**Engineering and Computational Mechanics**
Volume 169 Issue EM3

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ice | proceedings

**Proceedings of the Institution of Civil Engineers**
Engineering and Computational Mechanics 169 September 2016 Issue EM3
Pages 148–155 http://dx.doi.org/10.1680/jencm.15.00021
**Paper 1500021**
Received 04/10/2015 Accepted 11/07/2016
**Keywords:** groundwater/hydrology & water resource/management



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# Control of saltwater intrusion by aquifer storage and recovery

**Mohammed S. Hussain** BEng, MSc, PhD
Postgraduate research student, Department of Engineering, University of Exeter, Exeter, UK

**Akbar A. Javadi** BEng, MSc, PhD
Professor, Department of Engineering, University of Exeter, Exeter, UK (corresponding author: a.a.javadi@exeter.ac.uk)

**Mohsen M. Sherif** BEng, MSc, PhD
Professor, Civil and Environmental Engineering Department, United Arab Emirates University, Al Ain, UAE

**Reza Naseri-Karim-Vand** BEng, MSc
Postgraduate research student, Department of Engineering, University of Exeter, Exeter, UK

**This paper presents the results obtained from the application of aquifer storage and recovery (ASR) technique to control seawater intrusion (SWI) in coastal aquifers. The study is based on the numerical modelling experiments performed using the SUTRA (Saturated–Unsaturated TRAnsport) finite-element code on the Wadi Ham aquifer in the UAE. A three-dimensional numerical model of this aquifer is developed and calibrated based on the available hydrogeological data in real scale. A significant amount of SWI has been calculated for the year 2015 due to the high rates of pumping from the available local well fields. To study the future responses of the aquifer to different control actions, the transient responses of SWI are simulated over a 10-year planning horizon. The proposed management measure (ASR) is implemented in repeated cycles of artificial recharge, storage and recovery using an additional set of wells defined in the model. The results show that ASR is a reliable method in controlling SWI in coastal aquifer systems besides its conventional role in subsurface water banking.**

## 1. Introduction

Saltwater intrusion is the most common groundwater contamination problem in urbanised coastal areas especially in arid and semi-arid regions of the world. Overexploitation of groundwater to meet the domestic and irrigation demands of increasing population is among the most important of these factors (Sherif and Singh, 1996; Werner *et al.*, 2013). Some of the possible options to control seawater intrusion (SWI) and move towards sustainable management of coastal aquifers include the use of different arrangements of physical and hydraulic barriers (e.g. Javadi *et al.*, 2015; Kallioras *et al.*, 2013; Pool and Carrera, 2010; Sherif and Hamza, 2001; Todd, 1974; van Dam, 1999). With higher practical functionality and efficiency, the control of SWI using hydraulic barriers has gained more popularity than the design of physical barriers as engineering interventions (Oude Essink, 2001; Pool and Carrera, 2010; Werner *et al.*, 2013). The main types of hydraulic barriers include artificial recharge (recharge barrier), pumping of brackish or saline water along the seacoast (abstraction barrier) and combination techniques (mixed barriers). The most efficient form of mixed barrier is the simultaneous use of recharge and abstraction barriers (Abd-Elhamid and Javadi, 2011; Hussain *et al.*, 2015a). Continuous abstraction of brackish water near the coast, desalination of the abstracted brackish water for public use and simultaneous recharge of the aquifer using treated wastewater or other sources of good quality surface water (through surface infiltration basins or injection wells) have been introduced by Hussain *et al.* (2015a) and Javadi *et al.* (2015) for cost-effective control of SWI in coastal aquifers.

This paper presents the application of aquifer storage and recovery (ASR), as a mixed-barrier technique, to control SWI. ASR is commonly used for subsurface storage of freshwater and both of its (abstraction and recharge) processes are conducted through the same well system and in repeated cycles. Therefore, the objective of the current research is to investigate numerically the effects of these cycles of ASR on controlling of SWI in the Wadi Ham aquifer (in the UAE) using an additional set of wells that are introduced in the model. For this purpose, a numerical model of Wadi Ham aquifer is developed and calibrated using a variable-density flow and transport SUTRA (Saturated–Unsaturated TRAnsport) code developed by Voss and Provost (2010).

## 2. ASR

ASR is a technique that was introduced by Cederstrom (1947) and has been widely used in developed countries for the management of water resources as an alternative to surface storage of water such as in dams and reservoirs. The methodology involves continuous storage of excess water by deep injection through recharge wells into deep aquifers or other water-bearing formations, when water is available or during the wet and low demand season of the year. The stored water is then recovered when needed using the same wells to meet the water demand of the community and during the next dry or high demand season of the year (Pyne and David, 1995). Depending on the quality and level of contamination of the native groundwater in the aquifer and also the quality of the recharge water, the recovered water may be required to pass a short treatment process before use. The ASR process is repeated continuously during the years depending on the levels of water scarcity. The recovery efficiency (RE) in the ASR process is defined as the total volume of recovered water as the percentage of volume stored in each of the operating cycles while satisfying a target water quality criterion in the abstracted water (Pyne and David, 1995). The impacts of different hydrological factors on RE have been assessed by Lowry and Anderson (2006) through a set of parametric studies. The enhancement of ASR efficiency with multiple ASR cycles has been reported by Lu *et al.* (2011) and Sherif and Shetty (2013) using the numerical approach.

In ASR, the repeated cycles of recharge and abstraction also contribute to the improvement of water quality (Barlow and Reichard, 2010; Sherif and Shetty, 2013). Typically, the volume of the extracted water is less than the injected water and a buffer zone with marginal quality of water is created that helps in controlling the inland advancement of saltwater wedge (Misut and Voss, 2007). The buffer zone basically holds the recoverable fraction of water. Therefore, ASR can be considered as one of the management options to control SWI besides its other positive role in water production/demand issues and maintaining the seasonal fluctuation in groundwater storage (Chen, 2014; Lu *et al.*, 2011). Misut and Voss (2007) investigated the beneficial aspects of ASR in controlling SWI by defining a series of ASR wells in different confined/unconfined aquifers of a regional case study in the USA.

## 3. Study area and simulation model

The UAE is a country with large coastal boundaries. Due to its limited resources of freshwater, low rainfall and extensive groundwater withdrawals, saltwater intrusion has become a

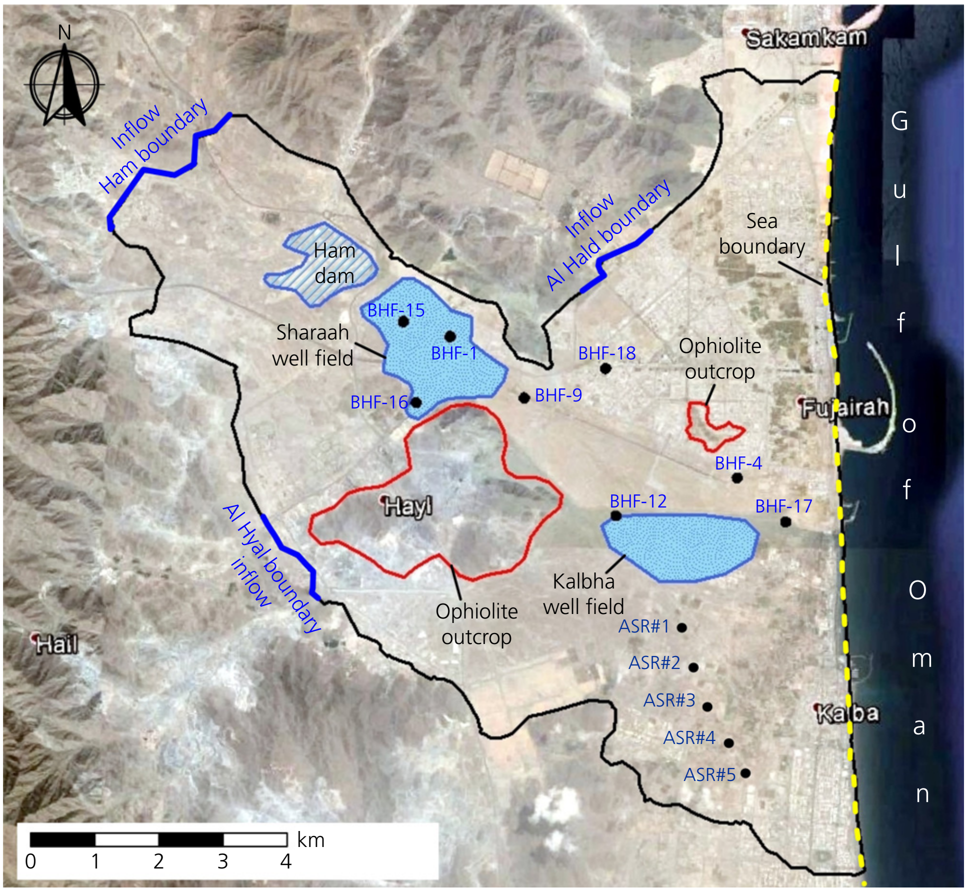


Figure 1. Study area and the applied boundary conditions

common problem threatening the quality and quantity of the freshwater resources and ecosystems all around the country (Dawoud, 2008). The study area is the lower alluvial plain of Wadi Ham catchment located in the Fujairah emirate of the UAE. The area generally consists of recent Pleistocene Wadi gravels underlain by fractured ophiolite rocks. Figure 1 shows the domain of Wadi Ham aquifer (total area of 80·26 km$^2$), the available hydrological/natural features and

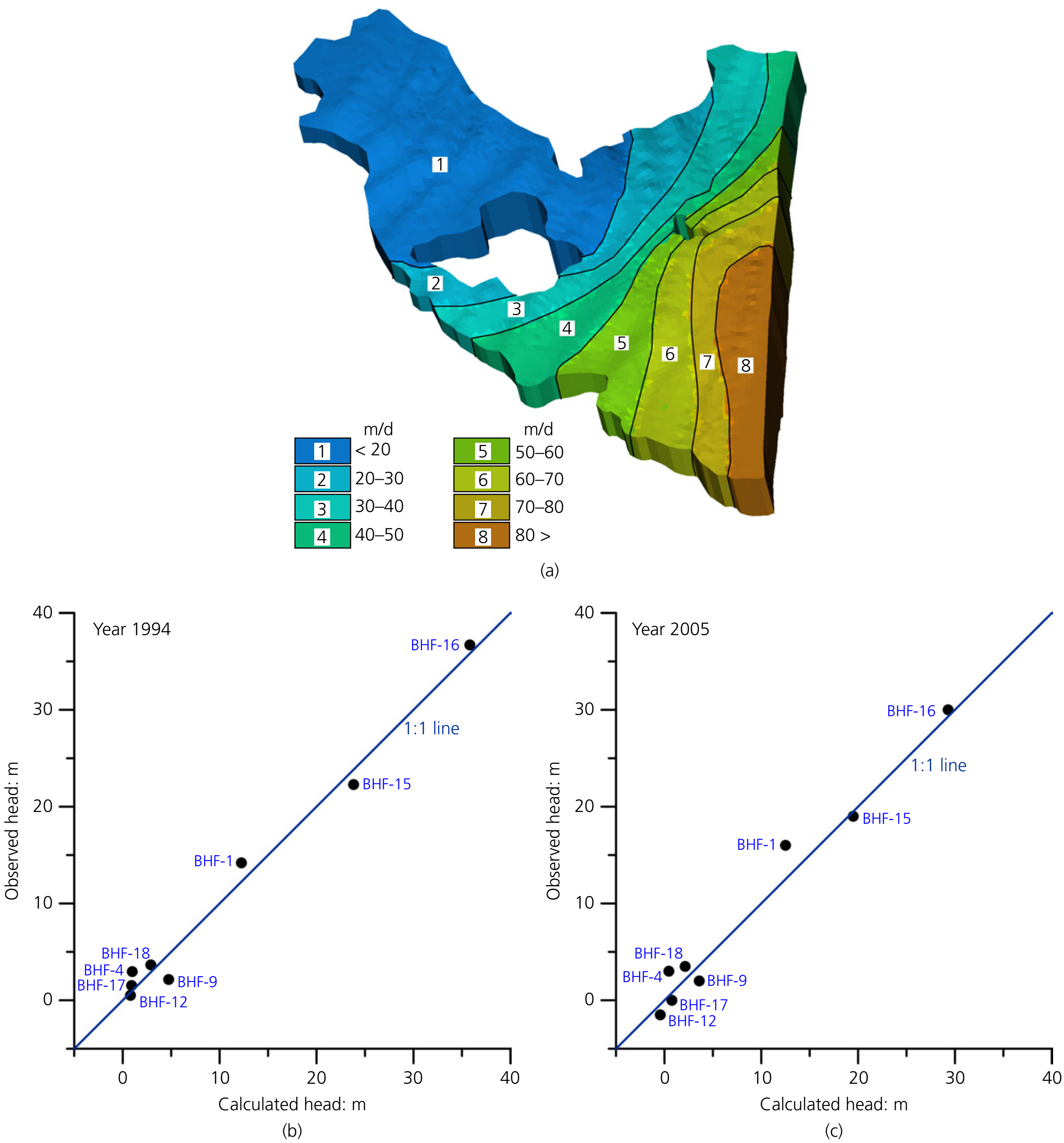


**Figure 2.** Calibration results: (a) the used hydraulic conductivity field and (b and c) the calculated against observed hydraulic heads (w.r.t. mean sea level)

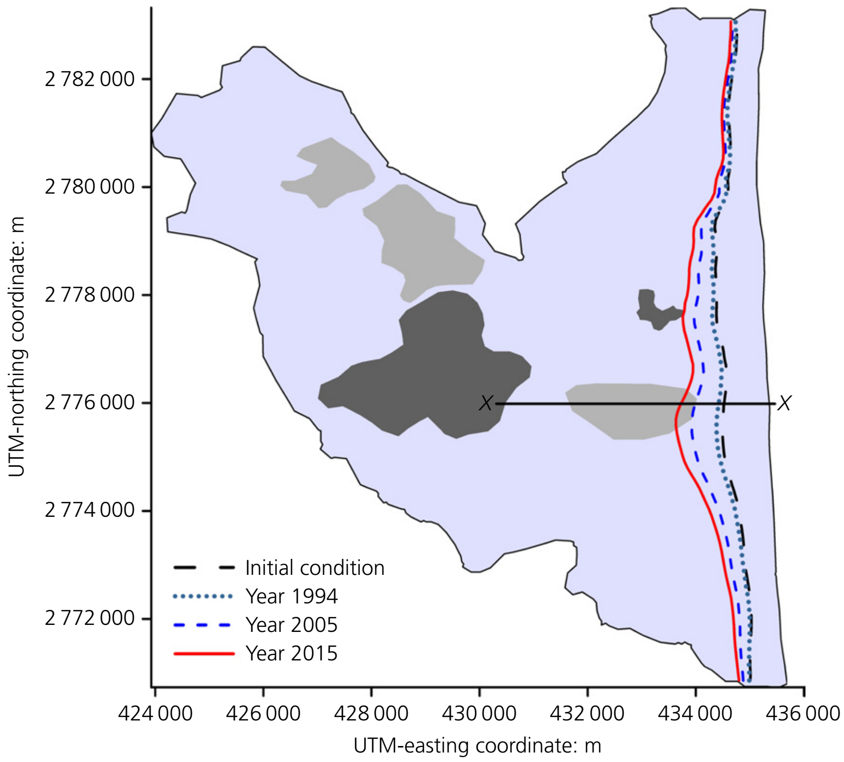


**Figure 3.** Transient progress of 0·5 isochlors across the base of aquifer in the *XY*-plane (from 1989 to 2015)

also the boundary conditions used in its numerical modelling. Hydrostatic pressure boundary condition with a constant head at the mean seawater level is used to define the coastline of the domain on the Gulf of Oman. A three-dimensional model of the aquifer is constructed and analysed using the finite-element-based model SUTRA (Voss and Provost, 2010). All the input data and the hydrogeological maps of the model are prepared using the ArcGIS platform and then imported as shape files into the user graphical interface of the SUTRA code. The aquifer model is calibrated based on the available groundwater-level measurements in eight observation boreholes (marked in Figure 1) for two different stress periods from year 1989 to year 1994 and from year 1994 to year 2005. By considering the data of the year 1989 as the initial condition, and by defining an appropriate permeability field (Figure 2(a)) obtained by trails as the calibration parameter, a good match between the calculated and the observed water levels is obtained for the years 1994 and 2005 (Figures 2(b) and 2(c)).

In the vertical direction, the model geometry is spatially discretised with ten elements. The final numerical mesh is discretised into 48 160 trilinear hexahedral elements and 55 990 nodes. The main solute transport parameters defined for the numerical simulation are 1250 and 1000 kg/m$^3$ for seawater and freshwater densities, respectively; $1 \times 10^{-9}$ m$^2$/s for coefficient of water molecular diffusion; 65 and 6·5 m for longitudinal dispersivity in horizontal and vertical directions of flow, respectively, and 0·65 m for transverse dispersivity. Moreover, the total dissolved solids (TDS) of 35 700, 250 and 100 mg/l are assigned as the salinity of seawater, inflow water and rainwater, respectively. A total recharge rate of 0·02 m/year is used for Ham dam. The total reservoir (ponding) area of the dam is 0·4 km$^2$. Two pumping well fields located in the study area are the Kalbha well field and the Sharaah well field with the average pumping of 13 600 and 3225 m$^3$/d, respectively. The average fluxes through Al Hyal, Ham and Al Hald inflow boundaries are 850, 1450 and 1100 m$^3$/d, respectively. According to the data recorded for the second stress period (from 1994 to 2005), the average abstraction rates from Sharaah and Kalbha wells are 2250 and 17 200 m$^3$/d, respectively. Further details about the hydrogeological setting of the study area can be found in Hussain *et al*. (2015b) and Sherif *et al*. (2012, 2013).

## 4. Management scenarios

By maintaining the boundary conditions and also the pumping rates from Sharaah and Kalbha well fields for the next 10 years of simulation period after year 2005, the current condition of the flow and salinity for the year 2015 is obtained. To assess and compare the future advancement of the saltwater under the ASR barrier in 2025, the current model is subjected to three different scenarios. In the first scenario (no-management scenario), all of the boundary conditions and pumping rates are kept unchanged during the simulation period. In the second scenario, a hypothetical ASR system (using five wells ASR#1, ASR#2, … and ASR#5) is defined in front of the current intruded saltwater wedge and as an additional feature to countermeasure the impacts of saltwater intrusion in the south part of the study domain (Figure 1). Each of these recharge/recovery wells is subjected to two full cycles of recharge, pause (storage) and recovery per year; with a time span of 75 d for each of recharge and abstraction stages and 32 d for the storage stage. Injection and recovery rates of 2000 $m^3$/d are applied in each of the ASR wells to guarantee 100% RE. Finally, in the third scenario, only one cycle of ASR process is considered for the same arrangement of ASR wells. By keeping the injection and recovery rates at 2000 $m^3$/d, the third scenario serves to guarantee 66·67% of RE, wherein the time spans of 180 d for recharge, 65 d for storage and 120 d for abstraction stages are used during each full cycle of ASR. The TDS of the injected water in both the ASR scenarios is assumed to be 150 mg/l.

## 5. Results

The transient penetration of the 50% iso-concentration lines in the simulation period between 1989 and 2015 along the aquifer bottom floor is illustrated in Figure 3 in the *XY*-plane. In 2015, the calculated inland advancement of 50% isochlor is 1650 m along a section *X*–*X* passing through the Kalbha pumping field at 2 776 000 m universal transverse mercator (UTM)-northing coordinate. In addition, the 10, 50 and 90% iso-salinity contours of the three management scenarios along the base layer of the model are illustrated in Figure 4. The projections of ASR wells' locations are also presented on this *XY*-plane. In the first (no-management) scenario, the system experiences a further intrusion of 98 m of 50% iso-concentration line compared with the results of the year 2015, measured on the *X*′–*X*′ section (Figure 4). The large distance of the evaluation points (section *X*′–*X*′) from the Kalbha well field and maintaining the current rate of pumping over the simulation period up to the year 2025 are the main reasons for this rate of SWI. However, due to future urbanisation and available

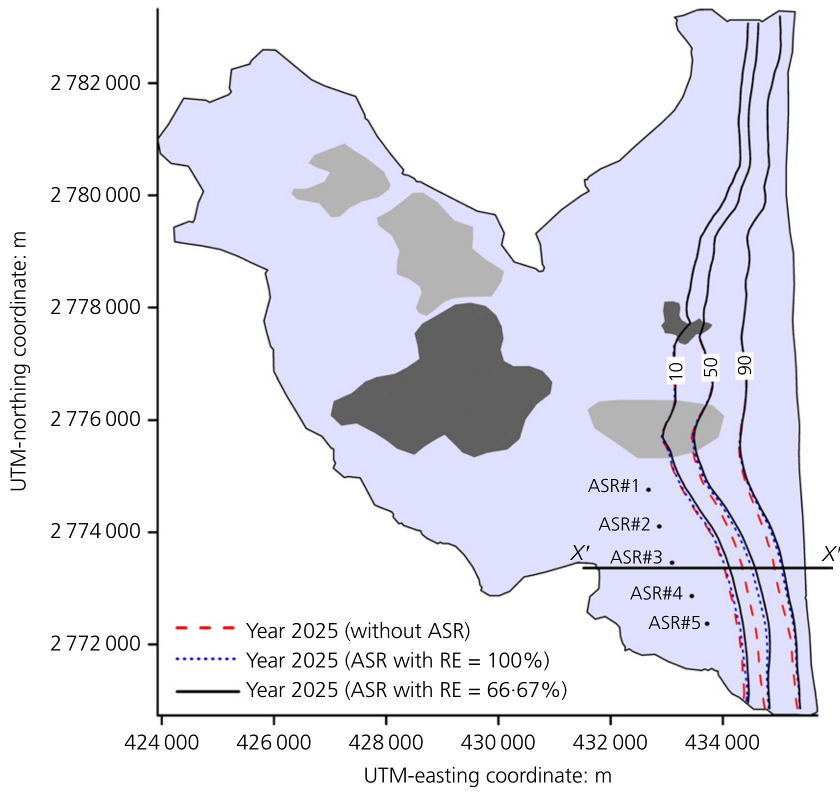


**Figure 4.** Inland progress of 10, 50 and 90% iso-concentration lines during the management scenarios

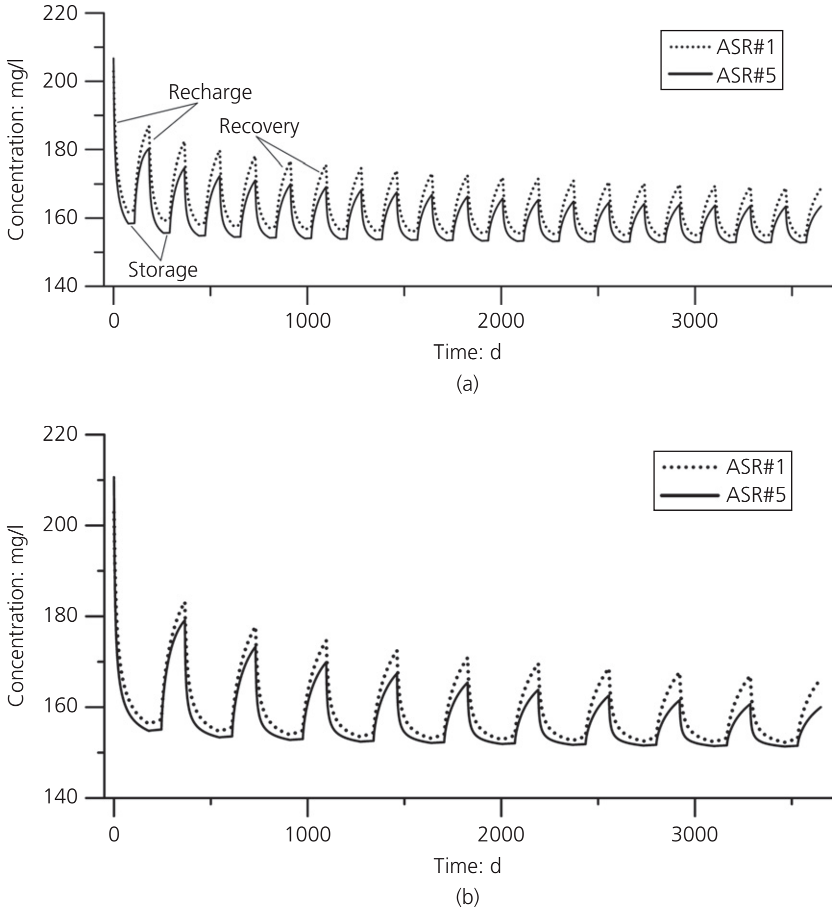


**Figure 5.** Variation of TDS level during ASR cycles in the (a) second and (b) third scenarios

intensive farming in this part of the study area, it is predicated that pumping from the Kalbha wells will have a growing uptrend that will make the SWI problem even worse. In the second scenario that involves ASR technique with 100% RE, the corresponding salinity level is reversed by 157 m compared with the no-management scenario, evaluated on the same *X′–X′* section. The positive role of the ASR system in controlling saltwater intrusion is more pronounced in the third scenario by recording about 226 m push back effect on the horizontal location of the 50% isochlor measured with respect to the simulated value in the first scenario. The better performance of the third scenario in the mitigation of SWI impacts is attributed to the shorter period of pumping than the recharge events implemented in each cycle of ASR (RE = 66·67%). The excess recharge water left in the buffer zone or aquifer after each cycle helps to increase the successive seaward hydraulic gradient in the system leading to the partial reversal of the intruded saltwater wedge back to the sea. During this comparison one should note that the ASR has multiple roles in that it protects the system against SWI while providing a remarkable amount of water recovered for public supplies. It is also shown from the results that the low concentration lines (<10%) are more sensitive to recharge and abstraction events of the ASR process.

The raising and lowering of the hydraulic head in each cycle of ASR is followed by the variations of salinity (TDS) in the location of the inserted wells and consequently in the entire aquifer. Figure 5 shows the overall progress of these repeated cycles during the simulation period in ASR#1 and ASR#5 wells and in both management scenarios. The other ASR wells follow exactly the same salinity trends that are bounded between the illustrated results/curves of ASR#1 and ASR#5. By recharging of the aquifer in the first cycle, the amount of salinity in the location of wells is significantly reduced due to mixing of the injected water with the ambient water, implying the improvement of water quality. In contrast, during the storage and abstraction phases of the process, the solute starts to progress towards the wells and therefore the salinity levels are partially reversed. The bandwidths of the corresponding repeated cycles decrease with the time and almost reach equilibrium at the end. In large-scale assessments, these repeating cycles of ASR process are simultaneously associated with seaward and landward advancements of intruded saltwater wedge. The overall response of the Wadi Ham aquifer to the mentioned gradual enhancement of water quality is positive. Although the system is under continuous pumping from the two local well fields, the ASR succeeds to control the SWI by keeping the freshwater/saltwater interface back to the seaward direction. However, the ASR, like any other management strategy, has some limitations and its implementation needs further attention. For instance, the high rates of mixing of injected water with poor native groundwater quality may tend to reduce the total recoverable volume of freshwater (i.e. RE).

## 6. Conclusions

A numerical simulation was performed to study the effects of the ASR system, as a management policy, on inland advancement of saline water in the Wadi Ham aquifer (in UAE). It has been shown that a considerable reduction in salinity levels occurs in the areas surrounding the system due to application of ASR-management scenarios. Deep confined or unconfined aquifers have been typically documented to be used for long-term underground storage of the injected water. However, in order to benefit from the presence of excess surface water during the intense rain events in the study area, the ASR system can be used to control saltwater intrusion in this unconfined aquifer with a relatively shallow hydrogeological setting (Wadi Ham aquifer).

## Acknowledgements

The authors acknowledge their gratitude to the British Council, UK, for providing funding (project code: SH-04509) to support this research.

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