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Use of Numerical Groundwater Modeling to Assess the Feasibility of Aquifer Storage and Recovery (ASR) in the Wadi Watir Delta, Sinai, Egypt

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Abstract

The lack of water resources in Egypt's Sinai Peninsula is a major constraint for further socioeconomic development, and flash floods in this region can damage roads and infrastructure. The Wadi Watir basin is the main water source for the groundwater aquifer, which supplies fresh water to Nuweiba city, where demands for groundwater are increasing. The objective of this research was to assess the hydrogeological suitability of installing Aquifer Storage and Recovery (ASR) systems in the Wadi Watir delta by using numerical groundwater models. The developed models were used to evaluate the effects of hydrogeological and operational parameters on the recovery efficiency of ASR systems at five potential locations in the study area. As the estimation of recovery efficiency depends on the salinity of recovered water, the recovered water salinity limit was assumed as 150% of the injected water salinity, where 150% refers to the point at which recovery has ended because the concentration of recovered water reached 150% of that of injected water. The most important output from the model runs was that the recovery efficiency of these ASR systems ranged from 25% to 54% with a longitudinal dispersivity of 10 m, volume of injected water of 12,000 m^3, and storage period of 180 days. The main conclusions are as follows. 1) Using coupled numerical groundwater flow and solute transport models is an effective tool for predicting the effects of mixing between injected water and ambient groundwater in ASR systems. 2) The groundwater aquifer in the study area is not suitable as strategic area for ASR systems because the thickness of the water storage layer is relatively small and the distance to the sea is very close; consequently, it is recommended that artificial recharge systems be developed with existing technology to replenish the groundwater aquifer in the Wadi Watir delta.

Keywords

Aquifer Storage and Recovery (ASR), Groundwater Modeling, Wadi Watir, Sinai, Egypt, Recovery Efficiency

1. Introduction

Rapid population growth, global climate change, and poor governance are negatively affecting available water resources in many areas [1]. One of the most important water sources in the world is groundwater, and more than one and half billion people depend on it [2]. The natural and regular recharge of groundwater aquifers happens slowly, and if the pumping rate is greater than the natural recharge, groundwater levels will decrease and degradations in quality can occur. Presently, the artificial recharge of groundwater aquifers has become an important way to enhance and increase groundwater storage [3].

A lack of water resources is a pressing concern in the Sinai Peninsula of Egypt, where this represents a major constraint for further socioeconomic development. Furthermore, flash flooding in some Wadis of the southern Sinai region has damaged roads and infrastructure. Recently, the Egyptian government has taken various steps to harvest the flash flood waters in Sinai to use the water to meet development demands while minimizing the negative effects of flash floods. In this respect, Wadi Watir in the southern Sinai region has received special attention over the past few years. The Wadi Watir basin is the main water source for the groundwater aquifer of the study area, and this aquifer is the major source of fresh water to Nuweiba city, which is located in the southeastern part of the Wadi Watir delta and is facing increasing demands for groundwater due to the rapid development [4]. **Figure 1** shows the location of the Wadi Watir delta.

Groundwater in the Wadi Watir delta flows as a thin layer of fresh water, and the groundwater here is very sensitive to pumping because of its location near the coast and consequent seawater intrusion (in particular, it is affected by the upwelling of deep saline deep groundwater) [5] [6]. In 1986, the Desert Research Center published a comprehensive water budget study for the Wadi Watir delta. The main recommendations of this study were to build some underground reservoirs to store a portion of the runoff in the eastern parts of the Wadi Watir delta, and to direct a considerable portion of the surface runoff by suitable means to recharge the groundwater aquifer in the western part of the delta. In addition, the study recommended that a numerical groundwater modeling approach be used for the proper management of fresh water resources in the Wadi Watir delta [7].

Storing water in groundwater aquifers for future use is defined as Aquifer Storage and Recovery (ASR), and this technology has been in use since the late 1960s, mostly in coastal areas of the USA [8]. In ASR systems, the surplus water

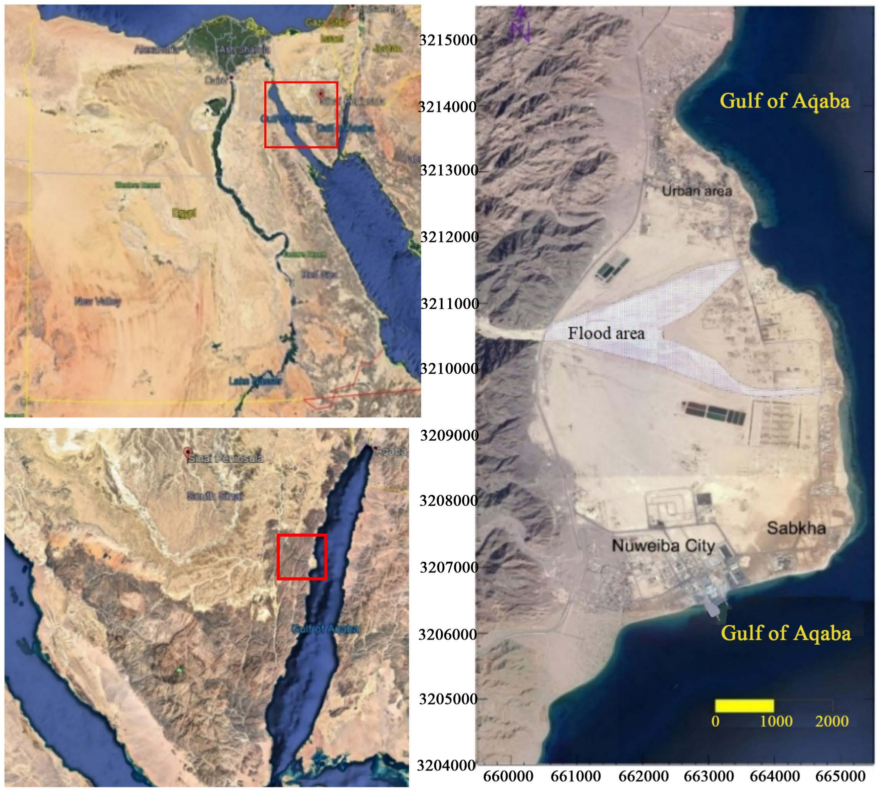

Figure 1. Location map of the Wadi Watir delta. The flood zone is located in the middle. There is a residential area in the north, and the city of Nuweiba is located in the south.

is injected into groundwater aquifers, and then, the water becomes mixed up with ambient groundwater, thereby creating "bubble" or "bottle brush" water as recently termed because of the heterogeneity of the aquifer [9]. When the demand increases, the injected water can be recovered, and in such cases, the percentage of recovered water after injection is termed the "recovery efficiency". Compared to surface reservoirs, use of ASR systems can provide for large water storage capacities, prevent seawater intrusion, and avoid many of the problems associated with surface water storage systems (e.g., harmful algal blooms) [8] [10]. There are many methods have been used to conduct preliminary evaluations of the hydrogeological parameters and their impact on the suitability of a groundwater aquifer for artificial recharge or ASR. One common method is Multi Criteria Decision Analysis (MCDA), but this method can be difficult to implement if there are insufficient hydrogeological data or when the area of assessment is very large [11]; therefore, more accurate quantitative assessment techniques are necessary, such as those involving numerical groundwater flow and transport models.

Socioeconomic development in the southern Sinai region is increasing, and thus, demands for water are expected to increase as well. In particular, there will be an urgent need for water storage of either surplus water or flood waters. This stored water can be used during peak periods of water demand or during drinking water emergencies. The objective of this research was to assess the hydrogeological suitability of installing ASR systems in the Wadi Watir delta of South Sinai in Egypt by using numerical groundwater models to achieve a better understanding of the aquifer parameters and operational parameters that control the system efficiency. The specific goals of this research were as follows:

- Review the available literature and previous studies on the geophysics, geology, and hydrogeology of the Wadi Watir delta aquifer.
- Develop a numerical groundwater model to simulate and calculate the aquifer recharge, pumping rates, and potential for seawater intrusion near the coast, as well as to simulate the vertical movement and migration of deep saline groundwater upward due to over pumping in the Wadi Watir delta.
- Use the developed model to evaluate the effects of hydrogeological parameters on the recovery efficiency of potential ASR systems; these parameters included the hydraulic conductivity, hydraulic gradient, effective porosity, and dispersion; additionally, operational parameters such as the volume of injected water and storage period time were evaluated.

2. Literature Review

The technology for ASR systems was pioneered in the 1960s in the USA, specifically, along the coastal areas of Florida and California. In 2005, 72 ASR systems were operational in the USA and approximately 100 systems were under study [12]. Presently, ASR systems are in use worldwide and numerous examples have been described in the literature, such as those installed in the Atlantic Coastal Plain [13] [14] [15] and in Charleston, South Carolina [16] [17]. In 2018, the Emirate of Abu Dhabi launched a mega project to store surplus desalinated water in the Liwa aquifer (ASR), where it is considered the world's largest storage site for desalinated water in groundwater aquifers; this project aims to supply the Emirate with drinking water during emergency periods [18].

Many researchers have discussed ASR suitability assessments at specific locations by ranking systems in terms of technical considerations, costs, and regulatory components [19] [20] [21] [22] [23]. Chowdhury *et al.* (2010) used the MCDA technique, satellite imagery, and a geographic information system (GIS) to delineate Potential zones of artificial recharge within an approximately 4500 km^2 area in West Bengal [24]. Hill (1997) used technical considerations, costs, and regulatory components to develop a screening tool to determine how ASR technology can assist with supply and storage water objectives [25]. Rashid *et al.* (2005) carried out detailed evaluations that included costs, the recharge water source, the storage volume, and plant operating costs to support economic decisions aimed at balancing the desalinated water production and demand [26].

A few research studies are available online that involve the use of physical and numerical models of groundwater as tools for evaluating the suitability of aquifers for the application of ASR systems. Kimbler *et al.* (1975) used physical laboratory models [27], while Yobbi (1996) used numerical modeling to assess the effects of fresh water injection into a saline coastal aquifer in Florida [28]. Streetly (1998) used a modeling technique to assess the effects of fresh water injection into fresh groundwater aquifers [29]. Moulder (1970) and Merritt (1986) classified the parameters that control the recovery efficiency of fresh water injected into saline aquifers by using three categories of features, namely, the stratification density, dispersion of the fresh and saline interface, and nature of groundwater flow [30] [31]. Ward *et al.* (2009) simplified the need for complex data from numerical groundwater models used in ASR injection studies within brackish groundwater aquifers by developing a predictive tool based on dimensionless values representing the lateral flow, dispersive mixing, mixed convection, and free convection. This method, however, necessitates information on the hydraulic conductivities in the vertical and horizontal direction, aquifer thickness, hydraulic gradient, and density of injected and ambient water [22]. Bakker *et al.* (2010) developed a numerical model to evaluate the recovery efficiency of ASR wells penetrating into a saltwater aquifer [32]. Pavelic *et al.* (2005) used FEFLOW software to develop a numerical simulation model to explore the dynamics of the injected water plume for a number of Aquifer Storage Transfer and Recovery ASTR scenarios [33].

3. Materials and Methods

3.1. Study Area

The Wadi Watir is one of the main wadis in the region of the Aqaba rift province of the Sini Peninsula in Egypt, and it is located between Taba in the north and Sharm El-Sheikh city in the south. The Wadi Watir basin is an important water resource area for Nuweiba city, which is located on its delta. The Wadi Watir basin is bounded by the range of basement mountainous to the west and the shoreline of the Gulf of Aqaba to the east [34]. The catchment area of Wadi Watir (3860 km^2) has a steep mountainous topography that consists of 12 sub-basins and about 32 main wadis, which drain toward the Gulf of Aqaba. High flows occur here mainly during two main storm periods, one in spring and the other in autumn. There are 5 to 10 rainy days per year with a mean annual rainfall amount ranging from 30 to 40 mm, and the bulk of the volume of rainwater falls within a period of a few hours [35]. Annually, the amount of rainfall affecting the Wadi Watir catchment areas is about 200 million m^3/year. The major proportion of this rainfall is lost to the Gulf of Aqaba as surface water runoff because of the steep nature of the surface topography and the dominant presence of hard rocks; **Table 1** shows historical information for flash flood occurrences and volumes in this region [35] [36].

3.2. Aquifer Hydrogeology

Quaternary deposits constitute the main water-bearing formation (Quaternary aquifer) in the Wadi Watir delta. This aquifer is unconfined, heterogeneous, and composed mainly of fine to coarse sands, gravels, sandstone, boulders of carbonate, and granitic rock embedded in a clay and silt matrix [37] [38]. The Quaternary aquifer in the study area can be categorized into five layers, and the

Table 1. Flash flood occurrence and volume modified after Cools et al. (2012). It is important to note that during the last 33 years, very high floods occurred 2 times in the years 1987 and 1997, and high floods occurred 5 times in the years 1988, 1990, 1993, 1997, and 2010; additionally, moderate floods occurred 7 times in the years 1988, 1991, 1994 to 1997, and 2002.

Flood Data	Volume (10^6 m^3)	Flash Flood	Flood Data	Volume (10^6 m^3)	Flash Flood
16 Oct 1987	45	Very High	16-17 May 1997	4.4	Moderate
20 Dec 1987	-	Low	28 May 1997	0.27	Low
20 Apr 1988	5	Moderate	18 Oct 1997	-	Very High
16 Oct 1988	15	High	15 Jan 2000	-	Low
12 Mar 1990	-	Low	9 Dec 2002	-	Low
20 Oct 1990	35	High	27-31 Oct 2002	-	Moderate
22 Mar 1991	-	Moderate	3 Nov 2002	-	Low
Mar 93	-	High	15 Dec 2003	-	Low
Oct 93	-	High	5 Feb 2004	-	Low
1 Jan 1994	-	Moderate	29 Dec 2004	-	Low
2 Nov 1994	-	Moderate	24 Oct 2008	-	Low
17 Nov 1996	-	Moderate	17-18 Jan 2010	-	High
14 Jan 1997	-	Moderate			

thickness and composition of each layer are shown in Figure 2, which illustrates hydrogeological cross sections in the study area [39] [40] [41].

The Quaternary aquifer in the Wadi Watir delta is an unconfined aquifer in which the water depths range from 2.4 to 40.8 m [41]. The fresh water layer with a salinity of less than 2500 ppm attains a thickness ranging between 12 m near the outlet of the wadi to approximately 7 m in the middle part of the Wadi Watir delta, while values reach to about 4 m near the shoreline. Groundwater over pumping from the Wadi Watir delta aquifer has caused seawater intrusion that is controlled to some extent by factors such as the distance from the shoreline, hydraulic conductivity, and aquifer recharge conditions. The first water table map was constructed based on measurements of water levels from October to November 1994 by Himida (1994) [4], while the recent water level contour map was constructed based on measurements of water levels from October to November 2012 by Eissa *et al.* (2013) [40]. Generally, groundwater flows from the northwestern to southeastern parts of the Wadi Watir delta, and the absolute groundwater level ranges between 0 to 2.5 m above mean sea level (amsl) (see Figure 3(a) and Figure 3(b)). The groundwater hydraulic gradient in the study area varies between 2.3×10^{-4} in the south and 2.7×10^{-3} in the north with an average value of about 1.5×10^{-3}.

The hydraulic conductivity map was created based on the results of the pumping tests that had been carried out by the Desert Research Center [4]. As shown in Figure 4, the values of hydraulic conductivity ranged between 1 and

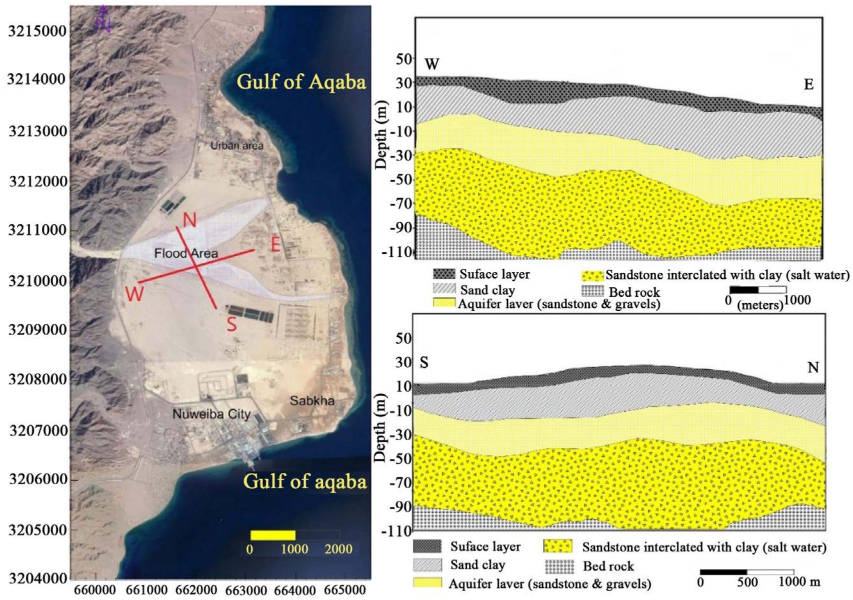

Figure 2. Hydrogeological cross sections showing that the upper two surface layers are composed of heterogeneous alluvial deposits with thicknesses generally less than 10 m, and the third layer is sandy clay with a thickness between 30 and 45 m. The fourth layer ranges between 20 and 40 m thick and is comprised of sand and gravel, while the fifth layer is comprised of sand interlayered with clay and ranges between 20 and 50 m thick.

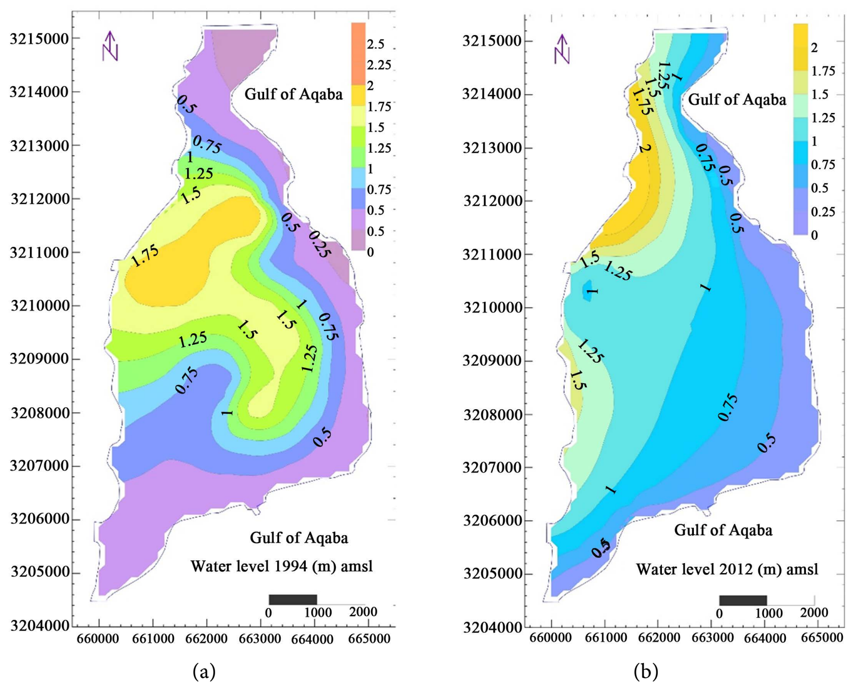

Figure 3. (a) Water level contour map of the study area in the year 1994 (after Himda, 1994); the water levels range from 2.5 m (amsl) near the outlet of the wadi to 1.5 m (amsl) in the middle part of the Wadi Watir delta, while levels are 0 m at the shoreline. (b) Water level contour map of the study area in the year 2012 (after Eisa, 2013); water levels range from 2.2 m (amsl) near the north of the wadi outlet to 1 m (amsl) in the middle part of the Wadi Watir delta, while levels are 0 m at the shoreline.

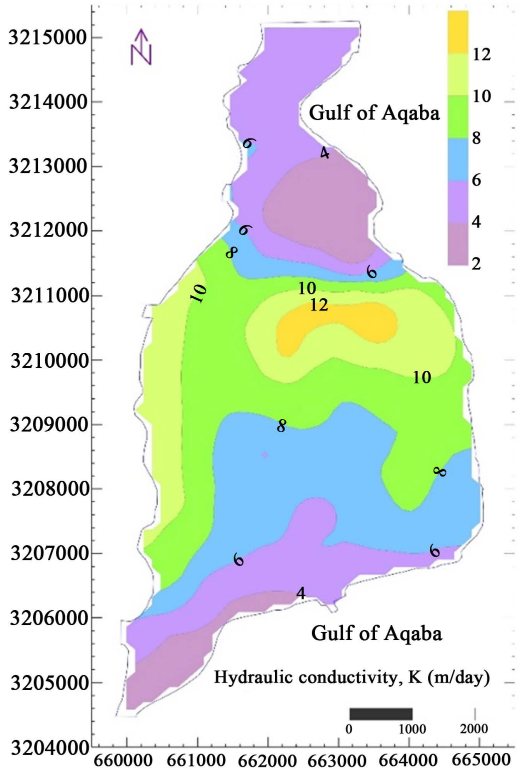

Figure 4. Hydraulic conductivity contour map in the study area, where low values (less than 4 m/day) were found in the north and south and high values (more than 12 m/day) were observed at the central part of the Wadi Watir delta.

12 m/day. Low values were found in the south and high values were observed at the central part of the Wadi Watir delta, whereas moderate values were observed in northern localities. The storativity of the water-bearing horizon in the Wadi Watir delta was estimated to vary between 3.16×10^{-4} and 0.01. The groundwater salinity map was created based on measurements taken in 75 shallow dug wells and deep wells distributed throughout the Wadi Watir delta. As shown in **Figure 5**, the values of groundwater salinity ranged between 2000 ppm and 8000 ppm. Low values of groundwater salinity were detected in the west at the wadi outlet and high values were observed at the eastern and southern parts of the Wadi Watir delta [34] [40].

3.3. Groundwater Recharge and Pumping

Groundwater natural recharge values have been estimated by many researchers such as [4] [5] [35] [36] [42] [43] [44]. The pumping rates in the study area varied through the period 1982 to 2012 depending on the groundwater availability and flash flood intensity and/or frequency. The average groundwater recharge in the Wadi Watir delta ranged between 3900 m^3/day (1982 to 1987) to 7770 m^3/day (1987 to 2002) with an annual daily average of 6000 m^3/day through the period from 1982 to 2009 (see **Table 2**). However, for each hand dug wells (40 hand dug wells), the pumping rates ranged between 0.5 and 7 m^3/day [40].

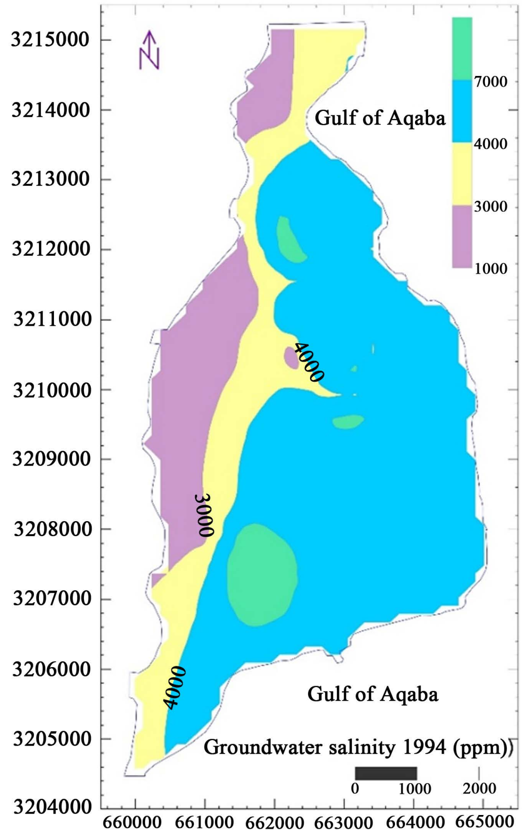

Figure 5. Groundwater salinity contour map in the study area, where low values (less than 3000 ppm) were found in the west and high values (more than 4000 ppm) were observed at the middle and eastern parts of the Wadi Watir delta.

Table 2. The amount of groundwater pumped from water supply wells on the delta (after Eissa et al., 2013).

Period	No. of Working Wells	Withdrawal Q m^3/Day
Feb 1982 to Feb 1986	1	870
Feb 1986 to Jun 1987	4	3640
Jun 1987 to Dec 1994	5	3900
Dec 1994 to Dec1998	5	2500
Dec 1998 to Dec 2001	6	1600
Dec 2001 to Dec 2008	6	1600
Dec 2008 to Apr 2009	5	1400
Apr 2009 to Apr 2013	5	1400

4. Groundwater Flow Model

4.1. Conceptual Model

To assess the hydrogeological suitability of installing ASR systems in the Wadi Watir delta, a numerical groundwater flow and transport model was developed to simulate the horizontal and vertical groundwater movement and upward migration of deep saline groundwater due to groundwater pumping and seawater intrusion; then, simulations of the mixing process between injected water and ambient groundwater were conducted because this process is one of the main factors governing the recovery efficiency in ASR systems. Finite-difference code MODFLOW linked to the particle tracking code MODPATH and solute transport code MT3DMS (Codes link https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs?qt-science_center_objects=0#qt-science_center_objects) were used; all three codes were run by using the graphical user interface. Visual MODFLOW flex 6, (https://www.waterloohydrogeologic.com/introducing-visual-modflow-flex-6-0) which is capable of simulating the groundwater flow in cases of injection and recovery water, was also used. MODPATH uses the average linear velocity calculated from heads that are generated by MODFLOW to track the movement of imaginary particles that are added to the injected water by advection. These particles were tracked throughout the duration of the storage and recovery cycles [45]. In order to quantify the volume of injected water recovered from the aquifer, the transport code MT3DMS was used to calculate the concentrations of water in the aquifer while considering both advection and dispersion and assuming that the aquifer is an equivalent porous medium with connected pore space; the code also assumes miscible flow and no density effects.

In the horizontal direction, an orientation grid (100 rows × 50 columns) along the north-south axes and east-west axes of the modeled area was created (see Figure 6), while in the vertical direction, the model grid consisted of two layers. The first layer with a hydraulic conductivity of 4 m/day represents the alluvial deposits, and the second layer was comprised of Pliocene to Pleistocene aged sand with a hydraulic conductivity from 4 to 12 m/day [34]. For each layer, the vertical hydraulic conductivity values were assumed to be one-tenth of the values of the horizontal ones. Aquifer materials were assumed to be homogeneous and mainly composed of poorly sorted sand, silt, gravel, and clay; hence, the total

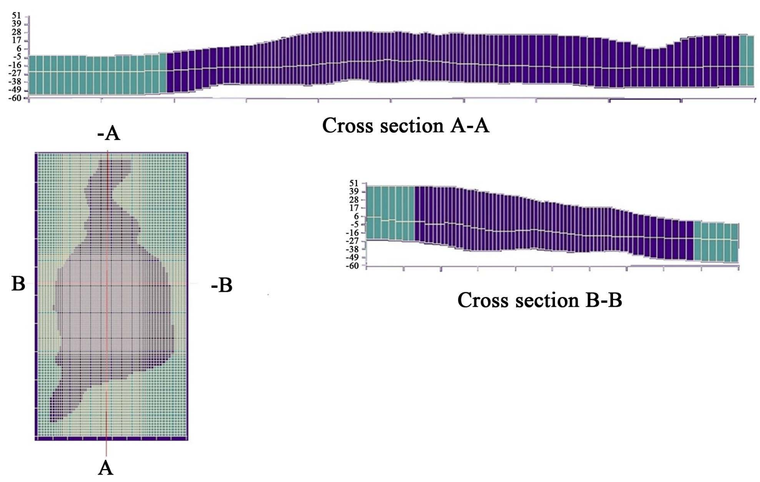

Figure 6. Developed model mesh and cross sections for the study area.

porosity was set to 0.1 [46] [47]. The storage coefficient value used for the model ranged from 3.16 × 10^{-4} to 0.01; also, the longitudinal dispersivity was assumed to be homogeneous and set to 10 m, the ratio of horizontal transverse dispersivity to longitudinal dispersivity was assumed to be 0.1, and the ratio of vertical transverse dispersivity to longitudinal dispersivity was assumed to be 0.01 [48].. The diffusion coefficient was assumed to be 9 - 10 cm/s [40]. The 10-m longitudinal dispersivity according to Gelhar (1992) was located within the category of high confidence in the small-scale field suite (1 - 1000 m) and in the category of low confidence for the entire scale of the Wadi Watir delta (for large scales of 10^3 - 10^6 m) according to contaminant events tracer tests [48].

4.2. Boundary and Initial Conditions

The model base was assumed to be the NO flow boundary, and for the flow and transport model, the constant head boundary was set to sea level at the shoreline, where the constant concentration was assumed to be 41,000; meanwhile, the western boundary was set to the source points boundary with a concentration value of 1000 ppm [40]. An initial water level map for the steady state was created from the values of the water levels that were measured in February 1986 [37]. Steady state conditions of groundwater flow and solute transport models were identified from simulations under initial conditions until reaching system stabilization and equilibrium for salt and physical flow within the models. The groundwater salinity values, which were obtained from the steady state, were modified with the salinity data for deep saline groundwater from an earlier study [34], where salinity reached 18,000 ppm at a depth of 34 m below sea level. In accordance with the data availability, simulations were carried out for the period from 1982 to 2012. Figure 7 shows the boundary condition observation points and abstraction wells for both the flow and transport models.

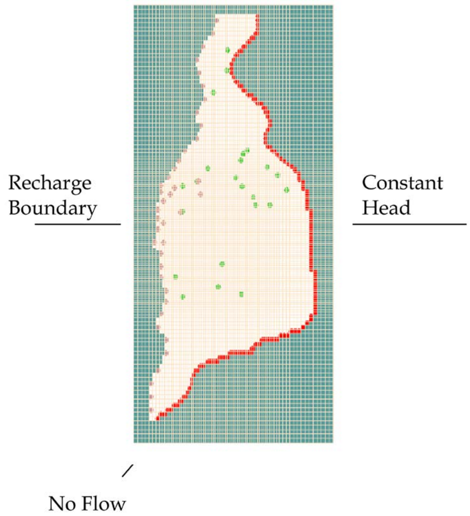

Figure 7. Model boundary conditions. The constant head boundary was set to sea level at the shoreline, and the constant concentration was assumed to be 41,000 ppm; the western boundary was set to the source points boundary with a concentration value of 1000 ppm.

The natural recharge in the model area was assumed to be zero because the annual average rainfall for the Wadi Watir area only ranges from 10 mm/year in the Wadi Watir delta to 50 mm/year in the highland areas [35]. On the other hand, the main recharge to the aquifer comes mainly from subsurface groundwater flow from the mountain blocks [5] [49], and the main source of subsurface recharge is flash floods that occur on average about every six years [4].

4.3. Model Calibration and Validity

The comprehensive groundwater flow and solute transport model that was developed was calibrated by obtaining general agreement between the observed and modeled salinity and water level values; this model was found to be more sensitive to porosity, hydraulic conductivity, and dispersivity values than the other factors. The recharge was the main factor controlling the head, while the recharge rates, pumping rates, dispersivity, and effective porosity were the main factors controlling the salinity. A total of 37 head observations [5] [34] [40] were used to calibrate the model in addition to the salinity observations (see **Figure 8**). The pumping rate through the drilled wells changed with time (8% to 15%) for each stress period through the modeled time (1982 to 2012) according to the original data that were collected. The model calibration was complete when a reasonable value of the relative error of less than 10.5% was achieved between the modeled and observed water levels. The sensitivity of the model was tested to the full range of hydrogeological and operational parameters. The model was found to be valid for most regions within the model area except for the area close to the coast and the area located in the Sabkha deposits.

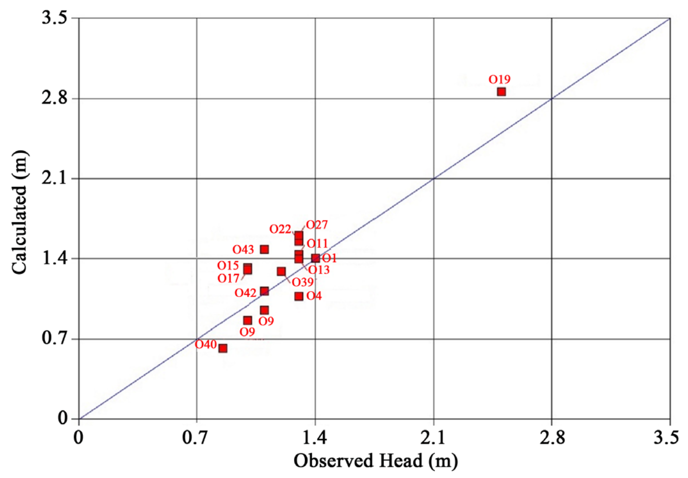

Figure 8. Measured versus model calculated water levels in cells in the groundwater flow model that contained wells. The relatively high error values obtained between the measured and simulated heads mainly can be attributed to the highly transient state throughout long-time periods, which occurred because of extensive pumping through the drilled wells located close by with in-between distances ranging from 250 to 500 m. Moreover, the flat-water level in the Wadi Watir delta, where the maximum water level relative to sea level was 2.4 m and the minimum was 0.21 m, with a mean average value of 1 m, made it difficult to obtain head observations that matched the calculated ones.

5. Results

The calibrated numerical model that was developed was used to evaluate the effects of hydrogeological and operational parameters on the recovery efficiency of ASR systems at five proposed locations in the study area (see **Figure 9**); these parameters included the regional hydraulic gradient, hydraulic conductivity, effective porosity, dispersivity, storage period, and volume of injected water. The mixing of injection water with ambient groundwater was also evaluated, where the salinity of the injected water was assumed as 1000 ppm, while the salinity of the ambient groundwater was assumed as 2500 ppm. Because the estimation of the recovery efficiency depends on the salinity of the recovered water, the recovered water salinity limits was set to 150% of the injected water salinity, where the 150% limit refers to the point at which recovery has ended because the concentration of recovered water reached 150% of that of injected water.

5.1. Effect of the Hydrogeological Parameters

The ASR systems were simulated in five specific locations in the Wadi Watir

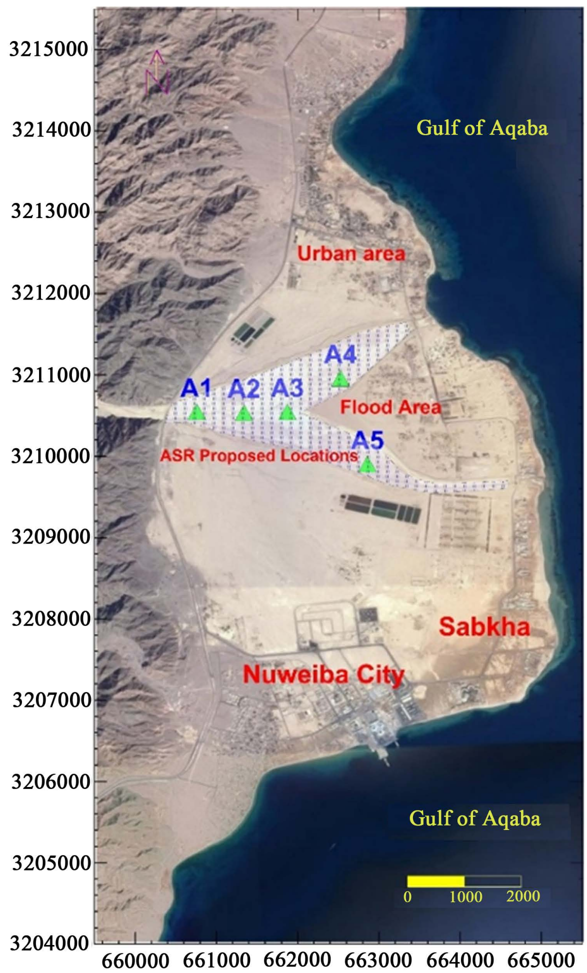

Figure 9. The proposed sites for testing the ASR systems; sites were selected in the flood zone and far from the Gulf of Aqaba, near Sabkha and the urban area.

delta by using different injection rates. The relative effects of selected hydrogeological parameters on the recovery efficiency were similar to those discussed by Lowry (2004) [50]. Notably, the dispersivity that describes the mixing process was one of the hardest parameters to quantify in terms of the recovery efficiency impacts in ASR systems. Thus, the effects of recovered water salinity on the recovery efficiency of ASR systems were evaluated at the five locations with different dispersivity values of 3, 10, 20, 50, 100, and 200 m. **Figure 10** shows the effects of dispersivity on the recovery efficiency of the aquifer model with a total volume of injected water of 12,000 m^3 and a storage period of 180 days.

5.2. Effect of the Operational Parameters

The main operational parameters that affected the recovery efficiency were the storage period and the volume of injected water, as shown in **Figure 11**, where the recovery efficiency decreased as the storage period increased; **Figure 12** shows that the recovery efficiency initially increased as the injected water volume increased, but then it decreased with large volumes of injected water because of the high hydraulic gradients created by water moving away rapidly from the ASR areas.

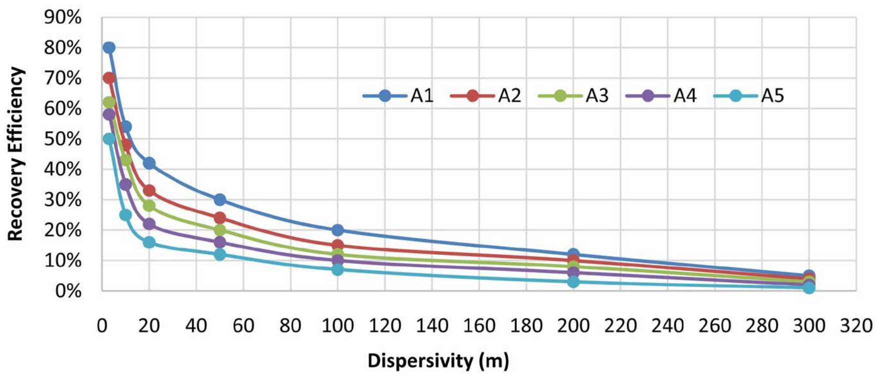

Figure 10. Effect of dispersivity on the recovery efficiency of the aquifer model with a total volume of injected water of 12,000 m^3 and a storage period of 180 days.

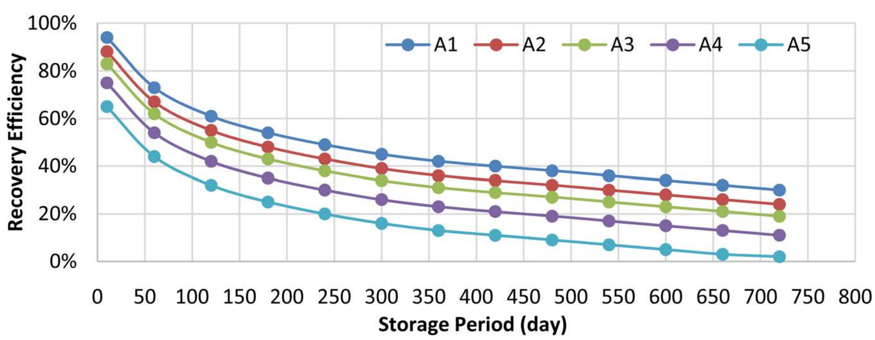

Figure 11. Comparison of the effect of the storage period on the recovery efficiency at five locations with a longitudinal dispersivity of 10 m, volume of injected water of 12,000 m^3, and a recovery concentration limit of 150% of injection water All simulations included the effects of advection and dispersion.

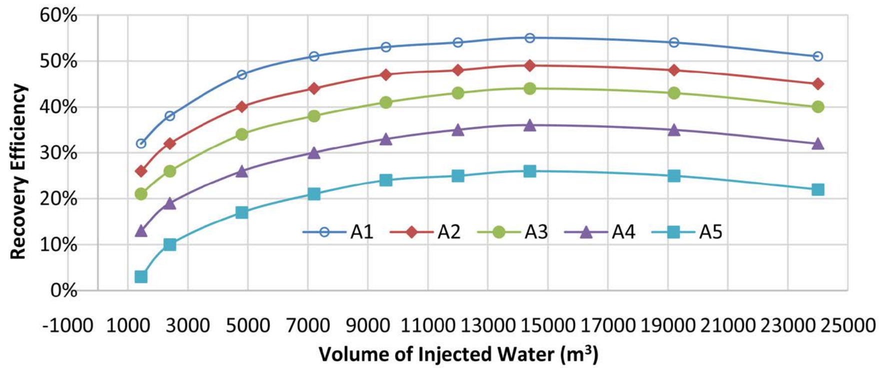

Figure 12. Comparison of the effect of the volume of injected water on the recovery efficiency at five locations with a longitudinal dispersivity of 10 m, storage period of 180 days, and a recovery concentration limit of 150% of injection water. All simulations included the effects of advection and dispersion. Table 3 shows that the recovery efficiency of the ASR systems at the five locations ranged from 25% (at A5) to 54% (at A1) with a longitudinal dispersivity of 10 m, volume of injected water of 12,000 m^3, and storage period of 180 days.

Table 3. The ASR recovery efficiency at selected locations in the study area. Results show that the recovery efficiency of the ASR systems in the study area was generally low for specific injection quantities and storage periods, and the recovery efficiency was highest in area A1 and lowest in areas close to the sea because of the impact of sea water intrusion and the lack of thickness of the target storage layer.

Parameter	A1	A2	A3	A4	A5
Injected layer thickness (m)	10	7	5	4	4
Hydraulic gradient	0.0004	0.0004	0.00063	0.00047	0.00047
Hydraulic conductivity (m/day)	9	10	11	11	9
Dispersivity (m)	10	10	10	10	10
Period of storage (day)	180	180	180	180	180
Volume of injected water (m^3)	12,000	12,000	12,000	12,000	12,000
Volume of recovered water at salinity limit 150% of injected water (m^3)	6840	5760	5160	4200	300
Recovery efficiency	54%	48%	43%	35%	25%

6. Conclusions and Recommendations

- Although the salinity of recovered water depends on the mixing process between the injected water and ambient groundwater, the dispersivity that describes this mixing process is one of the hardest parameters to quantify.
- Using coupled numerical groundwater flow and solute transport models is an effective tool for predicting the effects of mixing between the injected water and ambient groundwater in assessments of the recovery efficiency of ASR systems.
- The groundwater aquifer in the study area is not suitable as a strategic water storage site for ASR systems because the thickness of the water storage layer is relatively small and the distance to the sea is very close; consequently, it is

recommended that alternative artificial recharge systems be developed with existing technology to replenish the groundwater aquifer in the Wadi Watir delta.

- More research is required to evaluate the effective porosity that is inversely related to groundwater velocity and directly affects the recovery efficiency as well as the dispersivity, which is a difficult parameter to quantify as it can vary over a much smaller range than the other parameters and directly affects the recovery efficiency.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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