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RESEARCH ARTICLE



# Synergy of climate change and local pressures on saltwater intrusion in coastal urban areas: effective adaptation for policy planning

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## ABSTRACT

This article examines the relative impacts of anthropogenic interventions and global climate change on the dynamics of saltwater intrusion in highly urbanized coastal aquifers. For this purpose, simulations of the impacts of sea-level rise and abstraction scenarios for the near future were undertaken for a pilot aquifer using a multi-objective 3D variable-density flow and solute transport model. We find that sea-level rise associated with climate change has less influence on the encroachment of salinity than anthropogenic abstraction, which has a more appreciable impact on saltwater intrusion through greater sensitivity to water consumption and seasonality.

## ARTICLE HISTORY

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## KEYWORDS

Climate change; sea-level rise; groundwater abstraction; saltwater intrusion; adaptation

## Introduction

Landward intrusion of seawater into coastal aquifers, known as saltwater intrusion, is primarily caused by aquifer overpumping and land-use change (Singh, 2014; Werner et al., 2013). Saltwater intrusion increasingly threatens urban coastal communities worldwide by contaminating groundwater and reducing its productive and consumptive value (Bobba, 2002; Conrads & Roehl, 2007; Fatorić & Chelleri, 2012; Park, Jang, Ju, & Yeo, 2012; Sales, 2009; Sanford & Pope, 2010; Selmi, 2013; Zhang, Savenije, Wu, Kong, & Zhu, 2011). Climate change is expected to further exacerbate saltwater intrusion due to sealevel rise coupled with higher temperatures, which would cause higher water demand, and reduced precipitation, which would reduce the surface water available for aquifer recharge (IPCC, 2007, 2014; Kumar, Carsten, & Keith, 2007).

The importance of planning to adapt to saltwater intrusion lies in protecting the biophysical elements (subsurface aquifers and groundwater quality) and curtailing associated socio-economic burdens on coastal communities (impairment of water resources, damage to soil, plants and infrastructure, etc.). However, as coastal aquifer hydrodynamics and climate change impacts remain challenging to quantify and predict (Post VEA, 2005; Sanford & Pope, 2010; Werner et al., 2013), and as the interaction between impacts of global climate change and local anthropogenic impacts remains

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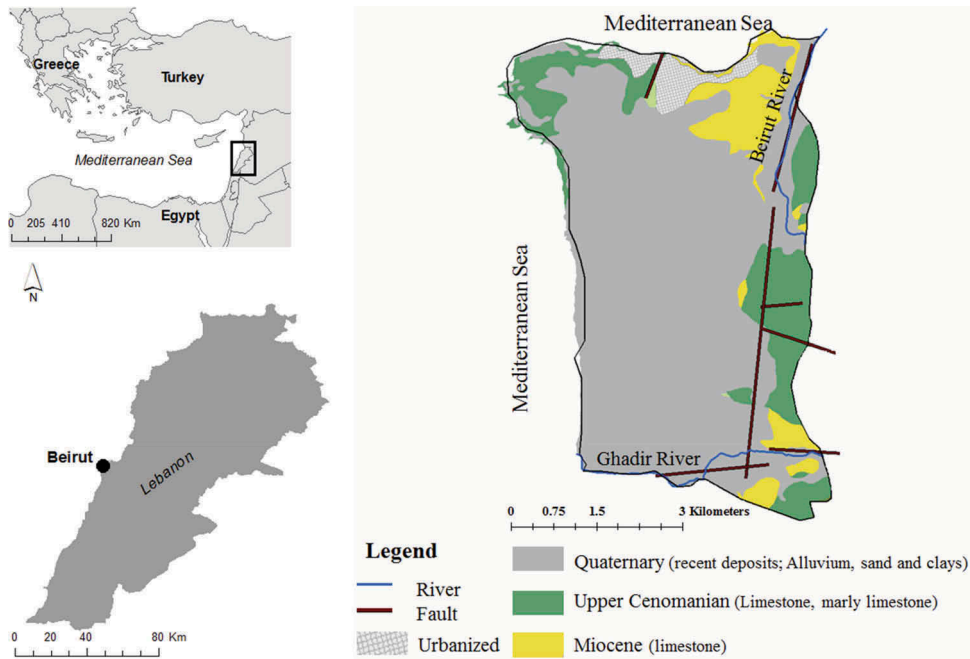
ambiguous, coastal managers have to plan and act under incomplete knowledge to cope with these impacts and protect the economic, social and environmental security of coastal communities (Tribbia & Moser, 2008). In this context, drivers of saltwater intrusion have often been assessed using mathematical simulations that account for major hydrogeological inputs as well as temporal and spatial variations in groundwater recharge and discharge and sea-level fluctuations, through mass balance and numerical analysis (Cobaner, Motz, & Motz, 2012; El Shinnawy & Abayazid, 2011; Harbor, 1994; Purandara, Venkatesh, & Choubey, 2010; Sophiya & Syed, 2013).

Groundwater overexploitation is strongly associated with lowering the water table and the advancement of the seawater front (Cobaner et al., 2012; Ergil, 2001; Koussis, Mazi, & Destouni, 2012; Selmi, 2013; Sherif, Kacimov, Javadi, & Ebraheem, 2012), and the ability of flushing a saltwater-contaminated aquifer by stopping or reducing pumping rates or managed aquifer recharge is seldom possible. Also, the impact of sealevel rise differs between confined and unconfined aquifers, with rising seas generally believed to first lift the entire aquifer, which would help alleviate the impacts of saltwater intrusion, before intrusion takes over again (Carretero, Rapaglia, Bokuniewicz, & Kruse, 2013; Chang, Clement, Simpson, & Lee, 2011; Werner et al., 2012). While the trends governing the physical, geological and chemical processes of interaction between the drivers of saltwater intrusion are generally similar, the rate and magnitude of these interactions remain highly context-specific (El Shinnawy & Abayazid, 2011; Melloul & Collin, 2006; Dausman & Langevin, 2005; Niang, Dansokho, Faye, Gueye, & Ndiaye, 2010; Oude Essink, 2001; Ranjan, Kazama, & Sawamoto, 2006), confirming the need for local examination in informed management and adaptation strategies. Similarly, the limited studies that examined opportunities for adaptation have showed that their effectiveness is variable and site-specific (Abarca, Carrera, Voss, & Sanchez-Vila, 2002; Ergil, 2001; Fatorić & Chelleri, 2012; Frank & Boyer, 2014; Georgopoulou et al., 2001; Kaleris & Ziogas, 2013; Masciopinto, 2013).

This study examines the additional factor of climate change impacts in comparison to local anthropogenic interventions in the occurrence and intensification of saltwater intrusion along urban coastal aquifers using a multi-objective 3D hydrogeological model responsive to the dynamics of population growth, recharge and climatic stresses. In parallel, it assesses the potential role of planned adaptation strategies in alleviating saltwater intrusion in an attempt to inform policy making on sustainable management of urban coastal aquifers.

## Methodology

The methodological framework consisted of three interrelated components: characterization of the pilot aquifer study area; identification of scenarios that account for local anthropogenic interventions, climate change, and planned adaptation strategies; and assessment of these scenarios for saltwater intrusion dynamics using a multi-objective 3D variable-density flow and solute transport model.



**Figure 1.** Location and surface geology of the pilot aquifer.

### **Aquifer characterization**

The pilot area is a fractured, heterogeneous aquifer underlying Beirut City and its suburbs, a highly urbanized metropolis with recognized water-shortage challenges and high dependence on groundwater resources. The study area stretches midway along the Eastern Mediterranean, with 16.5 km of diverse shorelines, including rocky beaches, sandy shores and cliffs, over a total area of  $\sim 44 \text{ km}^2$  (Figure 1). Its hydrogeology belongs to the Cretaceous and Quaternary periods, with restricted exposures of the Tertiary (Abdel Basit, 1971; Peltekian, 1980). The Cenomanian-Quaternary system (carbonate-sand) is considered one aquifer,  $\sim 700 \text{ m}$  thick, consisting mainly of hard and compact limestone and dolomite interbedded with chert, and intercalations of marl (Khair, 1992) overlain by Quaternary recent deposits. The aquifer is characterized by accessibility and relatively high transmissivity and low storativity, particularly in the Cenomanian formations, and high infiltration rates due to the presence of weak or partial cementation between the grains of sand in the Quaternary deposits, allowing moderate permeability (Khair, 1992). It is characterized by fractured and karst systems (Masciopinto, 2013; Shaban, Khawlie, & Abdallah, 2006) and is heavily jointed and faulted (Ukayli, 1971). Nearly 4500 small-scale wells reportedly tap into this aquifer (Saadeh, 2008; SOER, 2011), complementing the network water supply to nearly a million people (CAS, 2008).

## Development of scenarios

Abstraction and sealevel rise scenarios were developed for the near future (2012–2032), as proxies for local anthropogenic interventions and global climate change. Groundwater abstraction was estimated based on domestic water demand rates, using population growth and per capita consumption. Two growth rates were examined: an average of 1.75% (MoEW, 2010) and a high of 2.50% (WB, 2009). Total population estimates were based on the year 2010, with ~1.2 million inhabitants in the study area (CDR/DAR, 2014). Similarly, a constant average consumption rate of 180 litres per capita per day (LCD) (MoEW, 2010) and a variable high rate of 200 LCD increasing linearly to 300 LCD (including network losses) were tested (El-Fadel, Zeinati, & Jamali, 2000; Korfali & Jurdi, 2010; Saadeh, 2008).

Table 1 presents levels of input variables for scenario development, with a total of 11 scenarios simulated for the period 2012–2032. Water demand and availability vary between wet and dry seasons, and this variation was considered in the scenario development, where fewer surface water supplies are expected to be available in dry seasons, when the demand for water is at its highest. Assessment of the impact of sealevel rise was based on estimates for the Eastern Mediterranean of 12–25 cm by 2030 and 22–45 cm by 2050 (Cazenave, Cabanes, Dominh, & Mangiarotti, 2001), or 30–60 cm by 2040 (SNC, 2011). Accordingly, both a low (20 cm) and a high (65 cm) sealevel rise by 2032 were assumed, using rates of 1 and 3.25 cm/y, respectively. The cumulative impact of sealevel rise and abstraction on the dynamics of saltwater intrusion was analyzed for the baseline scenario (S1) as well as the worst-case scenario (S4).

Based on the understanding of the aquifer response to these drivers, potential adaptation strategies for mitigating saltwater intrusion were analyzed under the different scenarios. Given that the excessive spread of wells and the indiscriminate withdrawal of groundwater are necessitated by gaps between water supply and demand, the adaptation strategies focused on reducing abstraction by reducing the demand for groundwater in general as well as reducing the gap between supply and demand. In line with the national plans (MoEW, 2010), three levels of adaptation were evaluated to analyze for effectiveness and inform decision making in sustainable aquifer management. The scenarios tested were based on the 10-year plan of the Ministry of Energy and Water (MoEW), which consisted of (a) water conservation practices tailored to reduce network losses, currently estimated at 50% (MoEW, 2010); (b)

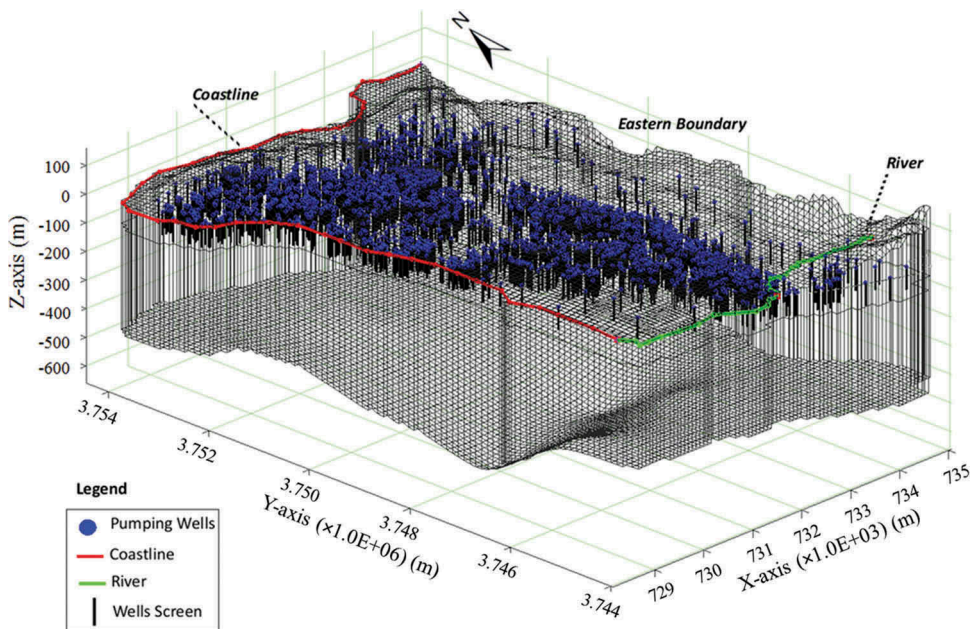
**Table 1.** Simulated scenarios with corresponding input parameters.

Scenario	Population growth (%)	Water consumption (litres per capita per day)	Description and details
S1	1.75	180	Baseline
S2	1.75	200–300	Most likely
S3	2.5	180	Modified baseline
S4	2.5	200–300	Worst case
S1A	1.75	180	Groundwater demand is reduced by 230,000 m <sup>3</sup> /day as a result of adaptation/mitigation measures starting in 2019
S2A	1.75	200–300	Groundwater demand is reduced by 350,000 m <sup>3</sup> /day as a result of adaptation/mitigation measures starting in 2019
S3A1	2.5	180	Groundwater demand is reduced by 350,000 m <sup>3</sup> /day as a result of adaptation/mitigation measures starting in 2019
S4A1	2.5	200–300	Abstraction is halted as demand is met as a result of adaptation/mitigation measures starting in 2019
S4A2	2.5	200–300	Abstraction is halted as demand is met as a result of adaptation/mitigation measures starting in 2019
S1L	1.75	180	Sea-level rise is included at 1 cm/y, i.e., rise of 20 cm by 2032
S4L	2.5	200–300	Sea-level rise included at 3.2 cm/y, i.e., rise of 65 cm by 2032

injection of treated wastewater for artificial aquifer recharge; and (c) a series of infrastructure projects, including the conveyance of water from inland to the urban area under study through a phased dam-lake project, the Beirut Awali Conveyor (MoEW, 2010). In line with the methodology, which is based on groundwater abstraction that is defined by demand, the selected adaptation strategies targeted groundwater demand and adopted the projected additional supply to Beirut from several planned projects. Adaptation Scenario A assumes additional water supply of  $\sim 230,000 \text{ m}^3/\text{day}$ , projected under Phase I ( $2.5\text{--}3 \text{ m}^3/\text{s}$ ) of the conveyor project (MoEW, 2010); Scenario A1 assumes the additional supply  $\sim 350,000 \text{ m}^3/\text{day}$  projected under Phase II ( $4.5\text{--}6 \text{ m}^3/\text{s}$ ) of the same project. Adaptation Strategy A2 assumes the adoption of unconventional water supplies (desalination), so that the entire demand is met through desalinated water, with no groundwater abstraction needed. All adaptation measures were assumed to start in 2019.

### Model set-up and simulations

A multi-objective 3D variable-density flow and solute transport model using SEAWAT (Langevin, Thorne, Dausman, Sukop, & Guo, 2008) was set for the target domain. Initial and boundary conditions, and sub-surface characteristics, were assigned to the mesh following the digitization of the study area. The boundary to the north and west is a specified head boundary condition corresponding to the monthly stage of sea level. Two rivers bound the domain to the north-east and the south (Figure 1). The southern river is dry, with occasional flow from stormwater runoff and groundwater influx, while the north-eastern river acts as a drain downstream and a river upstream. The influx to



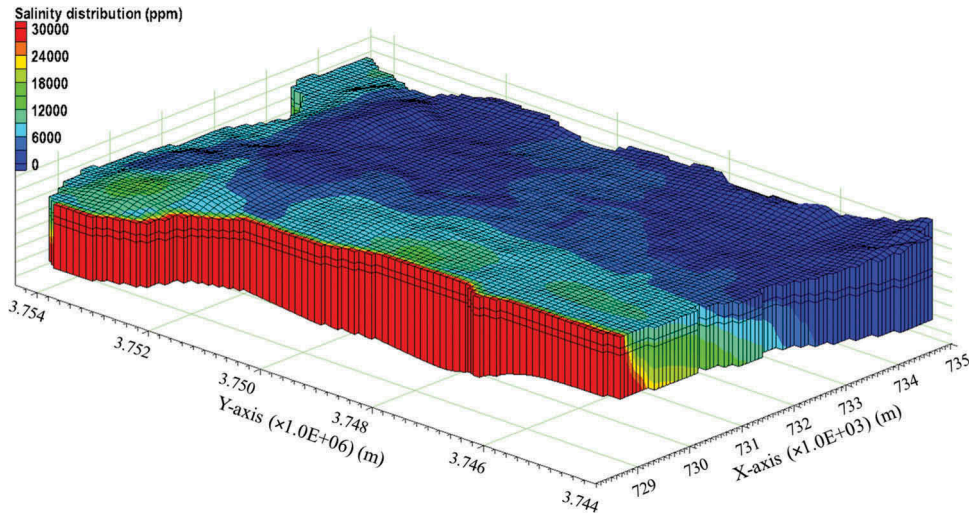
**Figure 2.** Model cells, boundary conditions and licensed wells in the Beirut aquifer (vertical magnification 4 $\times$ ).



the system is assumed to be primarily through recharge/runoff due to rainfall (Peltekian, 1980). In the last few decades, the rise in urban and suburban development in and around Beirut resulted in a significant amount of impervious surfaces. Therefore, aquifer recharge from surface runoff was considered nil in the model simulations. A Dirichlet boundary condition was used to specify the average salinity of the seaside boundary, with TDS of 35 g/L (Figure 2). The complex hydrogeology of the subsurface environment is not well documented. Therefore, assumptions on the aquifer's hydrogeological characteristics were made in the design of the model. The spatial heterogeneity of groundwater abstraction and the number of supply wells (~2500) tapping into the aquifer were assumed to be constant from 2012 to 2032. The boundary to the east (between the two rivers) was set as a no-flow boundary due to its adjacency to the middle Cenomanian formation (C4b), which has low hydraulic conductivity. The only opening in the Cenomanian formation in the eastern domain was characterized by a flux boundary condition with a low influx rate. Storativity was set at a constant of 0.3 for yield storage and  $10E-6$  for specific storage. The measurements of head and salinity field observations were considered reliable.

The model comprised a transient stress period (i.e., the computational time interval for a simulation, here taken as 1 month) of 20 years, subdivided into 240 sub-periods of one month each (from June 2012 to June 2032), that undergoes both steady-state and transient conditions. The first stress period (June 2012) was specified as steady state with the aim of providing a stable head distribution at the beginning of the transient period. Monthly averaged head observations from June 2012 to March 2014 were used in the transient model calibration in the Groundwater Modeling System (Version 10). The model used the advanced pilot-points parameterization coupled with PEST (Doherty, 2007) to characterize the spatial heterogeneity of hydraulic conductivity. The final results of model calibration suggested a range of 8–81 m/day for the hydraulic conductivity in the first numerical layer, containing the Quaternary, Cenomanian and Miocene formations. The hydraulic conductivity in the second and third layers varies between 5.02 and 182 m/day. Although the calibration results were generally satisfactory, with low model-to-measurement misfit error in terms of hydraulic head observations, the existing geologic data were not sufficient to validate the model calibration results for hydraulic conductivity. Therefore, expected uncertainty in estimation of hydraulic conductivity is recognized as a limitation of the model.

For model verification, salinity data collected during a 2013/2014 groundwater monitoring campaign were used (Rachid, El-Fadel, Alameddine, & Abu Najm, 2015). A steady-state MT3D model coupled with the steady-state head results of MODFLOW for June 2012 was run using the standard finite difference method with central-in-space weighting scheme through SEAWAT. The purpose of this steady-state simulation was to adjust the salinity distribution with the hydraulic head to estimate the initial saltwater wedge profile that would exist in the system prior to stressors (Figure 3). The salinity distribution was derived through kriging interpolation using 91 salinity measurements (in the range of 416–21,485 mg/L) collected during the groundwater monitoring programme. However, the salinity data were not sufficiently detailed to delineate a three-dimensional distribution within the aquifer. Since the vertical distribution was not known, the two-dimensional distribution was interpolated with the initial saltwater wedge profile (in 2012) produced by forecasting a historical model (which represents



**Figure 3.** Salinity distribution in the pilot aquifer in June 2012.

the water level in 1969) out to 2012 (the present water level). The saltwater–freshwater interface associated with the historical model was assumed to be under the non-intrusion condition when saltwater and freshwater were in balance.

Analysis of saltwater intrusion dynamics under the various scenarios focused on the mass encroachment of saltwater into the fresh groundwater aquifer as well as the volumetric displacement of the saltwater–freshwater interface over the 20 years of simulation. The volumetric extent of saltwater intrusion was computed using the areal extent of intrusion through vertically active cells overrun by salinity of greater than 7000 mg/L, equivalent to the threshold of brackish water. The volume of the interface with the iso-line  $\geq 7000$  mg/L was estimated by multiplying the number of cells with salinity  $\geq 7000$  mg/L with the cells' volumes (length  $\times$  width  $\times$  depth). The mass of salinity in the entire model domain was then calculated by multiplying the volume by the porosity and salinity  $\geq 7000$  mg/L.

Because two main mechanisms of saltwater intrusion are expected to take place,<sup>1</sup> the geologic layer in the pilot aquifer was divided into two numerical zones to characterize the dominant mechanism of intrusion: an upper zone where supply wells are tapping and a lower zone where the toe of the interface is located.

As a measure of the relative impacts of model variables (water consumption rate, population growth and adaptation level) on the magnitude of intrusion, prediction-scaled sensitivity (PSS) was calculated for the groundwater abstraction scenarios (S1a, S2, S2a, S3a1, S4 and S4a1). The PSS was defined as the percentage change in the model prediction (mass of salinity or volumetric displacement of the interface) given a change in the rate of groundwater abstraction on the basis of the change in water consumption rate, population growth and adaptation level (Hill & Tiedeman, 2007):

$$PSS_{ij} = \left( \frac{\partial y_{ij}}{\partial b_{ij}} \right) (b_j/100) (100/y_j) \quad (1)$$



Where  $\left(\frac{\partial y_{ij}}{\partial b_{ij}}\right)$  is the change in mass encroachment or volumetric displacement over the change in abstraction rate, evaluated in the  $i$ th scenario from the  $j$ th baseline scenario (mg/L over  $m^3/y$  or  $m^3$  over  $m^3/y$ );  $y_j$  is the mass encroachment of salinity or volumetric displacement of the interface in the  $j$ th baseline scenario (mg/L or  $m^3$ );  $\partial y_{ij}$  is the change in mass encroachment or volumetric displacement in the  $i$ th scenario from the  $j$ th baseline scenario;  $b_j$  is the abstraction rate at the  $j$ th baseline scenario ( $m^3/y$ );  $\partial b_{ij}$  is the change in abstraction rate in the  $i$ th scenario from the  $j$ th baseline scenario;  $i$  is the scenario (S1a, S2, S2a, S3a1, S4 or S4a1), and  $j$  is the associated baseline scenario (S1 and S3 for S2 and S4, respectively, and S1, S2, S3 and S4 for Adaptation A and Adaptation A1). For instance, if the abstraction rate increases from 10 to 12  $Mm^3$  (17% increase) and consequently the salinity mass increases from 2000 to 2200 tonnes (10% increase), the estimated PSS is  $(200 \text{ tonnes}/2 \text{ Mm}^3) \times (10 \text{ Mm}^3/100)$   $(100/2000 \text{ tonnes}) = 0.5$ . Note that PSS is dimensionless. PSS was calculated for both the mass encroachment of salinity and the volumetric displacement of the interface under seasonal conditions.

## Results and discussion

### Impact of abstraction

The model results indicate that under the baseline scenario (S1), the saltwater–freshwater interface moves landward, indicating increased salinization of the aquifer, with  $\sim 15\%$  mass encroachment of salinity and  $\sim 20\%$  volumetric displacement of the interface occurring in the upper zone of the aquifer within a depth of 100 m below sea level (where most wells are tapping). Concurrently, there is  $>80\%$  encroachment occurring in the lower zone of the aquifer, where the toe of the interface is located. Figure 4 illustrates the estimated abstraction per year over the whole simulation period for all scenarios in the absence of any adaptation

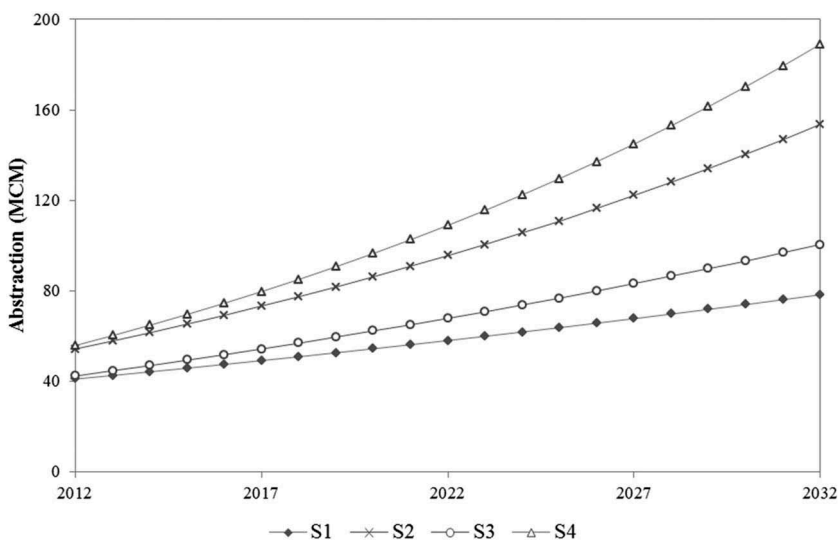
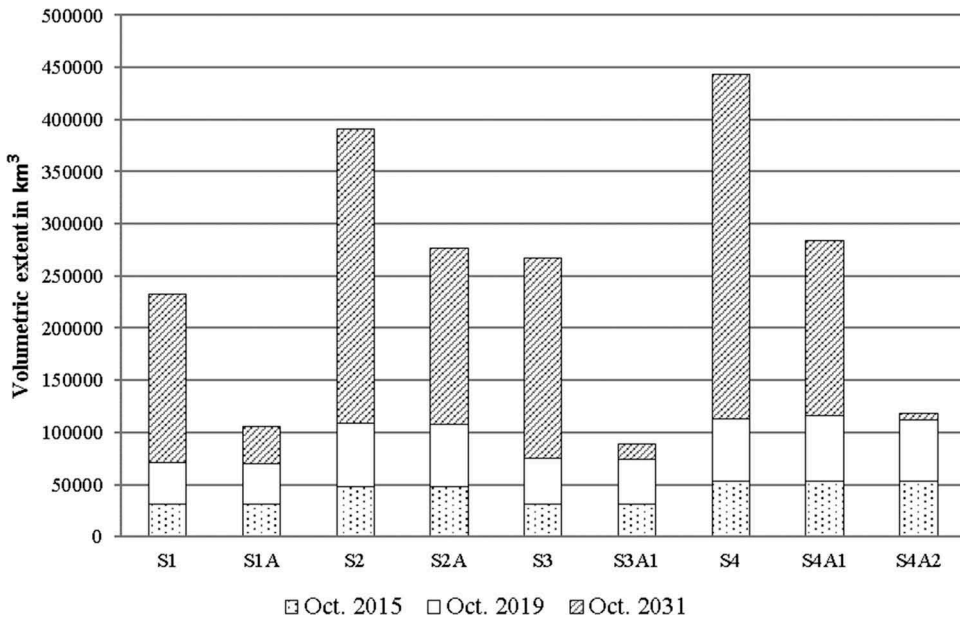


Figure 4. Variation in groundwater abstraction under the main simulated scenarios.

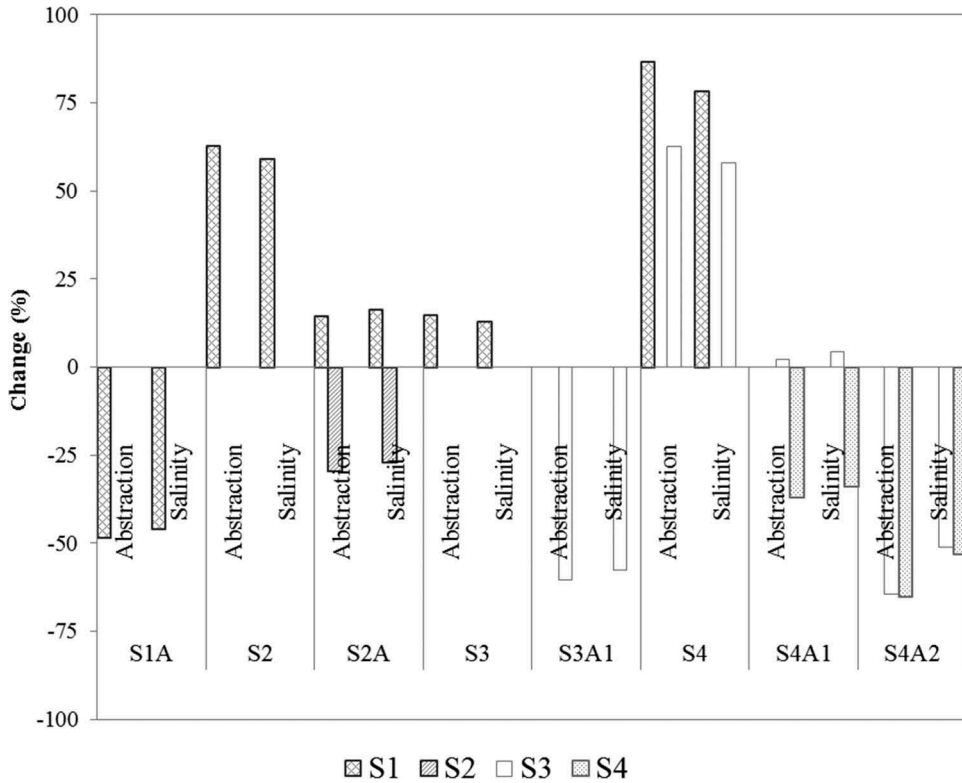


**Figure 5.** Volumetric extent of more than 7g/L salinity intrusion over the simulation period in October 2015 (end of the dry season), October 2019 (beginning of adaptation scenarios) and October 2031 (end of simulation period).

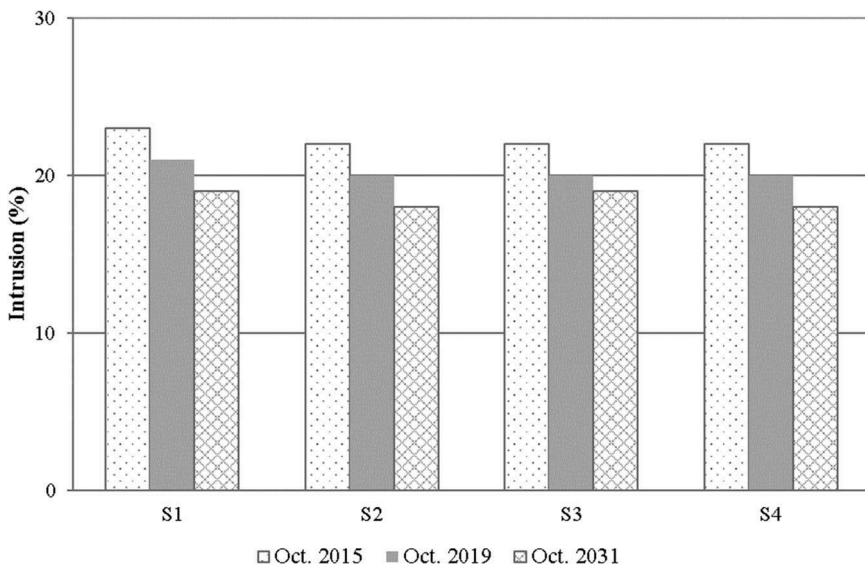
measure. Greater water consumption per capita rates result in a greater increase in abstraction (S1 vs. S2 and S3 vs. S4) as compared to that associated with population growth rates (S1 vs. S3 and S2 vs. S4). Raising water consumption from 180 LCD to 200–300 LCD under S2 (the most likely scenario) increases the total rate of abstraction by ~63%, which is translated into a ~60% increase in mass encroachment of saltwater intrusion and 70% additional displacement of the interface in 20 years (by October 2031) as compared to S1.

The volumetric displacement of elevated concentrations at the end of the dry season for the current state of salinity (October 2015), the beginning of adaptation scenarios (October 2019) and the end of simulation period (October 2031) are displayed in [Figure 5](#) across scenarios of groundwater abstraction. Simulations of the S3 scenario suggest that raising the rate of population growth from 1.75% (in S1) to 2.5% (in S3) increases the abstraction rate by 14.7% with ~12.8% exacerbation of salinity intrusion as compared to S1, suggesting that salinity encroachment is more sensitive to the rate of water consumption than to the rate of population growth. Increasing both population growth and water consumption rates under S4 (the worst-case scenario) led to a 78% increase in mass encroachment, which translated into a 90% increase in landward displacement as compared to S1. Under Scenario S4, the simulated landward displacement is 5% more than the combined predicted impact of increased population growth (S3) and water consumption rates (S2) due to the synergistic impact of both S2 and S3 scenarios on the dynamics of saltwater intrusion ([Figure 6](#)).

In the absence of adaptation measures (scenarios S1, S2, S3 and S4), it is expected that the upper zone now exhibiting saltwater intrusion with elevated salinity (>7000 mg/L) will experience a volumetric intrusion that is slightly reduced from the



**Figure 6.** Change in abstraction and mass encroachment over 20 years of simulation under various groundwater abstraction scenarios relative to the corresponding baseline scenarios.



**Figure 7.** Volumetric extent of over 7g/L salinity intrusion in the upper layer of the aquifer (100 m thickness).

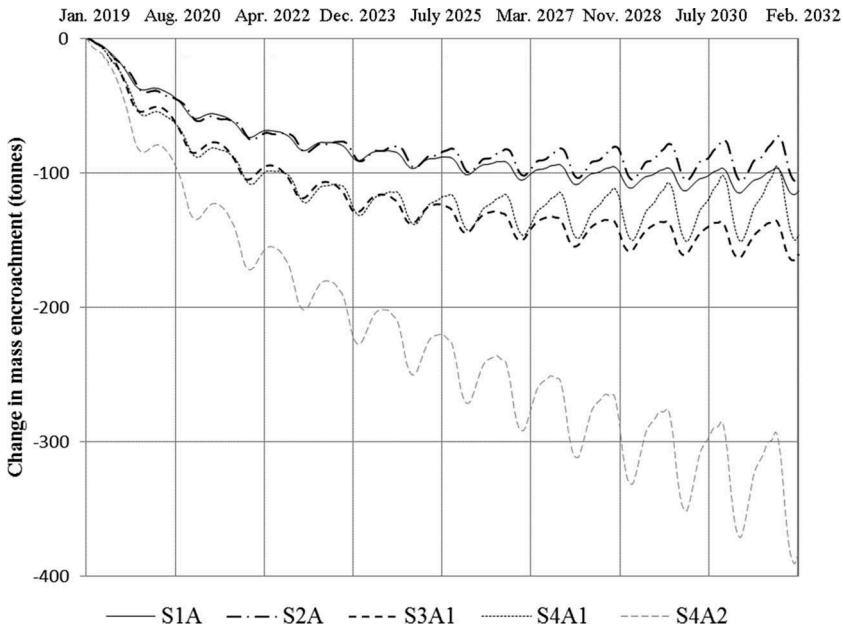
current rate of 20% (Figure 7). Since elevated concentrations are encountered mainly in the transition zone, the diminishing volumetric percentage of intrusion in the upper zone suggests that the dominant mechanism of temporal intrusion is lateral encroachment in the lower zone. Since groundwater abstraction increases under scenarios S2 and S4 in comparison to S1 (baseline), the volumetric percentage of intrusion in the upper zone drops further, while that of the lower zone increases, thus demonstrating that the movement of the interface toe is sensitive to abstraction rate. Hence, managing the abstraction rate is imperative for managing the lateral encroachment and potentially reversing the intrusion of saltwater.

### ***Impact of sea-level rise***

Simulation of a 1 cm/y sealevel rise (20 cm by 2032, S1L) applied to the baseline scenario (S1) resulted in a slight increase in the mass encroachment of salinity, which is equivalent to the impact resulting from a 1% increase in groundwater abstraction over the simulation period (20 years) under similar conditions. This suggests that a sealevel rise of 20 cm by 2032 has a relatively insignificant impact on saltwater intrusion dynamics relative to groundwater abstraction in the study area. Similarly, a high sealevel rise (S4L) of 3.2 cm/y (65 cm by 2032) applied to the worst-case scenario (S4) resulted in an additional mass encroachment equivalent to the impact of only a 1.7% increase in groundwater abstraction, reconfirming that the impact of a 65 cm sealevel rise by 2032 will largely be masked by the overwhelming impact of over-abstraction. While under the analyzed scenarios of groundwater abstraction (S1, S2, S3 and S4), a sealevel rise of 1 cm/y seems to be of minimal concern due to lower magnitude of intrusion in S1 than other scenarios (S2, S3 and S4), the impact of an additional 2.20 cm/y of sealevel rise (sealevel rise of 3.20 cm/y) on S1 is equivalent to the impact of a 2% increase in groundwater abstraction for the same scenario (S1). Accordingly, any adaptation strategy or management measure to alleviate saltwater intrusion must focus on controlling abstraction, which remains the main driver of saltwater intrusion. Note that sealevel rise may cause changes in the shape of the interface, which may increase the possibility of upconing near the coastline.

### ***Impact of adaptation scenarios***

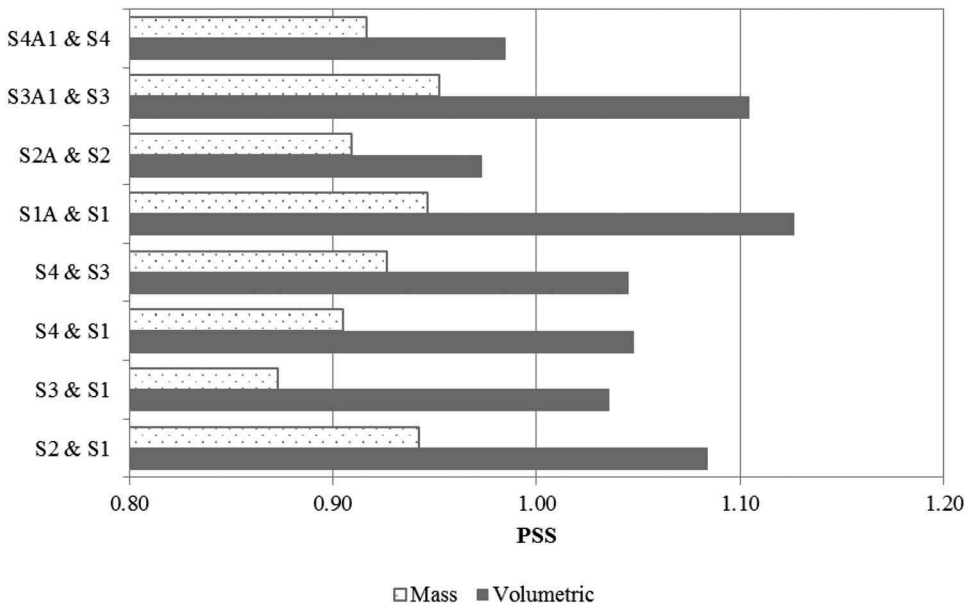
Figure 8 depicts the monthly change in saltwater intrusion considering adaptation scenarios throughout the simulation period (up to 2032). Both the mass and volumetric encroachment trends corresponding to scenarios 1A and 4A1 suggest that adaptation strategies under these scenarios would help reduce the demand for groundwater in the majority of years as compared to 3A and 6A1, where the demand for groundwater remained greater than the available supply defined in the adaptation strategies of those scenarios. For instance, S3A1 shows a 60% reduction in volumetric encroachment as compared to S3, suggesting that a reduction in demand of 350,000 m<sup>3</sup>/day can reduce pumping rates to nil in the wet season (for a couple of years). Note however that while total abstraction rates decrease under various adaptation strategies (Strategies A and A1), salinity still has an increasing trend, as expected, due to the higher rate of groundwater depletion as compared to the replenishment, particularly in the dry



**Figure 8.** Changes in mass encroachment under adaptation scenarios (S1A and S2A: reduction in groundwater abstraction by  $230,000 \text{ m}^3/\text{day}$  starting in 2019; S3A1 and S4A1: reduction in groundwater abstraction by  $350,000 \text{ m}^3/\text{day}$  starting in 2019).

season. Nevertheless, Adaptation Strategies A and A1 proved to be effective in reducing the total abstraction rates and halt the intrusion for a significant duration before abstraction takes over again (S2A and S4A1). Across Scenarios S2A and S4A1, the largest reduction in mass encroachment of salinity occurred in the wet season (November to April), as groundwater abstraction (in some years) fell to almost nil. In contrast, the minimal reductions were as expected during dry season (mostly in October, the driest month of the year), because the adaptation strategies could not meet freshwater demand.

The optimistic adaptation strategy, in which groundwater abstraction ceases by 2019 (with the demand being met through unconventional water resources, i.e. desalination) was tested under the worst-case scenario (S4), associated with assuming the highest abstraction rate and mass encroachment after 20 years (by 2032). In the simulation, the mass encroachment of salinity decreased by 47% (from S4 to S4A2) over a period of 13 years, from 2019 to 2032 (Figure 8), the total mass of salinity in 2032 was still significantly higher (250%) than in 2012. This suggests that while halting abstraction helps to freshen the aquifer system, a recovery period of 13 years did not undo the damage caused by seven years of abstraction under the worst-case scenario (S4), since more time is needed to aid the aquifer's recharge.



**Figure 9.** Simulated prediction-scaled sensitivity (PSS) of various scenarios for mass and volumetric encroachment of intrusion. S1: baseline scenario, with 180 litres per capita per day (LCD) water consumption and 1.75% population growth. S2: most likely scenario, with 200–300 LCD water consumption and 1.75% population growth. S3: modified baseline scenario, with 180 LCD water consumption and 2.5% population growth. S4: worst-case scenario, with 200–300 LCD water consumption and 2.5% population growth. S1A and S2A: reduction in groundwater abstraction by 230,000 m<sup>3</sup>/day starting in 2019. S3A1 and S4A1: reduction in groundwater abstraction by 350,000 m<sup>3</sup>/day starting in 2019. S4A2: abstraction in S4 is halted as demand is met as a result of adaptation/mitigation measures starting 2019. S1L: Sea-level rise is included at 1 cm/y, i.e., rise of 20 cm in S4 by 2032. S4L: Sea-level rise is included at 3.2 cm/y, i.e., rise of 65 cm in S4 by 2032.

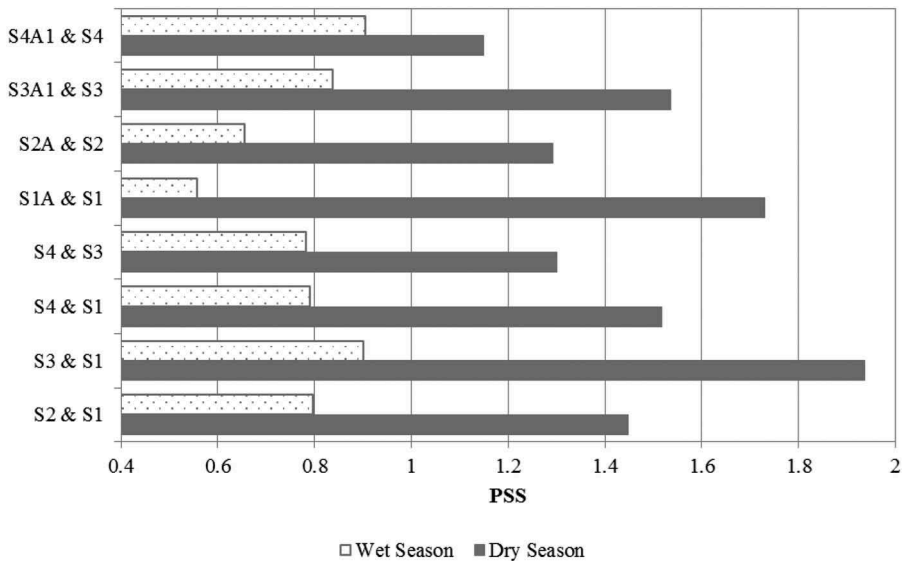
### Sensitivity analysis

The sensitivity analysis suggests that the volumetric displacement of the interface, rather than the mass encroachment, is sensitive to changes in abstraction rates (Figure 9). Volumetric encroachment is only associated with landward displacement of elevated concentrations (> 7000 mg/L), while mass encroachment involves concentrations in the full TDS range of 0–35,000 mg/L (seawater concentration), indicating that saltwater intrusion in the aquifer is governed by concentrations of more than 7000 mg/L. Salinity encroachment has a higher sensitivity to water consumption rate than to population growth rate (S2 and S1 [volumetric PSS = 1.08, mass PSS = 0.94] vs. S3 and S1 [volumetric PSS = 1.04, mass PSS = 0.87]). In parallel, the baseline scenarios (S1 and S3) exhibited more sensitivity to adaptation strategies (S1A and S1 [volumetric PSS = 1.13, mass PSS = 0.95] vs. S3A1 and S3 [volumetric PSS = 1.1, mass PSS = 0.95]) than S2 and S4 (S2A and S2 [volumetric PSS = 0.97, mass PSS = 0.91] vs. S4A1 and S4 [volumetric PSS = 0.98, mass PSS = 0.92]), where S1A and S3A1 highlighted a large decrease in the magnitude of intrusion with reduced water abstraction, particularly during the wet season. Nevertheless, the response to adaptation strategy A1 (reduction of groundwater demand by 350,000 m<sup>3</sup>/day) showed higher sensitivity than with adaptation A (reduction of



groundwater demand by 230,000 m<sup>3</sup>/day), even though A1 is applied to Scenario S3, which involves 15% more abstraction than S1. On the other hand, further increases in water consumption (under S2A and S4A1) reduced the impact of adaptation (S2A and S2 [volumetric PSS = 0.97, mass PSS = 0.91] vs. S4A1 and S4 [volumetric PSS = 0.98, mass PSS = 0.92]), particularly after a period of time where the increase in groundwater demand dominates again.

The seasonal sensitivity results indicate that the impact of adaptation strategies increased in the dry seasons, when the aquifer undergoes maximum intrusion (Figure 10). Since the aquifer does not suffer from excessive intrusion in the wet season under the baseline scenario S1, the system had the least sensitivity to the adaptation plan during the wet season (wet PSS = 0.56). This highlights the potential role of storing the excess water in the wet season for later use in the dry season, as a potential adaptation strategy to be further examined. However, the impact of adaptation on mass encroachment of salinity in the dry season was most effective under the baseline condition S1, when the PSS increased nearly four times from wet (0.56) to dry (1.73). The high sensitivity of the mass encroachment to the adaptation scenario S4A1 in the wet seasons indicates the vulnerability of the aquifer in the wet season to increases in population and water consumption rate (PSS = 0.9). While this higher sensitivity to population growth (PSS = 0.9) compared to water consumption (PSS = 0.8) in the wet



**Figure 10.** Seasonal prediction-scaled sensitivity (PSS) of simulated scenarios to the mass encroachment of intrusion. S1: baseline scenario, with 180 litres per capita per day (LCD) water consumption and 1.75% population growth. S2: most likely scenario, with 200–300 LCD water consumption and 1.75% population growth. S3: modified baseline scenario, with 180 LCD water consumption and 2.5% population growth. S4: worst-case scenario, with 200–300 LCD water consumption and 2.5% population growth. S1A and S2A: reduction in groundwater abstraction by 230,000 m<sup>3</sup>/day starting in 2019. S3A1 and S4A1: reduction in groundwater abstraction by 350,000 m<sup>3</sup>/day starting in 2019. S4A2: abstraction in S4 is halted as demand is met as a result of adaptation/mitigation measures starting in 2019. S1L: sea-level rise is included at 1 cm/y, i.e., rise of 20 cm in S4 by 2032. S4L: sea-level rise included at 3.2 cm/y, i.e., rise of 65 cm in S4 by 2032.

seasons (S3 vs. S2) is in contrast to the yearly sensitivity analysis results (where PSS is 0.87 for S3 and 0.94 for S2), it is because water consumption varies by season but population growth is fairly steady over a given year. This highlights the need for seasonal/monthly simulations to address the impact of seasonal changes in the rate of groundwater abstraction on saltwater intrusion for proper analysis of the impact of adaptation or mitigation strategies aimed at halting the intrusion.

### Adaptation/mitigation framework

While adaptation strategies can be very successful in slowing saltwater intrusion, even under scenarios of rapid population growth, water consumption rates must be controlled for this purpose. Scenarios of high consumption rates render adaptation strategies ineffective after an average period of 14 years as the increase in demand for groundwater masks the benefits of the adaptation. In this context, adaptation strategies should be planned together with mitigation measures in a comprehensive framework for effective saltwater intrusion control and sustainable aquifer management. While only three adaptation strategies were simulated, designing the adaptation framework necessitates examining all measures that can potentially reduce the water deficit, which is the main driver of groundwater abstraction, through targeting both demand and supply management options incorporated in national water plans in close coordination between relevant institutional and community stakeholders (Figure 11). In this context, the Ministry of Energy and Water and its Regional Water Establishments (RWE) are the main entities governing the water sector, in coordination with other regulatory bodies such as the Ministries of Public Health (MoPH) and Environment (MoE), which are responsible for health and environmental protection and set standards for water quality monitoring. The Ministry of Interior and Municipalities (MoIM) is involved in

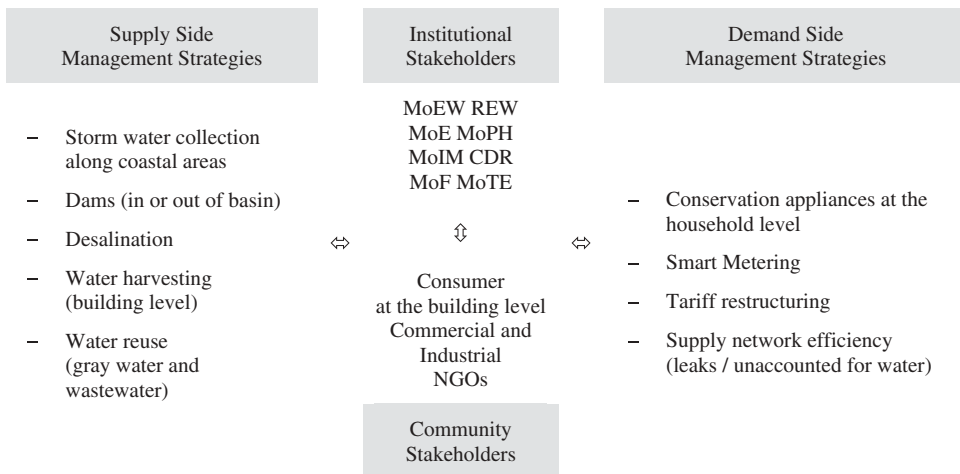


Figure 11. Adaptation framework.

Note: MoEW, Ministry of Energy & Water; RWE, Regional Water Establishments; MoPH, Ministry of Public Health; MoE, Ministry of Environment; MoIM, Ministry of Interior & Municipalities; CDR, Council for Development and Reconstruction; MoF, Ministry of Finance; MoET, Ministry of Economy and Trade.

executing and monitoring of small-scale municipal works that relate to water infrastructure, as well as enforcing regulations and penalties levied by other institutions. In practice, these ministries are also supported at times by the Council for Development and Reconstruction (CDR) through the funding of large-scale water supply projects such as dams by international organizations (MoE/UNDP/ECODIT 2011) and the Ministries of Finance (MoF) and Economy and Trade (MoET) through setting tariff structures and ensuring consumer protection.

Smart metering, tariff restructuring, and promotion of water conservation practices, as well as incentives for water-saving appliances, are important demand-side management measures, indispensable for sustainable water consumption and proper resource management. On the other hand, reducing unaccounted-for losses in the water supply network, currently estimated at 50% (MoEW, 2010), remains a priority supply management measure that can minimize groundwater abstraction and save invaluable surface water resources. Rainwater harvesting, benefiting from surface runoff (stormwater) along coastal areas, as well as reuse of treated grey water and wastewater, despite their associated sensitivity in terms of social acceptance, can also be incorporated in the framework. Other supply management methods, discussed in the national plans (MoEW, 2012), including the construction of a series of dams as well as conveying water from rural areas, could prove viable in the medium to long term when population growth and high consumption rates require boosting of available water resources. The latter should be considered in parallel to demand-management strategies and other supply management measures such as unconventional sources (desalination, water harvesting, water reuse, etc.). This framework should be managed concomitantly with a monitoring programme that continuously assesses the response of the aquifer system to groundwater extraction. Naturally, the framework needs to be implemented in a wise and timely manner where different measures are gradually undertaken at critical milestones to support and boost strategies that may grow ineffective and maintain desired performance.

## Conclusion and way forward

The impact of global environmental change and local anthropogenic interventions on the intrusion of saltwater in a coastal urban aquifer was analyzed using a multi-objective variable density model through analysis of groundwater abstraction and sea-level-rise scenarios. Annual simulations showed that while the aquifer system is highly sensitive to both water consumption rates and population growth rates, a 50% increase in the rate of water consumption leads to at least four times more volumetric displacement of the interface after 20 years than a similar increase in population growth rate. Interestingly, coupling of both has a synergistic effect that aggravates the displacement beyond the sum of the individual impacts. On the other hand, the aquifer system revealed a relatively limited sensitivity to sealevel rise (induced by climate change), whereby the impact on saltwater intrusion of a 65 cm rise by 2032 is masked by a 2% increase in abstraction rates under the baseline scenario despite other climate change impacts. Note however that the additional factors associated with the reduced precipitation and higher temperature (and hence higher net water demand) induced by climate change are indirectly embedded in water consumption rates.

The analysis of adaptation strategies indicated considerable effectiveness in slowing saltwater intrusion. While the adaptation strategy of halting abstraction could not effect system recovery or reverse the saltwater intrusion damage, it succeeded in stopping the intrusion. The effectiveness of adaptation strategies to secure the desired results hinges on proper planning in terms of timing, duration, capacity and context. This underlines the importance of understanding the aquifer system and its seasonal response as well as its interaction with drivers, before selecting an adaptation strategy for successful and sustainable aquifer management.

This study contributes to the understanding of the response of coastal aquifer systems to local and global stresses as well as the role of adaptation strategies in alleviating saltwater intrusion. It forms a platform for effective local adaptation planning, providing informed policy and decision making for sustainable aquifer management.

## Note

1. Lateral encroachment of recent seawater due to the high heterogeneity, in addition to upconing due to the high vertical velocity of water (as a result of low storativity).

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