A New Focus on Groundwater–Seawater Interactions
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Seawater intrusion in the coastal aquifer of Wadi Ham, UAE

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Abstract A transport model was developed to simulate the seawater intrusion in the aquifer system along the Kalbha and Fujairah coast of the United Arab Emirates. The model was used to simulate the salinity levels of the groundwater of Wadi Ham aquifer and its variation in time and space from January 1994 to March 2005. The area covering the coast of Gulf of Oman in the study domain was taken as a constant concentration boundary with an average salinity (TDS) value of 35 000 mg/L. The effect of artificial recharge on seawater intrusion was evaluated. The results of the simulation indicated that the seawater intrusion is affected by the dry and wet conditions. During the dry years, the velocity vectors are directed from the Gulf of Oman to the aquifer causing severe intrusion problems. During the wet years when rainfall is relatively high and groundwater recharge is encountered from the ponding area of Wadi Ham dam, the velocity vectors are reversed.

Key words numerical modelling; seawater intrusion; recharge; UAE

INTRODUCTION

In arid and semi-arid regions, groundwater constitutes the main, if not the only, source of natural freshwater. Many aquifers around the globe are located in costal areas and are thus vulnerable to the seawater intrusion phenomenon due to the direct hydraulic contact between freshwater in aquifers and the seawater. The growth of population in coastal areas and the conjugate increase in human, agricultural and industrial activities have imposed an increasing demand for freshwater in such areas. This increase in water demand is often covered by extensive pumping of fresh groundwater, causing subsequent lowering of the water table (or piezometric head) and upsetting the dynamic balance between freshwater and saline water bodies. The classical result of such a development is seawater intrusion. This phenomenon has been reported in many countries over the last few decades.

Seawater intrusion phenomena have been reported, with different degree, in almost all coastal aquifers around the globe. The problem is more severe in arid and semi-arid regions where the groundwater constitutes the main freshwater resource. A 3% mixing of seawater with the freshwater in a coastal aquifer would render the freshwater resource unsuitable for human consumption. The shape and degree of the seawater intrusion in a coastal aquifer depend on several factors. Some of these factors are natural and cannot be controlled, while others are manmade and could, thus, be managed. Groundwater resources in coastal aquifers should be carefully exploited to maintain the dynamic balance between the fresh and saline water bodies.

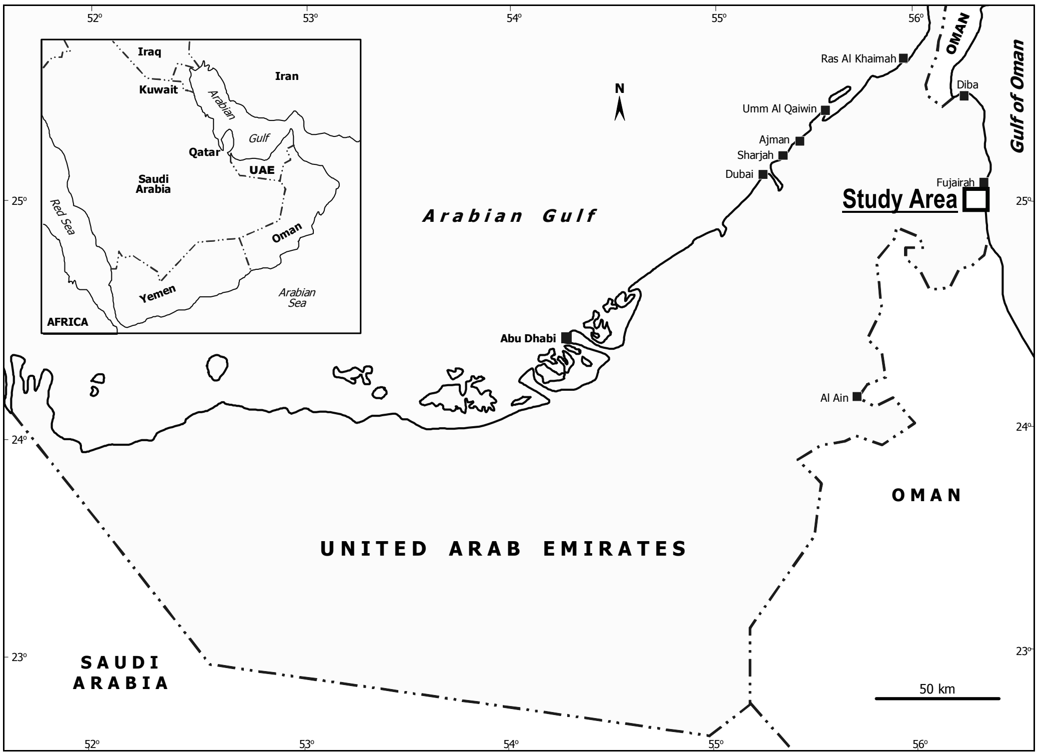

Fig. 1 Location map of the United Arab Emirates.

The United Arab Emirates (UAE) lies in the southeastern part of the Arabian peninsula between latitudes 22°40' and 26°00' N and longitudes 51°00' and 56°00' E. It is bounded to the north by the Arabian Gulf, on the east by the Sultanate of Oman and the Gulf of Oman and on the south and the west by the Kingdom of Saudi Arabia (Fig. 1). The total area of the UAE is about 83 600 km^2. The UAE is divided into two distinct zones: the larger low-lying zone and the smaller mountainous zone. Ninety percent of the country's area is covered by the low-lying zone (Al Hammadi, 2003). The low-lying zone ranges in altitude from sea level up to 300 metres. Its major part is characterized by the presence of sand dunes which rise gradually from the coastal plain reaching their highest elevation of 250 m above sea level (a.m.s.l.). Along the coast of the Arabian Gulf, the low-lying land is punctuated by ancient raised beaches and isolated hills which may reach up to 40 m a.m.s.l. in some locations (Baghdady, 1998).

Renewable water resources in the UAE are very limited. No surface water in the form of rivers or lakes is available. The rainfall is very scarce, random and infrequent. The average rainfall is about 110 mm/year. However, this annual rainfall is mostly encountered in a few events. Records indicate that the average number of rainfall events per year is five or less. These rainfall events are generally characterized by their short durations and heavy intensities. Such rainfall characteristics are quite consistent with regions classified as drought areas.

This paper is devoted to the simulation and assessment of seawater intrusion in the coastal aquifer of Wadi Ham, UAE. Visual MODFLOW (McDonald & Harbaugh, 1988; Waterloo Hydrgeologic Inc., 2000) was used to calibrate and simulate groundwater levels and flow patterns in Wadi Ham under different conditions. MT3D (Zheng, 1990) was used to simulate the solute transport and assess the impacts of groundwater recharge on the degree of seawater intrusion. It is concluded that rainfall and recharge events have a significant effect on the groundwater flow pattern and hence the seawater intrusion problem.

PHYSICAL SETTING OF THE STUDY AREA

A remote sensing image for the study area along with the location of existing monitoring wells and available geophysical sections is given in Fig. 2. The valley floor of Wadi Ham is a flat-gravelly plain with a triangular shape broadening to the sea and draining the surrounding mountains. It rises from sea level at Fujairah to approximately 100 m above sea level to the northwest. A few hills are scattered in different parts of the wadi. These hills subdivide the wadi into communicating zones. Along the coast, the inward land becomes a river terrace or alluvial plain. It is locally dissected by stream channels filled with cobble and gravel. The number and the depth of channels decrease towards the coast. The wadi plain is used for extensive agricultural activities. Some new industries have commenced in the vicinity of the coastal zone.

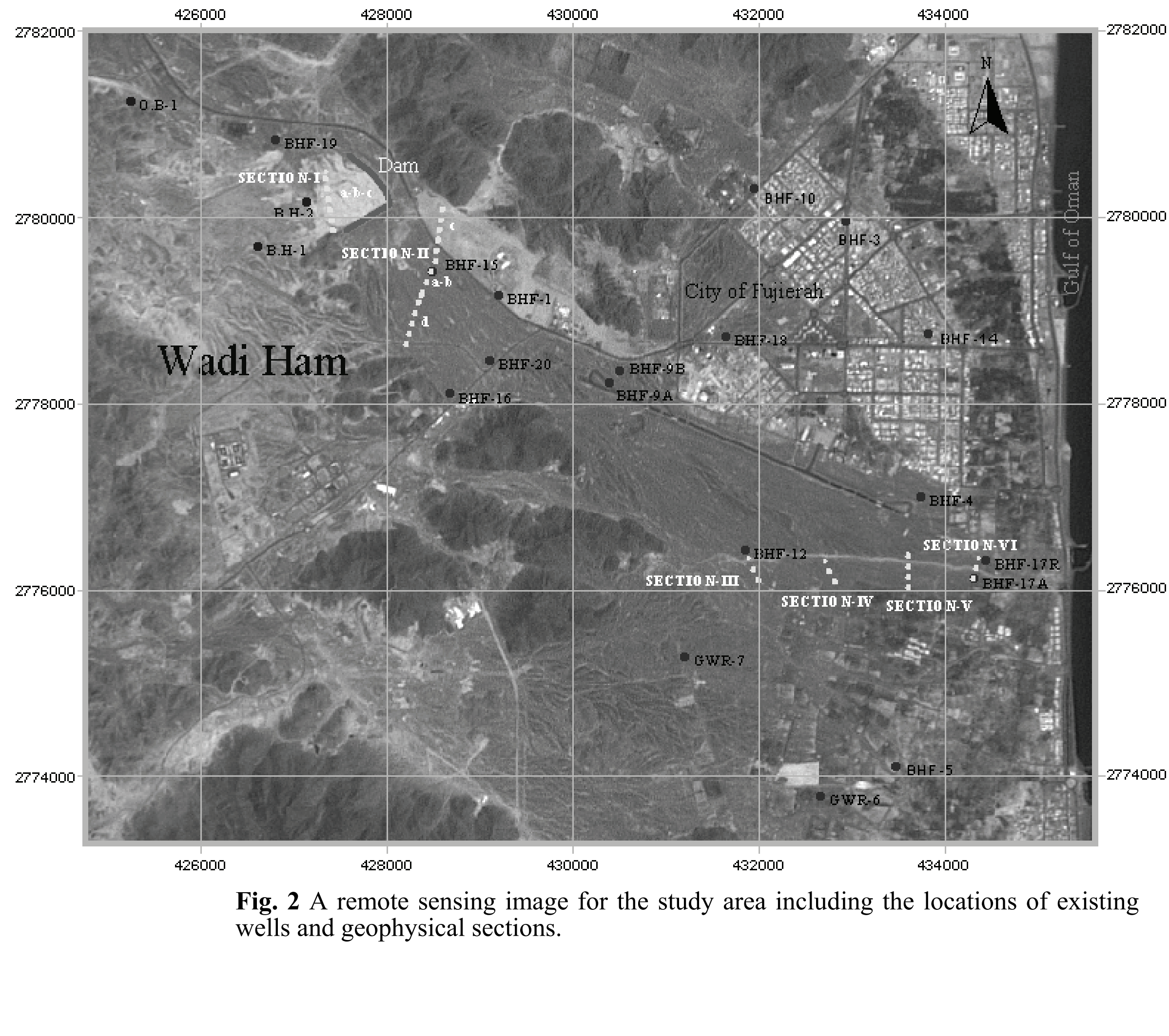

Fig. 2 A remote sensing image for the study area including the locations of existing wells and geophysical sections.

The thickness of wadi gravel in Wadi Ham varies from 18 m at the upstream side of the dam to about 100 m near the coast. The minimum thickness is found in the area of well number BHF-19, at the upstream of Wadi Ham dam and close to the mountain series. The maximum thickness is observed in the area of well number BHF-14 which is very close to the coast of Oman Gulf. The cross-sectional depth of wadi gravels and sand along the wadi course varies from 45 to 64 m.

The cross-sections (longitudinal profiles) in the area near to the Gulf of Oman show that the gravel depth varies from 24 m to 99 m. Its thickness decreases with increasing the distance from the shoreline. For example, within a distance of 3 km it varies from 24 m to 73 m. This is attributed to the regional dipping of the Ophiolite series towards the wadi channel. This information is restricted to the available boreholes and wells.

HYDROGEOLOGICAL PARAMETERS

Two main aquifers can be identified in the area of Wadi Ham, namely the Quaternary aquifer which is composed of wadi gravels and constitutes the main aquifer, and the Fractured Ophiolite which has a low groundwater availability potential. The gravels are highly permeable and of variable hydraulic properties. They tend to be unconsolidated at the ground surface, becoming better cemented and consolidated with depth. Electrowatt (1980, 1981) subdivided them into recent gravels, being slightly silty sand gravel with some cobbles; young gravels, which are silty sandy gravels with many cobbles and boulders; and finally old gravels, which are weathered and cemented.

Values of the hydraulic conductivity of the unconsolidated gravels tend to be very high, typically 6 to 17 m/day and in the range 0.086–0.86 m/day for the cemented lower layers, Electrowatt (1980, 1981).

In the unconsolidated gravels, primary porosity is very high when compared to the cemented gravels. The storage coefficients typically range from 0.1 to 0.3. At a distance of 3.5 km directly downstream of the dam, the saturated aquifer thickness ranges between 10 m and 40 m, with a transmissivity ranging from less than 100 to about 200 m^2/day. In sections where the saturated aquifer thickness varies between 50 m to 100 m the transmissivity may reach more than 1000 m^2/day. Fourteen short duration (8 to 300 minutes) pumping tests performed by ENTEC (1996) were analysed by using both Cooper and Jacob, and Theis methods.

Annual rainfall in the Wadi Ham ranges from 3.7 mm to 505.8 mm. The normal rainfall estimated for 24 years is 151 mm with a standard deviation 126.8 mm, kurtosis 1.36 and coefficient of asymmetry 1.18. The probability of occurrence of 75% and 50% normal rainfall were estimated as 51 and 64 percent, respectively. These numbers reveal that the distribution of rainfall in Wadi Ham is highly scattered and not dependable on annual basis (Sherif *et al.*, 2005, 2006).

GROUNDWATER FLOW MODEL

The study domain of Wadi Ham aquifer comprises an area of 117.81 km^2 with total length of 11.9 km east to west (dam to coast of Oman Gulf) and 9.9 km north to south

(Fujairah to Khalba). The modular three-dimensional finite-difference groundwater model, MODFLOW, (McDonald & Harbaugh, 1988) was employed in this study. It has a modular structure that allows modifying the code for a particular application.

The model area and the aquifer boundaries were delineated by digitizing the remote sensing image of Wadi Ham. The model domain includes the Gulf of Oman and the Ophiolite sequence rock out crops. The Ophiolite outcrops are specified as inactive or no flow areas. The area of separated outcrop is about 6.56 km^2. At the coast, many cells are located in the sea which is considered to be a constant (zero) head boundary. A ponding area was delineated and marked on the study domain. The total area of the pond at flood level was estimated as about 0.40 km^2.

The study area was divided into 119 columns and 99 rows with the size of each cell being 100 by 100 m. The model is comprised of a total of 11 781 equally spaced and square cells. However, the net area of aquifer consisted of only about 64.94 km^2 with 6494 active cells. The area of inactive cells is about 52.87 km^2 with 5287 cells.

The calibration period was selected as five years from January 1989 to December 1993 (1826 days). The length of stress period in this exercise was taken as one real month. However, the period during which recharge of either rainfall or dam storage took place was considered as an extra stress period. The total number of stress periods considered for the calibration period was 146. The model calibration was achieved by changing three parameters, namely, permeability, specific yield and pumping rates. Abstraction and inflow across the boundaries were also simulated by a number of computer runs until a reasonable groundwater level in each observation wells was achieved.

The validation of the flow model was carried out during the period from January 1994 to March 2005, for a total simulation time of 4108 days. The flow vectors were developed as shown in Figs 3 and 4 to identify the direction of flow, particularly at the boundary of the Gulf of Oman. In Fig. 3 the flow is directed towards the sea from the aquifer, a situation which represents the wet conditions with a relatively high rainfall. However, in the case of dry years (Fig. 4) the flow is coming from the aquifer only at the northeast part of the coast. In the southeast part, the flow is from the sea to the aquifer, where the Kalbha groundwater well field is in operation. The flow pattern was also affected by the recharge from the Wadi Han Dam.

TRANSPORT MODEL

A transport model was developed for the identification of seawater intrusion and movement of saline water into the coastal aquifer along the Kalbha and Fujairah coast of UAE. The validated flow model was used to simulate the salinity level of the groundwater aquifer and its variation in time and space from January 1994 to January 2006. The initial concentration grid was developed using the available historical data of some locations in the study domain during 1994 and 1995.

Dispersion is a physical process that tends to disperse the contaminant mass in different directions along and across the advective path of the contaminants and acts to reduce the solute concentration. Dispersion is caused by the tortuosity of the flow-paths of the groundwater as it travels through the interconnected pores of the soil and

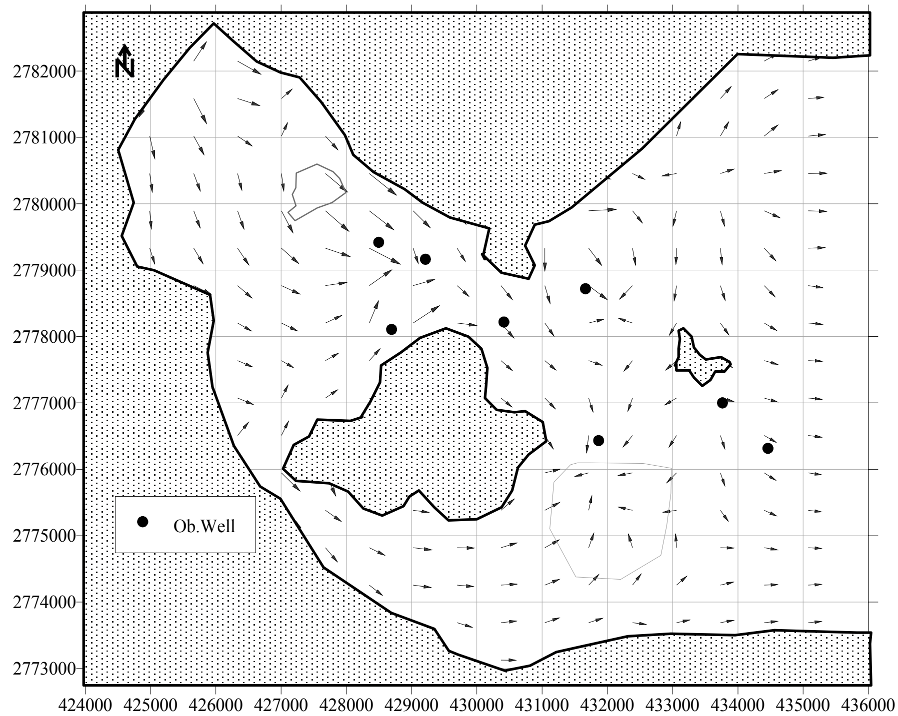

Fig. 3 Flow vector the January 1996 (wet year).

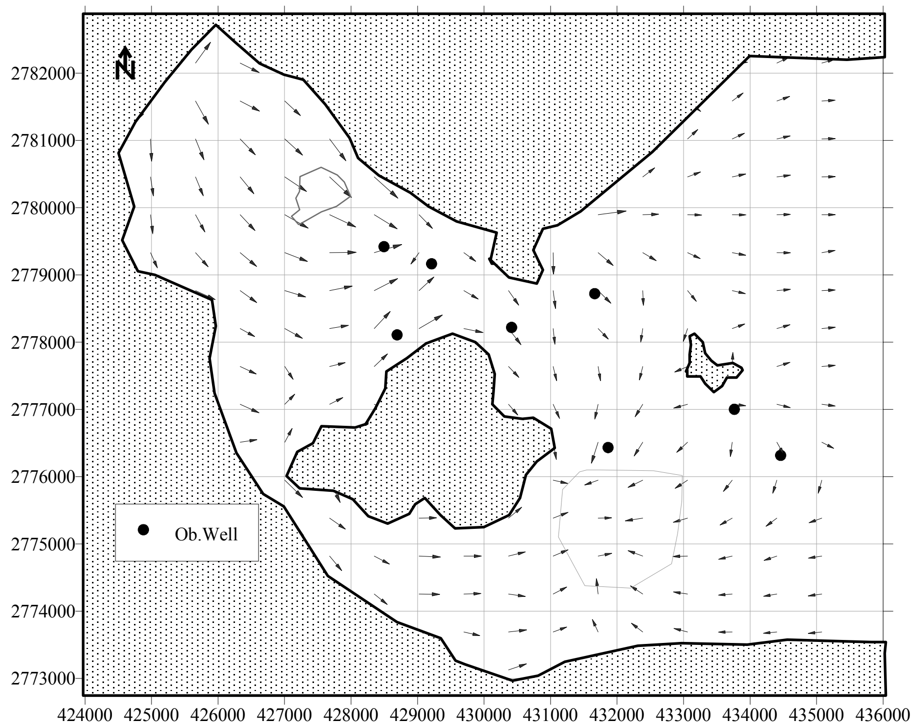

Fig. 4 Flow vector the December 1996 (dry year).

other factors, e.g. undetected heterogeneity of hydraulic properties of the rock. In the present simulation, 20 m of longitudinal dispersivity for each transport grid cell was considered. The ratio of horizontal to longitudinal dispersivity of the layer was 0.1 and the ratio of vertical to longitudinal dispersivity of the layer 0.01. The molecular diffusion coefficient 0.1 UNIT is missing! was considered for the layer.

The constant concentration boundary condition acts as a contaminant source providing solute mass to the model domain in the form of known concentration for a relatively long period of time. Therefore, the area covering the coast of Gulf of Oman in the study domain was taken as a constant concentration boundary with an average salinity (TDS) of 35 000 mg/L. The fluid density was assumed constant. The concentration of the recharge water in the ponding area of the Wadi Ham Dam was set as 500 mg/L and was applied over 40 cells of the model. The evapotranspiration concentration boundary condition specifies the concentration of each species accompanying the evapotranspiration flux specified in the corresponding model. In the present simulation, the extinction depth was considered to be 2 m, hence the evapotranspiration from the water table is negligible. Therefore, concentration accompanying the evapotranspiration flux was neglected.

EFFECT OF ARTIFICIAL RECHARGE

A recharge pond of 100 by 100 m was introduced in the study area using the calibrated and validated model where the experimental pond was constructed. Different scenarios were selected and the simulation was conducted for the flow and concentration levels in the study area, especially in the coastal zone of the Gulf of Oman. Tertiary treated wastewater and excess of desalination water during low-demand periods are the possible sources for the implementation of groundwater artificial recharge projects.

Two different recharge scenarios of 0.5 m/day and 1.0 m/day were applied from January 1994 to January 2006 for 4108 days. The changes of groundwater regime and the quality aspects were also simulated. The impact on the groundwater regime was compared in different locations of the study area. Examples of the water levels in some of the observation wells in the study area are provided in Fig. 5.

Figure 5 shows that there is a clear rise in the groundwater levels due to the recharge from the pond. However, the maximum impact was observed in the wells BHF-4, BHF-12, BHF-17A, BHF-17R and BHF-18 which are relatively closer to the recharge pond. The minimum impact was observed in BHF-1, BHF-9, BHF-15 and BHF-16. These wells are relatively far away from the pond.

The salinity levels were also compared under different recharge conditions. Figure 6 represents a comparison between the salinity distribution under no recharge and 0.5 m/day recharge after a simulation time of 4018 days. The salinity levels were also compared for the case of a recharge level of 1 m/day, as shown in Fig. 7. It is obvious that the recharge of freshwater from the pond will have a significant improvement effect on the groundwater quality. It should be noted, however, this improvement of the groundwater quality is mainly encountered in the vicinity of the recharge pond. A limited improvement is also observed elsewhere.

In order to provide a quantitative assessment for the expected quality improvements under artificial recharge conditions, specific contour lines were compared for the cases of no recharge, 0.5 m/d recharge and 1.0 m/day recharge. To that end,

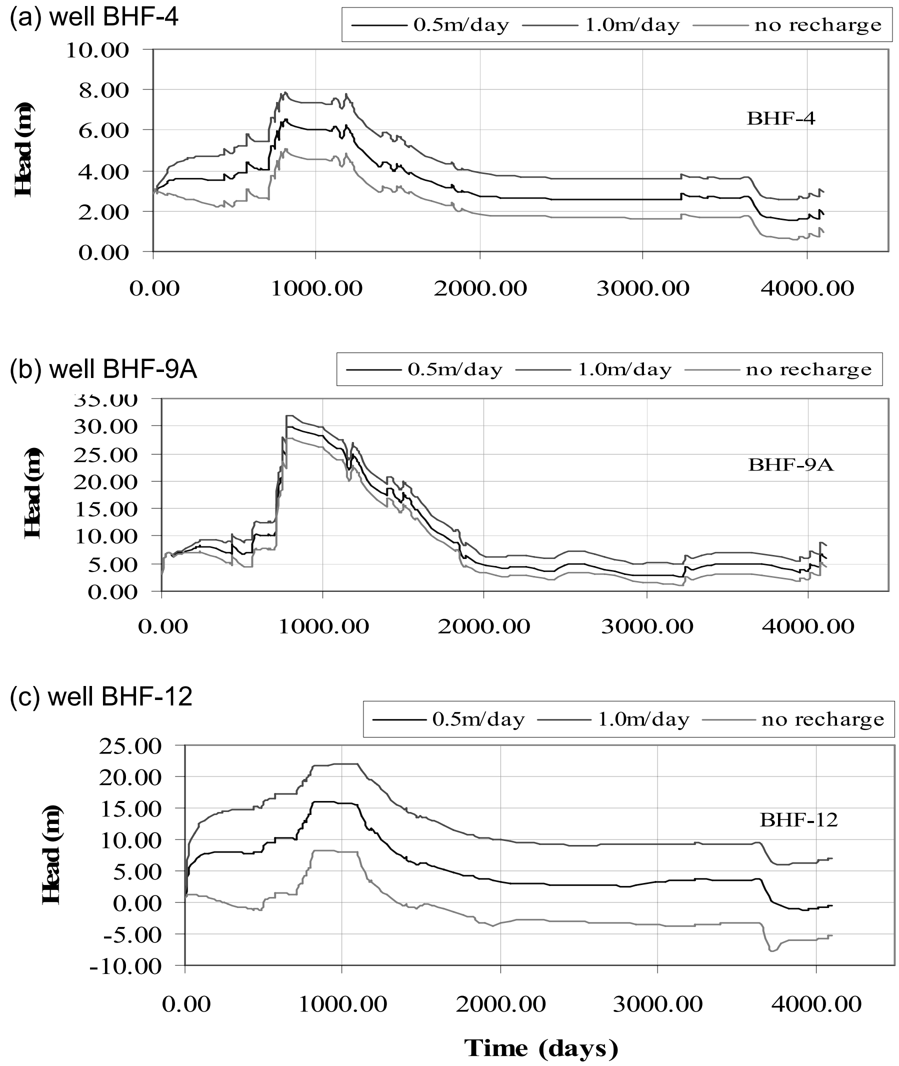

Fig. 5 Comparison of water level with and without recharge.

contour lines of 10 000 mg/L were compared for the above three recharge conditions. An example of the output for simulation period of 4018 days is given in Fig. 8. At the end of the simulation time, the 10 000 mg/L equi-concentration line moved a distance of about 1.25 km toward the Gulf of Oman. Other equi-concentration lines moved in the same direction but with different degrees indicating a significant improvement in the groundwater quality. It should be noted, that, like contamination in porous media, the quality improvement in groundwater systems is a lengthy process and may take a few decades to be recognized.

CONCLUSIONS

The seawater intrusion phenomenon in Wadi Ham is affected by the dry and wet conditions. During the dry years, the velocity vectors are directed from the Gulf of Oman to the aquifer causing severe intrusion problem. During wet years where rainfall

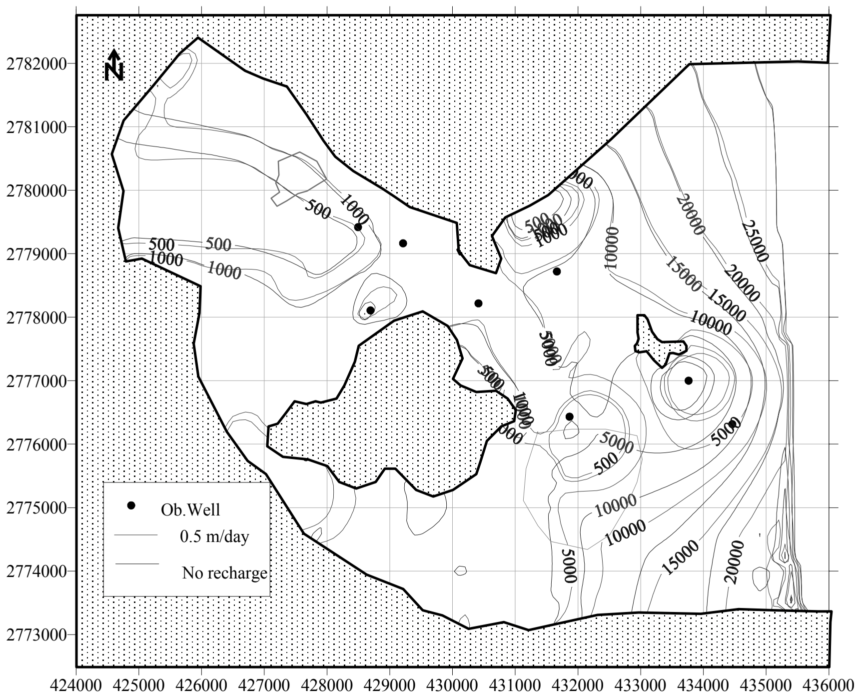

Fig. 6 Comparison of the salinity level after 4018 days with a recharge of 0.5 m/d.

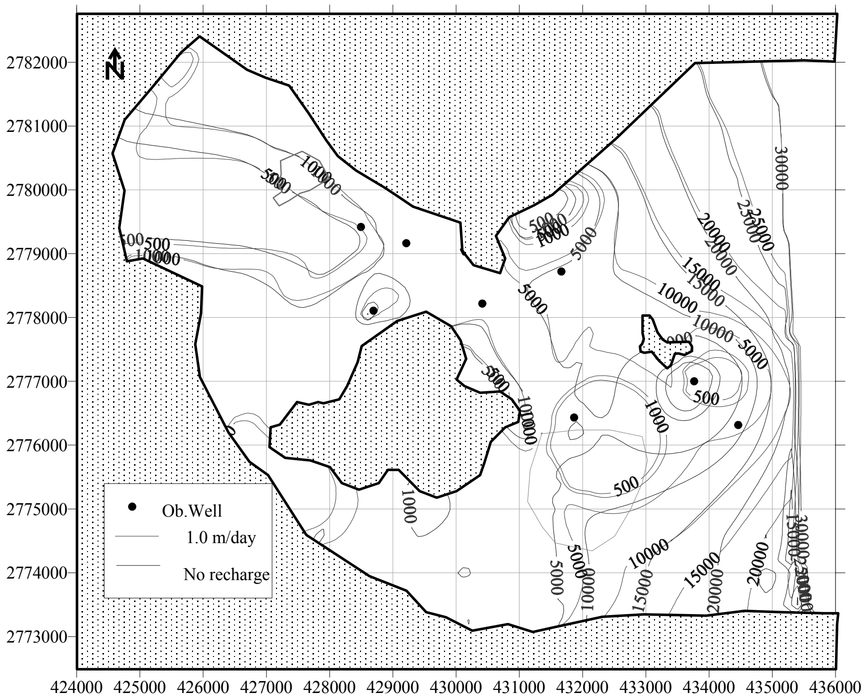

Fig. 7 Comparison of the salinity level after 4018 days with a recharge of 1.0 m/d.

is relatively high and groundwater recharge is encountered from the ponding area of the dam of Wadi Ham, the velocity vectors are reversed and the flow is directed from the aquifer to the Gulf of Oman through out the interface.

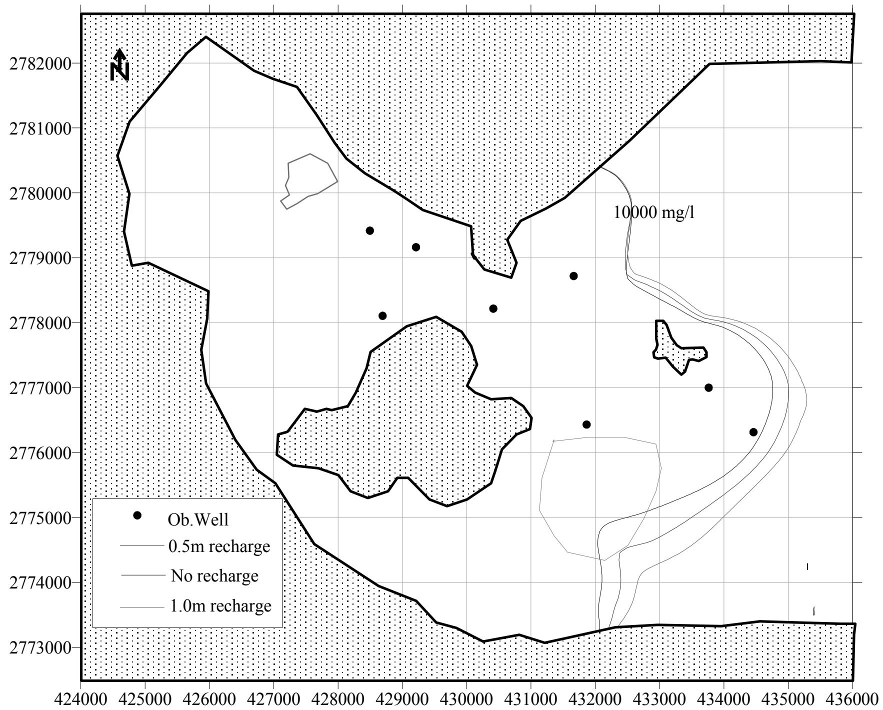

Fig. 8 Variation of TDS (10 000 mg/L) at 4018 days for the different recharge conditions.

The influence of artificial recharge from a pond with dimensions of 100 × 100 m was demonstrated using MODFLOW and MTD. The maximum impact of recharge (significant improvement in the quality of the groundwater) was observed in the wells relatively close to the recharge pond. The minimum impact was observed in the wells which are located far away from the recharge area.

The results of the numerical simulation indicated a backward movement (retardation) towards the Gulf of Oman of about 1.25 km of the equi-concentration line 10000 mg/L under a recharge condition of 1.0 m/day over a period of 4018 days. All parameters, including the pumping rates, were based on the actual data over the last 10 years. In the long term, the artificial recharge of groundwater in coastal aquifers will not only maintain, but will also enhance the groundwater quality in such aquifers.

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