

Article

Numerical Modeling of Seawater Intrusion in Wadi Al-Jizi Coastal Aquifer in the Sultanate of Oman

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Abstract: The Sultanate of Oman is an arid country in the Arabian Peninsula suffering from insufficient freshwater supplies and extremely hot weather conditions. The only source of recharge is rainfall, which is scarce and varies with space and time, for the aquifers being overexploited for the last few decades. This has led to depleting groundwater levels and seawater intrusion into coastal aquifers. In the present study, Ground Modeling System (GMS) was employed in Wadi Al-Jizi, which is one of the important aquifers in the Al Batinah coastal plain that caters to the needs of the country's 70% agriculture. MODFLOW and MT3DMS were used to simulate the groundwater levels and solute transport, respectively. These models were calibrated under steady and transient conditions using observed data from twenty monitoring wells for a period of seventeen years (year 2000–2016). After validation, the model was utilized to predict the salinity intrusion due to changes in groundwater abstraction rates and sea level rise owing to climatic change. These predictions show that, by the year 2040, salinity intrusion (TDS > 12,800 mg/L) will transgress by 0.80 km inland if the current abstraction rates are allowed to be maintained. Further deterioration of groundwater quality is anticipated in the following years due to the increased pumping rates. The models and the results from the present study may be utilized for the effective management of groundwater resources in the Wadi Al-Jizi aquifer.

Keywords: numerical modeling; coastal aquifers; groundwater; seawater intrusion; sea level rise; MODFLOW; MT3DMS



Citation: Akhtar, J.; Sana, A.; Tauseef, S.M.; Tanaka, H. Numerical Modeling of Seawater Intrusion in Wadi Al-Jizi Coastal Aquifer in the Sultanate of Oman. *Hydrology* **2022**, *9*, 211. <https://doi.org/10.3390/hydrology9120211>

Academic Editors: Ezio Todini and Ryan Bailey

Received: 6 October 2022

Accepted: 24 November 2022

Published: 27 November 2022

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1. Introduction

One-third of the world's land surface is classified as arid or semi-arid, putting several regions under severe and increasing water stress due to expanding population, rapid urbanization, increasing water consumption, and limited available water resources. The world's population has increased four times over the last 150 years, and it may quadruple in the next 30 years [1]. Over the past few centuries, the quality of groundwater and surface water has drastically declined in many regions of the world as a result of increased industrialization, urbanization, and agricultural activities [2–6]. Surface water sources, such as open channels and other water bodies, are relatively easier to monitor for contamination than underground sources, which makes restoring aquifers for clean water supplies a difficult task, as the subsurface pollution cannot be seen instantly [7].

The majority of the Arabian Peninsula's small- to medium-sized exploitable fossil aquifer systems will hit maximum depletion by 2050, and in 60–90 years, the complete depletion of groundwater supplies in all aquifer systems could occur [8]. The direct relationship between water, energy, and food makes tackling this problem and controlling seawater

intrusion vital to the economic and social development of a country. The exploration and management of groundwater thus become necessary for the sustainable development in such areas [9]. In the existing water shortage scenarios, the problems are accentuated by the expected temperature rise and the decline in precipitation, which would reduce the amount of recharge for renewable water supplies [8]. During the dry season, even relatively lower withdrawal of groundwater may result in seawater intrusion and, consequently, the chances of seawater intrusion remain higher during the dry season as compared with the rainy season [10]. The abstraction rate in response to population increase was found to be the most crucial factor as compared with other variables (such as rainfall, temperature, and evaporation). As the population increases, salinity intrusion moves further inland due to the over-extraction of water from the subsurface in the absence of proper replenishment in arid or semi-arid regions, which further emphasizes the need for the environmental impact mitigation.

Some of the previous legislative measures taken in the Al-Batinah region of Oman to decrease the intrusion of seawater were as follows: (1) the installation of fresh groundwater wells was banned and (2) recharge dams were constructed on the chosen wadis in the region. The 1999 salinity study showed that the water quality improved downstream of the recharge dams replenishing groundwater aquifers. An additional intervention to enhance the region's water quality requires a deeper knowledge of the issue of salinity intrusion. The use of a numerical model not only fulfills this objective, but it can also be served as a management instrument for making choices about pumping patterns and building fresh recharge facilities in the study region [11]. A reduction in the pumping rate is the simplest, most efficient, and most cost-effective, but temporary, method for preserving groundwater equilibrium in aquifers and managing SWI (Sea Water Intrusion) problems, apart from establishing surface and subsurface physical barriers in front of the intruding seawater body; Abstraction, Desalination, and Recharge (ADR); and Aquifer Storage and Recovery (ASR) [6].

The quality of the groundwater varies based on the distance from the shoreline and the depth below the seawater level [12]. If the transient conditions are not considered, coastal aquifers in semi-arid locations with inadequate groundwater recharge and salinity intrusion due to groundwater abstraction pumping could be underestimated. The pumping rates and locations, as well as aquifer characteristics, such as hydraulic conductivity and porosity, length-to-height relationship of an aquifer, density contrast between freshwater and saltwater, and recharge conditions, all influence seawater intrusion induced by freshwater abstraction from coastal aquifers [13]. It has been reported that there has been a rise in the water level in the groundwater observation wells due to the recharge dams constructed in the region of Al Batinah. Which also resulted in slightly lower salinity in some of the wadis (dry river channels or dry riverbeds) [14]. However, due to the overexploitation of aquifers near coastal areas, salinity intrusion occurred landward [15]. On the other hand, it was revealed that the groundwater from the wadi bed or recharge dam infiltration had a negligible effect on the groundwater and did not affect the water balance [16].

Salinity intrusion in the Al-Batinah region is a severe concern, because it has a detrimental impact on food security and the economy. It is imperative to create and execute sufficient and effective groundwater reclamation policies and strategies to prevent additional salinization and to manage and monitor groundwater salinity to protect agricultural lands and natural ecosystems [15]. The objective of the present study was to model the groundwater flow and quality using well-known numerical models (MODFLOW and MT3DMS). The results of the present study may help decision-makers in the effective management of water resources in the Al-Batinah region.

2. Study Area

The Sultanate of Oman is situated on the southeastern corner of the Arabian Peninsula and is considered to be the second-largest country, having a coastline of around 2100 km. At the foot of the Western Hajar Mountains lies the coastal plain of Al Batinah in the Sultanate

of Oman, which is the most densely populated region (1.25 million according to the 2020 census) in the country after Muscat (capital city).

According to an estimate, more than half of the Sultanate of Oman's cultivated land is located in this region, which has fertile soil and is crucial to the country's agricultural economy [11]. The Wadi Al-Jizi catchment, located in the Al Batinah region, was selected as the study area (located between latitudes 2,685,288.72 m N and 2,702,809.30 m N and longitudes 445,120.53 m E and 474,236.85 m E, covered in the topographic map (Figure 1)). The Sea of Oman lies in the north of the study area, and the Western Al-Hajar mountains are in the south. The total area of the Wadi Al-Jizi watershed is 1154 km². The eastern part of the aquifer system was studied, which has an area of approximately 123 km², extending from the sea toward the mountain region. This region of the aquifer was chosen because it is home to the majority of agricultural operations, pumping and observation wells, and salinity monitoring wells.

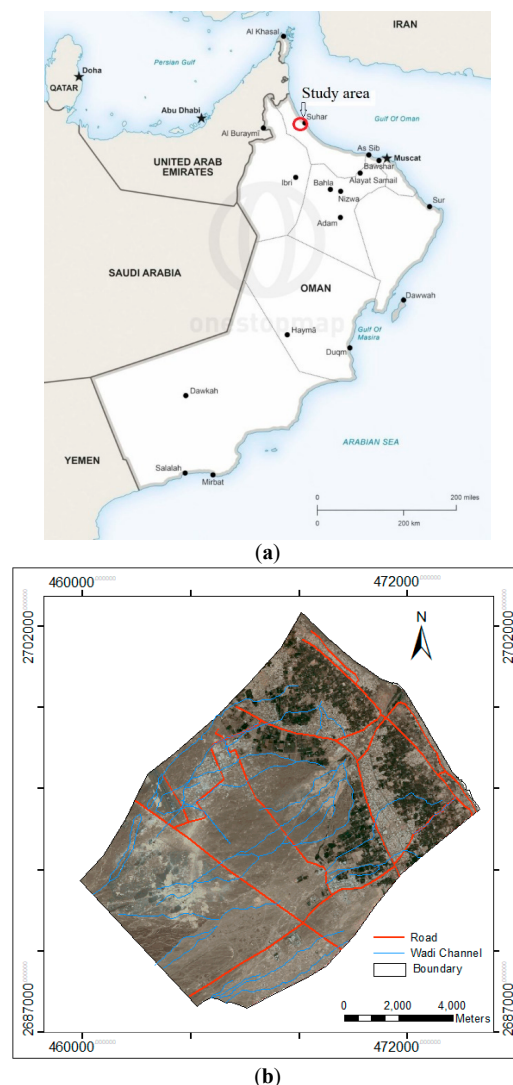


Figure 1. (a) Map of the Sultanate of Oman (onestopmap.com, accessed on 12 November 2022) with a red circle near Suhar showing the location of the study area. (b) Part of the Wadi Al-Jizi aquifer, which is the computational domain.

The Al Batinah coastal plain stretches northwest of the capital city Muscat for nearly 300 km along the west shore of the Gulf of Oman. It ranges in width from 10 to 30 km, extending inland to the foothills of Northern Oman Mountain [17]. Approximately one-third of the population of the country lives in the Al Batinah region, which accounts for

about 4% of the area of the country. High evapotranspiration rates and a dry climate characterize the eastern coastal plain [18]. It is characterized by a warm winter with low humidity, a very hot and sometimes humid summer, and low and erratic levels of rainfall. In the coastal area, the average annual air temperature is 28.5 °C, and that in the mountains is 17.8 °C. In the southern high region, high rainfall (300 mm per year) has been reported relative to the coastal region [19].

The Sultanate of Oman falls under the category of an arid region because it receives only about 100 mm of rainfall on average in a year. The ‘normal’ weather characteristics are clear, bright skies, and light wind for over 90% of the year. The winter is pleasantly warm and dry, and the summer is hot and dry. The Al Batinah aquifers’ primary source of freshwater replenishment is mountain rainfall [20]. A major part of the precipitation (80%) evaporates because of high prevalent temperatures, 5% flows to the sea through ‘wadis’ (seasonal watercourses or dry riverbeds), and the remaining 15% infiltrates to recharge the aquifers. It is generally accepted that most recharges occur along the ‘wadis’ in the upstream area of the alluvial fans adjacent to the mountains [21]. The groundwater from here moves slowly toward the ocean through the aquifers. The direct rainfall on the gravel plains between the shoreline and the hills does not seem to be the main cause of the recharge, as the quantity is comparatively low and most of it is absorbed by the ground and then lost to evaporation. The rain gauges in Eastern Al Batinah were classified into the coastal, valley, and highland areas, and the mean annual rainfalls for these areas were found to be 68 mm/year, 90 mm/year, and 174 mm/year, respectively [18]. This variation is regarded to be mainly due to the impact of the topography. The water deficit in Oman is more than 300 MCM per year, according to the projections by the Ministry of Regional Municipalities, Environment and Water Resources (MRMEWR) [22]. For this reason, the intrusion of seawater is imminent in the coastal aquifers where the majority of the population is located. From 1983 to 1999, the ministry conducted detailed salinity measurements covering over 1000 wells in the Al Batinah region [23].

The primary rainfall season in northern Oman occurs between December and April, mostly in the winter, representing 58 to 83% of the annual rainfall. The greatest rainfall in February and March represents 35 to 42% of the annual rainfall. The analysis of rainfall data from 1977 to 2003 found that the year with the highest annual average rainfall was 1997 and the year with the lowest annual average rainfall was 2001 [24]. Long-term measurements show mean average precipitation values in the upstream Hajar Mountain of up to 350 mm/year and around 50 mm/year along the coastline. The fluctuation of rainfall with respect to time and location is incredibly high; during years with high rainfall, there are comparatively moist intervals that are followed by protracted dry periods [25]. It was reported that the highest average record of 608 mm was in 1997, with continuous dry years up to 2010 in Southern Al Batinah, except in 2007. The average numbers of rainy days per year are 9.1 for the coastal plain of Al Batinah and 13 per year for the mountains of northern Oman [26].

The topography of the Al Batinah region varies from 1700 m above MSL at the southern mountain front to large flat areas near the coast. In the upstream watersheds near the Jabal Al Akhdar mountains (part of the Al-Hajar mountain range), the topography rises to up to 3000 m above MSL, whereas the coastal plain near the coastline varies from 100 and 0 m (above MSL) [26]. The Al Batinah region hydrogeology is regarded to be a significant factor in the occurrence of groundwater. The plain was formed by rainfall due to the natural weathering process. The Al Batinah region could generally be divided into two primary areas, distinguished by their rock type and geological environments, namely a mountainous region, consisting primarily of hard rocks, mainly ophiolite and calcareous rocks, and the lowland and coastal plain regions, consisting primarily of coarse gravel and boulders with occasionally cemented beds. The latter is the key aquifer, with a total thickness of over 300 m in the north and over 600 m in the south.

3. Literature Review

3.1. Salinity Intrusion

Saline water intrusion often occurs when fresh groundwater abstraction from coastal aquifers lowers the groundwater table, allowing saline water to move laterally or vertically, thereby degrading the quality of the groundwater [27]. Due to over-pumping for the past few decades, seawater intrusion has taken place, rendering many agricultural farmlands abandoned and wells non-operative [12,28]. Although natural brines, leachate from landfills, and irrigation can all contaminate water, the sea is a common source of saltwater [29–32].

In numerous locations, groundwater overdraft led to seawater intrusion up to 15 km inland. Many countries around the world, including the Sultanate of Oman, had to close hundreds of wells along the coastline [33,34]. The problem of seawater intrusion in Oman is most pronounced along the Al Batinah coastal plain and Salalah, where cultivation occurs over large areas. Owing to the seawater intrusion for more than two decades, precious agricultural land has become unfit for cultivation [30]. The infiltration of seawater persists because of a continuous shortfall brought on by excessive pumping in the area. As a result, several farms are currently in danger and a number of them have been abandoned (Figure 2). Due to saline intrusion, some 6000 hectares of agricultural land have been abandoned, while another 5000 hectares suffer moderate salinity effects. In rural regions, this has had a negative impact on livelihoods. These significant coastal aquifers were drained by excessive water abstraction and subsequent seawater intrusion. Using an 8% discount rate, saline intrusion has been estimated to cause a loss of US\$ 288 million (net present value) over a 25-year period. Crop production causes numerous losses, including the drying up of historical irrigation channels known as ‘aflaj’, losses to domestic consumers, increases in energy demand, and irreversible aquifer depletion [35].



Figure 2. An abandoned date palm garden in Al Batinah, Oman, due to salinity intrusion (Photograph taken by Javed Akhtar on 17 December 2021).

The quality of the groundwater is highly diverse in the Al Batinah region. The water quality in the hilly region is very good (<1500 mg/L); in the flat and lowland regions [26], the water quality reduces (1500–6500 mg/L) as groundwater dissolves salts (primarily calcium carbonate) on its way to the ocean. Salinity in water is normally measured and expressed in terms of Electrical Conductivity (EC) and Total Dissolved Solids (TDS). The values of EC are always expressed at a standard temperature of 25 °C to enable the comparison of readings taken under varying climatic conditions. Electrical Conductivity (EC) is the ability of a substance to conduct an electrical current. Water becomes a better

conductor of electricity as its TDS increases. The TDS can be estimated from the EC using available empirical relationships. The groundwater salinity classes are shown in Table 1.

Table 1. Classification of groundwater salinity (adopted from [26]).

Level of Salinity	Classification	Water Salinity	
		TDS (mg/L)	EC ($\mu\text{S}/\text{m}$)
Class 1	Freshwater	<1500	2.14
Class 2	Low Salinity	1500–3000	2.14–4.30
Class 3	Moderate Salinity	3000–5000	4.30–7.0
Class 4	Moderately High Salinity	5000–7000	7.0–10.0
Class 5	High Salinity	7000–10,000	10.0–15.0
Class 6	Very High Salinity	>10,000	>15.0

The Japan International Cooperation Agency (JICA), in 1982, started a five-year project to establish a hydrological observation network in the Al Batinah area and carried out detailed hydrological and hydro-geological surveys [36]. Increasing use and growing demand for irrigation water have been discovered to result in increased salinity in coastal aquifers. In that study, several mitigation measures were suggested. Three in-depth surveys were carried out between 1982 and 1984 by the Public Authority for Water Resources (PAWR) utilizing 345 coastal wells spread out from As-Seeb to Shinas, and they revealed a major salinity intrusion issue [37]. The groundwater quality along the Al Batinah beach deteriorated between 1983 and 1986 [38]. In the coastal region of Al Batinah, Hydroconsult conducted a preliminary soil and groundwater study in cooperation with the Ministry of Agriculture and Fisheries (MAF). It was found that the Al Batinah coastal plain experienced an annual water shortage of roughly 47 MCM [39]. The Ministry of Water Resources acknowledged the necessity for thorough technical studies at various places between the years of 1992 and 1995 in a report on salinity surveys. A sizable monitoring network of 1100 wells in the area has been utilized for this purpose [21]. In a later report from the Ministry of Water Resources, which spanned the years 1997 to 1999 and examined 1033 monitoring wells, it was revealed that the Al Batinah coastal plain aquifer had widespread groundwater scarcity. The Ministry staff collects water samples from the observation and production wells using a pump, and these samples are sent to the water quality laboratory for chemical analysis. When compared with the findings of the 1997 study, the salinity typically increased in the most impacted areas, which were located from Barka to As-Suwayq. The wells in Wadi Ahin (Saham) and Wadi Al Jizi (Sohar), which are situated on the downstream side of the dams, showed groundwater retrieval [23].

A significant decline in the quality of water in the Al Batinah region has been mentioned in earlier studies [14]. This was indicated by a decrease of 7% in the regions of appropriate agricultural water (2000–6000 $\mu\text{S}/\text{cm}$), reflecting a loss of 2714 hectares of irrigated land. Additionally, in the Wadi Al Taww Barka region, the saline interface was recorded to be 12 km inland. A saltwater wedge, stretched over several kilometers inland, lies beneath the freshwater aquifer in the coastal area. The interface between seawater and freshwater is progressing in all areas of Al Batinah, indicating the over-exploitation of the aquifer. As studied by the Ministry of Regional Municipalities and Water Resources (MRMWR), saline water intrusion in Wadi Al Taww and Wadi Al Maawil could not be reduced, despite the exceptionally heavy rainfall from 1995 to 1997. The Ministry has imposed a ban on the entablement of new pumping wells and recharge dams in the region were planned to be constructed to aid in surface water infiltration and increase water heads. From 1998 to 2004, low average rainfall and wadi flow resulted in the further deterioration of groundwater quality [40]. Table 2 shows a summary of the observed salinity values in groundwater in the countries of the Arabian Peninsula, highlighting that salinity intrusion is not an unusual phenomenon in the region.

Table 2. Observed salinity values in groundwater at various locations on the Arabian Peninsula.

S. No	Region/Aquifer	Country	Observed Salinity Values TDS (ppm)	Reference/s
1	Dammam Aquifer	Bahrain	2097–53,562	[41]
2	Al-Raudhatain/Umm Al-Aish	Kuwait	350–2400	[42]
3	Kuwait Aquifer	Kuwait	3000–8000	[43]
4	Kuwait Aquifer	Kuwait	1649–98,692	
[44] 5	Salalah Coastal Aquifer	Oman	446–6305	[30]
6	Al Batinah Coastal plain	Oman	849–53,562	[11,14,40]
7	Gulf of Aqaba	Saudi Arabia	800–10,018	[2]
8	Jazan Aquifer	Saudi Arabia	217–8010	
[34] 9	Saq Aquifer	Saudi Arabia	600–1180	[3]
10	Al Lusab Basin	Saudi Arabia	646–12,860	[45]
11	Abu Dhabi Emirates Aquifer	United Arab Emirates	≤1500–140,000	
[46] 12	Wadi Ham	United Arab Emirates	15,000–30,374	[12]
13	Al-Wakrah	Qatar	2420–9210	[47]
14	Wadi Siham, Tihama Basin	Yemen	363–9610	[48,49]

3.2. Numerical Modeling

Numerical models are very effective for analyzing the prevailing conditions and then managing and protecting coastal aquifers from salinity intrusion [50–52]. Groundwater models can provide real-time analysis and visualization of two- and three-dimensional flow and transport phenomena. User-friendly graphical interfaces make it easier for models to be used [51]. MODFLOW [53,54] is probably one of the most popular three-dimensional flow groundwater models for steady or transient flow conditions in the saturated zone in confined or unconfined aquifer systems. MT3DMS [55] is a three-dimensional multi-species transport model for the simulation of advection and solute transport. These models were effectively used to construct a regional representative 3D numerical groundwater flow and solute transport model for studying fluctuations in groundwater head and salinity intrusion in the Al Batinah aquifer and Salalah plain aquifers. These studies aimed at the implementation, calibration, and validation of MODFLOW for groundwater flow and MT3D for seawater intrusion in the aquifers of the Al Batinah and Salalah regions [11,56].

A 3D groundwater model (MODFLOW) was employed to simulate the complex multi-layer aquifer located in the Wadi Samail catchment in the Al Batinah region [57]. A four-layer conceptual model was used to represent the heterogeneous multi-layer aquifer. The study results revealed a major impact of unregistered pumping wells on groundwater levels and insisted on maintaining an inventory of uncounted pumping wells for proper water management. Another study used MODFLOW and MT3DMS to investigate the impact of climate change on the Samail Lower Catchment aquifer and Jamma aquifer in the Al Batinah region, Oman [58]. The watershed seemed to defy the seawater intrusion by maintaining groundwater flow toward the sea, but the Jamma aquifer was found to be stressed, severely affected, and vulnerable to saline intrusion. By using MODFLOW and MT3DMS, the groundwater and seawater intrusion pattern was investigated in the Eastern Al Batinah coastal plain. For the provided set of data, both models were run to replicate steady-state and transient conditions. Additionally, two scenarios to reduce seawater intrusion were simulated using the calibrated model: (1) a reduction in the pumping rate and (2) an artificial recharge of treated wastewater with continuous pumping. The model runs' outputs indicated that altering the pumping rate and artificial recharge would be a successful management strategy in the eastern Al Batinah coastal plain to fend against seawater intrusion [40]. Another study was conducted on seawater intrusion in Eastern Al-Batinah catchments and their unconfined aquifers in the Sultanate of Oman [59]. A

numerical model (SUTRA) and an analytical solution (Dupuit–Forchheimer) were used. It was inferred that the seawater intrusion could be mitigated by pumping saltwater from the intruded portion of the aquifer. A numerical groundwater model was used by [16] for the existing conditions of the coastal region in Oman. The study included an extension of the numerical simulation software OpenGeoSys using a numerical scheme to simulate the flow of fresh and saltwater in unconfined aquifers. The model was validated against a laboratory saltwater intrusion experiment and further calibration was carried out for a heterogeneous regional-scale model to simulate saltwater intrusion in a coastal aquifer. The groundwater modeling (MODFLOW and MT3DMS) and chemical results of the Salalah plain aquifer wells suggested that, if irrigation and domestic abstractions continue to increase, the freshwater zone will contract significantly over the coming years. Owing to the lack of annual rainfall, the outflow of freshwater to the sea is declining, allowing the seawater to intrude inland by more than 2 km. The deficit has been projected to increase in the coming years [30]. Shamma and Thunvik (2009) used a GMS (Groundwater Modeling System) that included MODFLOW and MT3DMS to represent the 3D groundwater flow and solute transport in Salalah, Oman. The current and future groundwater quality conditions were determined by predicting seawater intrusion for the next 15 years. The results obtained by the model were helpful in predicting aquifer responses under various water management methods. Shamma (2007) investigated the 1998 proposal to stop saline intrusion by artificially introducing cleaned sewage effluents to the Salalah plain aquifer in Oman. To stop the seawater intrusion, sewage collection and treatment were implemented, and the groundwater recharge program began in April 2003. The results showed that the artificial recharge of treated wastewater was effective to combat seawater intrusion and pushed back the saline front by 700 m.

FEFLOW has also been used to model the encroachment of saltwater in different layers of the multilayer aquifer system in the Pingtung Plain in Taiwan [60]. The model results revealed all layers of the aquifer were affected by the intrusion, but the top and bottom are affected more than the middle one. Another study used FEFLOW to model the pumping of brackish water from the intrusion zone to regulate the aquifer's seawater intrusion in Wadi Ham, U.A.E. [61]. Different simulation scenarios were run to achieve optimal pumping locations and rates. The findings showed a rise in groundwater salinity concentration under the non-pumping scenario when compared with the pumping scenario. SEWAT-2000, a paired MODFLOW-2000 and MT3DMS 5.2, was used by [62] to simulate 3D varying density subsurface water flow and multi-species transport in a coastal aquifer in Karnataka, India. A study was conducted for seawater intrusion in the lower alluvial plain of the Wadi Ham catchment, located in the Fujairah Emirate in the UAE, by using the finite element-based flow and solute transport model (SUTRA), in which artificial recharge is used for managing the infiltration of seawater into coastal aquifer systems, thus preventing the further deterioration of the quality of groundwater [63]. Using a newly established multi-layered system, the Nile Delta aquifer was simulated to obtain clearer knowledge of the intrusion of saltwater into the aquifer scheme by collecting all fresh information on an aquifer's heterogeneity and hydrochemistry by using the SEWAT program [64]. MODFLOW and MT3D were utilized to model the flow of groundwater and analyze the issue of seawater intrusion in Wadi Ham and potential mitigation schemes [12]. The developed model was used to study the effects of pumping and artificial recharge on seawater intrusion. The model results indicated that, by reducing the pumping from the Kalba well field, the seawater intrusion in the south-eastern part of the aquifer can be slowed. The experimental and numerical methods were used to study the sub-surface water quality in the central part of the Nile Delta, which was fertile agricultural land and densely populated. Considering the unsteady and three-dimensional flow, MODFLOW and MT3DMS were used for modeling [65]. A study on the Wadi Ham aquifer used FEFLOW to simulate the intrusion of seawater under transient conditions [28]. It was evident from the study that a reduction of 50% in the pumping rates will have a decisive impact and will help in reducing saltwater intrusion and improving the quality of groundwater. Conversely,

any increase in the rate of water abstraction would enhance the rate of salinity intrusion and would cause the quality of the groundwater to deteriorate further. The SUTRA model was employed to study the effect of climate change and SLR on the salinity intrusion in the coastal groundwater system of South Korea [66]. The findings revealed that, for an accurate assessment of climate change's impacts on seawater intrusion in coastal groundwater systems, both the freshwater recharge rates and Sea Level Rise (SLR) should be taken into account.

A case study was performed in the northern karst aquifer, Qatar, utilizing MODFLOW 2000 [67]. The number, positions, and distribution of pilot points in the results of model calibration were studied. The findings showed that, given the same number of points and uniform placement, the pilot points performed better than randomly placed points. Visual MODFLOW was employed to study the depleting level of groundwater of the Saq aquifer located in the Qasim area in Saudi Arabia [68]. The model results emphasized that the runoff, which was wasted previously, could be stored in the existing pond due to artificial recharge, which would also help in boosting the aquifer's life by 3%. If no preventive measure is taken and pumping continues, the water head in the region will drop by more than 65.0 m in the next three decades. MODFLOW was also used to conduct groundwater modeling of the Saq Aquifer, Saudi Arabia. Water demands have been increasing continuously in the Buraydah area, due to which the pumping of groundwater and the number of drilled wells has increased to an alarming situation, resulting in the depletion of the water head by 1.10 m per year. It was concluded that, if the current pumping rates increased by 10% per 10-year period, the water table would deplete by 33.5 m in the next 27 years [69].

4. Methodology

4.1. Conceptual Model

A conceptual model can be created by utilizing the geological and hydrogeological data of the aquifer under study and is an idealized representation of our hydrogeological understanding of the important flow processes of a system [56]. The groundwater flow system was represented in three dimensions using a two-layered conceptual model that considered the geological and hydrogeological information available for the study area (Figure 3).

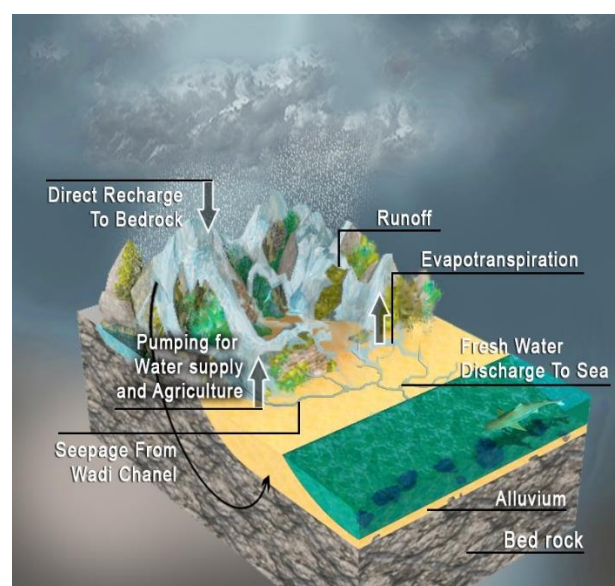


Figure 3. Conceptual model of Wadi Al Jizi groundwater flow system.

Only 43% of rain is thought to directly replenish aquifers; the remainder either evaporates or runs off as surface runoff into the ocean. Much of the recharge of the groundwater

system for model simulation comes from precipitation infiltration. The recharge rate for a steady state was calculated to be 0.0013581 m/day using the rainfall in the year 2000, based on the water balance of the study area [70]. There was a total of 22 pumping wells that encompassed the model domain. There were no publicly accessible records for the private pumping wells in the study region that could be used to estimate their pumping rates. However, the Public Authority for Water (PAW), Oman, which oversees the Sohar Development Office (SDO), had some information from the domestic water supply wells [70].

4.2. Numerical Model

The Groundwater Modeling System (GMS), which contains MODFLOW and MT3DMS for the processes of groundwater flow and solute transport, respectively, was employed in the current work. The governing equation in MODFLOW is shown in Equation (1).

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) \pm W = S_s \frac{\partial h}{\partial t} \quad (1)$$

where K_{xx} , K_{yy} , and K_{zz} are values of hydraulic conductivity (LT^{-1}) along the x , y , and z coordinate axes (assumed to be parallel to the major axes of hydraulic conductivity); h is the potentiometric head (L); W is a volumetric flux per unit volume (T^{-1}) representing the sources and/or sinks of water, with $W < 0.0$ for outflow from the groundwater system and $W > 0.0$ for inflow; S_s is the specific storage of the porous material (L^{-1}); and t is time (T). This equation, combined with appropriate boundary and initial conditions, describes transient 3D groundwater flow in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Details about the model and information regarding the studies that utilized MODFLOW can be found in [71,72]. The results obtained from MODFLOW for groundwater flow characteristics can be used to run MT3DMS, which is an advanced version of the 3D Mass Transport Model, MT3D, developed by [73]. The model is capable of modeling advection in steady and transient flow fields, anisotropic dispersion, first-order decay and production reactions, and linear and nonlinear sorption. MT3DMS is based on the general equation of mass transport, as shown in Equation (2):

$$R \frac{\partial C}{\partial t} = D_{xx} \frac{\partial^2 C}{\partial x^2} + D_{yy} \frac{\partial^2 C}{\partial y^2} + D_{zz} \frac{\partial^2 C}{\partial z^2} - V \frac{\partial C}{\partial x} + q_s C_s - \mu RC \quad (2)$$

where C is the concentration of solute (salinity in the present case) (ML^{-3}); D_{xx} , D_{yy} , and D_{zz} are the dispersion coefficients ($\text{L}^2 \text{T}^{-1}$) in the x , y , and z directions, respectively; V is the average pore water velocity (LT^{-1}); q_s is the volume flowrate per unit volume of the aquifer, which is positive for fluid sources and negative for sinks (T^{-1}); C_s is the concentration of the fluid source or sink (ML^{-3}); R is the retardation factor; and μ is the decay coefficient. For the simulation of salinity by MT3DMS, the decay constant is equal to zero; therefore, $\mu RC = 0$.

5. Results and Discussion

5.1. Steady-State Groundwater Flow Simulation

The groundwater flow model was calibrated primarily under steady-state conditions for the year 2000. The observed groundwater elevations are available every month (most of the time). Here, the average value over the year 2000 was used for steady-state calibration. For the steady-state model, trial-and-error modifications of hydraulic conductivity values were used until the observed and computed values matched in a subset of nine observation wells scattered across the model domain. In the observation wells, a difference of ± 1.5 m between the observed and simulated values for the water level was deemed acceptable. More details about the model calibration can be found in [70]. Table 3 shows the calibrated results in the steady state for the year 2000 with a Root-Mean-Square Error (RMSE) of 0.65.

Table 3. Observed versus computed head for selected observation wells in the steady-state calibration for the year 2000.

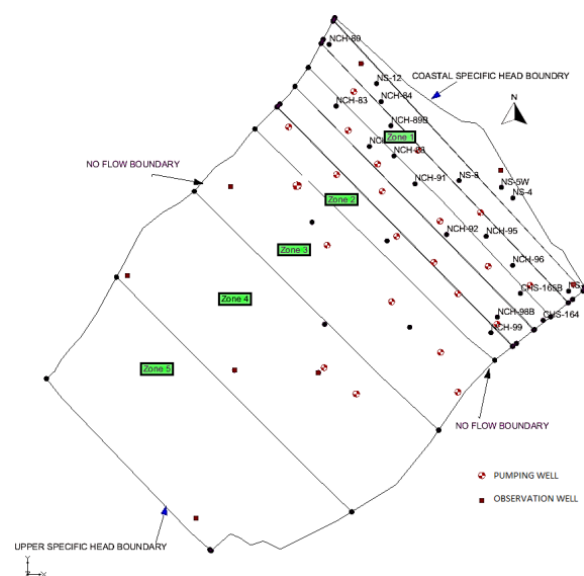
Observation Well	Observed Head (m)	Computed Head (m)	Difference
EA1	4.45	4.70	−0.25
JA5	7.75	6.50	1.25
NJ1	0.52	0.85	−0.33
NJ2	0.42	1.00	−0.58
NJ10	1.40	1.20	0.20
NJ9	3.05	3.38	−0.33
SARKM	1.37	3.19	−1.82
DE5	4.73	4.20	0.53
JA2	2.54	2.63	−0.09

5.2. Transient-State Model Calibration and Validation

Based on the initial conditions of the steady-state results, the transient model simulation was carried out from 2000–2017. Details about the transient model calibration and validation can be found in [73]. After the calibration and validation of the groundwater flow model, it was used for various prediction scenarios of the pumping rate increments and reductions and the sea level rise due to climatic changes [70].

5.3. Transient State Solute Transport Model Calibration and Validation

The transient model was calibrated and validated from 2000–2016, comparing the observed salinity values with the calculated values for selected 20 monitoring wells in the study area. Salinity data from the monitoring wells operated by the Ministry of Regional Municipality, Environment, and Water Resources (MRMEWR) were used. Figure 4 shows the locations of the selected salinity monitoring wells in the model domain. To mimic the actual variation in the model parameters, the model domain was divided into a number of zones and the model parameters were assigned to each zone separately. The model domain was divided into five zones (Zone 1 to Zone 5) for groundwater modeling (MODFLOW). Zone 1 and Zone 2 were adjacent to the coastline and more susceptible to the salinity intrusion, and were sub-divided into three parts each to obtain a clear picture of salinity intrusion. Zone 1 was divided into three parts (1A, 1B, and 1C) with average widths of 592 m, 678 m, and 515 m, respectively. Meanwhile, Zone 2 was also divided into three subdivisions (2A, 2B, and 2C) with average widths of 731 m, 653 m, and 840 m, respectively.

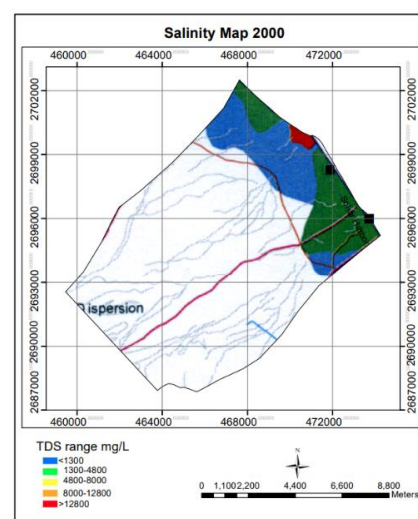


Calibration was performed by trial and error to achieve the appropriate degree of correlation between the observed and the model's measured average concentrations by changing the aquifer's initial concentration, porosity, and longitudinal dispersivity. Initial estimates of these values were based on the soil type and the available literature. The hydrological parameters porosity, longitudinal dispersivity, ratio of transverse dispersivity to longitudinal dispersivity, and ratio of vertical dispersivity to longitudinal dispersivity were calibrated by the trial-and-error method. The calibration led up to 0.6 for porosity and up to 14,000 for longitudinal dispersivity near the coast, and lower values moving toward the upper reaches. Table 4 highlighted the calibrated geo-hydrological parameters, such as the porosity, longitudinal dispersivity, ratio of horizontal dispersivity to the longitudinal dispersivity, and ratio of vertical transmissivity to the longitudinal dispersivity, used for the transient simulation. A total of 17 stress periods were used, with 12 time steps in each month and a multiplier of 1, resulting in 6209 days. Validation involved the simulation of longitudinal dispersivity, along with the pumping and recharge rate.

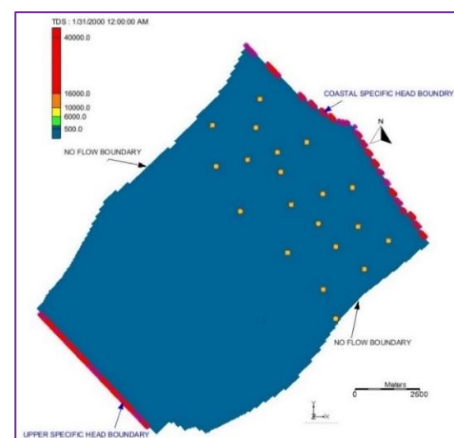
Table 4. Transient state calibrated parameter values.

Parameters	Calibrated Value	
	Layer 1	Layer 2
Hydraulic conductivity (m/day)	7.5–163	4.0–180
Vertical anisotropy	20–25	10–25
Porosity	0.2–0.5	0.2–0.6
Longitudinal dispersivity (m)	14,000 to 15	
Ratio of horizontal transverse dispersivity to longitudinal dispersivity	0.1	
Ratio of vertical transverse dispersivity to longitudinal dispersivity	0.01	

Figure 5 shows the computed salinity contours for the years 2000, 2005, 2010, and 2016, respectively. The observed values of the TDS recorded by MRMWR are also shown. In the year 2000, the observed salinity contours extended around 2.0 km (TDS 1300–4800 mg/L) from the shoreline (Figure 5a), whereas the model simulation showed TDS < 1300 mg/L for the whole modeled area (Figure 5b). The comparison between the observed and computed salinity is subject to a certain degree of bias due to the conversion of EC to the salinity using an empirical relationship. However, qualitative comparisons can be made, as conducted in the present study.

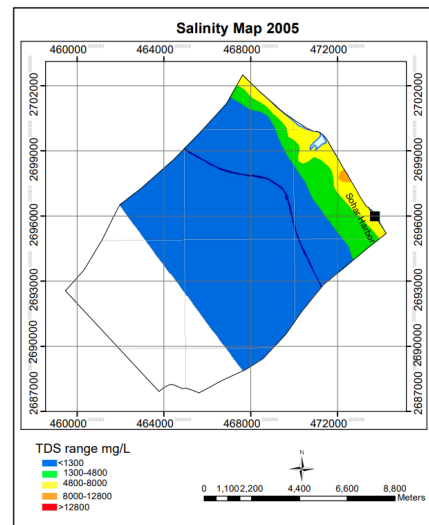


(a)

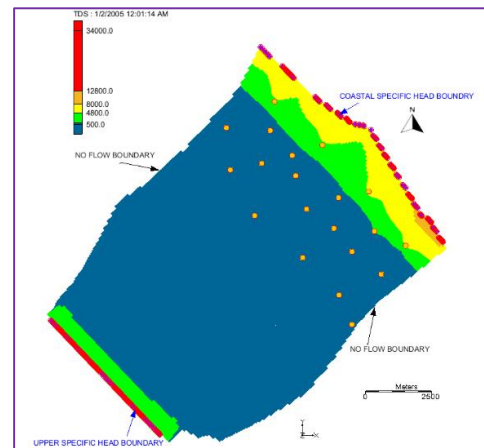


(b)

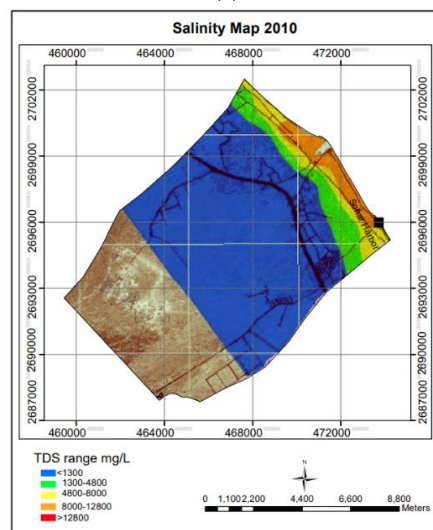
Figure 5. Cont.



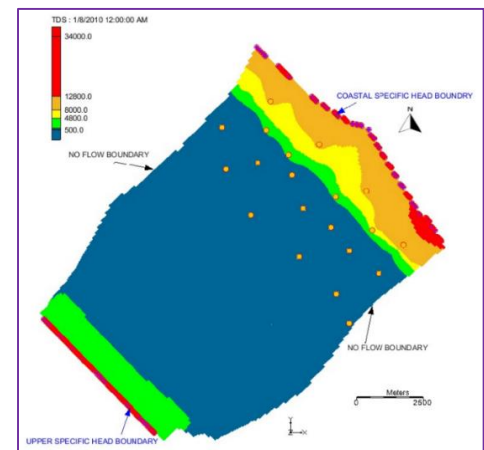
(c)



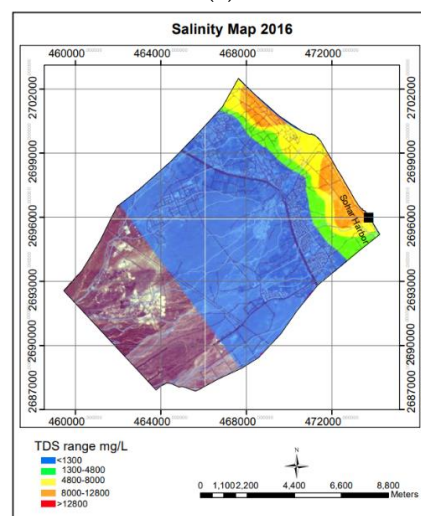
(d)



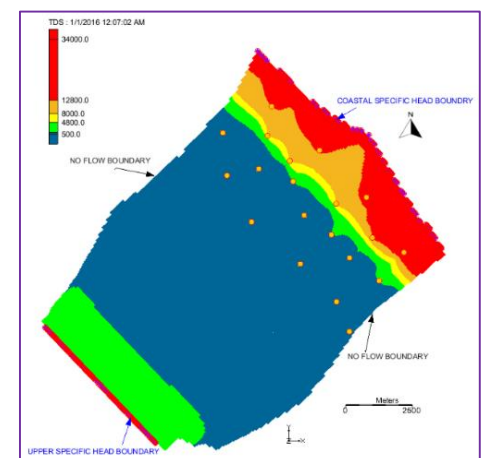
(e)



(f)



(g)



(h)

Figure 5. Salinity contour maps. (a) Year 2000 observations, (b) year 2000 simulations, (c) year 2005 observations, (d) year 2005 simulations, (e) year 2010 observations, (f) year 2010 simulations, (g) year 2016 observations, and (h) year 2016 simulations.

In the years 2005 (Figure 5c,d), 2010 (Figure 5e,f), and 2016 (Figure 5g,h), a good qualitative agreement was observed between the observed and computed salinity distributions throughout the area.

After the validation of the model, various management scenarios were studied to mitigate the seawater intrusion in the Wadi Al-Jizi aquifer.

5.4. Effect of Pumping Rates on Seawater Intrusion

Owing to the population increase and better quality of life, the trend of freshwater consumption is consistently increasing in Oman. The model was used to assess the impact of increasing or decreasing (as a result of water conservation efforts) pumping rates on salinity intrusion. To study the pumping impact, rates in the year 2017 were considered as the baseline pumping rates, and increases of 10%, 20%, and 30% from the baseline pumping rates of 2017 were considered. Moreover, decreases of 5% and 10% from the baseline pumping rates were considered. These increased or decreased rates were considered for all 22 pumping wells used in the model domain. The pumping scenarios were considered for the period between 2018–2040. The simulated groundwater levels in all cases of pumping scenarios were compared against the levels under normal pumping rates at different wells. It is clear that salinity will move inland with the increase in the pumping rates and retreat if pumping rates are decreased. However, the numerical model can predict the extent of seawater intrusion with reasonable accuracy if it is properly calibrated and validated.

In this case, the rate of water abstraction from the year 2017 was considered to remain constant for all of the future years until 2040 (Scenario-1). Figure 6 shows the predicted salinity intrusion contours in the Wadi Al-Jizi aquifer for the years 2030 and 2040. From the salinity contours using the model results, the saline water with a TDS of $>12,800$ mg/L was observed to intrude landward by average distances of 2.39 km and 2.56 km in the years 2030 and 2040, respectively.

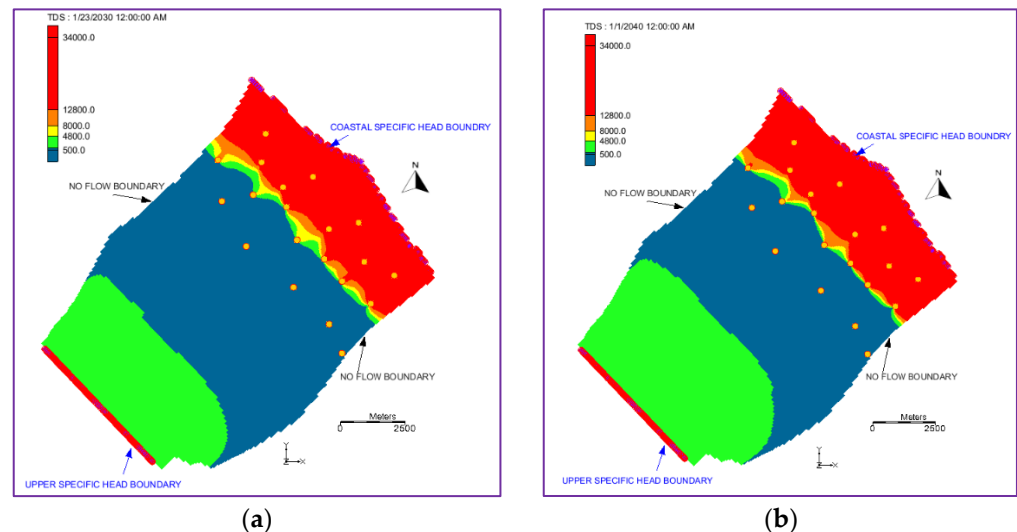


Figure 6. Salinity contours for Scenario-1 pumping rates from 2017: (a) 2030 and (b) 2040.

For the pumping rates increased by 10% with respect to the baseline pumping rate of 2017 (Scenario-2), the saline water would intrude inland to average distances of 2.42 km and 2.57 km in the years 2030 and 2040, respectively (Figure 7). In other words, a 10% increase in pumping rates from those in the year 2017 will not cause a significant deterioration in the next 20 years. However, when the pumping rates are increased by 20% with respect to the baseline pumping rate of 2017 (Scenario-3), the salinity would intrude inland at average distances of 2.58 km and 2.65 km in the years 2030 and 2040, respectively (Figure 8).

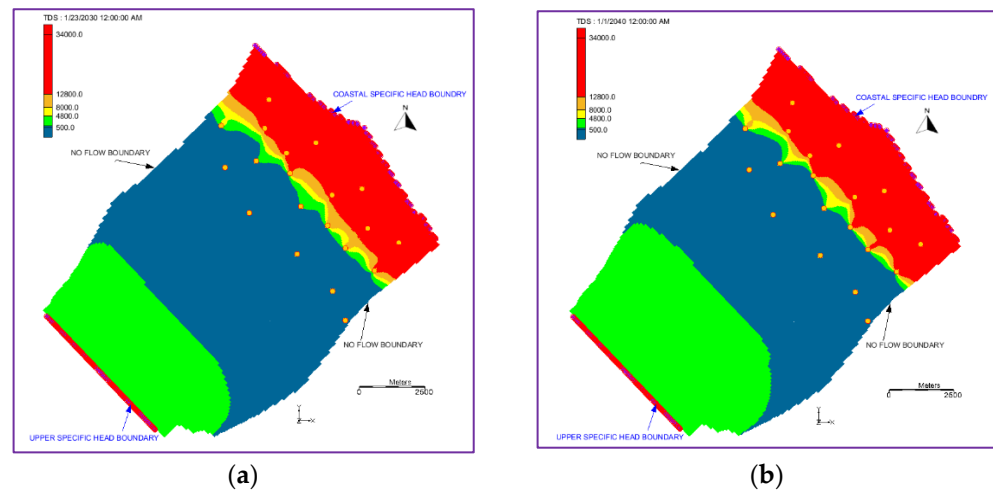


Figure 7. Salinity contours for Scenario-2 (pumping rates increased by 10% from those in the year 2017). (a) 2030 and (b) 2040.

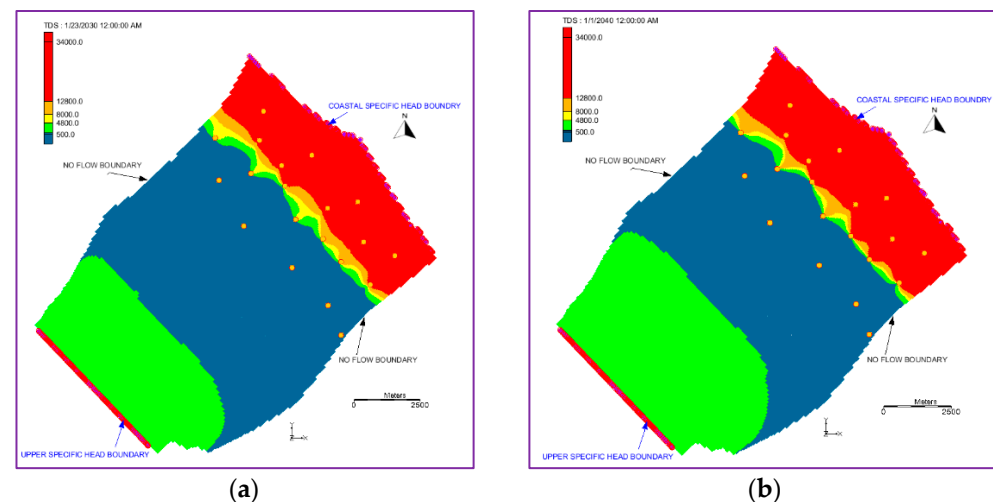


Figure 8. Salinity contours for Scenario-3 (pumping rates increased by 20% from those in the year 2017). (a) 2030 and (b) 2040.

For a further increase in the pumping rates (30% with respect to the baseline pumping rate of 2017), shown as Scenario-4, the salinity seemed to intrude landward at average distances of 2.37 km and 2.69 km in the years 2030 and 2040, respectively.

A reduction in pumping rates was also considered in response to the possibility of water conservation regulations and practices promoted by authorities. Scenario-5 represents a 5% decrease in the pumping rates from those in the year 2017. The salinity for Scenario-5 would retreat in the Wadi Jizi aquifer for the years 2030 and 2040. From the salinity contours, the salinity would intrude landward by average distances of 2.19 km and 2.41 km for the years 2030 and 2040, respectively. In Scenario-6 (10% reduction in the abstraction rates of the year 2017), the salinity would reach the landward side by average distances of 2.12 km and 2.15 km in the years 2030 and 2040 respectively.

5.5. Effect of Climate Change on Seawater Intrusion

The developed model was applied to simulate seawater intrusion in the Wadi Al-Jizi aquifer considering the sea level rise due to climatic change. The prediction of sea level rise as per the IPCC (Inter-Governmental Panel on Climatic Change) [74] and the other possible changes in the sea level (+0.25 m, +0.50 m, and −0.25 m with respect to the base sea level) were considered to simulate seawater intrusion in the study area.

The pumping rates in the year 2017 were kept constant and continued until 2040. The modeled groundwater elevations were observed to rise with the sea level rise. Similarly, the groundwater elevations fell in response to the fall of sea level (Figure 9). It is clear that the sea level rise would cause more seawater intrusion as compared with the baseline situation (groundwater elevations in the year 2017). However, to estimate the spatial and temporal movements of the seawater intrusion, MT3DMS was used.

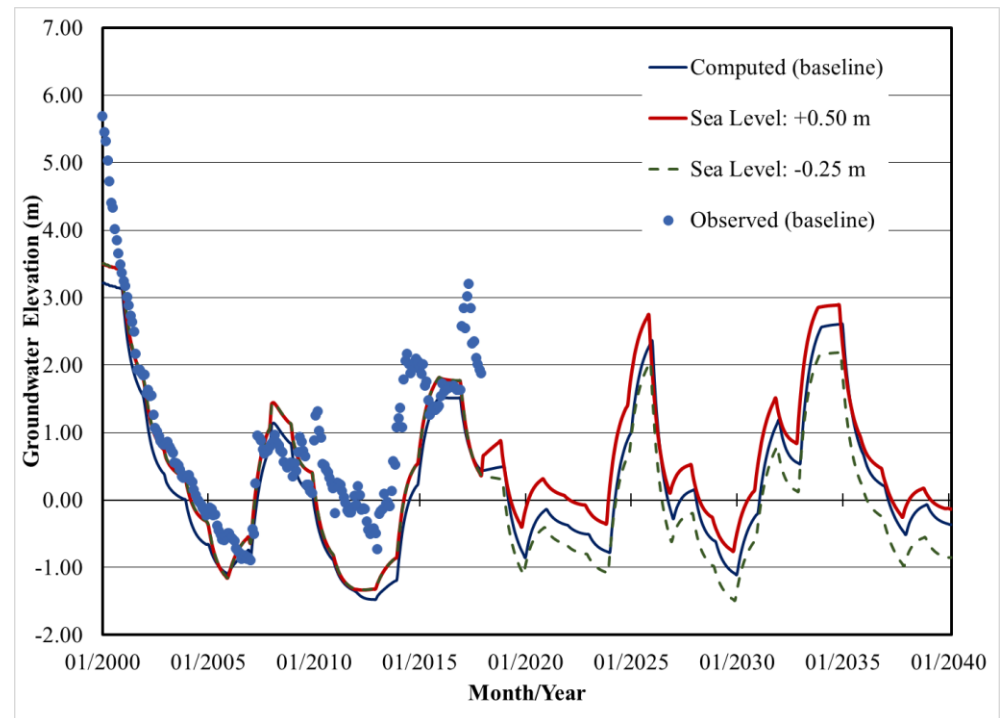


Figure 9. Groundwater elevations in Wadi Al-Jizi aquifer (Station EA1) in response to sea level rise until 2040. The existing observed elevations (2000 to 2017) along with the computed values from MODFLOW are shown from 2000 to 2040.

The sea level rise was considered as per RCP (8.5) (Scenario-7) mentioned in the Annual Report-5 of the IPCC [74]. As per RCP (8.5), a gradual increase of 0.31 m (0.26–0.42 m) was applied to the baseline sea level (0.65 m) for the transient model. The predictive scenario values were applied gradually from 2018–2040. The salinity contours for the years 2030 and 2040 were plotted to observe the impacts of sea level in the study area as per the IPCC prediction. The salinity intruded inland by average distances of 2.60 km and 2.63 km in the years 2030 and 2040, respectively. Similarly, a rise of 0.25 m above the baseline sea level (Scenario-8) resulted in salinity intrusion landward at average distances of 2.60 km and 2.65 km in the years 2030 and 2040, respectively. A rise of 0.50 m added to the baseline sea level (0.65 m) (Scenario-9) and a reduction of 0.25 m in the baseline sea level due to the possibility of sea level fall in the study area (Scenario-10) were considered. The results of all these scenarios are summarized in Table 5.

An increase in the abstraction rate of approximately 20% (Scenario-3) will cause almost the same extent of seawater intrusion as that caused by a sea level rise as per IPCC predictions (Scenario-7).

Table 5. Summary of the scenarios considering changes in the pumping rates and sea level changes.

Scenario Type	Scenario	Description of the Scenario	Predicted Salinity Intrusion Inland (km)	
			2030	2040
Pumping increment and reduction	1	Pumping at baseline pumping rates of 2017	2.39	2.56
	2	Pumping increment of 10% from the baseline pumping rate of 2017	2.42	2.57
	3	Pumping increment of 20% from the baseline pumping rate of 2017	2.58	2.65
	4	Pumping increment of 30% from the baseline pumping rate of 2017	2.69	2.73
	5	Pumping reduction of 5% from the baseline pumping rate of 2017	2.19	2.41
	6	Pumping reduction of 10% from the baseline pumping rate of 2017	2.12	2.15
Sea level rise due to climatic changes	7	Sea level rise as per IPCC prediction	2.60	2.63
	8	Sea level rise @ + 0.25 m to the base sea level	2.60	2.65
	9	Sea level rise @ + 0.50 m to the base sea level	2.61	2.70
	10	Sea level rise @ − 0.25 m from the base sea level	2.52	2.59

6. Conclusions

A numerical model is a reasonably accurate and economical tool to simulate and predict the head and quality of groundwater in coastal aquifers if it is properly calibrated using the available measurements of heads, pumping rates, and boundary conditions. The calibrated geo-hydrological parameters can then be used to validate the model for another set of measured data. Finally, predictions of the groundwater elevations and quality can be made for any anticipated situation occurring in the future. The Wadi Al-Jizi coastal aquifer is facing seawater intrusion along the coastal boundary. The seawater front changes sporadically as a result of seasonal recharge patterns, the ensuing groundwater level oscillations, and decreases in freshwater discharge to the sea, according to salinity contour maps based on the measured data. These salinity contour maps revealed that the seawater front moves transiently because of seasonal recharge patterns and the consequent groundwater table fluctuations and reductions in the freshwater discharge to the sea. The salinity concentrations in groundwater in most of the monitoring wells have increased when compared with historical data, indicating that the plain aquifer's groundwater quality is consistently deteriorating due to seawater intrusion. A consistent water deficit in the watershed due to agricultural activities is also aggravating the situation. If the baseline pumping rates of the year 2017 continue until the year 2040, salinity intrusion ($\text{TDS} > 12,800 \text{ mg/L}$) will encroach inland by 0.80 km. However, anticipated increases in the abstraction rates will result in further intrusion. On the other hand, if the public authorities reduce the water deficit through water conservation policies and strictly implement them, the saline wedge might retreat by the year 2040. Another phenomenon that will increase seawater intrusion is the sea level rise. The IPCC scenario showed saline wedge intrusion 0.70 km inland in the year 2040 when compared with the results of the year 2017. Sea level rises of 0.25 m and 0.50 m also showed further seawater intrusion. In case of a drop in the sea level by 0.25 m, the seawater will recede in the year 2040. The results of a GIS-based study of groundwater potential [41] may be updated using the modeling results from the present study. Improved groundwater development and aquifer management measures (monitoring and control of abstraction rates and water rationing schemes, promoting agricultural products using brackish water, and recharging aquifers with recycled water) would be necessary to supple-

ment the increasing water demands and safeguard the rapidly contaminating groundwater aquifers from seawater intrusion.

Author Contributions: J.A.: Conceptualization, original draft, model implementation, and numerical modeling. A.S.: Data curation, resources, writing—review and editing, and supervision. S.M.T.: Supervision and data curation. H.T.: Review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: The authors acknowledge the Environment Authority, Oman, for providing the groundwater elevations and groundwater quality data.

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

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