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# Impact of Burullus Lake on the Nile Delta Aquifer Overcoming Seawater Intrusion

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**Abstract**
Surface recharge of coastal aquifers is one of the management tools to overcome seawater intrusion. The success of this management tool depends on the geological settings and the hydrogeological characteristics of the site. This study addressed the impact of Burullus Lake on the Nile Delta aquifer overcoming the seawater intrusion. The Lake resides on a clay aquitard with a thickness of 25 m or even more. Eight scenarios were proposed and simulated. These scenarios include decrease of the water salinity in the Lake, increase of the water level in the Lake and/or reduction of the clay cap thickness. The baseline salinity in the Lake is 9000 mg/L. The aquifer salinity varies with depth and proximity to the shoreline. The simulation of the baseline scenario indicated that the aquifer salinity within the Lake footprint ranges from 2000 mg/L to 7700 mg/L. When the water salinity in the Lake is decreased to 3000 mg/L and 650 mg/L, the aquifer salinity decreases more than 8.5% and 17%, respectively after 10 years at a depth of 50 m at a middle point of the Lake footprint. Although decreasing the water salinity in the Lake had decreased the aquifer salinity in the upper parts of the aquifer, the salinity increased with time in all scenarios. This is attributed to the effect of seawater intrusion. Reducing the thickness of the clay aquitard, by 10% or 20%, within the Lake footprint had minor effect on aquifer salinity.
**Keywords:** Coastal Aquifer, Burullus Lake, Seawater, Intrusion, Visual MODFLOW

## 1. Introduction

Occurrence of seawater intrusion into coastal aquifers is a serious problem, which threatens the integrity of these aquifers. Seawater intrusion occurs when the hydraulic head of the intruding sea water is higher than the hydraulic head of the aquifer. One of the main causes of seawater intrusion is over pumping from the coastal aquifer in a rate exceeding the natural water recharged to the aquifer (Prieto et al. 2001,). Therefore, management of different water resources including aquifer recharge and discharge is necessary to preserve the aquifer quality.

Recharge of coastal aquifers has been addressed in a number of studies (Luyun et al., 2011; Timms et al., 2012; Werner et al., 2013; Abu-Bakr et al., 2016; Caschetto et al., 2016). The objective of the aquifer recharge is to enrich the groundwater resources and increase the groundwater level against the intruding seawater (Luyun et al., 2011; Shi and Jiao 2014; Abu-Bakr et al., 2016; Caschetto et al., 2016). Surface recharge of coastal aquifers, through natural or manmade lakes, depends on the hydrogeological characteristics of the vadose zone and the aquifer, groundwater level with respect to water level in the lake and the water depth in the lake. These settings dominate the interaction between the lake and the aquifer (Ting at el., 2007; Yuan et al., 2011). The interaction between surface water and groundwater in coastal areas has been addressed in a number of studies, which incorporated using a coupled model (Wilson and Gardner, 2006; Yuan et al., 2008; Yuan et al., 2011).

In their study on surface recharge from a paddy field, Tuong et al. (1994) stated that the water depth in the recharge paddy field and the hydraulic conductivity of the bed soil are the main parameters that dominate the infiltration rate into the subsurface aquifer. Accordingly, the infiltration capacity is high in sandy soils, which decreases as the clay content increases. Ting et al. (2007) studied the interaction between a manmade lake and a groundwater aquifer. In their study, the recharge flux to the aquifer was estimated by direct measurement of infiltration rate. The recharge flux depends on the water depth in the lake and the groundwater level with respect to the lake bed. Moreover, the groundwater level is dependent on the infiltration rate, which is limited by the accumulation of sludge at the lake bed. Zhang et al. (2012) developed a wetland network model to mitigate saltwater intrusion on river channels. The fresh water was stored in the wetlands and allowed to discharge into the impacted river channel once water salinity reached a threshold value.

Burullus Lake is the second largest lake in Egypt with an area of 410 km$^2$ (El-Adawy et al. 2013). Municipal, industrial and agriculture wastewater collected from the Nile Delta is discharged to Burullus, Edku, Manzala, and Mariut Lakes, which results in increased concentrations of metals and nutrients (Flower, 2011; El-Shazly et al., 2016). The metals concentrations in the harvested fish from the Lakes lay a health risk on the consumers (El-Shazly et al., 2016). El-Adawy et al. (2013) developed a hydrodynamic model, using Delft-3D Flow, to simulate the water levels inside and outside the Lake, inflow and outflow of the Lake, and the salinity and temperature distribution in the Lake. The study also discussed a number of management scenarios of salinity inside the Lake. In these scenarios, the drains were either diverted, partly diverted or completely diverted of the Lake. The salinity distribution in the Lake depends mainly on the inflow from the drains. The water generally flows from the Lake to the Mediterranean Sea.

The objective of this paper is to determine the interaction between Burullus Lake and the Nile Delta aquifer, the recharge of the Burullus Lake to the aquifer through infiltration, and the effect of recharge on raising the aquifer head overcoming the saltwater intrusion. A number of scenarios are proposed to address the surface recharge on aquifer recovery and overcoming the saltwater intrusion.

## 2. Materials and Methods

Saltwater intrusion occurs when the hydraulic head of the intruding sea water is higher than the hydraulic head of the aquifer. The latter could be increased through surface recharge of water with salinity concentration less than that in the aquifer. This research study focuses on surface recharge from a lake into a coastal aquifer. A number of factors affect the surface recharge of the aquifer and ability of the aquifer to overcome the intruding saltwater, including: water depth in the Lake, hydraulic head in the aquifer, hydraulic conductivity and thickness of the soil layers, and water salinity in the Lake and the aquifer. In this research, Burullus Lake is taken as the case study. A number of scenarios are considered to address the impact of Burullus Lake on the aquifer overcoming the saltwater intrusion. In these scenarios, the water depth in the Lake was set at 1.5 m above mean sea level, the water salinity in the Lake was changed from 9000 mg/L, which represent the baseline salinity concentration, down to 650 mg/L, which is the salinity concentration of tertiary treated wastewater. Another set of scenarios addressed decreasing the thickness of the aquitard through dredging the Lake. The scenarios were compared to salinity concentrations in the aquifer at two control points: north, between the Lake and the shoreline, and south, within the Lake footprint.

### 2.1. *Site description*

The study area, shown in Figure 1, is located at the north of the Nile Delta. It extends between longitudes 30° 30' 56.2", 31° 05' 49.5" east and latitudes 31° 21' 45.4", 31° 35' 54.1" north covering an area of 1440 km$^2$. The actual area of Burullus Lake is 410 km$^2$. The average topographic elevation is 4 m above mean sea level with spots of zero elevation and a mild slope from south (inland) to north (shoreline).

### 2.2. *Description of General Geological and the Hydrogeological Settings*

The study area is located at the north east of the Nile River. The geological formations are Quaternary sediments (Holocene), Mit Ghamr (Pleistocene), El Wastani (Pliocene), Kafr El Sheikh (Pliocene), Abu Madi (Pliocene), Rosetta (Miocene), Qawasim (Miocene) and Sidi Salem (Miocene). The Quaternary sediments consist of Nile silts, Undifferentiated Quaternary deposits, Sand Dunes and Stabilized Sand Dunes, and Sabkha deposits. The surface geology is composed of clay and silt, black sands, and sands and gravel. The top layer is clay with thickness of 30 meters underlain by 900 meters of sand and gravel with traces and lenses of clay, which sets on top of a thick clay layer. The top clay layer acts as an aquitard while the sand and gravel layer is the aquifer (Geological Map of Egypt, 1988). The latter is considered a part of Nile Delta Quaternary aquifer, which is a moderate productive aquifer. Figure 2 shows the lithology profiles of the top 175 m depth of two boreholes corresponding to Wells W1 and W2. The well data were obtained from the Research Institute for Groundwater, National Water Research Centre, Egypt.

 


Figure 1. The Study Area

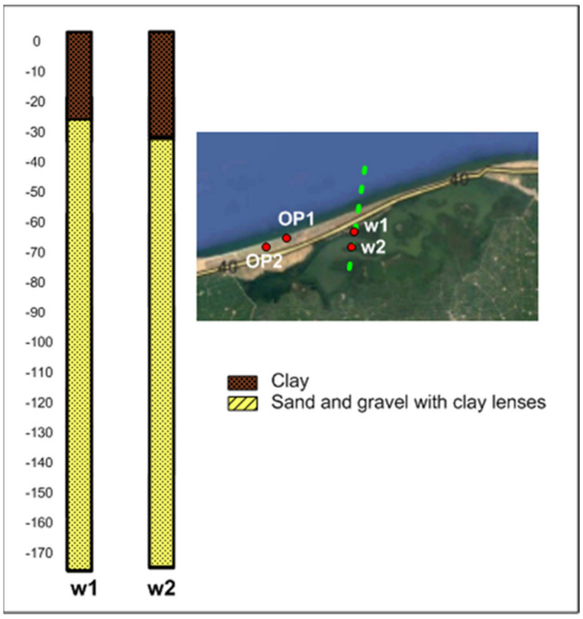


Figure 2. Lithology Profiles

2.3. *Baseline Conditions*

Groundwater samples were collected to assess the baseline condition of groundwater salinity. As shown in Figure 3, the salinity decreases with depth and ranges from 11000 to 3120 mg/L. Salinity profiles are provided at four points: W1, W2, OP1 and OP2. Salinity profiles were obtained from the Research Institute for Groundwater, National Water Research Centre, Egypt. Seawater salinity is 38500 mg/L and the Burullus Lake salinity is 9000 mg/L.

 

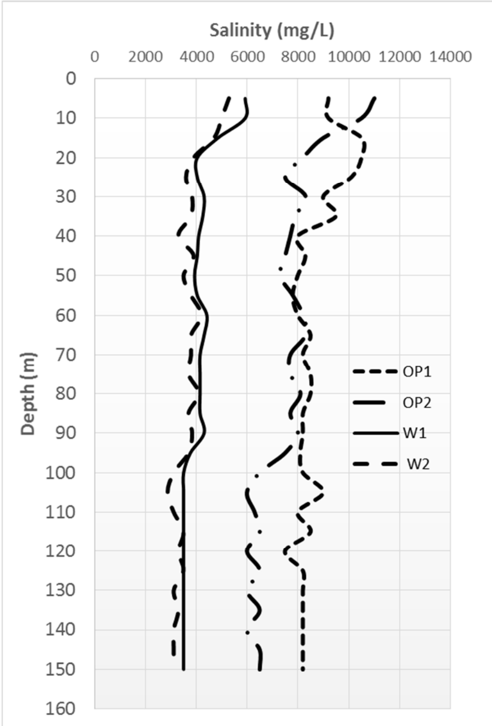


Figure 3. Salinity Profiles

2.4. *Conceptual Model*

A conceptual model for the interaction of Burullus Lake, Nile Delta aquifer and the Mediterranean Sea is provided in Figure 4. It shows the geological layers, hydraulic properties, boundary conditions, water levels and salinities. According to the hydrogeological characteristics of the aquifer, the model consists of three parts: Lake, aquitard and aquifer. The hydrogeological characteristics of the clay aquitard and the Nile Delta aquifer had been listed in literature (Shata and El Fayoumy, 1970; Farid, 1980; Mabrook et al., 1983; Zaghloul, 1985; Shahin, 1985; Leaven, 1991; RIGW, 1992; and Sherif et al., 2012) as follows: the hydraulic conductivity and porosity of the aquifer are 50 m/d and 0.3, respectively; the aquifer storativity ranges from $5 \times 10^{-4}$ to $50 \times 10^{-4}$; and, the hydraulic conductivity and porosity of the clay cap are 0.0025 m/d and 0.45, respectively.

2.3.1. Head Boundary Conditions

The flow in the aquitard is vertical with a no flow boundary condition. The north boundary is a constant head (Mediterranean Sea). The active south boundary of the domain coincides with the south boundary of the Lake and is set as a constant head boundary of 1 m, which is the same at the east boundary (Zaghloul, 1985 and Sherif et al., 2012). The north-eastern boundary and the western boundary coincide with the flow direction, which makes them no flow boundaries. The bottom boundary is a no flow boundary.

2.3.2. Salinities

As for salinity concentrations, the seawater salinity is 38500 mg/L, the aquifer salinity changes with depth from 11000 to 3120 mg/L and the Lake salinity is 9000 mg/L, which corresponds to the baseline condition. As shown in Figure 4.b., aquifer salinity decreases with depth and increases as approaching the shoreline. In this study, the Lake salinity is changed from 9000 mg/L to 650 mg/L for the proposed scenarios. The aquifer salinity response to changes in water level and salinity in the Lake is simulated and discussed hereafter.

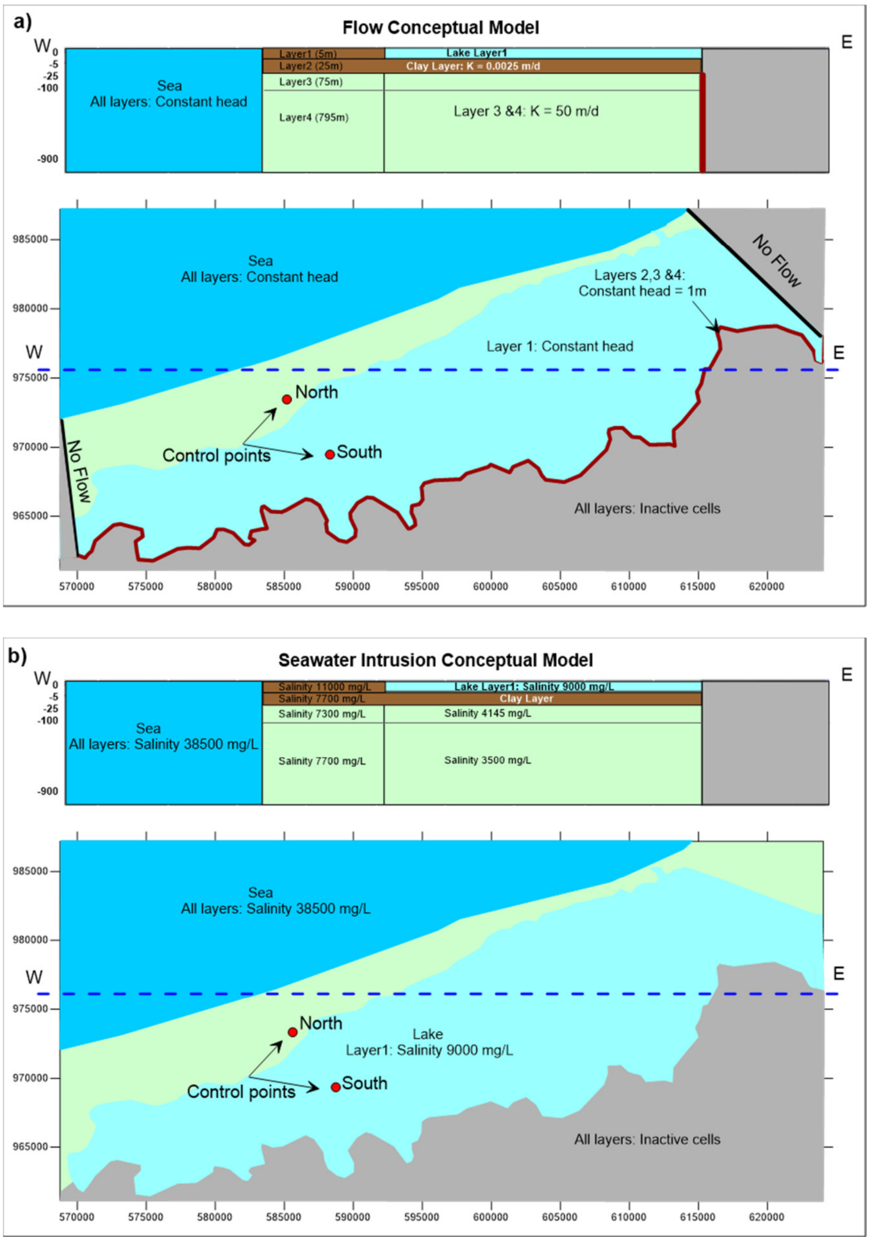

Figure 4.a) Flow Conceptual Model, b) Salinity Conceptual Model

### 2.5. *Numerical Model*

Visual MODFLOW and SEAWAT codes were used to simulate groundwater flow and saltwater intrusion showing the interaction of the Lake, the aquifer and sea. The water density depends on its salinity concentration and this affects the equivalent water head. MODFLOW and SEAWAT use the concept of equivalent freshwater head to simulate the density dependent flow and transport for saltwater intrusion problems. For the remaining parts of the paper, the term "head" refers to "equivalent water head".

The active model domain covers an area of 1010 km$^2$, the aerial discretization is taken as 110 m × 110 m. As per the conceptual model, there are two layers with a combined thickness of 30 m representing the clay aquitard and two layers with a combined thickness of 900 m representing the aquifer. The model was calibrated under steady state conditions based on the field data of year 2015, and then the model was run under transient conditions until year 2055.

## 3. Results and Discussion

### 3.1. *Pumping Tests*

Continuous and step drawdown tests were conducted in well W1 (shown in Figure 2). The test data is provided in Table 1. The well has been drilled to a depth of 175 m with an internal diameter of 250 mm. The well was constructed as multiple screened system, hence three different screens were installed in variable depths to give a total screen length of 48 meters. The lithological succession of the soil along the well log is sand and gravel with clay lenses. A gravel pack with a size range of 3-5 mm was used for the depth from 70m to 175 m. The aquifer extends to a depth of 900 m, which means that the well is partially penetrating the aquifer. Partial penetration effect is considered in the data analysis as an additional loss in head is expected when compared to a fully penetrating well due to the vertical convergence and the extra extension of the streamlines.

Table 1: Step Drawdown and Continuous Pumping Tests

| Test type | Duration (hr) | Discharge ($m^3$/hr) | Drawdown (m) |
|---|---|---|---|
| Step Drawdown Test | 2 | 70 | 1.65 |
| | 2 | 95 | 2.3 |
| | 2 | 120 | 3.95 |
| Continuous Test | 24 | 100 | 2.7 |

Theis (1935) method was used to analyze the step drawdown pumping test data and Hantush and Jacob (1955) method was used to analyze the continuous pumping test data. The lithology data indicated presence of clay lenses or traces of clay in the aquifer soil. Therefore, Moench Fracture Flow (1984) method was also used for pumping test data analysis to estimate the aquifer hydraulic conductivity and check the impact of clay lenses as a contributor to double porosity phenomena. These methods resulted in hydraulic conductivity values ranging from 35 m/d to 53 m/d. The value of the aquifer hydraulic conductivity is in close agreement with literature listed values.

### 3.2. *Groundwater Flow Model*

The groundwater flow direction is from south to north. According to data records of year 2015, the head in the aquifer was 1 m above mean sea level at the south boundary of the active domain and the head in the monitoring wells (W1 and W2) ranged from 0.2 m to 0.4 m above mean sea level. The model was calibrated using year 2015 field data. Calibration was conducted by changing the value of the constant head boundary of the aquifer at the Lake southern boundary and the aquifer hydraulic conductivity to see the effect on the equivalent water head at the monitoring wells. The model was calibrated until acceptable difference between measured and calculated hydraulic heads was achieved. Figure 5 shows calibrated groundwater levels at year 2015. Figure 6 shows the head calibration curve. The calibrated hydraulic conductivity value was 50 m/d and the constant head value at the south boundary was 1 m above mean sea level. The model was then run under transient conditions for a prediction period of 40 years (14,600 days). The stress period of the calibration run was set to one year (365 days). The prediction period was divided into 40 stress periods.

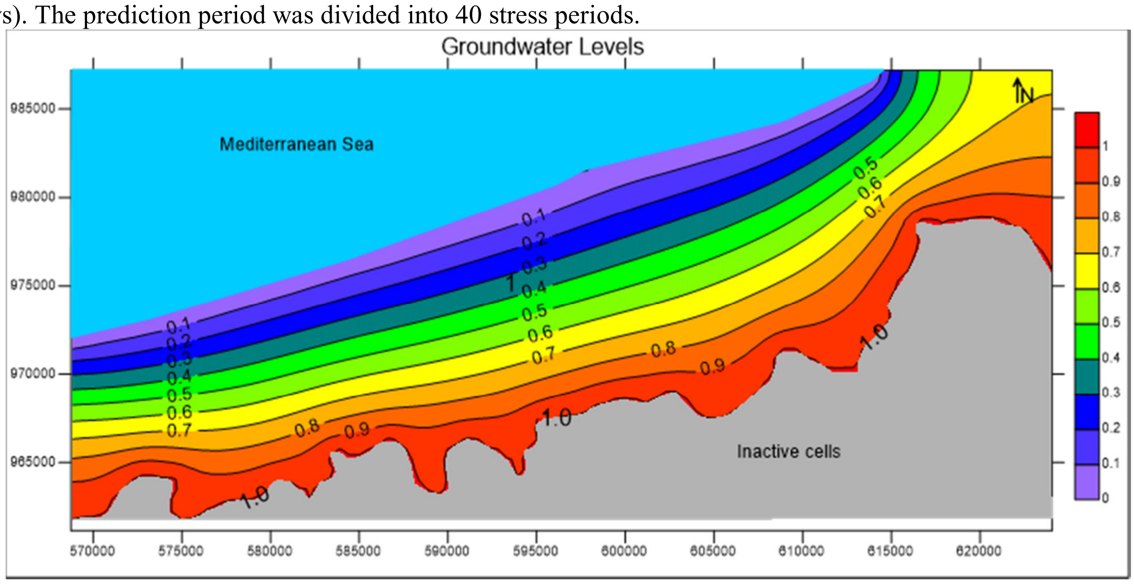


Figure 5. Calibrated Groundwater Levels at year 2015

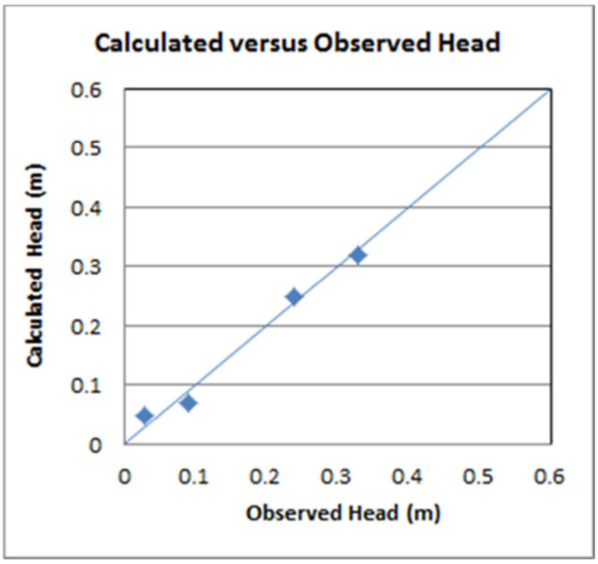


Figure 6 Head Calibration Curve

3.3 *SEAWAT Intrusion Model*

Initial salinity concentrations in the aquifer were set as year 2015 salinity data of groundwater well samples, described in the baseline conditions. Seawater salinity is 38500 mg/L and Burullus Lake salinity is 9000mg/L. The SEAWAT code was calibrated using the aquifer salinity data of year 2015. Figure 7 shows calculated aquifer salinities at year 2015 at depths 5 m, 30 m, 100 m and 900 m. The model was run under transient conditions for a prediction period of 40 years. Figure 8 shows the calibration curve for salinity values.

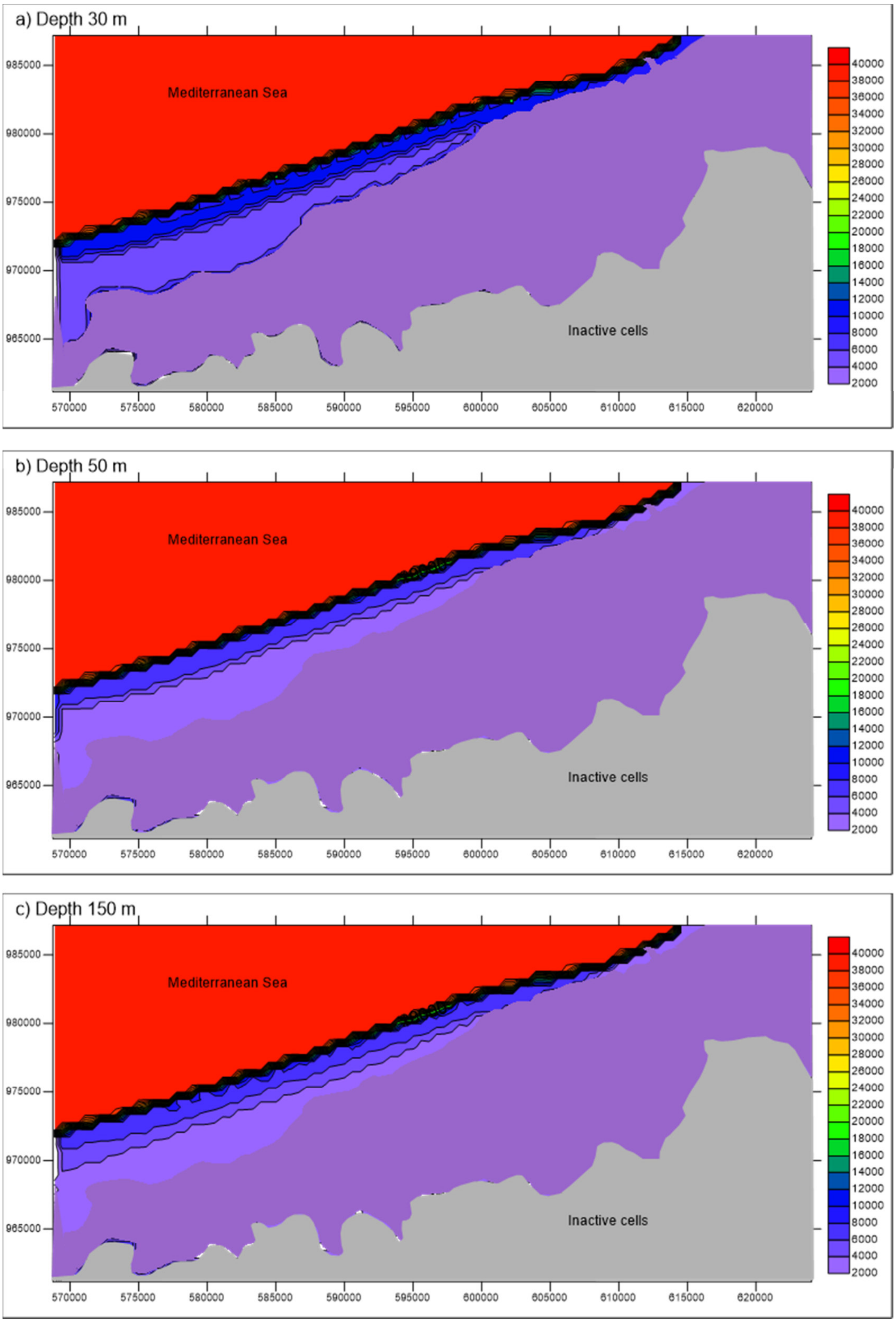


Figure 7 Calculated Aquifer Salinities of Year 2015 at a) Depth 30 m, b) Depth 50 m and c) Depth 150 m

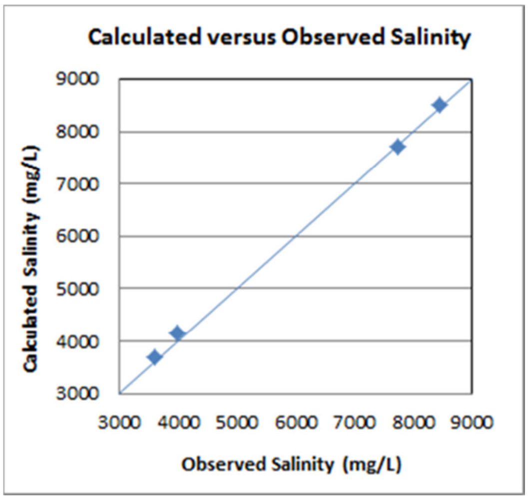

Figure 8 Salinity Calibration Curve

3.4 *Recharge Scenarios*
Eight scenarios were developed to assess the effect of 1) Lake salinity concentrations, and 2) thickness of the aquitard (i.e., Lake bed) on recharging the aquifer to overcome the saltwater intrusion. The simulation results of the eight scenarios are presented. The scenario results were compared to the initial salinity values (baseline condition) in the aquifer at the control points to show improvements, if any, in aquifer salinity when applying the proposed scenario. The scenarios are:

(1) Scenario Sc1: Salinity concentration of the Lake is set at 9000 mg/L, which is the baseline condition. The water level in the Lake is at mean sea level.
(2) Scenario Sc2: Salinity concentration of the Lake is set at 6000 mg/L. The water level in the Lake is at 1.5 m above mean sea level.
(3) Scenario Sc3: Salinity concentration of the Lake is set at 3000 mg/L. The water level in the Lake is at 1.5 m above mean sea level.
(4) Scenario Sc4: Salinity concentration of the Lake is set at 650 mg/L. This salinity value is equivalent to the total dissolved solids in a tertiary treated wastewater (Abu-Bakr et al., 2015). The water level in the Lake is at 1.5 m above mean sea level.
(5) Scenario Sc5: Salinity concentration of the Lake is set at 3000 mg/L and the clay cap thickness is reduced by 10% (this reduction in depth is replaced by increase in water depth in the Lake). The water level in the Lake is at 1.5 m above mean sea level.
(6) Scenario Sc6: Salinity concentration of the Lake is set at 3000 mg/L and the clay cap thickness is reduced by 20% (this reduction in depth is replaced by increase in water depth in the Lake). The water level in the Lake is at 1.5 m above mean sea level.
(7) Scenario Sc7: Salinity concentration of the Lake is set at 650 mg/L and the clay cap thickness is reduced by 10% (this reduction in depth is replaced by increase in water depth in the Lake). The water level in the Lake is at 1.5 m above mean sea level.
(8) Scenario Sc8: Salinity concentration of the Lake is set at 650 mg/L and the clay cap thickness is reduced by 20% (this reduction in depth is replaced by increase in water depth in the Lake). The water level in the Lake is at 1.5 m above mean sea level.

The water salinity in the Lake could be controlled to the values indicated in the scenarios by controlling the salinity of wastewater in the influent drains. These drains receive domestic, agricultural and industrial wastewater. It is proposed in these scenarios that the wastewater will be treated before discharged into the Lake to reach the indicated salinity values. The total dissolved solids in a tertiary treated wastewater is 650mg/L for wastewater treatment plants in Greater Cairo (Abu-Bakr et al., 2015).

Some of the scenarios require increasing the water level in the Lake to 1.5 m above mean sea level and, therefore, raising the Lake banks to a level more than 1.5 m above mean sea level. It is worth noting that the average topographic elevation, in the study area, is 4 m above mean sea with spots of zero elevation. A management plan has to be developed to address the feasibility of controlling the Lake salinity, required wastewater influents to increase the Lake water level to 1.5 m above mean sea level and raising the level of the Lake banks more than 1.5 m above mean sea level.

The clay cap thickness remains unchanged for scenarios Sc1 to Sc4. For scenarios Sc5 to Sc8, it is proposed to dreg or excavate the Lake such that the thickness of the clay cap, the aquitard, is reduced by either 10%, for scenarios Sc5 and Sc7, or 20%, for scenarios Sc6 and Sc8. In scenarios Sc5 to Sc8, the water depth in the Lake increases by a value equivalent to the reduction in the aquitard thickness. In each scenario, the salinity concentrations at the two control points were predicted after 3, 5, 7, 10, 20, 30 and 40 years at depths 50 m and 150 m as shown in Figures 9 and 10, respectively.

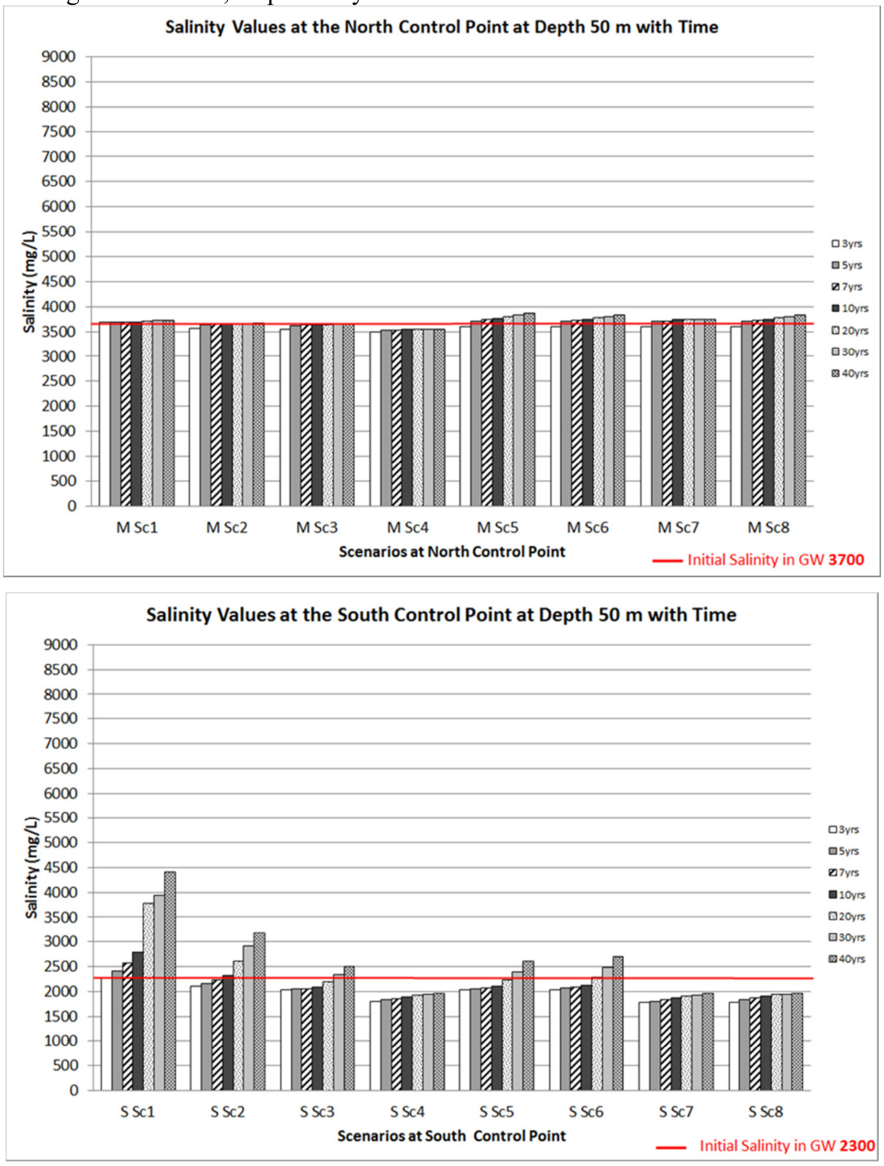


Figure 9 Predicted Salinity Concentration at the Control Points at Depth 50 m with Time

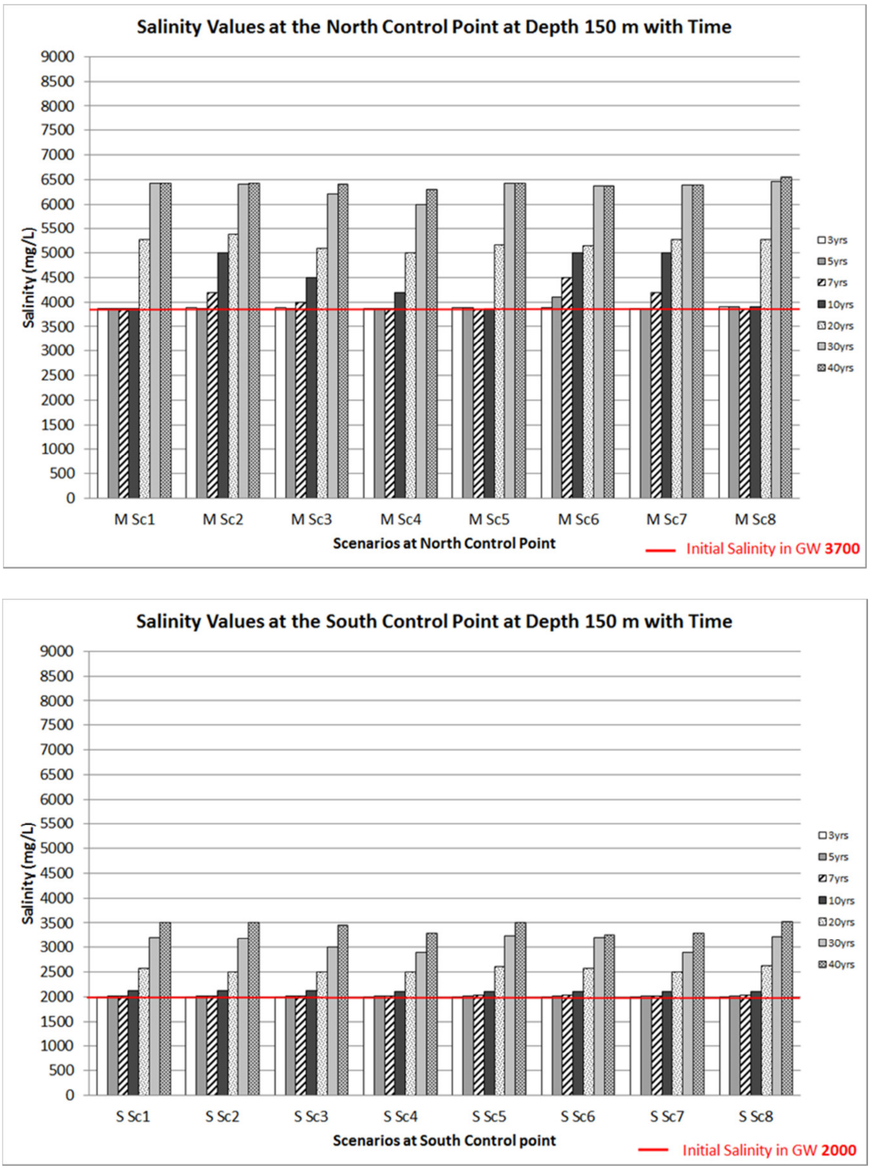


Figure 10 Predicted Salinity Concentration at the Control Points at Depth 150 m with Time

The Lake recharge flux to the aquifer is dominated by the hydraulic gradient across the clay cap, the hydraulic conductivity, and the thickness of the clay cap. The clay cap has a very low hydraulic conductivity, 0.0025m/d, and a thickness of 25 m from the base of the Lake to the aquifer. The hydraulic head in the aquifer ranges from 1 m above mean sea level, at the south boundary, to 0.3 m above mean sea level, at the north boundary. For scenario Sc1, the water level in the Lake is at mean sea level, which means that the flow is upward (i.e., from the aquifer to the Lake) and there is no recharge from the Lake to the aquifer. However, the diffusion is the dominant transport mechanism in the clay aquitard. This results in an increase in aquifer salinity with time at a depth of 50 m at the south control point. However, there is no change in aquifer salinity at a depth of 50 m at the north control point. This is attributed to the proximity of the north control point to the shoreline, in which the salinity concentration at this location is more dependent on the balance between the hydraulic head in the aquifer and the intruding seawater. Moreover, the north control point does not fall within the footprint of the Lake.

For scenarios Sc2, Sc3 and Sc4, the water level in the Lake is 1.5 m above mean sea level. As such, the flow will be downward and recharge occurs. However, recharge flux will take a very long time before it reaches the aquifer. Then the downward flow will cease at locations where hydraulic head in the aquifer equals 1.5m above mean sea level. As water salinity in the Lake is decreased, this helps decrease the salinity of the upper parts of the aquifer at the south control point (i.e., under the Lake footprint).

The change in aquifer salinity in response to changes in Lake water salinity or aquitard thickness (i.e., the scenarios) is apparent at upper parts of the aquifer. At deeper depths, the change in aquifer salinity in response to changes in Lake water salinity or aquitard thickness is negligible. Advection is the dominant transport mechanism, with the horizontal flow direction, in the aquifer. As a result, changes in the recharge flux or the salinity of the recharge flux are not reflected at deeper depths of the aquifer. Although there is an increase in salinity with time for each scenario at a depth of 150 m, the aquifer salinity reaches a similar value for all scenarios in 40 years. The increase in salinity is attributed to saltwater intrusion at deeper depths. This applies for south and north control points at a depth of 150 m as shown in Figures 9 and 10.

The aquifer salinity at locations close to the sea is not affected by changes in Lake water salinity or aquitard thickness. At a depth of 50 m at the north control point, there is no change in aquifer salinity between the different scenarios. As a result, the salinity concentration at this depth is similar to the baseline salinity, which is 3700 mg/L. This is attributed to the density-dependent flow and that the advection is the dominant transport mechanism in the aquifer. At a depth of 150 m at the north control point, the salinity increases from 3700 mg/L to 6500 mg/L in 40 years. This is due to the higher salinity and density of seawater, and even with the flow direction that is from south to north, mixing resulting from diffusion and dispersion leads to increase in aquifer salinity at deeper depths. This is apparent at the north control point as shown in Figures 9 and 10.

The change in aquifer salinity in response to changes in Lake water salinity and aquitard thickness is more apparent at locations away from the sea at a depth of 50 m. For the baseline condition scenario, the salinity increases from 2300 mg/L to 4400 mg/L in 40 years. As the Lake water salinity is decreased to 6000 mg/L, the salinity increases to 3200 mg/L in 40 years. For Lake water salinity of 650 mg/L, there is a noticeable decrease in aquifer salinity, such that the maximum salinity concentration is 2000 mg/L in 40 years. The 20% reduction in aquitard thickness has a minor effect on aquifer salinity. This is apparent by comparing scenarios Sc3, Sc5 and Sc6 or scenarios Sc4, Sc7 and Sc8 at depth of 50 m at the south control point. However, the change in Lake water salinity has a significant effect on aquifer salinity. This is apparent by comparing scenarios Sc1 and Sc4 at depth of 50 m at the south control point. The aquifer salinity increases with time for all scenarios. This is attributed to the effect of seawater intrusion.

## 4. Conclusions

Surface recharge of coastal aquifers is one of the management tools to overcome seawater intrusion. The success of this management tool depends on the geological settings and the hydrogeological characteristics of the site. This study addressed the impact of Burullus Lake on the Nile Delta aquifer overcoming the seawater intrusion. The Lake resides on a clay aquitard with a thickness of 25 m or even more. Eight scenarios were proposed and simulated. These scenarios include decrease the water salinity in the Lake, increase the water level in the Lake and/or reduce the clay cap thickness. The main conclusions are as follow:

- The water salinity in the Lake could be controlled to the values indicated in the scenarios by controlling the salinity of wastewater in the influent drains. These drains receive domestic, agricultural and industrial wastewater. It is proposed in these scenarios that the wastewater will be treated before discharged into the Lake. This requires developing and implementing a source control program for the industrial wastewater, and treatment of agriculture and domestic wastewater. Technical and financially feasibility of the source control program and the wastewater treatment are not addressed in this paper.
- Nutrients required to sustain the ecosystem in the Lake should be clearly addressed and maintained in the wastewater effluents. This paper focused on the impacts of the Burullus Lake on the saltwater intrusion and introduction of recharge scenarios to the Nile Delta aquifer without affecting the ecosystem.
- The baseline condition scenario indicates that the vertical flow direction is upward. Therefore, the Lake does contribute to the aquifer recharge. Since the water flow is upward, then the advection is upward. However, the water salinity in the Lake is more than water salinity at the top of the aquifer. Diffusion is the dominant transport mechanism in clay. Therefore, the Lake contribution to aquifer salinity is due to diffusion through the clay aquitard.
- The hydraulic head in the aquifer declines from 1 m at the south Lake boundary to 0.3 m at the north Lake boundary. The baseline water level in the Lake is at the mean sea level. When increasing the water level in the Lake to 1.5 m above mean sea level, it results in increase of the head in the aquifer against intruding seawater head.
- Increasing the water level in the Lake to 1.5 m above mean sea level reverts the flow direction from upward to downward and, likewise, the advection. Diffusion remains the dominant transport mechanism in the clay aquitard. Therefore, the water salinity in the Lake has to be decreased. A number of scenarios were addressed where water salinity in the Lake was decreased to 6000 mg/L, 3000 mg/L and 650 mg/L. There is noticeable improvement in the aquifer salinity. The improvement takes a long time due to the hydrogeological restriction of the clay aquitard and the low hydraulic gradient. When water salinity in the Lake is less than water salinity in the aquifer, the diffusion contribution to aquifer recovery is limited.
- When the water salinity in the Lake is decreased to 3000 mg/L and 650 mg/L, the aquifer salinity

decreases more than 8.5% and 17%, respectively after 10 years at a depth of 50 m at the south control point.

- Reducing the thickness of the aquitard within the Lake footprint has minor effect on the aquifer salinity.
- Although decreasing the water salinity in the Lake has decreased the aquifer salinity in the upper parts of the aquifer at the south control point, the salinity increases with time in all scenarios. This is attributed to the effect of seawater intrusion.
- It is recommended to obtain more detailed data of the salinity and the hydrogeological characteristics of the Nile Delta aquifer for a number of locations within Burullus Lake to enable identifying the impacts of the Lake on the aquifer overcoming the seawater intrusion.

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**References**

Abu-Bakr, H., Elkhedr, M., Ghanem, A., & Bazaraa, A., (2015), "Evaluation of Treated Wastewater Quality Changes through the Vadose Zone". *Civil and Environmental Research Journal*, 7 (7), 111-125.

Abu-Bakr, H., Elkhedr, M., Hassan, T. (2016), "Optimization of Abstraction Wells near Coastal Zones". *Journal of Earth Science Research*, 4(3), 30-42.

Caschetto, M., Colombani, N., Mastrocicco, M., Petitta, M., & Aravena, R. (2016), "Estimating Groundwater Residence Time and Recharge Patterns in a Saline Coastal Aquifer." *Hydrological Processes*, *30*(22), 4202-4213.

El-Adawy, A., Negm, A., Elzeir, M., Saavedra, O., El-Shinnawy, I. & Nadaoka, K. (2013), "Modeling the Hydrodynamics and Salinity of El-Burullus Lake (Nile Delta, Northern Egypt)", *Journal of Clean Energy Technologies*, 1(2), 157-163.

El-Shazly, M., Omar, A., Edmardash, Y., Ibrahim, M., Elzayat, E., El-Sebeay, I., Abdel Rahman, K., & Soliman, M., (2016), "Area reduction and trace element pollution in Nile Delta wetland ecosystems", *African Journal of Ecology*, John Wiley & Sons Ltd.

Farid, M. S. M., (1980), "Nile Delta Groundwater Study", *M.Sc. thesis*, Cairo University, Egypt.

Flower, R., (2001), "Change, Stress, Sustainability and Aquatic Ecosystem Resilience in North African Wetland Lakes during the 20th Century: An Introduction to Integrated Biodiversity Studies Within the CASSARINA Project". *Aquat. Ecol.* 35, 261–280.

Geological Map of Egypt 1:500 000. (1988), Conoco Coral, Printed in Germany by Institute for Angewandte Geodasie, Berlin.

Hantush, M.S. & Jacob, C.E., (1955), "Non-steady Radial Flow in an Infinite Leaky Aquifer," *Transactions of the American Geophysical Union* 36, 95-100.

Leaven, M. T., (1991), "Hydrogeological Study of the Nile Delta and Adjacent Desert Areas in Egypt with Emphasis on Hydrochemistry and Isotope Hydrology," *M.Sc. thesis,* Free University, Amsterdam, also published by RIGW/IWACO as Technical note TN 77.01300-91-01.

Luyun, R., Momii, K., & Nakagawa, K. (2011), Effects of Recharge Wells and Flow Barriers on Seawater Intrusion. *Ground Water*, *49*(2), 239-249.

Mabrook, B., Swailem, F., & El Sheikh, R. (1983), "Aquifer Parameters and Its Influence on Groundwater Flow Nile Delta Egypt", *Australian Water Resources Council Conference*, Series 8, pp. 187–197.

Moench, A. F. (1984). "Double‐Porosity Models for a Fissured Groundwater Reservoir with Fracture Skin." *Water Resources Research*, *20*(7), 831-846.

Prieto, C., Destouni, G., & Schwartz, J. (2001), "Seawater Intrusion in Coastal Aquifers: Effects of Seasonal Variations in Extraction and Recharge Rates", *Proceedings of First International Conference on Saltwater Intrusion and Coastal Aquifers-Monitoring, Modeling, and Management*, Essaouira, Morocco, April 23–25, 2001, pp. 1-11.

RIGW (1992), "Groundwater Resources and Projection of Groundwater Development", *Water Security Project,* (WSP), Research Inst. for Groundwater, Kanater El-Khairia, Egypt.

Shahin, M., (1985), "Hydrology of the Nile Basin" *Water Science*, 21, Amsterdam, Netherlands, Elsevier Science Publishers, B.V., pp 575.

Shata, A. and El Fayoumy, L. F. (1970), "Remarks on the Hydrology of the Nile Delta", *UAR, proceeding of the Bucharest Symposium, IASHIAIHS-UNESCO*, pp. 385-396.

Sherif, M., Sefelnasr, A., & Javadi, A. (2012), "Incorporating the Concept of Equivalent Freshwater Head in Successive Horizontal Simulations of Seawater Intrusion in the Nile Delta Aquifer, Egypt." *Journal of Hydrology*, 464, 186-198.

Shi, L., & Jiao, J. J. (2014), "Seawater Intrusion and Coastal Aquifer Management in China: a Review."

 

*Environmental earth sciences*, *72*(8), 2811-2819.

Theis, C.V. (1935), "The Relationship between the Lowering of the Peizometric Surface and the Rate and Duration of Discharge of a Well using Groundwater Storage." *Transactions of the American Geophysical Union* 16, Part 2: 519-524.

Timms, W. A., Young, R. R., & Huth, N. (2012), "Implications of Deep Drainage through Saline Clay for Groundwater Recharge and Sustainable Cropping in a Semi-arid Catchment, Australia." *Hydrology and Earth System Sciences*, *16*(4), 1203-1219.

Ting, C. S., Jean, J. S., Tseng, C. C., & Wu, M. C. (2007), "The Interaction between a Manmade Lake and Groundwater: An Example Site in the Aurku Area, Chiayi County, Taiwan." *Hydrological Processes*, *21*(5), 647-657.

Tuong, T. P., Marquez, J. A., Kropff, M. J., & Wopereis, M. C. S. (1994), "Mechanisms and Control of Percolation Losses in Irrigated Puddled Rice Fields." *Soil Science Society of America Journal*, *58*(6), 1794-1803.

Werner, A. D., Bakker, M., Post, V. E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., & Barry, D. A. (2013), "Seawater Intrusion Processes, Investigation and Management: Recent Advances and Future Challenges." *Advances in Water Resources*, *51*, 3-26.

Wilson, A. M., & Gardner, L. R. (2006), "Tidally Driven Groundwater Flow and Solute Exchange in a Marsh: Numerical Simulations." *Water Resources Research*, *42*(1), pp. 1-9.

Yuan, D., Lin, B., & Falconer, R. (2008), "Simulating moving boundary using a linked groundwater and surface water flow model." *Journal of hydrology*, *349*(3), 524-535.

Yuan, L. R., Xin, P., Kong, J., Li, L., & Lockington, D. (2011), "A Coupled Model For Simulating Surface Water And Groundwater Interactions In Coastal Wetlands." *Hydrological Processes*, *25*(23), 3533-3546.

Zaghloul, M. G., (1985), "Flow Distribution through Groundwater Aquifer of the Nile Delta", *M.Sc. Thesis*, Faculty of Engineering, Alexandria University, Egypt.

Zhang, Z., Cui, B., Fan, X., Zhang, K., Zhao, H., & Zhang, H. (2012), "Wetland Network Design for Mitigation of Saltwater Intrusion by Replenishing Freshwater in an Estuary." *CLEAN–Soil, Air, Water*, *40*(10), 1036-1046.

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