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Case Report

Optimized Pumping Strategy for Reducing the Spatial Extent of Saltwater Intrusion along the Coast of Wadi Ham, UAE

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Received: 2 March 2020; Accepted: 21 May 2020; Published: 24 May 2020

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Abstract: Many coastal aquifers are facing severe anthropogenic impacts such as urbanization, industrialization and agricultural activities are resulting in a saltwater intrusion. This establishes the need for a sustainable groundwater management strategy aimed to overcome the situation. Pumping of brackish/saline water to mitigate saltwater intrusion is a major potential approach to effectively control saltwater intrusion. However, this method has many challenges including selection of appropriate discharge rates under an optimum number of pumping wells and at specified wells distance from the shoreline. Hence, this study developed a Finite Element Flow and solute transport model (FEFLOW) to simulate three scenarios to assess the most appropriate pumping rates, number of wells and optimum well locations from the shoreline. These parameters were assessed and evaluated with respect to the change in groundwater saline concentration at different distance from the coastline. The 15,000 mg L^{-1} isosalinity contour line was used as a linear threshold to assess the progression of saltwater intrusion along three major locations in the aquifer. Scenario One was simulated with a constant number of wells and rate of pumping. Shifting of pumping wells to several distances from the shoreline was conducted. Scenario Two assessed the most appropriate number of pumping wells under constant pumping rates and distances from the shoreline and in scenario 3, the optimum pumping rates under a constant number of wells and distance from the shoreline were simulated. The results showed that the pumping of brackish/saline water from a distance of 1500 m from the shoreline using 16 pumping wells at a total pumping rate of 8000 m^3 d^{-1} is the most effective solution in contrasting the saltwater intrusion in the Wadi Ham coastal aquifer.

Keywords: coastal aquifer; numerical model; optimum pumping rates; saltwater intrusion; Wadi ham; UAE

1. Introduction

The United Arab Emirates (UAE) is in the Middle East and bounded by the Gulf of Oman and the Arabian Gulf. It has a total area of about 83,600 km^2 (Figure 1) located between 22°50′ and 26° North and between 51° and 56°25′ East. The country is in an arid climate zone which is characterized by limited rainfall, high temperatures, high humidity as well as high evapotranspiration. The UAE geomorphologic features include mountains, gravel plains, sand dunes, coastal zones and drainage basins [1]. Groundwater resource is highly influenced by geomorphic features such as potential groundwater resource with high recharge capability nearby Mountains at the east, available of freshwater as a lens in the dune surfaces and poor quality of groundwater near the coastal region due to the presence of Sabkha, a flat silty formation which lacks rainfall recharge [2]. The country has limited water resources and is faced with declining groundwater resources in both quantity and quality [3,4]. Agricultural activities consume about 80% of the available groundwater with total usage of 950×10^6 m^3, 1300×10^6 m^3 and 1400×10^6 m^3 in 1990, 1995 and 2000, respectively [5]. Overexploitation of groundwater for agricultural and domestic activities have resulted in freshwater resource depletion. In recent decades, UAE has turned in to one of the leading consumers of desalinated water [6]. Still, the contribution of groundwater for domestic and agricultural activities continues and exceeding the estimated rate of natural recharge in UAE, i.e., ranges from 130 to 190 [5,7]. In the year 2010, Abu Dhabi, one of the emirates in UAE itself utilized more than 2000×10^6 m^3 volume of water for agricultural activities [8]. The excess desalinated water from a constant rate of production and seasonal reduction in the water demand allows for the installation of artificial recharge structures such as open infiltration pond, aquifer storage and recovery (ASR), etc. The contribution of desalinated water is increasing in year in year out. However, the groundwater abstraction which is higher than the natural or artificial recharge rates causing groundwater salinization, especially along the coastal aquifers due to lateral saltwater intrusion and upconing [9]. The low level of precipitation plus high temperatures also results in severe shortage in the quantity of groundwater [10,11].

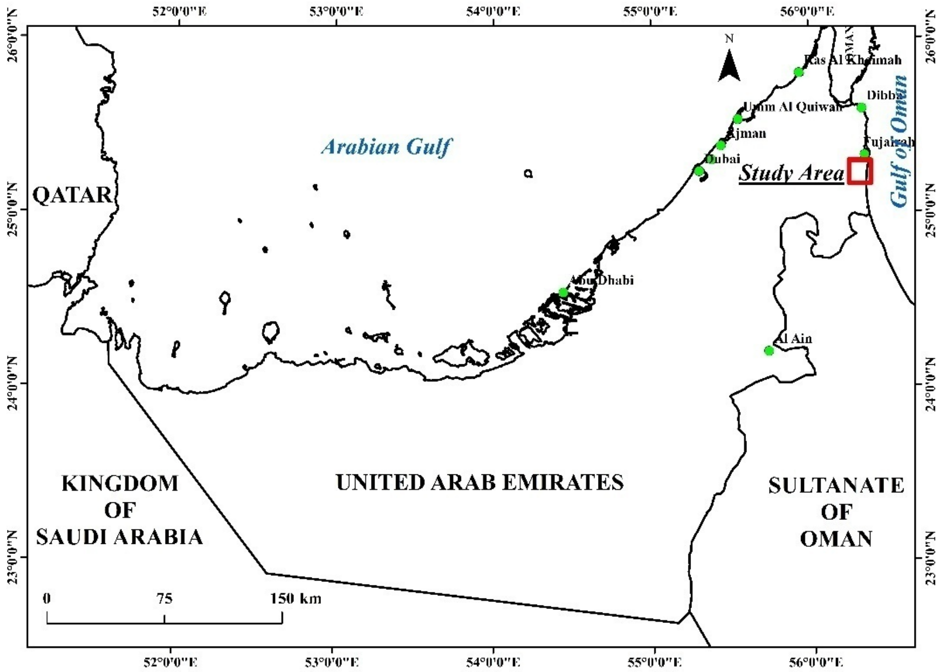

Figure 1. Location map of the United Arab Emirates and study area (bounded by red rectangle).

The study area of Wadi Ham, in the northern coastal part of UAE (Figure 1), has a catchment of 192 km^2. The main land uses are natural areas, irrigated agricultural lands and artificial surfaces (urban areas). The coastal aquifers have been extensively pumped for agricultural activities happening in the plains, in the areas along the Wadi, a non-perennial river channel and in the areas near the coast in addition to the industrial developments in the vicinity of the coastal zone. Water demand for all the above purposes is increasing, while the quality and quantity of existing available groundwater supplies are decreasing. Over the last two decades, there was a tremendous decline in the groundwater levels in the coastal aquifer of Wadi Ham [12]. This decline is also associated with limited aquifer recharge and resulting to significant deterioration in the groundwater quality due to saltwater intrusion.

As a result of this saltwater intrusion many wells have already been terminated and several farms were abandoned during the last decade. Unfortunately, additional artificial recharge structures or implementation of aquifer storage and recovery (ASR) is not under progress in this economically viable aquifer [13]. Finally, water desalination was left as the ultimate source of water supply in the study area as in most parts of the UAE. The use of treated wastewater to irrigate non-edible plants and greeneries are well underway in the area. Furthermore, studies and efforts are ongoing to prove and reassure the public that treated wastewater is suitable to irrigate edible crops and plants. Although it is worth mentioning that mentioning that this is mainly an issue because of cultural and religious beliefs. Another important management and mitigation strategy employed in the area is the use of brackish water to irrigate salt-tolerant crops such as quinoa [14,15]. Besides all, the improvement in the groundwater level and quality is still under the way and those benefits will strictly depend upon further mitigation measures that have to be adopted.

Based on the recent review by Hussain et al. [16], withdrawal reduction and relocation of pumping wells, physical surface or subsurface barriers, artificial recharge, abstraction of saline water along the coast, a combination of previous techniques [16] and subsurface water technologies (SWT) [17] are available methods of mitigation measures. The development of subsurface water technologies (SWT) provide robust, effective and cost-efficient solutions for freshwater management in coastal zones. In particular, "Fresh keeper" and "Fresh maker" proposed techniques extract brackish water to save or increase the coastal freshwater resources [17]. All these techniques have strengths and weaknesses. The choice of method is ideally determined by the nature of problem, availability of information and by the potential existence of the selective area. The selection criteria should strictly analyze not only the methodology, but also the geological settings, social and economic background of the operative site.

The present study examined the pumping of brackish water to mitigate saltwater intrusion aimed at halting saltwater intrusion and leading to the displacement of the dispersion zone or freshwater–saltwater interface. The dispersion zone is a saturated zone that is located between freshwater (salinity < 1 g L^{-1}) and saltwater (salinity > 35 g L^{-1}). The zone is also called "transition zone" ranging from few centimeters thick along the shoreline to several meters thick towards the inland. Starting from two decades ago, an abstraction of brackish water from the dispersion zone as a measure of saltwater intrusion control was experienced in several sites, especially in the country where energy supply is a low-cost asset [18–21].

Since the study area had gone through tremendous stress, it was investigated by several authors. Sherif et al. [12] has studied the response of groundwater quality to 50% increase and decrease in the validated groundwater pumping using a 2-dimensional numerical flow and solute transport model. The migration of transition zone was identified as a response to a decrease in the groundwater pumping. Meanwhile, the quantification of freshwater has also been done. To advance the investigation, the authors tried earlier to investigate one of the existing techniques called "brackish water pumping" to control the saltwater intrusion in the study area [22]. Using a 3-dimensional numerical model, the response of groundwater quality to a defined rate of pumping and number of wells located at a fixed distance from the shoreline was investigated in the previous study. However, this method is not yet well understood due to existing knowledge gap in terms of the required brackish water discharge rates at optimum, locations of pumping wells and time duration analysis [19]. Finding the response of aquifer to a varying rate of brackish water pumping, number and position of wells from the shoreline is important to identify the optimization in the proposed mitigation measures. The appropriate pumping rates, number and location of pumping well within the zone of brackish water from the shoreline will mitigate saltwater intrusion by which the freshwater storage will be retained in the study area.

The numerical model was developed by finite element approach using FEFLOW [23], one of the simulators widely used for saltwater intrusion and other density-dependent groundwater flow and transport problems in the world [24]. The 15,000 mg L^{-1} isosalinity contour line was used as a linear threshold to assess the shifting of saltwater zone in the aquifer after 4018 days of simulation. Three different scenarios were run and results were evaluated in order to find the best and most efficient combinations of the number of wells, pumping rates and well distance from the shoreline to reduce saltwater intrusion in the shallow coastal aquifer and move freshwater–saltwater interface towards the sea. The outcome of this study has a relevant impact and benefits for the sustainable water management of this coastal aquifer.

2. Geological and Hydrogeological Setting

Wadi Ham, is an arid region that facing temperature from 10.8 °C to 50.2 °C. It is located at the south and southeast of the Masafi Mountains and draining southeast into the sea "Gulf of Oman". The enclosing mountains are acting as the catchment zone composed of valleys and steep slopes leading down to the study area [25]. The study area is a flat-gravelly plain with a triangular shape broadening the mountains and sea. It is the passage of three wadies derived from the mountain and draining into the sea through temporary surface flow during high-intensity rainfall and through subsurface flow (Figure 2). The elevation rises from sea level to 100 m above sea level towards the northwest foothills of Masafi Mountain. At upstream of the coastal plain, the land becomes a river terrace or alluvial plain and locally dissected by the number of stream channels filled with cobble and gravel that decreasing towards the coast. The coastal plain is used for extensive agricultural activities and for the development of new industries [25]. Aquifer recharge takes place in three ways (i) rainfall recharge (ii) infiltration from the ponding area and (iii) inflow from the three wadies draining from the enclosing mountain. The average annual rainfall in the recent decade has become less than 80 mm yr^{-1} because of worldwide changes in the climate condition that is being proved by several researchers. Even before, the average rainfall in this arid region was only about 150 mm yr^{-1} with a range between 20 and 506 mm yr^{-1}.

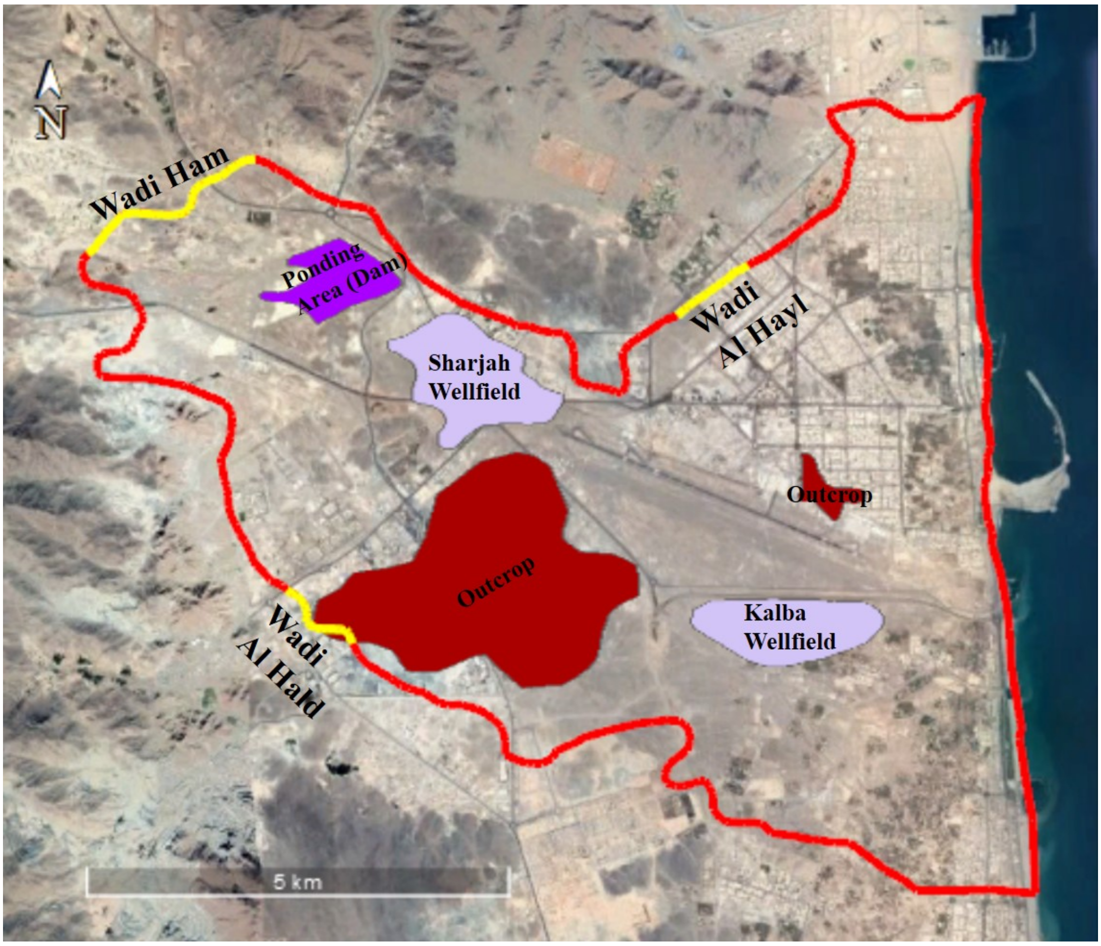

Figure 2. Land satellite image of Wadi Ham area including main features (Revised from Sherif et al., 2014).

Based on the interpretation of the available hydrological data [26], two Quaternary formations are present in the study area (Figure 3). A shallow formation, consisting of gravels, followed by hydrogeologically connected sandy formation. The extent of unconsolidated formation ranges with the depth. These quaternary formations are overlapping the Ophiolite sequence where groundwater potential is least and considered as impermeable. Figure 4 shows several subsurface cross-sections along different directions constructed to examine the geology of the aquifer with the location of respective wells in the study domain shown. As shown in Figure 4, the thickness of Wadi gravel in Wadi Ham varies from 18 m at the upstream side of the dam to about 100 m near the coast. Electrowatt [26] subdivided this gravel layer into recent gravels, being slightly silty sand and gravel with few cobbles. Hydraulic conductivity of the unconsolidated gravels tends to be high, typically ranging from 6 to 17 m d^{-1} and in the range 0.086 to 0.86 m d^{-1} for the cemented lower layers [26,27].

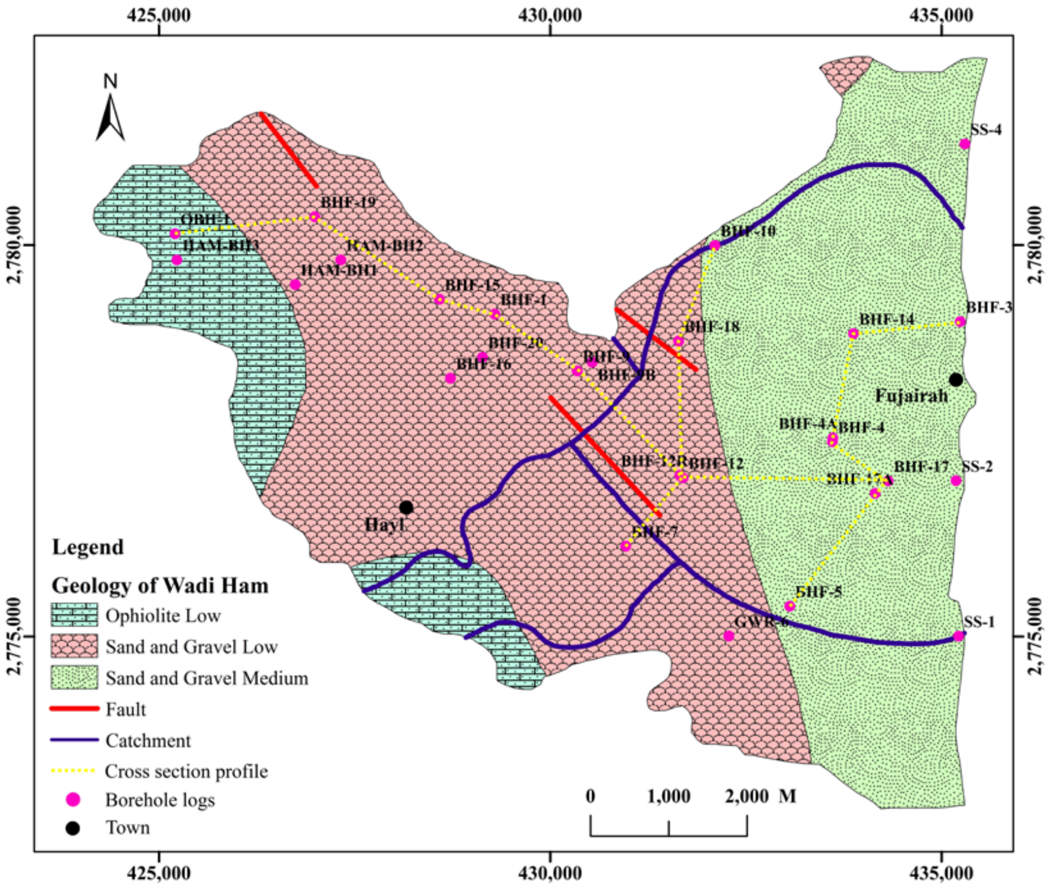

Figure 3. Geological map of Wadi Ham [26].

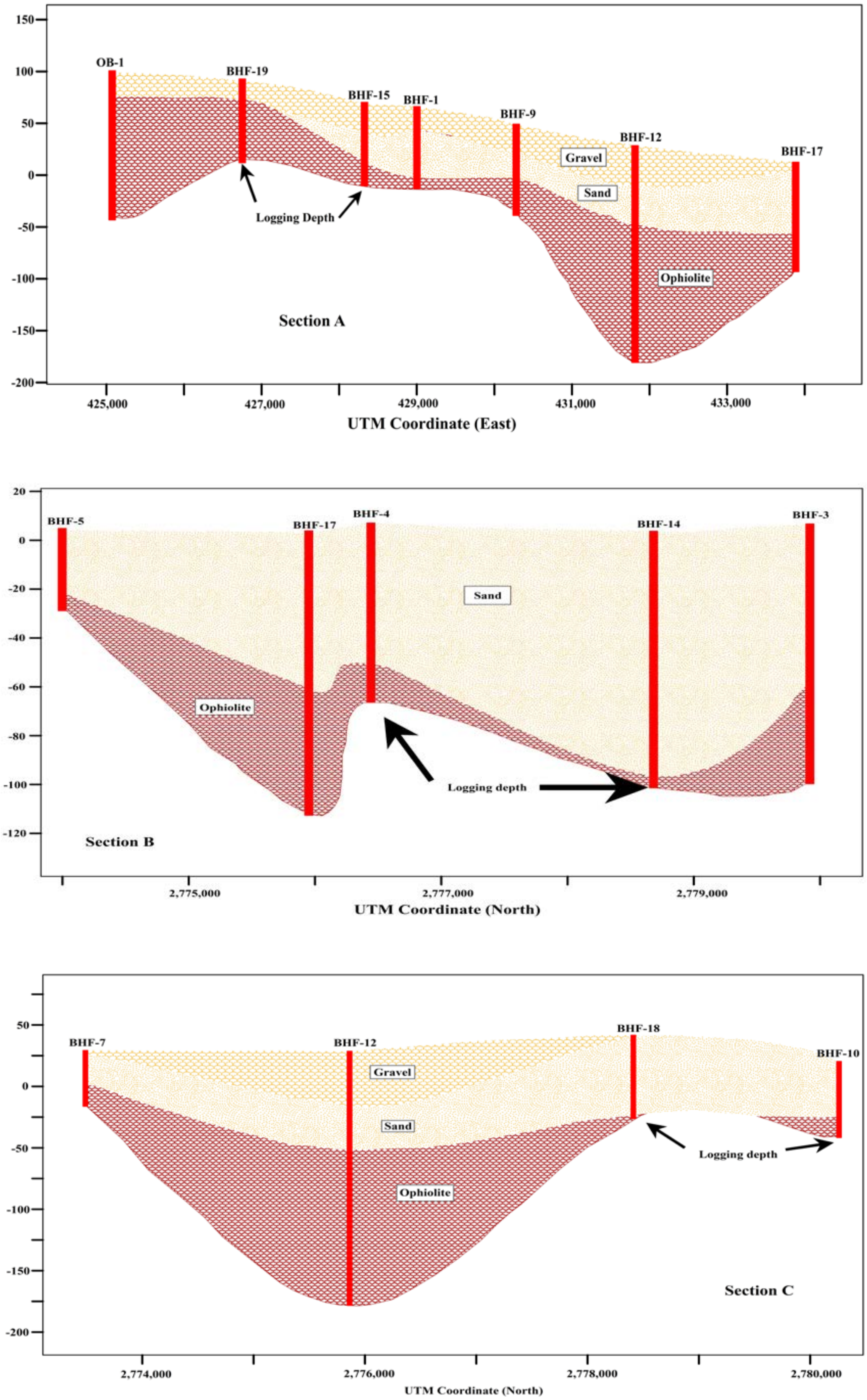

Figure 4. Several geological cross-sections across Wadi Ham [28].

3. Methodology

3.1. Model Code Selection

This study employed the numerical code FEFLOW to simulate 3D groundwater flow and solute transport in the study area. FEFLOW is a finite element groundwater modeling software package for modeling fluid flow and transport of dissolved constituents in the subsurface [23,29]. FEFLOW was selected as the preferred code for its flexibility in generating the mesh. It is an efficient tool in groundwater modeling that contains pre- and post-processing functionality with adequate simulation engine [24,30]. It also possess a public programming interface for user code, user-friendly in the spatial discretization of irregular boundaries, coarse discretization and editable to match the geometry, better control on numerical errors with a graphical interface that provides easy access to the extensive modeling options. Hence, FEFLOW was engaged to study a seawater intrusion by many researchers because of its compatibility in dealing with complex aquifer setup. Barazzuoli et al. [31] had investigated the causes of seawater intrusion in the multi-aquifer system of Albegna River coastal plain at Southern Tuscany, Italy. Similarly, Sefelnasr and Sherif [32], Sathish and Elango [30], Rajaveni et al. [33], Idris et al. [34], Sowe et al. [22] were used FEFLOW software for the development of a numerical model to investigate the present and future scenarios of seawater intrusion.

3.2. Conceptual Model Development

The model domain was conceptualized as unconfined single layer system. The aquifer is composed of Quaternary formation. The Wadi gravel is dominantly present in the upper part of the aquifer and capped by a thin high conductive semi-porous layer in some locations [12]. Further deep, the aquifer is dominantly composed of sand. The maximum thickness of these collective Quaternary formations goes up to 100 m towards the coastal boundary and overlying a thick impervious layer of the Ophiolitic sequence. Therefore, a single layer model composed of wadi gravel and sand was considered for the model development. The layer bottom of the model was kept as impermeable due to the presence of impervious Ophiolitic sequence.

The flow of groundwater occurs from west to east towards the coastal boundary. Moreover, groundwater elevation varies between 87 m along the western boundary and 0 m along the coastal boundary. Boundaries of the study domain were delineated and the boundary conditions adopted were the same as shown in Figure 2. Three inflow boundaries with a specified flux of 450 m^3 d^{-1} at Wadi Ham, 380 m^3 d^{-1} at Wadi Al Hyad and 370 m^3 d^{-1} at Wadi Al Hald [12] were assigned. The quantification of recharge across three wadies was extracted from Sherif et al. [12] and recharge across the wadies occurs during the rainy season. The wadies are normally dry during the rest of the year. The remaining sides of the domain were marked as no-flow boundary as shown in Figure 5 due to the presence of distinct physical boundaries such as bordering of sedimentary formations (gravel and sand) by hard rock formations. The area occupied by the Gulf of Oman about 12.6 km of shoreline in the model domain was considered as constant head boundary elements with a sea level (0.0 m) for the entire period of calibration and scenario studies. Figure 2 shows the Ophiolite outcrops covering an area of 6.56 km^2 which were specified as inactive or impermeable areas (Figure 6).

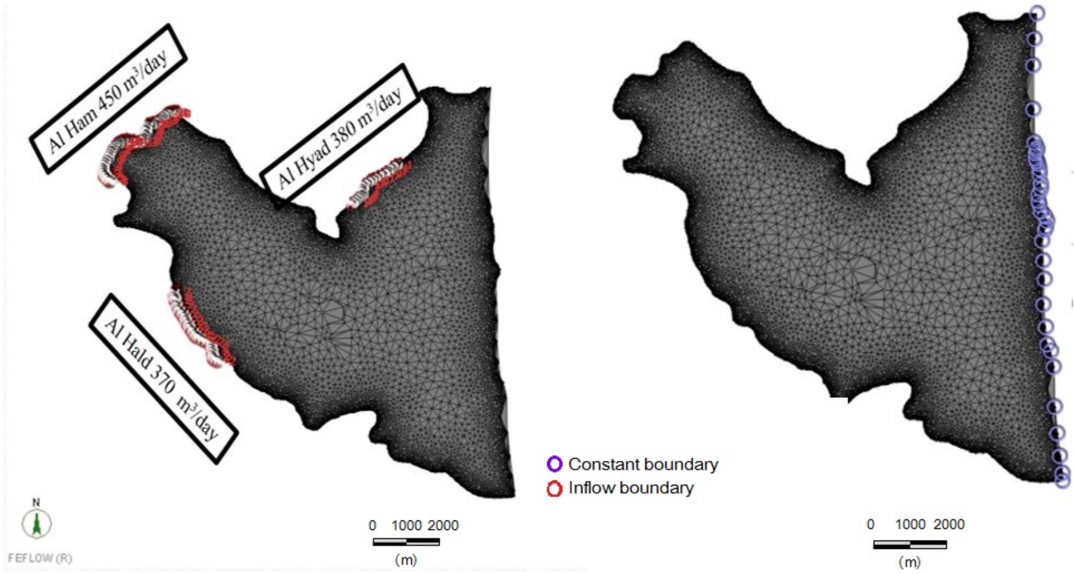

Figure 5. Inflow (red) and constant (blue) boundary conditions used in the model development.

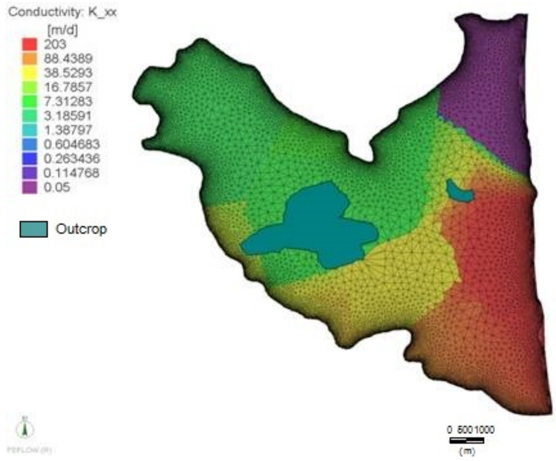

Figure 6. Hydraulic conductivity distribution obtained by pumping test [28].

3.3. Flow Model Calibration

More historic groundwater level data was reported from the period of May 1996 [28] and was considered as initial groundwater level. The aquifer parameters obtained from the field test were used as additional inputs in the model development. The model was calibrated in the steady state by altering the hydraulic conductivity within a range of ±10% from the values obtained by the pumping test (Figure 6). The one-tenth of hydraulic conductivity is employed as vertical hydraulic conductivity. Initial groundwater level was compared with the results of the steady state simulation. An ultimate match was obtained by a series of trial and error attempts.

The aquifer parameters that were confirmed after a steady state calibration were reloaded as input for the purpose of flow model calibration. Similarly, groundwater level data that was used for steady state calibration was again used as initial hydraulic head. A recharge factor such as soil property, topography, Wadi, etc., are considerably supporting aquifer recharge, but very minimum compared to the rate of extraction. A rainfall recharge, ponding infiltration (35%) and perennial Wadi inflow are the sources for aquifer replenishment [35]. A 20% of measured rainfall (mm d^{-1}) was assigned to all active cells daily during rainy days only. It was applied to the entire model domain except in the area where impermeable ophiolite formations are outcropped. The ponding area was delineated and storage was distributed in space over the nodes located within the ponding area (0.40 km^2) [12,22]. In the recent decade, the storage in the ponding area occurs only a few days due to sparse rainfall. The period of flow model calibration was 8 years from the period of May 1996 to April 2004. The observed groundwater levels during the same period were used to validate the model accuracy. The rates of abstraction were not uniform and few wells were abandoned due to dryness which were not considered for the purpose of calibration.

The occurrence of model accuracy is necessary to ensure realistic prediction during the scenario studies. Flow model calibrated results for well number BHF-1 at upstream and BHF-12 at downstream are presented in Figure 7. The accuracy of the model was obtained with the R^2 value of 0.889 and 0.962 in the upstream and downstream of the aquifer. The decline in the groundwater level is strongly noticed in the downstream due to heavy extraction for domestic and agricultural activities. The heavy decline in the groundwater level had led to the dryness of few wells.

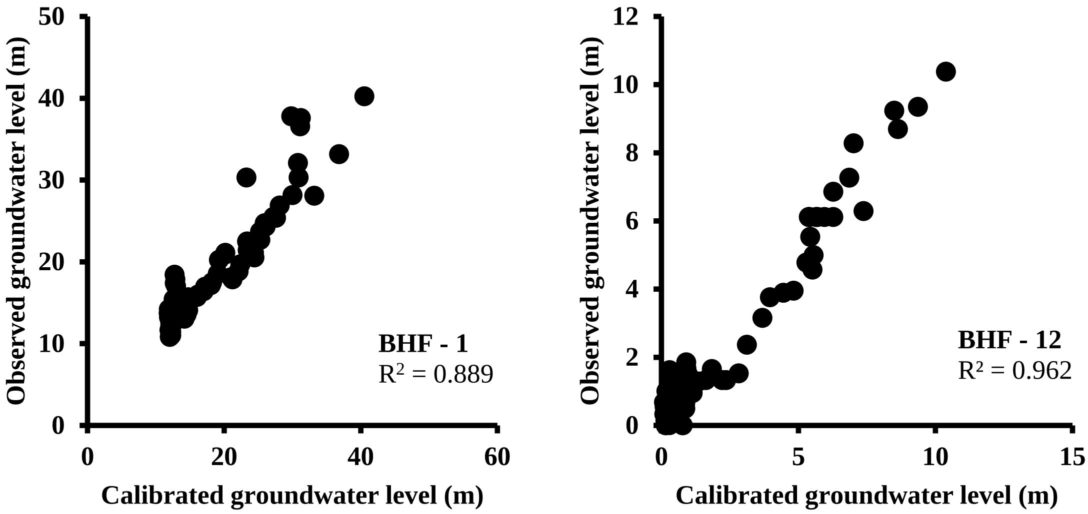

Figure 7. Observed and calibrated groundwater level at upstream (BHF-1) and at downstream (BHF-12).

3.4. Solute Transport Model Development and Calibration

A conservative solute transport model was developed in the study of pumping brackish/saline water from coastal aquifers to control saltwater intrusion. Factors inputted in the model include the retardation factor, taken as 1.0, is defined as the ratio of the average linear velocity of groundwater to the movement of the contaminant to deviate from groundwater motion. This means that the solute was considered to move with the same velocity of the groundwater. The other input parameter was the molecular diffusion coefficient which was set to be equal to 1×10^{-9} m^2 s^{-1}. The longitudinal dispersivity was varied for calibration between a range of 10 and 80 m [12]. A representative medium of the system was obtained with a longitudinal dispersivity of 65 m after several attempts. While comparing the hydraulic conductivity of aquifer, it is less than the value of hydrodynamic dispersion, a solute transport from higher concentration gradient to lower concentration gradient in most of the area other than southeast part where hydraulic conductivity is higher than the value of hydrodynamic dispersion. Hence, other than southeast part, hydrodynamic dispersion is dominant. An extinction depth of 2 m from the ground surface was assumed to allow evapotranspiration. Along the boundary, the evapotranspiration induced concentration changes were not considered due to the presence of groundwater level deeper than 2 m. The calibrated transport simulation parameters are shown in Table 1.

The initial salinity concentration in groundwater measured in December 1988 was used in the numerical model as presented in Figure 8. Along the coastline of the Gulf of Oman; a concentration of 35,000 mg L^{-1} of salinity was considered. A freshwater concentration of 100 mg L^{-1} was considered where a freshwater flux is encountered through the main three Wadi flux areas. Other than the Wadi flux areas, concentration flux across the boundary is set to be zero. Simulation results at the end of verification period showed that the salinity concentration in groundwater increased from the southeast part of the aquifer towards inland which is consistence with previous studies in the area done by Sherif et al. [12,35].

Table 1. Calibrated Parameters for the Transport Model [12,22].

Parameter	Value
Retardation Factor	1.0
Longitudinal Dispersivityα_L	65 m
Transverse Dispersivity α_T	0.65 m
Vertical Dispersivity α_V	0.065 m
Molecular Diffusion Coefficient	1×10^{-9} m^2 s^{-1}

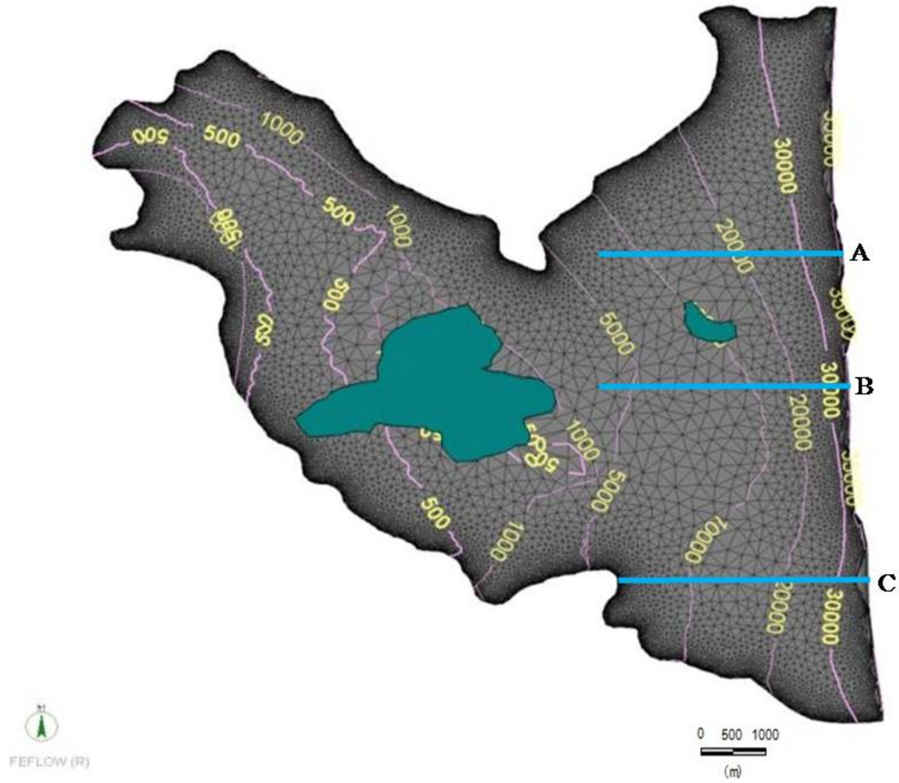

Figure 8. Salinity distribution set up in the groundwater model (mg L^{-1}) and transects A, B and C in which the 15,000 mg L^{-1} isosalinity contour displacements are measured on for each model scenario.

4. Results of Brackish Water Pumping Scenarios

Groundwater is pumped from the aquifer using well at different locations and depths. In addition to irrigation pumping, three well fields were in operation for the domestic water supply by the Federal Electricity and Water Authority. The ranges of pumping from the well fields are presented in Table 2. The average total pumping from these well fields are 18,325 m^3 d^{-1} or 6.6887 × 10^6 m^3 yr^{-1}. In addition to this pumping, an average of 1030 m^3 d^{-1} of pumping was reported from the wells at various locations. The calibrated solute transport model provided with a piece of insightful information about the main locations of brackish water within the aquifer. The zone of freshwater thickness in Wadi Ham aquifer is varying from less than 1 m near the shoreline to about 20 m at 3 km from the shoreline [35]. This information was used in the application of simulation scenarios of brackish water pumping from the coastal aquifer to assess its impacts on the control of saltwater intrusion. The screening of wells that are used for scenarios studies are starting at the depth below freshwater thickness where the brackish water was targeted.

Table 2. Range of Groundwater Pumping from Different Well Fields [12].

Well Field	Pumping Rate (m^3 d^{-1})		Average (m^3 d^{-1})	$\times 10^6$ m^3 yr^{-1}
	max	min		
Shaarah	5500	1200	3225	1.18
Fujairah	1800	1200	1500	0.55
Kalbha	16,500	5500	13,600	4.96
Total			18,325	6.69

Halting or reducing the saltwater intrusion by pumping of brackish water needs an understanding of proper pumping rates, wells location and number of wells. Three simulation scenarios are presented to assess the most appropriate (i) pumping rates, (ii) number of wells and (iii) optimum wells distance from the shoreline. Several combinations of the above three parameters were assessed and evaluated as to their most impact in transferring the spatial position of linear threshold isosalinity contour towards the shoreline.

In scenario 1, 14 wells with a pumping rate of 600 m^3 d^{-1} per well and variable wells locations were simulated. The well number and pumping rates were kept constant throughout the simulation. Location of pumping wells from the shoreline distances was varied to calculate the most appropriate distance from the shoreline to install pumping wells.

In scenario 2 the simulation was conducted using a variable number of pumping wells (from 8 to 16) with constant pumping rate (500 m^3 d^{-1} per well) and constant distance 1500 m from the shoreline.

In scenario 3, simulations were run considering a constant number of wells (10) at a constant distance of 1500 m from the shoreline, while changing the rate of pumping from the minimum of 600 m^3 d^{-1} to the maximum of 1000 m^3 d^{-1} per well.

The displacement of the 15,000 mg L^{-1} isosalinity contour was measured across the aquifer and along the traverses (A, B and C, 2650 m long, in Figure 8) from shoreline to inland. Location A and B are in the area with the lower to higher hydraulic conductivity, respectively, while the location C is in the area of highest hydraulic conductivity and suffers most from saltwater intrusion as shown in Figures 6 and 8. The initial location of 15,000 mg L^{-1} isoline at A, B and C before simulation were noted at a distance of 2066 m, 1210 m and 1833 m, respectively for all the simulated scenarios.

4.1. Scenario 1

The results of scenario 1 are listed in Table 3 and Figures 9 and 10. Variation in the distance of isoline 15,000 mg L^{-1} from the shoreline along the three traverse A, B and C are shown in Figure 9. The Figure shows that at location A, initial distance was steadily reduced as pumping well location was increased from the shoreline, meaning that the isoline 15,000 mg L^{-1} moved towards the shoreline. At location B, the distance was steadily decreased as pumping well locations were placed further inland and had minor variable changes in the concentration of groundwater salinity. Isoline 15,000 mg L^{-1} is moved further inland for location C as pumping location was changed in contrast. The increased impact of saltwater intrusion along the profile C is due to land use practice and aquifer characteristics. The increased number of agriculture water supply wells are encouraging severe saltwater intrusion which was also supported by higher hydraulic conductivity in this region and leaves a wider zone of dispersion between saltwater and freshwater. This trend was reversed after well locations were placed at 1100 m from the shoreline and this was consolidated at 1500 m. The highest decline in the isoline 15,000 mg L^{-1} was at wells locations of 1800 m from the shoreline. This scenario suggests that pumping of brackish water could be more effective if wells were located at 1800 m from the shoreline.

Figure 10 shows the spatial location of isoline 15,000 mg L^{-1} after 4018 days of simulation for 1800 m wells. The improvement in the volume of freshwater is noticed.

Table 3. Distance of 15,000 mg L^{-1} Isosalinity Contour along Traverse A, B and C after Constant Groundwater Pumping (600 m^3 d^{-1} per well) from Well at Different Distance from Shoreline (500–1800 m).

Scenario 1	Number of wells	Volume of Pumping (Q m^3 d^{-1})	Well Distance from Shoreline (m)	Isoline Distance at Traverse A (m)	Isoline Distance at Traverse B (m)	Isoline Distance at Traverse C (m)
Present	Nil	Nil	Nil	2066	1210	1833
1	14	8400	500	1315	308	1993
2	14	8400	800	1275	202	2443
3	14	8400	1100	1209	299	1535
4	14	8400	1500	1264	291	525
5	14	8400	1800	1334	276	355

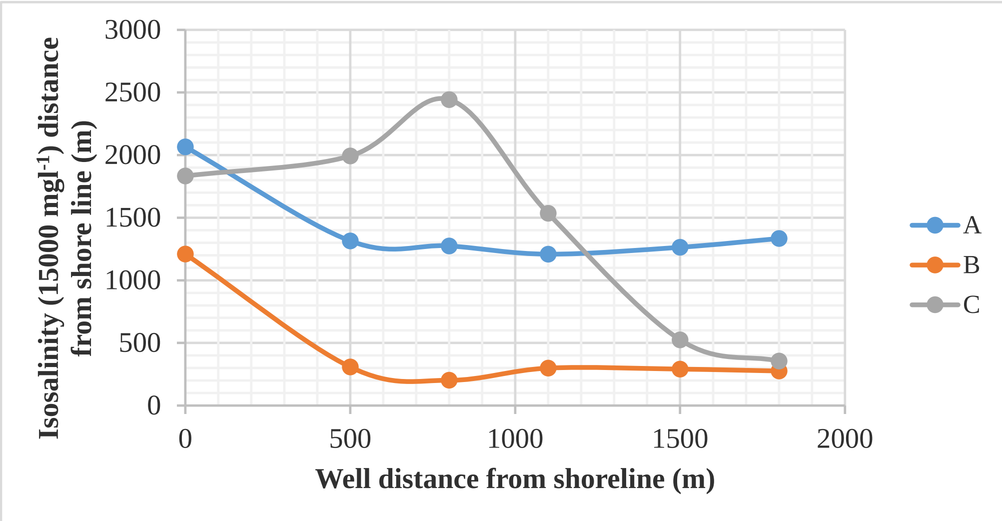

Figure 9. Location of 15,000 mg L^{-1} isosalinity contour line along A, B and C after 4018 days of simulation.

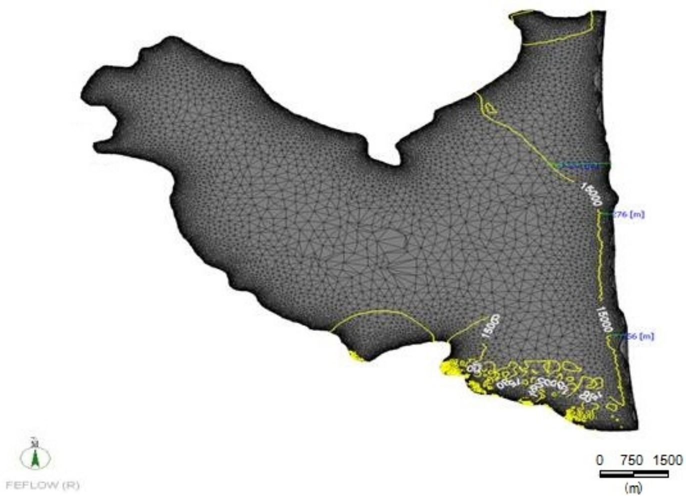

Figure 10. Location of 15,000 mg L^{-1} isosalinity contour at 4018 days against wells located at 1800 m from shoreline.

4.2. Scenario 2

The scenario deals with varying numbers of wells (Table 4). In the first attempt, 8 wells were installed and the result showed isoline 15,000 mg L^{-1} moved towards the shore at traverse A and B, while it moved further inland at traverse C. This is the normal trend for these respective areas (traverse C) as per field situation such as increased number of agriculture water supply wells and high hydraulic conductivity. This trend was continued until an increase in the number of wells to 14. However, a reversal of isoline 15,000 mg L^{-1} towards shoreline was found as the number of wells was increased to 16 as shown in Figure 11. This simulation showed that 16 number of pumping wells at a total rate of 8000 m^3 d^{-1} was the highest level of improvement in the movement of isoline 15,000 mg L^{-1} towards the shoreline. The spatial improvement of groundwater quality is shown in Figure 12. The location of isoline 15,000 mg L^{-1} at 4018 days for 16 pumping wells is noticed closer to the shoreline.

Table 4. Distance of 15,000 mg L^{-1} Isosalinity Contour along Traverse A, B and C using a Variable Number of Pumping Wells (8–16), with Pumping Rate of 500 m^3 d^{-1} per each well and well at 1500 m Uniform Distance from Shoreline.

Scenario 2	Number of Wells	Volume of Pumping (Q m^3 d^{-1})	Isoline Distance at Traverse A (m)	Isoline Distance at Traverse B (m)	Isoline Distance at Traverse C (m)
Present	Nil	Nil	2066	1210	1833
1	8	4000	1229	300	2321
2	10	5000	1230	290	2513
3	12	6000	1278	297	2310
4	14	7000	1260	276	2201
5	16	8000	1248	296	1142

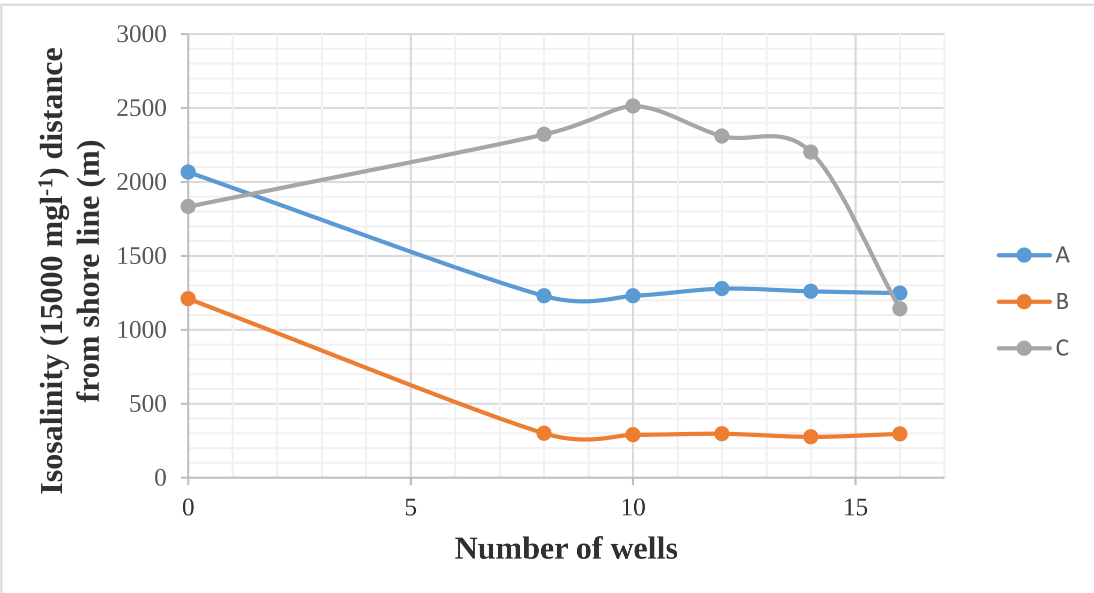

Figure 11. Location of 15,000 mg L^{-1} isosalinity contour line along A, B and C after 4018 days of simulation.

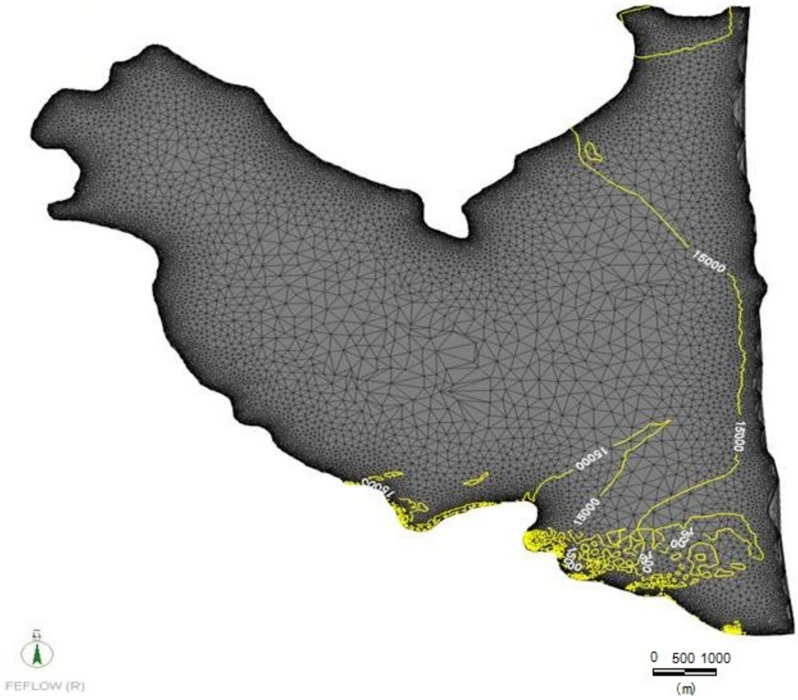

Figure 12. Location of 15,000 mg L^{-1} isosalinity contour at 4018 days after using 16 number of pumping wells.

4.3. Scenario 3

In the first run, a pumping rate of 600 m^3 d^{-1} was applied for the 10 installed wells and the result shows that an isoline 15,000 mg L^{-1} moved towards the shore at location A and B, while it moved further inland at location C. This trend is shown in Figure 13, however, it reversed as pumping rate was increased to 800 m^3 d^{-1} per well (8000 m^3 d^{-1} of total pumping using 10 number of wells) (Table 5). At location B, the reversal of an isoline 15,000 mg L^{-1} occurred maximum by 11 m against the pumping rate of 700 m^3 d^{-1} per well, but not very huge when compared to the reversal at the pumping rate of 800 m^3 d^{-1}. Location C is the area of focus since it is where the intensity of saltwater intrusion is high and its reversal suggests an improvement in its control. The result is evident along the profile C where total pumping of 8000 m^3 d^{-1} permits to keep the saltwater interface towards the shoreline, while greater pumping (>8000 m^3 d^{-1}) will produce a further impact of saltwater in to this freshwater aquifer. The location of isoline 15,000 mg L^{-1} and spatial improvement of groundwater quality after 4018 days is given in Figures 13 and 14, respectively.

Table 5. Distance of 15,000 mg L^{-1} Isosalinity Contour along Transects A, B and C using a Constant Number of Wells (10), Constant Distance from the Coastline (1500 m) and Varying Groundwater Pumping (600–1000 m^3 d^{-1} per well).

Scenario 3	Number of Wells	Volume of Pumping (Q m^3 d^{-1})	Isoline Distance at Traverse A (m)	Isoline Distance at Traverse B (m)	Isoline Distance at Traverse C (m)
Present	Nil	Nil	2066	1210	1833
1	10	6000	1430	293	2500
2	10	7000	1365	288	2625
3	10	8000	1315	299	1244
4	10	9000	1297	300	1554
5	10	10,000	1219	300	2093

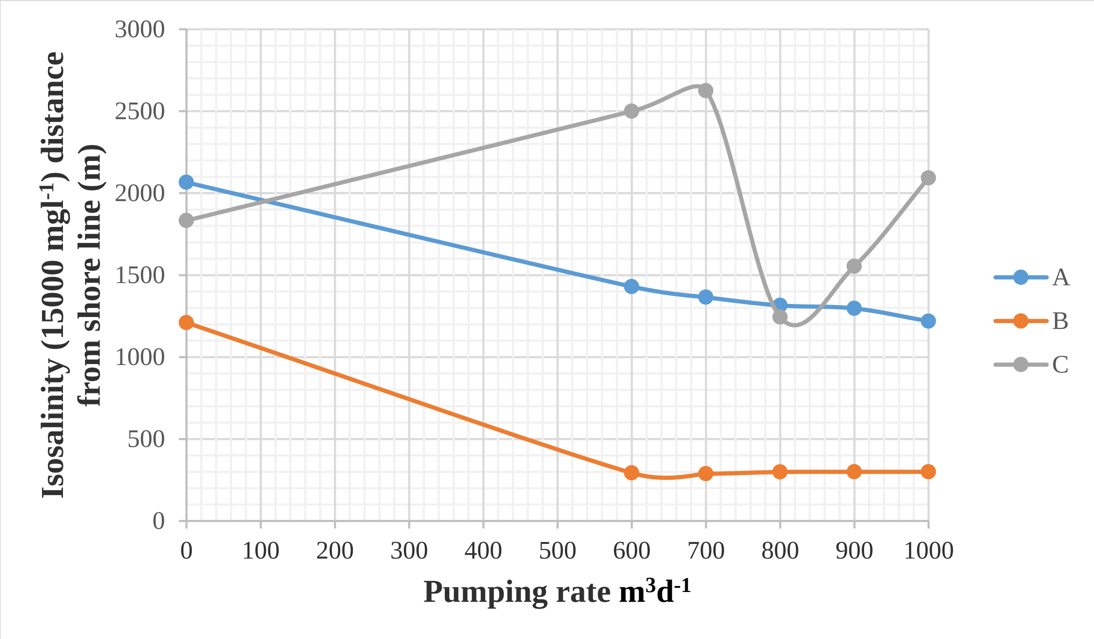

Figure 13. Location of 15,000 mg L^{-1} isosalinity contour line along A, B and C at 4018 days after a variable rate of pumping.

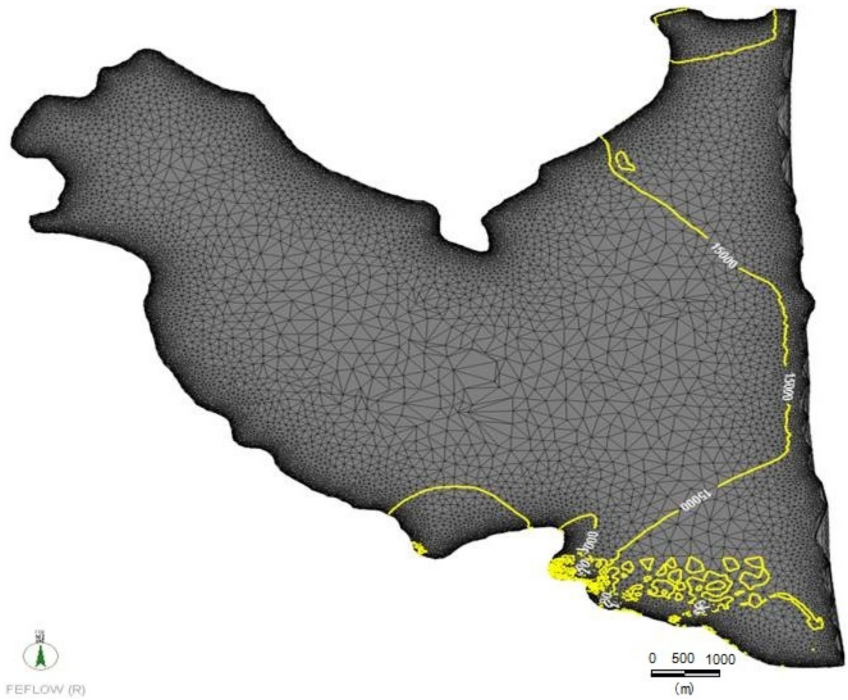

Figure 14. Location of 15,000 mg L^{-1} isosalinity contour at 4018 days after pumping rate of 800 m^3 d^{-1} per well.

5. Discussion and Management Implications

Model results indicate that brackish groundwater pumping can oppose saltwater intrusion along the coastal aquifer of Wadi Ham. Appropriate well location and rate of brackish water pumping will aid in the restoration of the coastal aquifer system and will aid in the efficient usage of the water resources for various activities. Comparing the above scenarios, several ranges of outcome in isoline shifting were reached.

Along the profile A and B in the first scenario, the better groundwater quality in comparison was obtained when the wells were placed at 1100 m (A) and 800 m (B). The differences are due to the variation in hydraulic conductivity and thickness of dispersion zone between saltwater and freshwater. If lesser the value of K and lesser thickness in the zone of dispersion have existed, pumping of brackish water closer to the shoreline (wells at 1100 m at location A) gives an improvement in the freshwater resource development. However, the long-term pumping of brackish water closer to the shoreline may lead to upconing of saltwater [36]. In the case of higher K and thicker zone of dispersion, pumping of brackish water could be at the location far away from the shoreline which also comparatively better for long term pumping.

Comparing the number of wells, the spacing between them is high in the scenarios with a smaller number of wells (Scenario 2 (1)). The higher spacing between wells, the seaward shifting of isoline is high in the zone of lesser hydraulic conductivity (Traverse A, where the hydraulic conductivity is lesser than the other two traverses). It is vice versa in the case of wells at lesser spacing and in the zone of higher hydraulic conductivity (Traverse C, where the hydraulic conductivity is higher than the other two traverses).

The volumetric rate of pumping and the number of wells were not coinciding in any of the scenarios and their sub-attempts. Even there is a coincidence in the rate of pumping between scenarios, the varying well spacing does not produce a similar range of outcomes. Each scale of spacing between wells and number of wells used in the scenarios deals with the shifting of well location. Shifting of well location will face differences in the heterogeneity of the aquifer. Hence, this may change the outcomes of the simulation.

Among several range of outcomes, a maximum progression of 15,000 mg L^{-1} isosalinity contour line towards shoreline was observed using 16 pumping wells with total pumping rate of 8000 m^3 d^{-1} (500 m^3 d^{-1}) at a well distance of 1500 m from the shoreline. The appliance of these parameters in the study area as mitigation measures will generate potential benefits to the groundwater resource management.

The aquifer characteristics are strictly depending on the existing hydrogeological setup of the given area. However, the rate of pumping, number of wells and distance from the shoreline obtained from this study is convenient for hydrogeological setup exist in the study area. Similarly, addition to the investigations made by a various number of wells, distance of wells and different rate of brackish water pumping, the inflow through the wadies used in the model development play a major role in the movement of isosalinity contour towards shoreline.

Agricultural activities are only able to thrive when there is no water crisis. The unorganized and heavy groundwater pumping resulted into a deterioration of groundwater quality, seawater intrusion and aborting of wells. The agriculture activities were reduced to some extent in the study area. To increase the agriculture production and GDP, the UAE has allowed desalinated water for agriculture activities as remedial measure likely for their industrial and domestic activities. The usage of nonconventional water can always be helpful in the absence of natural conventional water. The usage of desalinated water for agricultural sector can favor high yield and reduce entering of salt into the aquifer [37,38]. In addition, a significant aquifer recharge can occur in addition to recharge from rainfall. However, improving the natural groundwater resources is heavily needed. An implementation of the brackish water pumping at their optimum level can enhance the speedy restoration of aquifer and groundwater quality.

The application of the suggested well locations and pumping rates would provide for the use of less saline water for irrigation and an important step in the restoration of abandoned farms. It would generate an opportunity for the maximum utilization of the water resources by which agricultural production can be feasible. In addition, the identification of appropriate well locations would guide local authorities to issue new or renewing existing permits for new or old pumping wells. It will also allow for the building of new farms which is one of the challenges in UAE.

Abstracted brackish water could also be used by the local desalination plants for their water production purposes, reducing thus the costs [39,40]. In fact, the use of brackish water is ideally cheaper than direct saltwater from the sea as it requires less energy to desalinate. This will save lots of energy and protect the environment given that brine water disposal into the sea from the desalination plants are a major threat to marine ecosystem across the area. Additionally, the implementation of brackish water abstraction in other coastal regions of UAE can be useful to control waterlogging which is one of the major issues in recent days.

Improving the groundwater resources will also help arrest the need to construct new desalination plants. The restoration of the coastal aquifer would provide for the use of conventional water resources which is always better than the use of non–conventional water resources, such as desalinated water, treated wastewater, etc.

An implementation of the findings from this study will generate enormous benefits for social, economic and environmental sectors. With the recent study by Zuurbier et al. [17], more investigations are needed comparing the traditional well design for brackish water abstraction with the recently proposed horizontal directional drilled wells (HDDWs) [41] as Subsurface Water Technologies (SWT). Their appropriate design (length, diameter, pumping rates, etc.) is crucial for the purpose and further investigations are needed [42,43].

6. Conclusions and Recommendation

Pumping of brackish water has a significant impact on the control of saltwater intrusion in the coastal aquifer of Wadi Ham, in the United Arab Emirates. Using a FEFLOW groundwater flow and transport model, several scenarios were tested with the aim of assessing the adequate combination among pumping rates, number of wells and well distance from the shoreline. Model results indicate that the optimum solution to control saltwater intrusion includes the use of 16 pumping wells with a total pumping rate of 8000 m^3 d^{-1} at 1500 m from the shoreline. An overall improvement in the quality of groundwater was noticed. Additional observations are that if the brackish water zone is thicker and hydraulic conductivity is reasonably high, it is advisable to install the wells far away from the shoreline. The efficient combination of parameters obtained in this study is not applicable to all field conditions. The outcomes are suitable for the given hydrogeological setup, coastal morphology, topography, etc. Additionally, incoming flow through the Wadies are creating a hydraulic load to encounter the migration of the fresh water-saltwater interface towards the inland.

From the management and implementation point of view, it is also essential to think of a continuous monitoring plan to monitor the evolution of the aquifer system during the operation (installation of wells, pumping frequency, etc.).

This technique would improve groundwater quality and could further be exploited to achieve a win–win situation by using the pumped brackish water as feed for nearby desalination plants, thus, reducing thus the desalinization cost.

This study recommends an assessment of the cost involved in the construction of new pumping wells as well as pipelines or transport vehicles which would be used as desalination plants feed. An investigation on the most appropriate desalination method suited for the location is also recommended.

Author Contributions: M.A.S. is worked on the study conceptualization, literature review, data collection, methodology, model development, validation, formal analysis and writing of the original draft and participated in responding the reviewer's comments; S.S. supported the conceptualization, methodology, model development, investigation, validation, formal analysis, and review. He worked on the writing of the original draft preparation of this paper, participated in responding the reviewer's comments; N.G. supported the formal analysis, technical discussions and revision of the first draft of this paper. Also provided technical revision incorporated in this paper; M.M.M. supervised the present work, provided with a study material, guided its investigation and completion. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank you the United Arab Emirates University for providing Graduate Teaching Assistantship and the DHI-WASY GmbH (FEFLOW) for providing academic FEFLOW license. In addition, the authors would like to thank Sherif, National Water Center, UAE University for his support. He carried out tremendous work with varying objectives in the study area.

Conflicts of Interest: The authors declare no conflict of interest. Also this study is not funded by any authorities. Hence, "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results".

References

1. Boer, B. An introduction to the climate of the United Arab Emirates. *J. Arid Environ.* **1997**, *35*, 3–16. [CrossRef]
2. Sathish, S.; Mohamed, M.; Klammer, H. Regional groundwater flow model for Abu Dhabi Emirate: Scenario based investigation. *Environ. Earth Sci.* **2018**, *77*, 409. [CrossRef]
3. Murad, A.A. An overview of conventional and non-conventional water resources in Arid Region: Assessment and constrains of the United Arab Emirates (UAE). *J. Water Resour. Prot.* **2010**, *2*, 181–190. [CrossRef]
4. EAD. *Abu Dhabi State of Environment Report 2017*; Environmental Agency: Abu Dhabi, UAE, 2017.
5. Murad, A.A.; Al Nuaimi, H.; Al Hammadi, M. Comprehensive assessment of water resources in the United Arab Emirates (UAE). *Water Resour. Manag.* **2007**, *21*, 1449–1463. [CrossRef]
6. Mohsen, M.S.; Akash, B.; Abdo, A.A.; Akash, O. Energy options for water desalination in UAE. *Procedia Comput. Sci.* **2016**, *83*, 894–901. [CrossRef]
7. US Geological Survey. *Bibliography of National Drilling Company–United States Geological Survey Reports on the Water Resources of Abu Dhabi Emirate*; US Geological Survey Open File Report; US Geological Survey: Reston, VA, USA, 1996. Available online: https://pubs.usgs.gov/of/1998/0018/report.pdf (accessed on 22 May 2020).
8. SCAD. Water Statistics, Statistic Centre-Abu Dhabi, UAE. 2011. Available online: https://www.scad.gov.abudhabi/ (accessed on 22 May 2020).
9. Javadi, A.; Hussain, M.; Sherif, M.; Farmani, R. Multi-objective Optimization of Different Management Scenarios to Control Seawater Intrusion in Coastal Aquifers. *Water Resour. Manag.* **2015**, *29*, 1843–1857. [CrossRef]
10. Dawoud, M.A. The development of integrated water resources information management system in arid regions. *J. Environ. Hydrol.* **2011**, *6*, 1601–1612. [CrossRef]
11. Sathish, S.; Mohamed, M.M. Assessment of aquifer storage and recovery (ASR) feasibility at selected sites in the Emirate of Abu Dhabi, UAE. *Environ. Earth Sci.* **2018**, *77*, 112. [CrossRef]
12. Sherif, M.M.; Sefelnasr, A.; Ebraheem, A.A.; Javadi, A. Quantitative and qualitative assessment of seawater intrusion in Wadi Ham under different pumping scenarios. *J. Hydrol. Eng.* **2014**, *19*, 855–866. [CrossRef]
13. Ministry of Environment and Water. *United Arab Emirates Water Conservation Strategy*; Ministry of Environment and Water: Dubai, UAE, 2010. Available online: http://extwprlegs1.fao.org/docs/pdf/uae147095.pdf (accessed on 22 May 2020).
14. ACSAD. *Vulnerability of Groundwater Resources in United Arab Emirates*; Report submitted to the Ministry of Environment and Water; Ministry of Environment and Water: Dubai, UAE, 2013. (In UAE)
15. HydroAtlas, United Arab Emirates, Ministry of Environment and Water, UAE. 2014. Available online: https://www.moccae.gov.ae/en/media-center/news/12/4/2015/ministry-of-environment-and-water-to-launch-uaes-first-ever-hydroatlas-at-wetex-2015.aspx#page=1 (accessed on 22 May 2020).
16. Hussain, M.S.; Abd-Elhamid, H.F.; Javadi, A.A.; Sherif, M.M. Management of Seawater Intrusion in Coastal Aquifers: A Review. *Water* **2019**, *11*, 2467. [CrossRef]
17. Zuurbier, K.G.; Raat, K.J.; Paalman, M.; Oosterhof, A.T.; Stuyfzand, P.J. How subsurface water technologies (SWT) can provide robust, effective, and cost-efficient solutions for freshwater management in coastal zones. *Water Resour. Manag.* **2017**, *31*, 671–687. [CrossRef]
18. Mahesha, A. Control of Seawater Intrusion through Injection-Extraction Well System. *J. Irrig. Drain. Eng.* **1996**, *122*, 314–317. [CrossRef]
19. Sherif, M.M.; Hamza, K.I. Mitigation of seawater intrusion by pumping brackish water. *Transp. Porous Media* **2001**, *43*, 29–44. [CrossRef]
20. Sherif, M.; Kacimov, A. Pumping of brackish and saline water in coastal aquifers: An effective tool for alleviation of seawater intrusion. In Proceedings of the 20th Salt Water Intrusion Meeting (SWIM), Naples, FL, USA, 23–27 June 2008.

21. Kacimov, A.R.; Sherif, M.M.; Perret, J.S.; Al-Mushikhi, A. Control of sea-water intrusion by salt-water pumping: Coast of Oman. *Hydrogeol. J.* **2009**, *17*, 541–558. [CrossRef]
22. Sowe, M.; Sadhasivam, S.; Mohamed, M.M.; Sherif, M. Modeling the mitigation of seawater intrusion by pumping of brackish water from the coastal aquifer of Wadi Ham, UAE. *Sustain. Water Resour. Manag.* **2019**, *5*, 1435–1451. [CrossRef]
23. Diersch, H.J.G.; Perrochet, P. On the primary variable switching technique for simulating unsaturated-saturated flows. In *White Papers*; 2005; Volume 1, pp. 9–66. Available online: http://www.feflow.info/manuals.html (accessed on 10 December 2019).
24. Wheater, H.S.; Mathias, S.A.; Li, X. *Groundwater Modelling in Arid and Semi-Arid Areas*; Cambridge University Press: New York, NY, USA, 2010.
25. Sherif, M.M.; Kacimov, A. *Modeling of Groundwater in Two Selected Coastal Aquifers of UAE and Oman as a Precursor for Water Resources Management*; Final Report; Research Sectors of UAEU/SQU: Al Ain, UAE, 2006.
26. Electrowatt (Electrowatt Engineering Services Ltd.). *Wadi Ham Dam and Groundwater Recharge Facilities, Volume I Design*; Ministry of Agriculture and Fisheries: Dubai, UAE, 1981.
27. ENTEC, Entec Europe Limited. *Survey on Groundwater Recharge and Flow in Wadi Ham, Vol 1*; Ministry of Agriculture and Fisheries: Dubai, UAE, 1996.
28. Sherif, M.; El Mahmoudi, A.; Garamoon, H.; Kacimov, A.; Akram, S.; Ebraheem, A.; Shetty, A. Geoelectrical and hydrogeochemical studies for delineating seawater intrusion in the outlet of Wadi Ham, UAE. *Environ. Geol.* **2006**, *49*, 536–551. [CrossRef]
29. Diersch, H.J.G. *FEFLOW—Finite Element Subsurface Flow & Transport Simulation System: Reference Manual*; WASY: Berlin, Germany, 2005; p. 292. Available online: http://www.feflow.info/fileadmin/feflow6/user_manual.pdf (accessed on 10 December 2019).
30. Sathish, S.; Elango, L. Numerical simulation and prediction of groundwater flow in a coastal aquifer of Southern India. *J. Water Resour. Prot.* **2015**, *7*, 1483–1494. [CrossRef]
31. Barazzuoli, P.; Nocchi, M.; Rigati, R.; Salleolini, M. A conceptual and numerical model for groundwater management: A case study on a coastal aquifer in southern Tuscany, Italy. *Hydrogeol. J.* **2008**, *16*, 1557–1576. [CrossRef]
32. Sefelnasr, A.; Sherif, M. Impacts of seawater rise on seawater intrusion in the Nile Delta aquifer, Egypt. *Groundwater* **2014**, *52*, 264–276. [CrossRef]
33. Rajaveni, S.P.; Indu, S.N.; Elango, L. Finite element modelling of a heavily exploited coastal aquifer for assessing the response of groundwater level to the changes in pumping and rainfall variation due to climate change. *Hydrol. Res.* **2016**, *47*, 42–60.
34. Idris, A.N.; Aris, A.Z.; Narany, T.S.; Mangala, S.P.; Suratman, S.; Tawnie, I.; Shamsuddin, M.K.N.; Sefie, A. Simulation of saltwater intrusion in coastal aquifer of kg. Salang, Tioman Island, Pahang, Malaysia. *MATEC Web Conf.* **2017**, *103*, 4024. [CrossRef]
35. Sherif, M.M.; Kacimov, A.; Javadi, A.; Ebraheem, A.Z. Modeling groundwater flow and seawater intrusion in the coastal aquifer of Wadi Ham UAE. *Water Resour. Manag.* **2012**, *26*, 751–774. [CrossRef]
36. Jakovovic, D.; Werner, A.D.; de Louw, P.G.B.; Post, V.E.A.; Morgan, L.K. Saltwater upconing zone of influence. *Adv. Water Resour.* **2016**, *94*, 75–86. [CrossRef]
37. Ganot, Y.; Holtzman, R.; Weisbrod, N.; Bernstein, A.; Siebner, H.; Katz, Y.; Kurtzman, D. Managed aquifer recharge with reverse-osmosis desalinated seawater: Modeling the spreading in groundwater using stable water isotopes. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 6323–6333. [CrossRef]
38. Aznar-Sanchez, J.A.; Belmonte-Urena, L.J.; Velasco-Munoz, J.F.; Valera, D.L. Aquifer Sustainability and the use of desalinated seawater for greenhouse irrigation in the Campo de Nijar, Southeast Spain. *Int. J. Environ. Res. Public Health* **2019**, *16*, 898. [CrossRef]
39. Oosterhof, A.; Raat, K.J.; Wolthek, N. Reuse of salinized well fields for the production of drinking water by interception and desalination of brackish groundwater. In Proceedings of the 9th Conference on Water Reuse, International Water Association (IWA), Windhoek, Namibia, 27–31 October 2013.
40. Wolthek, N.; Raat, K.; de Ruijter, J.A.; Kemperman, A.; Oosterhof, A. Desalination of brackish groundwater and concentrate disposal by deep well injection. *Desalin. Water Treat.* **2013**, *51*, 1131–1136. [CrossRef]
41. Cirkel, D.G.; Van der Wens, P.; Rothuizen, R.D.; Kooiman, J.W. Water Extraction with HDD Drillings—One Horizontal Well for Multiple Vertical Wells, Land+Water. 2010. Available online: www.hddw.nl (accessed on 31 January 2020).

42. Sun, D.; Zhan, H. Flow to a horizontal well in an aquitard–aquifer system. *J. Hydrol.* **2006**, *321*, 364–376. [CrossRef]
43. Wang, J.Z.; Jiang, X.W.; Wan, L.; Wang, X.S.; Li, H. An analytical study on groundwater flow in drainage basins with horizontal wells. *Hydrogeol. J.* **2014**, *22*, 1625–1638. [CrossRef]