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Artificial recharge via injection wells for salinity ingress control of Salalah plain aquifer, Sultanate of Oman

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ABSTRACT

Seawater intrusion (SWI) has been considered one of the most widespread environmental problems that deeply threatened the quality and sustainability of fresh groundwater resources along coastal aquifer in Salalah. The main objective of this study is to determine the results of the same investigation conducted in 2008 by the same author with the results of the current actual transient scenario for the same period of years 2006–2020. The developed 3D flow showed that the wedge of the SWI in 2020 could possibly be tracked up to 2 km and less than 500 m from the shoreline under the predictive scenario and current actual transient scenario, respectively under constant underflow. The findings of the modeling simulation explained that the maximum path lines of the injection fluids were able to reach the abstraction wells located more than 1.2 km southward of the injection bores in one year travel time under the current actual transient scenario under constant underflow. In 2020 the injection of municipal treated effluents was found to be effective in pushing back the SWI zone front by more than 1.2 km under the current actual transient scenario compares to less than 500 m under predictive scenario under constant underflow, especially at the middle of the injection boreholes of the aquifer. This study revealed that the application and simulation of the method helped increase the groundwater levels and decrease the salinity total dissolved solids levels along the vicinity of the injection line.

Keywords: Salalah plain aquifer; Seawater intrusion; 3D groundwater modeling simulation; Injection boreholes; Artificial groundwater recharge; Municipal treated effluents

1. Introduction

Salalah, the capital of Dhofar Governorate is a city located in southern Oman about 1,000 km from Muscat the capital. It is situated along the coast of the Arabian Sea and is considered the second-largest city in the Sultanate of Oman. In the 2020 Omani census, the population of Salalah reached 331,949 people. The increase in population gives an impression of the progressive development in the region. The issuance of new laws and regulations has encouraged both local and international companies to increase the local economy in Salalah. With this case, there is also an increase in the water demand for municipal, commercial, agricultural, and industrial sectors.

The main Salalah saturated aquifer layers are the upper alluvium layer of the quaternary age and the second layer of fractured limestone, and the third saturated layer is marly limestone, deposited in the tertiary age. As early as 2013, the tertiary aquifer was the main source of water supply for all. Looking back in 1992, the status of the aquifer was constant, but in 2005 there was a discrepancy in groundwater quality in most of the agriculture strips. It was found out that the quality of drinking water did not meet the standards set by the Omani Standards [1]. Studies and investigations were conducted resulting to the heavy withdrawal of large quantities of groundwater from the Salalah aquifer and its effect on saltwater intrusion in Salalah plain aquifer [2–4].

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The results of the investigations became the most widespread environmental problems that deeply threaten the quality and sustainability of fresh groundwater resources along coastal aquifers [5]. Even the neighboring countries are experiencing similar problems and are implementing appropriate management strategies to control the impacts of intrusion problems considering acceptable limits of economic and environmental costs [6]. Similar to what is happening in Salalah, groundwater levels are declining across its plain aquifer as there are currently daily withdrawals from about 1,500 boreholes exceeding the rate of the natural water recharge. The application of method conducted by Shammas [7], about using artificial groundwater recharge that is municipal treated effluents (MTEs), found effective to control the continuously declining groundwater levels at Salalah plain aquifer.

In the past, the entire city likely depended on the karstic coastal plain aquifer for all domestic, and industrial purposes [8]. Pumping from Salalah and Saada wellfields were used for potable water usage for Salalah City. The traditional agricultural farms were utilizing 31.2 Mm^3/y. Garziz farm wells were pumping 10.61 Mm^3/y for the cultivation of Rhodes grass. With the situation, Salalah coastal aquifer started to suffer saline intrusion [3].

From 2013 seawater desalination facility owned by Sembcorp Salalah Independent Water and Power Plant Company (IWPP) is utilizing reverse osmosis technology and produces 25.2 Mm^3/y of water [9]. Pumping from Salalah and Saada wellfields were simulated during predictive scenario at 23.75 Mm^3 in 2020, whereas at current actual transient scenario both wellfields pumped only 10.6 Mm^3 in 2020. So, the abstraction from Salalah and Saada wellfields were reduced by almost 60% in 2020 as reverse osmosis technology facility compensated the balance in potable water demand. The second desalination plant based on reverse osmosis technology is owned by Dhofar Desalination Company and started its operation in mid of 2021 at a maximum capacity of 120,000 m^3/d, and the production depends on the demand. The plant is located at a coastal site adjacent to the existing Sembcorp IWPP in the Dhofar Region.

The unconfined layer in the upper portion of the aquifer is the quaternary Wadi alluvium where the traditional farms are utilizing 31.2 Mm^3/y for the main yielding zone as its groundwater depth is less than 10 m [10]. So, the net agricultural demand is modeled in this study at 46 Mm^3/y for the predictive scenario [3,11] and along the current transient actual scenario.

Due to the high groundwater consumption at 10.61 Mm^3/y before the year 2012 to irrigate Rhodes grass, and low economic returns of Rhodes grass [2,10], the government decided to convert three-quarters of Garziz farm area to residential areas as illustrated in Fig. 2. Presently, almost 75% of the former Garziz farm area has been converted to residential uses. Garziz farm which is owned by Dhofar Cattle Feed Company is illustrated in Fig. 2.

Simulation modeling of the impact of the reduction in groundwater recharge originating from the horizontal precipitation from the mountain indicated that the reduction of the tree cover would result in a significant impact on the aquifer sustainability [12]. The availability of the underflow recharge happens on annual basis operations intended for the mountains of the region and Salalah coastal plain, but the situations were threatened by the annual reduction of horizontal precipitation.

In places near the sea this phenomenon seawater intrusion (SWI) always happens as in the case of the Salalah coastal zone [13], because more than 1,500 wells were drilled to get groundwater for their houses and farms, the reason why SWI began to seep into the Salalah groundwater aquifer since 1993 [1,3,14,15].

Salalah central sewage treatment plant started its operation in 2003 providing 20,000 m^3/d treatment of municipal sewage until the tertiary stage and ended up with a chlorination process prior to the effluent output stage [3] and [16]. Fig. 2 illustrates the data of pumping rates utilized by both Garziz and Ministry of Agriculture and Fisheries of the Sultanate of Oman farms from the Salalah plain aquifer.

To halt salinity in the Salalah aquifer, Shammas [7] recommended the relocation of Garziz farm since they were accumulating 10.61 Mm^3/y pumps from those 13 wells for Rhodes grass cultivation since 2012. Presently, there are only 3 active pumping wells after the government decided to stop the operation of 10 wells to pump groundwater for Rhodes grass irrigation at approx. 2.26 Mm^3/y. This means that from 2012 to present, there is approx. 77% blocked pumps monitored and recorded at Garziz farm.

The present application of simulation is a sequel of the study and investigation conducted by Shammas [7], presented, and published by the same author, and proved that the injection method is effective in halting SWI. The present study assessed and measured once more the efficacy of the artificial recharge utilizing groundwater modeling in two scenarios. In the Sultanate of Oman, the volume of wastewater has been increasing rapidly in the last 30 years due to the increase in freshwater use for all domestic, industrial, and commercial purposes. Treated wastewater and sludge, which is a by-product of this treatment, can be resources under certain circumstances [17]. Related to this, the produced MTEs were able to meet the regulatory limits set by the Omani Standards except for some: nitrate, *Escherichia coli*, and the total suspended solids. Furthermore, it should be noted that the performance of Salalah and Darsait Sewage Treatment Plant can be classified as the best compared to the other four sewage treatment plants (STPs) studied in Oman as mentioned by the study of Baawain et al. [16].

A 3D flow and solute advection transport model were developed to assess the effectiveness of the proposed recharge scheme and tracked the solute transport with respect to the modern method/technique being utilized nowadays. The flow predicted the wedge along the saline intrusion and tracked up from the shoreline with the injection and without the injection for the period 2006 to 2020, respectively. The study simulated the predictive scenario vs. the real situation scenario in terms of water and salinity levels for the period 2006–2020. It was investigated and proven that the MTEs had increased the water levels at the vicinity of the injection line added to that, reducing the influence of saline inflows from the coastal areas. The former study Shammas [7] prediction is the act of forecasting what will happen in the future. Such actions manifested by the author were anchored by the prediction models that aim to quantify the effectiveness of the future based on a

Fig. 1. Location map of Garziz farm converted to residential areas. https://www.google.com/maps/search/garziz+farm/@17.0392622,54.1267529,3800m/data=!3m1!1e3

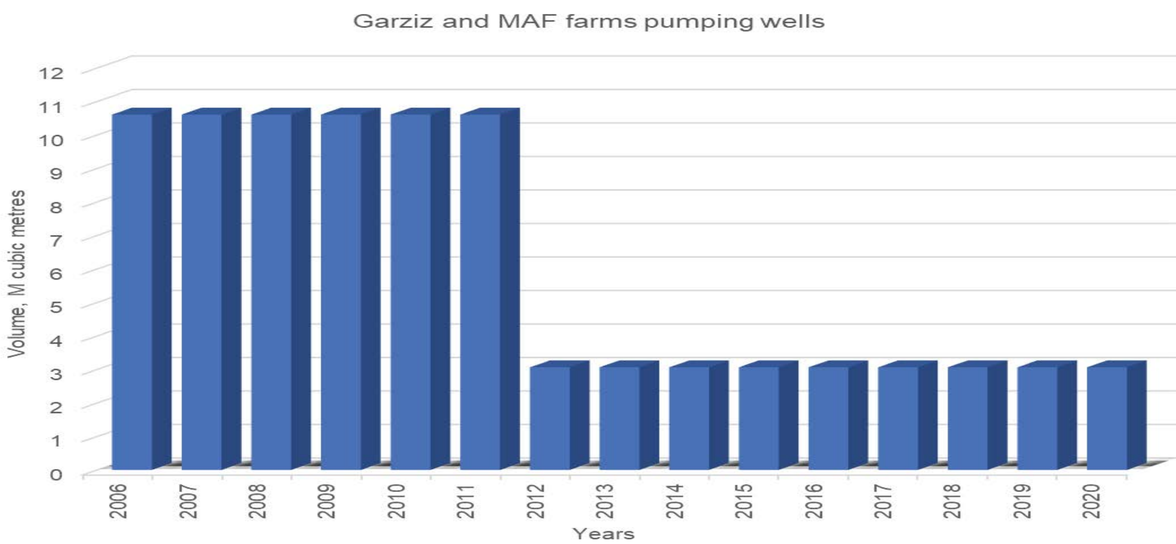

Fig. 2. Pumping rates of Garziz and Ministry of Agriculture and Fisheries of the Sultanate of Oman farms from Salalah plain aquifer.

set of predictors. Model scenarios are developed, validated, and updated to give importance to the effectiveness and sustainability of the artificial recharge. There is an urgent need for the best groundwater management technique to be used to combat the salinity. It is also prime and proper to investigate the plain aquifer hydrogeology flow system to determine if the artificial infiltration scheme is effective. It has been visualized by the investigator that the actual condition of the aquifer system and the prediction for the groundwater situation will be harmoniously balanced to halt SWI due to present and future abstraction simulation.

1.2. Salalah coastal aquifer

The plain aquifer is generally brackish, except for those areas where freshwater occurs in the central plain (<1,500 mg/L) and along the piedmont [18]. The main characteristics of this aquifer include saturated thickness typically 60–70 m with a maximum of about 120 m; very high transmission ranging from 1,000 to 200,000 m^3/d; high permeability associated with karstic features; and, hydraulic conductivity ranging between three orders of magnitude, from 10s to 1,000 s m/d. The natural annual recharge of the coastal well is approximately 50 MCM/y [10], with approximately 7.15 MCM/y of treated wastewater as reflected on Table 1. Groundwater table levels are constant in the plains area, ranging from 10 m above mean sea level near the mountain front to sea level near the coast. Given the unusually high transmission, groundwater level trends showed enough rising and declining trends as depletion in freshwater storage is rapidly replaced by adjacent brackish or seawater inflow. Given the experiences of salinity in Salalah plain with high vulnerability to SWI, wastewater treatment and injection project was established in 2003 [7].

In Salalah, coasts is about 20,000 m^3 of MTEs are injected daily to halt saline intrusion. Injection of MTEs into 40 boreholes is ongoing and still extended to a longitudinal distance of 12 km, considered a routine to discourage seawater intrusion. Table 1 displays the rate of artificial recharge conducted to treat effluents as revealed by Salalah Sewage Treatment Plant.

Table 1 reveals the variations of the injected volume of MTEs being injected from 2003 up to 2020. Such discrepancies were attributed to other transactions of agencies involved in the proceedings.

1.3. Objectives of the study

This follow-up investigation wanted to expose ground modeling scenarios utilized and developed by the author for salinity ingress of Salalah coastal aquifers towards sustainable groundwater through-flow [7,11,13], with the following objectives:

- To determine and compare the results of the predictive modeling scenario conducted in 2008 by the author is in harmony with the results of the current actual transient scenario for the same period of years 2006–2020.
- To apply MODFLOW, MT3DMS, and PMPATH numerical codes for the modeling simulation of artificial recharge via injection wells in the Salalah coastal aquifer.
- To study the efficacy of the artificial groundwater recharge by MTEs on halting SWI in the Salalah coastal aquifer.

Table 1
The artificial recharge rates of MTEs

Year conducted	Through flow to wells (million m^3)
2003	2
2004	2.43
2005	4.95
2006	1.74
2007	2.35
2008	2.54
2009	2.58
2010	2.42
2011	2.54
2012	2.6
2013	1.76
2014	1.6
2015	2.05
2016	4.56
2017	6.66
2018	2.27
2019	5.32
2020	7.15

1.4. The problem

The primary aquifers in terms of agricultural and municipal utilization are the shallow coastal aquifers that receive modern recharge from the mountain flowage, direct recharge from intense precipitation events, and indirect recharge through riverbeds infiltration [18]. One of the main challenges in coastal aquifers is how to provide the short-term water demand through abstraction from the coastal aquifers while maintaining their long-term water balance. Increased extraction of groundwater and reduction of flow towards the coast of Salalah has caused the saltwater interface to move inland. Apparently, the water increases due to the unbalanced allocation of water in the aquifers. In this situation, seawater intrusion is expected to increase causing serious problems to Salalah's domestic, industrial, and agricultural purposes. There was a pond injection project proposed before by Shammas [3] to combat this alarming situation way back in 1998, but due to permeable aquifer conditions, well injection was preferred, and the injection scheme had started in April 2003 [7].

However, the injection process continued with the 9.38 Mm^3 being injected till the end of 2005. This was found not sufficient to balance the Salalah aquifer [10]. Since there is a strong need for agricultural expansion beyond traditionally cultivated coastal plains, the situation led to the increased utilization of the aquifer. Presently, the region is experiencing desertification due to overgrazing in the Jabal area along the Dhofar mountains. Knowingly, this vast vegetation is important to recharge the underground reserves since this is supporting the water position in the Salalah plain [12]. There is a strong need for the implementation of policies that will protect the groundwater of Jabal as it contributes 98% of the Salalah aquifer recharge [12]. A policy to stop desertification in the Dhofar Region is very essential to protect the remains of the Jabal's unique biodiversity and to enhance the groundwater recharge for the Salalah aquifer [12].

In addition, it is essential to enhance the vegetation coverage at Jabal. The application of reforestation programs are possible measures to sustain the remaining natural rangelands. Tree planting should be given full attention to increasing fog water interception since this will benefit grassland production and increase groundwater recharge of the Salalah aquifer [12]. The importance of implementing fog water collection is crucial in this situation. This is the foremost reason why the author was prompted to conduct a follow-up investigation on the water levels and cross-check the effectiveness of artificial recharge set and discussed in the previous results and findings with comparison to the current actual results during the same time. The present investigation deals with the concrete balance between aquifer recharge and abstraction presented in two modflows and solute transport scenarios.

1.5. Review of the pilot scheme for the injection of treated wastewater

Salalah Central Sewage Treatment Plant (STP) started its operation in 2003 for the purpose of receiving and treating 20,000 m^3/d of Salalah's wastewater [7]. STP expansion of sewage influents treatment with a maximum of 50,000 m^3/d had been completed in 2018. The current amount of the MTEs that are being injected is about 40% of the total MTEs were injected into constructed boreholes situated parallel to Salalah coastline that extends until Al Muntazah Street and reduced from 90% of the MTEs that were being injected before [7]. The remaining balance has been discharged to Raysut Cement Factory, Bir Bint Ahmed Farm, and other related stakeholders. Injection of MTEs was started in the city of Salalah in 2003 through pipelines with 40 injection boreholes and 40 observation bores located along the coastal zone in distances of 1.5 to 2 km from the shoreline [7]. The injection bores are located 300 m apart from each other starting from west to east along the Salalah coastal agricultural strip [7] to monitor the groundwater levels and quality pertaining to total dissolved solids (TDS).

1.6. Importance of periodic modeling method for the MTEs in Salalah plain aquifer

In the last study of the effectiveness of the injection method, several salient ideas came up that triggered the author to continue what he started to halt SWI in the coastal aquifer. Groundwater depletion has become a critical issue that threatened water supplies for farmers and other users that resulted to rapidly progressing saltwater intrusion. Artificial groundwater recharge from then till present is the most direct way to address groundwater depletion with recycled water through injection well. The injection method stabilized the water levels and even reduced the SWI along the injection scope [7]. Artificial recharge was utilized to raise groundwater levels, prevent SWI, supplement water supplies, and remain in long-term storage for future use or drought mitigation [19]. The abstraction from the aquifer has been controlled and the quality of the water has been maintained according to Omani Standards OS 08/2012. The data gathered supported the results of the modeling scenarios that prompted the increase of water levels [7]. The injection method would not be effective unless there was controlled pumping of artificial water coming from both eastern and western parts of the coastal areas. The injection well with MTEs located in the central part of the Salalah coast was more effective than the central plain of Salalah due to higher permeability that supported the flushing and transporting of the underflow combined with the injected fluids towards the coast [7].

1.7. MTEs of water as an efficient measure to control SWI in Salalah aquifer

Groundwater recharge with MTEs is an attractive option for many reasons. It is more publicly acceptable than direct potable reuse because of the psychological value of the environmental buffer. Several analyses had been conducted

Fig. 3. (a) Collection tank of treated wastewater is located in Raysut area of Salalah City. (b) The injection borehole (in yellow color) serves as an observation well located along Salalah coastal plain (Fig. 3a and b after [7]).

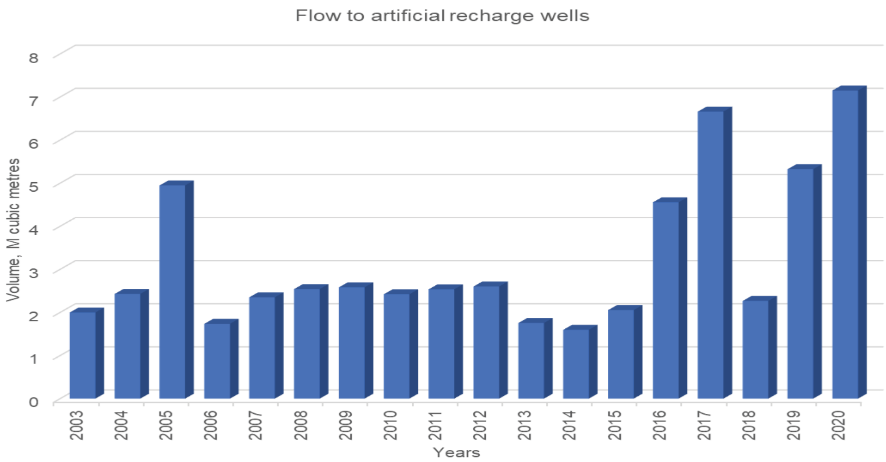

Fig. 4. Artificial recharge rates of MTEs from the Salalah Central STP.

to determine the positive potential of utilizing artificial recharge in the repulsion of SWI by means of experimental, analytical, periodic, predictive, and numerical modeling. Expounding on these scenarios are the piloting of several surface reservoirs to alter recharge systems like lakes, canals, and other spreading recharge possible to recharge unconfined aquifer systems through infiltration of collected water [20]. Illustrated in Fig. 4 are the artificial recharge rates of MTEs from the Salalah Central STP.

Similar to the findings of the study on the effects of a large dam in the retardation of SWI in Al Khoud, Muscat Oman, conducted by Abdalla and Al-Rawahi [21] it was found out that the artificial recharge of water is an efficient measure to control SWI and elevate the groundwater levels. By transporting river water to inner lakes through a pre-constructed canal, an integrated methodology for the future sustainability of the flow system had been developed. The study of Shammas [7] & Abdalla and Al-Rawahi [21] identified that the cost of providing high quality or desalinated water for recharging purposes is a challenge that the recharge barriers are facing. This strong notion prompted the author to monitor completely on placing renewable sources of water, such as MTEs as the sources of recharge for seawater intrusion mitigation. The utilization of MTEs for common utility sectors or artificial storage in subsurface layers could sustain the water demands and protect the system against SWI in Salalah coastal aquifer [7].

1.8. MTEs direct injection procedure

Salalah Sanitary Drainage Services Company (SSDSco) utilizes a biological treatment system, known as an activated sludge process, to achieve tertiary treatment. The quantities of MTEs projected in the investigation of Shammas [7], which are available for reuse is about 6.6, 8.6, and 10 MCM for 2006, 2015, and 2020, respectively. These quantities are sufficient to irrigate between 273, 356 and 414 Ha, respectively, of net water demand 24,170 m^3/ha/y as assumed by Geo-Resources Consultancy [4]. Whereas the actual MTEs injected were about 1.7, 2, and 7 MCM for 2006, 2015, and 2020, respectively (Fig. 4). Direct injection has been found effective in which recycled municipal wastewater has undergone tertiary treatment. They are injected directly into the groundwater aquifer via injection wells [7]. The water is then mixed with the groundwater and remains in the groundwater aquifer until it is pumped out for use. During the operation, the injection wells directly prevent SWI by acting as a hydraulic barrier. To form a hydraulic barrier, injection wells are lined up along the divide between saltwater and freshwater, and the injected freshwater takes up the space that the saltwater would otherwise encroach on. Shammas [7] investigation proves that direct injection of MTEs entails injecting high-quality MTEs into a confined groundwater aquifer.

Currently, Dhofar Municipality is utilizing 9,000 m^3/d (3.3 m^3/y) of the MTEs for irrigation of green landscapes at Salalah City. The use of MTEs on amenity plantings and water conservation measures are also considered appropriate instead of pumping this quantity directly from the Salalah aquifer.

2. Materials and method

A modeling scheme of 3D flow groundwater simulation model using MODFLOW [22] was utilized in this study under constant underflow. Solute transport predictive modeling was carried out in Salalah plain aquifer using MT3DMS [23] under constant underflow representing a mass transport simulation model and PMPATH was used for the advection transport. Predictive simulation and current actual transient simulation of the aquifer were carried out for the 2006–2020 years under constant underflow to predict the behavior of the aquifer under the injecting MTEs method. The baseline scenario assumes that underflow is constant through the predictive and current actual transient period.

The underflow was derived from the developed numerical groundwater flow modeling and calibration with hydraulic heads of 1992. The underflow from the Jabal was derived from the developed steady-state flow model at 50 Mm^3 [12].

The main argument of the present investigation is to determine whether the results of the predictive modeling scenario conducted in 2008 are congruent to the results of the current actual transient scenario for the same period of years 2006–2020. In the present study, both the predictive scenario and the actual/current transient scenario were modeled and simulated during the same period of 2006–2020 years under constant underflow. In this paper, the Salalah plain aquifer has been divided into three saturated layers [7]. The first layer was allocated for irrigation of coastal agricultural farms, the second layer for Garziz farm and Salalah wellfield wells. The direct injection of MTEs at 48 m depth below ground surface is taking place in the coastal agricultural zone, which has direct contact with the third layer of the same aquifer that is pumping from far inland area for potable water especially Saada wellfield which is located at distance almost 11 km inland from injection bores.

3. Results and discussions

The results of the predictive scenarios in the previous investigation of Shammas [7] are presented, discussed, and compared accordingly with the results of the current actual transient scenarios. The advection transport model predicted that in 2020 the maximum path lines of the injection fluids would reach the abstraction wells that are located approximately 1 km, southward of the injection bores in a year's travel time. The developed flow showed that the wedge of the SWI in 2020 would be tracked up to 2 km and less than 500 m from the shoreline under the predictive scenario and current actual transient scenario, respectively under constant underflow, especially at the middle of the injection boreholes of the aquifer.

3.1. Potentiometric heads result under constant underflow

Currently (2020) the injection method is effective in pushing back the saline zone front by 1 km. towards the sea. The investigation of the application of the injection method helped increase the water levels and reduced groundwater salinity (TDS) at the vicinity of the injection bores. The schematic figures below explained the results of the predictive modeling scenarios. In Fig. 5, water levels at 0.5 m amsl reached Garziz farm site approx. 4 km inland. The water levels at the coastal agriculture strip which is located between 500 m and 2 km distance from the shoreline are less than 0.5 m amsl.

In Fig. 6, the water levels in 2005 during the current transient model were illustrated. This shows that water levels at 0.5 m amsl reached Garziz farm site at approx. 5 km inland. The water levels at the coastal agriculture strip are less than 0.4 m amsl. At the east and west of the coastal agricultural strip the water levels were recorded at levels little more than 0 m amsl.

Meanwhile, in Fig. 7, the water levels in 2005 during the current transient model has been presented and compared. It shows that the water levels at 0.5 m amsl reached Garziz farm site at approx. 5 km inland. The water levels at the coastal agriculture strip are less than 0.4 m amsl. At the east and west of the coastal agricultural strip the water levels were recorded at levels little more than 0 m amsl.

In Fig. 8, the water levels at 0.5 m amsl reached areas behind Garziz farm site at approx. 5 km inland. The water levels at the coastal agriculture are less than 0.2 m amsl as shown below.

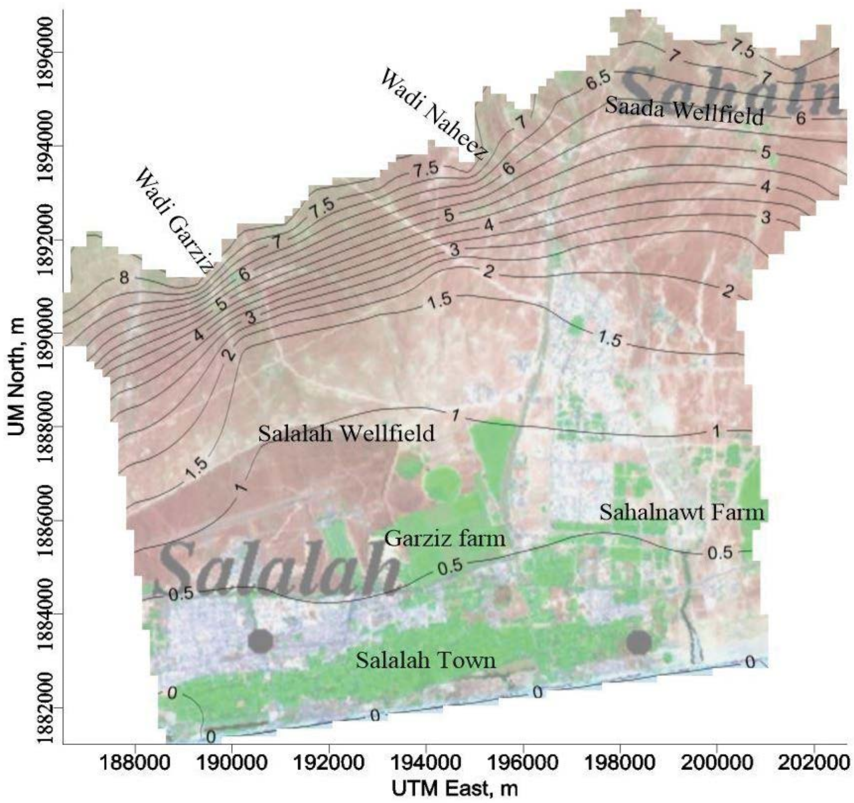

Fig. 5. Schematic diagram of water levels (m) with injection period 8-year 2000, current transient scenario.

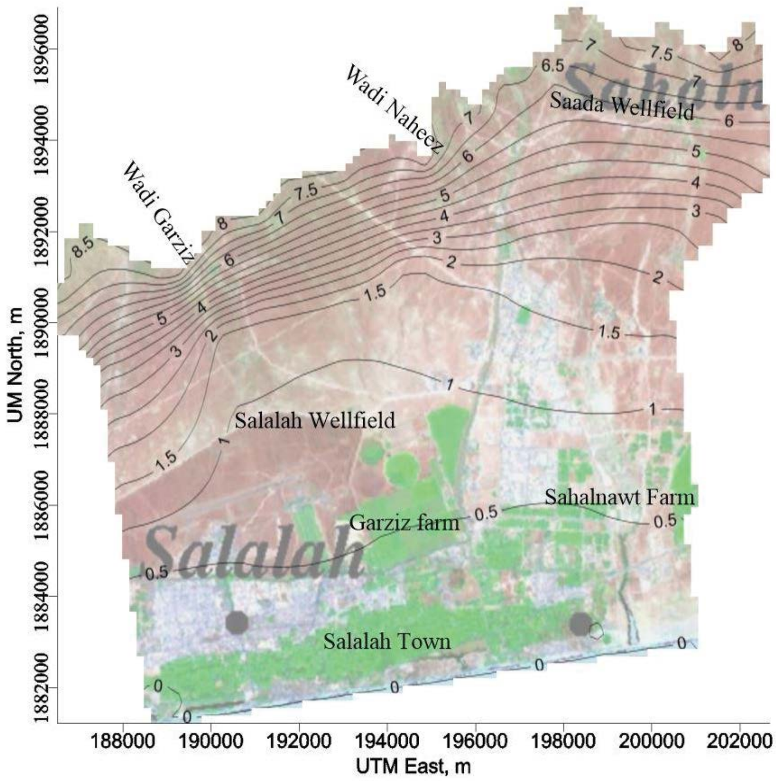

Fig. 6. Schematic diagram of water levels (m) with injection period 13-year 2005, current transient scenario.

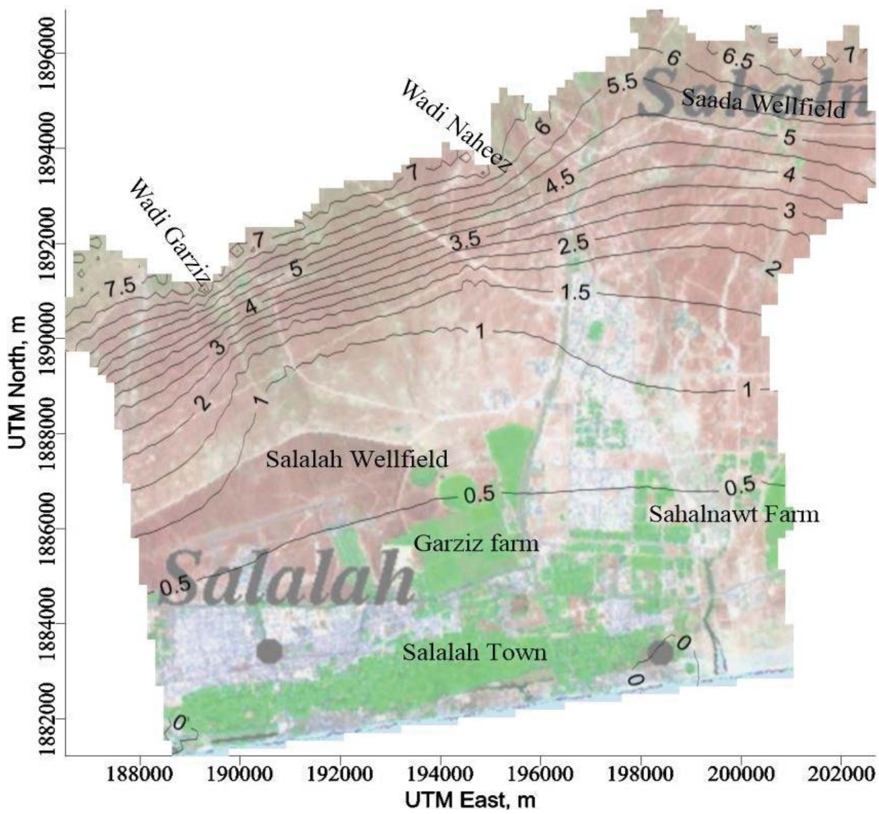

Fig. 7. Schematic diagram of water levels (m) with injection period 18-year 2010 with injection, predictive scenario.

Fig. 8 illustrates the water levels in 2010 during the current transient period. This explains that the water levels at 0.5 m amsl reached areas far behind Garziz farm site and reached Salalah wellfield areas at approx. 6 km inland. The water levels at the center of the coastal agriculture strip are less than 0.1 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl.

Fig. 9 shows the water levels in 2015 during the predictive transient. Fig. 9 explains that the water levels at 0.5 m amsl reached areas far inland and reached Salalah wellfield areas at approx. 7 km inland. The water levels at the center of the coastal agriculture strip are less than 0.1 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl.

Moreover, the above illustration, Fig. 10 illustrates the water levels in 2015 during the current transient period. It explains that the water levels at 0.5 m amsl reached Garziz farm site, at approx. 5 km inland. The water levels at the center of the coastal agriculture strip are less than 0.5 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl. To compare the predictive scenario with the current transient scenario during this period, it has been found that the water levels increased in the current transient scenario as compared with the predictive scenario during the same period. The results were compared based on the results of groundwater pumping reduction from the Salalah wellfield and Garziz farms.

Fig. 11 shows the water levels in 2020 during the predictive transient. Fig. 11 explains that the water levels at 0.5 m amsl reached areas far inland behind Salalah wellfield areas at approx. 8 km inland. The water levels at the center of the coastal agriculture strip are less than 0.05 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl.

The water levels in 2020 during the current transient period have been taken too and compared as shown in Fig. 12 where the water levels at 0.5 m amsl reached the areas under Garziz farm site, at approx. 4 km inland. The water levels at the center of the coastal agriculture strip are less than 0.5 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0.02 m amsl. To compare the predictive scenario with the current transient scenario in this periodic modeling, it was revealed that the results of water levels had increased in the current transient scenario as compared with the predictive scenario during the same period. The comparison has been elicited by means of groundwater pumping reduction from Salalah wellfield and Garziz farm.

3.2. Solute transport results under constant underflow

Fig. 13 shows that the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip of Salalah City accumulates 2,000 mg/L whereas along the eastern and western parts of the city, the TDS level exceeds 4,000 mg/L. This clearly explains that there was seawater intrusion as proven by the 10,000 mg/L excess in the majority areas of Salalah City with distances of 500 m from the base shoreline.

In Fig. 14 the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip of Salalah City is

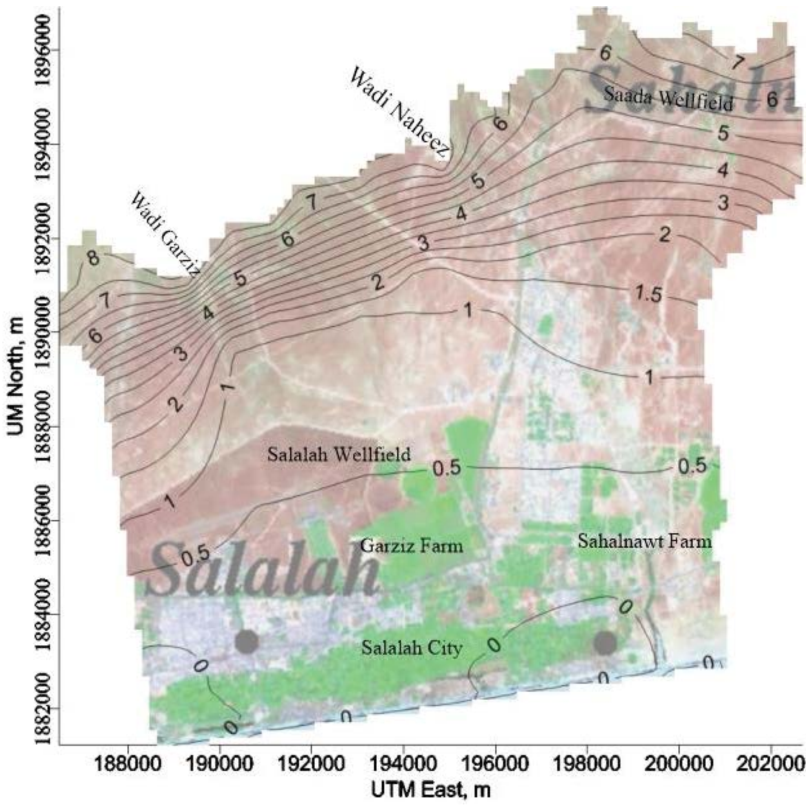

Fig. 8. Schematic diagram of water levels (m) with injection period 18-year 2010, current transient model.

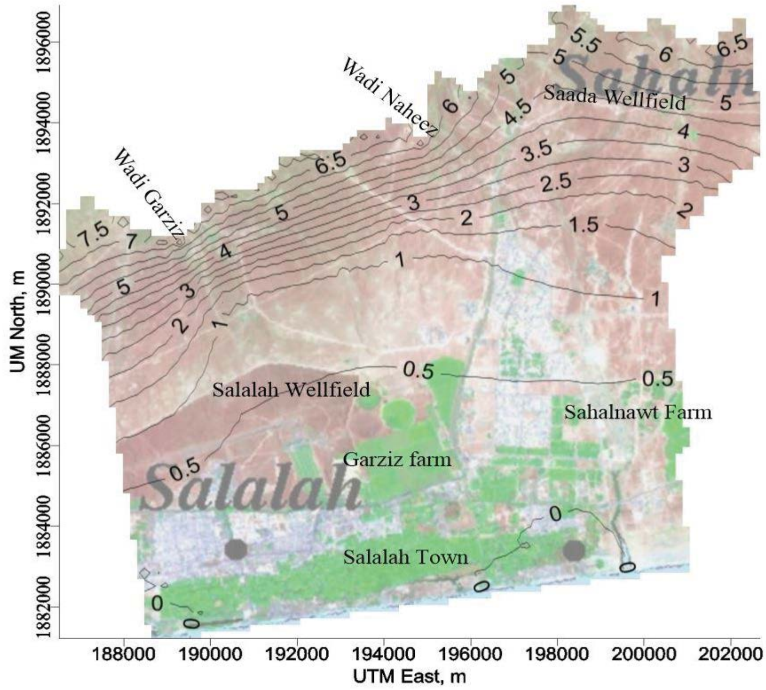

Fig. 9. Schematic diagram of WL baseline sc a p23 – 2015 with injection, predictive scenario.

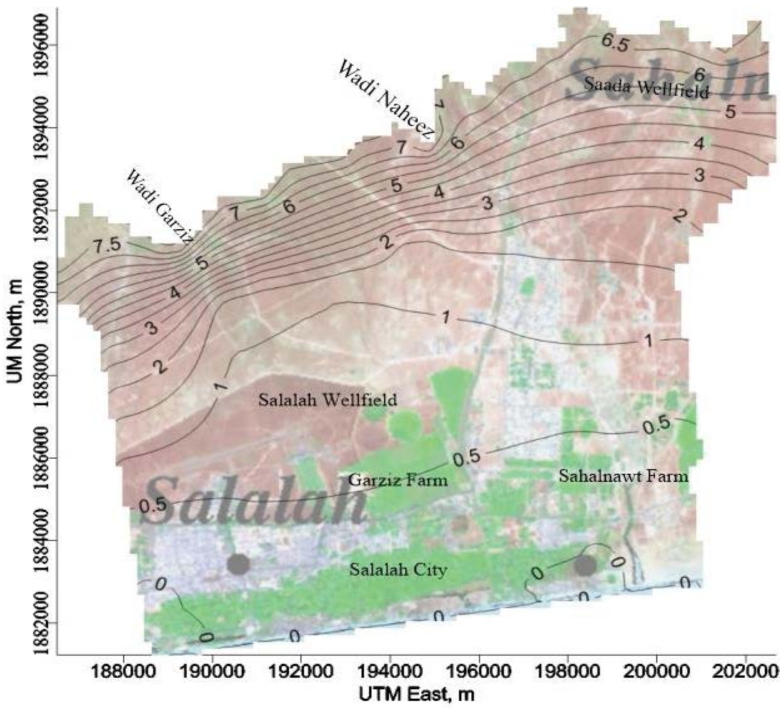

Fig. 10. Schematic diagram of water levels (m) with injection in layer 1 period 23 – year 2015, current transient scenario.

slightly higher than 2,000 mg/L that was accumulated in Fig. 13. It is clearly seen that along the eastern and western parts of the strip is an excess of 5,000 mg/L TDS. Seawater intrusion is obvious, and TDS exceeded 10,000 mg/L in most of the areas at distances 500 m from the shoreline.

In Fig. 15 the salinity levels (TDS, mg/L) at the center of the coastal agricultural strip (Salalah City) are within 2,000 mg/L whereas at the east and west parts of this strip, the TDS exceeded 4,000 mg/L. Similarly, there is a presence of seawater intrusion since the level of TDS exceeded

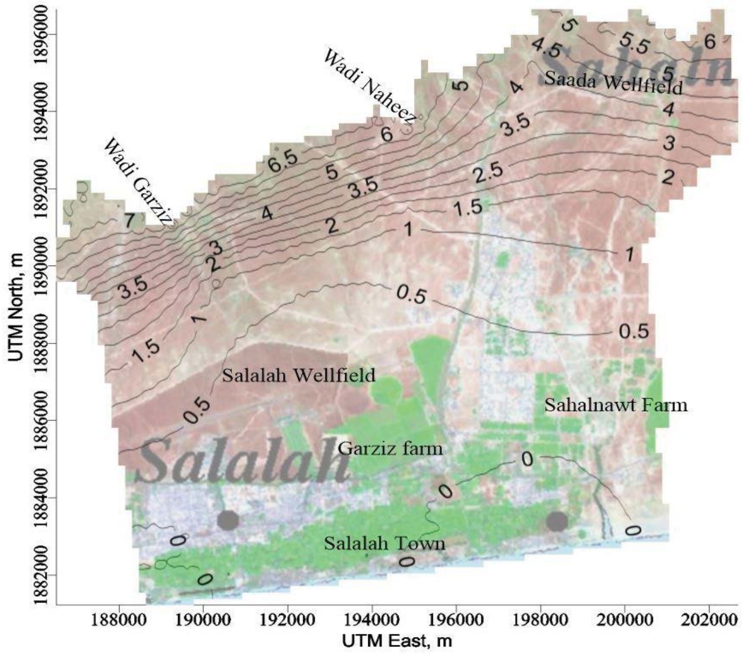

Fig. 11. Schematic diagram of water levels (m) period 28 – year 2020 with injection, predictive scenario.

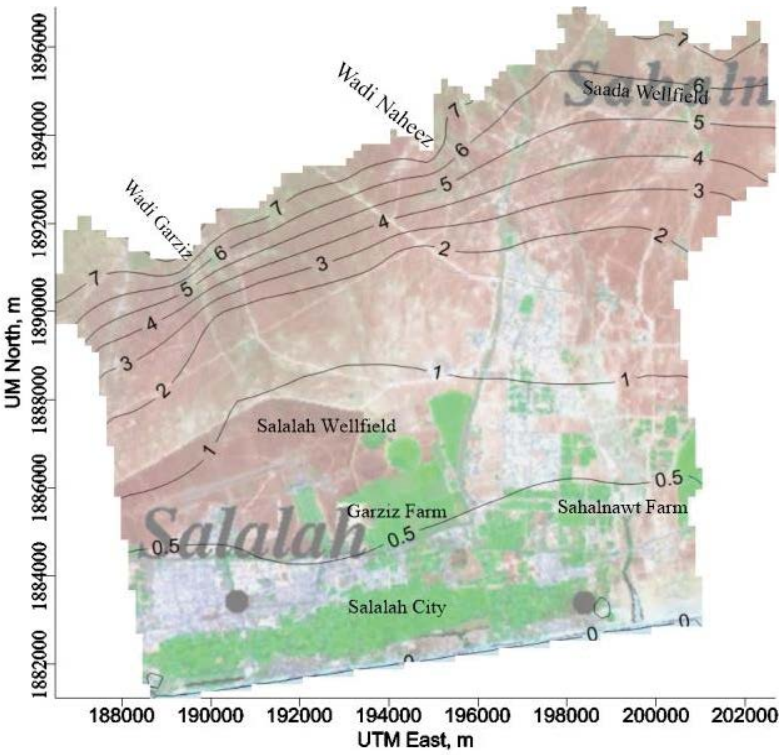

Fig. 12. Schematic diagram of water levels (m) with injection at year 2020, current transient scenario.

10,000 mg/L in most of the areas of Salalah City with distances 500 m from the shoreline.

In Fig. 16 the salinity levels (TDS, mg/L) which were found located at the center of the coastal agricultural strip in Salalah City is within 2,000 mg/L while on the eastern and western parts of the of the strip, the TDS exceeded 4,000 mg/L. This clearly implies the ingress of seawater intrusion as it exceeds 10,000 mg/L in most areas with distances 500 m from the shoreline. This figure shows that the TDS levels reached 2,000 mg/L at along the injection route

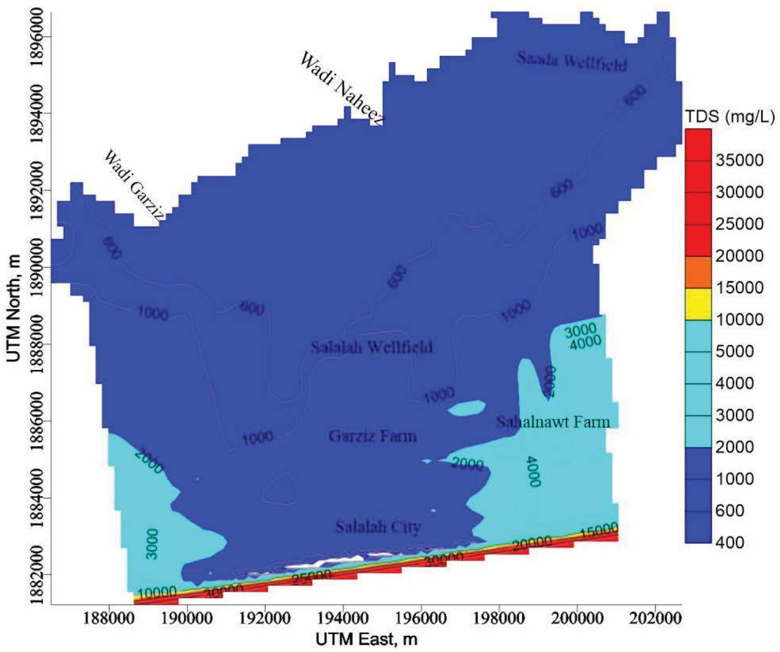

Fig. 13. Schematic diagram of TDS (mg/L) with injection in the year 2000, current transient scenario.

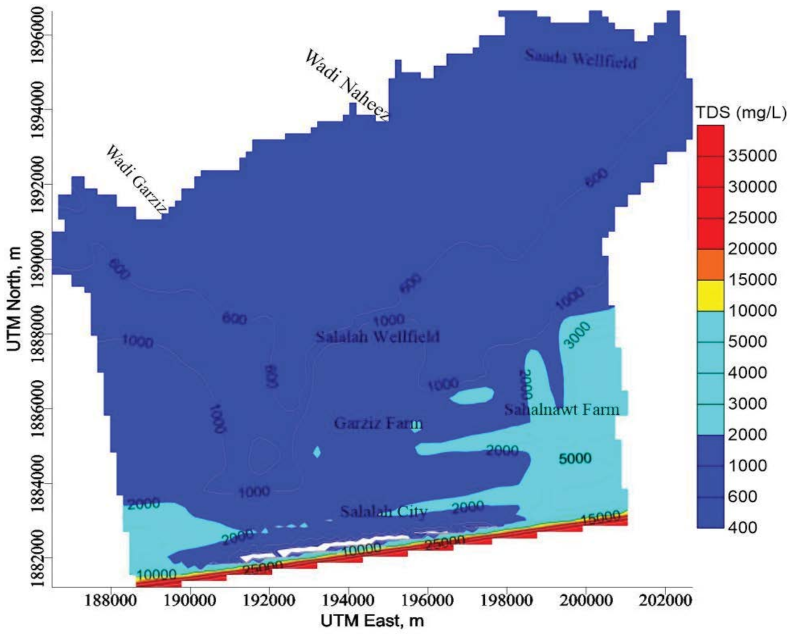

Fig. 14. Schematic diagram of TDS (mg/L) with injection in the year 2005, current transient scenario.

lines which are located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

Meanwhile, Fig. 17 explains that the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip of Salalah City is within 2,000 mg/L. It has been found also that along the eastern and western parts of this strip, the TDS exceeded 4,000 mg/L. This is another implication of the presence of SWI since the level exceeds 10,000 mg/L at most of the areas at distances 500 m from the shoreline. This figure shows that the TDS levels reached 3,000 mg/L along the injection route lines which are located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

In Fig. 18 the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip (Salalah City) is within 2,000 mg/L whereas, at eastern and western parts of this strip, the TDS exceeded 3,000 mg/L. Seawater intrusion

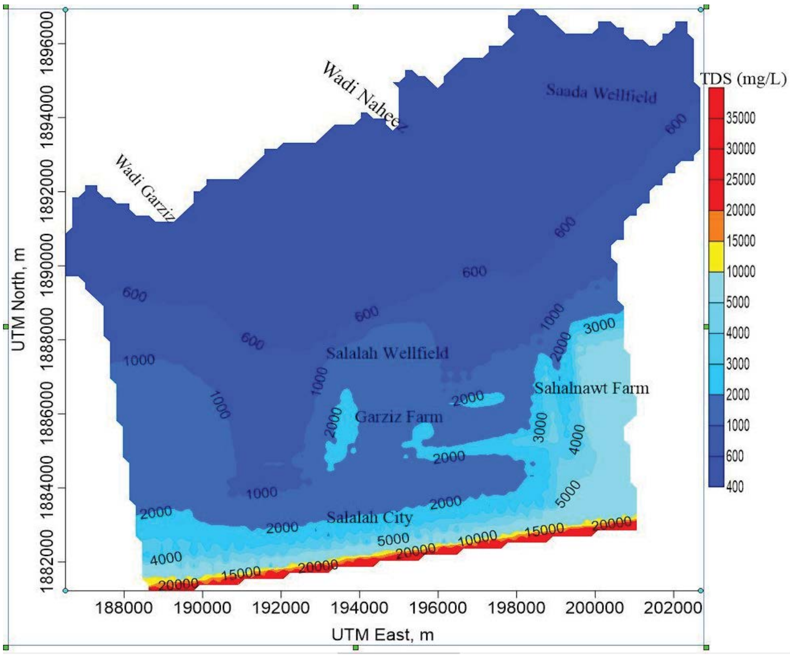

Fig. 15. Schematic diagram of TDS (mg/L) with injection in the year 2010, predictive scenario.

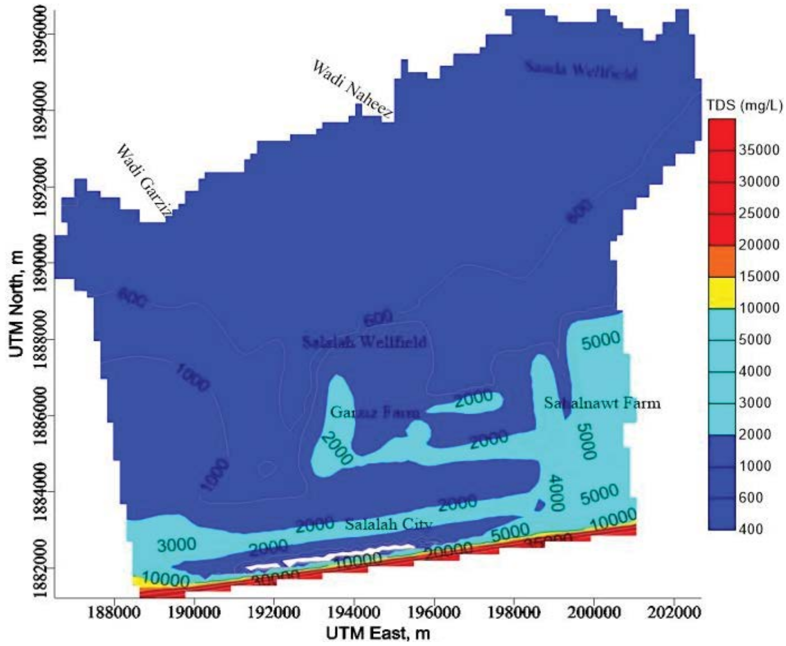

Fig. 16. Schematic diagram of TDS (mg/L) with injection in the year 2010, current transient scenario.

is obvious and TDS exceeded 10,000 mg/L at most of the areas at distances 500 m from the shoreline. This figure shows that the TDS levels reached 2,000 mg/L at along the injection route lines which are located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

To compare the predictive scenario vs. the current transient scenario, the solute transport modeling shows that salinity results decreased during the current transient scenario as compared to the predictive scenario during the same periods. These resulted to groundwater pumping reduction from Salalah wellfield and Garziz farms.

The salinity levels (TDS, mg/L) in Fig. 19 located at the center of the coastal agricultural strip (Salalah City) is within 3,000 mg/L while along the eastern and western parts, the TDS exceeded 4,000 mg/L. Seawater intrusion is obvious and TDS exceeded 10,000 mg/L at most of the areas inland at distances 500 m from the shoreline. This figure

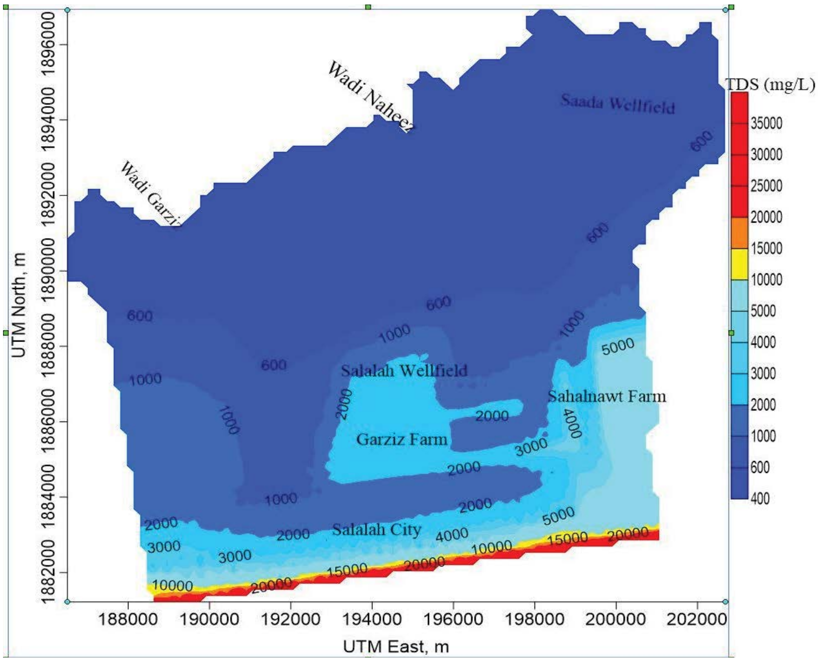

Fig. 17. Schematic diagram of TDS (mg/L) with injection in the year 2015, predictive scenario.

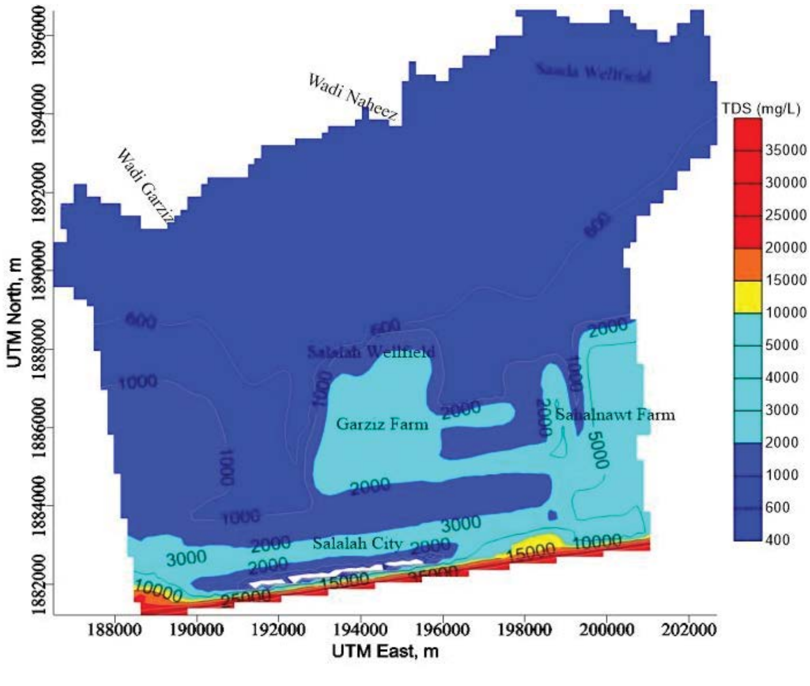

Fig. 18. Schematic diagram of TDS (mg/L) with injection in the year 2015, current transient scenario.

shows that the TDS levels reached 3,000 mg/L at areas along the injection route lines which is located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

In Fig. 20 the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip (Salalah City) is within 2,000 mg/L whereas, at east and west parts of this strip, the TDS exceeded 3,000 mg/L. Seawater intrusion is obvious and TDS exceeded 10,000 mg/L at most of the areas at distances 500 m from the shoreline. This figure shows that the TDS levels reached 2,000 mg/L at areas along the injection route lines which is located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

To compare the predictive scenario with the current transient scenario at this period, the solute transport levels show that salinity results were decreased in the current transient scenario as compared with the predictive scenario

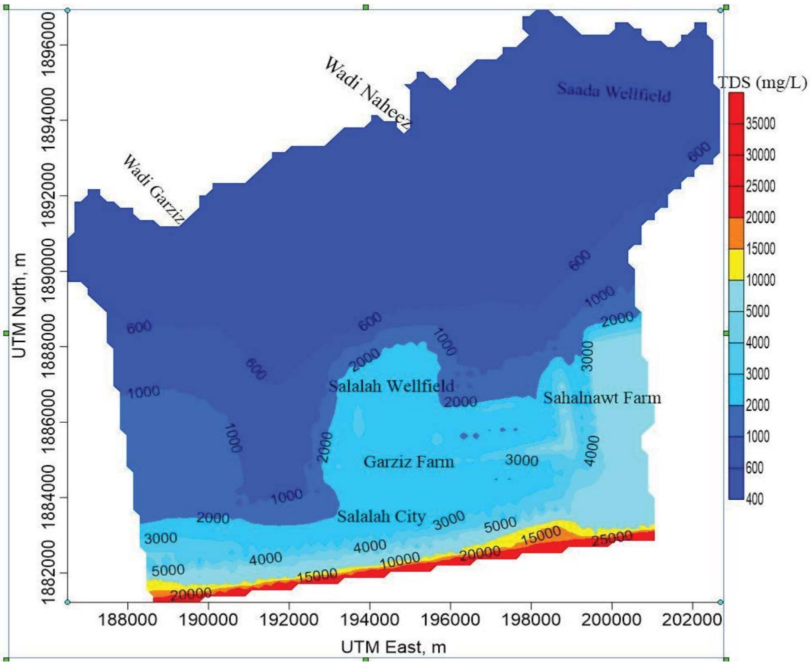

Fig. 19. Schematic diagram of TDS (mg/L) with injection in the year 2020, predictive scenario.

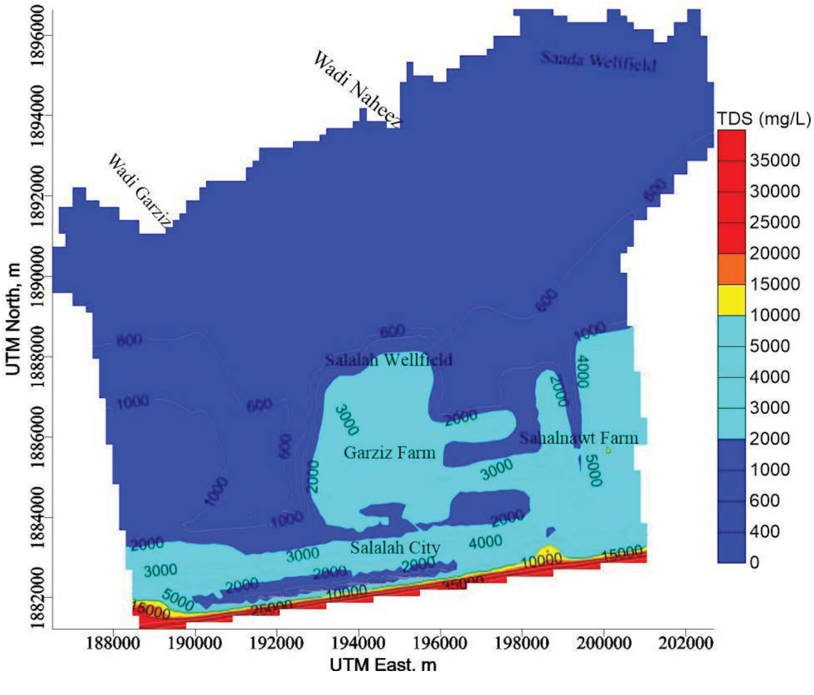

Fig. 20. Schematic diagram of TDS (mg/L) with injection in the year 2020, current transient scenario.

during the same period as a result of groundwater pumping reduction from the Salalah wellfield and Garziz farm.

3.3. Advection transport results under constant underflow

Fig. 21 shows the effectiveness of the injection method in combating SWI in 2020 under predictive scenario as revealed with no-management interference compared to Fig. 22 under current transient scenario with management interference. In Fig. 21, the solute transport of the injected MTEs could travel almost 500 m downstream in just one year by using PMPATH (advection transport) compared to the current transient scenario (Fig. 22), where the path lines could travel more than 1.2 km downstream of the injection lines in about one year.

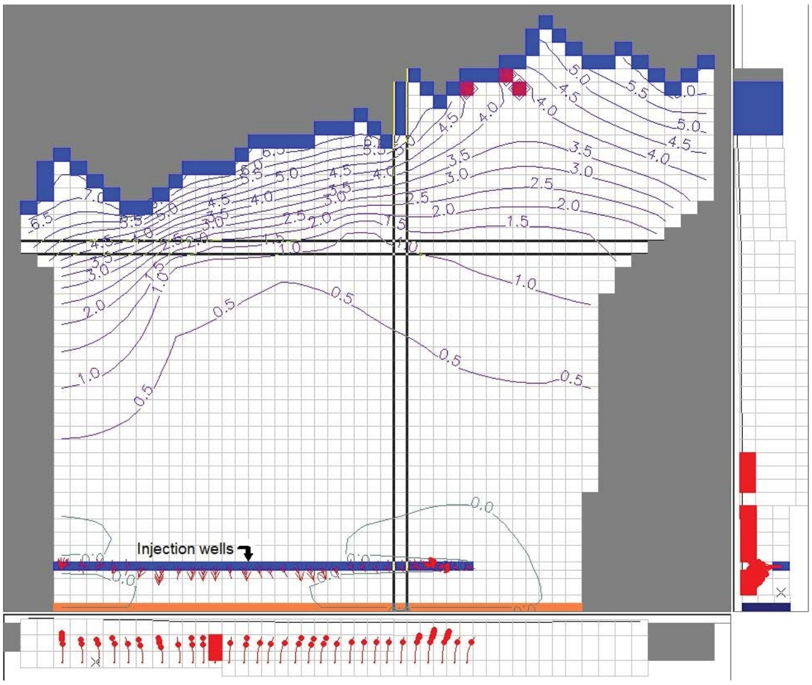

Fig. 21. PMPATH results of one-year simulation time, with the injection in 2020, predictive scenario.

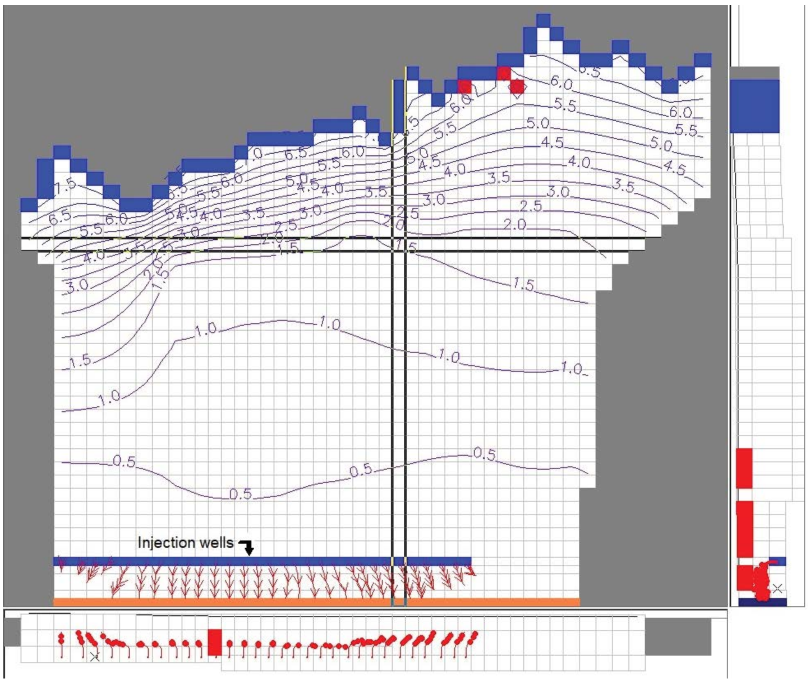

Fig. 22. PMPATH results of one-year simulation time, with the injection in 2020, current transient scenario.

3.4. Conclusion and recommendations

The injection scheme of the MTEs in the Salalah plain aquifer stabilized the water levels and reduced the salinity (TDS) along the injection lines. The abstraction from the aquifer has been able to manage about 77% of pumping rates of the wells that are operating at Garziz farm considerably blocked since 2012 until the present. In addition, the abstraction from the Salalah wellfield was reduced by more than 60% in 2020 as reverse osmosis technology facility started to operate concurrently producing 25.2 Mm^3/y of water since the year 2013.

From the results of the investigation conducted by Shammas [7] and the present investigation also conducted by Shammas, it has been found that the direct injection method conducted along the eastern and western edges of the Salalah coastal aquifer was found less successful as compared to the injection procedure conducted in the middle of the injection boreholes of the aquifer. Those manifestations were attributed to the slow movement of underflow recharges in the edges of the aquifer along with the fast movement of saline intrusion. To compare the predictive scenario with the current actual transient scenario, the solute transport shows that TDS results decreased in current transient scenario as compared with predictive scenario during the same period. Such manifestations could be attributed to the decrease of groundwater pumping that was being held from the Salalah wellfield and Garziz farm.

The following are strongly recommended for the sustainable management of the coastal aquifer:

- Since it was observed that there was weak subsurface flow, this study recommends refraining from injection procedures, instead, to allocate the rate of injection among other boreholes.
- It was observed, too that the middle boreholes of the coastal aquifer are found to be significantly effective for direct injection.
- Similar to the 2008 recommendation of the author, Garziz farm should be relocated since they are pumping 8 Mm^3/y from 13 wells for the cultivation of Rhodes grass. Since 2012, 10 wells were closed in Garziz farm, which means only 3 wells remain pumping groundwater at almost approx. 2.26 Mm^3/y. The implication that 77% of the pumping rates were blocked from 2012 to the present would definitely be helpful to the coastal aquifer.
- The expansion of the STP also took place and the central STP currently (2020) treats more than 50,000 m^3/d effluents to a tertiary level, of which only 40% of MTEs outputs were used (2020) for artificial recharge.
- Increase the injection rates by at least 80% of the total MTEs outputs daily. This study recommends reusing more than 80% of MTEs into injection bores. These processes can be considered as an effective integrated water resource management method for Salalah coastal aquifer.
- The quality and quantity of the MTEs, the depth of the injection bores, cost, and the source of providing the high quality of MTEs are the factors that should be taken into consideration in constructing an artificial recharge system.
- It is a fact that utilizing desalinated seawater is costly, thus, the application of MTEs can be alternate reliable water management having low cost but higher environmental benefits.

Acknowledgments

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List of notation

SWI — Seawater intrusion
MECA — Ministry of Environment and Climate Affairs
PAEW — Public Authority for Electricity and Water
DCFC — Dhofar Cattle Feed Company
DGEWRDG — Directorate General of Environment and Water Resources in Dhofar Governorate, MRMEWR
DWR — Department of Water Resources Affairs in the DGEWRDG
EC — Electrical conductivity
FAO — Food and Agriculture Organisation of the United Nations
GDP — Gross domestic product
GIS — Global information system
MTEs — Municipal treated effluents
m amsl — Metres above mean sea level
mg/L — Milligrams per litre
mm/d — Millimetres per day
Mm^3 — Million cubic metres
μS/cm — Micro Siemens/cm, a measure of electrical conductivity (EC)
MAF — Ministry of Agriculture and Fisheries of the Sultanate of Oman
MRMEWR — Ministry of Regional Municipalities, Environment and Water Resources of the Sultanate of Oman
MWR — (Former) Ministry of Water Resources of the Sultanate of Oman
NWD — Net water demand
NWI — National wells inventory
PCDESR — Planning Committee for Development and Environment of the Southern Region, Sultanate of Oman
PD-GIS — Planning Department-Geographic Information System Section for MRMEWR
SSDSCo — Salalah Sanitary Drainage Services Company
STP — Sewage treatment plant
TDS — Total dissolved solids
Ha — Hectare
MCM — Million cubic metres
Jabal — Mountain
IWPP — Independent water and power plant
OS — Omani Standards

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