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

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Abstract

There is no doubt that groundwater plays an essential role in people’s lives, especially in coastal areas. Therefore, it is very important to tackle this vital source of water from a strategic point of view and provide a management plan to conserve it at an ideal state. Moreover, the salination of groundwater is a serious matter that faces coastal communities due to the excessive pumping of groundwater from coastal aquifers, decrease in recharge, sea level rise, climate change, and other causes. Saltwater intrusion (SWI) is one of the most common problems that must be put into consideration, and it is considered a major risk to groundwater quantity and quality. It occurs when saline water is allowed to enter coastal aquifers to cause contamination of freshwater storage. The main objective of this review article is to highlight the definition of this phenomenon, its causes, the factors affecting it, and different monitoring techniques. In addition, different modeling methods, and management tools, including remote sensing, field surveys, modeling methods, and optimization techniques, are discussed. To avoid the harmful effects of SWI, several countermeasures to control it are illustrated with their advantages and disadvantages. In the final part, Also, some previous work related to SWI worldwide and case studies from the Nile Delta, Sinai Peninsula, and the North-West coast in Egypt will be overviewed. From these research studies, suggestions, adaption, and mitigation measures can be implemented for future studies.

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1. Introduction

Water is one of the most important natural resources on the earth[1][2]. The sources of water consumed by people are various, including surface water bodies like rivers and lakes, groundwater, rainfall, and flash floods [3][4]. When it comes to groundwater, it is an essential part of the hydrologic cycle and contributes to maintaining the ecological balance [5][6]. 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 **Fig. 1** [7].

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% [8]. In Egypt, groundwater is one of the most important resources of water, especially in the coastal areas. Moreover, groundwater is considered the second contributor to 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].

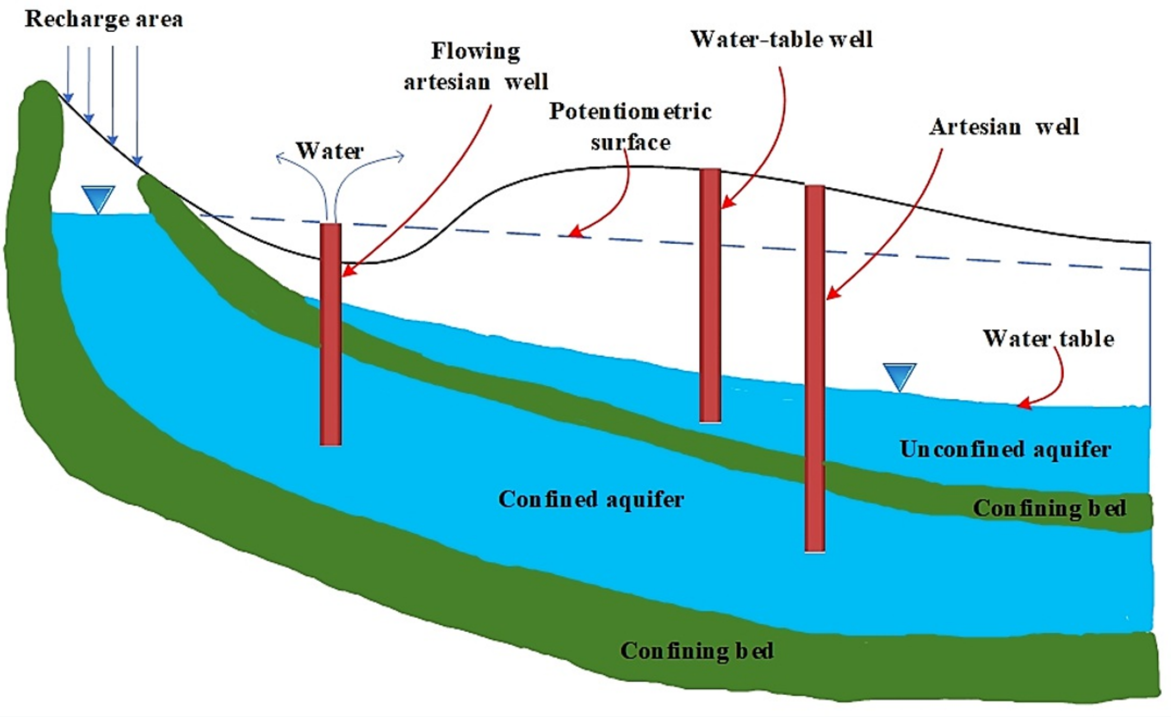

Figure 1. A layout showing types of aquifers and wells in the groundwater system.

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 **Fig. 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, a cone of depression at the water table and up coning at the saltwater surface at the well location [12].

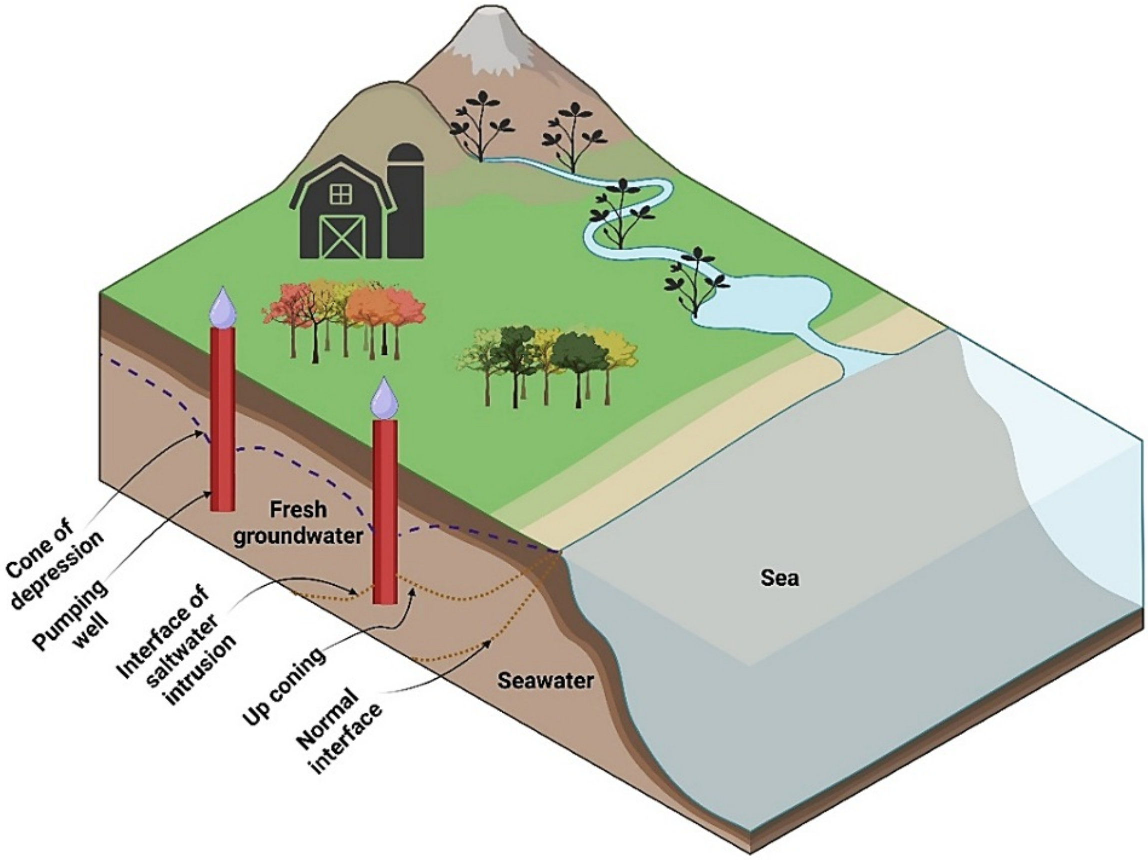

Figure 2. A sketch showing the saltwater intrusion phenomenon.

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 [13].

3. Handling Saltwater Intrusion Issue

Several research studies have been carried out to understand the nature of the groundwater-saltwater interface in coastal aquifers [14]. The numerical models developed are based on two main assumptions, **Fig. 3**, and could be categorized as:

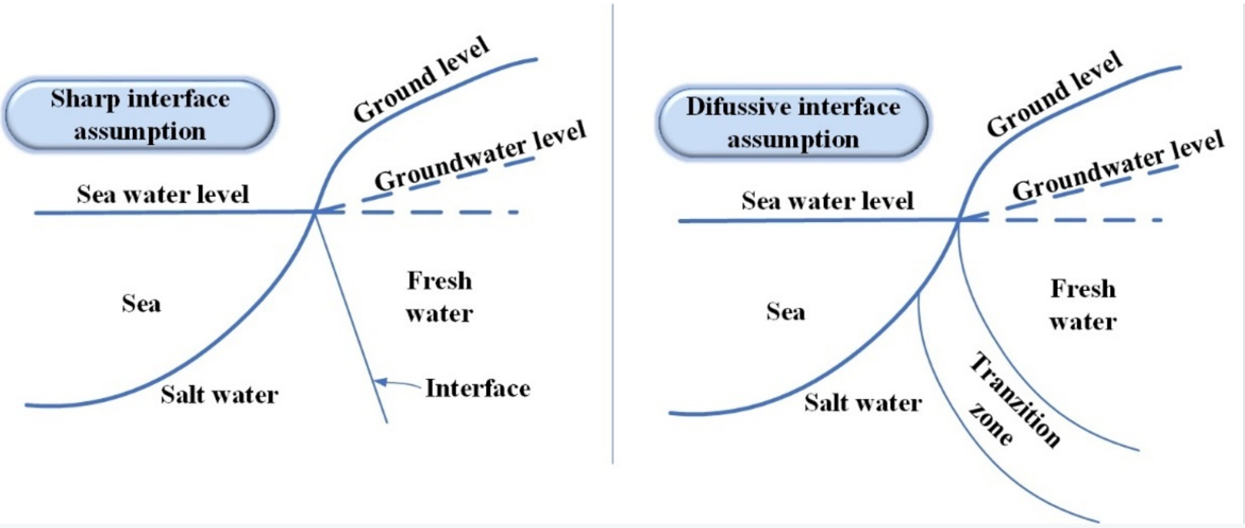

Figure 3. Sharp and Diffusive interface assumptions for modeling of saltwater intrusion.

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 [15]:

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

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 $\rho_f = 1 kg/m^3$, and $\rho_s = 1.025 kg/m^3$.

3.2. *Diffusive Interface Models*

In diffusive models, the boundary between fresh water and salt water is called the transition zone, diffusive zone, 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 [16].

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 [8]. 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 **Fig. 4** [17][18]:

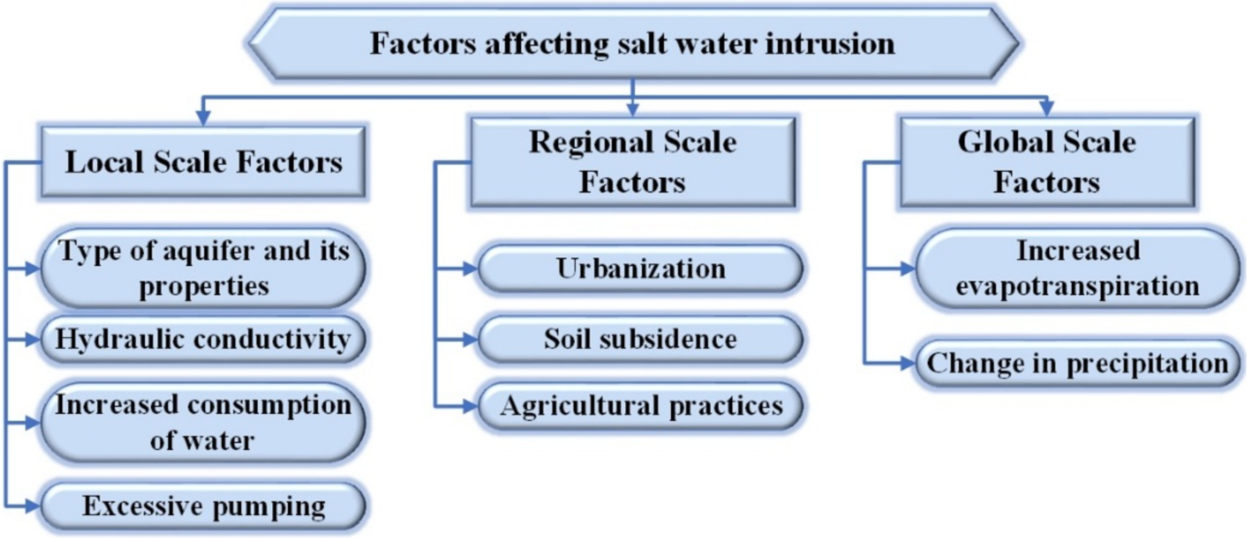

Figure 4. A flow chart showing factors that have effects on saltwater intrusion.

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 [19]:

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 [15].

6.2. *Geophysical Investigation*

Geophysical methods rely on physical characteristics such as electrical conductivity, velocity of seismic waves, thermal conductivity, and electromagnetic permeability [20]. Different methods can be used to determine the salinization in geological formations, such as surface geophysical methods, borehole geophysical methods, and integrated geophysical surveys [21].

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 [22]. 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 [8].

In 2005, a study was done by Todd and Mays to investigate the saline water interface using the ratio between chloride ions and bicarbonate and carbonate ions. The ratio starts at 0.5 for no saline water interface and ends at more than 15.5 for a 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 [23].

6.4. *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 [24].

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:

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 [25]. In addition, assessment of groundwater quality and vulnerability to pollution from saline water can be carried out [26][27].

7.2. *Field Surveys*

Investigation of groundwater quality based on field surveys by collecting groundwater samples and making the required analyses 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 [28].

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 **Fig. 5** [29][30].

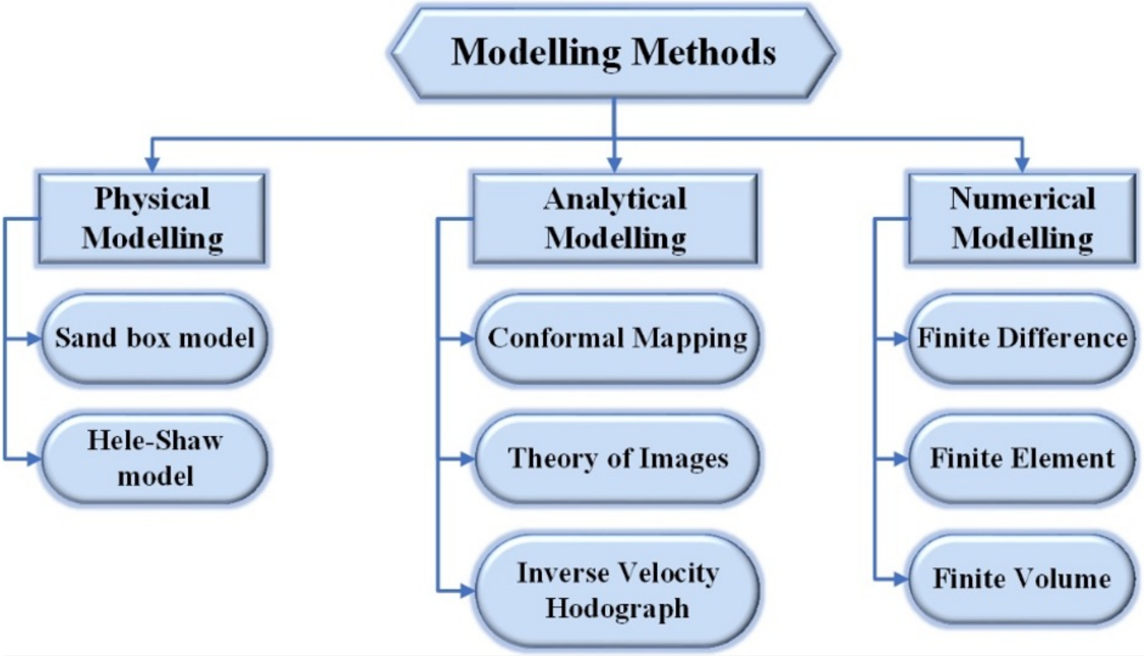

Figure 5. Different modeling methods for simulating saltwater intrusion.

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** [31]:

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 [32]. Different methods that can be used for this purpose are shown in **Fig. 6** [30][33].

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 [26].

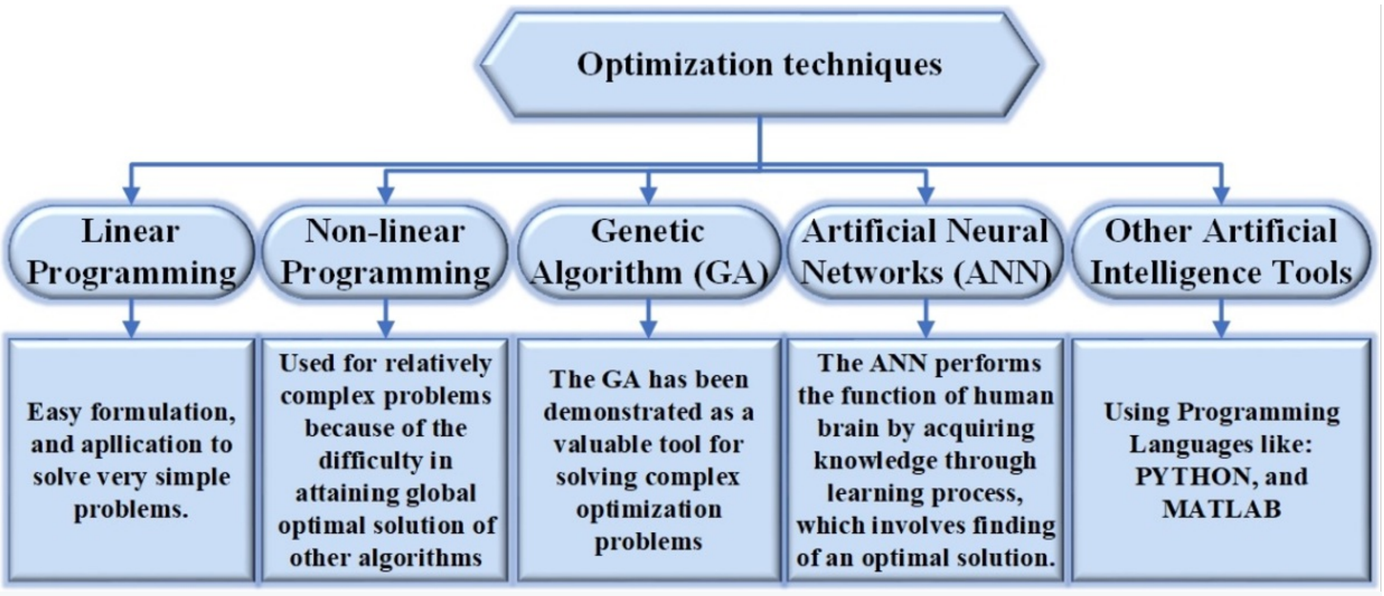

Figure 6. Optimization methods for saltwater intrusion.

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 (**Fig. 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, or 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 supply. 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 the 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 [34][35][36][37][38][39][40].

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 [29].

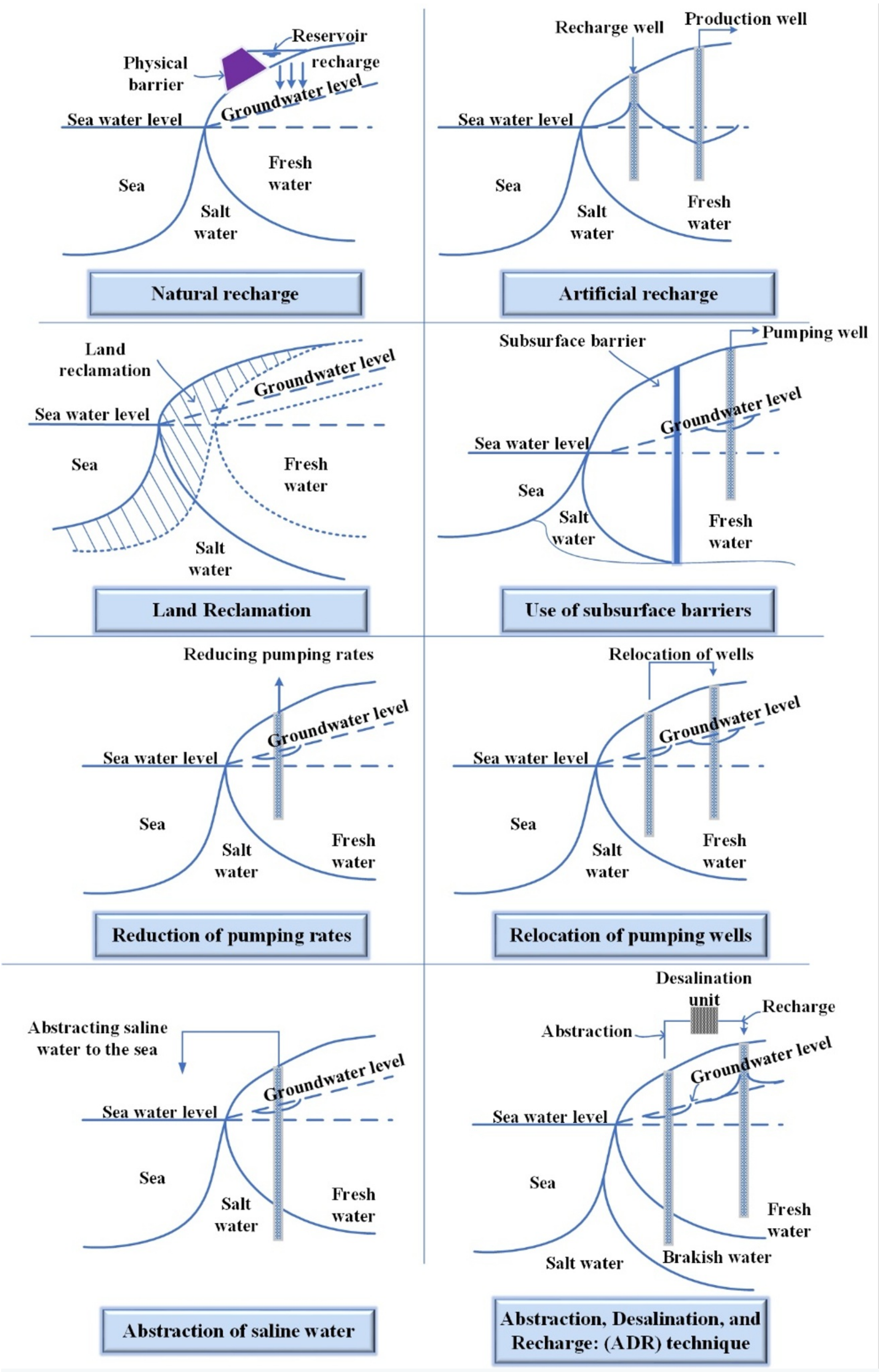

Figure 7. A schematic drawing showing different countermeasures to control saltwater intrusion.

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

Countermeasure		**Disadvantages**
Increasing recharge of groundwater	Natural recharge	• Barrier construction is very costly. • It is not valid for confined aquifers. • It needs highly permeable soil.
	Artificial recharge	• It may be ineffective and costly where the source of injected wells is unavailable.
Land Reclamation		• It does not prevent SWI, but it temporarily prevents it.
Use of subsurface barriers		• It may be costly in terms of construction, service, maintenance, and supervision. • It is not good for deep aquifers.
Reduction of pumping rates		• 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		• This method cannot be used for small-size aquifers. • It does not prevent SWI.
Abstraction of saline water		• 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		• 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 achieve 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 treatment 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 coasts. Moreover, these aquifers include the El-Arish-Rafah Aquifer, the Eastern North Coastal Aquifer, the Western North Coastal Aquifer of the 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 [41]. 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 [42].

Several research studies have been conducted in Egypt to mitigate SWI. Sherif and Al-rashed (2001)[43] 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) [44] 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) [45] 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.[46] 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 a finite element technique using 2D resistivity code, as shown in Figure. The results showed that the distance between the shoreline and the tip-top-portion (T.T.P) of the interface was about 1000 m. Also, the transition zone varied from 17 Ωm to 25 Ωm.

Elnashar (2014) [47] 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 **Fig. 8**.

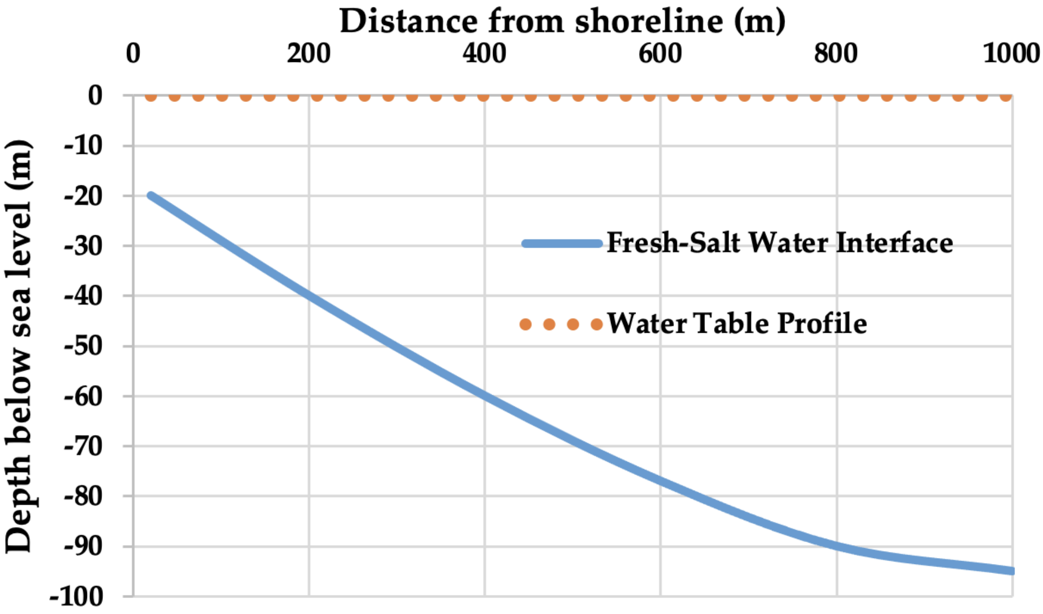

Figure 8. A sketch of the Fresh-Salt Water Interface versus the Water Table Profile related to the Western North Coastal Aquifer in Egypt.

Nofal et al. (2014) [48] 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 were considered by Sefelnasr and Sherif (2014) [49] 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 freshwater would be lost.

Bekhit (2015) [50] 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 move the line of 5000 mg/l only a distance of 80 m in 10 years, which was within the safer limits.

El-Alfy et al. (2015) [51] 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) [52] 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) [53] 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)[54] 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)[55] 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 of 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) [56] used numerical analysis by ArcGIS 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)[57] 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 that there was a perfect agreement between the experimental and numerical results. In addition, the effect of the construction of the Grand Ethiopian Renaissance Dam (GERD) 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) [58]. 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)[59] to assess the extensions of SWI in Ras El Hekma, a Western North coastal aquifer in Egypt. Also, a combination of hydrogeological and geochemical characterization was used, besides the sharp interface assumption between fresh water and sea water. The modelling results showed that the extension from Ras El Hekma to the inland was from 1700 m to 5000 m.

Masoud et al. (2018) [60] 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.[61] 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 a 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) [62] used a variable-density flow model (SEAWAT) to investigate the extent of the SWI in El Negila, situated on 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)[63] 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 the sharp interface assumption. The 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 that of SFLA. However, PGSL did not give the optimum solution but close to the optimum.

Abu Salem et al. (2022) [64] 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 identified 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)[65] investigated the impact of climate change on seawater intrusion in the Nile Delta aquifer (NDA) in Egypt, using the 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 [66][67]

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 [68].

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 [69][70].

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 [71].

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 [72].

11. Summary and Conclusion

SWI is a major problem affecting groundwater resources in coastal areas all over the world. So, it should be properly managed and controlled to overcome its bad effects. In this article, a comprehensive overview of this phenomenon, some of its characteristics, and the way to monitor it were discussed. Different countermeasures to control SWI and management tools were clearly illustrated. Therefore, it is necessary to choose the best arrangement of countermeasures to prevent SWI from occurring by choosing the best solution or a combination of them. In addition, an integrated management plan must be adopted to guarantee a safe yield of groundwater at coastal aquifers with the best quality against contamination from seawater. Recommendations and limitations to maintain the sustainability of groundwater supply based on quantity and quality perspectives should be suggested for the long-term future without neglecting environmental impact assessment. In addition, some case studies related to the Nile Delta, Sinai Peninsula, and the North-West coast in Egypt were mentioned to get the best understanding of SWI and to spotlight some threats regarding the future of water resources in Egypt. Also, the importance of coastal aquifers and the necessity to protect this vital source from the salinity of seawater using different control methods were put into consideration. That can be done through different analysis techniques, including modeling, optimization, and other approaches. Future studies should overcome limitations raised by different researchers.

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