

Review Article

Management of Saltwater Intrusion in Coastal Aquifers: A Review and Case Studies from Egypt

Ahmed M. Saqr , Mahmoud E. Abd-Elmaboud 

Irrigation and Hydraulics Department, Faculty of Engineering, Mansoura University 35516, Mansoura, Egypt

*Correspondence: Ahmed Saqr (email: ahmedsaqr@mans.edu.eg)

Abstract: Groundwater is undeniably crucial to people's lives, particularly in coastal regions. Therefore, it is imperative to address this vital water source strategically and implement a management plan to maintain its optimal state. The salinization of groundwater poses a significant challenge for coastal communities, stemming from factors like excessive groundwater extraction from coastal aquifers, reduced recharge, rising sea levels, climate change, and other causes. Saltwater intrusion (SWI) is a prevalent issue that needs attention, as it significantly threatens groundwater quantity and quality. SWI happens when saline water infiltrates coastal aquifers, contaminating freshwater supplies. This review article aims to define SWI, explore its causes and influencing factors, and discuss various monitoring techniques. Additionally, it examines different modeling methods and management tools, including remote sensing, field surveys, modeling approaches, and optimization techniques. To mitigate the adverse effects of SWI, several control measures are outlined, along with their pros and cons. The final section reviews previous SWI studies and case studies from the Nile Delta, Sinai Peninsula, and North-West coast in Egypt. These studies offer suggestions, adaptations, and mitigation measures for future research.

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1. Introduction

Water is a critical and essential natural resource on our planet [1]. The sources of water, which are consumed by people are various, including surface water bodies like rivers and lakes, groundwater, rainfall, and flash floods [2, 3]. When it comes to groundwater, it is an essential part of the hydrologic cycle and contributes to maintaining the ecological balance [4, 5]. Groundwater is fed through a recharge area and can be extracted through wells from different types of aquifers including confined and unconfined ones as shown in Figure 1 [6].

Groundwater is a resource that is much more critical than it is often understood. It accounts for around 22% of all fresh water on earth; polar ice accounts for 77%, while other fresh water in rivers and lakes accounts for about 0.3% [7]. In Egypt, groundwater is one of the most important resources of water, especially in the coastal areas [8]. Moreover, Groundwater is considered the second contributor of water needs after the Nile River with a percentage of 8% [9]. It plays an outstanding role in providing water for many purposes including domestic, industrial, and irrigational uses in many regions, especially coastal ones [10]. However, like any other water resource, it can be depleted or polluted if it is not properly managed. In confined and unconfined aquifers, excessive pumping can cause many harmful effects such as saltwater intrusion (SWI) [11, 12].

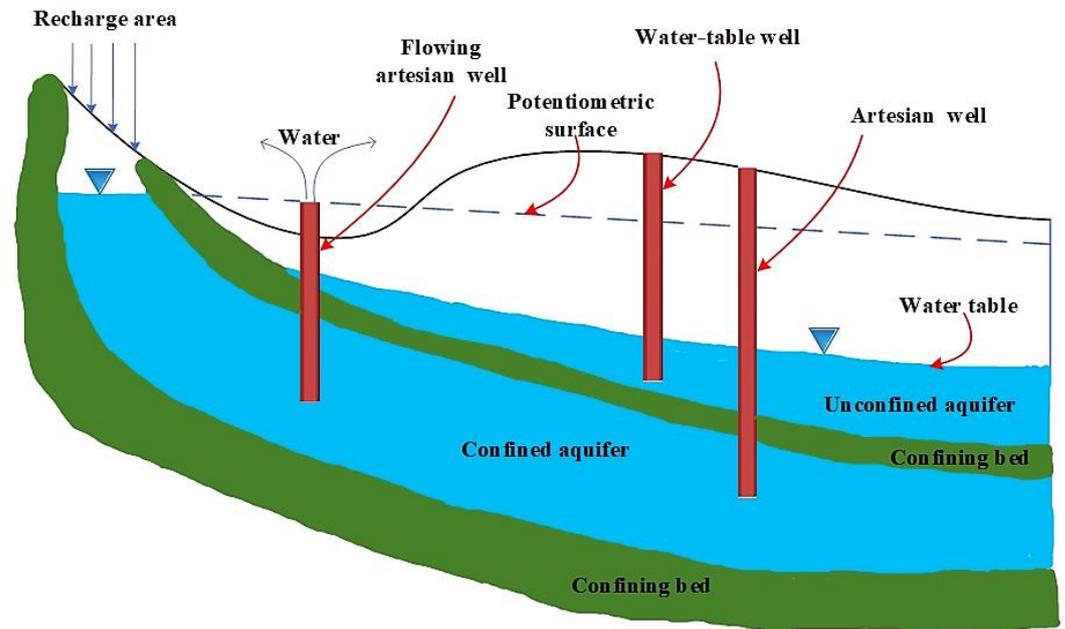


Figure 1. A layout showing types of aquifers and wells in the groundwater system.

2. Definition of Saltwater Intrusion

SWI is defined as the movement of saline water towards freshwater aquifers in coastal zones. As a result, salt water can push inland beneath the fresh water, and an imaginary line called an interface is developed between them as depicted in Figure 2. In addition, it can lead to groundwater quality degradation and other consequences. Due to groundwater abstraction from the well contaminated with salt water, two cones resulted. To illustrate, cone of depression at the water table and up coning at the saltwater surface at the well location [13].

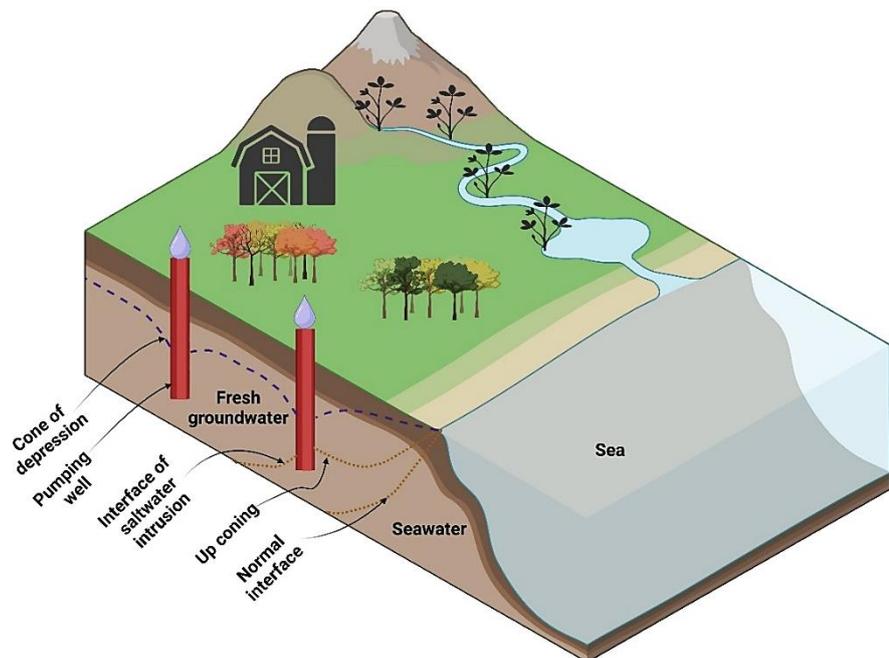


Figure 2. A sketch showing the saltwater intrusion phenomenon.

Generally, groundwater flows from areas with higher levels of groundwater to areas with lower groundwater levels. This natural flow of fresh water to the sea stops salt water from entering freshwater coastal aquifers. However, external factors can stop the amount of freshwater flowing towards coastal discharge areas. Thus, freshwater quantities in the aquifers will decrease as salt water may be drawn into the freshwater zones of coastal aquifers [14].

3. Handling Saltwater Intrusion Issue

Several research studies have been carried out to understand the nature of the groundwater-saltwater interface in coastal aquifers [15]. The numerical models developed are based on two main assumptions, Figure 3, and could be categorized as:

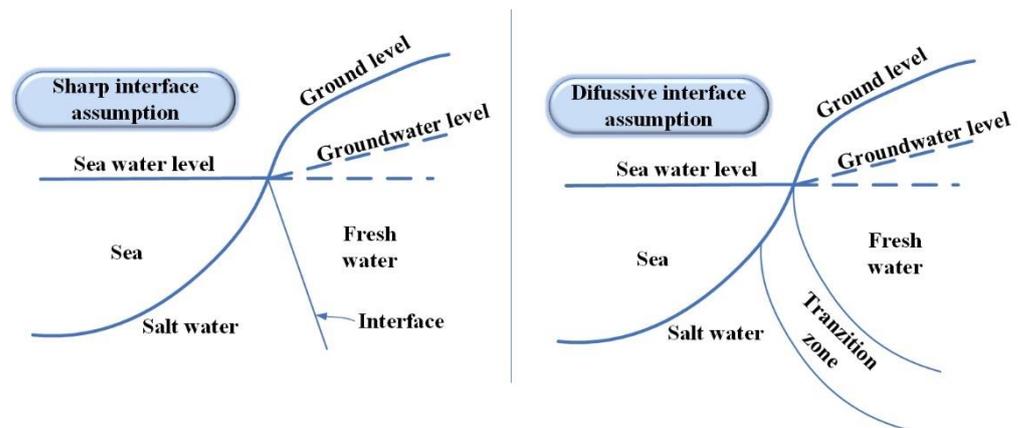


Figure 3. Sharp and Diffusive interface assumptions for modeling of saltwater intrusion.

3.1. Sharp Interface Models

When the width of the transition zone is relatively small or neglected, the sharp approximation of the interface can be used. The sharp interface between freshwater and seawater is a theoretical assumption based on the fact that freshwater and seawater are two immiscible fluids of differing densities. Under hydrostatic conditions, Ghyben-Herzberg derived the following relationship [16]:

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} * h_f \quad (1)$$

Where:

h_f : Thickness of freshwater zone above sea level;

h_s : Thickness of freshwater zone above sea level;

ρ_f : Density of fresh water; and

ρ_s : Density of saline water.

To simplify, for every unit of groundwater above the level of the sea, there are 40 units of fresh water below that level if $\rho_f = 1 \text{ kg/m}^3$, and $\rho_s = 1.025 \text{ kg/m}^3$.

3.2. Diffusive Interface Models

In diffusive models, the boundary between fresh water and salt water is called the transition zone or diffusive zone or dispersion zone or groundwater-saltwater interface zone. In addition, this zone has a mix of salt water and fresh water in which the density changes gradually. Moreover, the mixing zone in a coastal aquifer between fresh water and salt water is called the brackish water zone. Furthermore, this transition zone width mainly depends on many variables such as aquifer properties [17].

4. Main Causes of Saltwater Intrusion

SWI is a severe issue in coastal regions worldwide. It may occur due to natural processes or human activities. On one hand, it can naturally occur in coastal aquifers, owing to the hydraulic connection between groundwater and seawater as saline water has a higher mineral content than fresh water. Also, it is denser and has a higher water pressure, so freshwater floats on the top [8]. On the other hand, the concentrations of people in the coastal regions and the increased related activities contributed to an increase in groundwater resource abstraction.

There are many causes of SWI such as over-abstraction of the aquifer, tidal effects, seismic waves, climate change, dispersion, barometric pressure, and seasonal change in groundwater flow [7]. Moreover, the first cause is the key case of SWI while other causes are short-term effects such as tidal influence and barometric pressure, other long-term consequences like climate change, and other regular factors such as seasonal changes in natural groundwater.

5. Factors Affecting Saltwater Intrusion

Factors affecting SWI can be classified according to their spatial scale into three categories as illustrated in Figure 4 [18, 19]:

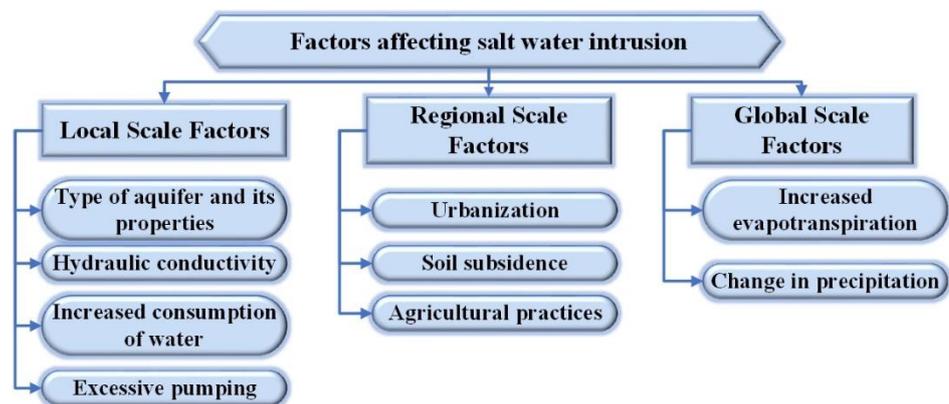


Figure 4. A flow chart showing factors that have effects on saltwater intrusion.

6. Monitoring of Saltwater Intrusion

It is very important to continuously monitor coastal aquifers to get an accurate representation of them and to measure important parameters. Many techniques can be used for this purpose, and they are illustrated as follows [20]:

6.1. Groundwater Head Measuring

The simplest way to identify SWI is to measure the groundwater head concerning the level of the sea. The above-mentioned equation derived by Ghyben-Herzberg (Eq. No. 1) can be used. If the groundwater level above the mean sea level is zero, the interface will be very near to the mean sea level. Therefore, the groundwater level must be maintained above mean sea level to avoid SWI [16].

6.2. Geophysical Investigation

Geophysical methods rely on physical characteristics such as electrical conductivity, velocity of seismic waves, thermal conductivity, and electromagnetic permeability [21]. Different methods can be used to determine the salinization in geological formation such as surface geophysical methods, borehole geophysical methods, and integrated geophysical surveys [22].

6.3. Geochemical Investigation

The salination of groundwater in coastal aquifers may result from the process of SWI and many other sources such as agriculture return flows, industrial and domestic wastewater, and saline water flow from adjacent or underlying aquifers [23]. The origin of salinity in coastal aquifers can be defined by several geochemical criteria such as Chlorine concentration, Chlorine/Bromine ratios, Sodium/Chlorine ratios, Boron isotopes, and Oxygen and Hydrogen isotopes [7].

In 2005, a study was done by Todd and Mays to investigate the saline water interface using the ratio between chloride ions with bicarbonate and carbonate ions. The ratio starts at 0.5 for no saline water interface and ends at more than 15.5 for very high saline water interface. Also, they recommended ranges for Total Dissolved Solids (TDS) for different types of water. For example, TDS ranges from 0 to 1000 mg/l for freshwater, but in the case of saline water, the range is between 10000 mg/l and about 35000 mg/l [24].

6.3. Isotopic methods

To study the dynamics of groundwater, Oxygen and Hydrogen isotopes have been used by many researchers. The high contrast in the isotopic signature between seawater and groundwater is used to identify the mechanism of SWI [25].

7. Management Tools

In several parts of the world, comprehensive research work has been carried out based on several management techniques with the goal of understanding the process of SWI. A summary of some of these techniques is stated as follows [12]:

7.1. Remote Sensing

Geographical Information Systems (GIS), and remote sensing software can be used for representing subsurface geology, carrying out change detection and spatial analyses, and defining groundwater potential zones as well as recharge areas [26]. In addition, assessment of groundwater quality and vulnerability to pollution from saline water can be carried out [27, 28].

7.2. Field Surveys

Investigation of groundwater quality based on field survey by collecting groundwater samples and making the required analysis for them. As a result, the most effective parameters, controlling the quality of groundwater can be determined such as hardness, total dissolved solids, and electrical conductivity [29].

7.3. Modelling Methods

Scientific modeling is an essential tool in the assessment of coastal aquifer dynamics and in identifying the different factors that influence groundwater movement. Different modeling methods are described in Figure 5 [30, 31].

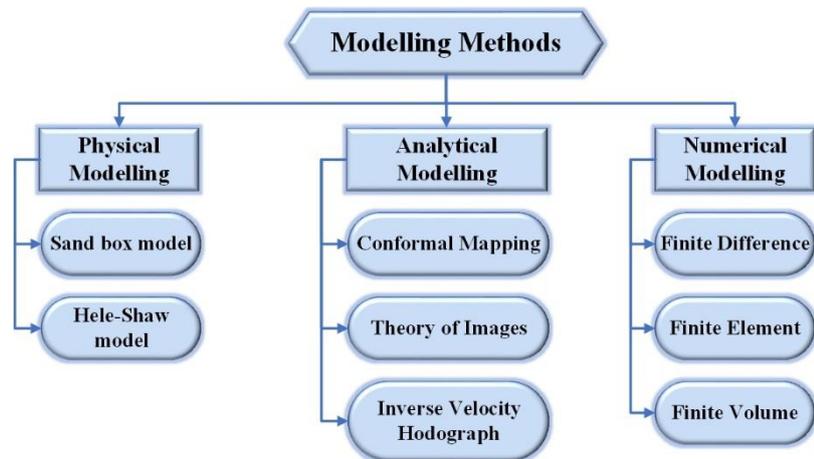


Figure 5. Different modeling methods for simulating saltwater intrusion.

7.4. Computer Codes

Many computer codes were developed over the past years to simulate the problem of SWI in coastal aquifers. These codes usually use both analytical and numerical approaches to get the best representation of the aquifer conditions based on three-dimensional hydrologic modeling of the domain under study. Examples of the most common programs are demonstrated in Table 1 [32].

Table 1. Common codes for simulating saltwater intrusion.

Code	Modeling approach	Modeling dimensions
SUTRA	Finite element	2D&3D
CODESA	Finite difference	3D
HST3D		
MOCDENS		
SWI		
SEAWAT		
FEFLOW	Finite element	

7.5. Optimization Techniques

Optimization of the different scenarios inside the study domain to get the optimal solutions for different parameters such as pumping rates, recharging quantities, and well locations is very essential to mitigate SWI [33, 34]. Different methods that can be used for this purpose are shown in Figure 6 [31, 35].

7.6. Integrated Approaches

Simulation of the domain under study can be done using a combination of all of the above tools or some of them. Great attention must be put to assessing the sustainability of groundwater based on its quantity and quality, and its impact on the surrounding environment [27].

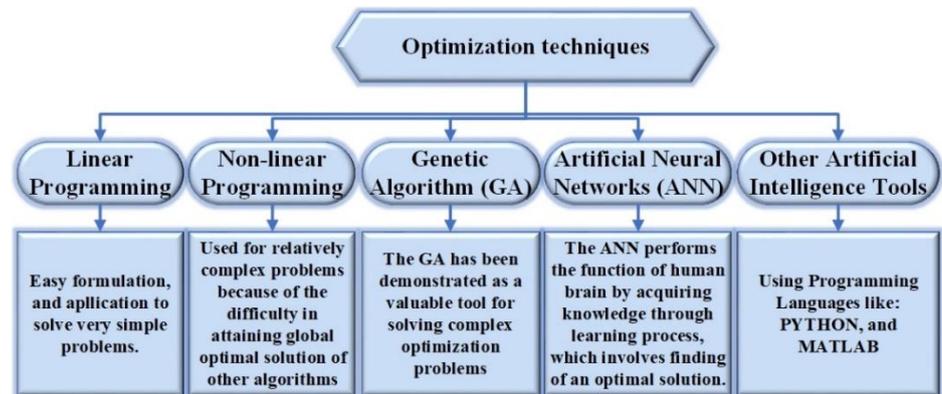


Figure 6. Optimization methods for saltwater intrusion.

8. Countermeasures to Control Saltwater Intrusion

The key to controlling SWI is to maintain a proper balance between water being pumped from the aquifer and water recharged to the aquifer. Many methods for controlling SWI in coastal aquifer systems were introduced as follows (Figure 7) [18]:

8.1. Increasing Recharge of Groundwater

The volume of available fresh water can be increased by groundwater recharge, which can cause the interface to move toward the sea by either natural recharge or artificial one

8.1.1. Natural Recharge

These methods rely on feeding the aquifer with fresh water from the reservoir of an impermeable barrier such as a dam or a weir. The water upstream of the dam then infiltrates into the soil to raise groundwater storage capacity.

8.1.2. Artificial Recharge

This technique depends on using deep recharge wells to pump an amount of fresh water into the aquifer. The source of the injected water may be from desalinated seawater, pumped groundwater, treated wastewater, and surface water.

8.2. Land Reclamation

The main idea of this method is to create a foreland where a body of fresh water may develop. In addition, this body can delay the inflow of seawater towards groundwater.

8.3. Use of subsurface barriers

This approach focuses on building a subsurface barrier such as grout cutoffs, and steel sheet piles. Moreover, this barrier can minimize the permeability of the aquifer in order to prevent the inflow of seawater into the basin.

8.4. Reduction of Pumping Rates

The pumping reduction seeks to reduce water consumption and to use other means to provide sufficient water use. It can be achieved by many things such as: increasing public awareness, seawater desalination, wastewater reuse, and reduction of water losses.

8.5. Relocation of Pumping Wells

This approach depends on rising groundwater levels and retaining ground storage by shifting the location of pumping wells to a more inland position.

8.6. Abstraction of Saline Water

This technique aims at reducing saltwater volume inside the aquifer by extracting this water from the aquifer and returning it to the sea.

8.7. Abstraction, Desalination, and Recharge (ADR)

This new technique consists of three major steps. First, the brackish water is abstracted. Second, this water is desalinated. Finally, the treated water is recharged in the aquifer. This technique was investigated by many researchers to control SWI in coastal aquifers based on modeling, optimization, and different management techniques. The results show the advantages of this method and how cheap it is [37-43].

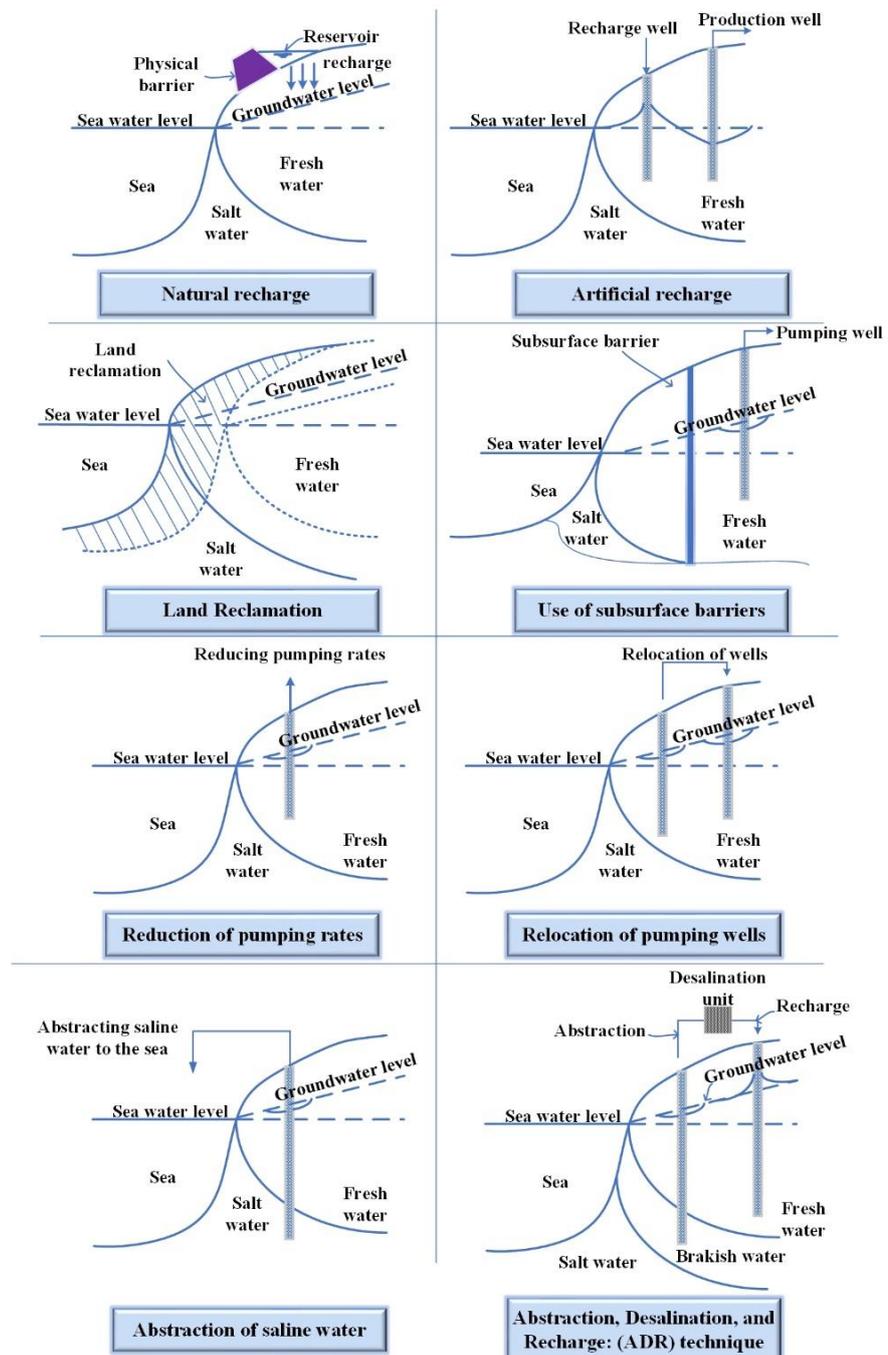


Figure 7. A schematic drawing showing different countermeasures to control saltwater intrusion.

SWI can be controlled also by combining two or more of the previous approaches to achieve the best SWI management solution in coastal aquifers. That is because every approach has some demerits. Table 2 illustrates the disadvantages of each technique [30].

Table 2. Disadvantages of each countermeasure technique to control saltwater intrusion.

Countermeasure		Disadvantages
Increasing recharge of groundwater	Natural recharge	<ul style="list-style-type: none"> ➤ Barrier construction is very costly. ➤ It is not valid for confined aquifers. ➤ It needs highly permeable soil.
	Artificial recharge	<ul style="list-style-type: none"> ➤ It may be ineffective and costly where the source of injected wells is unavailable.
Land Reclamation		<ul style="list-style-type: none"> ➤ It does not prevent SWI, but it temporarily prevents it.
Use of subsurface barriers		<ul style="list-style-type: none"> ➤ It may be costly in terms of construction, service, maintenance, and supervision. ➤ It is not good for deep aquifers.
Reduction of pumping rates		<ul style="list-style-type: none"> ➤ It does not preclude infiltration of salt water. ➤ The abstraction rate cannot be controlled with increasing population. ➤ Losses reduction wastewater reuse, and desalination are very expensive processes.
Relocation of pumping wells		<ul style="list-style-type: none"> ➤ This method cannot be used for small-size aquifers. ➤ It does not prevent SWI.
Abstraction of saline water		<ul style="list-style-type: none"> ➤ It may affect marine life, fishing, and tourism activities in these areas. ➤ In some cases, increasing saline water extraction may increase SWI.
Abstraction, Desalination, and Recharge: (ADR) technique		<ul style="list-style-type: none"> ➤ This technique is relatively costly if the transition zone is very close to the sea.

9. Case studies from Egypt

Egypt is a very arid country Egypt faces a continuous decrease in water share per capita due to many reasons, including population growth, urbanization, higher standards of living, an agricultural policy that emphasizes expanded production, developments upstream of the Nile River, and climate change. Therefore, there is an urgent need to improve the efficiency of water consumption and reduce the pressure on conventional water resources, especially the Nile River in Egypt. Also, the establishment of new communities and land reclamation projects in the Egyptian desert areas is one of the most important national targets for horizontal expansion outside the narrow Nile valley and

Delta. So, the role of groundwater is considerably increasing in the coming decades from economic, social, and environmental perspectives.

As a result, it is recommended that research studies must focus on the multi-purpose management of groundwater resources in coastal aquifers in Egypt against severe hazards. One of these problems is SWI which results due to many reasons. Therefore, safe pumping quantities of groundwater must be defined to get a balance between recharging and discharging without neglecting to preserve groundwater quality from pollution which is caused by seawater and other sources. Also, possible methods of treatments and desalination techniques should be recommended.

Major groundwater aquifers in Egypt are the Nile aquifer, Nubian sandstone aquifer, Fissured carbonate aquifer, Moghra aquifer, Coastal aquifer, and Hard rock aquifer. When it comes to coastal aquifers in Egypt, they lie along the Mediterranean and the Red Sea coast. Moreover, these aquifers include El-Arish-Rafah Aquifer, the Eastern North Coastal Aquifer, the Western North Coastal Aquifer of El-Akaba Gulf, the Western North Coastal Aquifer, and the Red Sea Coastal Aquifer. In fact, these aquifers are subjected to SWI, and rainfall is the main source of recharge. In addition, the geological formation of this aquifer consists of dunes, bars, shallow marine sands, and wadi deposits [44]. Generally, the range of salinity in Egypt is between 200 ppm and 12000 ppm. At the Nile aquifer, the concentration of salts is less than 1500 ppm, but it is about 2000 ppm for the North-West coast. However, the salinity varies between 2000 ppm and up to 9000 ppm at the Sinai peninsula [45].

Several research studies have been conducted in Egypt to mitigate SWI. Sherif and Al-rashed (2001) [46] presented different scenarios of sea level rise in the Mediterranean Sea for simulating SWI in the Nile Delta aquifer by using 2D-FED and SUTRA models. It was concluded that any rise of the sea level by 50 cm would cause the interface between seawater and groundwater to move 4.5 km inland. The study recommended reducing the pumping from the eastern and western parts of the region while any pumping practices should be done from the middle of the aquifer.

Kaiser and Geriesh (2007) [47] depended on some tools, including remote sensing, salinity distribution, and water well concentration using GIS to assess SWI in the El-Arish region during the period 1984-2006. It was noted that the main reasons for groundwater salinity were coastal erosion and the concentration of pumping wells. A recommendation was added to make a separation between the distribution network of domestic groundwater supply, and that used for drinking water.

Elshinnawy and Abayazid (2011) [48] presented a vulnerability assessment of groundwater resources to pollution by seawater in the Northeastern sector of the Nile Delta. Different scenarios of sea level rise for the years 2025, 2050, 2075, and 2100 based on numerical and analytical approaches were introduced. It was noted that the interface between fresh water and seawater witnessed advancements of 35, 180, 509, and 1065.8 m by the four mentioned years, respectively. Adaption measures were highly recommended to combat the movement of saline water inland causing severe harmful consequences.

In 2012, Khalil et al. [49] investigated SWI in the Sidi Abdel Rahman area located on the northwest coast of Egypt by using vertical electrical sounding (VES) and time domain electromagnetic (TDEM) techniques. They also applied finite element technique using 2D resistivity code as shown in Figure. The results showed that the distance between the shoreline and tip-top-portion (T.T.P) of the interface was about 1000 m. Also, the transition zone varied from 17 Ω m to 25 Ω m.

Elnashar (2014) [50] used the Glover equation to predict the shape of the interface between seawater and freshwater from the shoreline to a distance of 1 km towards the ground surface as depicted in Figure 8.

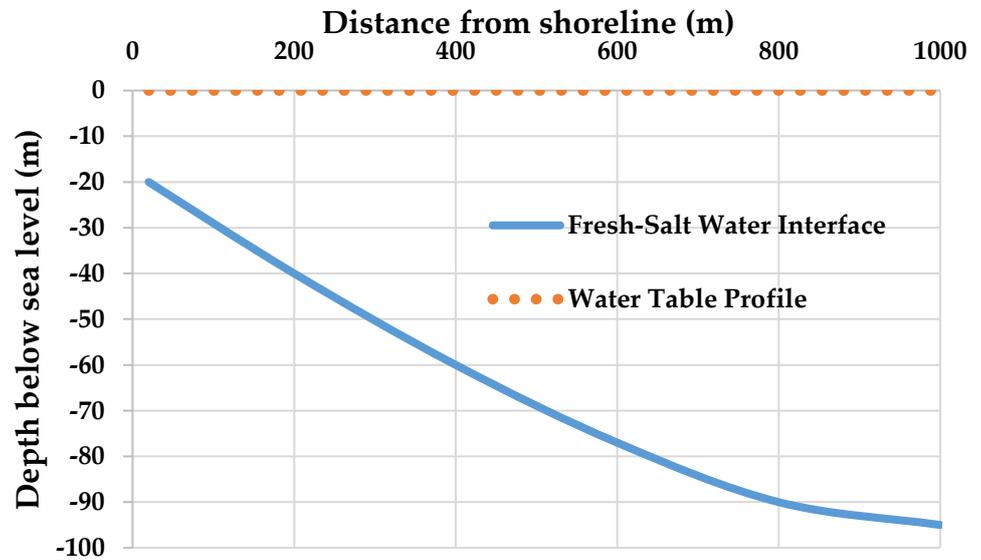


Figure 8. A sketch of Fresh-Salt Water Interface versus Water Table Profile related to the Western North Coastal Aquifer in Egypt.

Nofal et al. (2014) [51] used a variable density model to show the effect of SWI on the area between Gamasa and Ras El Bar with a width of 15 km inland. It was expected that the freshwater saltwater interface would witness an advancement of about 7 km inland corresponding to a sea level rise between 0.1 m and 0.5 m. A comparison between different solutions, including injection wells, subsurface barriers, and reducing groundwater abstraction to control this phenomenon was introduced. It was noted that impervious barriers gave the best results for thin aquifers.

Several investigations have been considered by Sefelnasr and Sherif (2014) [52] based on the GIS database and FeFlow code to simulate the effect of sea level rise by 0.5 m and 1m on the groundwater resources of coastal aquifers. The effect of the landward shift of the shoreline was taken into account. It was concluded that the second scenario is the worst under existing pumping conditions, and about one-third of fresh water would be lost.

Bekhit (2015) [53] developed and applied a framework to achieve the best management practices for groundwater resources in Rafah, Sinai Peninsula based on a combination of MODFLOW, MT3DMS, and SEAWAT. It was concluded that increasing the current demand by 304% could just move the line of 5000 mg/l only a distance of 80 m in 10 years which was in the safer limits.

El-Alfy et al. (2015) [54] developed a two-dimensional numerical model to simulate SWI in the Quaternary Aquifer in Delta Wadi El-Arish (QADWA), Sinai based on a sharp interface assumption between fresh water and salt water. During the period between 1962 and 2006, different scenarios were investigated for the salination risks and future situations. It was found that the interface toe would reach a distance of about 12 km from the shoreline. Also, the interface between seawater and freshwater was investigated for different future periods under different pumping discharges.

Gad and Khalaf (2015) [55] used the FEFLOW code to investigate SWI in the Quaternary Aquifer in the North Sinai coastal Area (QANSA) over 20 years of simulation time using three management scenarios. Different solutions were mentioned to solve the problem of salinity there. Also, it was recommended to monthly monitor groundwater levels for calibration and verification purposes.

Hussien (2015) [56] used the hydrogeochemical investigation to assess groundwater quality in the Ras Sudr area located in the southwest of the Sinai Peninsula. It was noted that cation exchange reactions caused the concentration of Ca^{2+} , and Mg^{2+} during the intrusion of seawater. A recommendation to continually monitor groundwater quality was suggested to assess the extent of SWI.

A calibrated model was composed by Nofel et al. (2015) [57] for the Nile Delta aquifer in terms of salt concentration, and hydraulic heads to determine the depth of groundwater salinity based on the SEAWAT program. In addition, the program was validated for the period between 2013 and 2015 using new measured data. From the modeling process, it was obvious that SWI occurred at shallow to medium depths.

A numerical model called 2D-FEST was employed by Hany Abd-Elhamid et al. (2016) [58] to study SWI in the Nile Delta aquifer. This model was verified by another model, namely SEAWAT. Three scenarios were used for investigation, including sea level rise, piezometric head decline, and a combination of both. It was clear that sea level rise had a significant effect on the brackish water zone, and a rise by 1m in the sea level would cause intrusion about 10 km from the shoreline while the third scenario is the worst case.

Wassef & Schüttrumpf (2016) [59] used numerical analysis by Arc GIS and FeFlow to investigate 6 scenarios of sea level rise and extraction discharges in the western area of the Nile Delta. It was clear from the results that the difference in salinity, between 1990 and 2100, varied from 100 mg/l to 5000 mg/l and covered about 10% of the study area. It was recommended to suggest a new crop pattern to suit the salinity concentration.

An experimental and numerical study was carried out by Armanous (2017) [60] to investigate SWI in the Nile Delta Aquifer in Egypt. The experimental study was based on the sandbox model while the numerical model was constructed using SEAWAT, and MODFLOW using different scenarios, including sea level rise, excessive groundwater pumping, and a combination of both. He found that the third scenario was the worst one and there was a perfect agreement between the experimental and numerical results. In addition, the effect of the construction of the Grand Ethiopian Renaissance Dam (GRAD) on SWI in the area under study was studied.

A comparison between different countermeasures to control SWI in the Nile Delta aquifer using the SEAWAT code was presented by Abdelhamid & Abd-elaty (2018) [61]. The methodologies used were freshwater recharge, brackish water abstraction, and a new methodology called TRAD. TRAD can be defined as the treatment of wastewater then recharge to the aquifer, abstraction of brackish water, and next desalination. The results clarified that TRAD is an economic and effective tool to control the salinity of groundwater in coastal aquifers with less environmental impact. For future studies, it was recommended to carry out optimization analysis for TRAD. Besides, experimental work for calibration purposes.

Analytical modelling was applied by Eissa (2018) [62] to assess the extensions of SWI in Ras El Hekma, Western North coastal aquifer in Egypt. Also, a combination between hydrogeological and geochemical characterization was used besides sharp interface assumption between fresh water and sea water. The modelling results showed that the extension from Ras El Hekma to inland was from 1700 m to 5000 m.

Masoud et al. (2018) [63] investigated groundwater quality in the Quaternary Aquifer in Delta Wadi El-Arish (QADWA) based on 294 samples from 14 groundwater supply wells over a period between 2008 and 2014 using chemical investigation. The main objective was to assess the significant trends in the concentration of many indicators, including Fe^{2+} , Mn^{2+} , Zn^{2+} , K^+ , Pb^{2+} , NO_3^- , PH, Al^{3+} , TDS, Total Alkalinity, and Fecal Coliform (FC). It was noted that most of the indicators exceeded the permissible limits except for Mn^{2+} . It was recommended to monitor the wells from time to time and introduce effective solutions to combat groundwater deterioration in quality.

In 2019, a comprehensive study was carried out by H. Abd-Elhamid et al. [64] to show the effect of the operation of the Grand Ethiopian Renaissance Dam (GERD) on the salinity of the groundwater resources in the Nile Delta aquifer. Moreover, the simulation was based on two scenarios of the reservoir filling during 3- and 6-years using groundwater flow and solute transport model called SEAWAT. The results showed that the contour lines 35000 ppm and 1000 ppm would go inside to reach 70.85 and 110.2 km, respectively for the first scenario, and 67.30 km and 108.25 km, respectively under the second scenario. It was recommended to reduce the abstraction rate by 60% and 40% for the two scenarios from the groundwater aquifer to keep the region from further intrusion by seawater.

Hagagg (2019) [65] used a variable-density flow model (SEAWAT) to investigate the extend of the SWI in El Negila situated in the Northwestern coast of Egypt. The results of the calibrated numerical model showed that SWI is limited under current conditions of recharge and abstraction. However, SWI may increase due to the excessive pumping from the aquifer. So, a range of rates of withdrawal was recommended.

The main objective of a research study carried out by El-Ghandour and Elbeltagi (2020) [66] was to optimize pumping rates in coastal aquifers based on a probabilistic global search optimization algorithm (PGSL). A comparison between this algorithm and another one, namely the Shuffled Frog Leaping Optimization Algorithm (SFLA) was performed to get the best results based on sharp interface assumption. Quaternary Aquifer in Delta Wadi El-Arish (QADWA) was used as a case study. The results showed that the performance of PGSL is less than SFLA. However, PGSL did not give the optimum solution but close to the optimum.

Abu Salem et al. (2022) [67] examined the hydrogeochemical processes and flow patterns within the freshwater/saltwater mixing zone of the Egyptian Nile Delta aquifer to manage SWI. Utilizing a multidisciplinary approach, including hydrogeochemical analysis, statistical methods, and DC resistivity measurements, the research identifies lateral and vertical changes in groundwater under salinization stress. Results indicate that SWI predominates in approximately two-thirds of the study area, with significant compositional thresholds for Na, Mg, Cl, and SO₄ at 600, 145, 1200, and 600 mg/L, respectively. Wells exceeding these thresholds are impacted by SWI. The study demonstrates the effectiveness of integrating hydrogeochemical facies and resistivity data to characterize large-scale salinization influences, offering crucial insights for long-term coastal groundwater management.

A research study conducted by Armanuos et al. (2024) [68] investigated the impact of climate change on seawater intrusion in the Nile Delta aquifer (NDA) in Egypt, using numerical models Visual MODFLOW and SEAWAT. The study simulates groundwater head and saltwater intrusion under various scenarios, including combinations of sea level rise (SLR) and changes in withdrawal rates. Findings indicate that seawater intrusion has advanced in the west and middle of the NDA, with a delayed effect in the east. Among the scenarios, the most severe outcome occurs with a 0.5 m sea level rise and double the current abstraction rate, significantly increasing salinity. Consequently, it is imperative to reduce or maintain current withdrawal rates and implement shore protection measures to mitigate further seawater intrusion.

10. Limitations and Future Studies

Research on saltwater intrusion, such as the studies conducted on the Nile Delta aquifer, often faces several limitations. One significant limitation is the accuracy and resolution of numerical models. While models like Visual MODFLOW and SEAWAT are advanced, their precision depends heavily on the quality and granularity of input data, which can be sparse or outdated. Additionally, these models often assume a homogeneous aquifer, which oversimplifies the complex geology and hydrogeology of coastal aquifers. Another limitation is the scale of temporal and spatial monitoring. Long-

term and wide-scale data collection is challenging due to logistical and financial constraints, leading to potential gaps in understanding the dynamic processes of seawater intrusion [69, 70]

Moreover, current studies may not fully account for the synergistic effects of multiple stressors, such as sea-level rise, groundwater extraction, and land-use changes. The interaction between these factors can lead to non-linear responses in the aquifer system that are difficult to predict with existing models. Finally, there is often a lack of integration between different disciplinary approaches, such as geophysical surveys, chemical analysis, and hydrodynamic modeling, which can limit the comprehensiveness of the findings [71].

Future studies should aim to address these limitations by incorporating more comprehensive and high-resolution data collection techniques. For instance, the use of remote sensing and advanced geophysical methods can enhance the spatial and temporal resolution of data. Additionally, developing more sophisticated models that consider heterogeneous aquifer properties and the coupled effects of multiple stressors would provide a more accurate prediction of saltwater intrusion patterns [72, 73].

Interdisciplinary approaches should be further emphasized, integrating hydrogeochemical, geophysical, and socio-economic data to create a holistic understanding of the aquifer system. Moreover, long-term monitoring programs are essential to capture the gradual and complex nature of saltwater intrusion processes. Implementing adaptive management strategies that are flexible and can be updated with new data will also be crucial [74].

Collaboration between scientists, local communities, and policymakers is vital to ensure that research findings are translated into effective groundwater management practices. By addressing these aspects, future research can provide more robust and actionable insights to combat saltwater intrusion and safeguard freshwater resources in coastal regions [75].

11. Summary and Conclusion

Saltwater intrusion (SWI) is a significant issue impacting groundwater resources in coastal regions worldwide. Proper management and control are essential to mitigate its adverse effects. This article provides a comprehensive overview of SWI, discussing its characteristics and monitoring methods. Various countermeasures and management tools for controlling SWI are clearly outlined. Choosing the best combination of solutions is crucial to prevent SWI effectively. An integrated management plan is necessary to ensure the safe yield and high quality of groundwater in coastal aquifers, safeguarding against seawater contamination. Recommendations and limitations for maintaining the sustainability of groundwater supply, considering both quantity and quality, are suggested for long-term planning, with attention to environmental impact assessments. Additionally, case studies from the Nile Delta, Sinai Peninsula, and North-West coast of Egypt are presented to enhance understanding of SWI and highlight future threats to water resources in Egypt. The importance of protecting coastal aquifers from seawater salinity through various control methods is emphasized. This can be achieved through analysis techniques such as modeling, optimization, and other approaches. Future research should address limitations identified by previous studies.

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References

- [1] A. M. Saqr, "A Hydraulic Study of Egyptian Irrigation Canals," M.Sc. Thesis, Fac. Eng. Mansoura Univ. Mansoura, Egypt, 2016. https://www.researchgate.net/publication/369527556_A_Hydraulic_Study_of_Egyptian_Irrigation_Canals
- [2] M. Noman et al., "Analysis of overcurrent protective relaying as minimum adopted fault protection for small-scale hydropower plants," *Int. J. Environ. Sci. Technol.*, vol. 21, no. 4, pp. 4457–4470, 2024. <https://doi.org/10.1007/s13762-023-05284-y>
- [3] A. Zidan, M. Abdalla, S. Khalaf, and A. Saqr, "Kinetic Energy and Momentum Coefficients for Egyptian Irrigation Canals," *Bull. Fac. Eng. Mansoura Univ.*, vol. 41, no. 1, pp. 1–16, 2020. <https://doi.org/10.21608/bfemu.2020.99368>
- [4] M. E. Abd-Elmaboud, A. M. Saqr, M. El-Rawy, N. Al-Arifi, and R. Ezzeldin, "Evaluation of groundwater potential using ANN-based mountain gazelle optimization: A framework to achieve SDGs in East El Oweinat, Egypt," *J. Hydrol. Reg. Stud.*, vol. 52, 2024. <https://doi.org/10.1016/j.ejrh.2024.101703>
- [5] J. O. Alao, D. A. Ayejoto, A. Fahad, M. A. A. Mohammed, A. M. Saqr, and A. O. Joy, "Environmental Burden of Waste Generation and Management in Nigeria," *Souabi, S., Anouzla, A. Tech. Landfills Waste Manag. Springer Water. Springer, Cham.*, pp. 27–56, 2024. https://doi.org/10.1007/978-3-031-55665-4_2
- [6] I. Andriyani, D. Jourdain, G. P. Shivakoti, B. Lidon, and B. Kartiwa, "Can Uplanders and Lowlanders Share Land and Water Services? (A Case Study in Central Java Indonesia)," *Redefining Divers. Dyn. Nat. Resour. Manag. Asia*, vol. 1, pp. 321–330, 2017.
- [7] J. Bear, A. H. Sorek, S. Sorek, D. Quazar, and I. Herrera, "Seawater intrusion in coastal aquifers, concepts, methods and practices," *Kluwer Acad. Publ. Dordrecht, Netherlands. ISBN 0-7923-5573-3.*, 1999.
- [8] A. M. Saqr, "Groundwater Resource Management: A Quantitative-Based Study for Meeting Sustainable Development in Southwestern Nile Delta, Egypt," Ph.D. Thesis, Egypt-Japan Univ. Sci. Technol. Alexandria, Egypt, 2023. https://www.researchgate.net/publication/369527718_Groundwater_Resource_Management_A_Quantitative-Based_Study_for_Meeting_Sustainable_Development_in_Southwestern_Nile_Delta_Egypt
- [9] M. Zidan and M. Dawoud, "Agriculture use of marginal water in Egypt: opportunities and challenges," *Springer Sci. Bus. Media*, pp. 661–679, 2013.
- [10] A. M. Saqr, M. G. Ibrahim, M. Fujii, and M. Nasr, "Sustainable development goals (SDGs) associated with groundwater over-exploitation vulnerability: Geographic information system-based multi-criteria decision analysis," *Nat. Resour. Res.*, vol. 30, no. 6, pp. 4255–4276, 2021. <https://doi.org/10.1007/s11053-021-09945-y>
- [11] A. Masria, A. K. Seif, M. Ghareeb, M. E. Abd-Elmaboud, K. Soliman, and A. I. Ammar, "Numerical modeling of vadose zone electrical resistivity to evaluate its hydraulic parameters," *Appl. Water Sci.*, vol. 13, no. 12, 2023, doi: 10.1007/s13201-023-02024-y.
- [12] A. M. Saqr and M. E. Abd-Elmaboud, "Saltwater Intrusion in Coastal Aquifers: A Comprehensive Review and Case Studies from Egypt," *Qeios*, 2024. <https://doi.org/10.32388/XLIS2F>
- [13] G. Sanchez, "Land Cover Change and The Impact on Fresh Groundwater Resources," *North Carolina State Univ.*, 2011.
- [14] P. Barlow, "Groundwater in Freshwater-Saltwater Environments of The Atlantic Coast," *US Geol. Surv. Circ.*, no. 1262, pp. 1–113, 2003.
- [15] Q. K. Ha, P. Le Vo, C. N. Phan, V. H. Pham, and V. K. Nguyen, "Identification of freshwater - Saltwater interface in coastal areas using combination of geophysical and geochemical methods: A case study in Mekong Delta, Vietnam," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 652, no. 1, 2021, doi: 10.1088/1755-1315/652/1/012006.
- [16] D. Closson, P. E. LaMoreaux, N. Abou Karaki, and H. Al-Fugha, "Karst System Developed in Salt Layers of The Lisan Peninsula, Dead Sea, Jordan," *Environ. Geol.*, vol. 52, no. 1, pp. 155–172, 2007.
- [17] S. W. Trimble, "Groundwater: Saltwater Intrusion," *Encycl. Water Sci. Second Ed.*, pp. 499–501, 2020, doi: 10.1081/e-ews2-120010083.
- [18] E. White and D. Kaplan, "Restore or Retreat? Saltwater Intrusion and Water Management in Coastal Wetlands," *Ecosyst. Heal. Sustain.*, vol. 3, no. 1, 2017.
- [19] S. Das, P. K. Maity, and R. Das, "Remedial Measures for Saline Water Ingression in Coastal Aquifers of South West Bengal in India," *MOJ Ecol. Environ. Sci.*, vol. 3, no. 1, 2018.
- [20] D. W. Adrian et al., "Seawater Intrusion Processes, Investigation and Management: Recent Advances and Future Challenges," *Adv. Water Resour.*, vol. 51, pp. 3–26, 2013, [Online]. Available: <http://dx.doi.org/10.1016/j.advwatres.2012.03.004>
- [21] G. M. Maillet, E. Rizzo, A. Revil, and C. Vella, "High Resolution Electrical Resistivity Tomography (ERT) in A Transition Zone Environment: Application for Detailed Internal Architecture and Infilling Processes Study of A Rhône River Paleo-Channel," *Mar. Geophys. Res.*, vol. 26, no. 2–4, pp. 317–328, 2005.
- [22] J. and Bear and A. Cheng, "Modeling Groundwater Flow and Contaminant Transport Theory and Applications of Transport in Porous Media," *Springer Sci. Media*, vol. 23, pp. 593–636, 2010.
- [23] M. L. Maslia and D. C. Prowell, "Effect of Faults on Fluid Flow and Chloride Contamination in A Carbonate Aquifer System," *J. Hydrol.*, vol. 115, no. 1–4, pp. 1–49, 1990.
- [24] Purnama and Marfai, "Saline Water Intrusion Toward Groundwater: Issues and its Control," *J. Nat. Resour. Dev.*, vol. 2, pp. 25–32, 2012.

- [25] M. Vengadesan and E. Lakshmanan, "Management of Coastal Groundwater Resources," *Coast. Manag. Glob. Challenges Innov.*, pp. 383–397, 2018.
- [26] A. M. Saqr, M. Nasr, M. Fujii, C. Yoshimura, and M. G. Ibrahim, "Monitoring of Agricultural Expansion Using Hybrid Classification Method in Southwestern Fringes of Wadi El-Natrun, Egypt: An Appraisal for Sustainable Development," *Environ. Sci. Eng.*, pp. 349–362, 2023. https://doi.org/10.1007/978-981-99-4101-8_27
- [27] A. M. Saqr, M. Nasr, M. Fujii, C. Yoshimura, and M. G. Ibrahim, "Delineating suitable zones for solar-based groundwater exploitation using multi-criteria analysis: A techno-economic assessment for meeting sustainable development goals (SDGs)," *Groundw. Sustain. Dev.*, vol. 25, 2024. <https://doi.org/10.1016/j.gsd.2024.101087>
- [28] M. E. Abd-Elmaboud, H. A. Abdel-Gawad, K. S. El-Alfy, and M. M. Ezzeldin, "Estimation of groundwater recharge using simulation-optimization model and cascade forward ANN at East Nile Delta aquifer, Egypt," *J. Hydrol. Reg. Stud.*, vol. 34, 2021, doi: 10.1016/j.ejrh.2021.100784.
- [29] J. O. Alao et al., "Evaluation of Groundwater contamination and the Health Risk Due to Landfills using integrated geophysical methods and Physiochemical Water Analysis," *Case Stud. Chem. Environ. Eng.*, vol. 8, 2023. <https://doi.org/10.1016/j.csce.2023.100523>
- [30] M. Elsayed, "Unsteady state studying of saltwater intrusion in coastal aquifers," M.Sc. Thesis, Fac. Eng. Mansoura Univ., 2014.
- [31] A. M. Saqr, M. Nasr, M. Fujii, C. Yoshimura, and M. G. Ibrahim, "Optimal Solution for Increasing Groundwater Pumping by Integrating MODFLOW-USG and Particle Swarm Optimization Algorithm: A Case Study of Wadi El-Natrun, Egypt," *Environ. Sci. Eng.*, pp. 59–73, 2023. https://doi.org/10.1007/978-981-99-1381-7_6
- [32] H. Alexander, S. Sorek, D. Ouazar, I. Herrera, and B. Jacob, "Seawater Intrusion in Coastal Aquifers Concepts, Methods and Practices," Univ. Delaware, Newark, Delaware, U.S.A., 1999.
- [33] A. M. Saqr, M. G. Ibrahim, M. Fujii, and M. Nasr, "Simulation-Optimization Modeling Techniques for Groundwater Management and Sustainability: A Critical Review," *Adv. Eng. Forum*, vol. 47, pp. 89–100, 2022. <https://doi.org/10.4028/p-5011j1>
- [34] A. M. Saqr, M. G. Ibrahim, M. Fujii, and M. Nasr, "Recent Applications of Simulation-Optimization Modeling Techniques for Groundwater Management and Sustainability," 3rd Int. Conf. Chem. Energy Environ. Eng. ICCEEE 2021, 2021. https://www.researchgate.net/publication/363196357_Recent_Applications_of_Simulation-Optimization_Modeling_Techniques_for_Groundwater_Management_and_Sustainability
- [35] H. El-Ghandour, "Analysis and Optimization of Saltwater Intrusion in Coastal Aquifers," MSc Thesis, Fac. Eng. Mansoura Univ., 2005.
- [36] H. F. Abd-Elhamid, "A Simulation-Optimization Model to Study the Control of Seawater Intrusion in Coastal Aquifers," PhD Thesis Water Eng. Coll. Eng. Math. Phys. Sci. Univ. Exet. United Kingdom, 2010.
- [37] Z. Payal, "Innovative Method for Saltwater Intrusion Control," *Int. J. Eng. Sci. Res. Technol.*, vol. 3, no. 2, pp. 3–7, 2014.
- [38] S. Sadjad Mehdizadeh, S. Badaruddin, and S. Khatibi, "Abstraction, Desalination and Recharge Method to Control Seawater Intrusion into Unconfined Coastal Aquifers," *Glob. J. Environ. Sci. Manag.*, vol. 5, no. 1, pp. 107–118, 2019.
- [39] A. A. Javadi, M. S. Hussain, H. F. Abd-Elhamid, and M. M. Sherif, "Numerical Modelling and Control of Seawater Intrusion in Coastal Aquifers," *Proc. 18th Int. Conf. Soil Mech. Geotech. Eng. Paris*, no. September, pp. 739–742, 2013.
- [40] H. F. Abd-Elhamid and A. A. Javadi, "A Cost-Effective Method to Control Seawater Intrusion in Coastal Aquifers," *Water Resour. Manag.*, vol. 25, no. 11, pp. 2755–2780, 2011.
- [41] H. Abd-Elhamid, "A Simulation-Optimization Model to Study the Control of Seawater Intrusion in Coastal Aquifers," 21st Saltwater Intrusion Meet., pp. 1–267, 2010.
- [42] H. F. Abd-Elhamid and A. A. Javadi, "Mathematical Models to Control Saltwater Intrusion in Coastal Aquifers," *Geotech. Spec. Publ.*, no. 179, pp. 790–797, 2008.
- [43] A. Javadi, M. Hussain, M. Sherif, and R. Farmani, "Multi-objective Optimization of Different Management Scenarios to Control Seawater Intrusion in Coastal Aquifers," *Water Resour. Manag.*, vol. 29, no. 6, pp. 1843–1857, 2015.
- [44] H. I. Abdel-Shafy and A. H. Kamel, "Groundwater in Egypt Issue: Resources, Location, Amount, Contamination, Protection, Renewal, Future Overview," *Egypt. J. Chem.*, vol. 59, no. 3, pp. 321–362, 2016.
- [45] A. R. Allam, E. J. Saaf, and M. A. Dawoud, "Desalination of Brackish Groundwater in Egypt," *Desalination*, vol. 152, no. 1–3, pp. 19–26, 2003.
- [46] M. M. Sherif and M. F. Al-rashed, "Vertical and Horizontal Simulation of Seawater Intrusion in The Nile Delta Aquifer," *First Int. Conf. Saltwater Intrusion Coast. Aquifers— Monit. Model. Manag. Essaouira, Morocco*, 2001.
- [47] M. F. Kaiser and M. H. Geriesh, "Water Resources Assessment at El-Arish Area, Using Remote Sensing and GIS, North Sinai, Egypt," *Int. Geosci. Remote Sens. Symp.*, pp. 5323–5326, 2007.
- [48] I. A. Elshinnawy and H. O. Abayazid, "Vulnerability Assessment of Climate Change Impact on Groundwater Salinity in The Nile Delta Coastal Region-Egypt," *Coast. Eng. Pract. - Proc. 2011 Conf. Coast. Eng. Pract.*, pp. 422–435, 2011.
- [49] M. A. Khalil, A. M. Abbas, F. M. Santos, U. Masoud, and H. Salah, "Application of VES and TDEM Techniques to Investigate Seawater Intrusion in Sidi Abdel Rahman Area, Northwestern Coast of Egypt," *Arab. J. Geosci.*, vol. 6, no. 8, pp. 3093–3101, 2013.
- [50] W. Elnashar, "Water Management in Egypt," *IOSR J. Mech. Civ. Eng.*, vol. 11, no. 4, pp. 69–78, 2014.
- [51] E. Nofal, A. Fekry, and S. El-Didy, "Adaptation to The Impact of Sea Level Rise in The Nile Delta Coastal Zone, Egypt," *J. Am. Sci.*, vol. 10, no. 9, pp. 1–7, 2014.

- [52] A. Sefelnasr and M. Sherif, "Impacts of Seawater Rise on Seawater Intrusion in the Nile Delta Aquifer, Egypt," *Groundwater*, vol. 52, no. 2, pp. 264–276, 2014.
- [53] H. M. Bekhit, "Sustainable Groundwater Management in Coastal Aquifer of Sinai Using Evolutionary Algorithms," *Procedia Environ. Sci.*, vol. 25, pp. 19–27, 2015.
- [54] K. El-Alfy, H. El-Ghandour, and M. Elsayed, "Controlling of Saltwater Intrusion Using Injection wells (Case Study: Quaternary Aquifer of Delta Wadi El-Arish, Sinai)," *Mansoura Eng. Journal*, vol. 40, no. 1, 2015.
- [55] M. I. Gad and S. Khalaf, "Management of Groundwater Resources in Arid Areas Case Study: North Sinai, Egypt," *Water Resour.*, vol. 42, no. 4, pp. 535–552, 2015.
- [56] R. A. Hussien, "Groundwater Quality Index Studies for Seawater Intrusion in Coastal Aquifer Ras Sudr, Egypt Using Geographic Information System," *Middle East J. Appl. Sci.*, vol. 5, no. 1, pp. 209–222, 2015.
- [57] E. R. Nofal, M. A. Amer, S. M. El-Didy, and A. M. Fekry, "Delineation and Modeling of Seawater Intrusion into The Nile Delta Aquifer: A new perspective," *Water Sci.*, vol. 29, no. 2, pp. 156–166, 2015.
- [58] H. Abd-Elhamid, A. Javadi, I. Abdelaty, and M. Sherif, "Simulation of Seawater Intrusion in The Nile Delta Aquifer under The Conditions of Climate Change," *Hydrol. Res.*, vol. 47, no. 6, pp. 1198–1210, 2016.
- [59] R. Wassef and H. Schüttrumpf, "Impact of Sea-Level Rise on Groundwater Salinity at The Development Area Western Delta, Egypt," *Groundw. Sustain. Dev.*, vol. 2–3, pp. 85–103, 2016.
- [60] A. Armanous, "Experimental and Numerical Study of Saltwater Intrusion in The Nile Delta Aquifer, Egypt," PhD Thesis Environ. Eng. Egypt-Japan Univ. Sci. Technol. (E-JUST), Egypt, 2017.
- [61] H. Abdelhamid and I. Abd-elaty, "Application of a New Methodology (TRAD) To Control Seawater Intrusion in the Nile Delta Aquifer , Egypt," *Exceed. Expert Work. Solut. Water Challenges MENA Reg.*, Cairo, Egypt, no. November, 2018.
- [62] M. A. Eissa, J. R. de Dreuzy, and B. Parker, "Integrative Management of Saltwater Intrusion in Poorly-Constrained Semi-Arid Coastal Aquifer at Ras El-Hekma, Northwestern Coast, Egypt," *Groundw. Sustain. Dev.*, vol. 6, pp. 57–70, 2018.
- [63] A. A. Masoud, E. A. Meswara, M. M. El Bouraie, and S. Z. Kamh, "Monitoring and Assessment of The Groundwater Quality in Wadi Al-Arish Downstream Area, North Sinai (Egypt)," *J. African Earth Sci.*, vol. 140, pp. 225–240, 2018.
- [64] H. Abd-Elhamid, I. Abdelaty, and M. Sherif, "Evaluation of Potential Impact of Grand Ethiopian Renaissance Dam on Seawater Intrusion in The Nile Delta Aquifer," *Int. J. Environ. Sci. Technol.*, vol. 16, no. 5, pp. 2321–2332, 2019.
- [65] K. H. Hagagg, "Numerical Modeling of Seawater Intrusion in Karstic Aquifer, Northwestern Coast of Egypt," *Model. Earth Syst. Environ.*, vol. 5, no. 2, pp. 431–441, 2019.
- [66] H. A. El-Ghandour and E. Elbeltagi, "Pumping Optimization of Coastal Aquifers Using Probabilistic Search – Case Study: Quaternary Aquifer of El-Arish Rafah, Egypt," *Hydrol. Res.*, vol. 51, no. 1, pp. 90–104, 2020.
- [67] H. S. Abu Salem, K. S. Gemail, N. Junakova, A. Ibrahim, and A. M. Nosair, "An Integrated Approach for Deciphering Hydrogeochemical Processes during Seawater Intrusion in Coastal Aquifers," *Water (Switzerland)*, vol. 14, no. 7, 2022, doi: 10.3390/w14071165.
- [68] A. M. Armanuos, M. S. Taha, and B. A. Zeidan, "Impact of Climate Changes on Seawater Intrusion in the Nile Delta Aquifer (Egypt)," Ali, S., Negm, A. *Groundw. Qual. Geochemistry Arid Semi-Arid Reg. Handb. Environ. Chem.* vol 126. Springer, Cham., 2024, doi: https://doi.org/10.1007/698_2023_1062.
- [69] C. T. Miller et al., "Seawater intrusion processes, investigation and management: Recent advances and future challenges," *Adv. Water Resour.*, vol. 51, pp. 3–26, 2013, [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S030917081200053X>
- [70] A. D. Werner, J. D. Ward, L. K. Morgan, C. T. Simmons, N. I. Robinson, and M. D. Teubner, "Vulnerability indicators of sea water intrusion," *Ground Water*, vol. 50, no. 1, pp. 48–58, 2012, doi: 10.1111/j.1745-6584.2011.00817.x.
- [71] G. Ferguson and T. Gleeson, "Vulnerability of coastal aquifers to groundwater use and climate change," *Nat. Clim. Chang.*, vol. 2, no. 5, pp. 342–345, 2012, doi: 10.1038/nclimate1413.
- [72] A. D. Werner and C. T. Simmons, "Impact of sea-level rise on sea water intrusion in coastal aquifers," *Ground Water*, vol. 47, no. 2, pp. 197–204, 2009, doi: 10.1111/j.1745-6584.2008.00535.x.
- [73] A. M. Nosair, M. Y. Shams, L. M. AbouElmagd, A. E. Hassanein, A. E. Fryar, and H. S. Abu Salem, "Predictive model for progressive salinization in a coastal aquifer using artificial intelligence and hydrogeochemical techniques: a case study of the Nile Delta aquifer, Egypt," *Environ. Sci. Pollut. Res.*, vol. 29, no. 6, pp. 9318–9340, 2022, doi: 10.1007/s11356-021-16289-w.
- [74] C. Lu and A. D. Werner, "Timescales of seawater intrusion and retreat," *Adv. Water Resour.*, vol. 59, pp. 39–51, 2013, doi: 10.1016/j.advwatres.2013.05.005.
- [75] S. Park and J. Y. Lee, "A multidisciplinary approach to assess the vulnerability of a coastal aquifer to seawater intrusion," *J. Hydrol.*, 2018.