DESALINATION IN THE ARABIAN GULF, RISKS AND THREATS

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Summary

The Arabian (Persian) Gulf, a shallow hypersaline sea, replenished with ocean water from the narrow Strait of Hormuz, is perhaps the most congested water body in the world. It is the most concentrated area of oil exploitation globally, a navigation center through which trillion US dollars of goods flow, the place where sensitive ecosystems exist, and the only long term freshwater source for the region.

The Gulf countries are characterized by extremely low precipitation and high evaporation, no surface waters, and groundwater of low quality, fast being depleted from over-pumping. Desalination has emerged as the answer to this limitation of the region to supply fresh water to an expanding population, to a small, local agricultural production, and to economic activities for the diversification of the Gulf States' economies away from oil and gas.

The risks and threats to the water and ecosystems of the Arabian Gulf come from a number of sources. Raw sewage discharge, alien species in ballast water, chemical and thermal pollution, deposition of microplastics and pollutants via dust storms are some of the threats to the Gulf's water. Brine discharge from desalination plants constitutes a serious threat increasing Gulf's salinity, reducing desalination plants' efficiency, and deteriorating the marine environment.

This chapter provides an overview of the issues related to the Arabian Gulf, focusing on desalinated water production. The water situation of the Gulf countries is presented first, detailing water resources, per capita water consumption, and water use per economic sector. Subsequently, the desalinated water production and technologies in each Gulf state are expounded. The Arabian Gulf's functions are discussed to demonstrate that the risks from desalination are only a part of a bigger picture, which requires a holistic management approach that considers all pollution sources and threats. The chapter concludes with a summary and perspective on the topic.

1. Introduction

The Arabian plate was initially part of the Afro-Arabian continent, which behaved as a single unit to plate tectonic movements. During the late Precambrian Period (ca. 542 Ma), this continent appears to have been glaciated, while later on, in the middle Cambrian (ca. 542-488 Ma), it was often covered by a shallow sea. During the Ordovician Period (ca. 488-444 Ma) Arabia passed near the South Pole becoming glaciated again together with most of North Africa. By the mid- Paleozoic the Afro-Arabian continent became part of the super-continent of Gondwana, which started breaking up in the Permian (ca. 299-252 Ma) and the Triassic (ca. 252-201 Ma). Since the end of the Paleozoic (ca. 251 Ma) Arabia remained in tropical and subtropical latitudes resulting in predominantly semi- to hyper-arid conditions with very low precipitation and high evaporation rates. The Arabian Peninsula was created about 25-30 million years ago when it separated from Africa, opening up and filling with sea water the area known today as Red Sea and Gulf of Aden (EAD, 2005). In modern times the Gulf region exhibits average annual precipitation that ranges from a minimum of 72mm in Bahrain to a maximum of 114mm in Kuwait, and evaporation rates that exceed 2m and can even reach 4m per year.

The Gulf region has been going through rapid economic expansion and significant population movement from neighboring Arab countries, as well as from Asia, primarily, from India, Pakistan, and the Philippines, with multi-million population cities being constructed in places where previously small-population, tribal towns existed. Water is a limiting resource for the economic development of the Gulf States, with this being needed not only for the drinking needs of the increasing population, but also for industrial production and the transformation of the Gulf States to less oil-dependent economies, the establishment of local agricultural production, in order to decrease the almost ninety percent dependence of their food market on imported goods, and the significant forestation efforts, the "greening of the desert", taking place in some of these States (Miracle Publishing, 2010).

Desalination has emerged as the solution to the scarcity of water resources in the Gulf region and in 2019, GCC (Gulf Cooperation Council) countries had reached 81% of the global desalinated seawater capacity (Emirates News Agency, 2019). At the same time the energy needs for construction and operation of buildings, infrastructure development, and for other economic activities, including desalination production, have led to disproportionate, to these States' population, greenhouse gas emissions. Thus in 2019, Iran, Saudi Arabia, the United Arab Emirates (UAE), Qatar, Kuwait, and Oman emitted 780, 582, 191, 109, 108, and 72 MtCO_2, respectively. In particular, Iran was ranked in 2019 sixth in the world in CO_2 emissions, Saudi Arabia tenth, UAE number 31, Qatar number 39, Kuwait number 40, and Oman was ranked 49 (Global Carbon Atlas, 2019).

At the same time the record for water conservation in the GCC appears to be poor. The Environment Agency Abu Dhabi (EAD), reported a 2017 daily domestic water consumption of 590L per capita per day (EAD, 2017), a similar number reached in 2014 by Bahrain, while Qatar estimated at 500 L/capita/day, and Kuwait at 445 L/capita/day (State of Kuwait, 2021), follow close after these two top, water-consuming Gulf countries. These four GCC countries compare very poorly with, for example, the 2020 domestic water use in the European Union (EU), which reached a high of 243 L/capita/day in Italy and a low of 50 L/capita/day in Malta (European Parliament News, 2020). Other countries in the Arabian Peninsula, such as Oman and Saudi Arabia are at about 260 L/capita/day (U.S.-Saudi Business Council, 2021), still high for the region, but almost half of the water that the top water-consuming GCC countries utilize.

The present chapter summarizes the water situation in the Gulf region, presents the desalination technologies utilized in the GCC and the allied environmental problems, discusses the characteristics and functions of the Arabian Gulf as a major shipping route for oil exportation, navigation, wastewater effluent outlet, tourism, and entertainment, and concludes by presenting the risks and threats to the quality of the water of this almost closed sea as a result of the existing and projected desalination activities.

2. The Water Situation in the Gulf Region

This section summarizes briefly the water resources of the GCC countries, illustrating their need for desalination as an alternative water source.

The UAE has an average annual precipitation of about 100mm, varying between desert and mountain regions, and an evaporation rate that exceeds 2.5m/yr. From the early 2000, the annual population growth rate reached about 6%, and it now has a population approaching 10 million people. The country lacks any surface water bodies and the fact that the geologic history of the region includes being the bed of a shallow sea, where evaporites precipitated, has made about 82% of its surficial aquifers to be brackish, saline, or brine. As a result of a desalinated-seawater aquifer storage and recovery program (ASR), approved in 2010 and completed in 2017, the UAE has in Abu Dhabi an emergency water reserve that can last for three months, whereas the other GCC States have emergency water reserves of the order of only a few days (Pavlopoulos and Kallioras, 2017). The only other significant area of fresh water is located at the northeast part of the country, naturally recharged through the Oman aquifers that are replenished by orographic precipitation.

The UAE's arable area was reported in 2018 to be 0.6% of this country's total land area by the World Bank Group (2021d). Agricultural production concentrates on the Emirate of Abu Dhabi, which covers 87% of the UAE's land area, and contains about 24,000 farms and approximately 100,000 wells. Agriculture, forestry, and parks, in 2016, utilized 71.3% of the water use in the Emirate of Abu Dhabi, UAE, which, in total, was estimated to be about 3,300 Mm^3/yr. This sector used 2,013 Mm^3/yr of groundwater

(EAD, 2017), as well as 21.7% of the consumed desalinated water, which in total was 1,078 Mm^3/yr for Abu Dhabi, and about 113 Mm^3/yr of the recycled water produced (SCAD, 2020). The discrepancy between annual natural aquifer replenishment, which is about 140 Mm^3/yr, and the above groundwater overdraft has led to significant water table drops and to many wells becoming dry. Areas of maximum groundwater depletion concentrate on the upper eastern and southern parts of the country with groundwater level drops, during the period of 2000 to 2016, exceeding forty meters at locations of intense farming (EAD, 2017).

The total of approximately 3,300 Mm^3/yr water consumption in Abu Dhabi is covered 60% by groundwater, 35% by desalinated water, and the remainder by recycled water (EAD, 2017). The other economic sectors rely exclusively on desalinated water, with domestic at 45.1%, the government at 11.8%, commercial at 18.5%, industry at 2.6%, and other at 0.3% completing (together with the 21.7% in agriculture) the desalinated water of 1,078 Mm^3/yr used in 2019 in Abu Dhabi (EAD, 2017; SCAD, 2020). At Dubai, the other major city of UAE, the Dubai Electricity and Water Authority (DEWA) announced in 2021 that it has increased its desalinated water capacity to 813 Mm^3 per year (DEWA, 2021). Grey water reuse in UAE is hindered by a public perception that although considers a water shortage in the future to be likely, still to a large percentage thinks that fresh water is plentiful (Maraqa and Ghoudi, 2016).

Qatar is a small peninsula with maximum length of 180km and maximum width of 65km and with a population that from 600,000 people in 2000 reached over 2.8 million in 2020. Qatar’s arable area is estimated to be only 1.2% (Kamal et al, 2021). The country has no surface waters, an average precipitation of 76mm/yr, which for the period of 1901 to 2020 had a minimum of 5.96mm in 1946 and a maximum of 207.37mm in 1976 (World Bank Group, 2021a), and an evaporation that is almost 30 times more than rainfall (Shomar et al., 2014).

Saltwater intrusion and significant groundwater drops compound some of the water problems in Qatar, with groundwater extractions utilized for the irrigation of farms, which are located at the northern and central part of the country. Groundwater abstractions exceed five times natural replenishment, with abstractions being about 225-250 Mm^3/yr versus 47.5 Mm^3/yr of the theoretical maximum exploitable groundwater volume, according to the Qatar Ministry of Development Planning and Statistics (Qatar MDPS, 2016). The Qatar Planning and Statistics Authority (2018) has estimated that in 2018 its total renewable water resources were 73.8 Mm^3/yr and hence the country depends on desalination to meet its municipal water needs (99% of domestic water demand is met by desalination). Qatar is proceeding with an aquifer recharge project for water security reasons as it currently has only two days of emergency water supplies.

Water use in Qatar in 2013 per economic sector was broken down to 285 Mm^3/yr used in agriculture, of which 55 Mm^3/yr came from treated sewage effluent (TSE); 19 Mm^3/yr in industry and construction, which includes mining and quarrying (including oil and gas), manufacturing, building and construction, and electricity; 43 Mm^3/yr in the commercial sector, which includes trade, restaurants, hotels, transport and communications, finance, insurance, real estate, and business and household services; 87 Mm^3/yr in the government sector (of which 24 Mm^3/yr came from reused TSE), which consists of the water use by the Qatar General Electricity and Water Corporation, and the irrigation of parks; and 245 Mm^3/yr for household consumption (Qatar MDPS, 2016).

Kuwait with a population of 3 million people in 2020 possesses the fifth in the world crude oil reserves, and its rich, oil-based economy relies heavily on food imports. It is one of the most water-stressed countries in the world, as a result of an average annual precipitation of 112mm over the last century and an annual evaporation that approaches 4m (Almedeij, 2012). As in other Gulf countries, precipitation is highly variable from year to year with droughts being a recurrent situation.

Groundwater withdrawals in Kuwait are 255 Mm^3/yr, 12 times the annual groundwater inflow (Ismail, 2015). Only 0.6% of Kuwait's land is arable, and land degradation and salinization, owing to the use of brackish water in agriculture, has led to reduced crop yields. Due to the danger of potential disruptions in the shipping routes through the Strait of Hormuz, Kuwait, together with other Gulf countries have promoted policies to increase food sufficiency, which conflict with their extremely limited water resources and the poor quality of their cultivated soil. High rates of withdrawal have led to increased salinity in the existing water supply. The country's desalination plants, which in 2001 had a total annual capacity of about 602 Mm^3/yr (Hamoda, 2001) had increased to about 723.5 Mm^3/yr by 2017 and these are the primary source for drinking water in Kuwait, representing 93% of the fresh water, and 73.5% of the total water resources used (which include low salinity brackish and recycled water) (Darwish and Al-Najem, 2005).

The World Bank Group lists Saudi Arabia with an average annual precipitation of about 80mm for the period of 1901-2020. This has fluctuated more strongly after the 1950s with a minimum of 54.37mm in 1970 and a maximum of 103.36mm in 1993. The southwestern part of the country receives almost four times more rain than the country's average (World Bank Group, 2021b). The evaporation rate in the Red Sea area was found through direct oceanographic observations to be about 2.06m/yr (Sofianos et al., 2002).

Total water demand during the period 2011 to 2018 in the Kingdom of Saudi Arabia (KSA), which has a population of about 35 million people, was between 19 and 24 Bm^3/yr, while this dropped substantially to about 15 Bm^3/yr in 2019 (Table 1) (KSA MEWE, 2019). Renewable water was estimated in 2014 to be about 2.4 Bm^3/yr (Ghanim, 2019). The water consumption per economic sector from 2010 to 2019 is presented in Table 2(KSA MEWE, 2019). Table 2 indicates that for the years 2010 to 2018, agriculture consumed from 80% to 84% of the total water allocated, while this percentage dropped in 2019 to 68%. Treated wastewater reuse is very limited in KSA and there exists significant potential for its beneficial use in forestry, parks, and for targeted crop irrigation.

The KSA arable area is only about 1.6% of the country's total area and the majority of this is watered by drip or sprinkler irrigation (about 67%), while the remaining with traditional irrigation methods. The total number of well licenses in 2019 was 151,497, whereas KSA at the same period had 522 dams with total reservoir capacity of 2.3

Bm^3/yr, most of which is utilized in the southwestern provinces of Asir, Mecca, and Jizan, which are characterized by significant surface and ground water resources (KSA MEWE, 2019).

A significant drop in the total water demand took place in 2019, which was 35.4% less than that of the previous year. This did not affect the allocations of water to the urban – which included the domestic and commercial use - and industrial sectors, but came exclusively from water reductions in the agricultural sector. Of the 3,493 Mm^3/yr of water consumed by the urban sector in 2019, 2,256 Mm^3/yr came from desalination, and the remaining 1,237 Mm^3/yr from groundwater sources (KSA MEWE, 2019).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Water use (Mm^3/yr)	17.447	19.193	20.884	22.260	23.416	24.833	23.934	23.350	23.828	15.3.93

Table 1. Water use in the Kingdom of Saudi Arabia (KSA) for the period 2010-2019 (KSA MEWE, 2019)

Year/Sector	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Agriculture	14,410	15,970	17,514	18,639	19,612	20,831	19,789	19,200	19,000	10,500
Industrial	753	800	843	890	930	977	1,015	1,000	1,400	1,400
Urban	2,284	2,423	2,527	2,731	2,874	3,025	3,130	3,150	3,428	3,493
Total	17,447	19,193	20,884	22,260	23,416	24,833	23,934	23,350	23,828	15,393

Table 2. Water consumption (Mm^3/yr) in the Kingdom of Saudi Arabia (KSA) per economic sector for the period 2010-2019 (KSA MEWE, 2019)

The Kingdom of Bahrain is composed of 36 islands, shoals, and inlets of which the main island comprises 85% of the total area of the country. Its economy is by and large oil-dependent, its population is about 1.7 million people, living in a country where the per capita renewable groundwater reserves are 3m^3, compared to a world average of 6,000m^3. Bahrain's arable area was reported in 2018 to be 2.1% of the country's total land area (World Bank Group, 2021d). As is the case for all other Gulf States, precipitation is mostly absent from the end of April to the end of October, and the historical precipitation record of 1901-2020 exhibits a minimum of 5.56 mm of rain that occurred in 1946, and a maximum of 205.97 mm in 1976. The hundred-and-twenty year precipitation average is at around 75-80mm per year (World Bank Group, 2021c).

Groundwater overdraft in Bahrain has resulted in both a significant drop of the water levels in the Dammam aquifer, and deterioration of the groundwater quality through saltwater intrusion (Miracle Publishing, 2010). As a result the Dammam aquifer has salinity that is less than 3,500 mg/L only at a small north-west strip of the main island. The relative high salinity of municipal water, which had reached 1,500 mg/L of Total Dissolved Solids (TDS) in 2005, and the infiltration of saline groundwater into the sewage piping system had led to the wastewater exhibiting a salinity of 4,000 mg/L, hence making it inappropriate for reuse (Fanack Water, 2020).

The water distribution systems in the Gulf region exhibit vulnerability as regards to the climate change, with similar inefficiencies and problems applying, to a greater or lesser degree, to all GCC countries. These include the following.

Despite the young age of the municipal water, as well as of the sewage networks in all Arab Gulf States, significant leaks exist, which approach those from European cities' aging water and sewerage systems. Thus, in the Kingdom of Bahrain leakage from water distribution pipelines was around 30% in 2008 (Al-Zubari et al., 2018). In the UAE in 2012, about 11% of Dubai's water was lost due to poor pipe welding from unskilled labors and uncertified contractors, according to official sources from DEWA (The National newspaper, Nov 26, 2012, "More than 10 percent of UAE's precious water supply leaking away"). In Abu Dhabi, EAD (2017) reported that 20% to 30% of the desalinated water production was lost through the transmission and distribution networks, with distribution being responsible for about 21% of the water losses. Leakage is also encountered in the sewerage network, with only 28.6% of the consumed desalinated water returning to it. In 2015, almost half of the treated wastewater in the Emirate of Abu Dhabi was disposed in the desert or the Arabian Gulf due to underdeveloped systems (EAD, 2017). In Qatar despite improvements in the water network by the water utility, which resulted to a reduction of water losses from 32% to 20.9%, according to Hussein and Lambert (2020), or to 17.7%, according to Qatar Planning and Statistics Authority (2018), with most of these losses due to unaccounted-for water. In Qatar, only 24% of the TSE is reused annually, the remaining being discarded in the Gulf. In Kuwait, most of the main water networks are made of ductile cement pipes, with the rest being asbestos or steel coated. The total length of the Kuwaiti water network, at the end of 2020, was about 18,200 km. There were 670 incidents, in Kuwait in 2020, of water pipe breakage, due to corrosion, decay, or from excavation and construction works, or land subsidence (The State of Kuwait, 2021), although Al-Khalid et al. (2013) had reported that freshwater losses did not exceed 12%.

The perception in a large part of the population of these countries that water is plentiful has led to excessive and wasteful water use. Thus, the Electricity and Water Authority (EWA) of Bahrain has estimated that up to 85% of the private properties' metered water can be expended in non-essential uses, such as car washing, lawn and garden watering, etc. Non-essential water usage, internal water leakages, and negligence represented on the average 48% of the metered private property water supply in Bahrain (Al-Zubari et al., 2018). A survey of the water habits of UAE's university students found that 53% of them do not close the tap while brushing their teeth, 58% keep the water running when showering, and 76% of the students do not turn off the tap while washing their face (Yagoub et al., 2019). At the same time, for religious and cultural reasons, public acceptance of greywater reuse in the Gulf countries, such as in Qatar and the UAE, is limited and restricted to outdoor use, such as for landscaping, gardening, and car wash (more than 70% acceptance rate), with less than 20% approval rate for indoor use, aquifer recharge, and discharge in swimming waters (Maraqa and Ghoudi, 2016; Hussein and Lambert, 2020).

Water pricing policies in the Gulf States have not helped motivate people practice water savings measures. The Qatari government fully subsidizes water for the nationals' main residence, whereas for the expatriates, which constitute almost 90% of the population, for blue-collar workers in the construction industry, water of the compound they live in is paid collectively by their employer, and for white-collar professionals their bill is part of their benefits package. In Qatar, only 8% of the nationals and 51% of the expatriates even receive a water and electricity bill, which for 55% of the expatriates that do receive a bill, this gets paid by their employer (Hussein and Lambert, 2020). The Abu Dhabi Distribution Company (ADDC) charges for nationals, 2.09 AED (1 USD is about 3.68 AED) per cubic meter of water, if consumption is up to 0.7m^3 for an apartment and up to 7m^3 of water for a villa, per day, which increases to 2.6 AED after that volume. For expatriates, the water tariffs are: 7.84 AED per cubic meter of water, if consumption is up to 0.7m^3 for an apartment and up to 5m^3 of water for a villa, per day, which increases to 10.41 AED above this consumption rate (ADDC, 2021). The water tariffs in Saudi Arabia are incremental depending on the water use, and they are categorized in five blocks: 0.027 USD per m^3 for a monthly consumption of water of up to 15m^3; 0.27 USD per m^3 for monthly usage of 16-30 m^3; 0.8 USD per m^3 for use of 31-45m^3 of water; 1.067 USD per m^3 for 46-60 m^3, and 1.6 USD per m^3 above 60 m^3 of water usage per month (Mcllwaine and Ouda, 2020).

Several major points can be summarized from the above exposition.

(i) All Arabian Gulf States are characterized by a hyper-arid climate with extremely low, spatially and temporally variable precipitation, of the order of a few tens of millimeters per year, and evaporation rates of the order of meters.

(ii) Water scarcity is a prevalent characteristic of the Gulf States, all of which have very limited renewable groundwater resources, of the order of a few cubic meters per person, while the global average is 6,000 m^3 per capita (World Bank Group, 2021c).

(iii) Despite the dire water situation, water consumption in these states is topping the list of the countries in the world, and there appears to be little comprehension by their populations of the severity of the problem and the need for water savings.

(iv) Gulf States' arable area is only a very small fraction (less than 2%) of their total land area, smaller than the 4.5% that characterizes the Arab world, and much lower than North America's 10.8%, EU's 24.7%, South Asia's 43.2%, and of the global average of 10.8% (World Bank Group, 2021d).

(v) Gulf States have by and large poor soils, and the combination of rapidly increasing population and limited local food production makes them rely heavily on food imports, raising the issue of food security for the whole region.

(vi) The effort to diversify their economies away from oil and gas, which for some countries, such as the UAE has met with significant success, requires the allocation of increased quantities of water for industrial and manufacturing purposes, which can only come at the expense of the water currently used for agricultural and household needs (Paleologos et al., 2018a). This becomes apparent from the relative efficiency of the water utilization in different economic sectors toward a country's GDP. Thus, for example, in Qatar, in 2016, 1L of water, which was used in agriculture generated 0.003 QR (Qatar Riyal) of the GDP, whereas the same 1L of water utilized by the commercial sector produced 1.29 QR, and from the industrial sector 47.63 QR of the GDP (Qatar Planning and Statistics Authority, 2018).

The size of the population, needed to support a dynamic economy, but which will also consume less water; efficient irrigation technologies, in the presence of high evaporation rates, in order to reduce external food reliance; diversification of the economy, which will require increased water quantities, all constitute a challenging and dynamic set of intertwined facets of the water-energy-food security nexus that the Gulf States are facing (FAO, 2014; IRENA, 2015; UN ESCWA, 2016).

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Biographical Sketch

Evan K. Paleologos holds BSc and MSc degrees in Civil and Environmental Engineering from Polytechnic University, New York (currently Tandon School of Engineering, New York University (NYU), New York), and a PhD (1994) in Hydrology from the Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA. From 1992-1995 he was employed by Intera Inc. under the US Department of Energy (DOE) Office of Civilian Radioactive Waste Management, where he was involved in the hydro-thermal modeling of the high-level radioactive waste repository at Yucca Mountain Project, Nevada. From 1995 to 2007 he was Assistant and tenured Associate Professor at the Department of Geological Sciences, University of South Carolina (USC), Columbia, South Carolina, USA. At USC he co-founded the Center for Water Research and Policy, through the award of a multi-million grant, served as Director of the Professional M.Sc. Degree in Environmental Geosciences and at the Faculty Senate, and he and his research group received multiple awards by the university, the state, and nationwide. Upon his return to Greece in 2007 at the Department of Environmental Engineering, Technical University of Crete he also served as Science Advisor on Water Issues to the Greek Minister of Energy, Environment and Climate Change (2011-12), and as Deputy Chairman of the Board of Directors of the Athens Water Supply and Sewerage Co. (2013-15), the sole water and wastewater authority for the city of Athens, Greece. In the United Arab Emirates, he is currently professor in Civil Engineering at Abu Dhabi University (ADU). From 2015-2020 he served as Chair of this department at ADU, and founded one of the three university's centers of excellence, of Sustainable Built Environment, serving as its director (2014-18). Dr. Paleologos has authored four books by Elsevier, McGraw-Hill, and the Geological Society of America (GSA), and over 110 refereed publications. He has been Associate Editor of three international scientific journals and is currently Vice-President for Middle East of the International Society of Environmental Geotechnology (ISEG).