Article

Proposing the Optimum Withdrawing Scenarios to Provide the Western Coastal Area of Port Said, Egypt, with Sufficient Groundwater with Less Salinity

Mohamed Abdelfattah ^{1,*}, Heba Abdel-Aziz Abu-Bakr ², Ahmed Gaber ¹ , Mohamed H. Geriesh ³, Ashraf Y. Elnaggar ⁴ , Nihal El Nahhas ⁵ and Taher Mohammed Hassan ²

¹ Geology Department, Faculty of Science, Port Said University, Port Said 42522, Egypt; ahmedgaber_881@hotmail.com

² National Water Research Centre, Research Institute for Groundwater, Cairo 13621, Egypt; heba_rigw@yahoo.com (H.A.-A.A.-B.); drtahermh@yahoo.com (T.M.H.)

³ Geology Department, Faculty of Science, Suez Canal University, Ismailia 41522, Egypt; helmi_mohamed@hotmail.com

⁴ Department of Food Science and Nutrition (Previously Chemistry), College of Sciences, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia; aynaggar@tu.edu.sa

⁵ Department of Botany and Microbiology, Faculty of Science, Alexandria University, Alexandria 21526, Egypt; niha.elnahhas@alexu.edu.eg

* Correspondence: mohamed_abdelfattah@sci.psu.edu.eg; Tel.: +20-1012409010

Citation: Abdelfattah, M.; Abu-Bakr, H.A.-A.; Gaber, A.; Geriesh, M.H.; Elnaggar, A.Y.; Nahhas, N.E.; Hassan, T.M. Proposing the Optimum Withdrawing Scenarios to Provide the Western Coastal Area of Port Said, Egypt, with Sufficient Groundwater with Less Salinity. *Water* **2021**, *13*, 3359. <https://doi.org/10.3390/w13233359>

Academic Editors: Maurizio Barbieri, Helder I. Chaminé, Maria José Afonso and Aldo Fiori

Received: 4 October 2021

Accepted: 24 November 2021

Published: 26 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: Recently, groundwater resources in Egypt have become one of the important sources to meet human needs and activities, especially in coastal areas such as the western area of Port Said, where seawater desalination cannot be used due to the problem of oil spill and the reliance upon groundwater resources. Thus, the purpose of the study is the sustainable management of the groundwater resources in the coastal aquifer entailing groundwater abstraction. In this regard, the Visual MODFLOW and SEAWAT codes were used to simulate groundwater flow and seawater intrusion in the study area for 50 years (from 2018 to 2068) to predict the drawdown, as well as the salinity distribution due to the pumping of the wells on the groundwater coastal aquifer based on field investigation data and numerical modelling. Different well scenarios were used, such as the change in well abstraction rate, the different numbers of abstraction wells, the spacing between the abstraction wells and the change in screen depth in abstraction. The recommended scenarios were selected after comparing the predicted drawdown and salinity results for each scenario to minimize the seawater intrusion and preserve these resources from degradation.

Keywords: groundwater sustainable management; groundwater abstraction; seawater intrusion; numerical modelling; coastal aquifer

1. Introduction

Water scarcity has recently become an important problem, especially in arid and semi-arid areas such as Egypt [1]. The continuing need for water due to the population increase in Egypt has led to an increase in the use of groundwater resources, since these needs are not being met by surface water sources [2]. Population growth increases the water requirements leading to increased pumping of the aquifers [3]. Therefore, groundwater is considered an important natural resource and the main source of water supply in many coastal regions [4]. In such regions, groundwater resources are over-exploited to meet the development and urbanization of coastal zones and the excessive pumping of groundwater in coastal aquifers has reduced the freshwater flux to the sea and allowed seawater to migrate inland [5].

The western area of Port Said is one of the coastal regions located in the north of Egypt, northeast of the Nile Delta, where the increase in population and human needs has resulted

in the development of projects that depend on water sources and need a permanent source of water. Water desalination is one of the ways to obtain a continuous water source and, in such coastal areas, the desalination plants rely on seawater [6]. Despite the Mediterranean Sea is located north of the study area, it cannot be relied upon and desalinated due to the problem of an oil spill which was previously monitored using satellite images [7–10]. Therefore, desalination has relied on saline groundwater, using appropriate solutions that reduce the resulting salinity, thus reducing the effect of seawater intrusion [11].

The Nile Delta aquifer is among the largest underground reservoirs in the world [12] with a total capacity of 500 Bm³ [3]. About 20% of groundwater comes from conventional water resources where the total abstraction from the Nile Delta Aquifer in Egypt was estimated to be 7 billion cubic meters (BCM) in 2016 [4,13,14]. Annual groundwater abstraction from the Nile aquifer system has been estimated to be 4.6 BCM [15]. The Nile Delta aquifer was affected by sea water intrusion, especially in the coastal areas [16], due to the combined effects of climate change-induced sea-level rise (SLR) [17] and excessive groundwater extractions for reclamation development projects [18]. Overexploitation of groundwater also occurred in the Nile Delta, as the rapidly growing population depends increasingly upon groundwater extraction for domestic water needs [19].

Seawater intrusion (SWI) is a worldwide problem in coastal aquifers where groundwater resources are significantly threatened by saline water [20]. Several studies have been performed to study aquifer salinization; see, for example, [12,21–25]. Due to major causes of SWI [3,26,27], groundwater withdrawals create a new hydraulic gradient, whereby the water level could be lowered to the extent that the piezometric head of a freshwater body becomes less than that of the adjacent saline water body [28]. This change in the hydraulic gradient of aquifers accelerates the progressive landward invasion of seawater toward the abstraction wells and consequently results in the degradation of the chemical quality of abstracted water and surrounding groundwater followed by other problems, such as decrease in fresh water availability, as well as human health and ecosystem damage [27,29].

Several strategies were put forward to minimize seawater intrusion into coastal aquifers, such as the construction of subsurface barriers and the installation of injection wells [30–32]. The optimization of abstraction wells can target the following: maximizing the abstraction rate [33], minimizing aquifer salinity [34], or minimizing seawater intrusion [35]. Artificial recharge helps to raise groundwater levels in aquifers [14] and the recharge can be used in the coastal aquifers to manage seawater intrusion [36–39]. The abstraction of saline water and its disposal in the sea helps to decrease the amount of saline water in coastal aquifers [14]. This method was applied to control saltwater intrusion in coastal aquifers by a number of researchers; see, for example [40,41]. A number of studies have been directed to identify SWI in the NDA using different numerical models [12,22–24,42–45]. A balance between abstraction rates and aquifer salinity should be considered [30].

Recently, many research studies investigated the evaluation of the aquifer by groundwater modeling [28,46–55], used MODFLOW [56,57], SEAWAT and a combined version of MODFLOW [58] and MT3DMS [59].

Therefore, the overall objective of this paper is to propose optimum withdrawing scenarios to provide the western coastal area of Port Said, Egypt, with sufficient groundwater with less salinity to be used in the desalination plant. The groundwater modelling technique was performed with Visual MODFLOW, with the MT3D and SEAWAT codes, to simulate groundwater flow and solute transport, as well as seawater intrusion on groundwater quality due to over pumping.

2. The Study Area

The study area is located 150 m south of the Mediterranean coast in the northeast of the Nile Delta and west of Port Said, Egypt (Figure 1a). As shown in Figure 1b, c, it extends between the latitudes of 31°21' to 31°21'12" east and longitudes of 32°4'57" to 32°5'18" north. The study area belongs to the northeastern part downstream of the Nile

watershed [60], covers an area of about 23.5 km² and is characterized by mild topography, as it does not exceed 5 meters above sea level, either to the north and south where the Mediterranean Sea and Manzala Lake are 0 and less than 0 meters, respectively. The main geomorphic units along the study area are the coastal sand dunes, which are concentrated on the north side of the study area (on the coast), and the sabkha, which is concentrated in the southern part in the direction of Manzala [61].

Figure 1. (a) A satellite image showing the Nile Delta region. (b) The location of the study area relative to Port Said city. (c) Digital elevation model for the study area and surrounding.

2.1. Meteorological Data of the Study Area

The study area is located in an arid climate region; the average daily temperature varies between 17 °C and 20 °C at the Mediterranean Sea coast [62]. The annual mean values for relative humidity in the morning and the evening are between 60% and 80%, respectively [4]. The highest average monthly rainfall in the study area is 50 mm in November (Figure 2a) and the highest average annual rainfall amount in the last 12 years was about 64 mm in 2015 (Figure 2b). The average values of the surface evaporation and

evapotranspiration are about 180 mm/year and 126 mm/year, respectively, in the study area [63]. Due to the high evaporation rates and limited precipitation in the study area, local rainfall provides negligible replenishment of groundwater [2,60]. The analysis of the time series of rainfall during the period 2009–2021 (Figure 2b) led us to conclude that rainfall will not notably change and will not contribute to the aquifer within the study area. Therefore, it is ignored.

Figure 2. (a) Monthly average rainfall. (b) Average annual rainfall amount (mm) and rainy days during the period 2009–2021 for Port Said [64].

2.2. Geological Setting

Generally, two main geological components in the ND region are Quaternary deposits and Tertiary deposits [65]. The Quaternary includes the Holocene and Pleistocene sediments. Holocene deposits are widely spread with a maximum thickness of about 77 m [66].

Moreover, the thickness of Quaternary deposits increases in a northward direction to reach 250 m in the south and 1000 m in the north [67].

The study area clearly consists of quaternary deposits [65]. These deposits are gravel and sand with some clay lenses belonging to Bilqas, Mit Ghamr and Wastany formations from the Holocene and Pleistocene periods.

2.3. Hydrogeological Setting

Hydro-geologically, these quaternary strata are very important with a significantly amount of water stored. According to well data, the groundwater aquifer system is classified into three aquifers (unconfined, leaky and deep), which have about 90 m, 200 m and 400 m thickness, respectively. Figure 3a shows the subsurface geological cross-sections in (Figure 3b) and around the study area (Figure 4). Five test wells are located in the study area to carry out full hydrogeological studies of the aquifer, rely upon the groundwater of the aquifer and desalinate it to improve its quality. The static water levels in the five wells within the study area were measured and indicated that the shallow wells (GW 01 and GW 05) range from -1.4 to -0.9 m and from -1.4 to -1.1 m, respectively, while the groundwater levels for the deep wells (GW 02, GW 03 and GW 04) range from 0.6 to 1 m, from 0.8 to 1.1 m and from 0.5 to 0.8, respectively. The aquifers' salinities were monitored and the hydraulic parameters of the aquifers were estimated through pumping tests of wells.

Figure 3. (a) The directions of geological cross sections using wells around the study area. (b) The locations of five test wells within the study area.

Figure 4. Subsurface geological cross sections: (a) A–A', (b) B–B' and (c) C–C'.

3. Methodology

Groundwater modeling is the most widely used method for understanding the flow regime of groundwater aquifers, as well as for assessing the amount of water that will be used to know the potential of the aquifer and the effect of seawater intrusion due to over-pumping.

To achieve the research objectives, field data were collected to identify the hydraulic properties and salinity of the aquifer. Groundwater flow and solute transport (seawater intrusion) were simulated using the MODFLOW and SEAWAT codes and the testing scenarios were developed to simulate flow and transport in the western Port Said coastal area for 50 years (from 2018 to 2068) to predict the drawdown as well as the salinity distribution due to the pumping of the wells on the groundwater coastal aquifer according to the methodology in Figure 5. This study defined the characteristics of the aquifer system and the baseline salinity of the coastal aquifer using field data and a numerical model. Eighteen scenarios were developed to minimize the effect of seawater intrusion on the Nile Delta aquifer within the study area. The simulation results were compared to the initial salinity values (baseline condition) in the aquifer at the control points, which indicated a change in the different scenarios.

Figure 5. Flow chart explaining the development of the groundwater modelling study.

The scenarios were utilized to predict future responses of the aquifer using the following principles:

- The change in well abstraction rate;
- The different numbers of abstraction wells;

- The spacing between the abstraction wells;
- The change in screen depth in the abstraction wells.

As mentioned in Figure 2b, there are five of wells in the study area on which the above-mentioned scenarios of the 2018 (steady state condition)–2068 projection were based; the different scenarios for each arrangement of the wells are discussed as follows:

- The first arrangement of the wells (Figure 6a) consists of five wells located in the northern part of the study area being used with two screen depths (unconfined aquifer and leaky confined aquifer); for each screen depth, different well abstraction rates are considered:
 - Sc a.1: screen depth in aquifer A, with total pumping of 50,000 m³/day;
 - Sc a.2: screen depth in aquifer A, with total pumping of 100,000 m³/day;
 - Sc a.3: screen depth in aquifer A, with total pumping of 150,000 m³/day;
 - Sc a.4: screen depth in aquifer B, with total pumping of 50,000 m³/day;
 - Sc a.5: screen depth in aquifer B, with total pumping of 100,000 m³/day;
 - Sc a.6: screen depth in aquifer B, with total pumping of 150,000 m³/day.
- The second arrangement of the wells (Figure 6b) consists of five wells on the southern part of the study area with different well abstraction rates from aquifer B (leaky confined aquifer):
 - Sc b.1: total pumping from 5 proposed wells of 50,000 m³/day;
 - Sc b.2: total pumping from 5 proposed wells of 100,000 m³/day;
 - Sc b.3: total pumping from 5 proposed wells of 150,000 m³/day.
- The third arrangement of the wells (Figure 6c) consists of ten wells with different well abstraction rates from aquifer B (leaky confined aquifer):
 - Sc c.1: total pumping of 50,000 m³/day;
 - Sc c.2: total pumping of 100,000 m³/day;
 - Sc c.3: total pumping of 150,000 m³/day.
- The fourth arrangement of five wells (Figure 6d) considers a spacing between wells of 100 m and different abstraction rates from aquifer B (leaky confined confined):
 - Sc d.1: total pumping of 50,000 m³/day;
 - Sc d.2: total pumping of 100,000 m³/day;
 - Sc d.3: total pumping of 150,000 m³/day.
- The fifth arrangement of five wells (Figure 6e) considers a spacing between wells of 200 m and different abstraction rates from aquifer B (leaky confined confined):
 - Sc e.1: total pumping of 50,000 m³/day;
 - Sc e.2: total pumping of 100,000 m³/day;
 - Sc e.3: total pumping of 150,000 m³/day.

These criteria for the scenarios (the change in well abstraction rate, the different numbers of abstraction wells, the spacing between the abstraction wells and the change in screen depth in abstraction wells) were taken into consideration as the requirements for the desalination plant. For example, the quantities of discharge were determined for what this plant would meet in terms of the quantities of water required to be used. In addition, the locations of the proposed wells were determined in accordance with the available places in the study area, taking into account the distances between wells and engineering constructions. The comparison of the scenarios was made using five observation points to observe aquifer salinity. The best and most appropriate scenario is the scenario with the lowest predicted salinity concentrations.

The hydrogeological conceptual model was developed to describe the site hydrogeological conditions. The flow conceptual model was built based on the findings of field investigations and the geological and hydrogeological characteristics of the subsurface

layers, while the transport conceptual model describes the transport of seawater and parameters of concern to the groundwater aquifers and, especially, into the abstraction wells.

Figure 6. Arrangement of proposed pumping wells for different scenarios: (a) first arrangement, (b) second arrangement, (c) third arrangement, (d) fourth arrangement and (e) fifth arrangement.

3.1. Model Geometry

The numerical model of the study area was carried out using a mesh of 48 rows and 48 columns with an area of about 23.5 km², as shown in Figure 7, in which the aquifer system defined in the conceptual model is composed of three aquifers: the first unit is unconfined shallow aquifer A, which belongs to the quaternary age, with an average thickness of 90 m; the second unit is leaky confined aquifer B, which belongs to the Mit Ghamr formation of the Pleistocene age, with an average thickness of 200 m; the third unit is confined deep aquifer C, which belongs to the Wastany formation of the upper Pleistocene age, with an average thickness of 200 m. There are two layers of clay with a thickness of about 20 meters; the first separates the shallow aquifer and the leaky aquifer B, while the other separates the aquifers B and C. All aquifers consist of sand and gravel with intercalated clay lenses.

Figure 7. The grid cells for conceptual groundwater model.

3.2. Boundary Condition

The hydrogeological boundary conditions were selected according to water level data from drilled wells and the hydrogeological map of the Nile Delta aquifer [1], as follows:

1. Northern boundary: Mediterranean Sea representing the northern constant head and constant salinity concentration (40,600 mg/L), according to water analysis.
2. Southern boundary: Manzala Lake representing the southern constant head with a -3 value and constant salinity concentration (50,760 mg/L), according to water analysis.

3.3. Hydrogeological Parameters

To identify the hydraulic properties of the aquifer, pumping tests were conducted on the five exploratory wells. After completion of well construction and development, step and continuous pumping tests were performed on each well.

Pumping tests were conducted in two wells in aquifer A (GW 01 and GW 05), in three wells in aquifer B (GW 02, GW 03 and GW 04) and reviewed from previous works [18,42,68].

According to the pumping test analysis, the transmissivity value ranges were determined as follows:

- GW 01: According to the pumping tests analysis by Theis, with Jacob correction for unconfined aquifer, the transmissivity values ranged from 586 to 1150 m²/d.
- GW 05: According to the pumping tests analysis by Theis, with Jacob correction for unconfined aquifer, the transmissivity values ranged from 1010 to 1270 m²/d.
- GW 02: According to the pumping tests analysis by Theis, for confined aquifer, the transmissivity values ranged from 1140 to 1170 m²/d.
- GW 03: According to the pumping tests analysis by Theis, for confined aquifer, the transmissivity values ranged from 763 to 890 m²/d.
- GW 04: According to the pumping tests analysis by Theis, for confined aquifer, the transmissivity values ranged from 1110 to 1950 m²/d.

Four-step pumping tests were conducted at each well with different pumping rates for each well with a six-hour duration in each step. Then, continuous pumping tests were conducted at each well with the highest pumping rate and different time durations, such as 24, 48 and 72 h. Table 1 summarizes the pumping rate and drawdown for the steps and continuous pumping tests.

Table 1. Pumping test field data for three aquifers.

Well	Step Pumping Tests		Continuous Pumping Test			Aquifer	Hydraulic Conductivity (m/day)		
	Discharge Rate (m³/hr)	Drawdown (m)	Discharge Rate (m³/hr)	Drawdown (m)	Time (Hour)				
GW 01	150	7.39	250	13.38	72	Sandstone (Unconfined)	13–28		
	183	9.32							
	215	11.12							
	250	13.28							
GW 05	182	13.8	300	24.34	24				
	215	16.44							
	265	21.37							
	280	23.48							
GW 02	150	13.59	300	31.33	72	Sandstone (Leaky Confined)	4–11		
	200	18.39							
	257	24.04							
	300	28.35							
GW 03	65	0.95	120	4.9	48				
	85	1.83							
	105	3.2							
	120	4.25							
GW 04	180	9.82	300	16.87	24,72	Sandstone (Deeper confined)	3–5.5		
	220	12.14							
	260	14.6							
	300	17.04							

The Boulton 1963, Hantush 1960 and Theis 1935 pumping test analysis methods [69–71] were used to estimate the hydraulic properties (transmissivity and storativity of pumped aquifer; vertical hydraulic conductivity and storage coefficient of aquitard) of unconfined, leaky confined (semi-confined) and confined deep aquifers, respectively (Figure 8).

Figure 8. Examples of analyzing the pumping tests in (a,b) unconfined aquifer, (c,d) leaky confined aquifer and (e,f) deep confined aquifer.

The results show that the values of hydraulic conductivity of unconfined sandstone ranging from 13 to 28 m/day were obtained from the pumping tests of two wells (GW 01 and GW 05), while the values of hydraulic conductivity of confined sandstone ranging from 4 to 11 m/day were obtained from the pumping tests of two wells (GW 02 and GW 03) and the values of horizontal hydraulic conductivity of confined deeper sandstone ranging from 3 to 5.5 m/day were obtained from the pumping tests of the GW 04 well. The vertical hydraulic conductivity value is one-tenth of the value of horizontal hydraulic conductivity [72].

3.4. Model Calibration

Boundary conditions, hydraulic properties and initial conditions are classic prerequisite parameters for the aquifer domain and the accuracy of the final output is highly dependent on these parameters [2], especially when simulating groundwater flow in such heterogeneous media [73]. To achieve an accurate simulation, the spatial distribution of

the aquifer hydraulic properties conditioned with physical measurement (e.g., hydraulic conductivity, porosity, storativity and dispersivity) should be determined [73].

The model was calibrated by trial and error by changing the hydraulic parameters and the calculated water levels and comparing them with the measured levels. Hydraulic conductivity was used as a calibration parameter. In model calibration, trial-and-error approaches were used to manually match the field and simulated data. A sensitivity analysis was conducted on hydraulic conductivity and porosity. The hydraulic conductivity ranged from 3 to 28 m/d and the porosity ranged from 0.2 to 0.45. The parameter of sensitivity was evaluated using the root mean square error (RMSE) method, which demonstrated that the model was sensitive to hydraulic conductivity but insensitive to porosity for the test range.

Regarding field data, the model was calibrated using 2018 field data. The year 2018 was chosen as the calibration year to calibrate the model under equilibrium (steady state) conditions. Figure 9 shows the groundwater flow in the study area where the flow direction gradually decreases from the Mediterranean Sea in the north to Manzala Lake in the south. The model was calibrated until the lowest possible error values were reached for five observation points and the results show that the residual varied between 0.098 m (GW 03) and 0.67 m (GW 01) with a root mean square (RMS) of 0.362 m and a normalization root mean square of 9.675%, as shown in Figure 10a.

The computed water budget consists of two parts, inflow and outflow. In the model studied, the inflow budget included one component, inflow across boundaries, while the outflow budget consisted of two components, outflow across boundaries and groundwater withdraw of wells, which was 0 m³/day in a steady state but changes according to discharge rates in the transient state of the model and is used in domestic and water supply. Table 2 shows that the calculated total inflow was 89,910.4297 m³/day and the total outflow was 89,919.2109 m³/day with a net flow of about 9 m³/day, which indicates that the discrepancy percentage was 0.01%.

Figure 9. Calculated groundwater levels in 2018.

Figure 10. (a) Calibration of the head at steady state (2018) and (b) calibration of the TDS (mg/L) at steady state (2018).

Table 2. Groundwater balance of the study area.

Component	Recharge (m ³ /day)	Discharge (m ³ /day)
Subsurface drainage	0	-
Seepage from the Nile and main canals	0	-
Inflow across boundaries	89,910.4297	-
Discharge by tile drains		0
Inflow to Damietta		0
Discharge into drains		0
Groundwater withdrawals		0
Evaporation		0
Outflow across boundaries		89,919.2109
Balance	89,910.4297	89,919.2109

The SEWAT code was calibrated using the existing salinity field data of 2018. The three main aquifers were simulated to study the effect of seawater intrusion. The initial conditions of TDS in the three aquifers were assigned according to the water samples analysis and the results of the EC logs. Seawater salinity was 40,600 mg/L TDS. For aquifer A, TDS was 32,410 mg/L. Aquifer B was divided into three sub-layers with salinities of 21,000 mg/L, 25,000 mg/L and 33,000 mg/L, respectively. Salinity of aquifer C ranged between 50,000 mg/L and 60,000 mg/L. This aquifer was divided into two sub-layers and the sensitivity analysis was performed to predict the impact of this bottom aquifer on the salinity of abstracted water.

Longitudinal dispersivity was used as a calibration parameter. Figure 10b shows the calibration curve between the field and simulated salinity values in 2018 for three observation points.

4. Results

4.1. Groundwater Flow Model

Groundwater flow and solute transport (seawater intrusion) were simulated under transient conditions for a prediction period using the MODFLOW and SEAWAT codes for 50 years (18,250 days), from 2018 to 2068, to predict the drawdown in groundwater levels and changes in groundwater salinity as a result of extraction scenarios. The stress period

of the calibration run was set to one year (365 days). The prediction period was divided into 50 stress periods.

Table 3 and Figure 11 explain the results of predicted drawdown in 18 scenarios as follows:

- The first three scenarios (Sc a.1, Sc a.2 and Sc a.3) refer to extraction from the first aquifer, with wells located at a distance of about 165 m from the sea, showing the drawdown of the water level would range, over time, from 2.5 m in Sc a.1 (50,000 m³/day) to 6.7 m in Sc a.3 (150,000 m³/day); according to the remaining three scenarios (Sc a.4, Sc a.5 and Sc a.6), in which extraction is performed from the second aquifer, the drawdown of the water level would range, over time, from 9.7 m in Sc a.4 (50,000 m³/day) to 29.3 m in Sc a.6 (150,000 m³/day).
- For scenarios Sc b.1, Sc b.2 and Sc b.3, where extraction is performed from the second aquifer, with wells located at a distance of about 300 m from the sea, the drawdown of the water level would range, over time, from 7.5 m in Sc b.1 (50,000 m³/day) to 22.6 m in Sc b.3 (150,000 m³/day).
- For scenarios Sc c.1, Sc c.2 and Sc c.3, where extraction is divided into 10 wells instead of 5, from the second aquifer, the drawdown of the water level would range, over time, from 9.2 m in Sc c.1 (50,000 m³/day) to 27.7 m in Sc c.3 (150,000 m³/day).
- For scenarios Sc d.1, Sc d.2 and Sc d.3, where extraction is performed from the second aquifer, with wells located at a distance of about 165 m from the sea with distance of 100 m between wells, the drawdown of the water level would range, over time, from 7.2 m in Sc d.1 (50,000 m³/day) to 21.6 m in Sc d.3 (150,000 m³/day).
- For scenarios Sc e.1, Sc e.2 and Sc e.3, where extraction is performed from the second aquifer, with wells located at a distance of about 165 m from the sea with a distance of 200 m between wells, the drawdown of the water level would range, over time, from 3.5 m in Sc e.1 (50,000 m³/day) to 10.7 m in Sc e.3 (150,000 m³/day).

Table 3. Summary of testing scenarios.

Scenario	Wells Arrangement	Screen Depth	Discharge (m ³ /d)	Drawdown after 50 Years (m)
Sc a.1	a	Aquifer A	50,000	2.5
Sc a.2			100,000	4.6
Sc a.3			150,000	6.7
Sc a.4		Aquifer B	50,000	9.7
Sc a.5			100,000	19.5
Sc a.6			150,000	29.3
Sc b.1	b	Aquifer B	50,000	7.5
Sc b.2			100,000	15.1
Sc b.3			150,000	22.6
Sc c.1	c	Aquifer B	50,000	9.2
Sc c.2			100,000	18.4
Sc c.3			150,000	27.7
Sc d.1	d	Aquifer B	50,000	7.2
Sc d.2			100,000	14.4
Sc d.3			150,000	21.6
Sc e.1	e	Aquifer B	50,000	3.5
Sc e.2			100,000	7
Sc e.3			150,000	10.5

Figure 11. Predicted drawdown after 50 years for 18 scenarios.

4.2. Simulation of Saltwater Intrusion

Here, the scenarios relative to future changes in seawater due to over-pumping of groundwater resources in the study area are discussed. Figures 12 and 13 show the predicted curves of salinity concentrations for 18 scenarios at one control point (GW 02).

Based on the results of the salinity of the monitoring well from the results of the representation of water salinity and the test of sea interference with groundwater, the following become clear:

- According to scenarios Sc a.1, Sc a.2 and Sc a.3 (Figure 12a), which refer to extraction from the first aquifer, over time, the salinity of the water would reach about 40,000 mg/L when the largest amount is extracted, which is 150,000 m³/day; however, these scenarios were excluded because they required studying the effect of the extraction of this amount of groundwater on the facilities, foundations and infrastructure of the station, as well as on the nearby facilities. According to scenarios Sc a.4, Sc a.5 and Sc a.6 (Figure 12a'), in which extraction is performed from the second aquifer, with wells located at a distance of about 165 m from the sea, the salinity would range from 38,000 to 40,000 mg/L.
- For scenarios Sc b.1, Sc b.2 and Sc b.3 (Figure 12b), in which extraction is performed from the second aquifer, with wells located at a distance of about 300 m from the sea, the salinity would range from 34,000 to 38,000 mg/L.
- For scenarios Sc c.1, Sc c.2 and Sc c.3 (Figure 12c), in which extraction is performed from 10 wells instead of 5, from the second aquifer, the salinity would range from 35,000 to 38,000 mg/L.
- For scenarios Sc d.1, Sc d.2 and Sc d.3 (Figure 12d), in which extraction is performed from the second aquifer, with wells located at a distance of about 165 m from the sea with a distance of 100 m between wells, the salinity would range from 36,000 to 38,500 mg/L.
- For scenarios Sc e.1, Sc e.2 and Sc e.3 (Figure 12e), in which extraction is performed from the second aquifer, with wells located at a distance of about 165 m from the sea with a distance of 200 m between wells, the salinity would range from 38,500 to 40,000 mg/L.

Figure 12. Predicted salinity curves over 50 years for scenario a (a,a'), scenario b (b), scenario c (c), scenario d (d) and scenario e (e) at one control point (GW 02).

Figure 13. Predicted maximum salinity after 50 years for 18 scenarios.

5. Conclusions

This study presents the sustainable management of groundwater resources in the coastal aquifer at the western area of Port Said, Egypt, due to human expansion activity in this area. The main objective is proposing the optimum withdrawing scenarios to provide the study area, with sufficient groundwater with less salinity. In this regard, a groundwater model was developed. The Visual MODFLOW and SEAWAT codes were used in the study area to simulate, over 50 years (from 2018 to 2068), groundwater flow and groundwater salinity and predict the drawdown and, consequently, the impact of seawater intrusion according to the testing scenarios. The eighteen testing scenarios included the change in well abstraction rate, the different numbers of abstraction wells, the spacing between the abstraction wells and the change in screen depth in the abstraction wells. After comparing, the results recommend the groundwater abstraction to be performed from aquifer B and, preferably, a time of 25 years in the scenarios Sc b.1, Sc b.2, Sc c.1, Sc c.2, Sc d.1 and Sc d.2 to minimize the highest values of drawdown and salinity concentration due to seawater intrusion. The average value of salinity would be about 35,000 mg/L if the groundwater abstraction was used in the quantities illustrated in the recommended scenarios in a shorter period of time, such as 25 years, in order to obtain a sufficient and permanent source of water required to be utilized as a main source of water. On the other hand, taking into consideration the groundwater salinity, this would achieve the goal of sustainable development of renewable resources such as groundwater.

Author Contributions: Conceptualization, M.A. and H.A.-A.A.-B.; methodology, M.A., N.E.N. and H.A.-A.A.-B.; validation, M.A., N.E.N., A.Y.E. and H.A.-A.A.-B.; writing—original draft preparation, M.A. and H.A.-A.A.-B.; supervision, writing—review and editing, A.G., A.Y.E., N.E.N., M.H.G. and T.M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research study received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank Taif University Researchers Supporting Project Number (TURSP-2020/32), Taif University, Taif, Saudi Arabia.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. RIGW. *Hydrogeological Map of Nile Delta, Scale 1: 500,000*, 1st ed.; MWRI Publishing Unit: Cairo, Egypt, 1992.
2. Eltarabily, M.G.A.; Negm, A.M. Groundwater management for sustainable development east of the Nile Delta aquifer. In *Groundwater in the Nile Delta*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 687–708.
3. Bear, J.; Cheng, A.H.-D.; Sorek, S.; Ouazar, D.; Herrera, I. *Seawater Intrusion in Coastal Aquifers: Concepts, Methods and Practices*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 1999; Volume 14.
4. Negm, A.M.; Sakr, S.; Abd-Elaty, I.; Abd-Elhamid, H.F. An overview of groundwater resources in Nile Delta aquifer. *Groundw. Nile Delta* **2018**, *73*, 3–44.
5. Abd-Elhamid, H.; Javadi, A.; Abdelaty, I.; Sherif, M. Simulation of seawater intrusion in the Nile Delta aquifer under the conditions of climate change. *Hydrol. Res.* **2016**, *47*, 1198–1210. [[CrossRef](#)]
6. Boumaiza, L.; Chesnaux, R.; Drias, T.; Walter, J.; Huneau, F.; Garel, E.; Knoeller, K.; Stumpp, C. Identifying groundwater degradation sources in a Mediterranean coastal area experiencing significant multi-origin stresses. *Sci. Total. Environ.* **2020**, *746*, 141203. [[CrossRef](#)] [[PubMed](#)]
7. Elbeih, S.F.; Negm, A.M.; Kostianoy, A. *Environmental Remote Sensing in Egypt*; Springer Nature: Basingstoke, UK, 2020.
8. Abou El-Magd, I.; El-Zeiny, A. Quantitative hyperspectral analysis for characterization of the coastal water from Damietta to Port Said, Egypt. *Egypt. J. Remote Sens. Space Sci.* **2014**, *17*, 61–76. [[CrossRef](#)]
9. El-Magd, A.; Zakzouk, M.; Abdulaziz, A.M.; Ali, E.M. The potentiality of operational mapping of oil pollution in the Mediterranean sea near the entrance of the Suez canal using Sentinel-1 SAR data. *Remote Sens.* **2020**, *12*, 1352. [[CrossRef](#)]
10. El-Magd, I.A.; Zakzouk, M.; Ali, E.M.; Abdulaziz, A.M. An open source approach for near-real time mapping of oil spills along the Mediterranean coast of Egypt. *Remote Sens.* **2021**, *13*, 2733. [[CrossRef](#)]

11. Abd-Elaty, I.; Shahawy, A.E.; Santoro, S.; Curcio, E.; Straface, S. Effects of groundwater abstraction and desalination brine deep injection on a coastal aquifer. *Sci. Total. Environ.* **2021**, *795*, 148928. [\[CrossRef\]](#)
12. Sherif, M.M.; Singh, V.P. Effect of climate change on sea water intrusion in coastal aquifers. *Hydrol. Process.* **1999**, *13*, 1277–1287. [\[CrossRef\]](#)
13. Molle, F.; Gaafar, I.; El-Agha, D.E.; Rap, E. *Irrigation Efficiency and the Nile Delta Water Balance*; Water and salt management in the Nile Delta: Report No.9; IWMI: Anand, India, 2016; p. 7.
14. Abd-Elaty, I.; Javadi, A.A.; Abd-Elhamid, H. Management of saltwater intrusion in coastal aquifers using different wells systems: A case study of the Nile Delta aquifer in Egypt. *Hydrogeol. J.* **2021**, *29*, 1767–1783. [\[CrossRef\]](#)
15. Abdel-Shafy, H.I.; Kamel, A.H. Groundwater in Egypt issue: Resources, location, amount, contamination, protection, renewal, future overview. *Egypt. J. Chem.* **2016**, *59*, 321–362.
16. El-Raey, M.; Nasr, S.; Frihy, O.; Desouki, S.; Dewidar, K. Potential impacts of accelerated sea-level rise on Alexandria Governorate, Egypt. *J. Coast. Res.* **1995**, *14*, 190–204.
17. IPCC; Field, C.B.B.; Barros, V.R.; Dokken, D.J.; Mach, K.J.; Mastrandrea, M.D.; Bilir, T.E.; Chatterjee, M.; Ebi, K.L.E.; Anokhin, Y.; et al. *Climate Change 2014—Impacts, Adaptation and Vulnerability: Regional Aspects*; Cambridge University Press: Cambridge, UK, 2014.
18. Morsy, W.S. Environmental Management to Groundwater Resources for Nile Delta Region. Ph.D. Thesis, Faculty of Engineering, Cairo University, Cairo, Egypt, 2009.
19. Mabrouk, M.; Jonoski, A.; Solomatine, D.; Uhlenbrook, S. A review of seawater intrusion in the Nile Delta groundwater system—the basis for assessing impacts due to climate changes and water resources development. *Nile Water Sci. Eng. J.* **2017**, *10*, 46–61.
20. Chang, C.-M.; Yeh, H.-D. Spectral approach to seawater intrusion in heterogeneous coastal aquifers. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 719–727. [\[CrossRef\]](#)
21. Wilson, J.L.; Townley, L.R.; Da Costa, A.S. *Mathematical Development and Verification of a Finite Element Aquifer Flow Model AQUIFEM-1*; Technological Planning Program; Tap Report; Massachusetts Institute of Technology: Cambridge, MA, USA, 1979; p. 114.
22. Amer, A.; Farid, M. About sea water intrusion phenomenon in the Nile Delta aquifer. In Proceedings of the International Workshop on Management of the Nile Delta Groundwater Aquifer, CU/Mit, Cairo, Egypt, 1981.
23. Darwish, M. Effect of Probable Hydrological Changes on the Nile Delta Aquifer System. Ph.D. Thesis, Cairo University, Cairo, Egypt, 1994.
24. Amer, A.; Sherif, M. *An Integrated Study for Seawater Intrusion in the Nile Delta Aquifer*; Working Paper for SRP; NWRC-MPWWR: Cairo, Egypt, 1996.
25. Sherif, M.; Singh, V. *Groundwater Development and Sustainability in the Nile Delta Aquifer*; Final Report; Binational Fulbright Commission: Giza Governorate, Egypt, 1997.
26. Mahlknecht, J.; Merchán, D.; Rosner, M.; Meixner, A.; Ledesma-Ruiz, R. Assessing seawater intrusion in an arid coastal aquifer under high anthropogenic influence using major constituents, Sr and B isotopes in groundwater. *Sci. Total Environ.* **2017**, *587*, 282–295. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Howard, K.W. Beneficial aspects of sea—Water intrusion. *Groundwater* **1987**, *25*, 398–406. [\[CrossRef\]](#)
28. Hussain, M.S.; Javadi, A.A.; Sherif, M.M. Three dimensional simulation of seawater intrusion in a regional coastal aquifer in UAE. *Procedia Eng.* **2015**, *119*, 1153–1160. [\[CrossRef\]](#)
29. Patel, A.S.; Shah, D.L. *Water Management: Conservation, Harvesting and Artificial Recharge*; New Age International (P) Limited, Publishers: Hyderabad, India, 2008.
30. Abarca, E.; Vázquez-Suñé, E.; Carrera, J.; Capino, B.; Gámez, D.; Batlle, F. Optimal design of measures to correct seawater intrusion. *Water Resour. Res.* **2006**, *42*. [\[CrossRef\]](#)
31. Tsanis, I.K.; Song, L.F. Remediation of sea water intrusion: A case study. *Groundw. Monit. Remediat.* **2001**, *21*, 152–161. [\[CrossRef\]](#)
32. Essink, G.H.O. Improving fresh groundwater supply—problems and solutions. *Ocean Coast. Manag.* **2001**, *44*, 429–449. [\[CrossRef\]](#)
33. Shamir, U.; Bear, J.; Gamliel, A. Optimal annual operation of a coastal aquifer. *Water Resour. Res.* **1984**, *20*, 435–444. [\[CrossRef\]](#)
34. Das, A.; Datta, B. Development of multiobjective management models for coastal aquifers. *J. Water Resour. Plan. Manag.* **1999**, *125*, 76–87. [\[CrossRef\]](#)
35. Emch, P.G.; Yeh, W.W. Management model for conjunctive use of coastal surface water and ground water. *J. Water Resour. Plan. Manag.* **1998**, *124*, 129–139. [\[CrossRef\]](#)
36. Narayan, K.; Schleeberger, C.; Charlesworth, P.; Bistrow, K. Effects of roundwater pumping on saltwater intrusion in the lower Burdekin Delta, North Queensland. In Proceedings of the MODSIM 2003 International Congress on Modelling and Simulation, Townsville, Australia, 14–17 July 2003; pp. 212–217.
37. Trichakis, Y. Modeling the saltwater intrusion phenomenon in coastal aquifers—a case study in the industrial zone of herakleio in crete. *Glob. NEST J.* **2005**, *7*, 197–203.
38. Kashef, A.-A.I. Control of salt-water intrusion by recharge wells. *J. Irrig. Drain. Div.* **1976**, *102*, 445–457. [\[CrossRef\]](#)
39. Mahesha, A. Transient effect of battery of injection wells on seawater intrusion. *J. Hydraul. Eng.* **1996**, *122*, 266–271. [\[CrossRef\]](#)

40. Maimone, M.; Fitzgerald, R. Effective modeling of coastal aquifer systems. In Proceedings of the First International Conference on Saltwater Intrusion and Coastal Aquifers-Monitoring, Modeling, and Management, Essaouira, Morocco, 23–25 April 2001; pp. 23–25.
41. Kacimov, A.; Sherif, M.; Perret, J.; Al-Mushikhi, A. Control of sea-water intrusion by salt-water pumping: Coast of Oman. *Hydrogeol. J.* **2009**, *17*, 541–558. [\[CrossRef\]](#)
42. Farid, M.S. Nile Delta Groundwater Study. Master's Thesis, Faculty of Engineering, Cairo University, Cairo, Egypt, 1980.
43. Farid, M.S. Management of Groundwater System in the Nile Delta. Ph.D. Thesis, Faculty of Engineering, Cairo University, Cairo, Egypt, 1985.
44. Mohsen, M.S.; Singh, V.P.; Amer, A.M. A note on saltwater intrusion in coastal aquifers. *Water Resour. Manag.* **1990**, *4*, 123–134. [\[CrossRef\]](#)
45. Sherif, M.; Sefelnasr, A.; Javadi, A. Incorporating the concept of equivalent freshwater head in successive horizontal simulations of seawater intrusion in the Nile Delta aquifer, Egypt. *J. Hydrol.* **2012**, *464*, 186–198. [\[CrossRef\]](#)
46. Abu-Bakr, H.A.e.-A.; Elkhedr, M.; Hassan, T.M. Optimization of abstraction wells near coastal zone. *J. Earth Sci. Res.* **2016**, *4*, 30–42. [\[CrossRef\]](#)
47. Abd-Elaty, I.; Zelenáková, M.; Krajníková, K.; Abd-Elhamid, H.F. Analytical solution of saltwater intrusion in coastal aquifers considering climate changes and different boundary conditions. *Water* **2021**, *13*, 995. [\[CrossRef\]](#)
48. Mastrocicco, M.; Busico, G.; Colombani, N.; Vigliotti, M.; Ruberti, D. Modelling actual and future seawater intrusion in the Variconi Coastal Wetland (Italy) due to climate and landscape changes. *Water* **2019**, *11*, 1502. [\[CrossRef\]](#)
49. Abdelhalim, A.; Sefelnasr, A.; Ismail, E. Numerical modeling technique for groundwater management in Samalut city, Minia Governorate, Egypt. *Arab. J. Geosci.* **2019**, *12*, 124. [\[CrossRef\]](#)
50. Hagagg, K.H. Numerical modeling of seawater intrusion in karstic aquifer, Northwestern Coast of Egypt. *Modeling Earth Syst. Environ.* **2019**, *5*, 431–441. [\[CrossRef\]](#)
51. Mabrouk, M.; Jonoski, A.; Oude Essink, G.H.; Uhlenbrook, S. Assessing the fresh–saline groundwater distribution in the Nile delta aquifer using a 3D variable-density groundwater flow model. *Water* **2019**, *11*, 1946. [\[CrossRef\]](#)
52. Mabrouk, M.; Jonoski, A.; HP Oude Essink, G.; Uhlenbrook, S. Impacts of sea level rise and groundwater extraction scenarios on fresh groundwater resources in the Nile Delta governorates, Egypt. *Water* **2018**, *10*, 1690. [\[CrossRef\]](#)
53. Abd-Elaty, I.; Abd-elhamid, H.; Fahmy, M.; Abd-Elaal, G. Study of Impact of some changes on groundwater system in Nile delta aquifer. *Egypt. J. Eng. Sci. Technol.* **2014**, *17*, 10–11. [\[CrossRef\]](#)
54. Abd-Elaty, I.; Abd-Elhamid, H.F.; Nezhad, M.M. Numerical analysis of physical barriers systems efficiency in controlling saltwater intrusion in coastal aquifers. *Environ. Sci. Pollut. Res.* **2019**, *26*, 35882–35899. [\[CrossRef\]](#)
55. Abd-Elaty, I.; Abd-Elhamid, H.F.; Qahman, K. Coastal aquifer protection from saltwater intrusion using abstraction of brackish water and recharge of treated wastewater: Case study of the Gaza aquifer. *J. Hydrol. Eng.* **2020**, *25*, 05020012. [\[CrossRef\]](#)
56. Langevin, C.D.; Shoemaker, W.B.; Guo, W. *Modflow-2000, the US Geological Survey Modular Ground-Water Model—Documentation of the SEAWAT-2000 Version with the Variable-Density Flow Process (VDF) and the Integrated MT3DMS Transport Process (IMT)*; US Geological Survey: Tallahassee, FL, USA, 2003; ISSN 2331-1258.
57. Bear, J. Seawater intrusion into coastal aquifers. In *Encyclopedia of Hydrological Sciences*; Anderson, M.G., Ed.; Wiley: Devon, UK, 2005.
58. McDonald, M.G.; Harbaugh, A.W. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*; US Geological Survey: Reston, VA, USA, 1988.
59. Zheng, C.; Wang, P.P. *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide*; Aquaveo Reseller Network: Provo, UT, USA, 1999.
60. Abd-Elaty, I.; Said, A.M.; Abdelaal, G.M.; Zelenáková, M.; Jandora, J.; Abd-Elhamid, H.F. Assessing the impact of lining polluted streams on groundwater quality: A case study of the eastern Nile delta aquifer, Egypt. *Water* **2021**, *13*, 1705. [\[CrossRef\]](#)
61. Abdelfattah, M.; Gaber, A.; Geriesh, M.H.; Hassan, T.M. Investigating the less ambiguous hydrogeophysical method in exploring the shallow coastal stratified-saline aquifer: A case study at West Port Said Coast, Egypt. *Environ. Earth Sci.* **2021**, *80*, 1–14. [\[CrossRef\]](#)
62. EEAA. *Egypt Second National Communication under the United Nations Framework Convention on Climate Change (UNFCCC)*; Egyptian Environmental Affairs Agency, Ministry of State for Environmental Affairs: Cairo, Egypt, 2010.
63. El Haddad, I. Hydrogeological Studies and Their Environmental Impact on Future Management and Sustainable Development of the New Communities and Their Surroundings, East of the Nile Delta, Egypt. Ph.D. Thesis, Mansoura University, Mansoura, Egypt, 2002. Unpublished.
64. Available online: <https://www.worldweatheronline.com/port-said-weather-averages/bur-said/eg.aspx> (accessed on 8 November 2021).
65. Sestini, G. Nile Delta: A review of depositional environments and geological history. *Geol. Soc. Lond. Spec. Publ.* **1989**, *41*, 99–127. [\[CrossRef\]](#)
66. Zaghloul, Z.; Taha, A.; Hegab, O.; El Fawal, F. The neogene-quaternary sedimentary basins of the Nile delta. *Egypt. J. Geol.* **1977**, *21*, 1–19.

-
67. El-Fayoumy, I.F. Geology of Groundwater Supplies in the Eastern Region of the Nile Delta and its Extension in North Sinai. Ph.D. Thesis, Faculty of Science, Cairo University, Cairo, Egypt, 1968.
 68. Dahab, K. Hydrogeological Evolution of the Nile Delta after the High Dam Construction. Ph.D. Thesis, Menoufia University, Al Minufiyah, Egypt, 1993.
 69. Boulton, N. Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. *Proc. Inst. Civ. Eng.* **1963**, *26*, 469–482. [[CrossRef](#)]
 70. Theis, C.V. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground—water storage. *Eos Trans. Am. Geophys. Union* **1935**, *16*, 519–524. [[CrossRef](#)]
 71. Hantush, M.S. Modification of the theory of leaky aquifers. *J. Geophys. Res.* **1960**, *65*, 3713–3725. [[CrossRef](#)]
 72. Bear, J. *Hydraulics of Groundwater*; Dover Publications: Mineola, NY, USA, 2007.
 73. Pasquier, P.; Marcotte, D. Steady-and transient-state inversion in hydrogeology by successive flux estimation. *Adv. Water Resour.* **2006**, *29*, 1934–1952. [[CrossRef](#)]