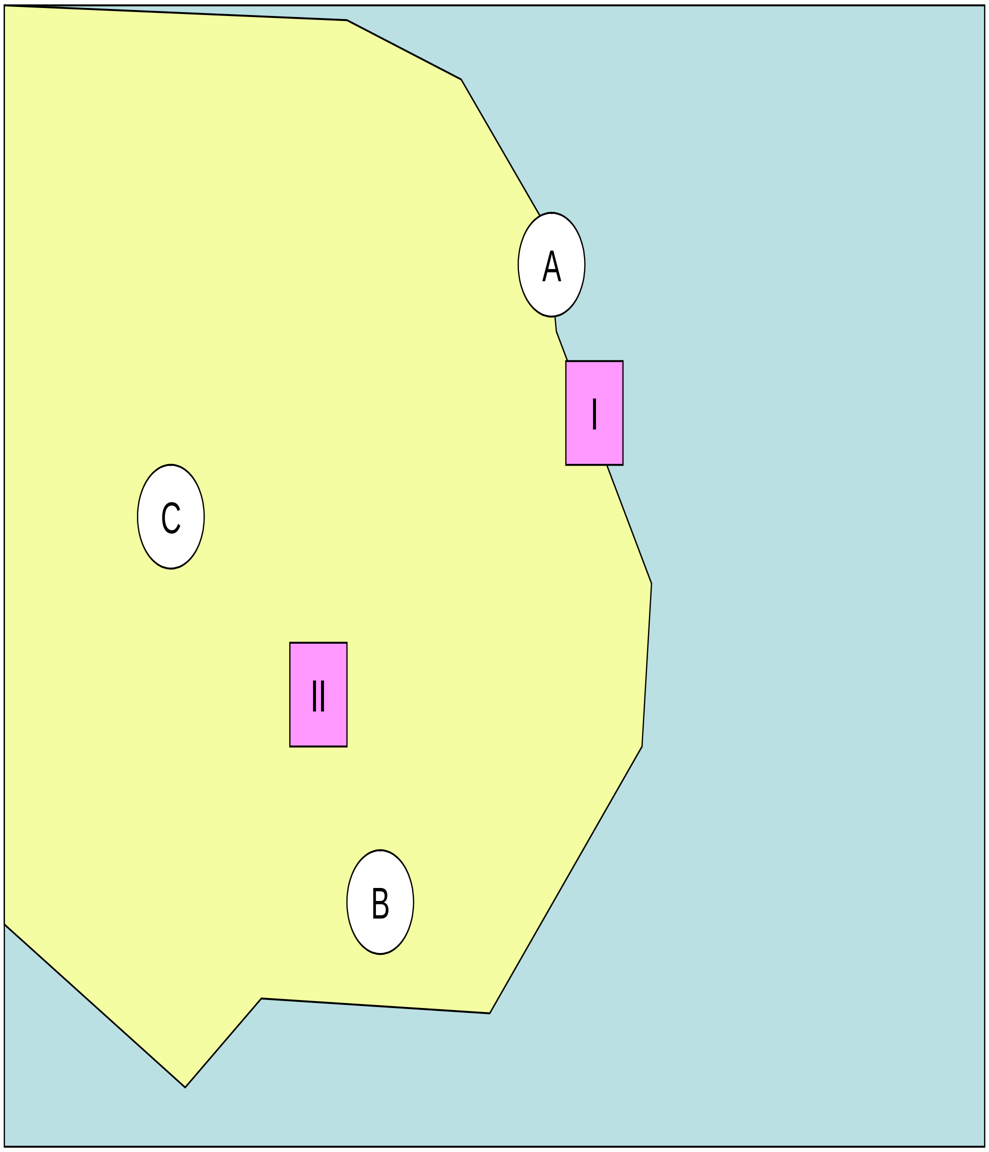

Fig.6 Scheme for the places of sources and sinks

Table 3 The distances between the sources and sinks

Source	**Sink**	**Distance (miles)**
A	I	5
A	II	120
B	I	130
B	II	45
C	I	140
C	II	40

The costs for each technology and sources like annualized fixed cost and operating cost are shown in Table 4. The cost of pumping and piping is taken to be 0.012 $\$/(m^3. \text{ mile})$.

Two desalination technologies are being considered: reverse osmosis (RO) and multi-effect distillation (MED). The following table provides cost and performance data of these technologies operating at the three water sources. To insure removal of non-salt impurities, any water stream must be treated in RO or MED prior to usage.

After using the Global Solver of LINGO version 10.1, the solution is described through a source-interception-sink representation as shown in Fig.7. The minimum total annualized cost of the system is calculated $106.5 MM/yr. The distribution of the various costs is given in Table 5.

Table 4 Costs for each technology and sources

Technology	**Water Source**	**Outlet Salt Content(ppm)**	**Water Recovery (m^3desalinated water per m^3 feed water)**	**Annualized Fixed Cost Function($/yr) Q is flowrate of desalinated water in m^3/day**	**Operating Cost ($/$m^3$ desalinated water)**
RO	A	400	0.40	$3322*Q^{0.8}$	0.25
MED	A	350	0.60	$2482*Q^{0.7}$	0.20
RO	B	200	0.55	$1166*Q^{0.8}$	0.18
MED	B	80	0.65	$2227*Q^{0.7}$	0.24
RO	C	100	0.61	$352*Q^{0.6}$	0.08
MED	C	80	0.70	$862*Q^{0.7}$	0.11

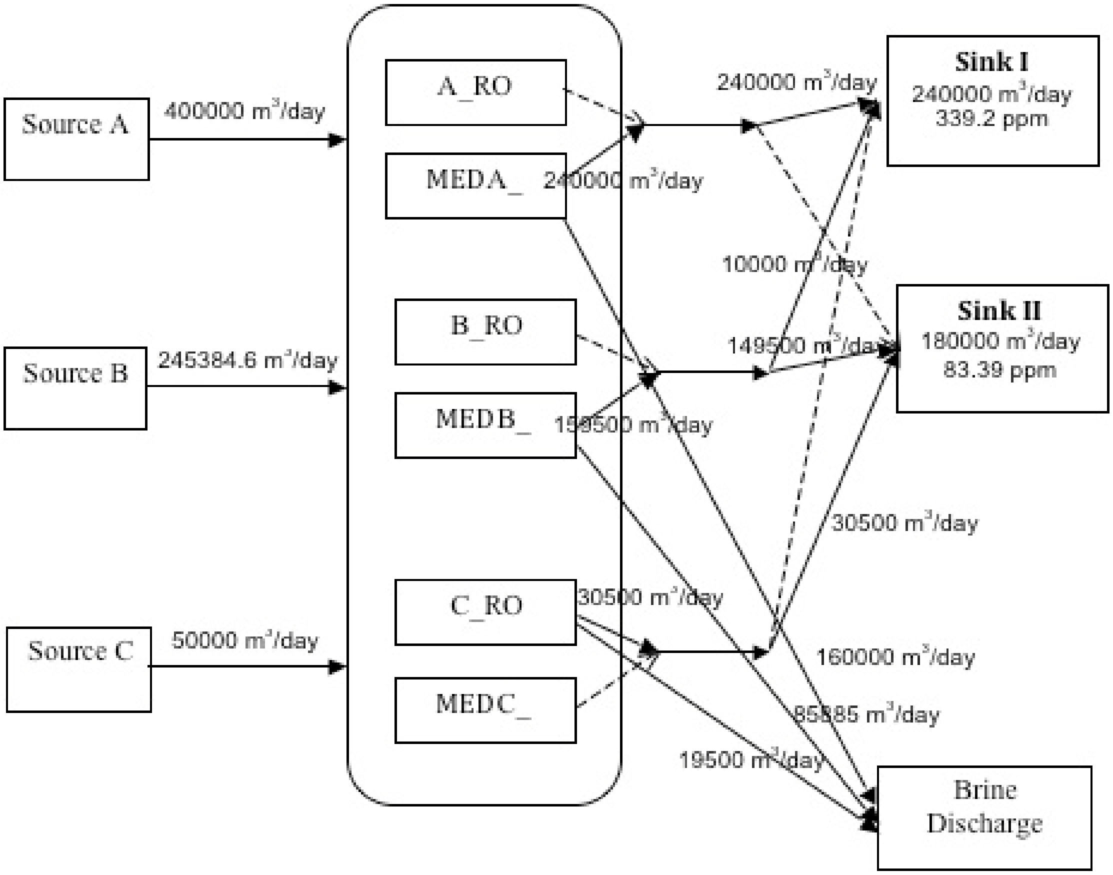

Fig.7 Optimal Solution of Case Study

Table 5 Cost Distribution of the Optimal Solution

Cost Items	Value (MM $/yr)
Annual operating cost	32.4
Annualized fixed cost	24.4
Annualized piping cost	45.8
Annual brine disposal cost	3.9

CONCLUSIONS

An integrated framework has been introduced for the development of water desalination and distribution networks for a whole region. In this framework, various desalination technologies are considered and their sizes, design, operation, and location are optimized. This optimization is carried out along with the design of the fresh water and brine rejection distribution networks. The result is an integrated strategy for a macroscopic system. A structural representation of sources, interceptors, and sinks has been used to embed all potential configurations of interest and to enable the formulation of the problem as an optimization task. The optimization formulation has been solved and demonstrated for a case study.

CHAPTER IV

A SYSTEMS INTEGRATION APPROACH TO THE OPTIMIZATION OF MACROSCOPIC WATER DESALINATION AND DISTRIBUTION NETWORKS: A GENERAL FRAMEWORK APPLIED TO QATAR'S WATER RESOURCES

INTRODUCTION

The availability of fresh water resources is becoming a major concern in several parts of the world. A particularly vulnerable area is the Middle East, which is one of the world's most arid regions. In contrast to the abundant energy resources, water is an extremely scarce resource in the Gulf Cooperation Council (GCC) countries. The GCC countries have become one of the biggest global energy hubs in recent decades and this has led to rapid increase in the local population (Wittholz et al. 2008). Furthermore, the growing levels of major industrial activities in the GCC countries are posing an additional load on the already scarce water resources. Indeed, recent studies point to the prediction that over the next decade, the GCC countries will be among the world's highest per-capita users of water (McKenna et al. 2010). Industrial water demand is likely to escalate faster than the economic growth in these countries. As a result of the excessive use of limited groundwater resources in recent years with the increasing population, larger seawater-desalination plants will have to be added(Atilhan et al. 2010c). Also, recycle/reuse activities must be enhanced. Currently about 3% of the world's total water requirements are met by desalination, and given the World Water Council's prediction of water shortages by 2025 there exists potential for increased use of this energy-intensive process. Because of the high-energy usage of the desalination plants, the long-run sustainability of the infrastructure is questionable (Cosgrove 2003).

Qatar is an excellent example of the growing water challenges in the GCC. Qatar’s population has increased with a massive 9 % annual rate since 2002. A major challenge is to provide sufficient and sustainable water distribution networks for the State of Qatar(Al Malki 2009; Wittholz et al. 2008). The increase in water demand has been largely induced by the huge economic boom from a natural-gas based economy. The proved world total natural gas reserves are estimated to be 185.8×10^{12} m^3 in 2010, which is a remarkable increment of 9.956×10^{12} m^3 when compared with 2009 data(Worldwide Look at Reserves and Production 2009). The analysis by countries shows that Qatar, with 25.28×10^{12} m^3 proved reserves, has the world’s third largest reservoirs, equivalent to almost 14 % of the total reserves of the world’s natural gas. In 2008, Qatar produced 75.9×10^{9} m^3 of natural gas, which is more than 5 times the amount produced in 1995; nevertheless, this quantity will increase remarkably in the next years (Energy Information Administration 2010). The majority of Qatar’s natural gas is located in the massive offshore North Field, the world’s largest nonassociated natural gas field. Increasing Qatar’s natural gas production will lead to large-scale projects such as new liquefied natural gas infrastructure, natural gas exports through the pipeline, large-scale gas-to-liquids projects, and the promotion of downstream industries that utilize natural gas as feedstock (Atilhan et al. 2010a). These activities in natural gas processing have dramatically increased the need of fresh water supply to its industrial and urban areas in the State of Qatar(Atilhan et al. 2010d). For this purpose, currently there are five desalination plants in Qatar with a total production capacity of 217 MIGD (986,000 m^3/day). There are two desalination plants that are being constructed with a combined capacity of 108 MIGD (491,000 m^3/day). On the other hand, the northern groundwater aquifer is the major source of groundwater in Qatar, estimated to contain 550,000 MIG (2,500 million m^3) of freshwater, which is mostly used for agriculture. Desalinated water is the primary source of the total water produced, and Qatar is almost dependent exclusively on the desalinated water based on these figures. In this situation, transmitting the desalinated water to industrial and urban areas becomes an important issue. For this purpose 5,400 km of transmission and distribution lines have been constructed so far in Qatar and currently 290 MIG of storage capacities exists that corresponds to 1.5-day usage capacity. There are 22 water-pumping stations installed in the water distribution network to provide transmission of the desalinated water. Since 2000, the average annual percentage increase in supply has been 10.3 %, and the average annual percentage increase in demand has been 9.9 %. These figures are expected to remain for the next decade. Thus, there will be additional desalination plants, and need of improved and optimized water distribution network will rise significantly (Al Malki 2009).

LITERATURE REVIEW

Because of the abundance of relatively inexpensive energy sources in the Middle East, thermal technologies are among the dominant methods for seawater desalination. In most cases, a power plant is tied to a thermal desalination plant (Atilhan et al. 2010b;

Raouf 2009). The synergism between the two facilities reduces the cost for power and water and the desalination plant provides effective methods for removing the excess heat produced by the power plant. Because of such linkage, it is not uncommon to produce excess desalinated water, which is discharged again to the sea when there is not sufficient demand or infrastructure to handle it (Bin-Mahfouz et al. 2009; Atilhan et al. 2011a). Issues pertaining to the biofouling of desalination plants and the associated use of biocides and water chemistry were studies by Bin Mahfouz et al. (Bin-Mahfouz et al. 2011).

Because of the need to integrate multiple water sources, an evolving infrastructure, and multiple users, process integration provides an attractive framework for the optimal design of macroscopic water networks. Process integration is a holistic approach to design and operation which emphasizes the unity of the system (El-Halwagi 1997). Several techniques for optimizing water systems within industrial processes (e.g., (El-Halwagi 2006; El-Halwagi 2011; Foo 2009; Gabriel and El-Halwagi 2005a) can be extended and adapted to address desalination networks for macroscopic systems. Atilhan et al. (Atilhan et al. 2010c; Atilhan et al. 2011a) introduced an integrated framework for the development of water desalination and distribution networks for a whole region. In this framework, various desalination technologies were considered and their sizes, design, operation, and location were optimized. This optimization was carried out along with the design of the fresh water and brine rejection distribution networks. The result was an integrated strategy for a macroscopic system. RO, MED and MSF distillation techniques were used for desalination purposes in the Gulf region.

Notwithstanding the usefulness of this approach, it was limited to screening the desalination technologies and did not account for fluctuations in waste demand and the availability of energy resources driving the desalination.

OBJECTIVES

In this work, we develop an optimization-based approach for the design of water desalination and distribution networks to satisfy the demands of the various water-consuming sectors. This approach accounts for fluctuations in water demand, and considers the available energy sources tied to desalination. The approach also accounts for the existing desalination capacities and water-storage systems. The developed optimization formulation handles the following tasks:

- Optimization of the water-distribution system
- Integration of various monthly supplies and demands and enabling short- and long-term storage
- Treatment and recycle/reuse of wastewater streams
- Incorporation of the value of different uses of water as well as the value of the short- and long-term storage while accounting for the cost of desalination, water treatment, and allocation.

The developed approach is applied to a case study dealing with the management of water resources in the State of Qatar.

PROBLEM STATEMENT

Given is a region with known water demands for industrial, agricultural, residential, and other uses. The monthly variations of these water demands are known. The desalinated water is produced via thermal plants that are linked to power plants. The capacities of the power and desalination plants are known. Several water sources are available including desalination plants, groundwater, aquifers, and recyclable water. Using the existing capacity of the water-desalination plants, it is desired to develop a systematic and generally applicable approach for the design and operation of a macroscopic water network that addresses the following key questions:

- How should the water be allocated from the sources to the users? What design changes are needed for the water-distribution system?
- What is the optimal strategy for operating the water desalination and distribution network?
- What are the prospects for using recycled wastewater streams?
- Should water be stored to handle the monthly fluctuations in demand?
- What are the opportunities for strategic storage of water in aquifers?

APPROACH AND MATHEMATICAL FORMULATION

The first step in the devised approach is the development of a superstructure that embeds all potential water-network configurations of interest. Fig. 8 is a schematic representation of the proposed superstructure. Four major building blocks are used: sources, interceptors, sinks, and storage systems. The sources include the water-supply resources such as the existing and new plants that render the water sources in a quality acceptable for the water users. The water sinks include all the consumers such as industrial, residential, and agricultural users. The interceptors represent the water-treatment units (e.g., to treat effluent water from residential or industrial systems). The storage systems include two types: short- and long-term systems. The short-term systems are in the form of storage tanks. Their capacities are typically in the range of days to weeks. The long-term systems are aquifers which can store water for months or years.

As Fig. 8 shows, each source is allowed to split and distribute to users directly or through water mains. The intercepted water streams are also allocated to the sinks. Additional water resources are allocated to short- and long-term storage systems. The capacities of the added desalination plants, storage tanks, and allocated flows from sources to interceptors and interceptors to sinks are unknown and are to be determined through optimization. Additionally, the monthly distributions of water streams are also to be identified according to an optimal policy. In order to pose the problem as an optimization task, a multi-period mathematical formulation is developed. The annual operation is discretized into a number of timer periods (e.g., 12 months) with the parameter t designating a time period. The following symbols are used in the formulation.

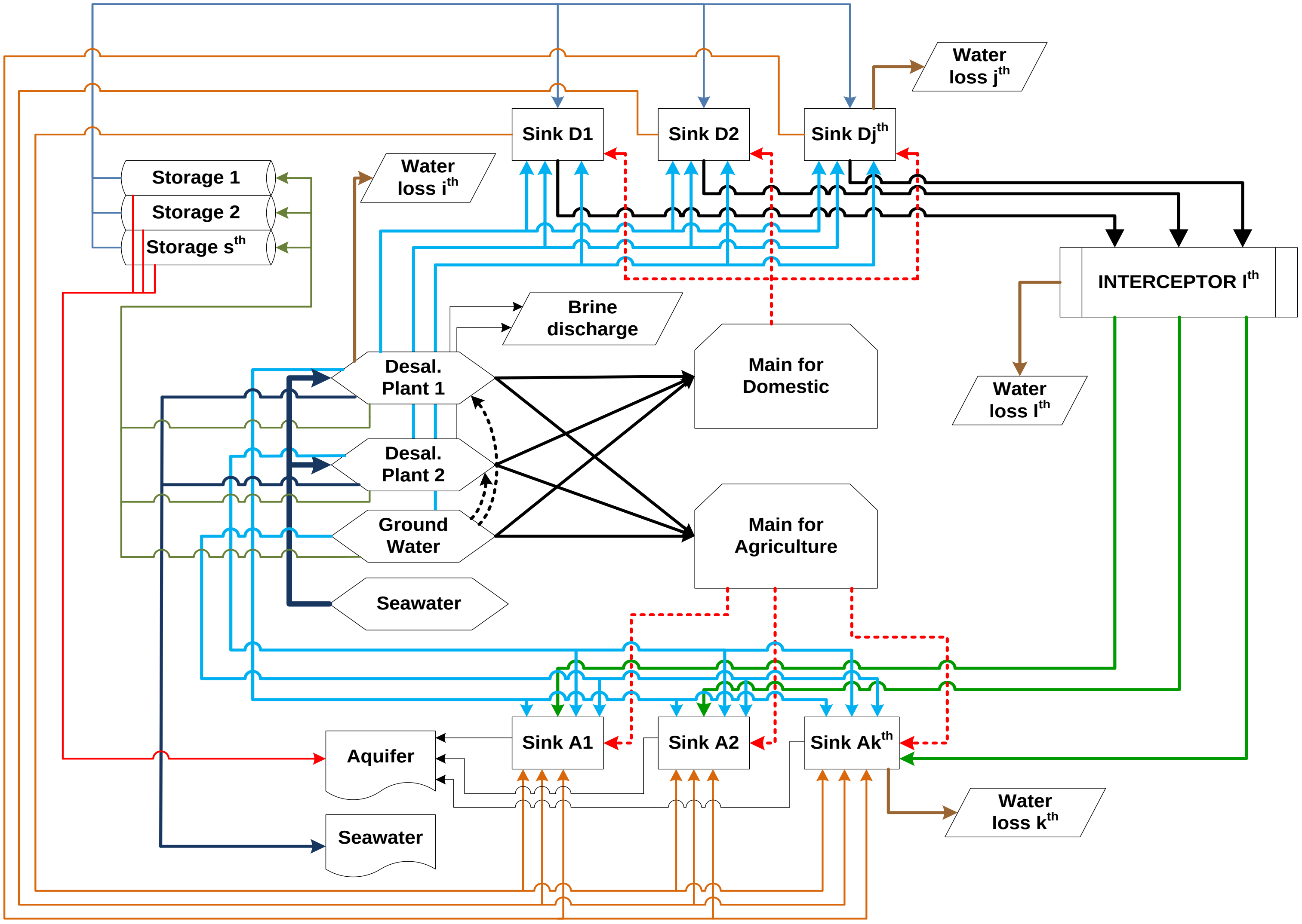

Fig. 8 Schematic representation of macroscopic water management problem

Mass balance around source i

As shown in Fig. 9, each source i receives water (e.g., from seawater and/or groundwater), performs desalination, and distribute desalinated water to the various sinks while discharging the brine. Excess desalinated water is discharged back to the sea. There are also water losses in the pipelines and in various uses. The water balance can be written as follows:

$$G_{i,t}^{\text{seawater}} + G_{i,t}^{\text{groundwater}} = \sum_{s=1}^{N_{\text{storage}}} G_{i.s,t}^{\text{storage}} + \sum_{j=1}^{N_{\text{sinkD}}} G_{i,j,t}^{\text{sink D}} + \sum_{m=1}^{N_{\text{mainD}}} G_{i,m,t}^{\text{main D}} + \sum_{k=1}^{N_{\text{sinkA}}} G_{i,k,t}^{\text{sink A}}$$

$$+ \sum_{n=1}^{N_{\text{mainA}}} G_{i,n,t}^{\text{main A}} + \sum_{p=1}^{N_{\text{aquifer}}} G_{i,p,t}^{\text{Aquifer}} + \sum_{d=1}^{N_{\text{discharge}}} G_{i,d,t}^{\text{discharge}} + G_{i,t}^{\text{brine}} + G_{i,t}^{\text{lossSource}}$$

$$\forall i\ ,\ \forall t \qquad (4.1a)$$

The performance of the desalination plant is given in terms of the water-recovery coefficient α (obtained from actual measurements of the plant or from modeling the system), which gives the ratio of the desalinated water to the incoming water, i.e.

$$G_{i,t}^{\text{Desalinated}} = \alpha_{i,t} \times (G_{i,t}^{\text{seawater}} + G_{i,t}^{\text{groundwater}}) \qquad \forall i\ ,\ \forall t \qquad (4.1b)$$

The desalinated water is distributed to the various sinks, i.e.

$$G_{i,t}^{\text{desalinated}} = \sum_{s=1}^{N_{\text{storage}}} G_{i.s,t}^{\text{storage}} + \sum_{j=1}^{N_{\text{sinkD}}} G_{i,j,t}^{\text{sink D}} + \sum_{m=1}^{N_{\text{mainD}}} G_{i,m,t}^{\text{main D}} + \sum_{k=1}^{N_{\text{sinkA}}} G_{i,k,t}^{\text{sink A}} + \sum_{n=1}^{N_{\text{mainA}}} G_{i,n,t}^{\text{main A}}$$

$$+ \sum_{p=1}^{N_{\text{aquifer}}} G_{i,p,t}^{\text{Aquifer}} + \sum_{d=1}^{N_{\text{discharge}}} G_{i,d,t}^{\text{discharge}}$$

$$\forall i\ ,\ \forall t \qquad (4.1c)$$

It is assumed that the quality of desalinated water meets the requirements of the various users. This is a reasonable assumption given that the desalination plants are designed to provide drinking-water quality. Therefore, there is no need to write a salt balance or to check on the satisfaction of requirements for salt-content for the sinks.

Mass balance around sinkD $_j$ for domestic use

Figs. 10 and 11 illustrate the balance of the water streams entering and leaving a domestic (residential) sink. The mathematical expressions are given by:

$$Q_{j,t} = \sum_{i=1}^{N_{source}} G^{source}_{i,j,t} + \sum_{m=1}^{N_{mainD}} G^{main\ D}_{m,j,t} + \sum_{s=1}^{N_{storage}} G^{storage}_{s,j,t} \qquad \forall j,\ \forall t \qquad (4.2)$$

$$Q_{j,t} = \sum_{l=1}^{N_{interceptor}} G^{interceptor}_{l,j,t} + \sum_{k=1}^{NsinkA} G^{sinkA}_{k,j,t} + G^{lossDomestic}_{j,t} \qquad \forall j,\ \forall t \qquad (4.3)$$

Mass balance around sinkA k for agricultural use (Fig. 12)

$$Y_{k,t} = + \sum_{i=1}^{N_{source}} G^{source}_{i,k,t} + \sum_{n=1}^{N_{mainA}} G^{main\ A}_{n,k,t} + \sum_{l=1}^{N_{interceptor}} G^{interceptor}_{l,k,t} + \sum_{k=1}^{N_{sinkA}} G^{sink\ A}_{j,k,t}$$

$$\forall k,\ \forall t \qquad (4.4)$$

Remaining unused water from sinkA k is discharged (Fig. 13)

$$Y_{k,t} = + \sum_{p=1}^{N_{aquifer}} G^{aquifer}_{p,k,t} + \sum_{d=1}^{N_{discharge}} G^{discharge}_{d,k,t} + G^{lossAgriculture}_{k,t} \qquad \forall k,\ \forall t \qquad (4.5)$$

Mass balance around interceptor (Fig. 14)

$$W_{l,t} = + \sum_{j=1}^{N_{\sin kD}} G_{j,k,t}^{\sin kD} \qquad \forall l,\ \forall t \qquad (4.6)$$

$$W_{l,t} = + \sum_{k=1}^{N_{\sin kA}} G_{l,k,t}^{\sin kA} + G_{l,t}^{\text{lossInterceptor}} + G_{l,t}^{\text{greening}} \qquad \forall l,\ \forall t \qquad (4.7)$$

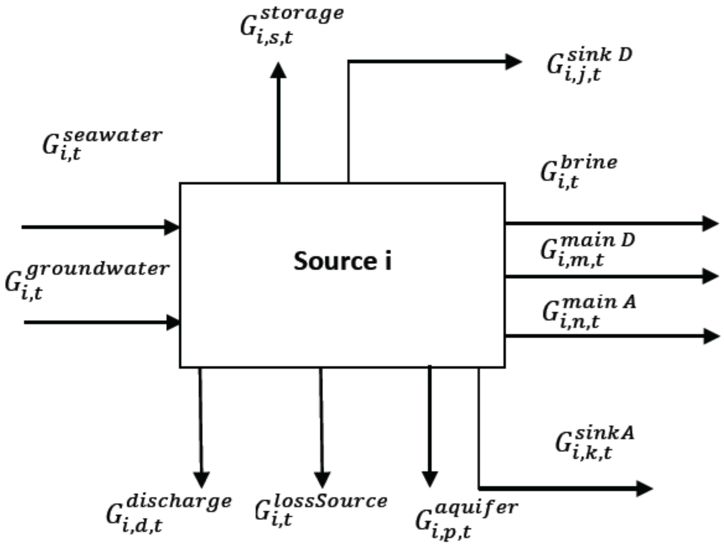

Fig. 9 Mixing and splitting of sources

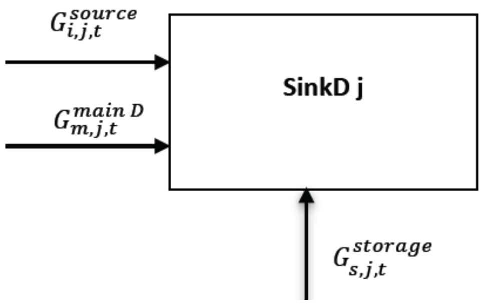

Fig. 10 Mixing with sink D for domestic use

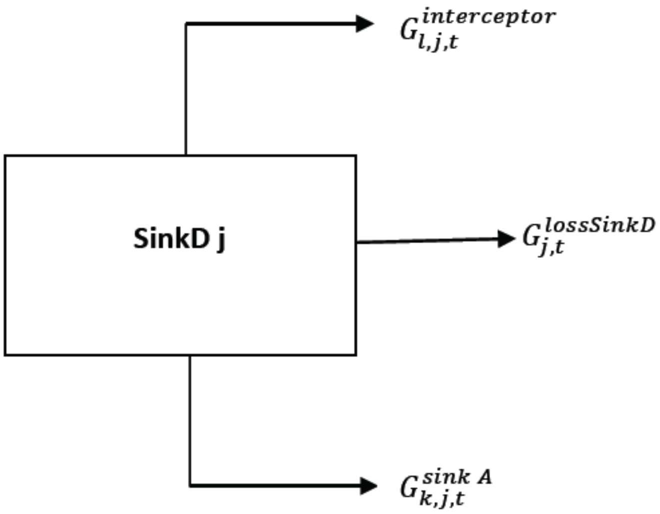

Fig. 11 Splitting of sink D for domestic use

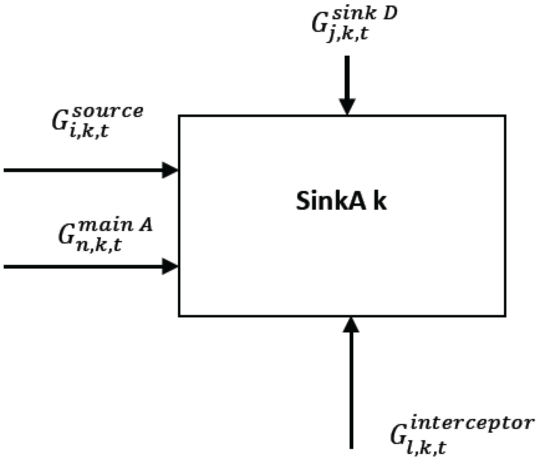

Fig. 12 Mixing with sink A for agricultural use

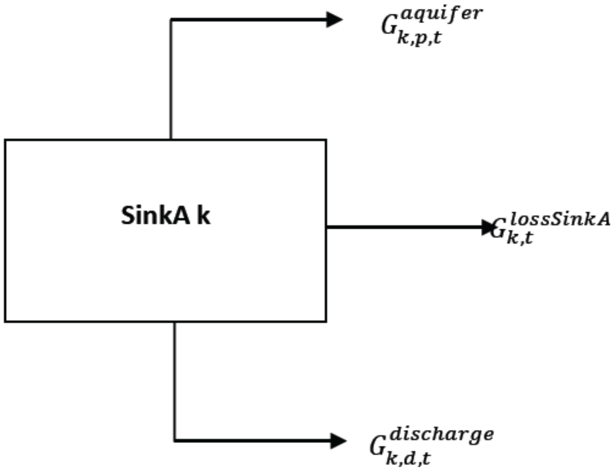

Fig. 13 Splitting of sink A for agricultural use

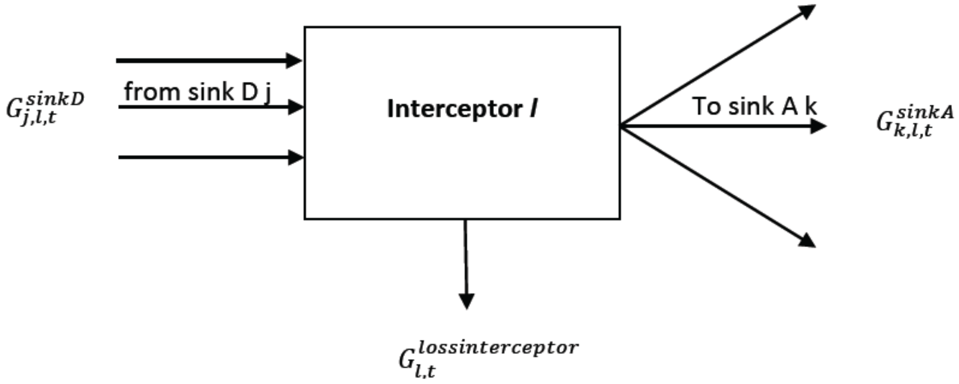

Fig. 14 Mixing and splitting of interceptor flow to sink for agricultural use

Storage balances

The short-term storage is achieved by using tanks. The long-term (strategic) storage is handled by injecting water in aquifers and later using the water as needed (aquifer storage and discharge). The water balance for the short-term storage systems over period t is given by:

$$\mathrm{Storage}_{s,t} = \mathrm{Storage}_{s,t-1} + \sum_{i} G_{i,s,t}^{\mathrm{Storage}} - \sum_{j} G_{s,j,t}^{\mathrm{Storage}} \qquad \forall s,\ \forall t \qquad (4.8)$$

The constraint accounts for the buildup or depletion of water in storage system s as a result of water added from the sources or water dispatched to the sinks. The maximum capacity of storage tank s should be the limit, i.e.

$$\mathrm{Storage}_{s,t} \le \mathrm{Storage}_{s}^{\max} \qquad \forall s,\ \forall t \qquad (4.9)$$

The desalination plants in this work are taken to be thermal units that are tied to the power plants. Excess heat from the power plants is used to drive these thermal systems. The rate of water desalination and power produced are related via a power-to-water factor β (which is obtained from actual data of the plant or from modeling the system):

$$G_{i,t}^{Desalinated} = \beta_{i,t} \times Power_{i,t} \qquad \forall i,\ \forall t \qquad (4.10)$$

Several objective functions can be formulated. We propose two functions: one dealing with the economic potential and the other one dealing with the conservation of water resources. For the economic potential, we define values ($/MIG) for the different water users and for the short- and long-term water storage. Although in most studies, aquifer storage is not assigned a value, it is important to provide such an economic incentive for storing water in aquifers for long-term strategic security of the country and for safeguarding against the increasing salinity of water in aquifers resulting from usage with recharging. The following symbols are used:

$C_i^{Seawater}$ = Cost of water desalinated from seawater ($/MIG of seawater)

$C_i^{Groundwater}$ = Cost of water desalinated from groundwater ($/MIG of groundwater)

$C_l^{Interceptor}$ = Cost of intercepted wastewater treated to greening quality ($/MIG of treated wastewater)

$C_j^{Domestic}$ = Value of water allocated to domestic user j ($/MIG)

$C_k^{\text{Agriculture}}$ = Value of water allocated to agricultural user k ($/MIG)

C_l^{Greening} = Value of water allocated to greening users ($/MIG)

C_p^{Aquifer} = Value of water saved in aquifer p ($/MIG). This number accounts for the assigned value of the water stored for strategic purposes less the cost of transport and injection.

C_s^{storage} = Value of water saved in storage system s ($/MIG). This number accounts for the assigned value of the water stored for short-term purposes less the cost of transport and storage.

The idea behind the objective function for maximizing the economic potential of the water resources is written by simple terms as:

(Total cost of water allocated to users) – (Total cost of desalinated water from sources)

Below equation shows the mathematical formulation that is needed to maximize the economic potential of the water resources:

$$\text{Maximize } \sum_j C_j^{\text{Domestic}} \times \sum_t Q_{j,t} + \sum_k C_k^{\text{Agriculture}} \times \sum_t Y_{k,t} + \sum_l C_l^{\text{Greening}} \times \sum_t W_{l,t} +$$

$$\sum_s C_s^{\text{Storage}} \times \sum_i \sum_t G_{i,s,t}^{\text{storage}} + \sum_p C_p^{\text{Aquifer}} \times \sum_i \sum_t G_{i,p,t}^{\text{Aquifer}} -$$

$$\sum_i C_i^{\text{Seawater}} \times \sum_t G_{i,t}^{\text{seawater}} - \sum_i C_i^{\text{Groundwater}} \times \sum_t G_{i,t}^{\text{Groundwater}} \tag{4.11}$$

Above objective functions includes cost optimization as well. However the main target of this work is to determine the water storage capacities in tanks and aquifers in State of Qatar. Cost allocation of the problems will be dealt with in the future work.

In other words, the objective function that is tacked in this work basically is to maximize the short- and long-term storage while meeting all the previously stated constraints. Objective function to conserve the water resources through the storage in tanks and in aquifers is given by:

(Total amount of water stored in storage tanks and aquifers) – (Total amount of used water by domestic users)

For cases when the infrastructure already exists, the objective is to maximize the usage of the existing infrastructure to store maximum possible amount of desalinated water for strategic and economic purposes, i.e.,:

$$\text{Maximize} \sum_{t}\sum_{i}\sum_{s} G_{i,s,t}^{storage} - \sum_{t}\sum_{j}\sum_{s} G_{s,j,t}^{storage} + \sum_{t}\sum_{i}\sum_{p} G_{i,p,t}^{aquifier} \qquad (4.12)$$

The following symbols are used:

$G_{i,t}^{Desalinated}$ = Desalinated-water flow from source i

$G_{i,d,t}^{discharge}$ = Excess water flow from source i to sea

$G_{k,d,t}^{discharge}$ = Excess water flow from sinkA k to sea

$G_{i,t}^{Groundwater}$ = Groundwater flow rate that enters source i

$G_{i,t}^{brine}$ = Rejected brine flow from source i

$G_{k,p,t}^{aquifer}$ =Remaining unused water flow from sinkA k to ground p

$G_{i,t}^{Seawater}$ = Seawater flow rate that enters source i

$G_{l,k,t}^{SinkA}$ = Treated sewage water flow rate from WWTP (interceptor) l to sinkA k

$G_{i,n,t}^{mainA}$ = Usable water flow rate from source i to agricultural main n

$G_{i,m,t}^{mainD}$ = Usable water flow rate from source i to domestic main m

$G_{i,k,t}^{SinkA}$ = Usable water flow rate from source i to agricultural sink (sinkA) k

$G_{i,j,t}^{source}$ = Usable water flow rate from source i to domestic sink (sinkD) j

$G_{i,s,t}^{storage}$ = Usable water flow rate from source i to storage s

$G_{s,j,t}^{storage}$ = Usable water flow rate from storage s to sinkD j

$G_{j,k,t}^{SinkA}$ = Usable water flow rate from sinkD j to sinkA k

$G_{j,l,t}^{SinkD}$ = Usable water flow rate from sinkD j to WWTP (interceptor) l

$G_{i,t}^{lossSource}$ = Water flow rate lost from source i

$G_{j,t}^{lossSinkD}$ = Water flow rate lost from sinkD j

$G_{l,t}^{lossInterceptor}$ = Water flow rate lost from interceptor l

$G_{k,t}^{lossSinkA}$ = Water flow rate lost from sinkA k

$Power_{i,t}$ = Power produced from the power plant tied to the i^{th} desalination plant

$Q_{j,t}$= Usable water flow rate entering sinkD j

$Storage_{s,t}$ = Amount of water stored in tank s at the end of period t

$W_{l,t}$= Usable water flow rate from interceptor l

$Y_{k,t}$ = Usable water flow rate entering sinkA k

The foregoing formulation is a linear program, which can be solved globally to determine the optimal production levels of water and the allocated and stored flow rates in each time interval. The following example illustrates the applicability of the developed formulation.

CASE STUDY: MANAGEMENT OF WATER RESOURCES IN THE STATE OF QATAR

This example deals with the design and operation of the macroscopic water distribution in Qatar. There are usable water sources from desalination plants and groundwater, sinks for domestic and agricultural use and greening, and interceptors as wastewater treatment facilities. The wastewater treatment facilities use advanced membrane and ultra-violet treatment technologies to reclaim high quality water for agricultural use and greening. The data for the sources and sinks are obtained from Kahramaa and are given in Table 6 (KAHRAMAA 2010). The following assumptions are made in the optimization formulation:

- Power/desalinated water supply ratio is 20 MW/MIGD
- Pipeline losses = 10%

- Domestic use losses = 30% (Salem 2009)
- 59% of sewage water is treated for greening and agricultural use (Shadid and Ahmed 1992)
- Maximum capacity of existing short-term storage tanks = 290 MIGD (Al Malki 2009)

Treated wastewater can only be allocated to greening uses (while meeting the quality requirements for greening).

The problem was formulated as a linear program and solved globally using the Software LINGO (Schrage 2006b). The program has 277 constraints and 914 variables. The solution shows that the current Qatari desalination infrastructure is sufficient to meet the water demands in Qatar. Furthermore, water can be stored for short- and long-term purposes. The solution results for the total monthly storage are shown by Table 7. The short-term storage facilities reach their maximum capacity (290 MIG) in the first month. Therefore, the excess fresh water can be stored in aquifers for long-term strategic security. Figs. 15-17 show sample results for the operation of the water network in three months (January, June, and December).

Table 6 Power/water supply and water demand for users in Qatar based on the 2010 data (Al Malki 2009; KAHRAMAA 2010)

Month	**Power Supply (MW)**	**Desalinated Water supply**	**Groundwater & Aquifer Supply**	**Domestic demand**	**Agricultural demand**	**Greening demand**
January	4617	231	133	151	173	39
February	4262	213	133	140	170	39
March	4972	249	133	163	177	50
April	5150	258	133	169	178	53
May	5683	284	133	186	183	59
June	5683	284	133	186	183	62
July	6038	302	133	198	186	62
August	6127	306	133	201	187	62
September	5772	289	133	189	184	56
October	5683	284	133	186	183	44
November	5505	275	133	180	181	41
December	4972	249	133	163	177	39

*Units are MIGD

Table 7 Monthly storage amounts

Month	**Storage (MIG)**
January	1057
February	1853
March	2743
April	3599
May	4559
June	5397
July	6438
August	7523
September	8584
October	10008
November	11393
December	12624

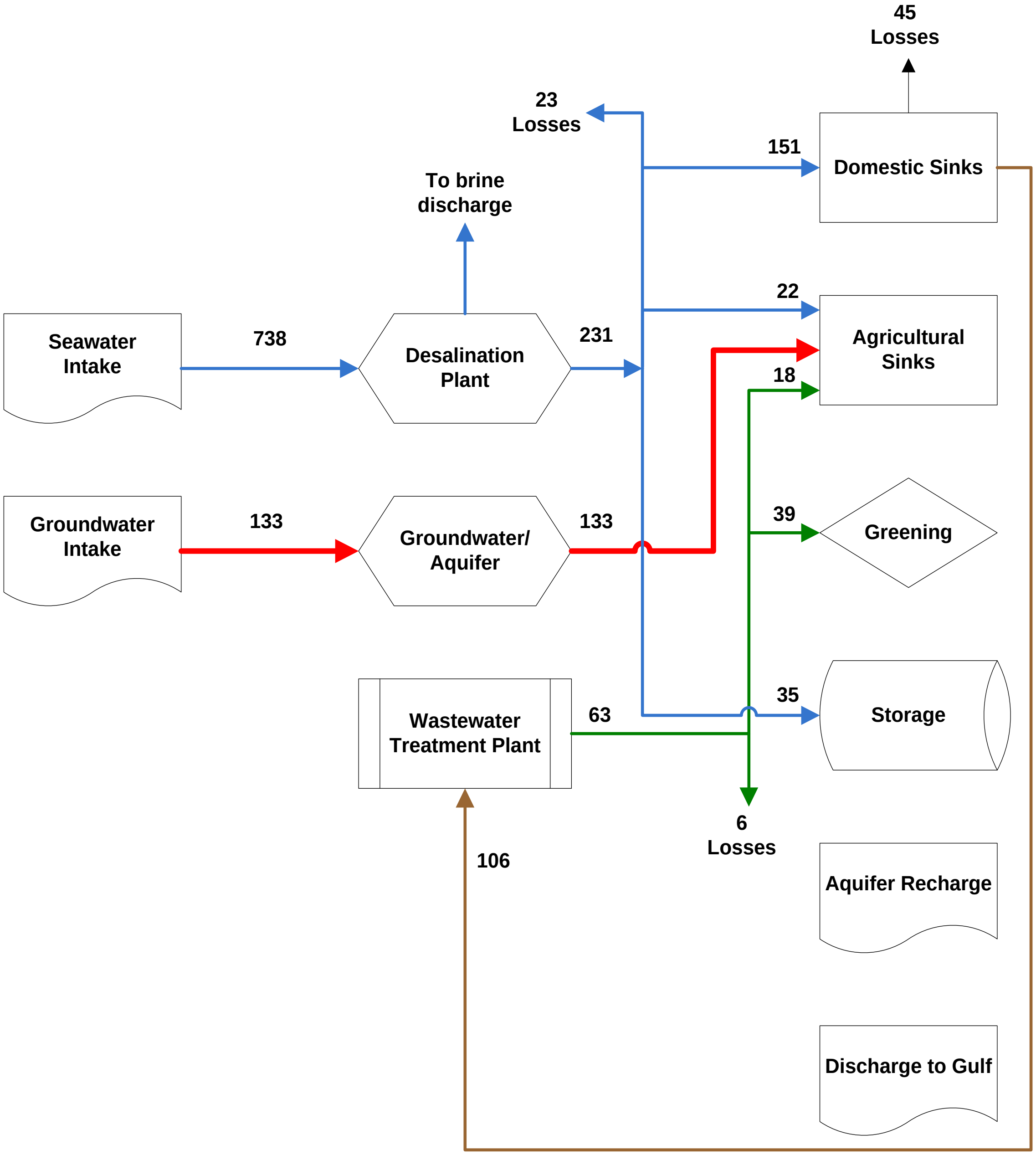

Fig. 15 Water network distribution in January (all numbers are in MIGD)

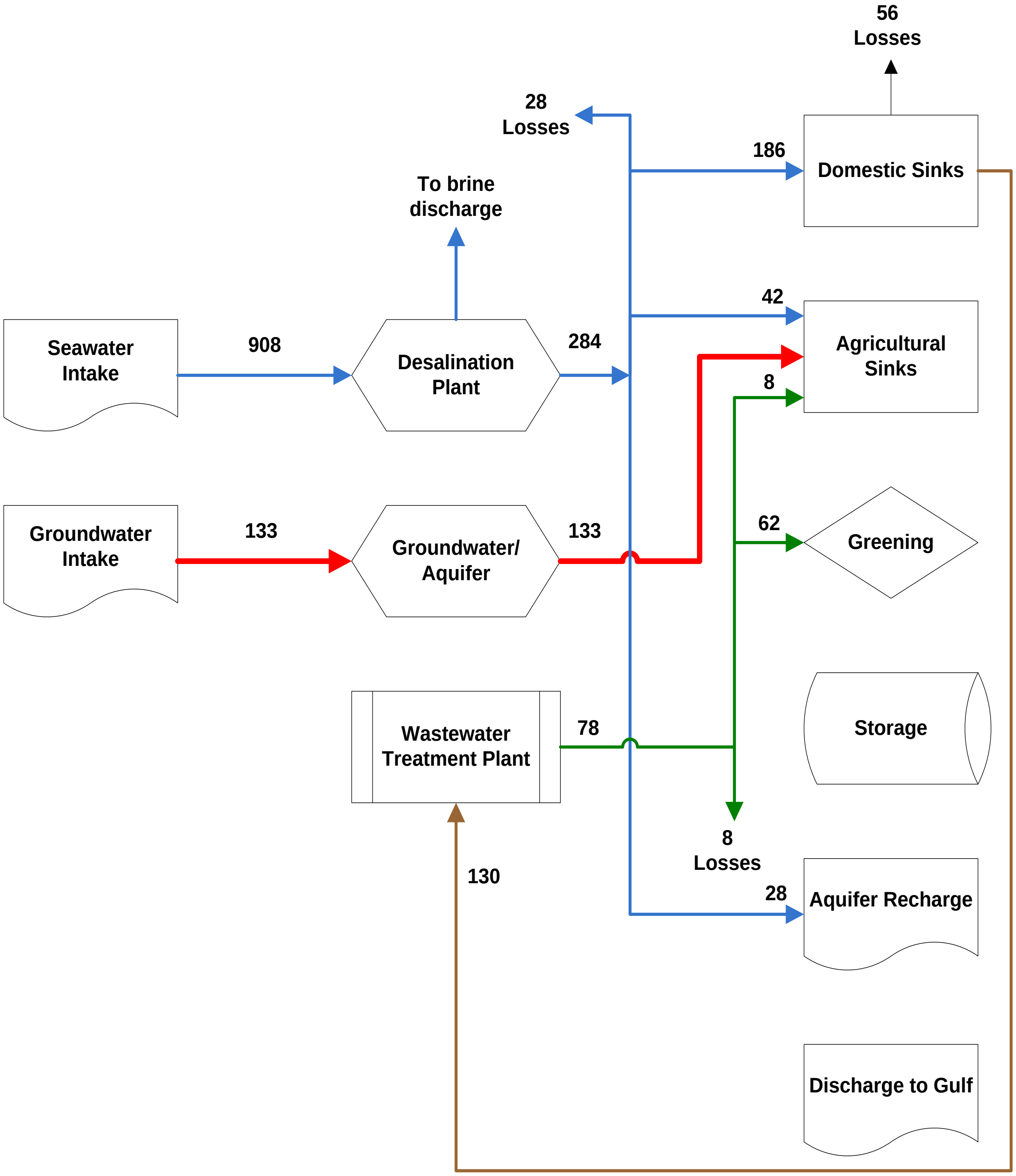

Fig. 16 Water network distribution in June (all numbers are in MIGD)

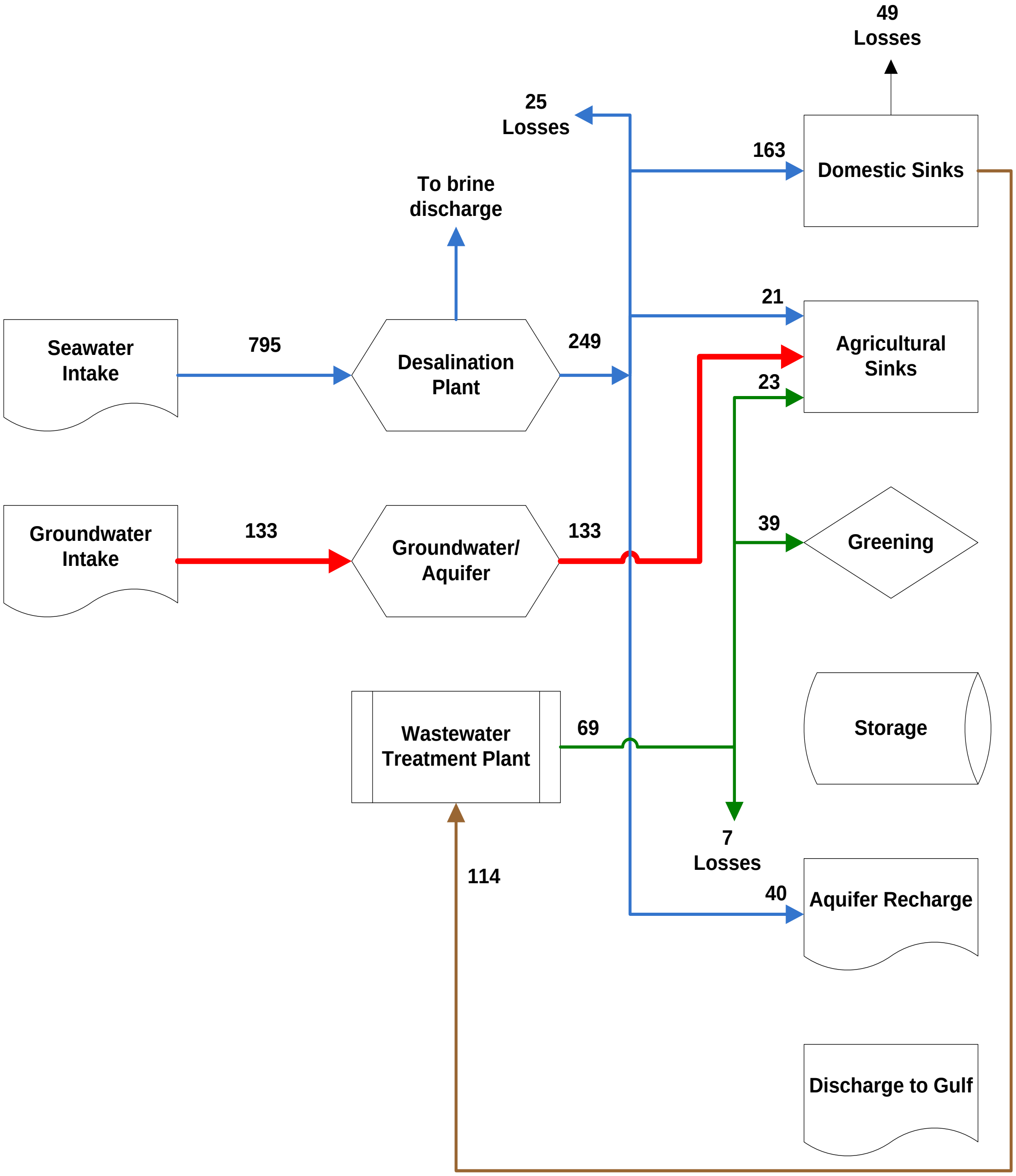

Fig. 17 Water network distribution in December (all numbers are in MIGD)

CONCLUSIONS

A systems-integration framework has been introduced for the design and operation of macroscopic water networks. A structural representation approach is developed to represent the water network using sources, sinks, interceptors, and storage. A linear-programming formulation is developed to determine the optimal design sizing of the desalination plants and the monthly allocation and storage of water. Two objectives are considered: economic potential and resource conservation. A case study has been solved on managing the water resources and infrastructure for the State of Qatar. As a result, the total monthly stored fresh water was calculated and the existing fresh water was stored and reached full storage capacity after the first month.

CHAPTER V

AN INTEGRATED APPROACH TO THE PLANNING OF INFRASTRUCTURE EXPANSION OF MACROSCOPIC WATER NETWORKS

INTRODUCTION

Economic growth around the world is causing a significant increase in the consumption of natural resources. For instance, in the last couple of decades there has been a tremendous boom in the industrial activities and the economy in the countries of the Gulf Cooperation Council (GCC). Industrial activities and population of the GCC States have been on the rise on a constant base (Al-Zubari 2003; Bushnak 1990; Alawadhi 1999). Oil- and gas-based economy and related side businesses have brought many foreigners to migrate to GCC countries at all levels of the labor spectrum (Dawoud 2007). Rapid population growth have resulted in dense populations concentrated in cities and such increase has brought its own problems related to the basic human needs such as public service infrastructure. This has caused a huge increase in the consumption of natural resources including water. The scarcity of fresh-water resources is one of the major problems in the GCC region (Ismail et al. 2003; Mishra 2009; Salem 2009). This brings up the questions about the ability of the GCC countries to cope with high rate of water demand increase resulting from the enormous population growth. Not only does the increase in water demand pose challenges in the cities, but it also remains as a major problem in the industrial areas. The growing levels of major industrial activities (mostly related to the oil and gas industry) in the GCC countries are posing an additional load on water consumption (Al-Zubari 2003; Khouri 2003; Nairn 2003; Rizk and Alsharhan 2003; Dawoud 2005; Lattemann et al. 2010). Indeed, recent studies point to the prediction that over the next decade, the GCC countries will be among the world's highest water users per-capita (McKenna et al. 2010). In order to meet such needs, utilization of current recourses through integrated water networks is as important as utilizing oil and gas reservoirs for the region (Dajnak and Lockwood 2000; Virk et al. 2001; GarcÌa-RodrÌguez 2002; Kim et al. 2002). Therefore, new fresh water producing plants, fresh water storage needs, source and sink allocation have to be studied in detail to demonstrate the actual needs and provide a road map to the booming industries through a sustainable development scheme for the next decade and beyond.

Recent work by Atilhan et al. (Atilhan et al. 2011b) has focused on the macroscopic management of water resources for existing infrastructure. In this work, we expand the scope of macroscopic water management to account for the need to add desalination capacity and to screen competing technologies and to develop a planning scheme for enhancing the water-desalination capacities to respond optimally to the increase in water demands. Moreover, technology use (i.e. reverse osmosis, membrane technology improvements and advancements), electricity cost and desalination size design criteria have also been considered via detailed cost analysis in this work. The case study focuses on infrastructure expansion and water needs for the State of Qatar.

PROBLEM STATEMENT

Given a region with an expected set of water demands over a planning period: DEMANDS = $\{W_t | t=1,2,\ldots,N_{Planning}\}$ where W_t is the required flowrate of water in period (e.g., year) t and $N_{Planning}$ is the time horizon over which the planning is made. The specific water requirements for the different sectors (e.g., domestic, agricultural, and industrial) are also given over the planning period in terms of flowrates and quality. It is desired to determine an infrastructure-expansion plan for water desalination that meets the expected demands at minimum cost.

In deciding the optimal infrastructure-expansion plan, the following factors should be considered:

- Adding a desalination capacity that matches the annual increase in water demand is not necessarily an optimal decision. Large increases in capacity benefit from the economy of scale but incur and additional maintenance and replacement cost.

- Competing desalination technologies should be considered with the possibility of switching from one technology to another during expansion periods.

- Certain desalination technologies are closely tied to power plants. Therefore, the infrastructures for water and power should be simultaneously considered.

- In addition to planning and design, an operating strategy should be developed for allocating water to the different users over the planning time horizon.

APPROACH

First, a structural representation is developed to embed all potential water-network configurations of interest. Here, we generalize the source-interception-sink representation developed by Atilhan et al. (Atilhan et al. 2011b) to account for expanding desalination capacities while considering competing technologies. Fig. 18 is an illustration of the superstructure. The capacities of the desalination plants are allowed to vary over the planning period and water is to be allocated to the different users. An optimization formulation is developed to determine the infrastructure-expansion decisions while accounting for the various constraints.

The following symbols are used:

Annualized fixed cost of the desalination technology = AFC(Z)

where AFC is the functional form of the annualized fixed cost and Z is the design criterion (e.g., area of reverse-osmosis modules).

Annual maintenance and replacement cost = AMRC(Z)

where AMRC is the functional form of the annual maintenance and replacement cost.

MATHEMATICAL FORMULATION

1) Minimization total annualized cost =

Annualized fixed cost of the desalination technology (AFC(Z)) +

Annual maintenance and replacement cost (AMRC(Z))

e) Annualized Fixed Cost of Desalination Technology = $\sum_{t=1}^{N_{planning}} AFC(Z_t)\left(\frac{\$}{time}\right)$

$$\forall t \qquad (5.1)$$

f) Annualized Maintenance and Replacement Cost of Desalination Technology=

$$\sum_{t=1}^{N_{planning}} AMRC_t \left(\frac{\$}{time}\right) \qquad (5.2)$$

where

$$AMRC_t = \alpha\left(\frac{\$}{unit\ mass}\right) * Z_t\left(\frac{mass}{time}\right) + \sum_{t=1}^{N_{planning}-1} \alpha\left(\frac{\$}{unit\ mass}\right) * Z_t\left(\frac{mass}{time}\right) \qquad \forall t \qquad (5.2a)$$

α is a coefficient for maintenance and replacement cost of the desalination technology.

2) $\sum_{t=1}^{N_{planning}} Z_t\left(\frac{mass}{time}\right) \geq \sum_{t=1}^{N_{planning}} W_t\left(\frac{mass}{time}\right) \qquad \forall t \qquad (5.3)$

where W_t is water demand difference for each year and Z_t is an additional capacity added in a year.

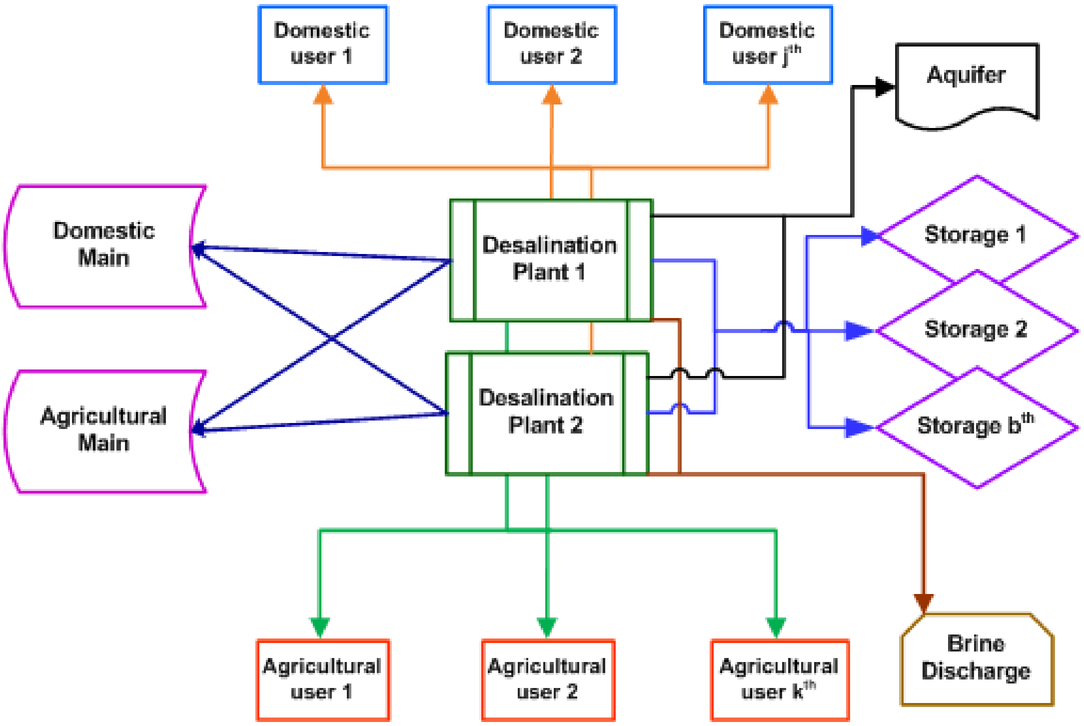

Fig. 18 A source-interception-sink representation scheme for water distribution from desalination plants (Atilhan et al. 2011b)

Desalination system and water distribution network are adapted by (Atilhan et al. 2011b). Problem representation is also drawn in Fig. 18. General water balance is shown in Equation 5.4.

$$
\begin{aligned}
F_{i,t}^{seawater} + F_{i,t}^{groundwater} = {} & \sum_{b=1}^{N_{storage}} F_{i.b,t}^{storage} + \sum_{j=1}^{N_{Domestic\ user}} F_{i,j,t}^{Domestic\ user} + \sum_{m=1}^{N_{mainD}} F_{i,m,t}^{main\ D} \\
& + \sum_{k=1}^{N_{Agricultural\ user}} F_{i,k,t}^{Domestic\ user} + \sum_{n=1}^{N_{mainA}} F_{i,n,t}^{main\ A} + \sum_{e=1}^{N_{aquifer}} F_{i,e,t}^{Aquifer} \\
& + \sum_{d=1}^{N_{discharge}} F_{i,d,t}^{discharge} + F_{i,t}^{brine} + F_{i,t}^{desalinatedloss}
\end{aligned}
\qquad \forall i\,,\ \forall t \qquad (5.4)
$$

The desalinated water is distributed to the various users, i.e.

$$
\begin{aligned}
F_{i,t}^{desalinated} = {} & \sum_{b=1}^{N_{storage}} F_{i.b,t}^{storage} + \sum_{j=1}^{N_{Domestic\ user}} F_{i,j,t}^{Domestic\ user} + \sum_{m=1}^{N_{mainD}} F_{i,m,t}^{main\ D} \\
& + \sum_{k=1}^{N_{Agricultural\ user}} F_{i,k,t}^{Agricultural\ user} + \sum_{n=1}^{N_{mainA}} F_{i,n,t}^{main\ A} + \sum_{e=1}^{N_{aquifer}} F_{i,e,t}^{Aquifer} \\
& + \sum_{d=1}^{N_{discharge}} F_{i,d,t}^{discharge}
\end{aligned}
\qquad \forall i\,,\ \forall t \qquad (5.5)
$$

Equation 5.6 shows that the ratio of the desalinated water to the incoming water called water recovery coefficient ε helps to calculate the performance of the desalination plant.

$$
F_{i,t}^{Desalinated} = \varepsilon_{i,t} \times (F_{i,t}^{seawater} + F_{i,t}^{groundwater}) \qquad \forall i\,, \forall t \qquad (5.6)
$$

Desalinated water assigned to domestic users and agricultural users are shown in Equation 5.7 and Equation 5.8 and are presented in Figs. 19 and 20, respectively.

$$B_{j,t} = \sum_{i=1}^{N_{desalinated}} F_{i,j,t}^{desalinated} + \sum_{m=1}^{N_{mainD}} F_{m,j,t}^{Domestic\ main} + \sum_{b=1}^{N_{storage}} F_{b,j,t}^{storage} \quad \forall j,\ \forall t \qquad (5.7)$$

$$U_{k,t} = \sum_{i=1}^{N_{desalinated}} F_{i,k,t}^{desalinated} + \sum_{n=1}^{N_{Agricultural\ main}} F_{n,k,t}^{Agricultural\ main} + \sum_{r=1}^{N_{WWT}} F_{r,k,t}^{WWT} + \sum_{k=1}^{N_{Agriculturaluser}} F_{k,j,t}^{Agricultural\ users} \quad \forall k,\ \forall t \qquad (5.8)$$

Water distributions after domestic and agricultural user are given by Equation 5.9 and Equation 5.10.

$$B_{j,t} = \sum_{r=1}^{N_{WWT}} F_{r,j,t}^{WWT} + \sum_{k=1}^{N_{Agricultural\ user}} F_{k,j,t}^{Agricultural\ user} + F_{j,t}^{Domestic\ water\ loss} \quad \forall j, \forall t \qquad (5.9)$$

$$U_{k,t} = \sum_{e=1}^{N_{aquifer}} F_{e,k,t}^{aquifer} + \sum_{d=1}^{N_{discharge}} F_{d,k,t}^{discharge} + F_{k,t}^{Agricultural\ water\ loss} \quad \forall k, \forall t \qquad (5.10)$$

Water balances around wastewater treatment unit are shown in Equation 5.11 and Equation 5.12.

$$P_{r,t} = \sum_{j=1}^{N_{\text{Domestic user}}} F_{j,k,t}^{\text{Domestic user}} \qquad \forall l, \forall t \qquad (5.11)$$

$$P_{r,t} = \sum_{k=1}^{N_{\text{Agricultural user}}} F_{k,r,t}^{\text{Agricultural user}} + F_{r,t}^{\text{WWTloss}} + F_{r,t}^{\text{greening}} \qquad \forall l, \forall t \qquad (5.12)$$

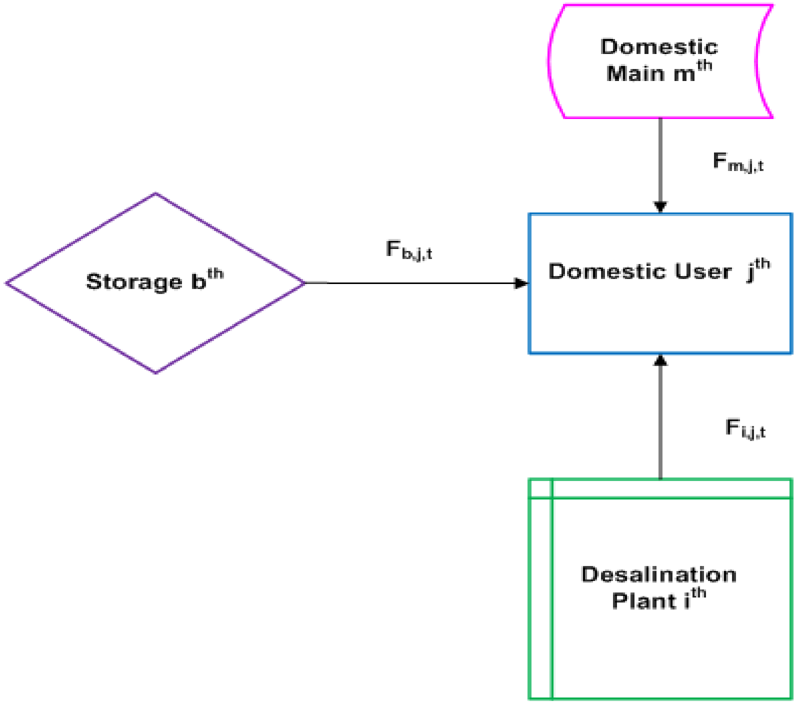

Fig. 19 Desalinated water assignment to domestic users

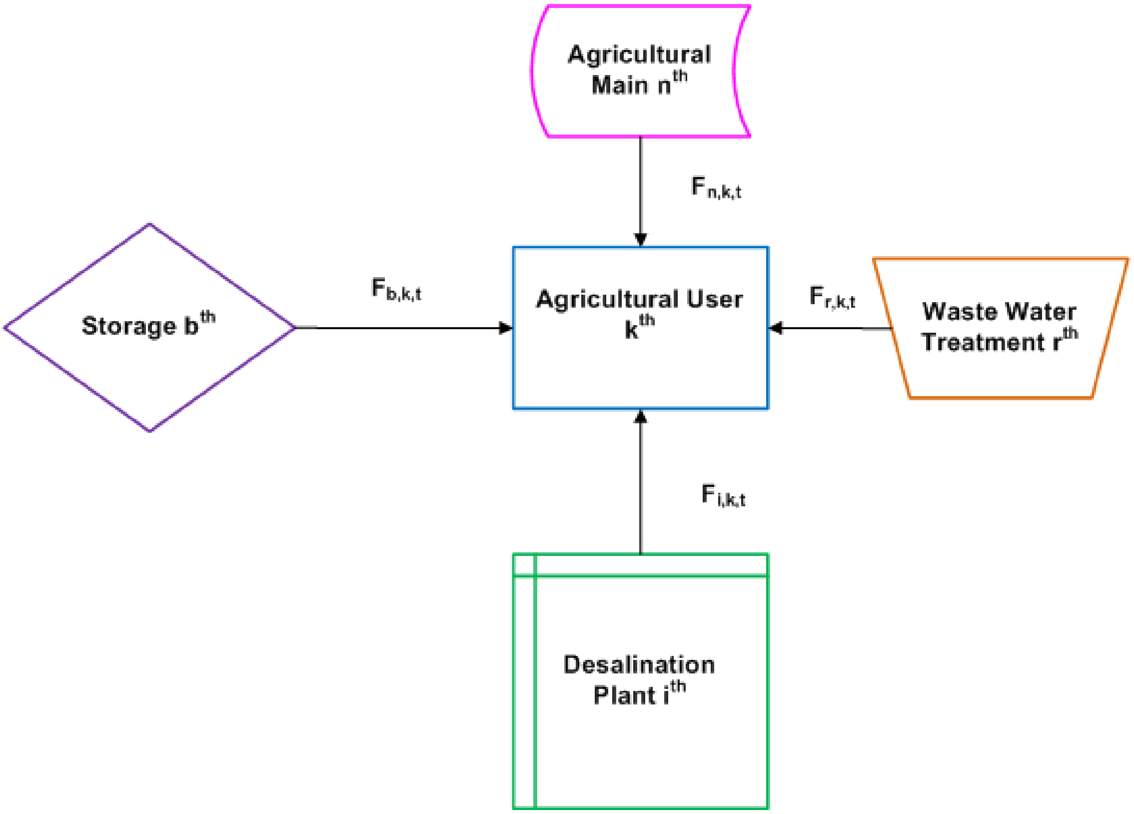

Fig. 20 Desalinated water assignment to agricultural users

CASE STUDY

At present, the large desalination systems in many countries in GCC region that can reach a daily production of even 500,000 m^3, use mainly conventional desalination methods such as thermal desalination (Karagiannis and Soldatos 2008). Obviously, the cost of water produced from desalination systems using conventional source of energy, (gas, oil, electricity) is much lower when compared with reverse osmosis (RO) or multistage flash (MSF) desalination methods (Mathioulakis et al. 2007; Charcosset

2009; Gomri 2009). However, use of RO for the desalination of seawater becomes more and more common during the last years, as the technology enabled more efficient and low cost of water production for this purpose. Therefore, desalination powered by RO and MSF, as opposed to conventional desalination, has already started to be an attractive solution in terms of both induced environmental impact due to lower conventional energy consumption/lower gas emissions and reduced cost in the long run. Thus, in this manuscript, we used RO for seawater desalination and the cost is manipulated based on the energy cost and membrane cost over the next decade till 2020 accordingly.

We consider water demand differences during 2010-2020 in a region. Water demand changes are shown in Table 8. In this framework, reverse osmosis desalination technology is considered. During this period, additional desalinated water capacities are optimized. Economic analysis was done to reach optimum design criteria.

Annual fixed cost ($/yr) is defined as $2227*Z^{0.7}$ where Z is m^3/day (Atilhan et al. 2011a). Maintenance and replacement cost constant is used as 0.4 $/$m^3$ for this study.

The optimization problem was solved using the software LINGO version 11 by LINDO Systems Inc. (Schrage 2006b). The nonlinear program (NLP) is formulated to solve water management problem. The Global Solver (with non-linear and linear solver options) of the software LINGO version 11 is used to solve the problem. In this case study, we have 40 variables and 41 constraints.

Table 8 Water demand changes between 2010-2020

Year	Incremental Water Demand During that Year (MM m^3/day)
2010-2011	0.255
2011-2012	0.114
2012-2013	0.364
2013-2014	0.167
2014-2015	0.037
2015-2016	0.170
2016-2017	0.212
2017-2018	0.213
2018-2019	0.089
2019-2020	0.432

Additional water capacities added between 2010-2020 are calculated and shown in Table 9. The minimum annualized total cost of the system during 10 years is given in Fig. 21.

Table 9 Additional water capacity required for 10 years

Year	Additional capacity added in a year (m^3/day)
1	1533138
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	88647
10	431870

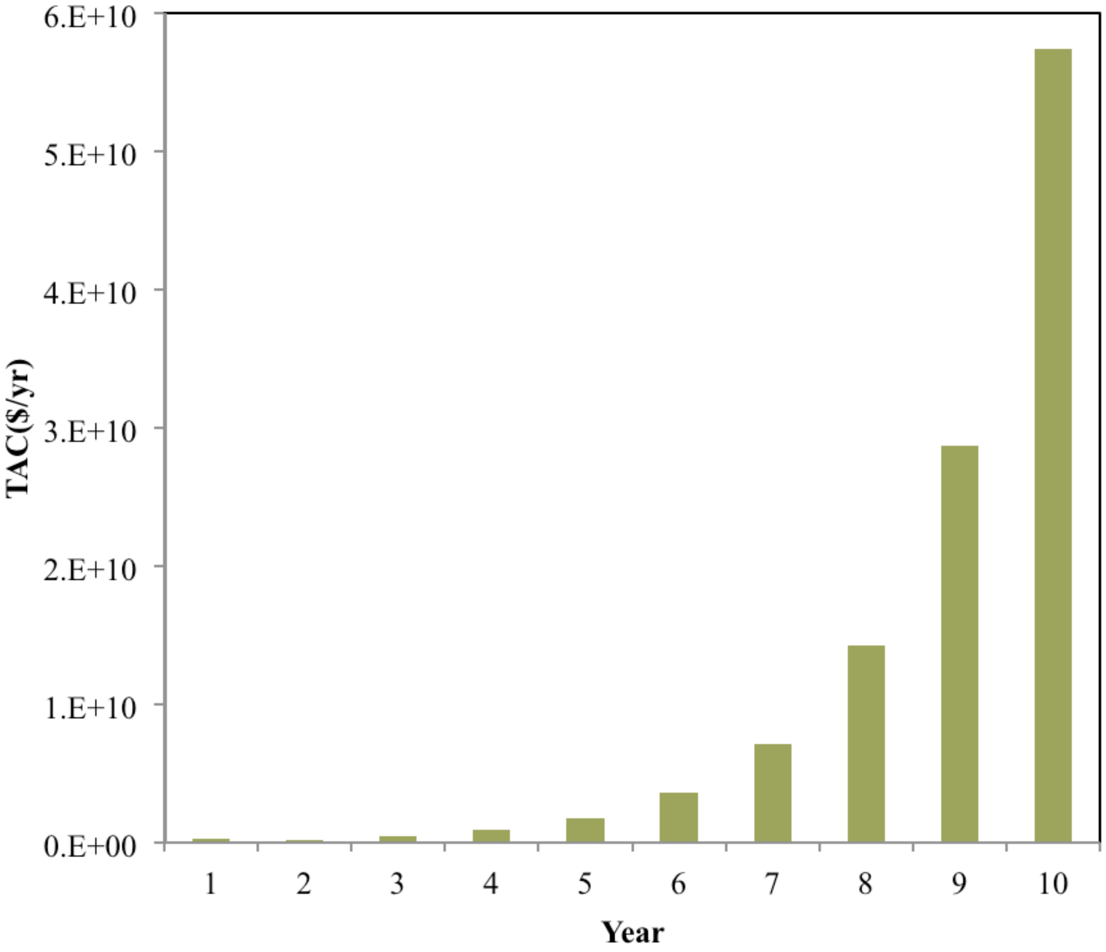

Fig. 21 Total annual cost distribution of the optimal solution during 10 years (2010-2020)

Nomenclature

AFC: Annualized fixed cost

AMRC: Annual maintenance and replacement cost

F, B, U: Water flow rate

W: Water demand difference

Z: Sizing criteria

Z_t: Additional water capacity for each year

Subscript

b: storage

d: discharge

i: desalination plants

j: Domestic users

k: Agricultural users

m: Domestic main

n: Agricultural main

p: Aquifer

r: Waste water treatment

t: Time

Greek letters

α: Maintenance and replacement cost constant of desalination technology

ε: Water recovery coefficient for desalination plant

CONCLUSIONS

In this work, a structural representation of all potential water-network configurations has been developed for the generic case of planning the expansion of water-desalination infrastructure. The representation and the associated optimization formulation can be applied to any particulate region. A case study was solved for planning the desalination infrastructure over a ten-year horizon. Seawater desalination via RO technologies and associated cost were accounted for based on the energy and membrane cost with an expected profile of water demand for the period of 2010-2020. The solution identifies the incremental expansion of desalination infrastructure over the planning horizon while trading off the various cost items so as to minimize the total annualized cost.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This work has introduced an integrated framework for the optimization of water desalination and distribution networks for a whole region. Three related problems have been addressed:

- Optimal design of desalination and allocation networks for a given demand
- Optimal operation of an existing infrastructure of water desalination, distribution, and storage
- Optimal planning for expanding the capacity of desalination plants to meet an increasing water demand over a time horizon

A source-interception-sink superstructure has been developed to embed potential configurations of interest. For the operation and planning problems, a multi-period modeling approach has been adopted. Optimization formulations have been developed to minimize the cost of the system while meeting all technical constraints. Various desalination technologies have been considered and their sizes, design, operation, and location have been optimized. This optimization is carried out along with the design of the fresh water and brine rejection distribution networks. The result is an integrated strategy for a macroscopic system. The optimization formulations have been solved and demonstrated for several case studies.

The following issues are recommended for future research:

- Incorporation of the economic, technical, and environmental effects of brine discharge
- Inclusion of time-based performance of the technologies. For instance, the performance of reverse osmosis declines over time due to fouling. This dynamic change in performance should be included in the optimization formulation.
- Tracking multiple species in the desalinated water (e.g., boron)
- Inclusion of safety analysis in the comparison of alternatives
- Design under uncertainty for the seawater characteristics and performance of the desalination technologies

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