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مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative

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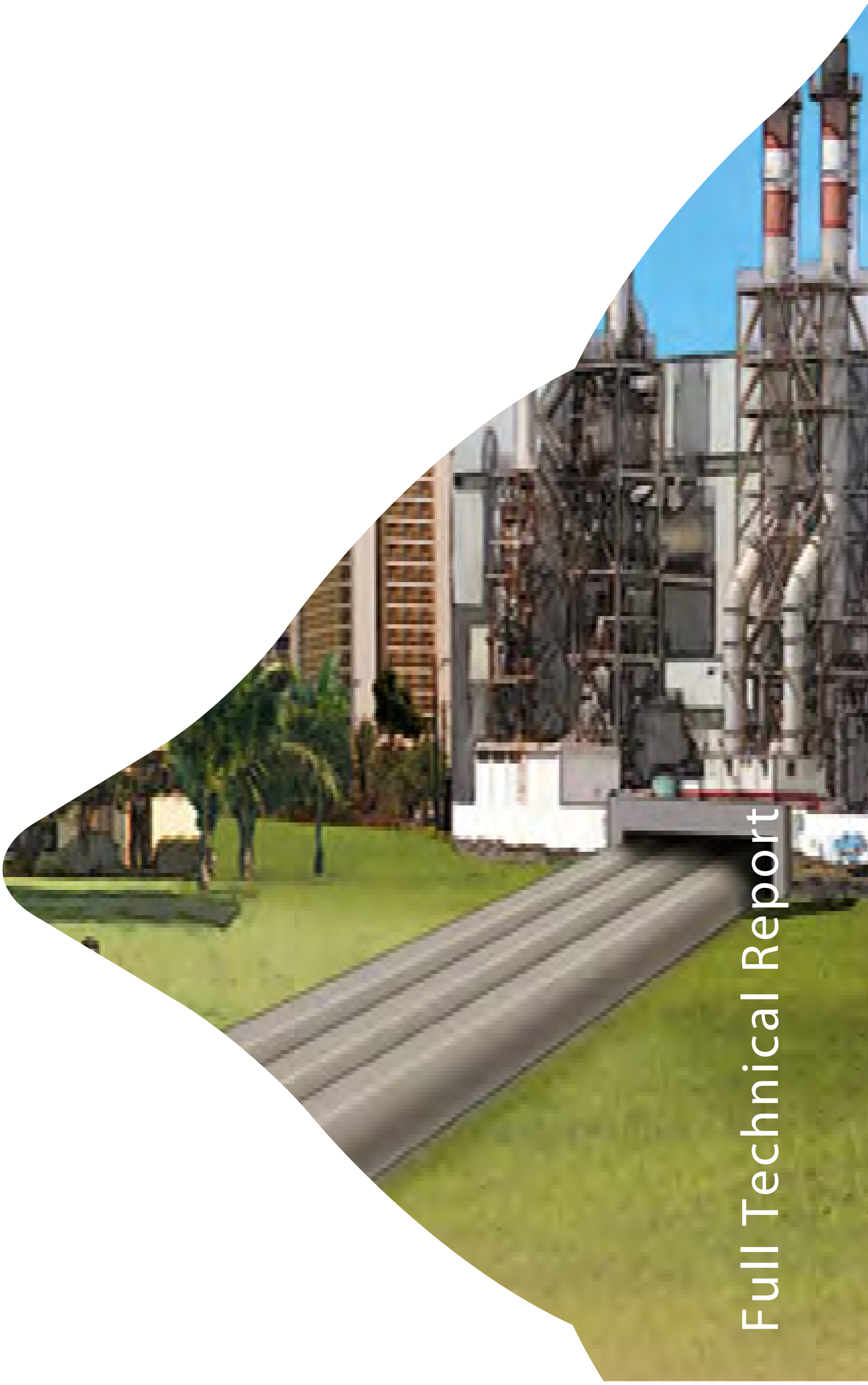
CLIMATE CHANGE PROGRAMME

SOCIOECONOMIC SYSTEMS: DESALINATED WATER SUPPLY

- Atmospheric Modelling
- Arabian Gulf Modelling
- Terrestrial Ecosystems
- Marine Ecosystems
- Transboundary Groundwater
- Water Resource Management
- Al Ain Water Resources
- Coastal Vulnerability Index
- **Desalinated Water Supply**
- Food Security
- Public Health Benefits of GHG Mitigation
- Sea Level Rise



Full Technical Report

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Abu Dhabi Global Environmental Data Initiative

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About this Final Technical Report

In October 2013, the Abu Dhabi Global Environmental Data Initiative (AGEDI) launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder-driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research sub-projects across 5 strategic themes.[1] The "Desalination and Climate Change" sub-project within this Programme aims to assess the vulnerability of the Arabian Gulf waters to climate change in the context of socioeconomic growth in the region.

The purpose of this "Final Technical Report" is to offer a summary of what has been learned in carrying out all research activities involved in the "Desalination & Climate Change" sub-project. Ultimately, this report seeks to provide the reader with a comprehensive review of the methodological approach, analytical framework, data acquisition challenges, key assumptions, major findings, and other issues that can encourage future research regarding the strengthening of measures to protect Arabian Gulf waters.

The authors of this report are José Edson, Ilana Wainer, and Bruno Ferrero from the Oceanography Institute at the University of Sao Paulo in Brazil. The authors would like to acknowledge the contributions of Bill Dougherty from the Climate Change Research Group and Patrick Keys from Colorado State University who assisted with projection of future brine discharges into the Gulf

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[1] For more information on the LNRCC programme and the desalination sub-project, please contact Jane Glavan (lnrclimatechange@ead.ae).

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List of Acronyms

°C	Degrees Celsius
AG	Arabian Gulf
AGEDI	Abu Dhabi Global Environmental Data Initiative
AR5	The 5th Assessment Report of the IPCC
AVHRR	Advanced Very High Resolution Radiometer
CCSM4	The NCAR Community Earth System Model Version 4
cm	centimeter
CMIP5	Climate Model Intercomparison Version 5
CO_2	Carbon dioxide
CTD	Conductivity-Temperature-Depth
DCOM	Downscaled Climate Ocean Model
DSL	Dynamic Sea Level
EAD	Environment Agency of Abu Dhabi
ECMWF	European Center for Medium Range Forecast
ESM	Earth System Model
GCM	General Circulation Model (or General Climate Model)
GHG	Greenhouse gas
GMSL	Global Mean Sea Level
GTE	Global-ocean Thermal Expansion
GWI	Global Water Intelligence
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
LLJ	Low Level Jetstream
LNRCCP	Local, National, and Regional Climate Change Programme
LTR	Long-Term Run
m/s	meters per second
Mm^3	million cubic meters
MPI	Max Planck Institute
MPIMR	Max Planck Institute Mixed Resolution model
NODC	National Oceanographic Data Center

OCL	Ocean Climate Laboratory
psu	practical salinity unit
RCP	Representative Concentration Pathway
ROMS	Regional Ocean Model System
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TCS	Turbulent Closure Scheme
TS	Temperature-Salinity
W/m^2	watts per square meter
WOA	World Ocean Atlas
WOD	World Ocean Database
WRF	Weather Research and Forecasting model

Selected Glossary

Advection	Denotes the horizontal transport (or movement) of a fluid and its properties.
Baroclinic	Refers to how misaligned the gradient of pressure is from the gradient of density in a fluid. It denotes the depth-dependent part of ocean-stratified flow. In the ocean, temperature and salinity dominate the density gradients. The baroclinic ocean component is responsible for most of the long term mixing processes and water masses formation, contributing to overall climate balance.
Barotropic	In a barotropic fluid, density is a function of pressure only, constant in a first order of approximation. Therefore, barotropic flows are observed along the entire water column and dissipates energy at the bottom (drag coefficients). In the ocean, the barotropic and baroclinic components are complementary, with relevance pending on the phenomena.
Water Masses	These are quantities that can be observed in the stratified ocean. They have a core property, described by the temperature, salinity, dissolved oxygen etc. They usually have a formation zone, where specific core properties are obtained.
Circulation	The flow, or movement, of a fluid (e.g., water or air) in or through a given area or volume.
Climate	Climate is not the same as weather, but rather, it is the averaged weather pattern for a particular region. Weather describes the short-term state of the atmosphere, whereas climate refers to the low frequencies and trends. Thus, in a simplified view, climatic changes are about the long-term changes in the planetary average weather conditions.
Climate Model	A quantitative way of representing the interactions between the atmosphere, oceans, cryosphere (all ice components), lithosphere (land areas), biosphere (Earth bio-chemistry) and anthropogenic greenhouse gases effects. Their complexity is proportional to the physics they couple, thus in permanent evolution.
Climate projection	An analogous concept for forecasting (derived from weather), but applied to long-term climate changes. From this term derives the expressions "climate ocean projection" and

	"regional climate ocean projections", which consists of isolating and projecting in time changes in specific ocean regions.
Gyre	The equilibrium slow averaged flow of water around an ocean basin or balanced by gradients in the middle of the oceans. Their instability may yield mesoscale eddies which cascade to turbulence or propagate till merging with another ocean structures. Ocean gyres occur also in the vertical, combining concepts of baroclinic gradients and water masses.
Kelvin Wave	A well-known kind of trapped wave, formed in any rotating fluid with physical boundaries. In the ocean they are usually observed in ocean basins, propagating barotropic signals counter-clockwise (clockwise) in the North (South) hemisphere. In the ocean, an eastward-moving equatorial kelvin wave is also formed, trapped by the equator rotational properties.
Mixing layer	The top/bottom/lateral layer of the ocean in which wind/bottom drag/lateral walls and convection stir it up, creating conditions that uniforms ocean properties.
Salinity	In a very simplified way, salinity can be understood as the total amount of dissolved material in grams in one kilogram of seawater.
Sea Surface Height	The variable height of the sea surface above or below the geoid.
Sea Surface Temperature	The temperature of the upper layer of seawater (approximately 0.5 meters deep), in contact with the atmosphere.

Executive Summary

Under current conditions, the Arabian Gulf is already one of the most stressed marine environments on earth. It is a semi-enclosed, highly saline sea between latitudes 24°N and 30°N surrounded by a hyper-arid environment. The Arabian Gulf is characterized by salty ocean water inflow from the Gulf of Oman along the Iranian coastline and limited freshwater inflow via the Tigris, Euphrates, and Karun rivers at the delta of the Shatt al Arab in Iraq. The Arabian Gulf produces, by unbalanced evaporation, high saline water mostly on its shallows zones. Compounding this highly saline picture of the Arabian Gulf is the fact that it is also a region of intense seawater desalination activity. Today, about 40% of freshwater needs in the Arabian Peninsula region are met by the desalination of seawater.

Under climate change, the Arabian Gulf will become even more highly stressed, quite apart from any environmental impacts associated with increasing desalination. As part of another sub-project within the LNRCCP, the response of the Arabian Gulf was modeled under climate change conditions associated with Representation Concentration Pathway 8.5 (RCP8.5) as reported in Edson, et al., 2015. This study found a number of key impacts regarding temperature and salinity for the Gulf, including changes in the dynamics and a likely increase of the Southwest coastal salinity, due to local effects of global warming. However, this earlier study did not account for socioeconomic growth in the region and the corresponding increase in desalination activities to keep pace with water demand.

The current study investigated the combined impacts of climate change and desalination on the physical properties of the Gulf. Desalination is likely the only viable water supply option for the hyper-arid countries of the Arabian Peninsula. However, the intensification of desalination activities within an already stressed Arabian Gulf may pose adverse a range environmental implications under climate change. Desalination processes separate seawater (or some other source of water containing a high proportion of suspended solids) into freshwater which is then distributed to meet the freshwater demands of households, businesses, amenity, and industry; while hot brine concentrate is disposed into the Arabian Gulf, leading to changes in temperature and salinity levels. The focus of the modeling was on both vertical changes (i.e., deep and shallow areas) and lateral changes (i.e., northern and southwestern areas) from an intensification of desalination activities. Figure ES-1 shows the spatial domain of the study.

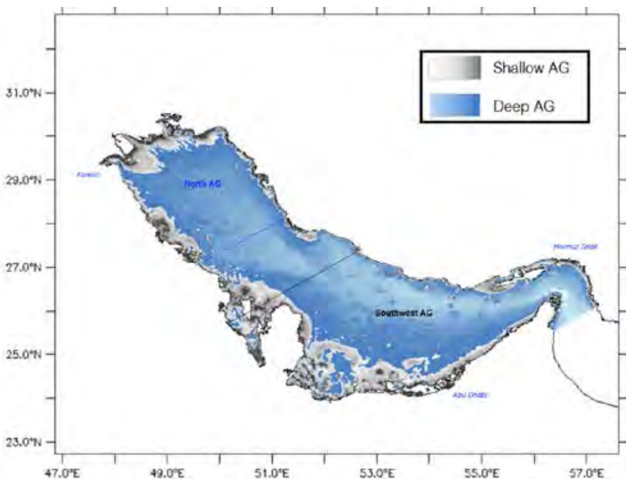


Figure ES-1: Spatial domain of the study

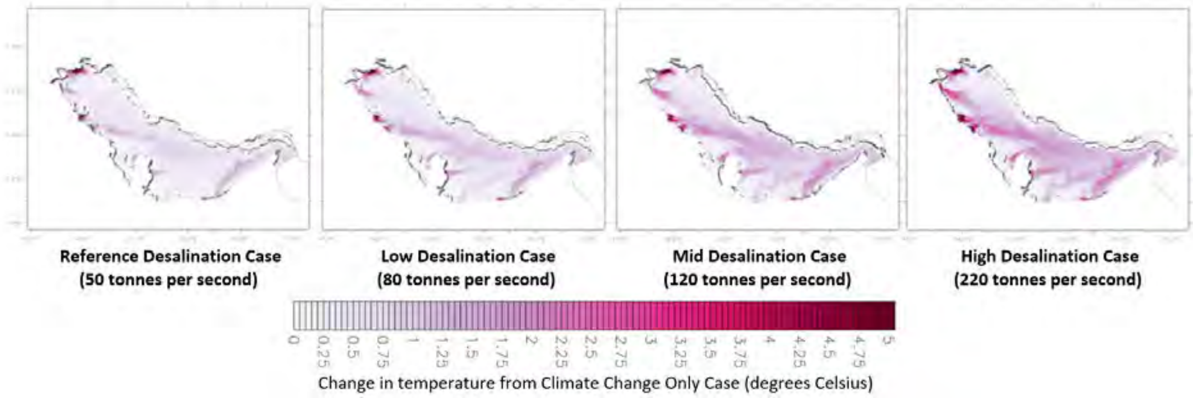
Predicting the future combined impact on Gulf waters from climate change <u>and</u> desalination was a multifaceted challenge that

required three simplifying assumptions. First, the starting point for the modeling effort was the previous experiment in the Arabian Gulf in which a validated regional ocean model was developed for the Arabian Gulf and used to project the impact of climate change to 2050 (Edson et al, 2015). Second, the large number of desalination units that use Arabian Gulf waters as a feedstock were spatially reduced into fourteen (14) representative points whose annual brine discharges were collectively equivalent to the magnitude from all plants. These are called “saline rivers” in this study. Third, the saline rivers were modeled as direct injections of hot brine into the Gulf. Given the uncertainty, of future desalination activity, a scenario approach was adopted in which four (4) potential scenarios of hot brine discharge levels were modeled.

The study found that desalination activities will significantly impact surface and bottom temperatures throughout the Gulf. This is illustrated in Figure ES-2a for which shows the difference in average bottom temperature for four (4) potential scenarios of future desalination activity in the Arabian Gulf relative to the Climate Change Only modeling results from the earlier study. The differences in temperature correspond to the middle of the 21st Century (i.e., 2040 to 2049). Figure ES-2b summarizes the magnitude of average temperature

Figure ES-2: Change in average bottom seawater temperature from layering Desalination Cases onto the Climate Change Only Case, 2040-2049

a) Mapped summary of results

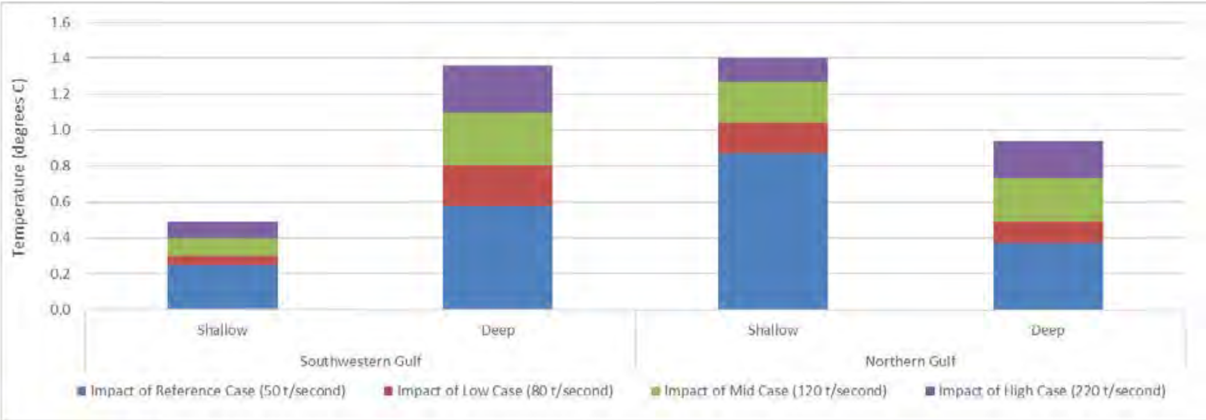

Reference Desalination Case (50 tonnes per second)

Low Desalination Case (80 tonnes per second)

Mid Desalination Case (120 tonnes per second)

High Desalination Case (220 tonnes per second)

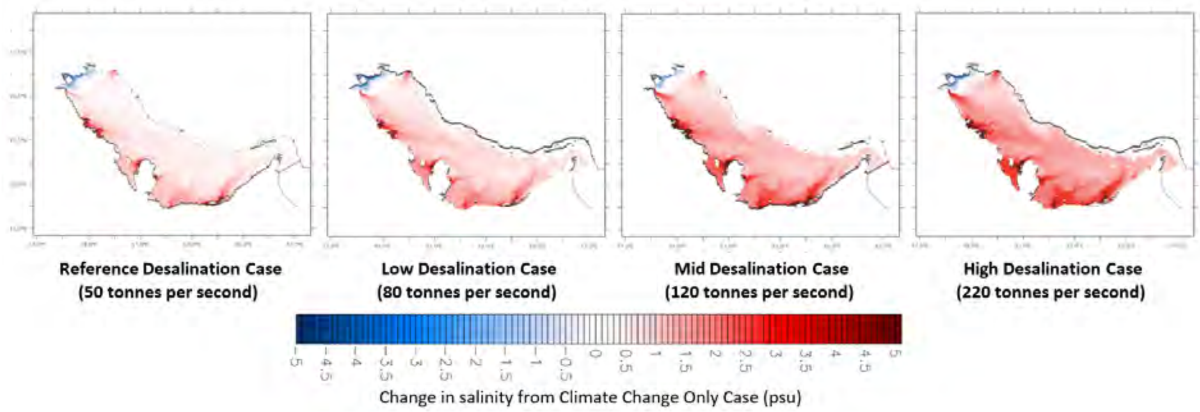
b) Graphical summary of results (average temperature change)



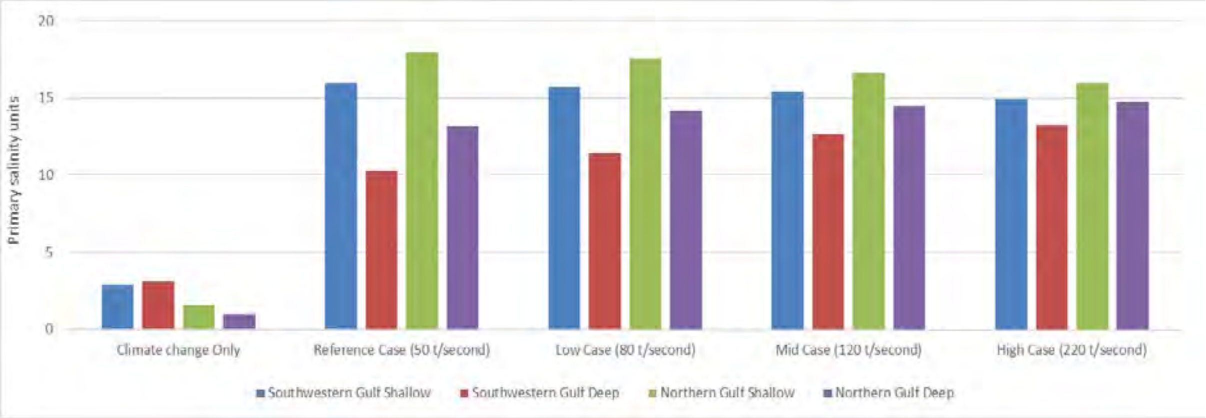
change in shallow versus deep areas, as well as in southwestern versus northern areas. In the southwestern area of the Gulf temperatures are projected to increase up to about 1.4 °C in deep areas in the High Desalination case. In the northern Gulf, temperatures are also projected to increase up to about 1.4 °C in the High Desalination case, but in the shallow areas.

Figure ES-3: Change in average bottom seawater salinity from layering Desalination Cases onto the Climate Change Only Case, 2040-2049

a) Mapped summary of results



b) Graphical summary of results (difference between maximum and average salinity)



The study also found that desalination activities would significantly impact surface and bottom salinity throughout the Gulf. This is illustrated in Figure ES-3a, which shows the difference in average bottom salinity for four (4) potential scenarios of future desalination activity in the Arabian Gulf relative to the Climate Change Only modeling results from the earlier study. The differences in salinity correspond to the middle of the 21st Century (i.e., 2040 to 2049). Figure ES-3b illustrates the magnitude of how maximum salinity levels change relative to average salinity levels in shallow versus deep areas, as well as in southwestern versus northern areas. In the southwestern area of the maximum salinity is projected to increase up to about 16 practical salinity units (psu) in shallow areas above average salinity levels. In the northern Gulf, maximum salinity levels are projected to increase up to about 18 psu above average levels, also in the shallow areas.

In summary, the increasing reliance on the Arabian Gulf as the sink for highly saline brine discharges from intensifying desalination activity will come at an adverse environmental cost to the physical properties of the Arabian Gulf. Hot brine effluent from is heavier than seawater and sinks to the bottom, likely causing harm to sea grasses and other ecosystems on which a large range of aquatic life (e.g., dugongs) depend. The combination of desalination and climate change will lead to substantial increases in the Gulf's salinity and temperature, depending on location and depth.

Going forward, it is important to note that there are cascading uncertainties inherent to the results. This is common to research efforts of this type and is a direct function of the uncertainties underlying the Earth System Models that serve as the basis for regional modeling experiments. Such models typically display high internal variability and are in a constant state of improvement and software updating, as methods improve and scientific knowledge evolves. In broad terms, the following bullets highlight priority areas for further work that could help quantify these uncertainties and improve ocean modeling accuracy in the support of future policymaking.

- *Apply an ensemble approach to estimate impacts on the Gulf.* A natural evolution of the current regional ocean-modeling framework would be to use several different experiments from the same ensemble (MPI-MR), reproducing the same ensemble approach to bracket uncertainties. This would increase the robustness of the understanding of overall Gulf dynamics. This would also enable a quantification of how uncertainties propagate within the regional ocean model itself.

- *Capture the impact of climate change on local sea level rise.* Sea level rise scenarios for the Arabian Gulf could be either a) integrated into the current modeling framework for explorations beyond the mid-century period or b) incorporated into an ensemble approach focused on specific internal variabilities or even using direct outputs from multiple earth system models.

- *Increase the number of saline rivers.* Ideally, the spatial and performance characteristics of all existing and proposed desalination facilities would be represented at their actual brine discharge locations. For all Gulf countries, this would amount to 486 locations at present, with additional points to denote unplanned additions to meet future desalinated water demand.

- *Run additional experiments to better characterize short-term and micro-scale Gulf dynamics.* It would be good to extend and fine-tune Arabian Gulf circulation behavior relative to short-term forcing sources to explicitly model, for example, the impact of tides, whose effects have been parameterized in the current modeling framework, and sea breezes, whose effects have been ignored in the current modeling framework.

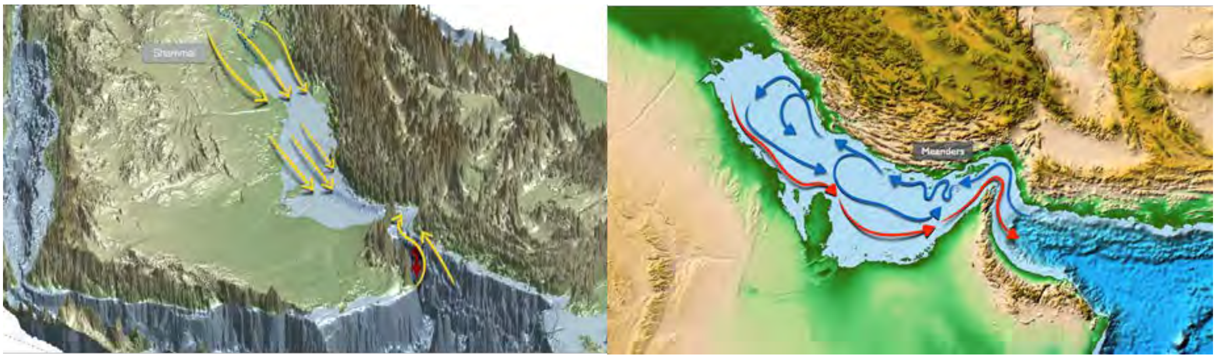
1. Background

This section provides a synthesis of the methods for evaluating the impacts on the Arabian Gulf under the combined influences of climate change and the intensification of seawater desalination activities. It offers a brief summary of previous work regarding the overall desalination context, methodological approach, and key analytical steps. For additional information on these topics, the reader is kindly referred to the previously submitted “Preliminary Findings", "Visualizations" reports, as well as the previous draft of this technical report.[2]

1.1. The desalination context

Under current conditions, the Arabian Gulf is already one of the most stressed marine environments on earth. It is a semi-enclosed, highly saline sea between latitudes 24°N and 30°N surrounded by a hyper-arid environment. Its bathymetry shows large areas of shallow water (less than 10 meters deep) with a maximum depth reaching about 110 meters along the central channel. Northwesterly Shamal winds affect Gulf waters in the winter, while southeasterly Shamal winds dominate in the summer (see Figure 1-1, left). Such winds significantly affect the Gulf’s surface circulation patterns and contribute to “seasonal stratifications” observed in the area.[3]

Figure 1-1: Arabian Gulf topography and bathymetry showing some wind patterns on the left map and ocean circulation on the right map (source: Edson et al, 2015)



Understanding seasonal stratification in the Arabian Gulf is central to understanding desalination impacts. Arabian Gulf seasonal stratification dynamics, as reported in Reynolds (1993) are characterized by saline (although less saline or “fresher” than internal waters) ocean water inflow from the Gulf of Oman along the Iranian coastline and limited freshwater inflow via the Tigris, Euphrates, and Karun rivers at the delta of the Shatt al Arab in Iraq.

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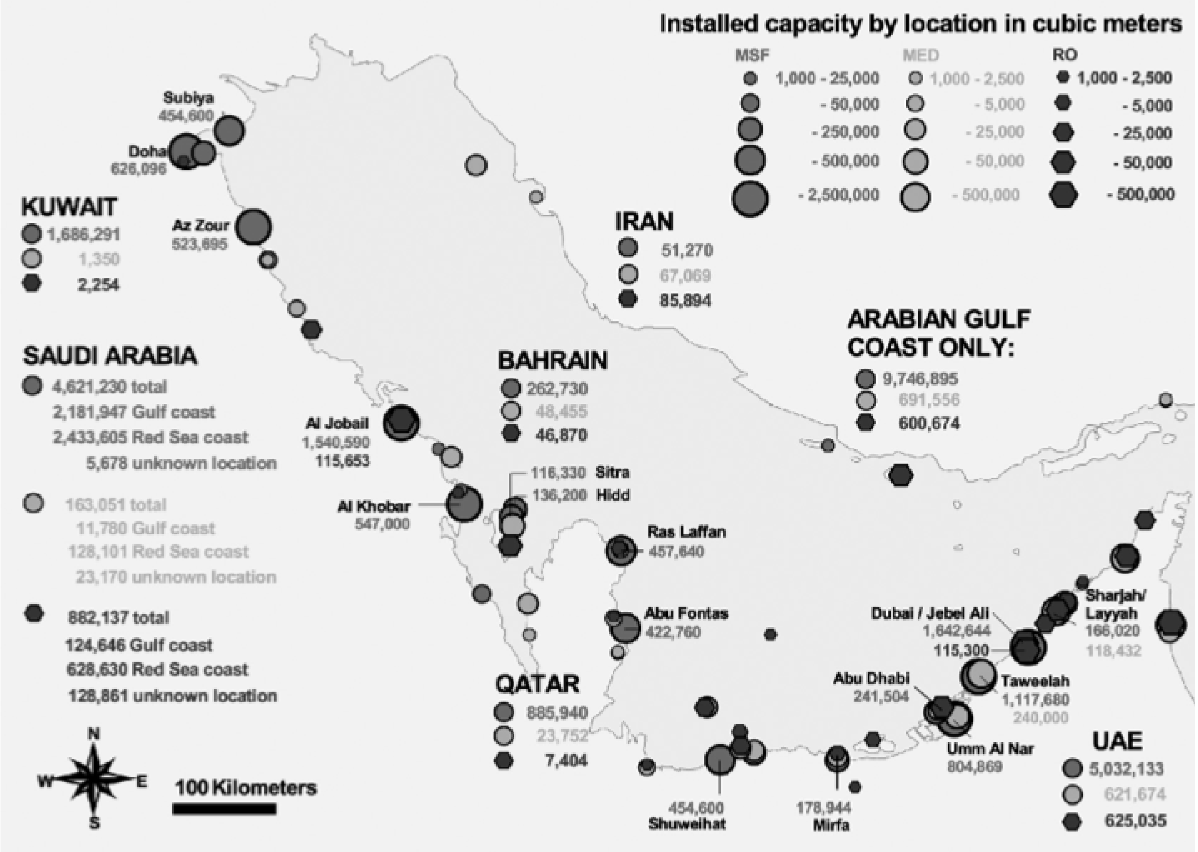
[2] Please contact Jane Glavan (lnrclimatechange@ead.ae) for a copy of the reports.

[3] “Seasonal stratifications” refer to changes in the vertical profile of Arabian Gulf waters relative to physical properties such as salinity and temperature.

Precipitation in the region is very low, thus leading to net high evaporation rates in the shallow areas. In turn, this tends to induce high saline natural water mass formation, which contributes to the Gulf circulation system. Vertically, this is baroclinic forcing that overturns the meso-scale balance. Horizontally, the internal forces, composed with winds, form an anticlockwise gyre along the entire Gulf (see Figure 1-1, right).

The Arabian Gulf is also a region of intense seawater desalination activity. Today, most of the power and freshwater needs in the Arabian Peninsula region are met by the desalination of seawater (Uddin, 2014). Of the 100 largest desalination plants in operation, in construction, or planned in the world as of 2005, 47 plants, accounting for 13.7 million cubic meters per day in production capacity, or 64%, are located in the eight countries bordering the Arabian Gulf namely, Bahrain, Iraq, Iran, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE (Pacific Institute, 2011). The overwhelming majority of these large plants (i.e., 43 out of 47) use seawater from the Arabian Gulf as the feedstock to produce potable water, with the rest using either brackish water or wastewater to produce potable water. When considering units of all sizes - and based on initial estimates - there are currently over two thousand desalination plants of all sizes and feedstocks either operating, in construction, or planned for the Middle East, corresponding to about 13% of the world total (Global Water Intelligence, 2015). Figure 1-2 illustrates the spatial distribution and capacities of desalination plants throughout the Arabian Gulf region.

Figure 1-2: Desalination plants in the countries bordering the Arabian Gulf (Lattemann & Höpner, 2008).



In the Arabian Gulf region, most desalination plants are combined with power plants for electricity generation to meet on-site requirements and to satisfy national electricity needs. There are three major types of desalination technology currently used in the Gulf for seawater – Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Multi-Effect Distillation (MED). All of these technologies use high levels of electricity, while multi-stage flash and multi-effect distillation also require extensive amounts of process heat.

For some desalination technologies, intake salinity is closely linked to electricity requirements. This is true for reverse osmosis (RO) plants, the assumed technology of choice in the future, electricity consumption is directly related to the salinity of the feedwater; the higher the salinity the greater the amount of electricity required to produce potable water, or the need to de-rate plant capacity. On the other hand, for the other distillation processes used in the Arabian Gulf (i.e., MSF and MED), the salinity of the feedwater has less of an impact on overall electricity and heat consumption (World Bank, 2004). All three technologies are capable of operating at feedstock salinity levels up to 50 ppt (World Bank, 2004). Typically, cogeneration of electricity and water in the region takes place using high-efficiency natural gas combined cycle units.

Desalination activities within the already highly stressed Arabian Gulf pose adverse implications for marine biodiversity. Desalination processes separate seawater (or some other source of water containing a high proportion of suspended solids) into freshwater which is then distributed to meet the freshwater demands of households, businesses, amenity, and industry; and concentrate (also known as retentate, brine, or reject) which can be disposed through a variety of ways such as surface water discharge, sewer discharge, deep well injection, evaporation ponds, land application, and thermal processes for near zero liquid discharge (Xu, et al., 2013).

The environmental impacts of desalination are associated with the release of hot brine, treatment chemicals, and other trace elements. The environmental impacts associated with such concentrated brine discharges include increasing levels of biocides, chlorination, and descaling chemicals (Hopner and Lattemann, 2002; Younos, 2005; Dawoud & Mulla, 2012; Uddin, 2014).For the Arabian Gulf, this can lead to chronic toxicity and small-scale alterations to community structure in marine environments, particularly for corals (Jenkins, Paduan, Roberts, Schlenk, & Weis, 2012; Uddin, 2014). Moreover, hot brine effluent from RO plants can be up to 85 ppt and 50 ppt for MSF units. As the effluent is heavier than seawater, it sinks to bottom and slowly circulates causing harm to sea grasses and other ecosystems on which a large range of aquatic life (e.g., dugongs) depend (Areiqat & Mohamed, 2005; Lattemann & Höpner, 2008; Mohamed, 2009).

1.2. The climate change context

Under future conditions, the Arabian Gulf will become even more highly stressed, quite apart from any environmental impacts associated with increasing desalination. As part of another sub-project within the LNRCCP, the response of the Arabian Gulf was modeled under climate change conditions (Edson, Wainer, & Ferrero, 2015). The study focused on the region between the Musandam peninsula near the Strait of Hormuz to the Shatt al-Arab delta. Using the Regional Ocean Model System (ROMS) formulation (Shchepetkin & McWilliams, 2005) and established boundary condition forcing fields results from Earth System Models (ESM) and local data for the Arabian Gulf region. A Downscaled Climate Ocean Model setup (DCOM) was implemented, validated to historical periods and used to develop projections for the mid (i.e., 2040-2049) and late (i.e., 2080-2099) 21st century under climate change.

The analysis relied on a single greenhouse gas (GHG) emission scenario to define future conditions under climate change. This scenario is called “Representative Concentration Pathway (RCP) 8.5”, as defined by the Intergovernmental Panel on Climate Change (IPCC). It is one of 4 RCPs considered by the IPCC and is the one that is considered a “Business-as-Usual” (BAU) scenario of future global GHG emissions. Up through 2050, this BAU scenario shows little to no difference from the other three RCPs, this offering a basis to capture the impacts of climate for all plausible emissions futures from a mid-term planning perspective. Beyond 2050, the use of the BAU scenario allows is equivalent to a worst case scenario that illustrates the implications of climate change on the Gulf for a policy context global GHG mitigation activities are inadequate. A synthesis of key results appears in the following bullets with a focus on the mid-century (i.e., 2050) results.

- *Sea surface temperature:* These temperatures are projected to increase throughout the Gulf. By mid-century, temperature increases of around 1°C are evenly distributed throughout the Arabian Gulf. The areas showing the largest temperature increases relative to present-day are located at the Strait of Hormuz and along the coastline of Saudi Arabia and Qatar.
- *Sea surface salinity:* These salinity changes are projected to both decrease and/or increase, depending on location. By mid-century, an uneven distribution of salinity is observed throughout the Arabian Gulf, with increased levels mostly along the UAE coast and freshening (i.e., lower salinity levels) along the Gulf's main channel. The largest increases in salinity are located in Salwa Dawhat, a bay to the west of Qatar.
- *Circulation:* Climate change will lead to a disruption of the Gulf's vertical overturning circulation. Circulation is driven by water density gradients that are created by surface heat and freshwater fluxes from the Gulf of Oman. By mid century, these parameters are highly affected along the eastern side of the Gulf as fresh water inflow reaches a maximum and results in reduced salinity levels along vertical profiles compared to earlier periods.
- *Turbulence:* Turbulence is typically measured by the vorticity metric and is highly related to salt layering and mixing processes. Vorticity changes significantly with climate change due to a general increase of the system energy, which causes a decrease in small-scale eddies, particularly in wintertime. In the northern end of the Gulf where there are dense water formation zones, warmer atmospheric conditions lead to an increase in high frequency eddies.
- *Currents and wind:* Wind patterns play an important role in the general circulation system in the Arabian Gulf. Any change in the main averaged wind signal has direct impacts on ocean currents and residual circulation. Historically Southeastward predominant winds drive the high saline water at the surface from North to South, along the southwest coast; while along the northeast coast, Southeastward winds drive fresh water inflow from the south. Modeling showed that changes in wind patterns by mid 21st century have no discernible impact on ocean currents.

The outputs of the regional ocean modeling study have provided the baseline representation of how key ocean parameters in the Gulf are projected to be affected under climate change. The modeling framework used to develop those outputs offers the advantage of being suitable for being applied to analyze the environmental impacts associated with a quantification of brine discharges to the Gulf up through the mid-21st Century. In the broader context, the regional modeling framework and outputs provide an Arabian Gulf-specific basis on which to conduct subsequently planned vulnerability assessments within the LNRCCP regarding the marine environment, while also being a potential asset to other researchers in the region regarding future climate change and the marine environment.

1.3. Key questions and objectives

There are several core research questions underlying the sub-project that have been identified on the basis of stakeholder feedback. These included: 1) How will the high levels of socioeconomic growth projected for each country in the region affect the magnitude of brine discharges into the Gulf over time? 2) How are key Gulf physical properties affected by the middle of the 21st Century due to the combination of climate change and intensified desalination activities? And 3) To what extent does climate change potentially exacerbate the environmental impacts of future desalination activity?

The overall goal of the sub-project is to better understand the future impact of desalination activity on the marine environment of the Arabian Gulf in the face of climate change by the middle of the 21st Century. This involved a quantification of the magnitude of brine discharges that accounts for socioeconomic growth in the region, as well as a regional ocean modeling assessment of the impact of these discharges on spatial salinity and temperature patterns, and by extension the impacts on circulation, turbulence, and currents. There are several major objectives, as outlined in the following bullets.

- Establish the current physical characteristics of all desalination facilities on both sides of the Gulf that extract seawater and return brine. This involves the development of a database that incorporates information on historical trends of desalination activities, types of technologies, spatial distribution of brine discharge zones, quantities extracted and discharged, etc.
- Project future seawater quantities extracted from the Gulf and future brine discharges to the Gulf. This involves adopting a scenario approach that applies low-, mid-, and high-socioeconomic growth rates on country-by country basis and developing country-based relationships regarding economic activity and desalinated water requirements.
- Use the regional ocean model developed under sub-project #2 (regional ocean modeling) to assess the impact of increasing desalination levels under both historical Gulf conditions and climate-changed conditions. This involves introducing the magnitude of brine discharges into the boundary conditions of the regional model and then quantifying that effect on key ocean parameters.
- Conduct sensitivity runs of the regional ocean model under several scenarios of future brine discharges to bracket uncertainty and to infer key physical responses of Arabian Gulf water to the combination of climate change and desalination activities.

1.4. Methodological approach and key assumptions

The overall methodological approach for this sub-project sought to address each of the issues discussed in the previous section. These issues focus on the interactions in the Arabian

Gulf between climate change and increasing seawater desalination activity. Broadly speaking, these interactions encompass two major areas, namely i) estimating of the future levels of brine discharges to the Arabian Gulf associated with desalination activities; and ii) modeling the incremental impact on the Gulf from the discharge of increasing levels of brine from desalination activities by using a validated regional ocean model that incorporated climate change effects.[4]

Predicting the future combined impact on Gulf waters from climate change and desalination was a multifaceted challenge that required the development of a number of simplifying assumptions. This is primarily due to the complexities involved in the integration of hyper-saline discharge from a set of desalination plants into a validated, fine-tuned, high-resolution regional ocean model in which climate change signals have been downscaled. Hence, several assumptions were made to reduce the overall modeling dimensionality, without unduly sacrificing modeling attention to those factors that are most significant for understanding the impact of future brine discharges to the Gulf. Specifically, these key simplifying assumptions are:

- *Modeling framework:* The starting point for the modeling effort was the previous experiment in the Arabian Gulf in which a regional ocean model was developed and validated relative to historical conditions in the Gulf. This validated model was then used to downscale the IPCC's Representative Concentration Pathway 8.5 (RCP8.5) up the end of the 21st century to estimate changes in the Gulf associated with climate change (Edson et al, 2015).[5]
- *Desalination plant spatial reduction:* Currently, there is a large number of desalination units that use Arabian Gulf waters as a feedstock and return large quantities of highly saline brine discharge. However, available computing resources dictated the actual number of saline discharge points that could be effectively integrated into the regional ocean model.[6] Hence, the number and location of desalination plants were spatially reduced into fourteen (14) representative points whose annual brine discharges were collectively equivalent to the magnitude from all plants. Hereafter, we call these representative plants "saline rivers".

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[4] This refers to the regional ocean model that was developed under sub-project #2 of the LNRCPP (Edson et al, 2015).

[5] This corresponds to regional ocean modeling carried out under sub-project #2 of the LNRCPP. This research used a specific set of outputs from Max Plank Institute's Earth System Model (MPI-MR) to represent climate change, based in the "business as usual" scenario (i.e., RCP8.5) from the IPCC and accounted for open ocean boundaries and all atmospheric fluxes variables.

[6] Computing resources consisted of an SGI Cluster, based on Advanced Micro Devices (AMD) architecture. The modeling used 600 dedicated CPUs and 48 Tb of storage. While these computing resources are significant, they still required about 60 days per model run using a reconfiguration of the of number desalination plants.

- *Brine discharge magnitude projections:* This involved the development of several estimates of future annual brine discharges to the Arabian Gulf over the period 2010 through 2050. For the Base Year of 2010, this involved calculations for each facility regarding a) annual seawater intake (in million cubic meters), b) equivalent sea salt intake (million tonnes), c) water recovery (million cubic meters), d) brine discharge (million cubic meters), and e) equivalent sea salt discharge (million tonnes). For the years 2011 through 2050, this involved a projection of Base Year estimates using the simplifying assumptions of the elasticity of desalinated water demand.
- *Saline river modeling approach:* The saline rivers were modeled as direct injections of hot brine into the Gulf. From a methodological perspective, this required real-time brine processing in the mixing zones during the model execution in order to establish a thermodynamic balance between the saline rivers and the receiving Gulf waters. It is important to note that the modeling approach does not account for local effects in the immediate vicinity of the underwater brine discharge structures. That is, only far-field modeling was undertaken (i.e., using a roughly 1 km resolution). There was no near field modeling of the immediate zones of brine discharge (i.e., requiring less that a 5-meter resolution) as it was beyond the scope of the study.

Much of the modeling effort focused on overcoming the challenges inherent in the integration of the above assumptions into a stable and reliable modeling system that was able to account for Saline River forcing into the climate-changed Arabian Gulf hydrodynamic system. The simulation period was the 2040-2050 period and the global GHG emission scenario was the IPCC's Business-as-Usual (i.e., RCP8.5). The next sections describe our approach for addressing each of the four simplifying assumptions above.

2. Regional ocean modeling framework

This section describes the foundational modeling framework that was used to evaluate the combined impacts of desalination and climate change on the Arabian Gulf. It is important to note that desalination modeling we conducted benefitted from an earlier LNRCCP research phase (i.e., Sub-project #2: Regional Ocean Modeling) in which a robust regional ocean modeling framework was developed and fully validated under historical conditions in the Gulf. The subsections below provide an overview of some key inputs and outputs of this regional ocean model in order to provide essential context. After providing a review of the background of the earlier study, several key topics are reviewed. These include the spatial domain of the study; model replication of historical conditions; role of desalination; model projections of some key physical parameters; key temporal characteristics; and salinity anomalies.

2.1. Background

The desalination study relied on a regional ocean-modeling framework that was developed as part of earlier LNRCCP study. Specifically, the point of departure was the regional ocean model developed earlier. It is important to note that this regional ocean model focused exclusively on understanding the impact of climate change on physical parameters such as sea surface temperature, salinity, dynamic sea level rise, among others. *Brine discharges from desalination plants were not considered in this earlier study.*

The outputs of this earlier work have been incorporated into AGEDI's "LNRCCP Inspector" toolkit. This is a website (under development) for both visualizing outputs and downloading the range of databases associated with each of the 5 strategic themes and 12 sub-projects in the overall programme (see the conceptual illustration of the toolkit website that appears in Figure 2-1). Within the LNRCCP Inspector, the "Arabian Gulf" Inspector (i.e., bottom left icon in Figure 2-1) can be accessed at http://www.ccr-group.org/#!agedi-climate-change-inspectors/bmhq7. The "Arabian Gulf Desalination" Inspector located as the top right icon in Figure 2-1 is under development and will be available at the same site when completed.

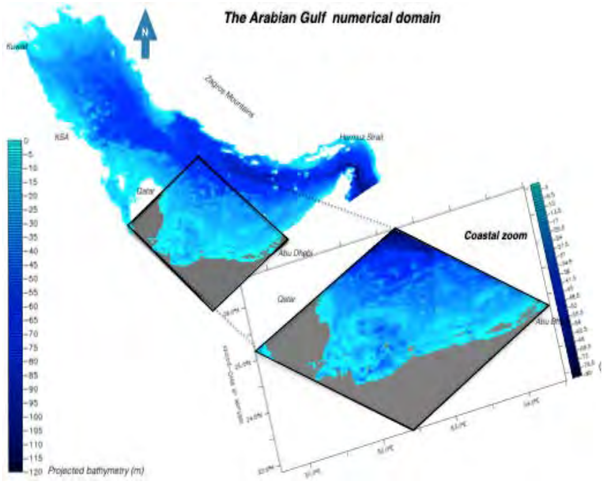
Figure 2-1: Opening page of the LNRCCP Inspector toolkit

The previously developed regional ocean model for the Arabian Gulf was considered to offer a sound basis upon which to explore interactions between climate change and desalination. After extensive experimentation with salt loadings, it was confirmed that the model was fully suitable as a basis for modeling the incremental impact of desalination activities associated with large future quantities of highly saline brine discharge to the Gulf. To provide context to this modeling effort, a brief overview of the selected results from this earlier work is offered in the next subsections. The focus is on key aspects of the modeling framework that affect the combination of desalination and climate change within the modeling framework.

2.2. Spatial domain

The spatial domain of the regional model is the entire Arabian Gulf, from a boundary just south of the Straits of Hormuz to the Shatt-al-Arab in Iraq. This is shown in Figure 2-2, which also shows the bathymetry of the overall Gulf plus an amplification of the coastal zone in the southwest region of the Gulf, an area that showed noteworthy impacts from climate change. The domain grid size (spatial resolution) is approximately one km, varying with latitude. After several early experiments, this final domain and resolution was concluded to be the most suitable relative to the study objectives (climate projections), the Gulf system dynamics, and available computing resources.

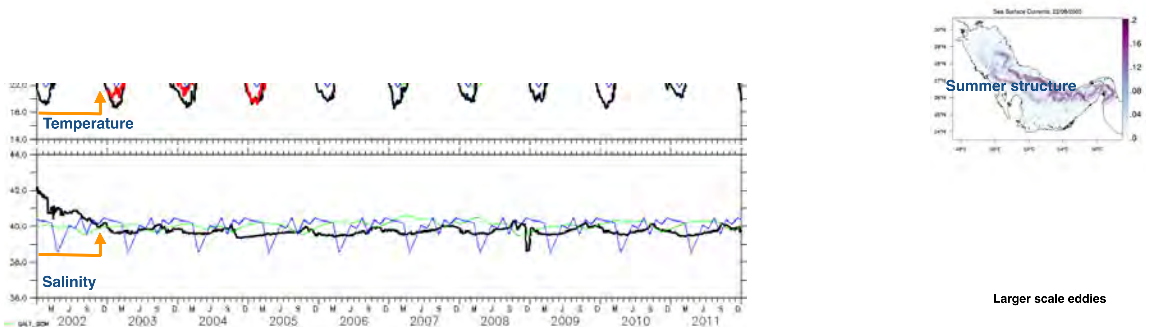
Figure 2-2: Arabian Gulf spatial domain showing bathymetry and area detail



2.3. Replication of historical observations

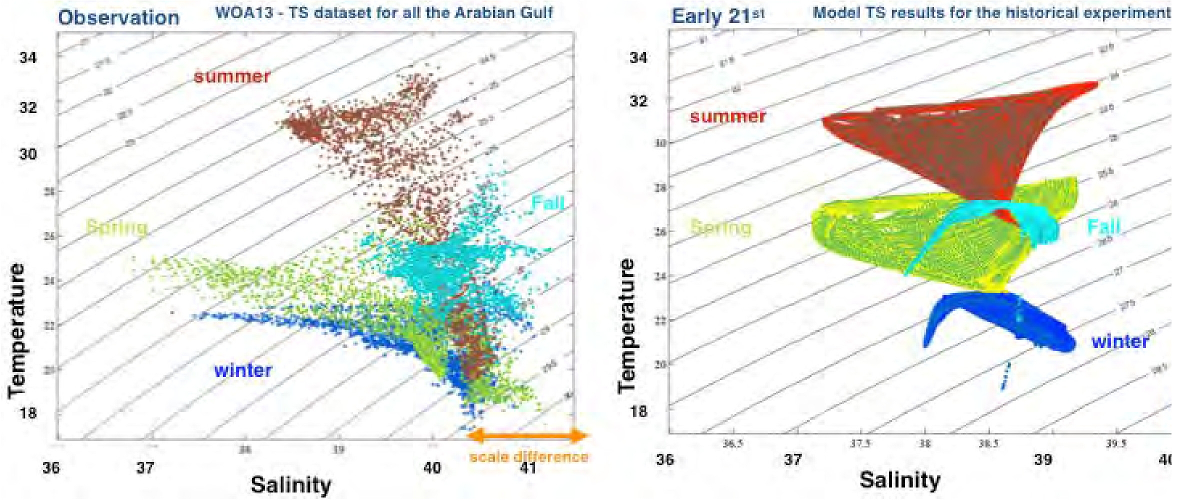
The regional ocean model was able to reproduce observed data within a reasonable range. This means that the model was adequately calibrated to historical climate conditions and hence considered reliable to project future conditions under climate change. A key activity in this calibration process was model initialization and spin-up which consisted of 4 “warm-up” stages, with the last stage being a non-stop process to ensure that the model starts at least one year before the start year in the reporting period. The purpose of these warm-up stages was to ensure that all physical parameters are adequately specified to produce model outputs consistent with historical observations over the period 1980-2010. Figure 2-3 shows the

Figure 2-3: Early 21st century model validation. Sea surface temperature and salinity timeseries comparison, as internal legend (Edson et al, 2015)



comparison for salinity and temperature between historical observations (i.e., WOD2011 and AVHRR) and the outputs of model runs. The Figure confirms that the regional ocean model was adequately able to replicate historical observations.

Figure 2-4: TS diagrams for the Arabian Gulf based on the observed record (left) and modelled results (right) (Edson et al, 2015)



2.4. Role of desalination in the earlier regional ocean model

The regional ocean modeling framework was built exclusively to evaluate the role of climate change. It is important to note that the role of desalination was not considered at the time sub-project #1 of the LNRCCP was undertaken. A simple comparison of the observational and modeled temperature-salinity (TS) diagrams confirms this.[7] Figure 2-4 illustrates the TS diagrams in the Arabian Gulf for the 1980-2000 historical period based on observed data (left) and results from running the regional ocean model (right). Comparing the two TS diagrams, it is possible to observe that the historical observations exceed modeled results by about 1 psu in the salinity field (i.e., the seasonal salinity results on the left graph are roughly 1 psu higher than the seasonal salinity results on the right graph). This difference is directly related to the absence of the desalination plants in the earlier modeling experiment.

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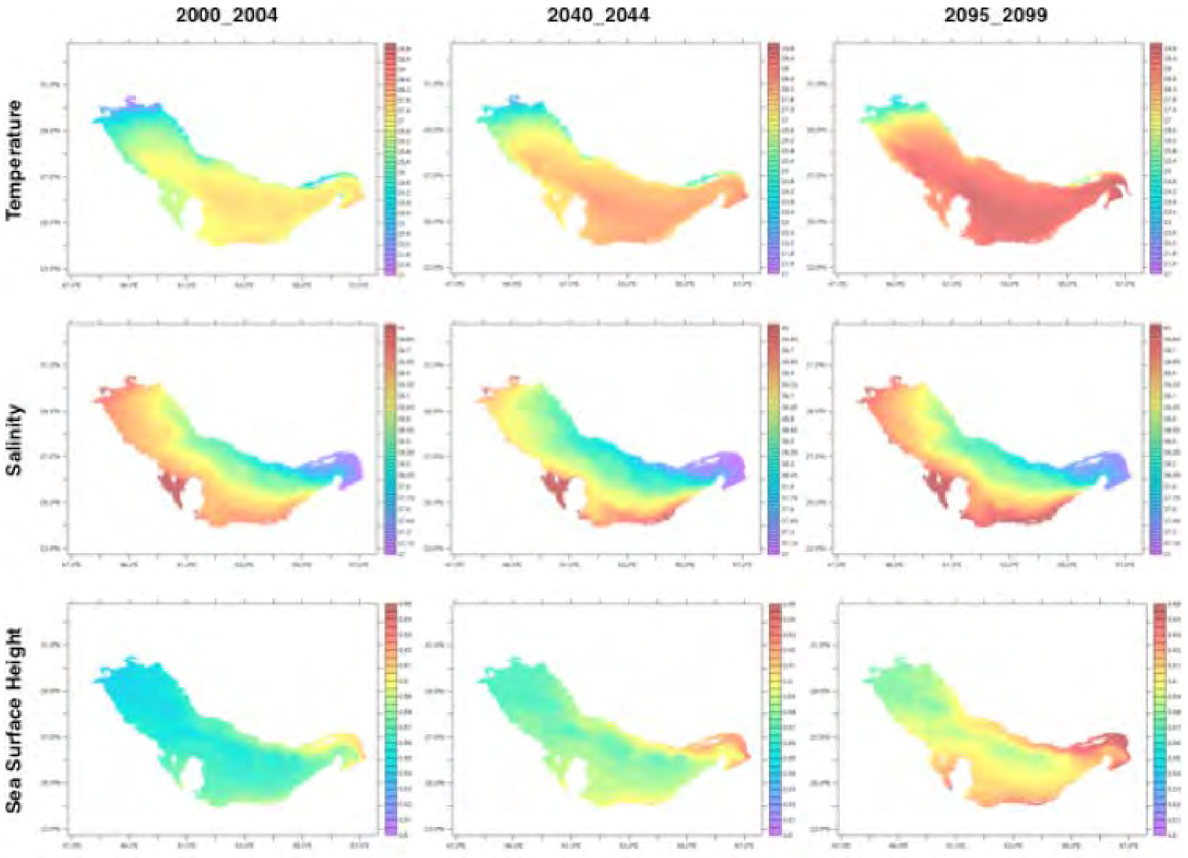
[7] TS diagrams are a useful tool in ocean modeling research for establishing the relationship between temperature and salinity for a water mass. Temperature and salinity combine to form the water's density, which is represented in a TS diagram by lines of equal density, where salinity is plotted on the x-axis and temperature on the y-axis. These lines of equal density (or "isopycnals" as they are called) are determined by the interaction of temperature and salinity.

2.5. Projections of Arabian Gulf conditions under climate effects only

Model runs and outputs of key ocean parameters were developed for three distinct time periods. After 2 years of the 4th warm up stage, the run was extended for 20 years, from 2000-2019, called the "Early 21st century" experiment. The "Mid-century" experiment was executed for the period 2040-2049 (under RCP8.5). Finally, the "Late 21st century" experiment was executed for the period 2080-2099 (under RCP8.5). A visual synthesis of regional ocean modeling results from the earlier study appears in Figure 2-5. This figure shows average values for sea surface temperature (SST) on the top, sea surface salinity (SSS) in the middle and sea surface height (SSH, or dynamic sea level rise) on the bottom. The results highlight some important features of the Arabian Gulf under climate change only, as outlined in the bullets below.

- *Temperature:* There is distributed warming gradient toward the southwest regions of the Gulf (top maps). The high uniformity of temperature changes can be explained by the characteristics of its main climate forcing, as will be later discussed.
- *Salinity:* Spatial patterns of salinity were quite different from temperature patterns. They show a decrease in salinity throughout large portions of the Gulf, with sharp salinity increases limited to the UAE coastline just south of the northernmost emirates (middle maps). This process is due to the Gulf's residual cyclonic circulation (counter clockwise), which tends to accumulate water along the shoreline.

Figure 2-5: Earlier experimental results under RCP8.5 forcing for averaged SST (top), averaged SSS (middle) and averaged SSH (bottom) (Edson et al, 2015)



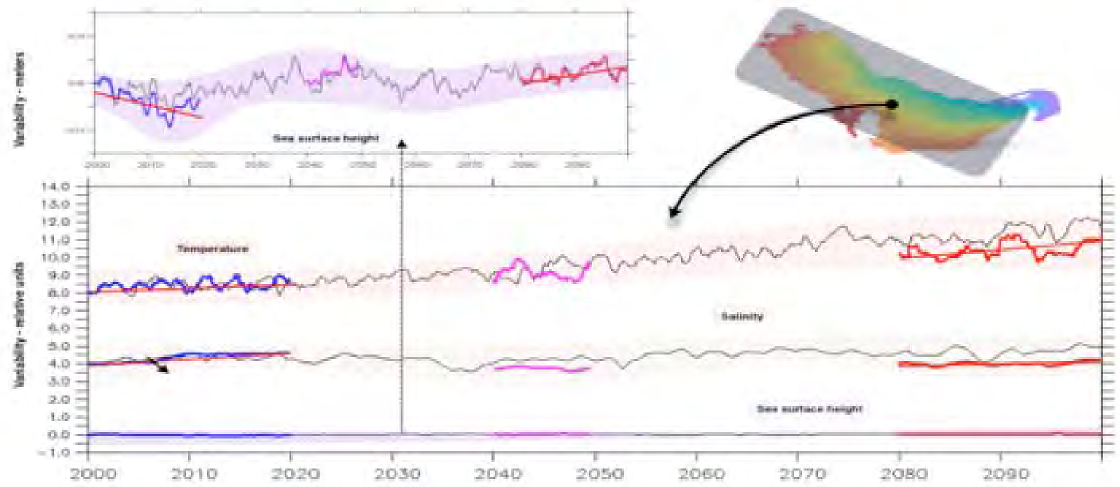
- *Sea surface height:* The impact of the Gulf's residual cyclonic circulation is also evident in sea surface height patterns (bottom maps). Typical coastal trapped waves, e.g. Kelvin waves (Thompson, 1879) are a very likely dynamical mechanism that supports such a barotropic (i.e., independent of ocean depth) gradient of dynamic sea level rise along the coast.

2.6. Key temporal characteristics

The temporal implications of the spatial trends discussed above are also important to understand as the underlying context for desalination and climate change modeling. Average values for SST, SSS and SSH obtained from the earlier model runs are summarized in time series plots shown in Figure 2-6. The three time slices of 2000-2020, 2040-2049 and 2080-2099 corresponding to the Early, Mid and Late 21st Century simulation results are superimposed onto the results of the Max Planck Institute Mixed Resolution (MPIMR) model results.

The trends shown in Figure 2-6 reinforce the spatial results presented previously. At least two distinct processes are likely in the region under climate change. One is essentially thermodynamic in nature, defining the level of vertical mixing (subsidence) in the Gulf scale, based on Late 21st experiment conclusions. The other is dynamic in nature, defining the rate of inflow of low saline waters due to surface gradients (surface elevation), without the extremes effects of the temperature. Together, these processes change the intensity and shape of the cyclonic gyre in the Gulf under climate change. These characteristics are essential to understand as these conditions are further perturbed due to the introduction of the effect of an intensification of desalination activities.

Figure 2-6: Arabian Gulf averaged timeseries (annually filtered) for SST (degrees C), SSS (practical salinity units, or psu) and dynamic SSH (meters). MPI-MR in black, ROM-AG results in blue (early), purple (mid), late (red) and linear trends in red. Detail (up left) expands the SSH trends. Detail map shows the coverage area (Edson et al, 2015)



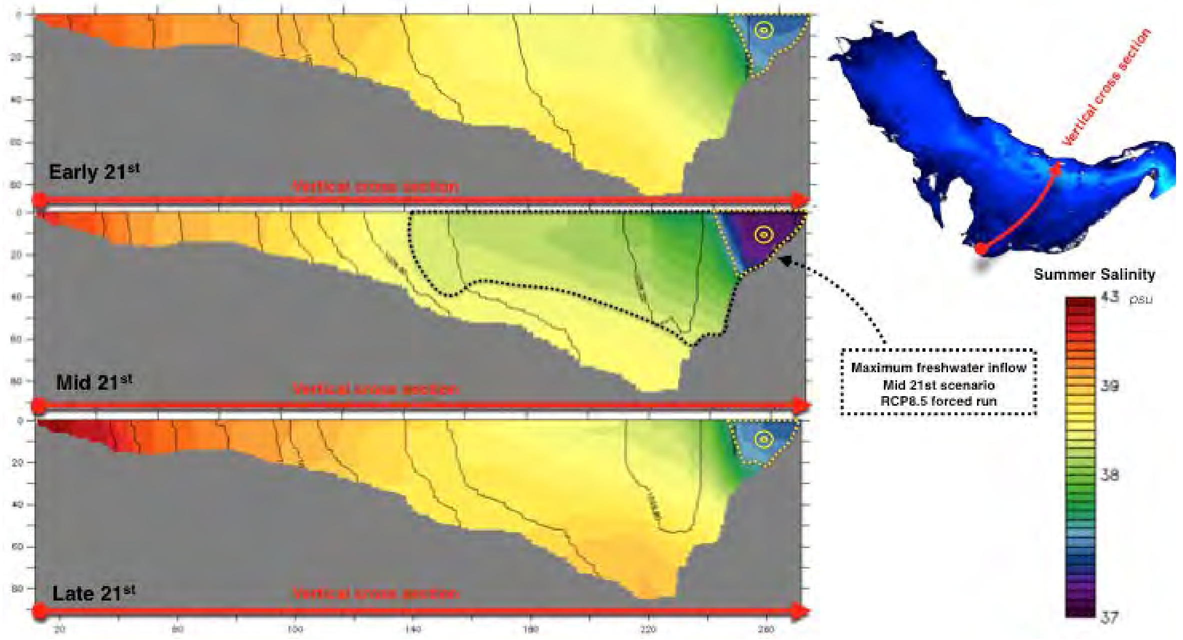
2.7. Salinity anomalies under climate change

The inflow of lower salinity (i.e., fresher) seawater into the Gulf through the Hormuz Straits is another important feature that emerged from the earlier climate change modeling. A visual way to quantify the pattern of the southerly fresh water inflow is presented in Figure 2-7 for the summer months when the inflow from the Gulf of Oman is greatest. The left side of this figure shows seasonal vertical salinity profiles for the Early, Mid and Late 21st Century runs for a cross-section of the Arabian Gulf from the UAE to Iran, as represented by the red line along on the map at top right. Inspection of these profiles confirms the “freshening” processes associated with inflows of lower salinity waters through the Straits. This is particularly evident for the Mid 21st Century results which shows the lowest salinity near Iran, for the three time slices. Although not illustrated here, the modeling results suggest this freshening process has a high inverse correlation with sea surface height changes near the southern boundary of the spatial domain (i.e., the Hormuz Straits). Moreover, the results of the global circulation modeling experiment (i.e., MPIMR under RCP8.5), also shows significant freshening around the Straits of Hormuz. This is notable in view of the fact that there is more precipitation projected for the northern areas when compared with the southern part of the Arabian Gulf.

3. Desalination plant spatial reduction

This section describes the process involved for developing a database of brine discharge points suitable for subsequent modeling. Essentially, this involved a consolidation of the

Figure 2-1: Salinity vertical section (reference up right). Dashed lines show the fresher water inflow from Oman and Arabian Sea (Edson et al, 2015)



hundreds of desalination plants along the shoreline of the Arabian Gulf into a manageable set of brine discharge points. Hence, a numerical simplification was adopted to reduce the spatial distribution of desalination plants. After providing a review of essential background for this spatial reduction, several key topics are reviewed. These include the desalination plant inventory, optimal number of discharge points from a modeling perspective, and the resulting spatial distribution of projected brine discharge magnitude around the Arabian Gulf.

3.1. Background

Currently, there is a large number of desalination units that use Arabian Gulf waters as a feedstock and return large quantities of highly saline brine discharge. Ideally, a desalination modeling effort would integrate the locations and performance characteristics of each plant into the modeling framework. Indeed, this was the point of departure for the modeling effort. However, an initial assessment of required runs times (in calendar terms) suggested that the computer run time burden for configuring the model to account for each current desalination plant location would be excessive. Even with the high level of computer resources mobilized (see footnote #5), a single run for the 2040-2050 period would have taken about 84 months to complete due to the need to account for the mixing dynamics associated with the hundreds of brine discharge points.

Hence, it was clear that a spatial reduction of these plants was required. The aim of the spatial reduction process was to develop a small representative number of brine discharge points where annual brine discharge magnitudes would be equivalent to annual brine discharge magnitudes from the entire desalination plant inventory. This means that large levels of brine discharge would be modeled from a small number of discharge points rather than small levels of brine discharge from a large number of discharge points. For the purposes of the study, these two approaches are functionally equivalent, as the modeling framework does not seek to account for local effects in the immediate vicinity of the underwater brine discharge structures.

3.2. Desalination plant inventory

Developing a desalination plant inventory was an initial step in estimating historical brine discharge levels to the Gulf. Across the Arabian Peninsula, there are currently about 2,241 desalination plants.[8] Of these, there are 982 plants corresponding to the eight countries (i.e., Bahrain, Iraq, Iran, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE) included in the study, which depend on seawater as the feedstock. And of these, there are 486 plants accounting for over 14 million cubic meters per day of capacity that discharge brine and other chemical by-products directly to the Arabian Gulf. The location, capacity, and other characteristics of these plants are identified in Annex A. Overall results are synthesized in Figure 3-1. It is this

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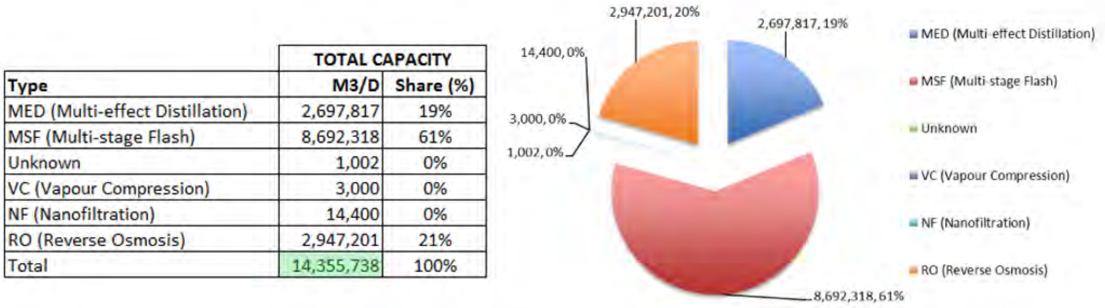
[8] Based on data contained in the DesalData database available from Global Water Intelligence (GWI).

set of plants that forms the basis for the subsequent estimation of the magnitude of brine discharges.

Figure 3-2: Summary desalination plant capacity, by technology, that use Arabian Gulf waters as a feedstock (GWI, 2015)



	TOTAL CAPACITY	
Type	**M3/D**	**Share (%)**
MED (Multi-effect Distillation)	2,697,817	19%
MSF (Multi-stage Flash)	8,692,318	61%
Unknown	1,002	0%
VC (Vapour Compression)	3,000	0%
NF (Nanofiltration)	14,400	0%
RO (Reverse Osmosis)	2,947,201	21%
Total	14,355,738	100%

3.3. Optimal number of brine discharge points

From a modeling perspective, the optimal number of brine discharge points that could be efficiently modeled was fifteen (15). Fourteen (14) of these locations are associated with brine discharges. They were spaced uniformly (more or less) across the Gulf to ensure that running the regional model would not be adversely affected by any near-field microphysics and/or anomalies. The locations of these brine discharge points, or saline rivers as they are referred to in this report, are illustrated in Figure 3-2 (left), with the corresponding assumed national share of brine discharge summarized in the table on the right of the Figure. The 15th discharge point is not a brine discharge point. Rather, it corresponds to the freshwater flux associated with the Shatt al-Arab waterway formed by the confluence of the Euphrates and the Tigris rivers. This discharge point is identified as “12 Abadan” in Figure 3-2.

Figure 3-3: Saline river zones distributed along the AG area based on a consolidation of desalination plant locations (left) and a summary table indicating shares by country of total national brine discharge (right)

Country	National share	Saline river #	Description
Oman	100%	1	Hormuz
UAE	5%	2	Al-Khaimah
	20%	3	Dubai
	30%	4	Abu Dhabi
	25%	5	Tarif
	20%	6	Barakah
	100%		*Subtotal*
Qatar	100%	7	Doha
Bahrain	100%	8	Salwa Bay
Saudi Arabia	40%	9	Jubail
	60%	10	Tanajib
	100%		*Subtotal*
Kuwait	100%	11	Kuwait
Iraq	100%	12	Abadan
Iran	70%	13	Deylam
	20%	14	Neyband
	10%	15	Mellu
	100%		*Subtotal*

4. Projected brine discharge magnitudes

This section describes the process involved for projecting brine discharge magnitudes to the Arabian Gulf for the 2010-2050 period. Essentially, this involved combining the spatial reduction of desalination plants with data and assumptions regarding historical water consumption characteristics in the region, regional population growth rates estimates, and shifts to more efficient desalination technologies. After providing a review of essential background for brine projection, each is briefly review in the subsections below.

4.1. Background

The methodology for projecting brine discharge magnitudes for the 2040-2050 period decade focused on a bottom-up estimate of salt transport in the saline rivers. This involved a set of detailed assumptions and calculations. A summary of the major assumptions used in the estimate is provided in Annex B. A summary of the various calculation components comprising the spreadsheet calculation of the saline river salt transport estimate is provided in Annex C.

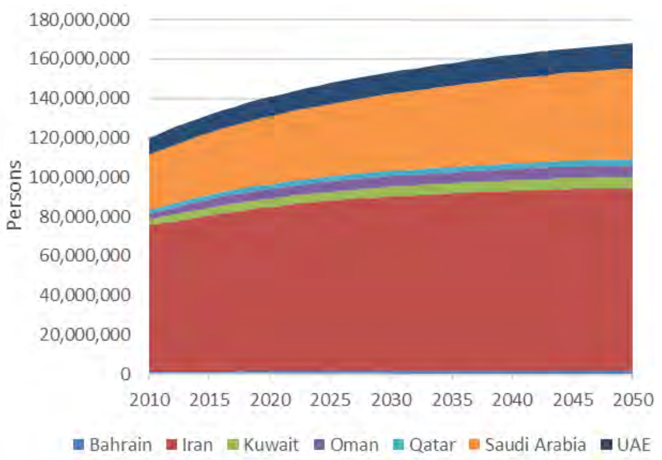
Projecting brine discharge magnitudes relied on historical data combined with certain assumptions for the future period. For the Base Year of 2010, the calculations involved the development of estimates for each saline river based on the period 2000-2010 for which data was assembled regarding a) annual seawater intake (in million cubic meters), b) equivalent sea salt intake (million tonnes), c) water recovery (million cubic meters), d) brine discharge (million cubic meters), and e) equivalent sea salt discharge (million tonnes). For the years 2011 through 2050, the calculation involved projecting the Base Year estimates based on assumptions regarding future water consumption per capita, regional population growth, and shifts to more efficient desalination technologies. Each is briefly review in the subsections below. The section concludes with a discussion of the projected magnitudes of brine discharge by saline river location.

4.2. Regional population growth

Regional population growth is a fundamental driver of desalinated water production. Historical population levels were based on statistics maintained by the Population Division of the United Nations for the 8 countries of the Arabian Peninsula (United Nations, 2015). This information was used to develop per capita estimates of desalinated water consumption in the region for the 2000-2010 historical period. Projections of future national population up to 2050 relied on the central variant for each country from UN Population Division. A summary of trends in future population appears in Figure 4-1. In short, the populations of the countries on both sides of the Arabian Gulf are projected to increase from about 120 million in 2010 to 168 million in 2050, or a growth rate of about 0.85% per year.

4.3. Desalinated water production

Figure 4-1: Population projections for the countries in the Arabian Peninsula (UN, 2015)



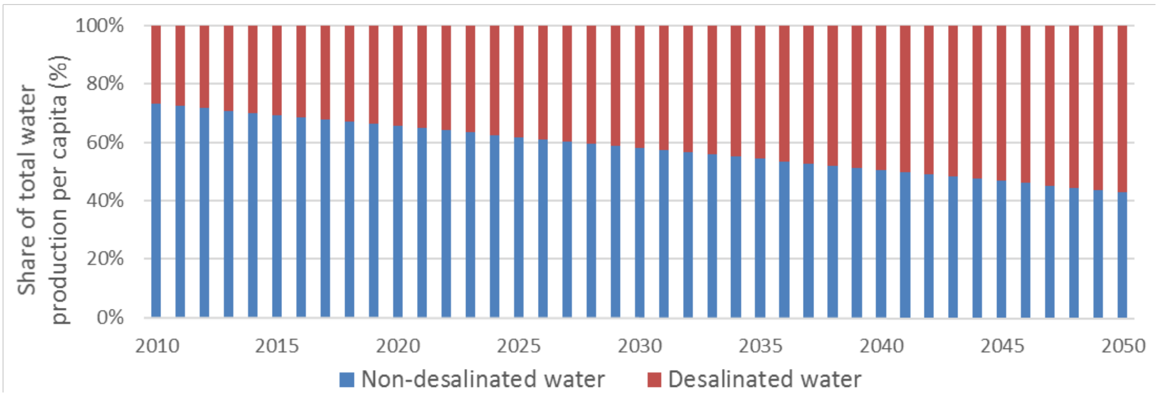
Annual levels of desalinated water production by technology type determine the total amount of brine discharged to the Gulf. Data on historical water production for the period 2000-2010 was obtained from the research team implementing Sub-project #5 of the LNRCCP (i.e., Regional Water-Energy Nexus under Climate Change). This sub-project established water production patterns by type (i.e., desalinated water, groundwater, surface water, and treated wastewater) based on information provided directly by sub-project stakeholders in combination with available technical literature in peer-reviewed journals (Al Hashemi, Zarreen, Al Raisi, Al Marzooqi, & Hasan, 2014; Dawoud & Mulla, 2012; Fath, Sadik, & Mezher, 2013).

For desalinated water, annual seawater intake quantities were determined based on technology performance characteristics. That is, the amount of seawater required producing a cubic meter of desalinated water varied considerably across technology type. For example, multi-flash technology, the most prevalent type of desalinated capacity in the region, requires about 7.3 cubic meters of sea water to produce 1.0 cubic meters of desalinated water (see Annex B for other technologies). As a conservative measure (i.e., a worst case scenario), the assumed share of desalinated water production as a share of total water production reaches 100% by 2050 for all countries in the region except for Saudi Arabia for which it was assumed to reach only 50% and Iran for which it was assumed to remain at 2010 levels. Hence, desalinated water production per capita is assumed to grow at a higher rate that population.

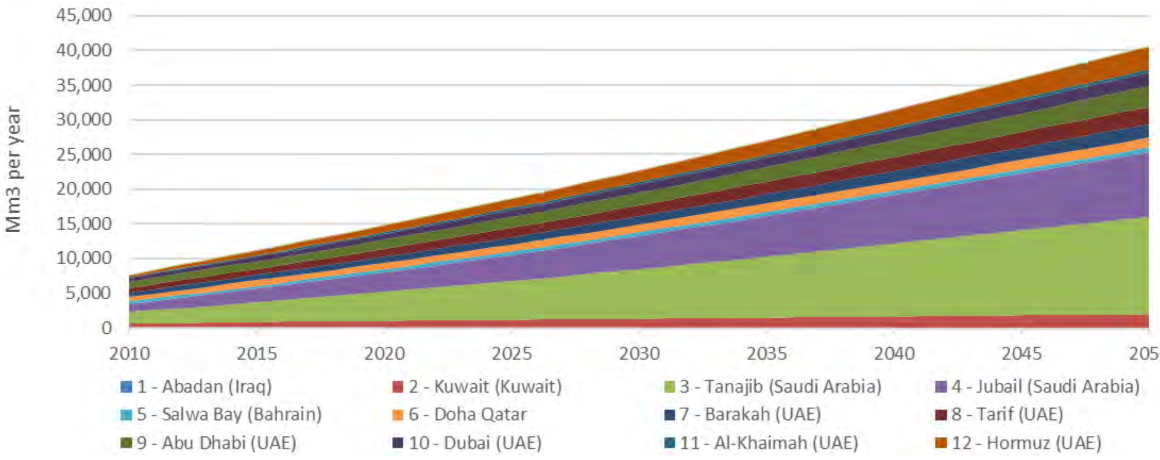
Figure 4-2 illustrates the impact of these assumptions. Figure 4-2 (top) shows how the share of desalinated water production per capita change over time. This figure shows that desalination water supply, as a share of total water supply per capita, increases from about 27% in 2010 to nearly 60% by 2050. Figure 4-2 (bottom) shows actual desalination production levels over time. This figure shows the effect of the combination of increased desalinated water use per capita and increasing population in the region. Total desalinated water production is expected to increase from about 8,000 Mm^3 per year to about 41,000 Mm^3 per year by 2050. Of projected non-desalinated water production in 2050, most is associated with Iran. Less than 10% is associated with GCC countries (i.e., Saudi Arabia).

Figure 4-2: Projected desalinated water production

a) Assumed change in share of desalinated water supply, 2010-2050, across all saline rivers



b) Projected change in magnitude of desalinated water supply, 2010-2050, by saline river



4.4. Shifts to more efficient desalination technologies

Desalination water production projections also considered changes in technology that could be adopted in the region, based on a review of the literature (Ahmed, Shayya, Hoey, & Al-Handaly, 2001; Al-Hengari, El-Bousiffi, & El-Mudir, 2005). This was an essential consideration as the choice of technology affects both the magnitude and quality of brine discharge back to the Arabian Gulf. We assumed that the share of RO technology increases by about 5% over 2010 average shares by the year 2050.[9]

4.5. Projected salt loading to the Arabian Gulf

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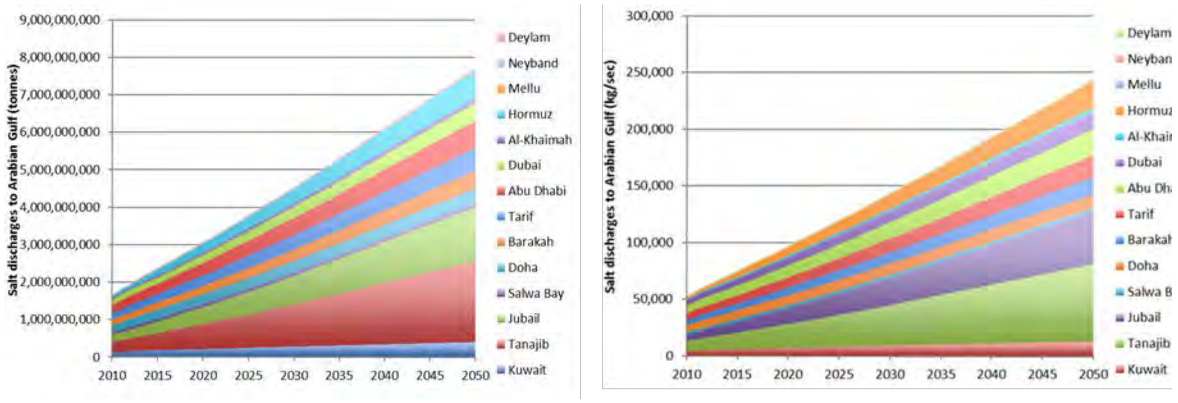
[9] This is based on page 73 of "A Review of Desalination Trends in the Gulf Cooperation Council Countries" by R. Al Hashemi, S. Zarreen, A. Al Raisi, F.A. Al Marzooqi, S.W. Hasan, International Interdisciplinary Journal of Scientific Research, 2014 where it states that RO technology is projected to be more prevalent in the future.

The methodology for projecting brine discharge magnitudes for the 2040-2050 period decade focused on a bottom-up estimate of salt transport in the saline rivers. This involved a set of detailed assumptions and calculations. A summary of the major assumptions used in the estimate is provided in Annex B, including the mapping of total brine discharge quantities by the desalination plants by saline river location. A summary of the various calculation components comprising the spreadsheet calculation of the saline river salt transport estimate is provided in Annex C.

A summary of brine discharge magnitudes is shown in Figure 4-3. This Figure shows resulting salt loadings by discharge location for the 2010-2050 period in both absolute terms and discharge rate terms. Salt discharge to the Gulf is projected to increase from about 1.7 million tonnes per year in 2010 (or about 50 tonnes per second) to about 7.8 million tonnes per year in 2050 (or about 244 tonnes per second), roughly an average of 3.9% per year. The estimate of 50 tonnes per second for the historical period is quite close from the literature estimates for the same period (Latteman, 2010). The temperature impact associated with these salt loadings was included in the subsequent modeling as a simple weighting relative to the discharge location and quantity. This is an approximation based on methodologies efficiency and changes in outflow (Dawoud & Mulla, 2012; Lattemann & Höpner, 2008).

Figure 4-3: Saline river discharge in salt mass (tonnes; left figure) salt mass rate (kg/s; right figure) across all technologies, sal river location



5. Conceptual approach to modeling climate change & desalination

This section describes the process associated with the modeling of impacts on the Arabian Gulf of projected brine discharges under climate change for the mid 21st Century period (i.e., 2040-2050). Overall, this involved a two-step approach. First, the hot brine was distributed as point sources entering the Arabian Gulf at the fourteen (14) saline river locations. Second, the impacts of these saline rivers were modeled using the validated regional ocean model for the Gulf. Within this overall approach, there are several key components, including setting up the methodological stages, establishing the metrics to quantify the impact of saline rivers, and the treatment of the freshwater input from the Shatt-Al-Arab waterway. After providing a review of essential background for saline river modeling, each analytical step is briefly review in the subsections below.

5.1. Background

As discussed previously, the regional ocean modeling system (ROMS) developed for the Arabian Gulf is a robust programming system that is capable of modeling the impacts associated with increasing levels of brine discharge. Essentially, ROMS is a modular hydrodynamic system that includes the runoff or direct river forcing in real time. Theoretically, it could be used for saline river (or anti-river) forcing as well. Prior to settling on the saline river approach, other modules within ROMS were evaluated for their effectiveness in the simulation of hot brine discharges. These included modules representing indirect methods that relied on high evaporation zones (dense water production) that could replicate the projected levels of brine discharge as well as direct methods that accounted for local saline sources to replicate projected brine levels. However, both of these methods showed undesirable effects when imposing high saline zones to a sensitive regional ocean model under climate change.[10] Our conclusion after completing this module vetting process was that the saline river approach offered the best option for accurately reflecting gulf conditions.

5.2. Methodological stages

The saline river approach avoids the undesirable effects of the other potential methods by the use of a technique called real-time brine processing. That is, brine discharges are simulated as direct injections of salt in the hydrodynamic model during model execution. The regional ocean model evaluates these inputs in real (computer) time to avoid hydraulic shocks in the mixing zones that would otherwise be accounted for by an unrealistic infusion of freshwater. This approach allows for reaching a gradual equilibrium between the pre-existing thermodynamics of the Gulf and the saline rivers themselves.

The saline river approach involves two key methodological stages. These stages are illustrated in Figure 5-1, using an electrical circuit analogy to explain the process. In the first stage (left hand side), a (anti) river-like forcing is activated and connected with an infinite source of energy. This is basically a radiation boundary condition.[11] The major functions from

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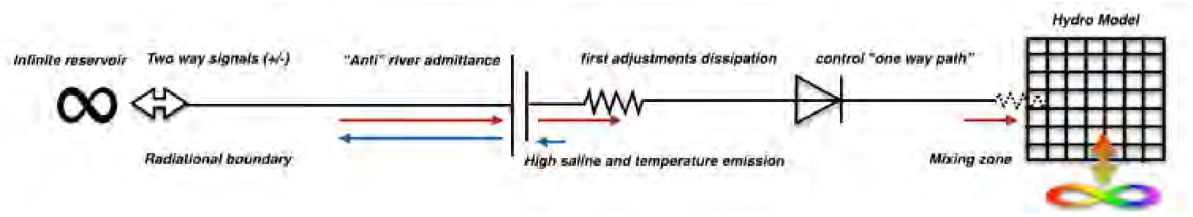
[10] In brief, the main reasons for this are the mass and volume conservation imposed by the hydrodynamic equations and the model domain's rapid response to instabilities (which are natural in the area), which improperly (from a real-world perspective) compensates by introducing large quantities of freshwater.

[11] Radiation boundary conditions have the property that wave motions from the interior of the domain pass through the boundary with small reflections or perturbations. In our modeling, we used such a boundary conditions to simulate an artificial open boundary to reduce the computational domain.

Figure 5-1: Hydronamic sketch of the pre-processing "mechanism" that will provide an already hydrostatic and geostrophic balanced flow to the saline river outflow. To help ilustration, some symbols used are analogous to the electric circuits.



this first stage are to a) provide internal energy to the river forcing from an external source, not the model itself; and b) radiate backward the unbalanced energy out of the system. For example, high salinity fields are supplied by the infinite external source of energy and the freshwater production nearby the saline river position radiates back to the same reservoir in 3-dimensional space.

The second stage (right hand side) has the same function, although not the same origin, as a near-field modeling. The right hand side from the circuit illustrates signal deterioration from the initial saline river prescription, which is already in contact with the real time hydrodynamic variables. There are two physical important processes steps in this stage: the first one allows residual freshwater to be absorbed backwards and a vertical adjustment of the density profile, i.e. the system enters in a hydrostatic equilibrium. The hydrodynamic model itself incorporates the second step, in the second stage. At this point, the model takes the "brine flow" already in geostrophic and hydrostatic equilibrium and mixes its physical variables with the environment.

There are several saline river physical input variables needed for adjusting the hydrodynamic structure described in the circuit analogy of Figure 5-1. These include salinity, volume per second, temperature, radiation spurious outflow factor, river admittance, near field river mixing coefficients (resistance), and, hydrostatic equilibrium conditions. These factors represent the key controls to avoid reversing flux after river admittance stage and to allow final geostrophic adjustments near the field zone. From a modeling perspective, it is important to note that all these variables are controlled by mass, heat and volume transport conditions at the saline river mouth.

5.3. Metrics to evaluate brine modeling simulations

The methodological stages (or model configuration) described above are able to represent a real time saline river forcing into the regional ocean modeling simulation under climate change. It is important to note that the modeling configuration does not integrate all the 486 brine discharge locations along the Arabian Gulf coast, as previously discussed. However, we do expect to achieve some degree of "realism" in the present simulations, since we are using a country-specific and proportional distribution of projected brine discharges at 14 locations that are equivalent to the total mas and discharge rate of all 486 brine discharge locations along the Arabian Gulf coast.

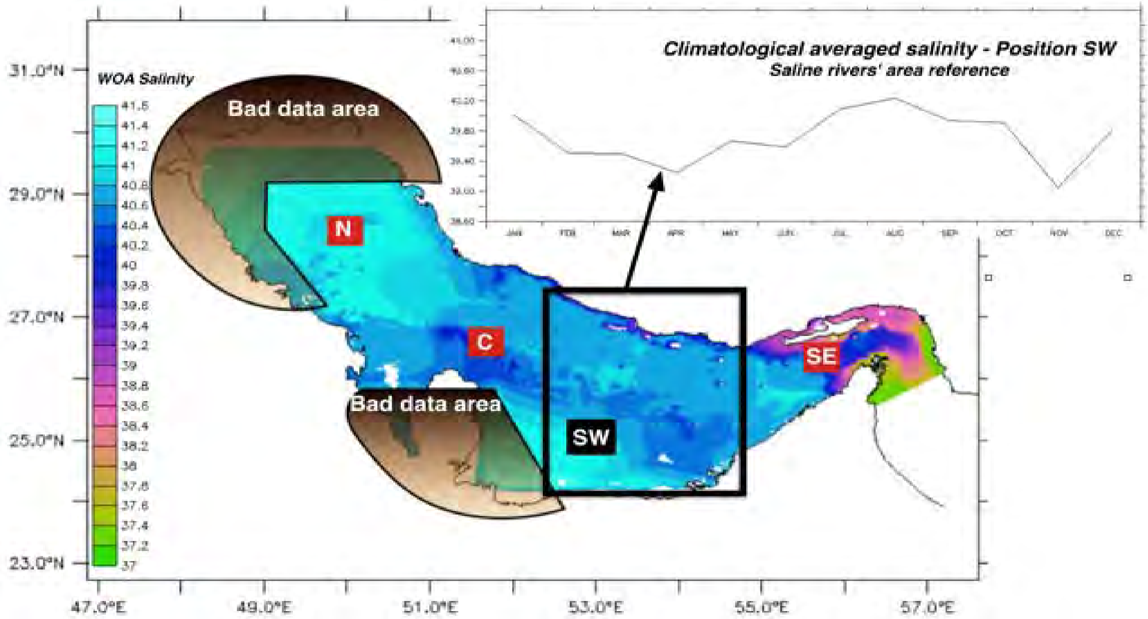
We used three different, but complementary, metrics to evaluate the model control simulation. The first metric was a direct indication of brine loadings. This is associated with the desalination water production datasets, hot brine discharge rates, and related literature, as discussed and summarized in Sections 3 and 4. These data, when reduced to mass flux in kilograms per second, were used to simulate the magnitude and rate of the Saline River forcing into the RCOM and also used to control the equivalent mass flux reproduced by the model (see earlier Figure 4-3).

The direct mass transport computation is not a fully reliable metric because of its double use, i.e., to force and to control. Moreover, the precision of the transport calculations within the model domain is rather limited, basically because the plume flux is rather turbulent and nonlinearly overlaid with the pre-existent mass flux (background dynamics). Thus, the mass transport calculation has been mostly used to define the saline river fluxes and its relative proportions along the Arabian Gulf coastline. It has also been used to estimate the projected change for the mid-century experiment, basically with rate of discharge to the Gulf that is about 5 times larger than the historical period.

Another metric was needed in order to evaluate the impact of brine discharges on salinity patterns in the Gulf. This metric, although indirect, is based on physical observational data as incorporated in the World Ocean Atlas 2013 (Levitus et al., 2012; Locarnini, Mishonov, Antonov, Boyer, & Garcia, 2006). The various data in these datasets for the Arabian Gulf were selected to visually compare salinity and temperature time series from the outputs of the regional ocean model under climate change only. Figure 5-2 shows the area covered by these data. Observed salinity from the World Ocean Atlas 2013 (WOA13) datasets was used as metric to evaluate the final model salinity for regions of the Gulf where there were good data. (See Figure 5-2).

The WOA13 datasets were a useful metric for establishing baseline conditions. They have been climatologically reduced, comprising data between the 20th end and early 21st centuries. In our study, it is assumed that they capture, at least in the Gulf's deepest zones, the anthropogenic saline sources in the first decade 21st century. Comparisons between the model, with and without brine discharge, and the WOA13 products offer a means to quantify the impact of brine discharge influence in the salinity field outputs. These results have been used as a control in a specific location of the Gulf, denoted by the "SW" area in Figure 5-2.

Figure 5-2: WOA13 Sea Surface Salinity extrapolated to the gridded model domain. The coastal areas have to be avoided for comparisons (i.e., the "bad" data regions), because of the limiations in the nature of this historical dataset.



One final metric was considered for evaluating the influence of brine discharge. These correspond to local salinity observations and field data analysis and conclusions from the peer review literature for the region. The results presented in the literature have proved useful for evaluating the effects in model dynamics. They discuss the following observations:

- An increase level of salinity (4-5 psu) is expected in the vicinity of the desalination plants outfall (Mohamed, 2009);
- Observed salinity in Kuwait bay shows a range between 42-44 psu during 2007-2013 period (Uddin, 2014);
- Dawoud & Mulla (2012) in a case study expects average salinity abut 45 psu (AG averaged locally), increasing 5-10 psu from plants discharges;

- Maxima salinity observations in the Gulf of Salwa reached 57.7 psu at surface and 59.2 psu at bottom, with temperature ranges between 15.9°C up to 37.8°C (John, Coles, & Abozed, 1990);
- Combining population and desalination growth along AG basin, there are reports about expected averaged salinity changes due to desalination discharges as 0.42 psu in 1996, 0.93 in 2008 and 2.24 psu projected by 2050 (Bashitialshaaer, Persson, & Aljaradin, 2011).

In conclusion, the combined sets of metrics were adequate as inputs fin the impact evaluation of the brine discharges into the Arabian Gulf. The three metrics (i.e., brine discharge projections, WOA13 datasets and the available technical literature) allows the investigation of the salinity changes and, are also used to the validation of the model control simulation.

5.4. Treatment of freshwater inflow

Except for the Shatt al-Arab waterway, there is no surface water runoff into the Arabian Gulf. This is based on salinity field observations in which no fresh water plumes have been detected. For the earlier climate change simulations, river runoff into the AG was not significant relative to climate change impacts. However, the Shatt al-Arab waterway plays an important role in modeling local circulation impacts near Kuwait Bay. The freshwater flux from this waterway has been combined with brine discharge plumes have been considered in the present experiment.

Box 5-1: Overview of Shatt al-Arab key characteristics

The Shatt al Arab waterway is 140 km wide with a landscape characterized by green marshy areas, lakes, lagoons and estuaries, bordered by irrigated lands and date palm plantations and surrounded by desert (Basin et al., 2004). Water temperatures range from 9-40°C. Runoff varys from dry and saline estuarine-like fluxes (200 m^3/s) to values up to 14,000 m^3/s (Basin et al., op. cit.). Over the past decades, a steady decay in water inflow to the Shatt al Arab tributaries has been observed.

A brief description of the Shatt al-Arab waterway is offered in Box 5-1. It is formed after the confluence of the Tigris and Euphrates rivers where, at its southernmost part, there are two major tributaries, the Kharkenh and Karun rivers (see figure 5-3). Because of the variety of water uses, the number of countries envolved (i.e., Turkey, Iran, Iraq), and climate change, future runoff projections are complex and highly uncertain. Historical estimates in the area, considering the main tributaries account for aproximately 1,400 m^3/s (R Michael Reynolds, 1993). Using stream flow gaging stations, it has been projected that by 2020 there may be a decrease to a total water inflow by about 2,000 m^3/s and a demand increase of aproximately 2,500 m^3/s (Issa, Sherwany, & Knutsson, 2014). These estimates suggest that the Shatt al-Arab waterway may dry up in the coming decades.

In order to model climate change together with desalination activities, it was necessary to establish a discharge rate for the Shatt al-Arab waterway. Based on an asessment of projections in the literature, we assumed a fixed freshwater runoff for the historical period of 1,000 m^3/s and a smaller value in 2050 of 400 m^3/s for saline river location #12 (i.e., “Abadan“ in earlier Figure 3-2). Both estimates will be able to impose a positive freshwater flux to the

Figure 5-3: The Shatt al-Arab basin, composed of the Tigris and Euphrates Rivers, and near the Arabian Gulf, the Karkhenh and Karun rivers (UNESCWA, 2013)

Arabian Gulf, making the fresh water plumes noticeable during the modeled historical and future periods. Lower values will create a saline estuary in the numerical river system, which basically implies that the river flux and baroclinic gradients are not enough to constrain the Arabian Gulf to its boundaries.

5.5. Treatment of sea level rise

Except for Dynamic Sea Level (DSL) variability and trends, there was no explicit consideration of climate change-induced sea level rise impacts in the modeling of desalination impacts on the Arabian Gulf. DSL is defined as the sea level deviation from the geoid or to a fixed local level called Relative Sea Level (RSL). Essentially, the geoid is the shape that the surface of the oceans would take under the influence of Earth's gravitation and rotation alone, in the absence of other influences such as winds and tides. DSL is the component of sea level related with the ocean dynamics responses from natural and forced fields (e.g. wind setup, barotropic and baroclinic gradients etc.). Thus, it can be adequately represented within the current suite of global circulation models. It has been fully accounted for in the regional ocean model used for the current analysis.

It is important to note that DSL is the smallest of three components comprising sea level changes due to climate change effects. The sea level will also vary due to Global Thermal Expansion (GTE) of the ocean waters and the melting of glaciers (deglaciation). Regarding GTE, as water heats up, it expands and takes up more space, thereby raising sea levels. Regarding deglaciation, as ice melts (i.e., from glaciers, ice shelves, and ice sheets), the oceans receive these waters, thereby changing sea levels. Together, GTE and deglaciation are the largest contributors to sea level rise projections, accounting for up to 85% of sea level rise since the 1970's. Additional details about the factors contributing to sea level rise – as well as limitations in representing these processes in the current suite of general circulation models - are provided in Annex D.

Hence, the modeling results discussed in the next section do not account for the impact of GTE and deglaciation. Nevertheless, this is not likely to significantly affect the results discussed in the next section. This is due to the fact that the full impacts of GTE and deglaciation are not expected until late in the 21st century, well after the 2050 year used as the mid-term planning end year in the analysis. Up through the 2050 period, the impact of GTE and deglaciation on salinity and temperature changes in the Gulf are qualitatively assessed to be in the negligible to marginal range.

6. Saline river modeling results

This section describes the results of modeling the impacts on the Arabian Gulf of projected brine discharges from desalinated water production under climate change. Overall, this involved a two-step approach. First, the hot brine was distributed as point sources entering the Arabian Gulf at the fourteen (14) saline river locations. Second, the impacts of these saline rivers were modeled using the validated regional ocean model for the Gulf. Within this overall approach, there are several key components, including setting up the methodological stages, establishing the metrics to quantify the impact of saline rivers, and the treatment of the freshwater input from the Shatt-Al-Arab waterway. After providing a review of essential background for Saline River modeling, each analytical step is briefly review in the subsections below.

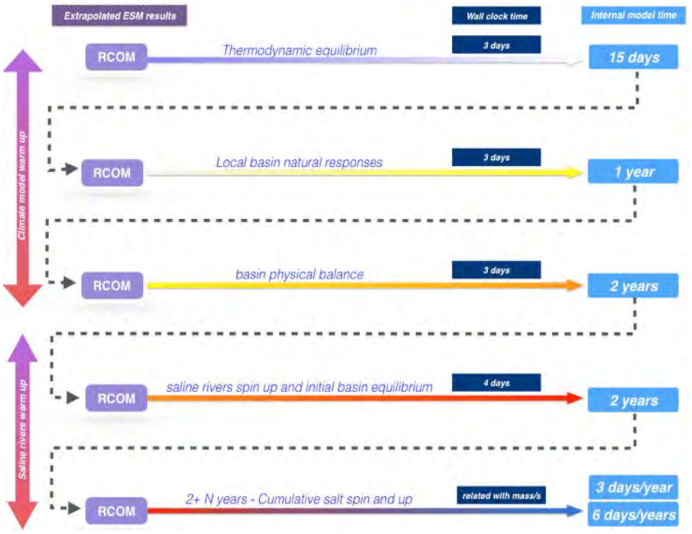
6.1. Background

This section necessarily describes some of the underlying technical details associated with Saline River modeling. This mostly technical information is included here so that reviewers and stakeholders can understand the qualities and limitations of the specific processes we used to establish brine input into the DCOM. Some of the more technical discussion regarding modeling procedures is likely to be of interest mostly to ocean modelers. Several topics are covered, including the type of experiments conducted, model warm-up requirements, and results of the validation run. Each is briefly reviewed in the subsections below. The section concludes with a discussion of the impacts of desalination and climate change at multiple scales in the Arabian Gulf.

6.2. Model warm-up process

Pre-processing was required prior to the actual saline river modeling. This consisted of two major 2 stages of model “warm-up” incorporating 5 distinct steps, as illustrated in Figure 6-1.[12] The first stage corresponds to the RCP8.5 climate projection scenario. This stage required 3 preliminary steps before the fourth and final spin up and the actual model simulation. The second stage corresponds to the Saline River forcing. This stage required 2 steps, starting from the final warm up from the first stage (before spin up), which is rewound back by two years to a new warm up step, considering the saline river forcing (2 years), until reaching a new hydrodynamic equilibrium. This eliminated any spurious signals related to initialization of hydraulic jumps.

Figure 6-1: The sketch of the two major warm up stages and five distinct required to start a specific model simuation.



After the pre-processing stages were completed, one further action was required. The already stabilized system with saline rivers was rewound two years back again, and a new warm up started, before beginning the process of saving the results for the simulation period. The simulation wall clock time varies depending on the saline river inflow intensity.[13] This is due to the lower parallelization efficiency and the natural salt fingering (vertical mixing) processes, which decreases the baroclinic time step (lower left blue boxes in Figure 6-1). This figure shows the warm up first stage, when ocean boundaries and atmospheric forcings under climate change are settled (first 3 steps in Figure 6-1). The second stage (2 last steps in Figure 6-1) sets the saline river warm up. Internal and wall clock time are listed as reference, based on a SGI cluster, using at least 256 CPUs.

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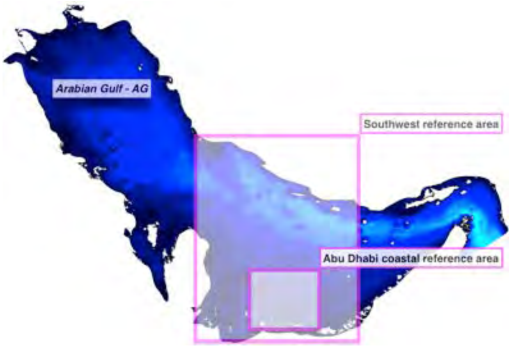
[12] For a review of the role of the warm-up step in the modeling process, please refer to Section 2.3 which describes the process for the earlier climate change (only) runs.

[13] In the context of regional ocean modeling on a computer, “wall-clock time” is a measure of the real time that elapses from the start to the end of a run, including time that passes due to programmed (i.e., artificial) delays or waiting for computing resources to become available. In other words, it is the difference between the time at which a run finishes and the time at which the run started.

6.3. Model Run framework

There were a total of seven (7) complete experiments that were part of this assessment. Each of these runs is listed in Table 6-1. This Table shows both the pre-existing simulations based on historical and RCP8.5 climate projection without saline river outflow (i.e., Early 21st and Mid 21st runs) and the saline river simulations (i.e., Validation, Reference, Low saline, Medium saline, and High Saline). Each experiment is briefly described in the bullets below, with the specific area for which the experiments were conducted illustrated in Figure 6-2. A discussion of the reasons underlying this experiment framework is provided in subsequent subsections. It is important to note that the salt transport values (tonnes/s) do have an intrinsic error, probably around 15%, which is associated with the cumulative impact of the various assumptions.

Figure 6-2: The "Southwest reference area" is the focus of the seven (7) experiments.



- *Early 21st:* This run corresponds to the outputs of the original experiment undertaken in sub-project #2 under historical climatic conditions only. Hence, no anthropogenic increments in atmospheric greenhouse gas concentrations or salt loadings are included. The time period corresponds to the 2000-2004 period.
- *Mid 21st:* This run corresponds to the outputs of the original experiment undertaken in sub-project #2 under conditions of climate change only (RCP8.5). Anthropogenic increments in atmospheric greenhouse gas concentrations are included, but no anthropogenic salt loadings are considered. The time period corresponds to the 2040-2050 period.
- *Validation:* This run corresponds to running an experiment under historical climatic conditions with a low level of anthropogenic brine discharge rate in the saline rivers (i.e., 50 tonnes per second). The time period corresponds to the 2000-2004 period, which datasets are available to evaluate the model results. The difference between the Validation run and the Early 21st run sets apart the impact of current desalination activity.

Table 6-1: List of the experiments conducted

Experiment brief description	Brine discharge (tonnes/s)	Name
No saline rivers Early 21st Century Run: historical	0	Early 21st
No saline rivers Mid 21st Century Run: RCP8.5	0	Mid 21st
Early 21st Century Run + saline rivers	50	Validation
Mid 21st Century + saline rivers	50	Reference
Mid 21st Century Run + saline rivers	80	Low saline
Mid 21st Century Run+ saline rivers	120	Medium saline
Mid 21st Century Run+ saline rivers	220	High saline

- *Reference:* This run corresponds to running an experiment under conditions of climate change (RCP8.5) together with a low level of anthropogenic brine discharge rate in the saline rivers (i.e., 50 tonnes per second). The time period corresponds to the 2040-2050 period. The difference between the Reference run and the Mid 21^{st} run sets apart the impact of future desalination activity.
- *Low saline:* This run corresponds to running an experiment under conditions of climate change (RCP8.5) together with a higher level of anthropogenic brine discharge rate in the saline rivers (i.e., 80 tonnes per second). The time period corresponds to the 2040-2050 period. The difference between the Reference run and the Low saline run address uncertainty in the projection of future desalination activity.
- *Medium saline:* This run corresponds to running an experiment under conditions of climate change (RCP8.5) together with an even higher level of anthropogenic brine discharge rate in the saline rivers (i.e., 120 tonnes per second). The time period corresponds to the 2040-2050 period. The difference between the Reference run and the Medium saline run addresses uncertainty in the projection of future desalination activity.
- *High saline:* This run corresponds to running an experiment under conditions of climate change (RCP8.5) together with the highest level of anthropogenic brine discharge rate in the saline rivers (i.e., 220 tonnes per second). The time period corresponds to the 2040-2050 period. The difference between the Reference run and the High saline run addresses uncertainty in the projection of future desalination activity.

The four brine discharge scenarios are intended to explore the sensitivity of Gulf waters to different future desalination scenarios. Considered individually, they can be viewed as a way to bound uncertainty given that the socio-economic conditions driving the installation and operation characteristics of unplanned desalination capacity are difficult to predict. For example, the “high saline” scenario could be likened to future in the region under conditions of high socio-economic growth coupled with a reliance on thermal desalination technologies. Considered comparatively, they can be viewed as a way to indirectly explore the impact of water efficiency and conservation policies, as well as the impacts of a transition to alternative water sources (e.g., treated wastewater). For example, the difference between the “low saline” scenario and the “reference” scenario could represent the impact on Gulf waters associated with a future in the region where substantial progress has been made in conserving and recycling water.

6.4. Modeling historical desalination activities

As noted above, the difference between the Validation run and the Early 21^{st} run separates the impact of desalination activity for the historical period. These runs simulate the hydrodynamic response of the Arabian Gulf under historical climatic conditions (i.e., assuming no climate change), with and without direct forcing by saline rivers. The direct forcing by the saline rivers in the Validation run relies on the various parameters described in Section 3 and 4, namely the spatial distribution of the saline rivers, salt mass transport (in kilograms per second), and saline water discharge (in cubic meters per second of hot brine). The model has been executed for a total of 10 years, including the five-step warm up process over 5 years from 1995 to the end of 1999, as well as the 5-year output period from 2000 to the end of 2004.

Desalination activities significantly impact the spatial distribution of salinity levels throughout the Gulf. The impact of Saline River forcing on surface and bottom salinity is illustrated by the maps in Figure 6-3 for the "reference area" marked in the previously shown Figure 6-2. This area corresponds to a region where WOA13 data are denser and more reliable for establishing a baseline reference. Specifically, the impacts of desalination activities under historical climatological conditions can be summarized as follows:

- *Surface salinity:* Desalination impacts are limited to roughly a 100-meter zone away from the coastline. Salinity levels increase by about 1% to 12% in these areas (i.e., between 0.5 to 4.9 psu). The modeling results indicate no surface salinity impact from desalination in the middle portions of the Gulf.
- *Bottom salinity:* The impact of desalination on bottom salinity is greater than that of surface salinity. Desalination impacts are evident throughout the Gulf, including the deeper middle portions. Along the coast, salinity levels increase by about 10% to 15% (i.e., between 0.5 to 4.9 psu. In the middle portions of the Gulf, bottom salinity levels increase by about 0.5% to 1% (i.e., between 0.3 to 2 psu)

Desalination activities also significantly impact temporal salinity intensities throughout the Gulf. The maps in Figure 6-4 for the "Southwest reference area" depicted in Figure 6-2 illustrate the impact of Saline River forcing on surface and bottom salinity. This plot corresponds to the period 1998 to 2008. The following key points can summarize the impacts of desalination activity under historical climatic conditions:

Figure 6-3: Time averaged salinity for the historical period (i.e., 2000-2005; no climate change) for the Early 21st (left) and Validation (right) runs, with surface salinity (top pair of maps) and bottom salinity (middle pair of maps). The bottom pair of maps illustrates the difference (or impact of desalination) for surface salinity (left) and bottom salinity (right).

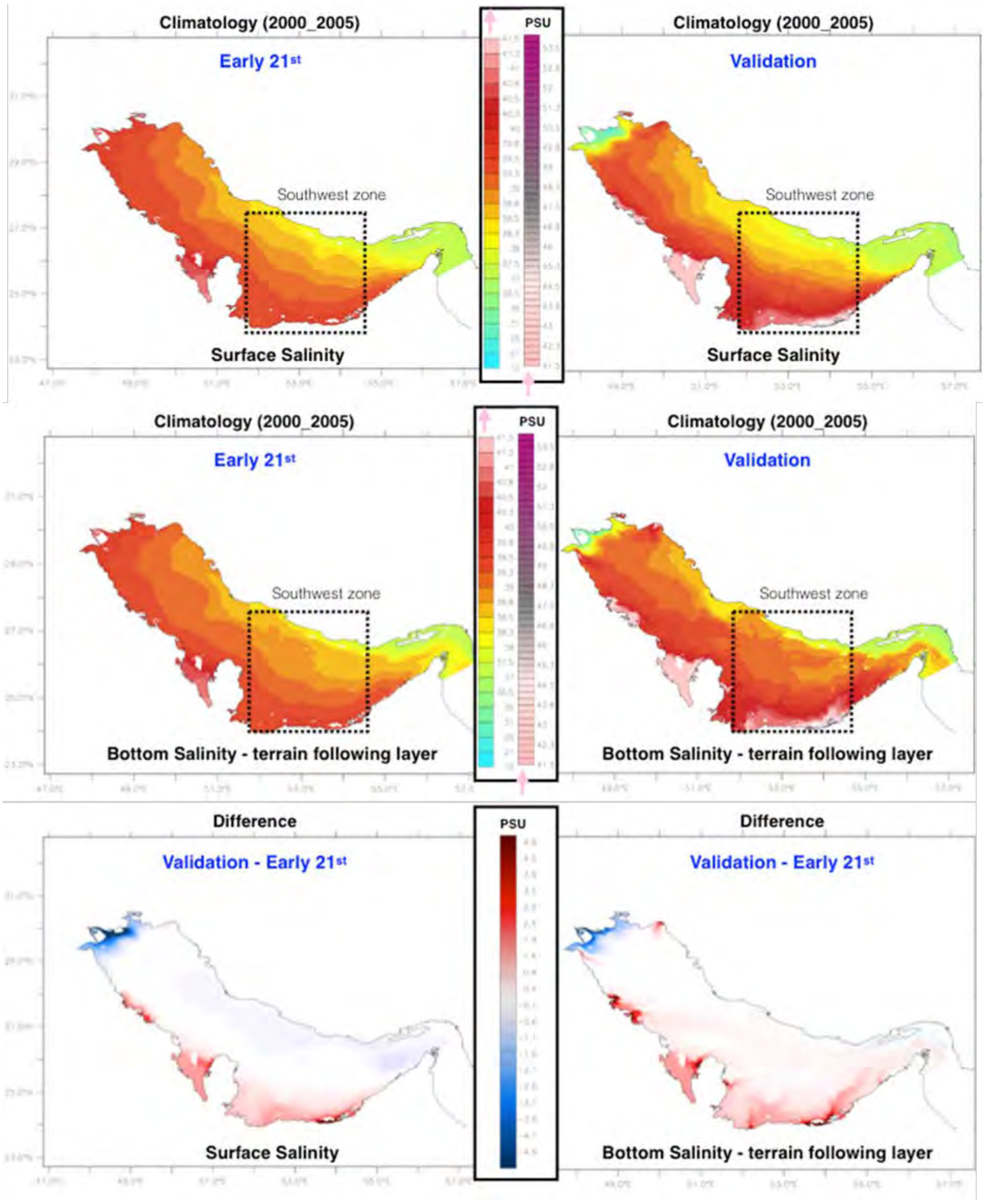
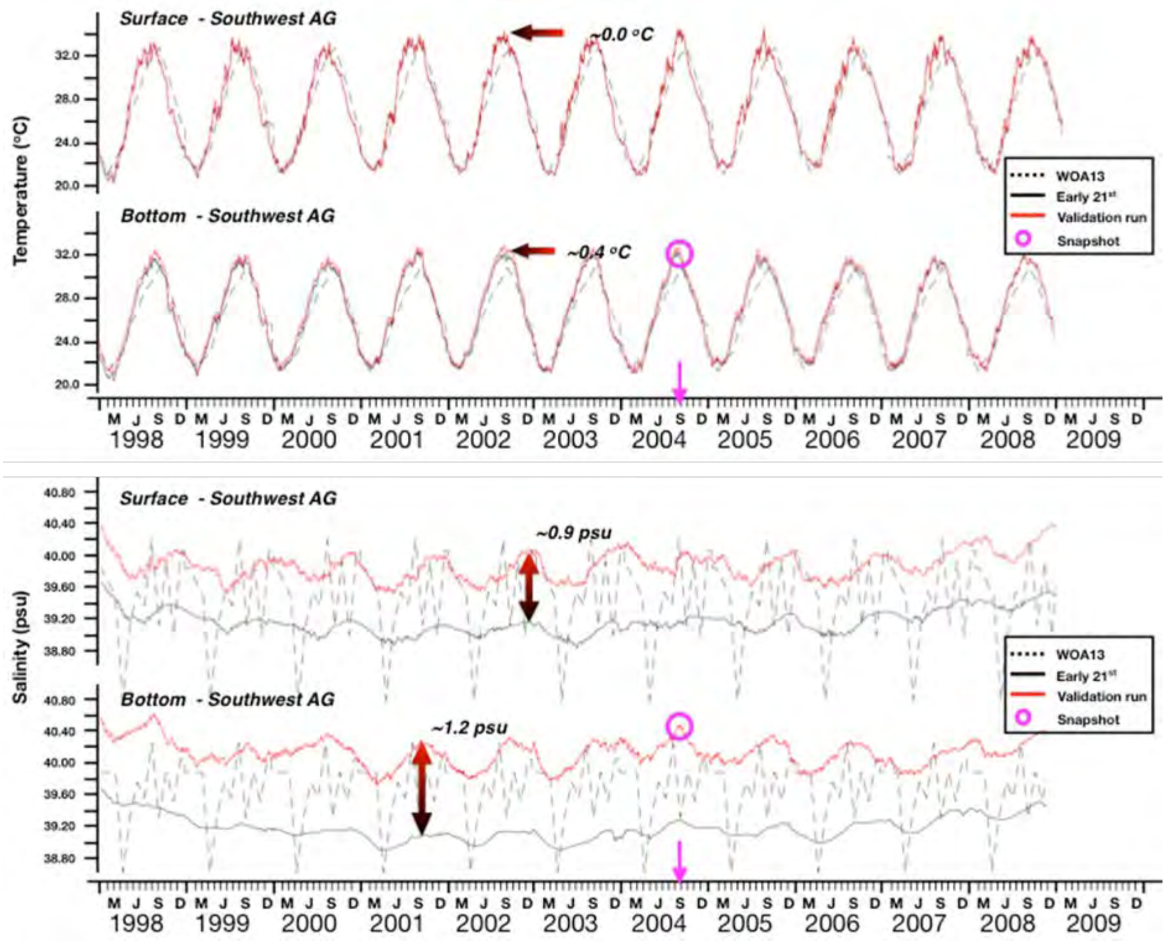


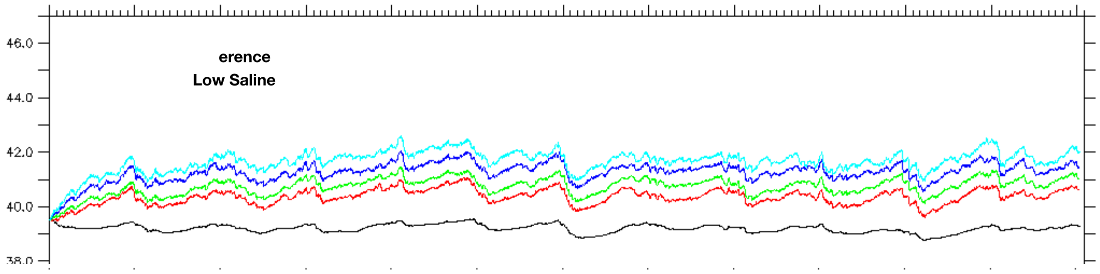
Figure 6-4: Temperature and saliniy timeseries for the historical period, comparing the Early 21st run with the Validation Run. Black-red arrows indicate the average change for temperature and salinity. The circle is a time mark for future reference.



- *Surface salinity:* At the surface, modeled desalination activities increase average salinity levels by about 0.9 psu throughout the 10-year period. This finding confirms the findings presented in Section 2.4 where a comparison of TS diagrams showed a roughly 1 psu increase in the salinity field from desalination activities. Basically, this result validates the use of the saline river modeling approach.
- *Bottom salinity:* At the bottom, modeled desalination activities increase average salinity levels by about 1.2 psu throughout the 10-year period, which confirms the results in Figure 6-3 that showed bottom salinity increases were greater than those at the surface.

Finally, to further illustrate the impact of desalination activity on the historical period, results for bottom salinity and temperature are shown in Figure 6-5, for the Validation run.[14] This Figure presents only maximum <u>bottom</u> (terrain following) conditions typically experienced in late summer (i.e., September), as denoted by the magenta circles in the previous Figure 6-4. It is important to note that there are two labels for each variable to stretch the shaded variability to their extremes (expected temperatures up to around 40°C and expected salinities values, up to around 54 psu.

Figure 6-5: Salinity timeseries for the all the five 2040-2050 scenarios experiments. Averaged for two different areas coastal and southweast AG (i.e. see earlier Figure 6-2). The time series includes the warm-up period. The light blue line refers to the still running high saline experiment (ongoing). The magenta arrow points to the date (a summer condition) for which all the experiments have been climatologically reduced and analysed.



6.5. Potential Gulf-wide impacts of future desalination activities

As noted earlier in Section 6.3, the difference between the Reference run and the Mid 21st run separates the impact of desalination activity in the future period under climate change. In other words, the difference between any of the desalination rate runs (i.e., Low Saline, Medium Saline, High saline) with respect to the Reference Run isolates the impact of potentially higher levels desalination activity in the future under climate change. This approach ensures that we can directly quantify the deviation of model results from an expected average signal.

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[14] As noted earlier, the validation run corresponds to the modeling of brine discharge of 50 tonnes/second from desalination activities within Gulf water characterized by historical conditions

Figure 6-6: September, 2004 snapshot from bottom temperature (left) & salinity (right) for validation run

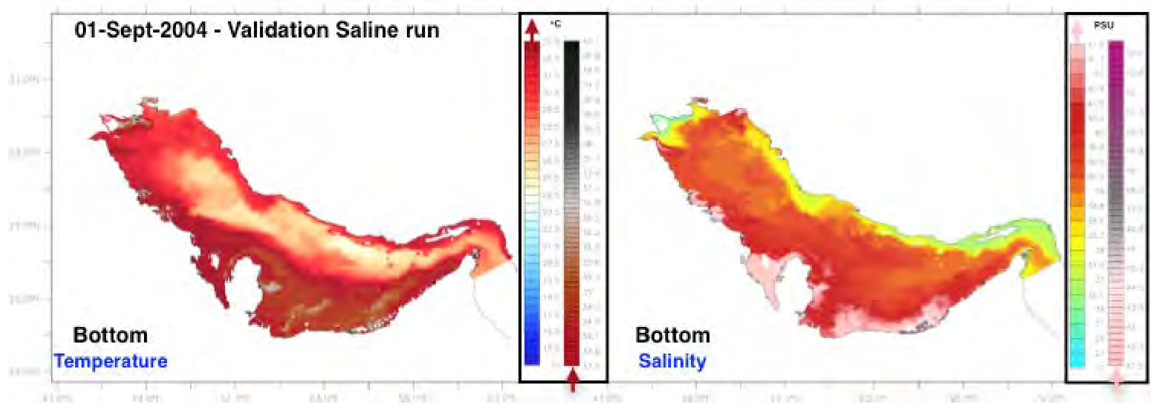


Figure 6-6 illustrates the temporal impact of potentially higher salt loadings to the Arabian Gulf under climate change. This Figure shows a time series of the bottom salinity levels for two areas in the Arabian Gulf for the Reference and for all three desalination rate experiments. The top plot shows results for the “Southwest coastal area” and the bottom plot shows results in the “Abu Dhabi coastal area” (see earlier Figure 6-2 to review the specific location of these areas). The increasing levels of bottom salinity corresponding to increasing brine discharge rates show that the regional ocean model is capturing and quantifying the impact of increasing levels of desalination activity.

Figure 6-7 illustrates a snapshot of the spatial impact of potentially higher salt loadings to the Arabian Gulf under climate change. This Figure shows a snapshot of average bottom salinity levels during the summer months of 2045. The salinity map at top is based on the climate change only run (i.e., no desalination or saline rivers assumed). The four salinity maps below the top map corresponds to increasing brine discharge rates (i.e., from 50 to 220 tonnes per second). Two key observations are offered below regarding the impact of future desalination activities on the spatial distribution of bottom salinity.

- *Large salinity increases from desalination:* A large difference between upper and lower plots in noticed in Fig. 6-7. Highly saline (and warmer) brine outflows occur in the vicinity of the “saline river mouth”. This leads to high energy mixing processes and after sinking; the outflow is stabilized on the bottom of the Gulf. These results are evident throughout, depending on brine discharge quantities, in all the fourteen saline river sources.
- *Convergence around maximum salinity levels:* Another general behavior observed when comparing all the scenarios, is that average salinity levels in the Gulf do not increase linearly with brine loading rates.

Figure 6-7: Maps of bottom salinity corresponding to the summer of 2045. The black arrow points to experiments increasing in the saline river outflow, as text details on the right side of the plots.

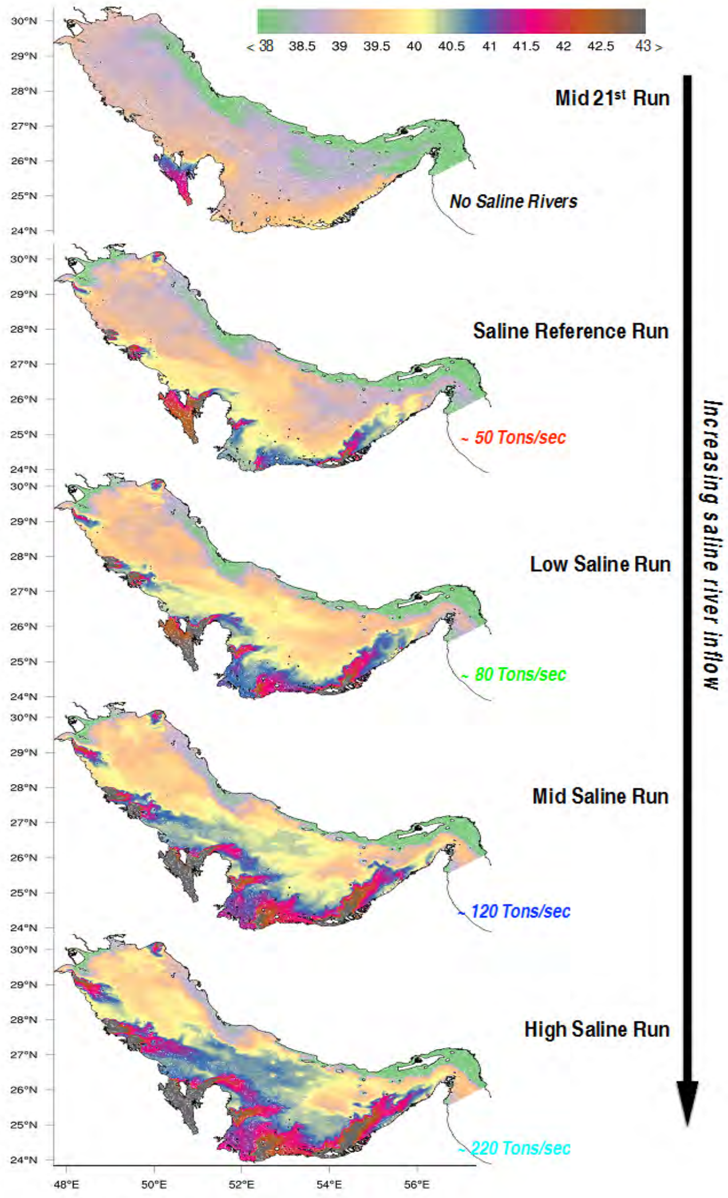
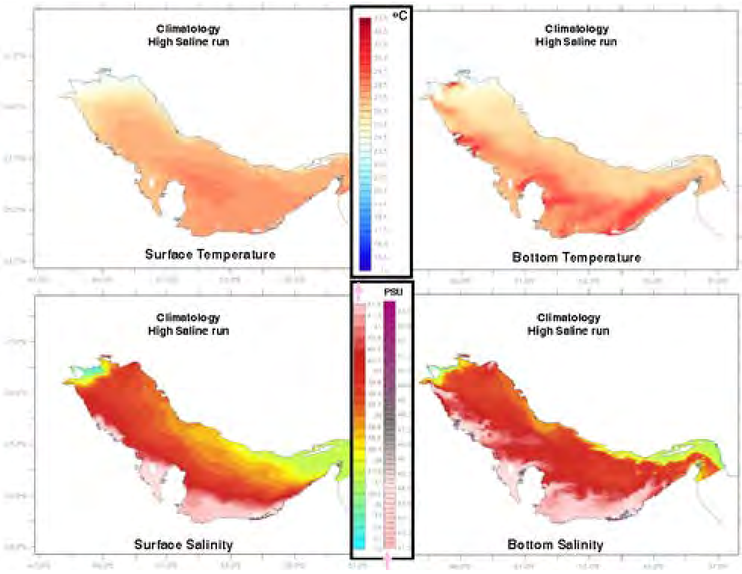


Figure 6-8 shows average temperature and salinity for the 2040-2050 period for the surface and bottom of the Arabian Gulf for the high salinity experiment. Both variables, temperature and salinity, show the prominent influence of the saline river outflow on the bottom layers, where the bottom plume's tracks are clearly noticeable, even in a highly reduced statistical result over the 10-year period. Even at the surface, the previously evident thermo-dynamical fields are still quite perceptible.

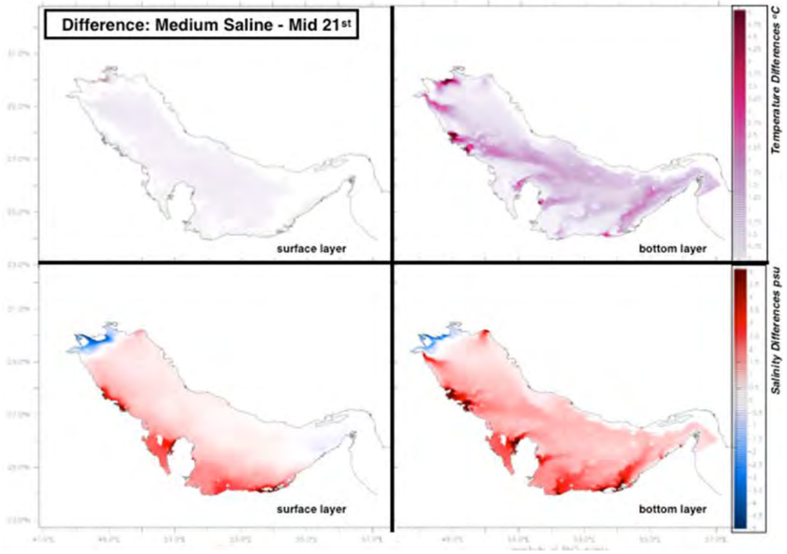
Figure 6-9 illustrates the differences between the High Saline run and the Mid 21st run. This offers a way to better assess general impacts in the horizontal circulation structure throughout the Arabian Gulf. Discussion points here are in bullets below, followed by subsections that explore the implication of future desalination activities, for a set of key features along vertical profiles of the Gulf.

Figure 6-8: Results for the high saline experiment, with ~220 kg/s saline outflow. Surface and botom temperature and salinity climatology to qualify these statistically stable patterns



- *Bottom temperature circulation dynamics:* Temperature changes are more evident at the bottom. The very high density of the brine discharge trap the warmer, highly saline water in the bottom Gulf layers. This flows to the AG's central channel, and then heads out to the Gulf of Oman through the Hormuz Straits.
- *Surface salinity circulation dynamics:* Salinity changes show large spatial variations. The negative differences to the north are associated with the Shatt al-Arab freshwater runoff that has been considered only in the saline river scenarios, where it contributes to mixing and circulation in the northernmost areas of the Gulf. Along the coast, the most intense saline river outflows are

Figure 6-9: Temperature and salinity differences associated with the High saline and the Mid 21st runs for the surface and bottom (terrain following).



evident in the surface layers with waters in the southwest trapping the advected surface salinity from northernmost and westernmost zones.

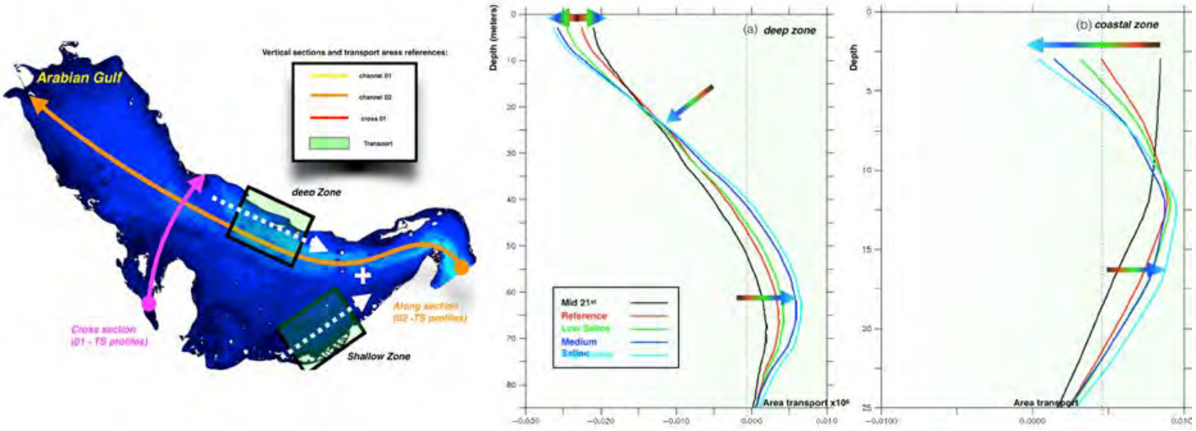
- *Bottom salinity circulation dynamics:* At the bottom, there is a very likely equilibrium condition reached between the circulation and the increased salinity into the Gulf. There are permanent flows formed by the density gradients at the bottom layers that will increase with the projected increase of saline rivers outflows.

6.5.1. Salt transport characteristics

Figure 6-10 shows the transport profile associated with the Mid 21st, Reference and the three saline river runs. The shaded arrows in the two vertical profile plots single out the trends observed with the progressive increase in the saline river AG's total outflows. Transport increases at greater depths as well as in the intermediate depths where water are still dense. Moreover, transport in the northward direction also increases but in a lower rate. A possible explanation is a likely flux composition of the shallow saline shallow waters formation, increased by the effect of climate change in the 2050's and the high dense waters produced by the desalination plants along the gulf. Two other observations can be inferred from the plots, as noted below.

- *Deep zone profile:* At surface layers, there is a relatively steady state at surface transport (slow increase), which is directly connected with a negative fresher water inflow transport (northward specific conventions), as a function of changes implied in the saline river runs. For the Mid 21st run (i.e., climate change only), It was previously noticed that this increase of northward inflow is highly correlated with barotropic external gradient forces and dynamic sea level variability at the Hormuz Straits. At bottom layers, an expected and broad increase in the transport is observed as a funciton of the saline river discharges.

Figure 6-10: Arabian Gulf bathymetry (left map); vertical profile transport/m for deep zone plot (a) and shallow zone plot (b). The deep and shallow vertical transport plots correspond to the shaded areas on the map at left. The shaded arrows on the plots indicate the trend direction for the curves that are a function of salinity.



- *Shallow zone profile:* There is a systematic decrease, even signal eversion, in surface layers transport, indicating plume effects on local transport dynamics. A reasonable assumption about this dynamic behavior can be the strengthening in the local baroclinic structure, merged with an increase in the dynamic impedance (resistance) to the wind driven forces, which usually driven the surface current structures in this area, as evident in the Mid 21st run. At bottom layers, the same has happened if compared with the deep zone profile, an increase in the transport as function of the saline river outflow.

6.5.2. Temperature and salinity profiles

Figure 6-11 shows the vertical profile of temperature and salinity changes corresponding to the north-south cross section. The orange arrow from the Straits of Hormuz to the Shatt al-Arab in the previously shown Figure 6-10 indicates this cross section. The temperature and salinity profiles correspond to the difference between the Medium saline run and the Mid 21st" run (climate change only; no saline rivers), average across the 2040-2050 period for the summer month of June. The maximum averaged saline plumes typically occur between August and September depending on the area of the Gulf. However, June was chosen because it shows the maximum influence of the Salwa Bay along and across the entire Arabian Gulf.

Figure 6-11: Along channel (02) vertical section (see Figure 6-10, left map for reference). The temperature (top) and salinity (down) sections show the scenario maxima differences (High saline – Mid 21st), climatological summer reduction. Orange arrow indicates direction (northward) and circles indicating the contact point position for the cross section.

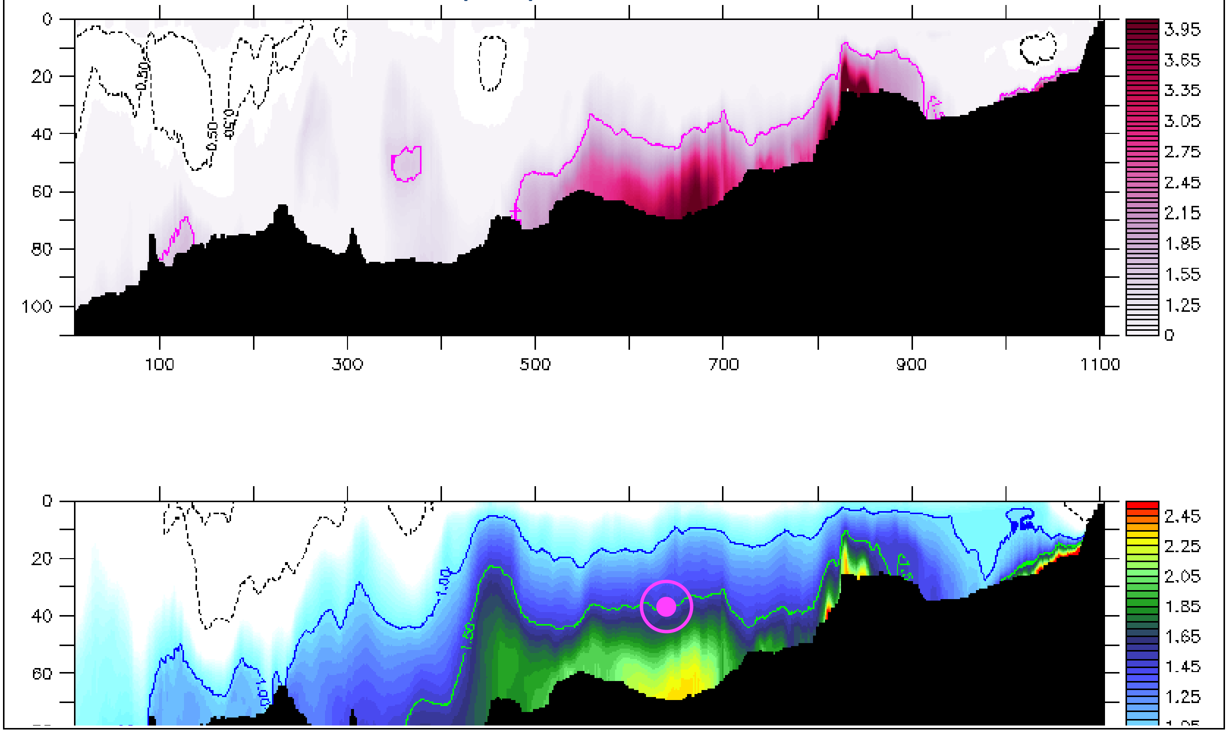


Figure 6-12: Cross channel (02) vertical section (see Figure 6-10, left map for reference). The temperature (top) and salinity (down) sections show the scenario maxima differences (High saline – Mid 21st), climatological summer reductions. Magenta arrow indicates direction (Eastward) and circles indicating the position, where the contact point with the along channel section

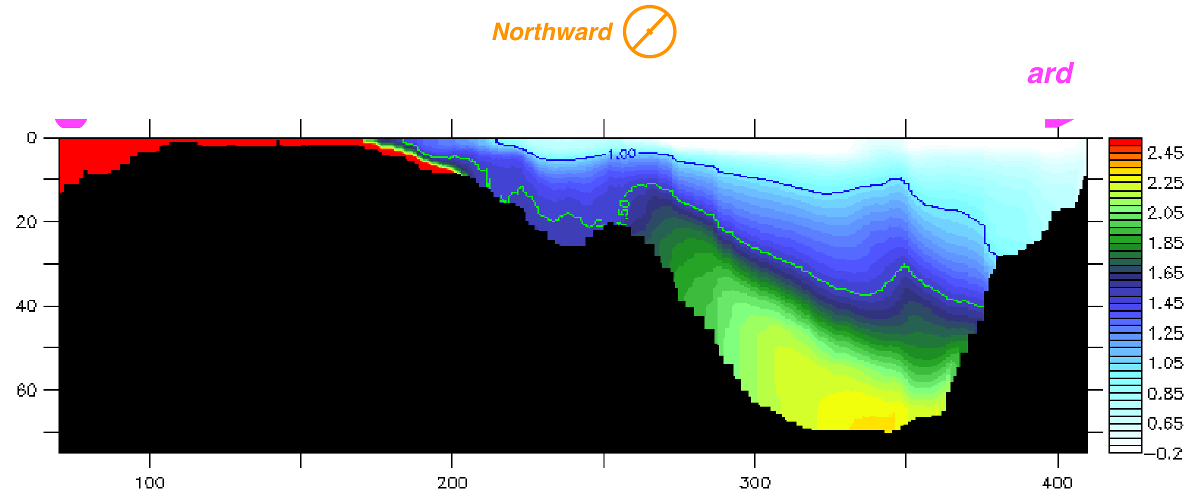


Figure 6-12 shows the vertical temperature and salinity changes corresponding to the east-west cross section. The magenta arrow from Salwa Bay near Qatar to Iran in the priosuly shown Figure 6-10 indicates this cross-section. The temperature and salinity profiles also correspond to the difference between the Medium saline run and the Mid 21st" run (climate change only; no saline rivers), average across the 2040-2050 period for the summer month of June. Temperature is rather uniform along the cross section. Salinity has larger differences likely due to the fact that one of the saline rivers is located in the area but also because it naturally captures northern advected saline fluxes from north, repeating the same physical pattern noted earlier for climate change effects alone.

Some additional patterns are evident from Figures 6-11 and 6-12. The average projected change in the temperature of intermediate waters is approximately 1°C, reaching a maximum between 3 and 4°C, depending on proximity to the saline river outflow. The salinity impacts are more significant with respect to water depth and ranges from 1 psu up to 3 psu, which is associated with Salwa Bay. Moreover, the dashed black contour lines along the north-south profile denote where negative differences are observed.[15] This feature is observed for both temperature and salinity from the Hormuz Strait up to the middle of the Gulf. This is due to

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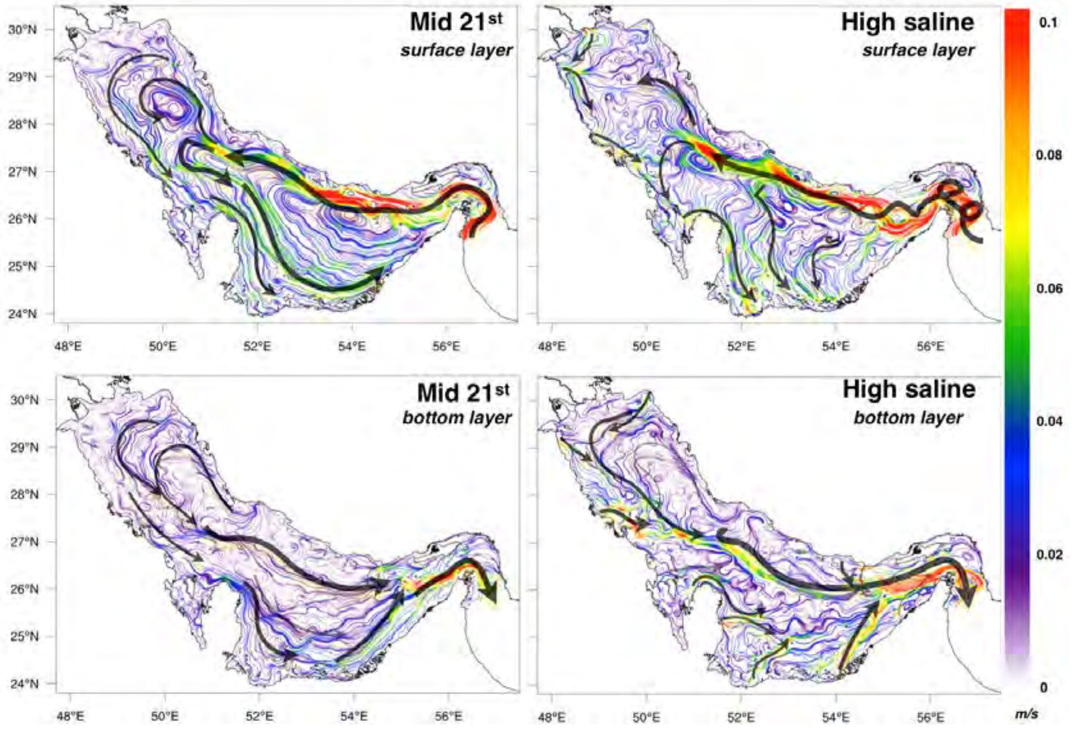
[15] A negative difference indicates that the Mid 21st run has a higher salinity level than the Medium saline run.

freshwater inflows and is constrained to the deep channel and near the southern areas of the Gulf.

6.5.3. Horizontal residual current patterns

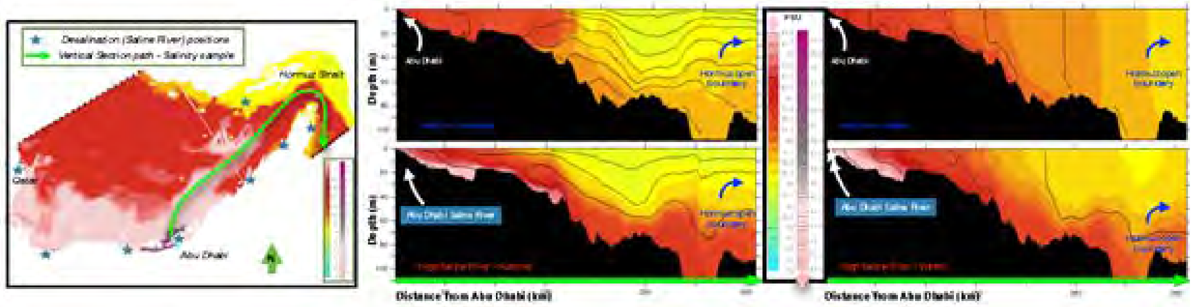
Notwithstanding the significant impact on bottom layers (salt and volume transport), the vertical volume transport of the Gulf remains consistent with historical averages (see previous Figure 6-10), although changes in the shallow areas are evident. The key question is: how much has the strengthening of bottom saline flow affected the general horizontal circulation? We already know that the overturning stability, and the AG's anticlockwise circulation are unlikely to be disrupted by 2050, due to only global warming effects (Edson et al., 2015). To observe the combined effects of climate change and desalination, Figure 6-13 combines the maxima dynamic effect from desalination plants achieved in the High saline experiment (i.e., brine discharge rate of 220 tonnes/second; right side of the figure) and the horizontal residual current patterns for the Mid 21st experiment (i.e., climate change only; left side of the figure). These maps highlight the relationship between bottom saline flow strengthening and general horizontal circulation patterns.

Figure 6-13: The residual current (10 years average) for two scenarios. The RC8.5 based (Mid 21st) and the High saline run. Colors indicate current intensity and faded black arrows suggest the mainstream fluxes.



At the bottom of the Gulf, the lower two maps in Figure 6-13 show quite similar residual circulation. This circulation is distorted by the saline river baroclinic flows, which explains the overall Gulf's increase in the volume and mass transport at bottom layers (as shown in the previous Figure 6-10). At the surface of the Gulf, the upper two maps in Figure 6-13 indicate that there will likely be an increase in surface waters through the Hormuz Straits. At the same time, there is a resistance from the system to absorb and mix these relatively fresher waters from the Gulf of Oman. Although severely disturbed, the average anticlockwise circulation in the Arabian Gulf remains at the upper layers.

Figure 6-14: Seasonal salinity vertical sections following plume (green line on area plot) until the Hormuz Strait. Top profiles corresponds to Mid 21st run; bottom profiles corresponds to High Saline river run



6.5.4. Vertical mixing processes between Abu Dhabi and Hormuz

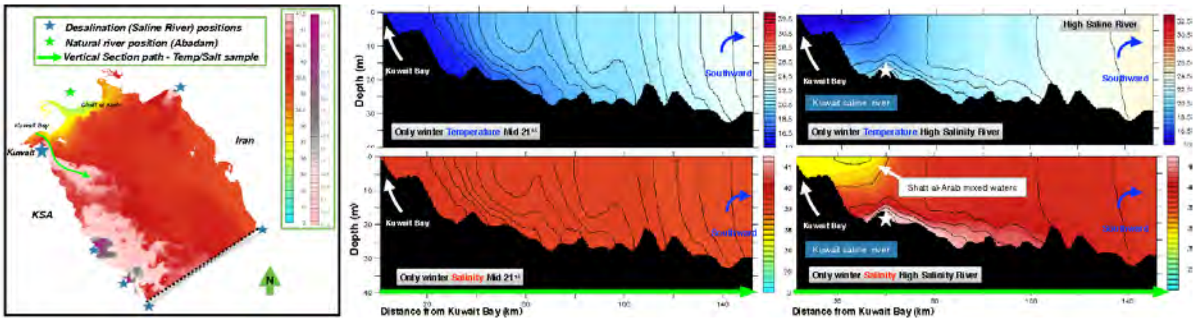
There are some important impacts to vertical mixing processes observed, especially in the baroclinic structure, due to future desalination activities under climate change. These local changes have the potential to introduce adverse effects, such as lowering the capacity of the Arabian Gulf to admit lower salinity waters from the Gulf of Oman, as previously discussed. This effect is likely to happen on average throughout the Gulf but will likely be mostly concentrated along the western side of the Gulf and along the central deep channel. The eastern side and the Hormuz vicinity shows the opposite behavior, balancing the extremely high saline outflow gradients, as seen previously in Figure 6-11.

Figure 6-14 illustrates impacts to vertical mixing processes. This figure shows the southwest area of the Gulf and two vertical profiles, chosen to follow the Abu Dhabi saline river plume (i.e., green line on the area plot at left) until it reaches the deep channel and the western Hormuz boundary. The detail in Figure 6-14 shows the horizontal pathway line used to sample the model salinity and density results, for 2 cases, Mid 21st and High saline run, summer and winter climatological seasons. Several conclusions can be reached from this figure, as summarized in the bullets below.

- *Relative to summer months:* During summer months, there is a clear stratification reduction associated with the saline river discharge near the Hormuz Straits, as shown on Figure 6-14 (middle profiles). The reduced stratification with high average density will have the effect of decreasing the system's admittance of deep salinity waters. Hence, a well stratified Gulf is likely projected and with high admittance to fresher water inflow, will increase resistance in the system, due to reduced stratification at Hormuz.

- *Relative to winter months:* The opposite effect is observed during winter seasons (rightmost profiles). A usually well-mixed structure (top-right) results in a stratified profile, which has presents less resistance to lower salinity waters inflows. Hence, a poorly stratified Gulf is likely projected (or well mixed), reducing resistance to fresher water inflow.

Figure 6-15: Vertical section following the Kuwait saline river plume untill it reaches deeper zone. Only winter season, but temperature and salinity visual comparison, between Mid 21st and High saline runs



- *Relative to shallow areas along the coast:* Moreover, where the saline plume is well defined, a two-layer system is formed in shallow areas. This reduces the effective surface mixing layer depth for wind-driven or other surface forces, as the vertical transport profiles have shown (see previous Figure 6-10).
- *Relative to currents:* The residual current structure (see previous Figure 6-13), at surface for the high saline river scenario, complements the information from the vertical section above. There is a residual current intensification at surface, along Hormuz up to 27° N (center of the Gulf), including residual eddies along the channel entrance.

6.5.5. Shatt al-Arab and Kuwait Saline river mixing (winter season)

The modeling results for the northern part of the Gulf shows noteworthy results, particularly for the winter months. The saline river discharges at the northernmost area of the Gulf are significant, mostly the Kuwait and Deylam saline rivers (Figure 6-15 left as reference). Because of the saline plumes formed in the area, the inclusion of the Shatt al-Arab runoff has been considered in all of the saline river scenarios. Because winter season is the period when the Gulf reaches its maximum vertical mixing, a seasonal average comparison from this period is presented in Figure 6-15 (temperature profiles in center; salinity profiles at right). Focusing on the winter months highlight the impact of saline rivers in the profiles. Several conclusions can be reached from these maps, as summarized in the bullets below.

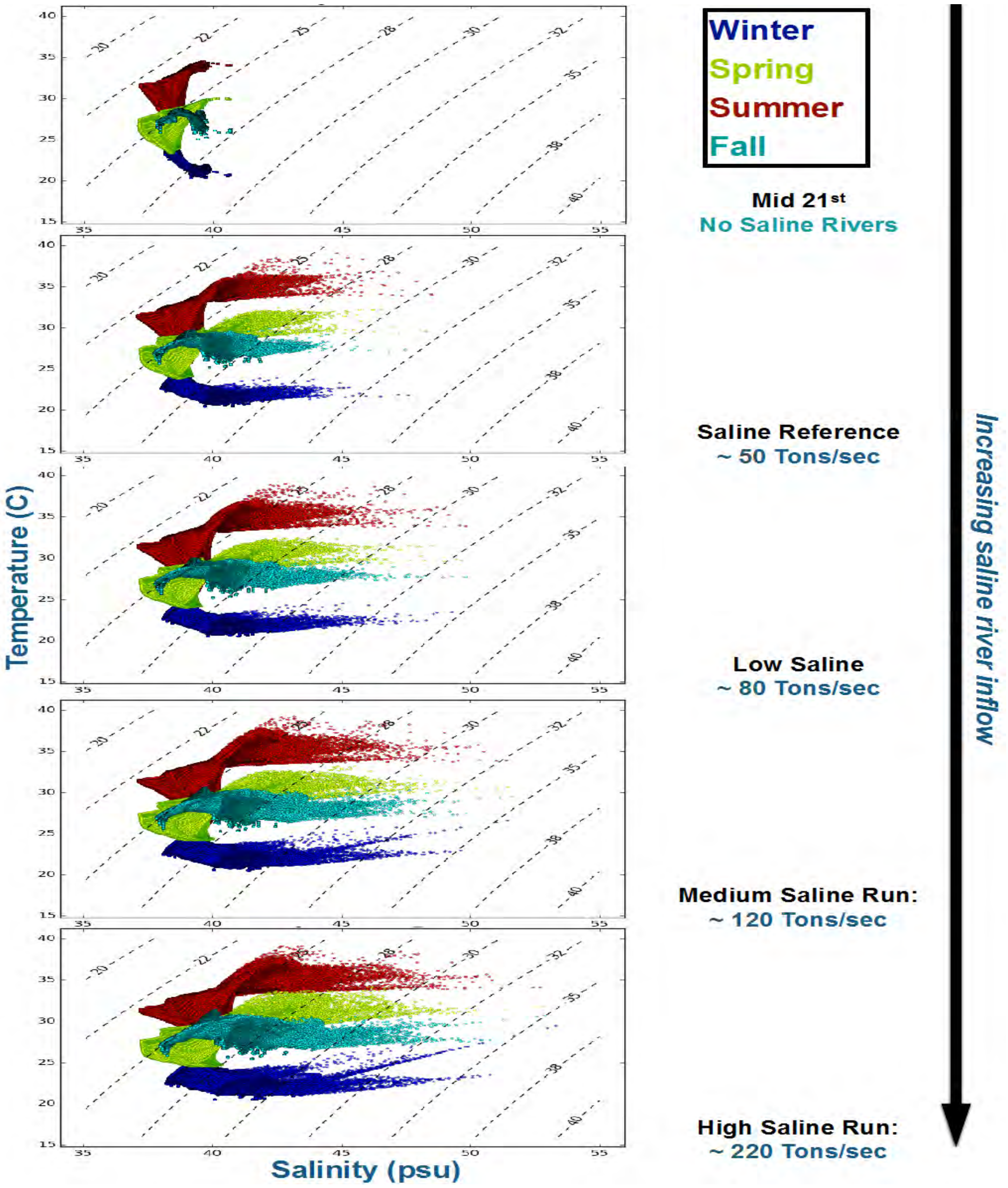
- *Relative to freshwater plume dispersion:* The fresh water plume stays trapped in the northern area, eventually spreading southwestward, reaching the Kuwait Bay, and consequently mixing with the saline plume from the Kuwait Saline River position.

- *Relative to brine plume dispersion:* The saline river plume oscillates in a north-south direction, before propagation to deeper zones (southeast ward). This effect combined with the River fresh and warmer plume reduces the baroclinic fronts observed in the Mid 21st run.
- *Relative to seawater temperatures:* Cold waters are constrained in the Kuwait Bay by the combined effects of the freshwater plume (at north end of the Gulf) and saline plume (at south end of the Gulf). The lower salinity waters from east are also observed into the Kuwait bay, to the same period.

6.5.6. The Arabian Gulf statistical changes due to desalination

Each of the saline rivers introduced into the regional ocean model has its own characteristics, related with the local dynamics and their own thermodynamic properties. Another way to visualize these effects in a broader analyze is the TS diagrams, which are quite useful to locate and typify water masses and their mixing processes. To assess these parameters, all the model experiments results have been combined in Figure 6-16 as a function of the season (shown as different colors) and the specific saline river scenario (designated in order of increasing brine discharge rate by arrow at right). The largest change is observed between the Mid 21st experiment (i.e., climate change only) and the reference experiment (i.e., historical salt flux of 50 tonnes/second). The largest increase in the salt flux (i.e., 220 tonnes/second) shows a relatively smaller impact than the lowest Saline River experiment.

Figure 6-16: TS-Diagrams as function of the scenario (saline river outflow). Magenta arrows indicate the average maxima salinity at the spreading zone, likely in the vicinity of the saline rivers mouths. The mode dense spreading observed, is a water mass characteristic of the bottom flow.



The results shown in Figure 6-16 correspond to average results over a large area in the Arabian Gulf, hence reflecting the overall response of the Gulf. To assess and extract statistics in smaller scale, the Abu Dhabi Saline River vicinities has been evaluated further (see the Abu Dhabi coastal reference area in the previous Figure 6-2). This area is close enough to the coast to capture some extremes from the Saline River forcing but at the same time, far enough from the coast to allow the gulf dynamics to mixing the plume into the background environment. Figure 6-17 presents these results as a TS diagram, focusing on the Saline River in the Abu Dhabi coastal reference area. Some key observations are offered in the bullets below.

- Salinity maximums, averages and deviations for the three scenarios do change between scenarios, but not in the same proportions as suggested by the salt plumes extensions (see previous Figure 6-7).
- The disproportionate change in salinity maximums, averages and deviations for the three scenarios is evident because not only has the mass transport (i.e., tonnes/second) increased but also the volume transport (i.e., Mm^3 per year).[16] The area is still large enough for mixing the brine discharge with ambient waters.
- Higher salinities values are observed in the transient zone, between the anti-estuarine system (part of the hydrodynamic circuit) and the baseline domain.

7. Conclusions and recommendations

This study has explored the combined impacts of climate change and desalination on the physical properties of the Gulf. Desalination is likely the only possible water supply option for the hyper-arid countries of the Arabian Peninsula. However, the intensification of desalination activities within an already stressed Arabian Gulf may pose adverse environmental implications under climate change. Desalination processes separate seawater (or some other source of water containing a high proportion of suspended solids) into freshwater which is then distributed to meet the freshwater demands of households, businesses, amenity, and industry; while hot brine concentrate is disposed into the Arabian Gulf, leading to changes in temperature and salinity levels.

On the one hand, this section offers broad-level conclusions from the outputs of the regional ocean modeling experiments. Specifically, the discussion below is focused on conclusions regarding macro-level trends relative to future average and maximum conditions throughout the Gulf. Starting from the findings, assumptions and limitations the numerical assessment of the AG main physical properties (natural and anthropogenic), some specific considerations regarding the modeling refinement of this area is also presented. It is important to note that the conclusions offered are suggestions based on present knowledge and limited by the (cumulative) uncertainties associated with the RCP8.5 projections, brine outflow projections and assumptions, and the regional ocean modeling system itself, as discussed throughout the previous sections.

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[16] Brine discharge volume increases as function of the population grown rates as shown in the previous Figure 4-1.

On the other hand, this section offers some feedback to policymakers about potential next steps. Specifically, part of the discussion below is focused on potential research directions that build off what has been learned so far with a view toward refining the modeling approach and reducing the uncertainties. They are offered here for information only. Nevertheless, the options offer a framework for follow-up explorations to further establish long-term impacts on the Arabian Gulf due to climate change and desalination activities.

7.1. Scope, framework and tradeoffs

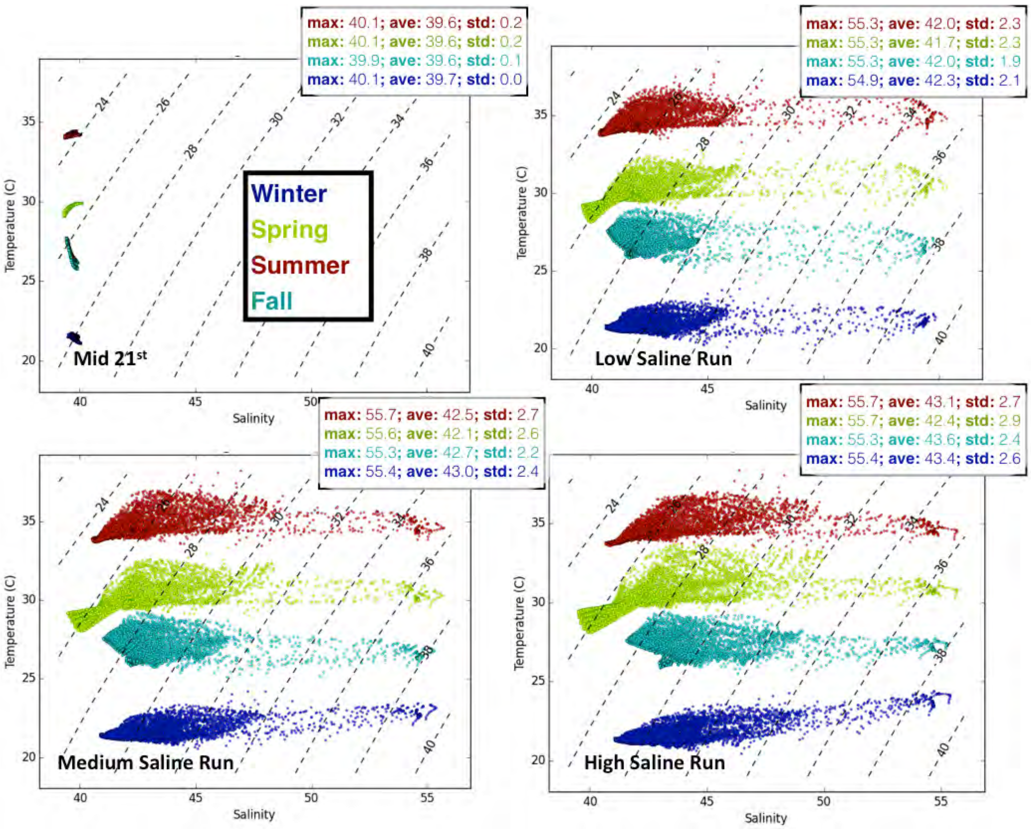
The Desalination & Climate Change study was undertaken in two phases. In the first phase, a regional ocean model was implemented using a 1.1 km spatial resolution, validated to reproduce historical climate conditions in the Gulf. This model was then used to dynamically downscale outputs from a well-accepted global circulation model, based on Representative Concentration Pathway 8.5 (i.e., the IPCC's "business as usual" scenario), for the early- mid- and late-21st Century periods (i.e., approximately 2000-2020 for early-term, 2040-2050 for the mid-term and 2080-2090 for the later period). Anthropogenic sources of salinity to the Gulf (i.e., brine discharges from desalination) were ignored in this phase. In the second phase, the previous Arabian Gulf regional ocean model based on climate change only was used to explore the impact of brine discharges on overall climate scale temperature and salinity effects throughout the Gulf.

A "saline river" approach was used to simulate the spatial distribution of future hot brine discharges to the Gulf. Four brine discharge scenarios - ranging from 50 tonnes per second to 220 tonnes per second - were modeled in an effort to control and observe how far this particular ocean numerical system could be stressed with high saline brine outflow, without losing its physical consistency. Again, there were no attempts to evaluate the uncertainties involved, since it would require a much larger number of experiments and analysis to delineate statistically defensible deviations.

The scope of the regional ocean modeling focused on the Arabian Gulf area shown in Figure 7.1. Within the overall area, the analysis identified four distinctive regions as described in the bullets below.

- *Northern Gulf:* This region extends from the Shatt-al Arab in Iraq to just south of Jubail in Saudi Arabia.
- *Southern Gulf:* This region extends from the southern parts of Bahrain to the northern area of the Straits of Hormuz.

Figure 7-1: Focused TS diagram, vicinity of the Abu Dhabi Saline River, to the low, medium and high salinity scenarios. Colors for seasons and top-right tables to basic statistics. Mid 21st as baseline reference.



- *Shallow areas:* These areas refer to shallow water less than 15 meters in depth (Grey zone in Figure 7-1). These areas are shown in grey on the Figure 1. Within shallow areas, the focus is on the surface layers and bottom layers, in a terrain following structure, where thickness varies from 0.1 up to 0.5 meter.
- *Deep areas:* These areas refer to deeper waters greater than 15 meters in depth. These areas are shown in blue on the Figure 7-1. Within deep areas, the focus is also on the surface and bottom layers, where the same conventions are applicable.

It is important to note that there are several caveats and limitations associated with the underlying regional ocean modeling effort. These are outlined in the bullets below. Combined, these caveats and limitations introduce a not unexpected level of uncertainty into the results.

- *Brine discharge quantities:* Future quantities of saline discharges into the Gulf were estimated on the basis of past trends in desalination technology and desalinated water demand. Projected brine discharges in 2050 were based on four plausible scenarios governed by economic growth and other assumptions.

✓ *"Saline river" approach:* From a modeling perspective, the optimal number of brine discharge points (or "saline rivers") that could be efficiently modelled was fifteen (15). They were spaced proportionally across the Gulf to bring some realistic equivalence to the real brine distribution along the gulf. The total magnitude of brine discharge was distributed across the saline rivers consistent with projected national levels of desalinated water supply.

✓ *Near-field modelling:* There was no explicit and offline near field modelling of the immediate zones of the brine discharge plume. This process is internalized by the saline river formulation and processed in real time, within the modeling process. There are advantages in this process, since all the mixing happens in the same way, as an estuarine like system. However, all the saline rivers configuration requires a very tailored and careful configuration, until they reach the required flux parameters (specified by the previous item, the saline rivers distribution).

It is also important to note that there were some inherent tradeoffs relative to research scope and available computing resources. That is, an optimal strategy for conducting the experiments within resource constraints required the following key elements.

✓ *Regional modeling framework:* To project climate change impacts on the Arabian Gulf, the presently available global results (IPCC, 2015; Stocker et al., 2013) were used to force a physically complete, sensitive and well known model, the Regional Ocean Model System – ROMS. The Max Plank daily experiment was statistically selected as the model most able to reproduce the Gulf's historical record.

✓ *Physical boundary conditions:* The only open artificial open boundary (southern border of the spatial domain) has been positioned at the Straits of Hormuz, using the local sharp bathymetric gradients as the natural boundary. This minimizes numeric-related problems, allowing the Gulf's complex physics to be modeled within a self-contained domain.

- ✓ *Grid size resolution:* Since small-scale eddies are critical to a precise representation of mixing processes and, consequently, the cascading energy from low-frequency climate patterns of the Gulf, the highest grid cell resolution that was computationally achievable was selected, namely a grid cell resolution of 1.1 km.
- ✓ *Desalination plant inventory:* For information on desalination plants, the reliance was on local datasets provided by AGEDI, technical literature about spatial desalination plants distribution, and a commercial dataset of current (i.e., 2015) desalination plants in the Arabian Gulf region maintained by Global Water Intelligence. We have estimated the total number of plants using seawater and directly discharging to the Gulf at 486, a subset of the over 2,000 desalination plants in the region.
- ✓ *Desalination plant inventory redux:* Across the region, at present there are hundreds of desalination plants along the eastern and western coastlines that discharge brine directly into the Gulf. In the future (i.e., by 2050), the number and/or capacity of these plants is certain to increase, especially in view of growing concern about groundwater depletion. There were three main reasons why it was necessary to aggregate these plants by location consistent with a control total corresponding to all plants. First, while the location of currently operating plants was known, the location of future units up to the end of the planning horizon was unknown. Second, the estimate of the time to undertake the analysis of a single brine discharge scenario, using all the known plants and based on the computer cluster of 600 dedicated CPUs, was about 500 calendar days for 10 years of model time. Third, the objectives of the study were focused on large-scale impacts to the Gulf rather than on micro-level impacts focused on the immediate vicinity of the discharge outlets.

7.2. Synthesis of results

The results of average and maximum temperature and salinity are summarized in Tables 7-1 and 7-2, respectively. A total of six (6) scenario results are provided. For Phase 1 modeling (i.e., climate change only), results for the first two (2) scenarios correspond to historical conditions and Mid 21st century climate change. For Phase 2 modeling (i.e., desalination & climate change), results for the remaining four (4) desalination scenarios are included. In the next few sections, some of the key trends that are evident from an examination of these summary results are provided.

Table 7-1: Summary of temperature modeling results for key areas of the Arabian Gulf (degrees Celsius)

Regional model run	Scenario #	Time period	GHG emissions	Brine discharge rate to Arabian Gulf (tonnes per second)	Arabian Gulf South Region								Arabian Gulf North Region							
					shallow area				deep area				shallow area				deep area			
					surface		bottom		surface		bottom		surface		bottom		surface		bottom	
					ave	max	ave	max	ave	max	ave	max	ave	max	ave	max	ave	max	ave	max
Historical - No climate change	1	1985-2005	NA	0	27.0	41.4	27.2	46.4	27.3	37.2	26.5	39.4	24.3	44.5	25.2	48.9	25.9	37.0	25.2	40.2
Mid 21st Century - No climate change; No desalination	2	2040-2049	RCP8.5	0	27.7	42.5	27.7	42.7	28.0	38.9	26.6	38.9	25.1	40.1	25.1	40.2	26.6	37.6	25.6	37.6
Mid 21st Century - Climate change; Reference desalination	3	2040-2049	RCP8.5	50	27.7	42.6	27.9	49.2	28.0	38.6	27.2	41.9	25.1	45.6	25.9	49.9	26.7	39.0	26.0	41.0
Mid 21st Century - Climate change; Low desalination	4	2040-2049	RCP8.5	80	27.7	42.6	28.0	48.3	28.0	38.7	27.4	41.7	25.1	46.1	26.1	50.9	26.7	39.2	26.1	41.5
Mid 21st Century - Climate change; Medium desalination	5	2040-2049	RCP8.5	120	27.7	42.9	28.1	46.7	28.0	38.4	27.7	42.8	25.2	46.0	26.3	51.7	26.7	39.4	26.3	41.8
Mid 21st Century - Climate change; High desalination	6	2040-2049	RCP8.5	220	27.7	42.6	28.1	46.8	28.1	38.5	28.0	42.9	25.2	46.0	26.5	51.8	26.8	39.4	26.5	41.6

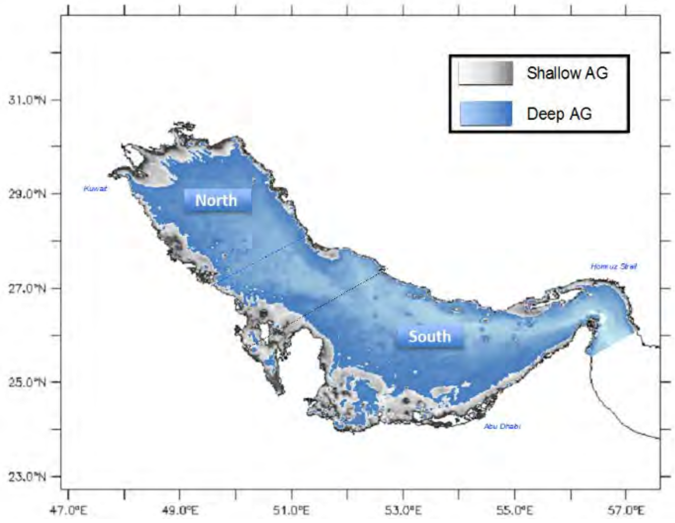
Table 7-2: Summary of salinity statistical results for key areas of the Arabian Gulf (psu)

Regional model run	Scenario #	Time period	GHG emissions	Anthropogenic brine discharge rate to Arabian Gulf (tonnes per	Arabian Gulf South Region								Arabian Gulf North Region							
					shallow area				deep area				shallow area				deep area			
					surface		bottom		surface		bottom		surface		bottom		surface		bottom	
					ave	max	ave	max	ave	max	ave	max	ave	max	ave	max	ave	max	ave	max
Historical - No climate change	1	1985-2005	NA	0	40.5	56.8	40.7	56.7	38.8	47.6	39.3	50.0	38.2	56.5	39.2	57.2	39.0	48.5	39.2	52.6
Mid 21st Century - No climate change; No desalination	2	2040-2049	RCP8.5	0	39.4	42.2	39.4	42.2	38.5	41.8	38.7	41.8	39.1	40.6	39.1	40.6	38.7	39.9	38.7	39.7
Mid 21st Century - Climate change; Reference desalination	3	2040-2049	RCP8.5	50	40.4	56.8	40.7	56.7	38.7	47.2	39.2	49.5	38.3	56.6	39.2	57.2	39.0	47.8	39.2	52.4
Mid 21st Century - Climate change; Low desalination	4	2040-2049	RCP8.5	80	40.8	57.0	41.1	56.8	38.8	48.9	39.5	50.9	38.5	56.2	39.6	57.2	39.2	49.8	39.5	53.6
Mid 21st Century - Climate change; Medium desalination	5	2040-2049	RCP8.5	120	41.2	56.5	41.6	57.1	39.0	50.4	39.9	52.6	38.7	56.5	40.0	56.6	39.4	52.0	39.8	54.3
Mid 21st Century - Climate change; High desalination	6	2040-2049	RCP8.5	220	41.5	56.8	42.0	56.9	39.1	52.1	40.2	53.5	38.9	56.9	40.3	56.2	39.6	53.5	40.1	54.8

The average temperature impacts on the Arabian Gulf from climate change and desalination are illustrated in Figure 7-2. A summary of key observations is offered in the bullets below. It is important to note that these are comparisons between unique experiments (i.e., non-statistical comparisons by nature) and centered on the middle of the 21st Century. These represent upper bound impacts.

- In surface layers throughout shallow and deep areas of the Gulf, climate change represents the overwhelming majority of the impact on average temperature. In the southern Gulf region, climate change accounts for about 95% of the roughly 0.8°C increase in average temperature, while accounting for 89% to 95% in the northern region.

Figure 7-2: Distinctive regions considered in the Arabian Gulf



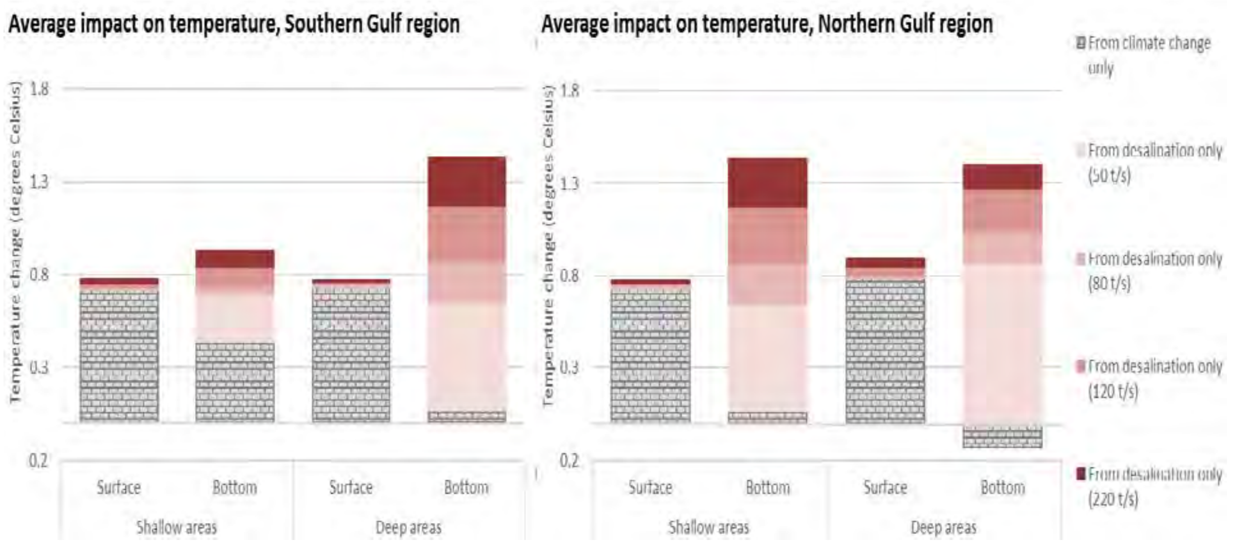
- In bottom layers throughout shallow and deep areas of the southern Gulf, desalination dominates the impact on temperature. Desalination accounts for between 27% and 53% of the roughly 1°C increase in average temperature in shallow areas, across all brine discharge rate scenarios. In deep areas, desalination accounts for between 41% and 95% of the roughly 1.4°C increase in average temperature.
- In bottom layers throughout shallow and deep areas of the northern Gulf, desalination represents the overwhelming majority of the impact on average temperature. Desalination accounts for between 41% and 95% of the roughly 1.4°C increase in average temperature in shallow areas, across all brine discharge rate scenarios. In deep areas, desalination accounts for the entire increase of up to 1.5°C increase in average temperature.

The maximum temperature impacts on the Arabian Gulf from climate change and desalination are illustrated in Figure 7-3. A summary of key observations is offered in the bullets below. It is important to note that direct climate change impacts on the Gulf dynamics dominate temperature extremes, as the warmer waters will be trapped at surface layers. On the other hand, temperature extremes assessed in the saline river experiments, will capture the internal saline river forcing and thermodynamic accommodation. Also observed was the fact that brine discharge temperature is a direct (although nonlinear) function of the ambient seawater intake temperature.

- Desalination impacts on *maximum* temperatures far exceed those on *average* temperatures. This is most evident for surface layers in deep areas of the Northern Gulf where maximum temperature increases from desalination are about 6.0°C compared to only a 0.1°C average temperature increase for the same area, or roughly 60 times greater. This is also evident for bottom layers in deep areas of the Southern Gulf where the maximum temperature increase from desalination is about 3 times greater than the average increase; 4.1°C average temperature increase compared to only a 1.4°C average temperature increase.

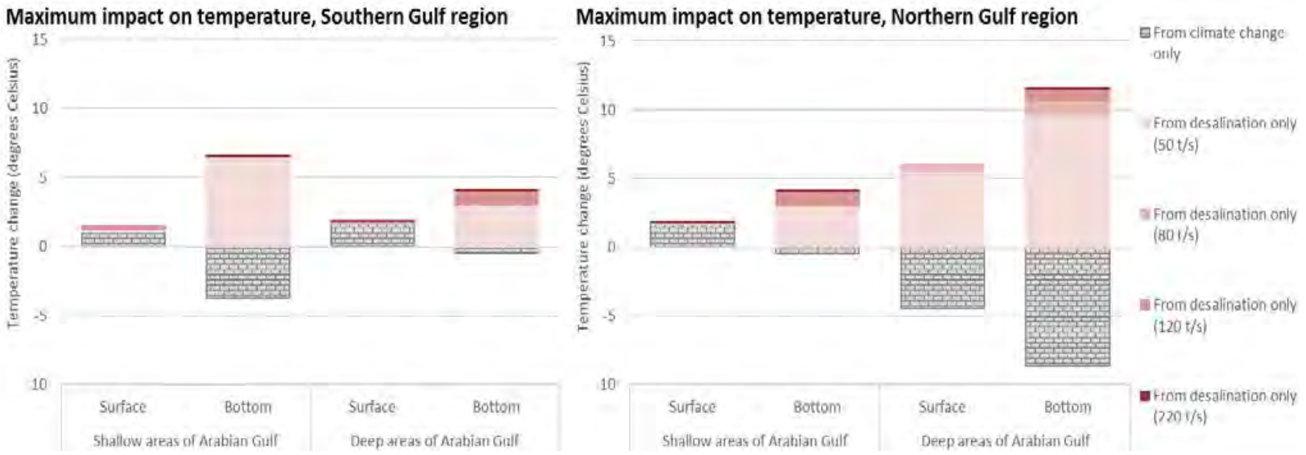
- In surface layers in the Southern Gulf, climate change represents the overwhelming majority of the impact on maximum temperature. In this region, climate change accounts for about between 74% (1.0°C) and 91% (1.7°C) of the total increase in maximum temperature.

Figure 7-3: Average temperature impacts in the Arabian Gulf from climate change and desalination



- In bottom layers throughout shallow and deep areas of the Southern Gulf, desalination represents the entire impact on maximum temperature. Under climate change, maximum temperatures actually *decrease* in bottom layers through the Southern Gulf. With desalination, maximum temperatures are projected to rise up to 6.6°C and 4.2°C in shallow and deep areas, respectively.
- In bottom layers throughout deep areas of the Northern Gulf, desalination represents the entire impact on maximum temperature. Under climate change, maximum temperatures actually *decrease*. With desalination, maximum temperatures are projected to rise up to 4.2°C and 11.6°C in shallow and deep areas, respectively.
- In surface layers in the Northern Gulf, the impact of desalination shows mixed results. In shallow areas, climate change represents the overwhelming majority of the increase in maximum temperature, 1.7°C or 91%. In deep areas, maximum temperatures actually *decrease* under climate change, whereas maximum temperatures increase by up to 6.0°C due to desalination activities.

Figure 7-4: Maximum temperature impacts in the Arabian Gulf from climate change and desalination

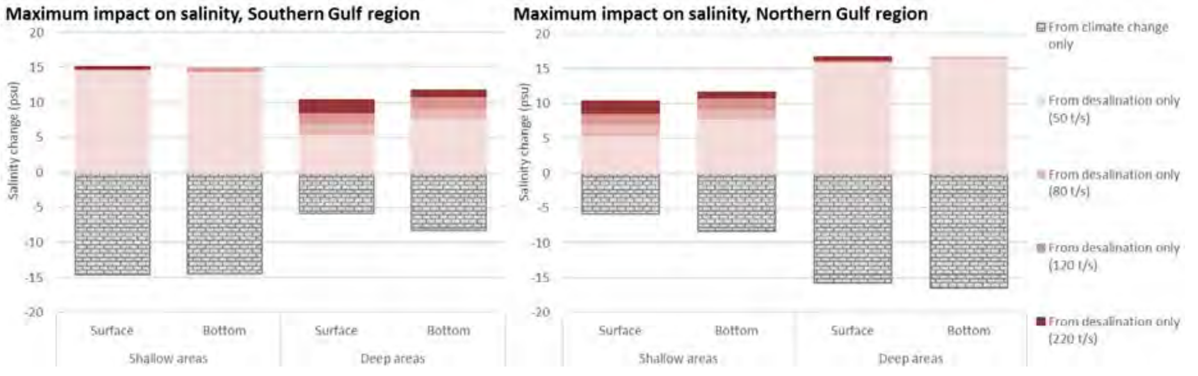


The average salinity impacts on the Arabian Gulf from climate change and desalination are illustrated in Figure 7-4. It is important to note that the Mid 21st climate change only experiment is characterized by its particular dynamic behaviour, when maxima "fresher" water entrainment trough Hormuz Strait has been observed. Thus, a reduced analysis will reflect only that aspect. A summary of key observations is offered in the bullets below.

- In shallow areas throughout surface and deep layers of the Northern and Southern Gulf, desalination represents the entire impact on average salinity. Under climate change, average salinity actually *decreases*. Depending on the brine discharge rate scenario, average salinity is projected to rise between 1.1 and 2.6 psu in the Southern Gulf and between 0.6 and 1.6 psu in the Northern Gulf.
- In bottom layers throughout deep areas of the Northern and Southern Gulf, desalination represents the entire impact on average salinity. Under climate change, average salinity actually *decreases*. With desalination, average salinity is projected to rise up to between 0.6 and 1.6 psu in the Southern Gulf across the range of desalination scenarios. In the Northern Gulf, average salinity is projected to rise up to between 0.1 and 1.2 psu.
- In surface layers throughout deep areas of the Northern and Southern Gulf, the impact of desalination shows mixed results. In the Southern Gulf, desalination represents the entire increase on average salinity (0,2 to 0.6 psu) as average salinity actually *decreases* under climate change. In the Northern Gulf, desalination represents between 0 and 1.4 psu (0% to 42%).

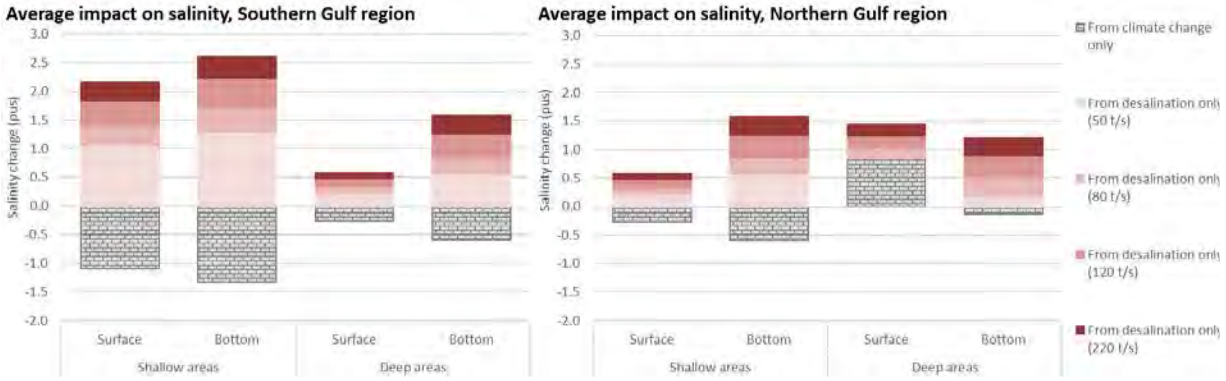
The maximum salinity impacts on the Arabian Gulf from climate change and desalination are illustrated in Figure 7-5. The saline river approach considers the environment salinity and an arbitrary salinity force (based on brine observations). A summary of key observations is offered in the bullets below.

Figure 7-6: Maximum salinity impacts in the Arabian Gulf from climate change and desalination



- In surface and bottom layers throughout shallow and deep areas of the Northern and Southern Gulf, desalination represents the entire impact on maximum salinity. Under climate change, maximum salinity actually *decreases*. With desalination, maximum salinity is projected to rise from 5.5 psu in the lowest brine discharge scenario up to 16.5 psu in the highest brine discharge scenario.
- Desalination impacts on *maximum* salinity far exceed those on *average* salinity. This is evident throughout all regions of the Gulf. The ratio of maximum to average salinity under the highest brine discharge scenario ranges from 6 to 27. This is equivalent to a range in maximum salinity increase from 14.8 to 16.5 psu.
- Throughout the Gulf, the greatest impact on maximum salinity is associated with the lowest brine desalination scenario.
  - ✓ For shallow areas in the Southern Gulf, about 95% of the impact on maximum salinity is due to an average brine discharge rate of 50 tonnes per second. Even higher shares are evident for deep areas in the Northern Gulf for the same scenario. For both these regions, salinity increases by about 0.3 psu for every increase of 1 tonne per second of brine discharge, up to 50 tonnes per second; above this discharge rate (i.e., between 50 and 220 tonnes per second) salinity increases by only 0.003 psu for every increase of 1 tonne per second of brine discharge.

Figure 7-5: Average salinity impacts in the Arabian Gulf from climate change and desalination



- ✓ For deep areas in the Southern Gulf, between 53% and 66% of the impact on maximum salinity is due to an average brine discharge rate of 50 tonnes per second. Similar shares are evident for shallow areas in the Northern Gulf for the same scenario. For both these regions, salinity increases between 0.11 and 0.15 psu for every increase of 1 tonne per second of brine discharge, up to 50 tonnes per second; above this discharge rate (i.e., between 50 and 220 tonnes per second) salinity increases by a range of only 0.02 to 0.03 psu for every increase of 1 tonne per second of brine discharge.

7.3. Reflections on potential next steps

The findings for the desalination and climate change project encompass two major regional ocean modeling experiments. The first experiment focused on the impact on the Gulf due to climate change only; the second focused on the impact on the Gulf due to climate change combined with an intensification of desalination activity relying on the Gulf as the brine discharge sink. Within the various research stages of each experiment, there were numerous assumptions made, possible directions explored, sensitivity testing, and hypotheses/approximations made. These activities were both inevitable and essential as a better scientific understanding the Gulf’s complex hydrodynamic system. This kind of approach helped to build scientific knowledge in an incremental way, based on the cumulative insights afforded by the multiple research stages.

It is important to note that there are cascading uncertainties inherent to the results. This is common to research efforts of this type and is a direct function of the uncertainties underlying the Earth System Models (or as previously known as General Climate Models) that serve as the basis for the regional modeling experiments. Such models typically display high internal variability. Moreover, the climate change projection underlying such models is another layer of uncertainty. These projections themselves encompass multiple scientific disciplines (e.g., physics, statistics, bio-chemistry, social sciences) in establishing a greenhouse gas emission trajectory. Earth system models are in a constant state of improvement and software updating, as methods improve and scientific knowledge evolves.

Nevertheless, the uncertainties were kept as low as possible, given resource constraints. As a practical matter, the accuracy of the regional modeling for the Arabian Gulf results is within an acceptable bound of uncertainty for research of this kind. Hence, the research team believes that they are suitable for informing subsequent policy dialogues regarding possible mitigation of brine discharge impacts to the Gulf (acknowledging the limitation of the regional climate model itself) and most important, for establishing potential next research steps that could further reduce the levels of these natural or inhered uncertainties. In broad terms, the following bullets highlight priority areas for further work that could help quantify these uncertainties and improve ocean modeling accuracy in way that is suitable for this area and its main characteristics/phenomena.

- *Apply an ensemble approach to estimate impacts on the Gulf.* The MPI-MR earth system model that was used as the basis for current regional ocean modeling framework was a) the best model for representing historical Gulf conditions, based on the IPCC's last available Assessment Report (AR5, 2013) and b) well within the upper and lower bounds of projections from other earth system models. A natural evolution of the current regional ocean-modeling framework would be to use several different experiments from the same ensemble (MPI-MR), reproducing the same ensemble approach to bracket uncertainties. This would increase the robustness of the understanding of overall Gulf dynamics. This would also enable a quantification of how uncertainties propagate within the regional ocean model itself.
- *Capture the impact of climate change on local sea level rise.* The current results do not capture all the components contributing to future sea level rise due to the present-day Earth System Modeling limitations (see Annex D for background on this issue). However, there are already estimates reliable enough to be used in statistical or parameterized approaches that could be integrated into a potential scenario-driven approach for a relatively small region like the Arabian Gulf (Carson, Köhl, & Stammer, 2015; Perrette et al., 2013). Such scenarios could be either a) integrated into the current modeling framework for explorations beyond the mid-century period or b) incorporated into an ensemble approach focused on specific internal variabilities or even using direct outputs from multiple earth system models.
- *Increase the number of saline rivers.* The current results are based on total brine discharge from 14 "saline river" locations. This was a modeling convention adopted in order to reduce the dimensionality of the regional ocean model. This simplification rendered the computations tractable relative to computer hardware limitations. Ideally, the spatial and performance characteristics of all existing and proposed desalination facilities would be represented at their actual brine discharge locations. For all Gulf countries, this would amount to 486 locations at present, with additional points to denote unplanned additions to meet future desalinated water demand. Such a number of desalination plants will also require an increase in the present grid resolution (1.1 km), which is already very high for long-term climate experiments. The best approach in this case would be a practical tradeoff between computational resources and a reasonable representation of the spatial distribution of desalination plants. In this case, the additional complexity implied by this level of physical granularity would make the need for a high-capacity supercomputing resource unavoidable.
- *Run additional experiments to better characterize short-term and micro-scale Gulf dynamics.* The current results have focused on long-term and major forcing sources such as air temperature, ocean currents and rainfall. Ideally, it would be good to extend and fine-tune Arabian Gulf circulation behavior relative to short-term forcing sources. For example, the impact of tides, whose effects have been parameterized in the current modeling framework, and sea breezes, whose effects have been ignored in the current modeling framework, could be directly modeled. On the one hand, these experiments are

possible now, since a foundational understanding of Gulf dynamics has been established and the related datasets assembled. On the other hand, the same sensitivity experiments would require large computational resources (supposing the previous steps has been accomplished) and datasets that are yet not available in any global climate projections. Moving forward, it would be good to transition from large-scale circulation to smaller-scale sensitivity experiments, which could use the main large-scale experiments as a foundation. This would involve:

- ✓ Creation of an enhanced database consisting of local (coastal) variabilities, sea levels (hourly observations from tide gauges); temperature and salinity observation near important desalination plants; high resolution satellite observations of the Gulf; vertical profiles with a high sampling rate, wind observations along the Gulf (high sampling rate and long time series) and high resolution topographic and bathymetric data.
- ✓ Validation of the regional ocean model to specific parameters listed in the preceding bullet, or a re-validation in the case of variables that have already been scrutinized within the current regional ocean modeling.
- ✓ Setting up of very short-term experiments (i.e., one year long) with high sampling output and the initial boundary conditions currently defined (or further improved) by the regional climate modeling results in order to evaluate the impact of high frequency ocean events, such as tides, sea breezes, large sea level changes or even extreme events[17]. These short-term "scenarios" could be also developed based on socio-political criteria (as per the IPCC standards to assess climate impacts on sea level).
- ✓ Establishment of a secondary regional modeling foundational analysis with shorter time periods but with a very high temporal resolution. This foundation could be used to launch experiments to better understand the impact of plausible sea level rise scenarios for time projected periods throughout the 21st century.

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[17] Extreme events are usually related with storm surges leading to coastal flooding. While ROMS is able to physically represent such dynamics, an alternative modeling system that only considers such events is recommended.

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Annex A: Characteristics of desalination plants using the Arabian Gulf as a feedstock, 2015 (GWI, 2015)

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
1	30565	Askar (Alba)	Bahrain	26.0940	50.6050	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	43,000
2	30577	Al Hidd 1	Bahrain	26.2220	50.6630	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	136,380
3	30589	Manama	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
4	30599	Refinery	Bahrain			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,160
5	43005	Bahrain	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
6	43006	Manama	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
7	44073	Ad Dur IWPP	Bahrain	25.9710	50.6080	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	218,000
8	50169	Ad Dur Rehabilitation	Bahrain	25.9710	50.6080	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	45,500
9	51331	Al Hidd 3	Bahrain	26.2220	50.6630	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	272,760
10	51483	Kooheji Water Project	Bahrain			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
11	51523	Universal Rolling	Bahrain	26.2220	50.6630	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
12	51767	Manama	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,000
13	51768	Ras Abu Jarjur	Bahrain	26.0740	50.6220	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,105
14	51771	Alba Power Station	Bahrain	26.0940	50.6050	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,785
15	51773	Alba RO3	Bahrain	26.0940	50.6050	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	11,355
16	51776	Bahrain	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,350
17	51800	Aqua-Cleer SW 22K	Bahrain			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,056
18	51831	Bahrain	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
19	51832	Bahrain	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,600
20	51835	Ad Dur	Bahrain	25.9710	50.6080	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	22,750
21	53138	Bahrain	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,350
22	53584	Durrat Al Bahrain II	Bahrain	25.8381	50.6050	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	12,000
23	53733	Nass Ice & Water Plant Factory	Bahrain			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	600
24	54361	Durrat Al Bahrain Resort	Bahrain	25.8381	50.6050	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,000
25	55574	Arab Shipbuilding and Repair	Bahrain	26.2220	50.6630	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,000
26	56334	Hawar	Bahrain			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	300
27	56836	Bahrain	Bahrain	26.2190	50.6636	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,304
28	57110	Durrat Al Bahrain Resort	Bahrain	25.8381	50.6050	Raw seawater	Arabian Gulf	Unknown	Online	1,000
29	43	Kish Island	Iran	26.5686	54.0044	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	9,084
30	32288	Assaluyeh	Iran	27.6111	52.4933	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	12,500

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
31	32295	Kish Free Zone	Iran	26.5586	54.0172	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	20,000
32	32301	Band Azzaluyeh	Iran	27.6111	52.4933	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	37,500
33	32366	Kharg Island	Iran	29.2456	50.3261	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,544
34	32369	Kish Island	Iran	26.5686	54.0044	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,000
35	32387	South Pars	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,400
36	32388	South Pars	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	6,000
37	32389	South Pars 2+3	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	3,900
38	42350	Kish - Damoon	Iran	26.5647	53.9861	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
39	42352	Dolphin Park, Kish Islan	Iran	26.5058	54.0358	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
40	42353	Kish Island	Iran	26.5686	54.0044	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	250
41	42998	Basrah	Iran			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	700
42	43031	Kharg Island	Iran	29.2456	50.3261	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,000
43	43032	Sirri Island	Iran	25.9125	54.5244	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,000
44	43033	Bandar Abbas	Iran	27.1272	56.1017	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,400
45	43034	Assaluye Port	Iran	27.6111	52.4933	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,000
46	43035	Lavan Island	Iran	26.7997	53.3503	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,200
47	43036	Assaluye Port	Iran	27.6111	52.4933	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,000
48	43037	South Pars	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	4,500
49	43038	Assaluye Port	Iran	27.6111	52.4933	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,800
50	43040	Bandar Abbas	Iran	27.1272	56.1017	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,400
51	44029	Kharg Island	Iran	29.2456	50.3261	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,000
52	50312	South Pars Gas Field	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,154
53	50315	Kharg Island II	Iran	29.2456	50.3261	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	360
54	50122	South Pars	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,200
55	51480	Kish MED Plant	Iran	26.5686	54.0044	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,000
56	51769	BANDAR ABBAS REFINERY	Iran	27.1272	56.1017	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	6,000
57	51770	Bandar Abbas new Refinery	Iran	27.1272	56.1017	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	12,000
58	51778	Almahdi Alluminium Complex	Iran			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,000
59	53904	Kish MED Plant	Iran	26.5686	54.0044	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,500
60	52265	Lavan Island	Iran	26.7997	53.3503	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,400
61	52266	Hengam Oil Field Project	Iran	26.6817	55.8872	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	4,000
62	52267	Kavian Petrochemical	Iran	27.5725	52.5264	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	12,000
63	52769	Bandar Abbas Power Plant III	Iran	27.1272	56.1017	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,400
64	53439	POGC Iran SWRO Plant	Iran	27.6111	52.4933	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,000
65	53723	Kish Gas Field Development	Iran	26.5686	54.0044	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	4,560
66	53900	Qeshm Island	Iran	26.9503	56.2783	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,000

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
67	53971	Keshar Village SWRO, Khamir	Iran	26.9517	55.5897	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,500
68	54021	South Pars Gas Field	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,300
69	54366	South Pars Gas Field	Iran	26.5733	51.9911	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	4,000
70	54646	Chabahar and Konarak	Iran	25.4392	60.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	15,000
71	55476	Sirri Island II	Iran	25.9125	54.5244	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,200
72	55315	Qeshm Cogeneration Plant	Iran	26.9292	55.9636	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	18,000
73	32503	Iraq	Iraq			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	450
74	32505	Iraq	Iraq			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
75	43000	South Region	Iraq			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,780
76	52598	Basra	Iraq	30.9103	46.6447	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,271
77	54122	Basra	Iraq	30.9103	46.6447	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	20,000
78	54209	Hurronsbury Army Camp	Iraq			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10,000
79	55313	Zubair OilField	Iraq	30.1969	47.8758	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,800
80	55314	Zubair OilField	Iraq	30.1969	47.8758	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	24,000
81	57011	Basrah	Iraq	30.9103	46.6447	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10,400
82	34370	Kuwait	Kuwait			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	378
83	34374	Az Zour South 3	Kuwait	28.7017	48.3728	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	130,920
84	34375	Az Zour South 2	Kuwait	28.7017	48.3728	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	130,920
85	34413	Shuwaikh RO	Kuwait	29.3517	47.9406	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	136,260
86	34421	Subiya 1+2	Kuwait	29.5636	48.1703	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	227,300
87	34422	Subiya 3	Kuwait	29.5636	48.1703	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	227,300
88	34427	Kuwait	Kuwait			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,200
89	44065	Shuaiba North	Kuwait	29.0350	48.1553	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	204,390
90	43784	Kuwait	Kuwait			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	178
91	52745	Az-Zour South hybridisation	Kuwait	28.7017	48.3728	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	136,000
92	54350	Equate Waste Water Recycle	Kuwait			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,800
93	55402	Jurassic	Kuwait			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,280
94	35228	Goat Island	Oman	26.3672	56.3597	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
95	35232	Kumzar	Oman	26.3389	56.4156	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	120
96	35259	Ruwais	Oman	22.1779	59.7666	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	120
97	42698	Sheesa-Mussandam	Oman	25.6505	56.2697	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
98	52364	Bukhaa	Oman	23.7084	57.9860	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
99	52366	Wilayat Diba	Oman	25.6505	56.2697	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
100	53029	Six Sense Resort	Oman	25.7104	56.2722	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
101	55721	Musandam Gas Plant (MGP)	Oman	26.0619	56.0881	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,600
102	170	Ras Abu Fontas B2	Qatar	25.2033	51.6141	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	136,380

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
103	2389	Ras Laffan B	Qatar	25.9303	51.5441	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	272,760
104	2996	Ras Laffan 1	Qatar	25.9280	51.5461	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	182,000
105	4088	Ras Abu Fontas A1	Qatar	25.2107	51.6176	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	45,000
106	4272	Ras Abu Fontas A2	Qatar	25.2033	51.6141	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	90,000
107	4375	Ras Abu Fontas B	Qatar	25.2033	51.6141	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	150,000
108	35520	Doha	Qatar	25.2044	51.6140	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
109	35523	Doha	Qatar	25.2044	51.6140	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
110	35525	Doha	Qatar	25.2044	51.6140	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	190
111	35526	Doha	Qatar	25.2044	51.6140	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
112	35530	NGL-4	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	100
113	35531	Qatar	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	300
114	35532	Qatar	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
115	35539	Ras Abu Fontas A4	Qatar	25.2033	51.6141	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	45,460
116	35554	Doha	Qatar	25.2044	51.6140	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
117	35561	Offshore	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	100
118	35562	Offshore	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	150
119	35563	Platform PS1	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	100
120	35569	Ras Laffan	Qatar	25.9280	51.5461	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,000
121	35574	Ras Laffan	Qatar	25.9280	51.5461	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,200
122	35582	Umm Bab	Qatar	25.2090	50.8019	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	600
123	35586	Umm Said	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,040
124	35598	Qatar	Qatar			Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,640
125	35600	Qatar	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,248
126	42016	Ras Laffan	Qatar	25.9280	51.5461	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,880
127	42690	Qatar	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	400
128	42693	RasGas LNG Train-6	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	6,480
129	52732	Qafco plant	Qatar	24.9212	51.5676	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,640
130	43096	Ras Laffan Pearl Gas to Liquids	Qatar	25.9064	51.5050	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	7,200
131	43581	Ras Laffan C	Qatar	25.9349	51.5212	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	286,400
132	44105	Ras Abu Fontas A1 Extension	Qatar	25.2033	51.6141	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	204,570
133	50418	Qatar	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,000
134	50419	Qafco 7 - Mesaieed	Qatar	24.9226	51.5689	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,640
135	50756	Umm Bab cement	Qatar	25.2087	50.8088	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,300
136	51140	Dosing System 2.0	Qatar			Raw seawater	Arabian Gulf	Unknown	Online	2
137	51214	Mesaieed	Qatar	24.9707	51.5774	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	9,000
138	51303	Gulf Coast Cement (GCC)	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,500

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
139	51472	Pearl Qatar - Temporary RO	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,500
140	52731	Qafco plant	Qatar	24.9212	51.5676	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,640
141	51682	CCIC Midfield Area Access	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
142	51691	SWRO Plant for the Pearl	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	35,000
143	52019	Qafco 5 plant	Qatar	24.9240	51.5432	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,400
144	54737	Mesaieed Industrial City MED	Qatar	24.9707	51.5774	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,760
145	52565	Ras Laffan Beach House	Qatar	25.9349	51.5212	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
146	53743	Al Jaber Labour Camp	Qatar	23.7059	53.6933	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	600
147	54239	PMP	Qatar			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,167
148	55031	Containerized SWRO for CGC	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
149	55041	Banana Island STP, SWRO &	Qatar	25.2975	51.6446	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
150	55103	Containerized SWRO for	Qatar	25.3210	51.5384	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	250
151	55203	Sheik Abdullah Beach Villa	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
152	55213	Doha	Qatar	25.2044	51.6140	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
153	55215	Qafco 5	Qatar	24.9240	51.5432	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	6,000
154	55216	Qatar Solar Technologies	Qatar	25.8979	51.5199	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	12,000
155	55967	500 m3/day SWRO Dukhan	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
156	56123	Shamal containerized SWRO	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
157	56135	Occidental Petroleum AWS	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	72
158	56419	Al Sharq Hotel	Qatar	25.2862	51.5566	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
159	56420	Flora Mineral Water	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	800
160	56624	Umm Bab SWRO	Qatar	25.2087	50.8088	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,000
161	56627	QNCC MED	Qatar	25.2087	50.8088	Raw seawater	Arabian Gulf	VC (Vapour Compression)	Online	3,000
162	56631	Pilot Plant, Doha	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
163	56632	Mobile Plant, Doha	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
164	56705	2x300 CMD SWRO Ras Bu	Qatar			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	600
165	57260	Ras Abu Fontas A3	Qatar	25.2033	51.6141	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	90,920
166	4695	Al Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	800,000
167	35674	Khursaniyah	Saudi	27.1451	49.2105	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,000
168	35772	Al Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	90,909
169	35800	Al Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	24,240
170	35803	Al Khafji	Saudi	28.5102	48.4610	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	4,800
171	35913	Al Khobar 3	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	280,000
172	35992	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
173	36134	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	600
174	36135	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	720

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
175	36136	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,500
176	36137	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,440
177	36138	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
178	36139	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,325
179	36140	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	250
180	36141	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	150
181	36142	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,400
182	36143	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	816
183	36144	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	200
184	36182	Dhahran	Saudi	26.3234	50.1243	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,700
185	36184	Dhahran	Saudi	26.3234	50.1243	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
186	36257	Ghazlan	Saudi	26.8576	49.8835	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	12,000
187	36334	Hofuf	Saudi	25.3406	49.5708	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
188	36535	Al Juaimah	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	216
189	36538	Al Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,500
190	36707	Ras Azour	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	240
191	36708	Ras Mishab	Saudi	28.1077	48.6108	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,000
192	36709	Ras Tanura	Saudi	26.7131	50.0489	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,700
193	36718	Rastanniya	Saudi			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,800
194	37133	Ras Tanajib	Saudi	27.8622	48.8150	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,000
195	37142	Um Al Sahik	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	300
196	37143	Umm Luji	Saudi			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	9,000
197	41663	Al Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	14,000
198	42961	Al Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	100,000
199	43016	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
200	44055	Auto Moto, Khobar-Rakkah	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
201	44116	Maaden Phosphate	Saudi	27.5406	49.1936	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	13,464
202	51955	Al Khobar	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
203	51957	Al Khobar	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
204	44285	Durrat Al Bahrain	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	12,000
205	50430	Al Jubail retrofit	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	66,660
206	50439	Hawiyah LNG Project	Saudi	24.8082	49.4096	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,824
207	50446	Al-Hajri Camp - Jubail	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,500
208	41638	Al Khafji	Saudi	28.5102	48.4610	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	4,800
209	51064	Al Khafji	Saudi	28.5102	48.4610	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	5,678
210	51194	Manifa Field Causeway	Saudi	27.6015	49.0032	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	330

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
211	51449	Khafji Camp Water Facilities	Saudi	28.5102	48.4610	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	350
212	51455	Khursaniyah	Saudi	27.1451	49.2105	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,500
213	51456	Khursaniyah	Saudi	27.1451	49.2105	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10,790
214	51481	KJO Desalination Plant & Fresh	Saudi			Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	9,084
215	51600	Al Khobar	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,000
216	51605	Al Khobar	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
217	51703	Al Khafji Desalination Plant	Saudi	28.5102	48.4610	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	6,813
218	51958	DAMMAM	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	600
219	52793	Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	60,000
220	52887	Jubail	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	20,000
221	52947	DAMMAM	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
222	53091	Al khobar	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	7,056
223	53287	Ras Al-Khair (RO)	Saudi	27.5406	49.1936	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	306,700
224	53675	Al Khoraef (ADC)	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,500
225	53821	Saipem	Saudi	26.3685	50.0101	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	300
226	53992	Damman	Saudi	26.4766	49.8231	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,500
227	54147	Al-Khobar	Saudi	26.1829	50.1957	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,598
228	54276	Durat Al Bahrain (TSI Plant)	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
229	54856	Qurayyah IPP- independent	Saudi	25.8911	50.0938	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	17,352
230	55068	Sendan Camp Facility	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	160
231	55168	Jubail SWRO - Phase 2	Saudi	26.9008	49.7796	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	58,500
232	55196	Gulf Cooperation Symbols	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
233	55312	Aujan Industries Soft Drinks	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,400
234	56022	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	300
235	56057	Dammam	Saudi	26.5414	49.9677	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	205
236	56385	Sadara unit 360 Propylene	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,800
237	56765	Aramco Refinery	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
238	57006	Tanajib Seawater Treatment	Saudi			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	19,000
239	32	Shuweihat 1	UAE	24.1654	52.5678	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	454,200
240	36	Shuweihat 2	UAE	24.1654	52.5678	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	459,146
241	2414	Jebel Ali L1	UAE	25.0487	55.1144	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	317,800
242	2416	Umm Al Nar B IWPP	UAE	24.4350	54.4833	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	115,287
243	2573	Al Layyah 6	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	48,960
244	2577	Al Layyah 7	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	48,960
245	2581	Al Mirfa	UAE	24.1231	53.4433	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	73,800
246	2701	Qidfa 2	UAE	25.3098	56.3701	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,550

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
247	2703	Al Mirfa	UAE	24.1231	53.4433	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,550
248	2705	Sila	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,150
249	2991	Jebel Ali G Ext	UAE	25.0525	55.1182	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	34,100
250	2992	Jebel Ali K1	UAE	25.0553	55.1211	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	91,100
251	2993	Jebel Ali K2	UAE	25.0553	55.1211	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	182,000
252	3015	Al Ruwais	UAE	24.1421	52.7340	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	18,240
253	3852	Ajman	UAE	25.4029	55.4520	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	13,640
254	4025	Al Taweelah A1 (Phase1)	UAE	24.7705	54.6822	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	98,000
255	4027	Al Mirfa	UAE	24.1231	53.4433	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	9,080
256	4049	Al Taweelah A1 (Phase1)	UAE	24.7705	54.6822	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	32,730
257	4072	Al Ghalilah	UAE	26.0152	56.0816	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
258	4198	Qidfa 1	UAE	25.3098	56.3701	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	9,000
259	4441	Jebel Ali L2	UAE	25.0487	55.1144	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	250,000
260	4563	Dalma	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	9,100
261	4564	Jebel Dhana	UAE	24.1711	52.6082	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	9,100
262	4571	Al Ghalilah	UAE	26.0152	56.0816	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,500
263	4922	Al Layyah NF/MSF (Unit 9)	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	41,000
264	4924	Palm Jumeirah	UAE	25.1385	55.1310	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	64,000
265	35217	Das Island	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	650
266	38614	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
267	38617	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
268	38628	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
269	38634	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,000
270	38635	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	8,000
271	38644	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,000
272	38645	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	3,000
273	38653	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	136
274	38661	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
275	38662	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,400
276	38663	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,000
277	38673	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	5,760
278	38674	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,500
279	38675	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	27,252
280	38676	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	27,252
281	38677	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	60,000
282	38698	Al Hamra	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	648

No.	ID	PROJECT NAME	COUNTRY	LOCATION		INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
				LATITUDE	LONGTITUDE					
283	38712	Umm Al Quwain	UAE	25.5558	55.5506	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,000
284	38718	Dalma	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	4,540
285	38733	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,920
286	38758	Jebel Ali D	UAE	25.0629	55.1284	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	113,910
287	38763	Al Fujairah 1 (RO)	UAE	25.1690	56.3571	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	170,500
288	38764	Qidfa	UAE	25.3098	56.3701	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,000
289	38767	Habshan	UAE	23.8423	53.6359	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
290	38768	Habshan	UAE	23.8423	53.6359	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,400
291	38774	Jebel Dhana	UAE	24.1711	52.6082	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	18,180
292	38776	Jebel Ali D2	UAE	25.0629	55.1284	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	96,300
293	38777	Jebel Ali	UAE	25.0525	55.1182	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,800
294	38778	Jebel Ali	UAE	25.0525	55.1182	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	127,200
295	38783	Jebel Ali G	UAE	25.0525	55.1182	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	273,000
296	38784	Jebel Ali (private department)	UAE	25.0525	55.1182	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	113,500
297	38790	Jebel Ali M Station	UAE	25.0438	55.1094	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	636,440
298	38795	Jebel Dhana	UAE	24.1711	52.6082	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	4,540
299	38803	Al Mirfa	UAE	24.1231	53.4433	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,000
300	38804	Al Mirfa	UAE	24.1231	53.4433	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	102,144
301	38808	Offshore	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	720
302	38809	Offshore	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,200
303	38810	Qidfa	UAE	25.3098	56.3701	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,650
304	38814	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,000
305	38815	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,000
306	38816	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,000
307	38817	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	1,000
308	38818	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,620
309	38819	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,700
310	38821	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	13,640
311	38822	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	68,190
312	38823	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,700
313	38827	Al Ruwais	UAE	24.1421	52.7340	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	30,000
314	38835	Kalba	UAE	25.0563	56.3473	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	9,090
315	38841	Sharjah	UAE	25.3521	55.3695	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	110
316	38850	Sharjah	UAE	25.3521	55.3695	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,500
317	38854	Al Layyah 5	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	22,700
318	38855	Layyah 13	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	36,368

No.	ID	PROJECT NAME	COUNTRY	LOCATION		INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
				LATITUDE	LONGTITUDE					
319	38856	Al Layyah 10	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	22,848
320	38857	Al Layyah 11	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	22,848
321	38869	Al Taweelah B1	UAE	24.7705	54.6822	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	340,950
322	38870	Al Taweelah B2	UAE	24.7705	54.6822	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	104,400
323	38873	Umm Al Nar B	UAE	24.4350	54.4833	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	285,489
324	38876	Umm Al Nar East B	UAE	24.4300	54.5113	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	102,285
325	38877	Umm Al Nar East A	UAE	24.4300	54.5113	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	82,500
326	38879	Umm Al Nar West 5-6	UAE	24.4350	54.4833	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	41,823
327	38880	Umm Al Nar West 1-4	UAE	24.4350	54.4833	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	83,646
328	38881	Umm Al Nar B (MED)	UAE	24.4350	54.4833	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	31,822
329	38882	Umm Al Nar West 7-8	UAE	24.4350	54.4833	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	58,189
330	38884	Umm Al Quwain	UAE	25.5558	55.5506	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
331	38885	Umm Al Quwain	UAE	25.5558	55.5506	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
332	38893	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
333	38894	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	960
334	38895	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
335	38897	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	250
336	38912	Unknown	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
337	38913	UAE	UAE			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	10,000
338	38914	UAE	UAE			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	10,000
339	41433	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,000
340	41434	Qatar	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,000
341	41543	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	360
342	41563	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	720
343	41719	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
344	42026	Ajman	UAE	25.4029	55.4520	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	13,638
345	42027	Ajman	UAE	25.4029	55.4520	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	13,638
346	42028	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	13,638
347	42093	Jebel Ali	UAE	25.0525	55.1182	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	121,134
348	42334	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	95,000
349	42369	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	114
350	42676	UAE	UAE			Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	2,500
351	42691	Unted Arab Emirates	UAE			Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	2,000
352	52733	Layyah 12	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	36,368
353	42973	Al Taweelah B3	UAE	24.7705	54.6822	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	314,600
354	43003	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,200

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
355	43056	Al Layyah 8	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	22,700
356	43057	Al Layyah 9	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	22,700
357	43270	Kalba	UAE	25.0563	56.3473	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,640
358	51000	Emal & Saydiat Island SWRO	UAE	24.8021	54.7167	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	20,322
359	44393	Al Zawrah	UAE	25.4452	55.4738	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,650
360	50571	Al Zawrah	UAE	25.4452	55.4738	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	27,300
361	50572	Layyah Power Plant	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	22,700
362	50573	Khor Fakhan Power Plant	UAE	25.3652	56.3399	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	22,700
363	50575	Layyah Power Plant	UAE	25.3516	55.3700	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	12,000
364	50576	Al Yasat	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	9,470
365	38868	Al Taweelah A1 (Phase1) ext.	UAE	24.7784	54.6959	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	240,000
366	38867	Al Taweelah A2	UAE	24.7784	54.6959	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	227,000
367	50010	Mussafah	UAE	24.3242	54.4619	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	24,600
368	50012	Dalma Island	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	7,500
369	50014	Aryam	UAE	24.3517	54.2053	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	7,500
370	50017	Saida 2	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,650
371	50016	Saida 1	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5,650
372	50022	Shahama	UAE	24.5140	54.6454	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,900
373	50036	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	910
374	51069	Palm Jebel Ali	UAE	25.0369	54.9937	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	240
375	51173	Satah Facilities, Supply,	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
376	51239	DEWA	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	30
377	51249	SETAOSMO SW-500, Dubai	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,500
378	51266	N/A	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,135
379	51272	N/A	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
380	51273	N/A	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	180
381	51275	N/A	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	114
382	51310	Hamriah Free Zone BOOT	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,440
383	51408	JAH	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	960
384	51425	Tiger Woods Dubai Projects	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	20,000
385	51458	Dalma	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	15,152
386	51500	CSWRO for Rem Ram Site	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
387	51623	AGD 2 Gas production	UAE	23.3173	54.1731	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,100
388	51731	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	23,000
389	51732	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,127
390	51734	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	22,000

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
391	51759	Barge SWRO pretreatment	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	11,000
392	51761	Al Zawrah	UAE	25.4452	55.4738	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	27,250
393	51766	Al-Yasat	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	9,470
394	51833	Sharjah	UAE	25.3521	55.3695	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	150
395	51850	Das Island	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,728
396	51971	Ghalilah	UAE	26.0152	56.0816	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	68,100
397	52336	HAMPS Phase II RO Desal Plant	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	91,000
398	52337	EMAL	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	20,304
399	52338	Zirku Island	UAE	24.8729	53.0765	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	800
400	52339	Valentine	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	120
401	52342	C SHR 42 AM	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
402	52540	Al Fujairah 2 MED	UAE	25.3097	56.3700	Raw seawater	Arabian Gulf	MED (Multi-effect Distillation)	Online	454,200
403	52542	ASAB- OIL FILED	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,600
404	52589	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	30
405	52594	Sharjah	UAE	25.3521	55.3695	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	379
406	52595	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	456
407	52597	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	908
408	52605	Unknown	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,500
409	52786	Al Fujairah 1 (MSF)	UAE	25.1690	56.3571	Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	284,000
410	52809	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	38,877
411	53357	Mussafah (Abu Dhabi) Steel	UAE	24.3242	54.4619	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	40,000
412	52860	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	218
413	52862	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	546
414	52932	Dalma	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	15,152
415	52948	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	180
416	52976	C SHR 42 AM	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	500
417	52994	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	409
418	52996	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	409
419	52998	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	409
420	53001	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	409
421	53033	Satah Facilities, Supply,	UAE	24.8691	53.0740	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
422	53061	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	7,992
423	53097	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	7,032
424	53117	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,528
425	53120	SETAOSMO SW-500	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,500
426	53129	DEWA	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	30

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
427	53155	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	151
428	53157	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	151
429	53213	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,905
430	53234	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,392
431	53240	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,080
432	53254	JAH	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	960
433	53259	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,288
434	53260	Abu Dahbi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,008
435	53455	Dalma Island (addition of 2nd	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	7,570
436	53524	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,180
437	53614	Ras Al Khaima	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,400
438	53634	Dalma Island II	UAE	24.4795	52.3063	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	12,490
439	53808	OSMO SHR 36 AM	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	400
440	54046	Verfar International	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
441	54282	Fidelity Corp.	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
442	54284	Water Wheel LLC	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
443	54379	Ras Al Khaimah	UAE	25.7984	55.9586	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3,835
444	54502	UAE	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
445	54519	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	698
446	54523	Sheikh Mansur Bin Zayed Plant	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
447	54526	WIP Beach Villa Plant	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
448	54528	Dragon Oil	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100
449	54642	National Tobacco & Matches	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	250
450	54696	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	455
451	54892	Umm-Lulu Field Development	UAE			Raw seawater	Arabian Gulf	NF (Nanofiltration)	Online	14,400
452	54977	Police	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6
453	54986	Abu Dhabi	UAE	24.4381	54.4864	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,000
454	54987	Private Farm	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	2,000
455	55393	S3 Power Generation Plant	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,680
456	55471	New Qidfa RO Plant	UAE	25.3098	56.3701	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	13,650
457	55472	Ruwais Refinery	UAE			Raw seawater	Arabian Gulf	MSF (Multi-stage Flash)	Online	13,248
458	55679	Tk2360 - Sea Water	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6,819
459	55859	Quality Water Purifying LLC	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	1,200
460	56051	Dubai	UAE	25.0286	55.0871	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	240
461	56091	Seadrill AWS 680-75	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	150
462	56129	Consolidated Projects Ltd AWS	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	100

				LOCATION						
No.	ID	PROJECT NAME	COUNTRY	LATITUDE	LONGTITUDE	INTAKE SOURCE	DISCHARGE LOCATION	TECHNOLOGY	STATUS	CAPACITY M3/D
463	56137	Kito Enterprises AWS 680-72	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	72
464	56142	Atlantic Maritime Group AWS	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	60
465	56150	Jawar Al Khaleej AWS 480-50	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	50
466	56151	Nabors AWS 480-50	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	50
467	56152	Nature Surf Systems AWS 480-	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	50
468	56153	Trans-Rig FZ-LLC AWS 480-50	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	50
469	56168	Hercules Liftboat AWS-280-30	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	30
470	56169	Nabors AWS 280-30	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	30
471	56170	Hercules Intl Drillling AWS 280-	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	25
472	56171	Jawar Al Khaleej AWS 280-25	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	25
473	56184	Ibrahim Al Tamimi AWS 340-10	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10
474	56185	Proteas Marine AWS 340-10	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10
475	56186	Proteas Marine AWS 340-10	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10
476	56187	Top Fenders AWS 240-5	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	10
477	56192	Mobile, Police Force SWRO	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	6
478	56197	AMS Dubai AWS 240-5	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5
479	56198	Midgulf Offshore AWS 240-5	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5
480	56199	SGBC AWS 240-5	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5
481	56200	The office of H.H. The Crown	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	5
482	56203	Jawar Al Khaleej AWS 32540-3	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	3
483	56300	Khorkhwair	UAE	25.9587	56.0578	Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	45,000
484	56304	Al Ashoosh	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	4,500
485	56318	Seih Al Hammah Camp, Al Ain	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	454
486	57009	Upper Zakum UZ750	UAE			Raw seawater	Arabian Gulf	RO (Reverse Osmosis)	Online	705

Annex B: Key assumptions for projecting brine discharges to the Arabian Gulf

Ambient historical seawater salinity in the Gulf

			Source:
In units of parts per million	45,000	ppm	page 28 of "Environmental Impacts of Seawater Desalination: Arabian Gulf Case Study" by Mohamed A. Dawoud and Mohamed M. Al Mulla, International Journal of Environment and Sustainability, Vol. 1 No. 3, pp. 22-37 (2012).
Conversion factor to milligrams per liter	1	mg/l per 1 ppm	
In units of milligrams per liter	45,000	mg/l	

Water recovery (% of intake converted into potable water)

Technology	Minimum	Maximum	Assumed	Source:
RO (reverse osmosis)	60%	90%	75%	Upper limit from "Reverse Osmosis Recovery Maximization", Desalination and Water Purification Research and Development Program Report No. 119, U.S. Department of the Interior, 2008; lower limit from "Environmental Issues of Desalination", by Tamim Younos, JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION, ISSUE 132, PAGES 11-18, DECEMBER 2005
MSF (Multi-Stage Flash)	11%	14%	12%	"Desalination for water supply: a review of current knowledge", Foundation for Water Research, 2011
MED (Multi-effect Distillation)	12%	14%	13%	"Desalination for water supply: a review of current knowledge", Foundation for Water Research, 2011

Iran desalination plants (2006-2012)

		Source:
Total capacity (m3/day)	236,352	Desalination plant database maintained by Golbal Water Intelligence (GWI), 2015
Share - Reverse osmosis	10%	Assumption
Share - Thermal	90%	Assumption
Min capacity factor - Reverse osmosis	78%	"￼Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates" by Mushtaque Ahmed, Walid H. Shayyab, David Hoey, Juma Al-Handaly, Desalination 133 (2001) 135-147
Max capacity factor - Reverse osmosis	100%	"￼Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates" by Mushtaque Ahmed, Walid H. Shayyab, David Hoey, Juma Al-Handaly, Desalination 133 (2001) 135-148
Assumed capacity factor - Reverse osmosis	**89%**	Assumption
Min Capacity factor - Thermal	81%	"Performance analysis of a MSF desalination unit" by Salah Al-Hengari, Mohamed El-Bousiffi, Walid El-Mudir, Desalination, Volume 182, Issues 1–3, 1 November 2005, Pages 73–85
Max Capacity factor - Thermal	100%	"Performance analysis of a MSF desalination unit" by Salah Al-Hengari, Mohamed El-Bousiffi, Walid El-Mudir, Desalination, Volume 182, Issues 1–3, 1 November 2005, Pages 73–86
Assumed Capacity factor - Thermal	**91%**	Assumption

Mapping of country total brine discharge quantities by salt river location

Assumed share of total discharge (%)			
	Name	**Country**	Source:
100%	Abadan	Iraq	Assumption
100%	Kuwait	Kuwait	Assumption
60%	Tanajib	Saudi Arabia	Assumption
40%	Jubail	Saudi Arabia	Assumption
100%	Salwa Bay	Bahrain	Assumption
100%	Doha	Qatar	Assumption
20%	Barakah	UAE	Assumption
25%	Tarif	UAE	Assumption
30%	Abu Dhabi	UAE	Assumption
20%	Dubai	UAE	Assumption
5%	Al-Khaimah	UAE	Assumption
100%	Hormuz	Oman	Assumption
10%	Mellu	Iran	Assumption
20%	Neyband	Iran	Assumption
70%	Deylam	Iran	Assumption

2050 share of potable water produced by thermal and reverse osmosis dessalination

2050	**ischarge location**		
Reverse Osmosis	**No.**	**Name**	**Country**
0%	1	Abadan	Iraq
41%	2	Kuwait	Kuwait
60%	3	Tanajib	Saudi Arabia
60%	4	Jubail	Saudi Arabia
59%	5	Salwa Bay	Bahrain
14%	6	Doha	Qatar
26%	7	Barakah	UAE
26%	8	Tarif	UAE
26%	9	Abu Dhabi	UAE
26%	10	Dubai	UAE
26%	11	Al-Khaimah	UAE
26%	12	Hormuz	UAE
0%	13	Mellu	Iran
0%	14	Neyband	Iran
0%	15	Deylam	Iran

Assumed average physical parameters of the areas near the salt river intake locations under historical conditions

2005-2009 period	Brine discharge location			
Temperature (°C)	**Salinity (% of**	**No.**	**Name**	**Country**
22.8	0%	1	Abadan	Iraq
24.1	88%	2	Kuwait	Kuwait
25.9	88%	3	Tanajib	Saudi Arabia
26.3	88%	4	Jubail	Saudi Arabia
26.7	90%	5	Salwa Bay	Bahrain
27.2	88%	6	Doha	Qatar
27.3	88%	7	Barakah	UAE
27.8	88%	8	Tarif	UAE
27.6	88%	9	Abu Dhabi	UAE
27.0	87%	10	Dubai	UAE
26.9	86%	11	Al-Khaimah	UAE
25.4	85%	12	Hormuz	UAE
22.6	85%	13	Mellu	Iran
25.8	86%	14	Neyband	Iran
25.7	88%	15	Deylam	Iran

Assumed average physical parameters of the areas near the salt river intake locations under future climate change conditions associated with RCP8.5

2045-2049 period	Brine discharge location			
Temperature (°C)	**(% of ambient)**	**No.**	**Name**	**Country**
23.8	0%	1	Abadan	Iraq
24.7	87%	2	Kuwait	Kuwait
26.7	87%	3	Tanajib	Saudi Arabia
27.9	87%	4	Jubail	Saudi Arabia
27.3	90%	5	Salwa Bay	Bahrain
27.7	87%	6	Doha	Qatar
27.7	88%	7	Barakah	UAE
28.2	88%	8	Tarif	UAE
28.0	88%	9	Abu Dhabi	UAE
27.5	87%	10	Dubai	UAE
27.4	85%	11	Al-Khaimah	UAE
26.5	84%	12	Hormuz	UAE
23.4	83%	13	Mellu	Iran
26.2	85%	14	Neyband	Iran
23.4	86%	15	Deylam	Iran

Assumed groundwater water production during historical period

Country										
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Bahrain	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.08	0.10
Iran										
Kuwait	140.33	157.84	185.98	203.90	222.28	238.37	260.67	268.40	276.81	283.07
Oman	1088.50	1103.46	1121.52	1139.56	1141.72	1159.01	1182.02	1205.68	1213.47	1238.26
Qatar	0.12	0.12	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.11
Saudi Arabia	9239.05	9268.20	9337.91	9615.36	9653.96	9742.84	9836.75	10031.69	10362.41	10463.62
UAE	1907.88	1887.21	1895.75	1922.21	1892.11	1864.30	1897.14	1896.77	1870.55	1951.01
Total	12,375.87	12,416.83	12,541.28	12,881.15	12,910.18	13,004.64	13,176.72	13,402.72	13,723.45	13,936.17

Source: LNRCCP Sub-project #5 datasets

Assumed wastewater production during historical period

Country										
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Bahrain	46.72	46.13	47.78	47.33	47.09	44.99	46.10	46.01	46.16	47.75
Iran										
Kuwait	96.00	95.36	96.21	95.68	96.21	95.14	94.72	93.33	90.18	85.92
Oman	34.29	35.32	36.38	37.47	38.59	39.75	40.95	42.17	43.44	44.74
Qatar	67.55	67.79	67.83	67.83	67.83	67.83	67.83	67.83	67.83	67.83
Saudi Arabia	390.12	383.61	375.74	368.66	362.28	356.12	350.43	344.89	338.51	333.48
UAE	280.44	287.31	294.05	300.93	306.78	312.30	316.49	320.21	323.74	326.98
Total	915.13	915.52	917.99	917.90	918.79	916.12	916.51	914.45	909.85	906.70

Source: LNRCCP Sub-project #5 datasets

Assumed desalinated water production during historical period

Country										
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Bahrain	198.98	208.53	218.54	229.03	240.03	250.78	259.33	262.65	264.64	264.87
Iran										
Kuwait	390.11	390.10	390.10	390.10	390.10	390.10	390.11	390.11	390.11	390.13
Oman	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Qatar	185.77	190.67	203.58	209.83	215.90	221.05	232.25	240.29	250.86	264.92
Saudi Arabia	1356.53	1356.53	1356.53	1356.53	1356.53	1356.53	1356.53	1356.53	1356.53	1356.53
UAE	613.61	632.39	651.73	671.67	692.23	713.41	735.25	757.75	780.93	804.83
Total	2,747.54	2,780.76	2,823.03	2,859.70	2,897.32	2,934.40	2,976.00	3,009.86	3,045.60	3,083.81

Source: LNRCCP Sub-project #5 datasets

Water production during historical period in Iran (billion m3 per year)

Area	Variable Name	Variable Id	Year	Value	Symbol	Assumed desalination shares (%) RO	Thermal	Total
Iran (Islamic Republic of)	Total water withdrawal	4253	1995	83				
Iran (Islamic Republic of)	Total water withdrawal	4253	2001	89.7	I			
Iran (Islamic Republic of)	Total water withdrawal	4253	2004	93.3				
Iran (Islamic Republic of)	water withdrawal (primary and secondary)	4261	2004	39.85	I			
Iran (Islamic Republic of)	water withdrawal (primary and secondary)	4262	2004	53.1				
Iran (Islamic Republic of)	water withdrawal (primary and secondary)	4263	1995	83	I			
Iran (Islamic Republic of)	water withdrawal (primary and secondary)	4263	2001	89.7	I			
Iran (Islamic Republic of)	water withdrawal (primary and secondary)	4263	2004	92.95	I			
Iran (Islamic Republic of)	Desalinated water produced	4264	1991	0.003		0%	100%	100%
Iran (Islamic Republic of)	Desalinated water produced	4264	1995	0.003	I	0%	100%	100%
Iran (Islamic Republic of)	Desalinated water produced	4264	2000	0.003	I	0%	100%	100%
Iran (Islamic Republic of)	Desalinated water produced	4264	2004	0.2	I	0%	100%	100%
Iran (Islamic Republic of)	irect use of treated municipal wastewater	4535	2003	0.154				

E - External data
I - AQUASTAT estimate
K - Aggregate data
L - Modelled data
(c) FAO of the UN
The information contained in AQUASTAT is provided free of charge to all users. Please quote as follows:
FAO. 2015. AQUASTAT Main Database - Food and Agriculture Organization of the United Nations (FAO). Website accessed on[06/12/2015 15:52]

Average share of m3 produced per person per year in 2050

Brine discharge location		Average		
No.	Country	Non-	Desal	Total
1	Iraq	0.0%	0.0%	0.0%
2	Kuwait	0.0%	100.0%	100.0%
3	Saudi Arab	50.0%	50.0%	100.0%
4	Saudi Arab	50.0%	50.0%	100.0%
5	Bahrain	0.0%	100.0%	100.0%
6	Qatar	0.0%	100.0%	100.0%
7	UAE	0.0%	100.0%	100.0%
8	UAE	0.0%	100.0%	100.0%
9	UAE	0.0%	100.0%	100.0%
10	UAE	0.0%	100.0%	100.0%
11	UAE	0.0%	100.0%	100.0%
12	UAE	0.0%	100.0%	100.0%
13	Iran	99.9%	0.1%	100.0%
14	Iran	99.9%	0.1%	100.0%
15	Iran	99.9%	0.1%	100.0%

Source: Assumption

Average annual growth rate in m3 per person per year during historical period, 2011-2050

Brine discharge location		Total
No.	Country	
1	Iraq	0.0%
2	Kuwait	0.0%
3	Saudi Arab	0.0%
4	Saudi Arab	0.0%
5	Bahrain	0.0%
6	Qatar	0.0%
7	UAE	0.0%
8	UAE	0.0%
9	UAE	0.0%
10	UAE	0.0%
11	UAE	0.0%
12	UAE	0.0%
13	Iran	0.0%
14	Iran	0.0%
15	Iran	0.0%

Source: Assumption

Population projections (source: regional water-energy nexus research team datasets (i.e., sub-project #5)

Country	2010	2015	2020	2025	2030	2035	2040	2045	2050
Bahrain	1,261,319	1,377,237	1,486,111	1,570,590	1,641,656	1,704,899	1,758,926	1,796,547	1,821,834
Iran	74,253,373	79,109,272	83,403,280	86,496,638	88,528,877	89,996,161	91,205,167	92,059,532	92,218,838
Kuwait	3,059,473	3,892,115	4,316,618	4,672,201	4,986,872	5,252,058	5,499,031	5,724,986	5,924,172
Oman	2,943,747	4,490,541	4,815,876	5,058,236	5,237,931	5,376,076	5,506,877	5,658,608	5,843,555
Qatar	1,765,513	2,235,355	2,452,180	2,639,581	2,781,374	2,902,063	3,013,398	3,114,885	3,204,970
Saudi Arabia	28,090,647	31,540,372	34,366,240	36,846,750	39,132,369	41,235,387	43,135,740	44,762,954	46,059,398
UAE	8,329,453	9,156,963	9,822,014	10,434,235	10,977,456	11,500,285	11,994,711	12,429,693	12,789,108
Total	119,703,525	131,801,855	140,662,319	147,718,231	153,286,535	157,966,929	162,113,850	165,547,205	167,861,875

Desalinated water production projections in units of million m^3 (source: calculation based on previously states assumptions)

Brine discharge location											
No.	**Name**	**Country**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
1 -	Abadan	(Iraq)	0	0	0	0	0	0	0	0	0
2 -	Kuwait	(Kuwait)	605	833	994	1,152	1,311	1,466	1,624	1,784	1,943
3 -	Tanajib	(Saudi Arabia)	1,708	2,881	4,189	5,617	7,161	8,805	10,529	12,293	14,057
4 -	Jubail	(Saudi Arabia)	1,138	1,921	2,793	3,745	4,774	5,870	7,019	8,196	9,371
5 -	Salwa Bay	(Bahrain)	390	434	478	515	549	581	611	635	656
6 -	Doha	Qatar	642	832	934	1,027	1,106	1,179	1,250	1,318	1,383
7 -	Barakah	(UAE)	563	719	877	1,045	1,218	1,401	1,591	1,783	1,973
8 -	Tarif	(UAE)	704	898	1,096	1,306	1,523	1,751	1,988	2,229	2,466
9 -	Abu Dhabi	(UAE)	845	1,078	1,316	1,567	1,827	2,101	2,386	2,674	2,959
10 -	Dubai	(UAE)	563	719	877	1,045	1,218	1,401	1,591	1,783	1,973
11 -	Al-Khaimah	(UAE)	141	180	219	261	305	350	398	446	493
12 -	Hormuz	(UAE)	225	608	937	1,283	1,639	2,000	2,374	2,774	3,210
13 -	Mellu	(Iran)	14	14	15	16	16	16	17	17	17
14 -	Neyband	(Iran)	27	29	31	32	32	33	33	34	34
15 -	Deylam	(Iran)	95	101	107	111	113	115	117	118	118
Total			7,661	11,247	14,863	18,722	22,791	27,069	31,527	36,084	40,653

Desalinated water production projections in units of million m^3 – Reverse osmosis (source: calculation based on previously states assumptions)

Brine discharge location											
No.	**Name**	**Country**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
1	Abadan	Iraq	0	0	0	0	0	0	0	0	0
2	Kuwait	Kuwait	227	316	380	445	512	578	647	718	789
3	Tanajib	Saudi Arabia	996	1,688	2,465	3,320	4,252	5,251	6,306	7,395	8,493
4	Jubail	Saudi Arabia	664	1,125	1,644	2,214	2,834	3,501	4,204	4,930	5,662
5	Salwa Bay	Bahrain	220	247	273	296	316	336	355	371	385
6	Doha	Qatar	58	80	95	111	126	141	156	172	189
7	Barakah	UAE	125	163	203	247	294	345	400	457	515
8	Tarif	UAE	157	204	254	309	368	432	500	571	644
9	Abu Dhabi	UAE	188	245	305	371	442	518	600	685	773
10	Dubai	UAE	125	163	203	247	294	345	400	457	515
11	Al-Khaimah	UAE	31	41	51	62	74	86	100	114	129
12	Hormuz	UAE	50	138	217	304	396	493	597	711	838
13	Mellu	Iran	0	0	0	0	0	0	0	0	0
14	Neyband	Iran	0	0	0	0	0	0	0	0	0
15	Deylam	Iran	0	0	0	0	0	0	0	0	0
Total			2,842	4,410	6,092	7,927	9,908	12,027	14,265	16,582	18,931

Desalinated water production projections in units of million m^3 – Thermal technologies (source: calculation based on previously states assumptions)

Brine discharge location											
No.	**Name**	**Country**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
1	Abadan	Iraq	0	0	0	0	0	0	0	0	0
2	Kuwait	Kuwait	378	517	613	706	799	888	977	1,066	1,154
3	Tanajib	Saudi Arabia	712	1,193	1,724	2,297	2,909	3,554	4,223	4,898	5,564
4	Jubail	Saudi Arabia	474	795	1,149	1,531	1,939	2,369	2,815	3,265	3,709
5	Salwa Bay	Bahrain	169	188	205	220	233	245	256	264	271
6	Doha	Qatar	584	752	838	916	980	1,038	1,093	1,146	1,195
7	Barakah	UAE	438	555	674	797	924	1,055	1,191	1,326	1,458
8	Tarif	UAE	548	694	842	997	1,155	1,319	1,488	1,658	1,822
9	Abu Dhabi	UAE	657	833	1,011	1,196	1,385	1,583	1,786	1,989	2,187
10	Dubai	UAE	438	555	674	797	924	1,055	1,191	1,326	1,458
11	Al-Khaimah	UAE	110	139	168	199	231	264	298	332	364
12	Hormuz	UAE	175	470	720	979	1,243	1,507	1,777	2,063	2,372
13	Mellu	Iran	14	14	15	16	16	16	17	17	17
14	Neyband	Iran	27	29	31	32	32	33	33	34	34
15	Deylam	Iran	95	101	107	111	113	115	117	118	118
Total			4,819	6,837	8,770	10,795	12,883	15,042	17,262	19,502	21,722

Annex C: List of calculation components comprising the saline river salt transport estimate

Worksheet name	Worksheet description
SUMMARY	Summary of results
REVISION HISTORY	Spreadsheet revision history
MAP	Assumned brine discharge points
ASSUMPTIONS	Key assumptions
DESAL PLANT CAPACITIES	Characteristics of desalination plants using the Arabian Gulf as a feedstock, 2015
SALT RIVER INTAKE SALINITY	Assumed average feedwater salinity of the areas near the salt river discharge locations under historical and future conditions
SALT RIVER INTAKE TEMPERATURE	Assumed feedwater temperature of the areas near the salt river discharge locations under historical and future conditions
HISTORICAL NON-DESAL WATER	Annual non-desalinated water production in historical period, All sources
HISTORICAL DESAL WATER	Annual desalinated water production in historical period, All technologies
HISTORICAL TOTAL WATER	Annual total water production in historical period, All sources and desalination technologies
HISTORICAL POPULATION	Population in historical period
HISTORICAL NON-DESAL WATER_CAP	Non-desalination water production per capita in historical period, All sources
HISTORICAL DESAL WATER_CAP	Desalination water production per capita in historical period, All technologies
HISTORICAL TOTAL WATER_CAP	Total water production per capita in historical period, All sources and technologies
FUTURE DESAL WATER_CAP	Desalinated water production per capita in future period, by location
FUTURE POPULATION	Population in planning period by country and brine discahrge point (number of persons)
FUTURE DESAL WATER	Desalinated water production in planning period, all technologies (million m3 per year)
FUTURE PRODUCTION TECHNOLOGY	Desalinated water production in planning period, by technology (%)
FUTURE PRODUCTION-RO	Desalinated water production in planning period, Reverse Osmosis technology (million m3 per year)
FUTURE PRODUCTION-THERMAL	Desalinated water production in planning period, Thermal technologies (million m3 per year)
FUTURE PRODUCTION-TOTAL	Desalinated water production in planning period, All technologies (million m3 per year)
FUTURE SEAWATER INTAKE-RO	Seawater intake in planning period, Reverse Osmosis technology (million m3 per year)
FUTURE SEAWATER INTAKE-THERMAL	Seawater intake in planning period, Thermal technologies (million m3 per year)
FUTURE SEAWATER INTAKE-TOTAL	Seawater intake in planning period, All technologies (million m3 per year)
FUTURE SALT INTAKE-RO	Intake of salt during the desalination process in planning period, Reverse osmosis technology (tonnes per year)
FUTURE SALT INTAKE-THERMAL	Intake of salt during the desalination process in planning period, Thermal technologies (tonnes per year)
FUTURE SALT INTAKE-TOTAL	Intake of salt during the desalination process in planning period, all technologies (tonnes per year)
BRINE DISCHARGE-RO	Discharge of brine into Arabian Gulf in planning period, Reverse Osmosis technology (million m3 per year)
BRINE DISCHARGE-THERMAL	Discharge of brine into Arabian Gulf in planning period, Thermal technologies (million m3 per year)
BRINE DISCHARGE-TOTAL	Discharge of brine into Arabian Gulf in planning period, All technologies (million m3 per year)
BRINE SALINITY-RO	Salinity of brine discahrged into Arabian Gulf in planning period, All technologies (mg/l)
BRINE SALINITY-THERMAL	Salinity of brine discahrged into Arabian Gulf in planning period, All technologies (mg/l)
BRINE SALINITY-TOTAL	Salinity of brine discahrged into Arabian Gulf in planning period, All technologies (mg/l)
BRINE MASS-RO	Discharge of salt during the desalination process in planning period, Reverse osmosis technology (tonnes per year)
BRINE MASS-THERMAL	Discharge of salt during the desalination process in planning period, Reverse osmosis technology (tonnes per year)
BRINE MASS-TOTAL	Discharge of of salt into Arabian Gulf in planning period, All technologies (tonnes)
BRINE MASS-TOTAL (E6 TONNES)	Discharge of of salt into Arabian Gulf in planning period, All technologies (million tonnes)
BRINE MASS-TOTAL (KG PER SEC)	Discharge of of salt into Arabian Gulf in planning period, All technologies (kg per second)
TEMP CHANGES BY TECH	Assumed average temperature change of the seawater intake
COMBINING METHODS	Synthesis of methods

Annex D: Additional details regarding sea level rise and regional ocean modeling of the Arabian Gulf

Sea level rise and global climate change

Global climate change causes Mean Sea Level (MSL) to rise due to three main groups of physical factors. First, mean sea levels rise locally due to changes in Dynamic Sea Level (DSL), which is defined as the sea level deviation from the geoid or to a fixed local level, in the case called Relative Sea Level (RSL). In an approximate definition, the geoid is the shape that the surface of the oceans would take under the influence of Earth's gravitation and rotation alone, in the absence of other influences such as winds and tides. DSL changes are associated with the fluid dynamic state of the ocean as currents, density, boundary fluxes of mass and buoyancy (Stephen M. Griffies & Greatbatch, 2012). DSL typically accounts for up to 15% of regional sea level rise (Yin, 2012).

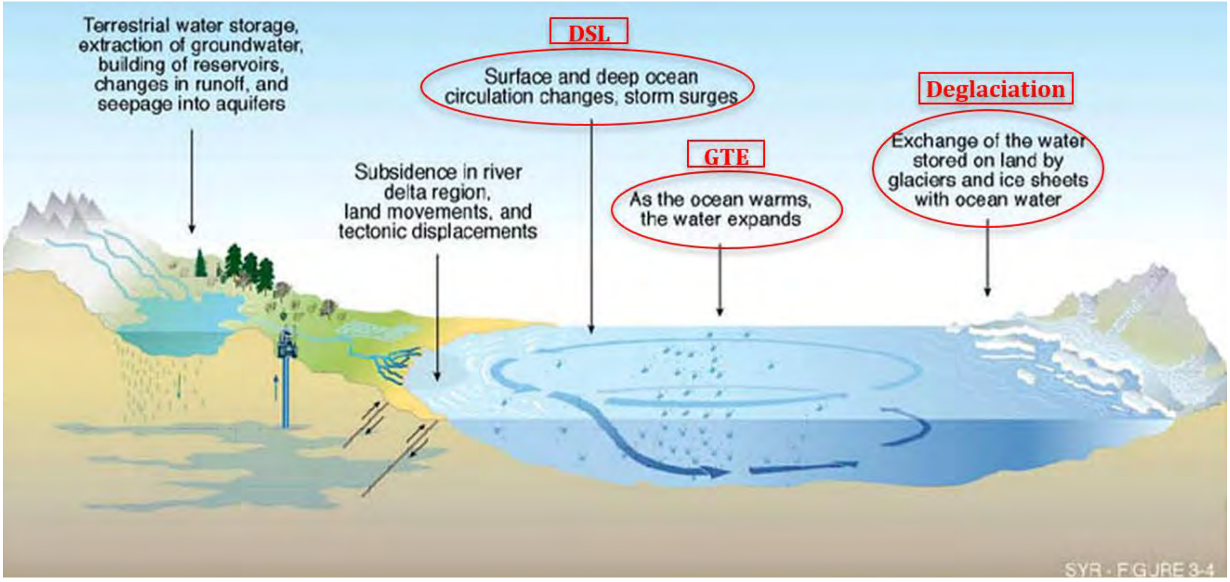
Second, mean sea levels rise due to Global Thermal Expansion (GTE) of the ocean waters (Yin, op. cit.). It is complex theoretical problem (Griffies & Adcroft, 2008; Griffies & Greatbatch, 2012) and is still an ongoing research issue that is trying to address diverse density effects within the ocean. However, simply put, as water heats up, it expands and takes up more space. Roughly half of the past century's rise in sea levels has been linked to warmer oceans simply occupying more space (Griffies & Greatbatch, 2012; Griffies, Pacanowski, & Hallberg, 2000). With rising atmospheric temperatures due to increasing concentrations of greenhouse gases, oceans function as heat sinks that absorb this excess heat and mean sea levels rise to maintain atmosphere-ocean equilibrium. GTE explains between 30% and 40% of sea level rise since the 1970’s (Yin, op. cit.).

Finally, mean sea levels rise due to a process known as deglaciation (Church & Clark, 2013) This refers to a large number of melting processes (Church & Clark, 2013b) and roughly can be associated with ice melting processes associated with glaciers**,** Antarctic ice shelves, and Greenland ice sheets. As temperatures warm, glaciers retreat unless snow precipitation increases to make up for the additional melt. The decline in Arctic sea ice over the last several decades, both in extent and thickness, has been cited as evidence for rapid climate change (Church & Clark, 2013; Church & Clark, 2013b). Deglaciation is the largest contributor to the SLR projections, likely accounting for the remaining 45% to 55% of sea level rise since the 1970's.

In addition, there are several other minor contributors to mean sea level rise. These include local factors such as sedimentation compaction and transport; land tectonic subduction; and gravitational changes; and others. In summary, all factors contributing to changes in mean sea level can be expressed as follows, and are illustrated in Figure D-1.

Mean Sea Level rise ≈ (Dynamic sea level) + (Global Thermal Expansion) + (Deglaciation) + other processes

Figure D-1: What causes the sea level to change? (Houghton et al, 2007) [Red annotations added for clarity]



Modeling sea level rise

Projecting future changes in mean sea level is based on coupled atmosphere-ocean general circulation models. Such models allow the simulated climate to adjust to changes in climate forcing, such as increasing atmospheric carbon dioxide. The Coupled Model Intercomparison Project (CMIP) began in 1995 to coordinate atmosphere-ocean general circulation modeling efforts and has evolved over time. In its Fifth Assessment Report (AR5), the IPCC's CMIP-5 protocols and related publications describe a rather complex research status on modeling mean sea level rise indicating the use of a combination of hydrodynamic approaches for modeling some variables and a combination of semi-empirical and statistical approaches for modeling other variables (Church & Clark, 2013b; Griffies & Greatbatch, 2012; Yin, 2012).

Ongoing sea level rise modeling efforts are based on a multi-model ensemble approach that can capture the impact of some but not all of the three main factors described above. Of the three driving factors contributing to sea level rise, presently only Dynamic Sea Level is capable of being suitably incorporated in current modeling platforms for the reasons briefly outlined in the bullets below:

- *Dynamic Sea Level:* Earth System Models (ESM) and the Atmospheric-Ocean Global Circulation models used in CMIP3, presented in TAR (Houghton et al., 2001) CMIP4 presented in AR4 (Alley et al., 2007; IPCC, 2007)and more recently the AR5 standards (Stocker et al., 2013) have internally modeled this variable. This is the only sea level rise variable that was modeled in the regional ocean-modeling sub-project.
- *Global Thermal Expansion:* Earth System Models (ESM, CMIP5) and the Atmospheric-Ocean Global Circulation models (AO-GCMs) used in CMIPs 3 and 4, are typically not able to internally model this variable due to the difficulty in representing it with other ocean dynamics and processes with online models. In CMIP5, it has only been considered as a simplified globally-averaged variable (Church et al., 2013; Yin, 2012).

- *Deglaciation:* Earth System Models (ESM) and the Atmospheric-Ocean Global Circulation models (AO-GCMs) used in CMIP3, CMIP4, and CMIP5 do not internally model ice-melting processes due to the high levels of uncertainty associated with the future rate of glacial retreat and ice sheet dynamics. Estimates of the contribution of deglaciation to sea level rise are only available as either globally averaged time series or in offline models (Griffies & Greatbatch, 2012). These limitations will be addressed in the upcoming CMIP6 process (S M Griffies et al., 2014).

Regional Ocean Modeling of climate change

Final results of the regional ocean modeling experiment for the Arabian Gulf for climate change (only) show a rise in sea level of a maximum of 4 cm by the late 21st century. There is a high degree of confidence in this result because the regional ocean model used was able to adequately represent changes in the internal dynamics of the Gulf such as currents, density, boundary fluxes of mass and buoyancy. Moreover, the magnitude of sea level rise comports very well with the results of Earth System Model trends and higher frequency variability for the area.

It is important to emphasize that the regional ocean modeling experiment for the Arabian Gulf only accounted for the Dynamic Sea Level (DSL) factor in sea level rise. This was because it was the only variable that was accounted for in the Earth System Model (ESM) that was used to establish the boundary conditions for the regional modeling experiment in the Gulf. The other two factors affecting sea level rise globally, namely Global Thermal Expansion and Deglaciation were not internally modeled in the Earth System Model for the reasons discussed earlier. Notably, Dynamic Sea Level is the smallest of the three major contributors to sea level rise and not surprisingly, leads to a small magnitude of sea level rise. The local contribution from GTE and Deglaciation are local variables that are indeterminate.

It is also important to note that the Earth System Model datasets do include information on Global Thermal Expansion and Deglaciation. However, these two other variables are available only as a single time series for global means and are not internally modeled by the Earth System Model itself. Including them in the regional modeling effort would have severely compromised the study's primary goal to reproduce the local Gulf dynamics to the greatest degree of physical accuracy possible because it would have led to unresolvable seawater volume and mass imbalances. Moreover, including the approximations of Global Thermal Expansion and Deglaciation factors from the Earth System Mode would have rendered the regional modeling outputs of questionable value for subsequent use in the upcoming vulnerability assessments regarding marine biodiversity and increased desalination activities in the Gulf.

Addressing Global Thermal Expansion and Deglaciation in regional ocean modeling

Approaches are beginning to emerge for undertaking regional ocean modeling that incorporate those factors that are currently too complex or too uncertain to model. For example, the regional model results can be used to recompose the MSL in the Arabian Gulf if there is willingness to consider the IPCC's semi-empirical analysis methodology, as in Church (2013b) and translating the Global Mean Sea Level (GMSL) information from the MPI-ESM-MR ensemble to the area, using measurements as described in (Alothman, Ayhan, & Arabia, n.d.). This methodology supposes the GMSL signals transposed to the Arabian Gulf, a challenge study by itself. The signal transference from global averages to local trends allows the regional model to compose in the boundary the: already known and well reproduced DSL, the GTE and melting processes contributions. There will be large uncertainties, but the regional climate model will be able return the expected (climate based) values ranges for SLR to the area.

The analytical scenario based SLR recovered signal can be used to force diagnostic experiments using the Regional Model forced on its open boundary (Hormuz Strait). Since the background dynamics has been established using consistent forces, an analytical trend could be included in the open boundary to simulate all the GMSL contributions to the area, again supposing transference from the GMSL to the regional means (Dougherty et al., op. cit.). The gain from the previous approach would be a simplified transference function (scenario based), however increasing the computational coasts and introducing another sources of uncertainties. There is a reasonable assumption to suppose that the regional model will sustain that condition for a time long enough to better evaluate internal dynamic impacts in the dynamics.

Another, more modeling-intensive approach to recover the full Sea Level Rise (SLR) in the Arabian Gulf would be a bold full nested modeling approach. This approach can transfer all the GMSL from a telescopic boundary (e.g. from Atlantic and Pacific Oceans) or even in global scale, using a coarse grid. In the same direction, the upcoming results from CMIP6 although still on planning process, could eliminate the expensive nesting processes, if there will be a proper modeling evolution, regarding GMSL and its components.

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Abu Dhabi Global Environmental Data Initiative

an initiative of
UNEP
هيئة البيئة - أبوظبي
Environment Agency - ABU DHABI

Abu Dhabi Global Environmental Data Initiative (AGEDI)
P.O Box: 45553
Al Mamoura Building A, Murour Road
Abu Dhabi, United Arab Emirates

Phone: +971 (2) 6934 444
Email : info@AGEDI.ae

agedi.org

LNRClimateChange@ead.ae