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Note

Evaluation of the long-term variability of seawater salinity and temperature in response to natural and anthropogenic stressors in the Arabian Gulf

Abubaker Elhakeem [a], Walid Elshorbagy [b,*]

[a] Water Resources Graduate Program, UAE Univ., United Arab Emirates
[b] Civil Environmental Engineering Dept., UAE Univ., United Arab Emirates

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ABSTRACT

Evaluating the long-term variability of the seawater salinity and temperature due to climate change is a limiting economical and operational factor in planning the design of new and expansion of existing desalination plants. This need is amplified in the Arabian Gulf due to the natural arid climate and anthropological stresses related to energy exploration and ongoing major developments. The lack of data in this region further adds additional dimension to the problem. The present work represents a systematic innovative approach to evaluate the anticipated long-term changes in the seawater salinity and temperature under the stresses of projected climate change and massive industrial effluents using statistical correlation and hydrodynamic simulation. The proposed approach employs the direct relation between the net freshwater losses (evaporation) entrenched with the investigated stressors and the mean sea salinity and sea temperature variation of an inverse estuary to formulate the statistical correlation and the hydrodynamic simulation conditions.

1. Introduction

The Arabian Gulf (AG) is a shallow semi-enclosed inverse estuary adjacent to the Arabian Peninsula located in a subtropical, hyper-arid region. With summer high temperatures and winter dry winds, the Gulf experiences evaporation rates of 2–5 m/yr (Ross and Stoffers, 1978; Meshal and Hassan, 1986; Ahmad and Sultan, 1991; Reynolds, 1993) exceeding by far the net freshwater input by precipitation of 0.15 m/yr (Johns et al., 2003) and river inflows equivalent to 0.15–0.19 m/yr (Wright, 1974; Saad, 1978; Reynolds, 1993; Johns et al., 2003). In most Gulf waters, salinity greater than 39 psu occurs (Alessi, 1999) and salinities of over 70 psu are observed at low flushing major embayments in its central and southern parts (Kämpf and Sadrinasab, 2006).

The region is expected to be under higher stresses due to the anticipated climate change impacts generally manifested by the IPCC 4AR (2007) as an increase in air temperature and likely decrease in precipitation leading to higher evaporation rates. Sheppard et al. (2010) provided a thorough review of the substantial changes that have taken place in marine habitats and resources of the Gulf over the past decade and concluded that major impacts come from numerous industrial, infrastructure-based, and residential and tourism development activities. Such a rapid development has dictated the need of vast fresh water and electricity supplies in response to the increasing demands. In the absence of other reliable alternatives, the AG is serving as a source and sinks for mega seawater desalination and power plants producing some 14 milion m^3/day of fresh water and 660 GW h of electricity respectively and returning simultaneously a reject effluent of brine and cooling water. Furthermore, the energy exploration, processing, storage and transporting facilities are currently handling a daily production of 25.5 million barrels and using the same water source for cooling and routine operations imposing additional stresses on the seawater quality. The 2010 report of the GCC water experts committee (GCC, 2010) has indicated that the desalination planned projects and those under construction are intended to add almost 6 million m^3/day of fresh water to the current capacity. Beside the conventional thermoelectric power plants, nuclear plants for electricity production have come into picture in the United Arab Emirates were two units have been licensed for production by 2017 to secure the countries' 9% annual increase in electricity demands.

There is a pressing need to develop a robust methodology to estimate the potential regional impacts of natural and anthropogenic stresses on the seawater quality parameters namely the sea temperature (ST) and sea salinity (SS) given the generally limited access to observational data. The issue of data collection, disclosure and sharing is a particularly sensitive issue in this region mainly due to security reasons pertinent to the oil industry and other political grounds. A major advantage of the proposed methodology

* Corresponding author. Tel.: +971 504485064; fax: +971 37134997.
E-mail address: Walid.shorbagy@uaeu.ac.ae (W. Elshorbagy).

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is its utilization of the readily available observational weather data to project the long-term changes in the seawater conditions by which the need for unavailable or inaccessible field measurements is minimal.

Long term probabilistic methodologies such as the univariate or multivariate statistical procedure could be further employed to successfully produce the final results at the projected years at any time interval using the obtained historical data set of ST and SS produced by the proposed method.

The results of the developed method is intended to provide the decision makers in the marine ecology and desalination industry sectors with a relatively accurate and comprehensive evaluation of the anticipated changes that might eventually affect the proposed expansion plans, design conditions, adopted technologies and long-term water security strategies.

2. Approach

The proposed method benefits from the recent findings of Nunes-Vaz (2012) showing that the mean salinity of the North Spencer Gulf varies predictably and consistently with the effects of net freshwater loss (net evaporation). The AG owns similar environmental conditions to the studied area (inverse estuary) allowing the adaptation of the same concept. The methodology is proposed for the well stressed AG, but can be easily adopted for any other sea area.

The net evaporation (NE) concept will be considered as a proxy to evaluate the long term spatial variability of seawater salinity and temperature in the AG using hydrodynamic modeling. Desalination brine discharges, industrial cooling water effluents and climate change stressors are evaluated and translated into evaporation-equivalent over the entire AG surface area as mm/day for the investigated time periods. For a set of formulated scenarios, the combined value of evaporation-equivalent of different stressors is assigned as an input parameter in the heat flux module in a calibrated hydrodynamic model to produce the AG basin-wide projections of sea temperature (ST) and sea salinity (SS) fields. The HD-model simulations are intended to produce the long-term spatial distribution of SS and ST for a range of scenarios (SRES, 2000).

Similar to the IPCC projections we are using the 1990 as a reference year and simulations at a 30 year time intervals (2020, 2050, 2080) are used based on the findings of Sommariva et al. (2001) who elaborated on the design life of MSF and MED desalination plants and concluded that developments in materials technology have resulted in the adoption of nobler materials, and expected that the second generation of large MSF desalination plants installed in the last 10 years – similar to those in use in the AG – will last for more than 30 years with minimum maintenance and minor overhauling.

Furthermore, long term probabilistic methodologies will be attempted to attain better estimates at targeted years. In such approach and after obtaining the historical data set of ST and SS by the proposed approach, a univariate (Ross, 1987) or more possibly multivariate statistical procedure (Joe, 1997; Salvadori and De Michele, 2010; Salvadori et al., 2013) will be applied for the obtained historical data sets.

Delft3D-FLOW software system for 3D flow simulations is employed (Gerritsen et al., 2007) to model velocity, temperature and salinity distributions in space and time. The model solves the Navier–Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions. It simulates the three-dimensional (3D) unsteady flow and transport phenomena resulting from tidal and meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (Delft3D-flow user manual, 2011).

3. Data preparation

The proposed method combines and manipulates data from various sources including weather observations, sea surface measurements, hydrodynamic simulation results; general circulation models (GCMs') projections, and calculated evaporation. Available weather data are utilized for investigating the observed climate and for calculating evaporation. Data for the time period 1983–2012 are provided by Bahrain International Airport and include Mean temp (°C), Rainfall (mm), Relative humidity (%), Wind speed (m/s), Evaporation (mm/d), and Cloud cover (%). Multiple regression analysis will be used to test the significance of the weather parameters against the measured evaporation. The produced representative mathematical model is then used to conclude the evaporation calculations by substituting the future climate change conditions.

The weather parameters are also used to define a baseline conditions to which climate change scenarios apply. The total Net Evaporation (NE) is computed based on the following formulae:

$$NE = E_b + E_d + E_e + E_c - P$$

where E_b is the background evaporation from the calibration phase; E_d is evaporation due to desalination impacts; E_e is evaporation due to industrial effluents impacts; E_c is projected evaporation due to climate change impacts and P is precipitation.

Water temperature and salinity at the open boundary at the end of each simulation period is used as input for the next period simulation and restart file will be used as initial conditions.

Projected SLR from the GCM's will be introduced as an anomaly file in the "additional parameters" specified in the MDF file set up.

4. Estimating evaporation from desalination

The desalination brine is characterized by its high salinity and temperature (thermal distillation) or its high salinity (reverse osmosis). The international desalination association statistics showed that the thermal distillation technique is dominant in the AG by approximately 83% of the total production capacity (Bleninger and Jirka, 2010).

The gross impact of the desalination brine component is quantified using the evaporation-equivalent calculated from the combined production capacity of all the desalination plants in the AG divided by its total surface area. Fig. 1 shows the Cumulative MSF, MED and RO capacities in m^3/day by site location (dots) and by country (triangles). The map shows all sites with an installed capacity $\geqslant 1000\ m^3$/d and displays sites with a capacity $\geqslant 100{,}000\ m^3$/d by name and capacity. The map was first published in Lattemann and Höpner (2003) and updated by Bleninger and Jirka (2010) using raw data from IDA and GWI (2008).

5. Estimating evaporation from industrial effluents

The industrial effluents impacts involving the use of seawater for cooling and other production processes are quantified as fresh evaporation-equivalent based on the process involved. The U.S. Department of Energy report (USDE, 2006) and the technical report of EPRI, 2002a provides data on the range of water consumed (evaporated) for the energy and thermoelectric power plants operations (Table 1). The reported values are used here to estimate the collective total evaporation based on the statistics of produced quantities of oil, natural gas and electricity in the Gulf countries.