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# Three dimensional simulation of seawater intrusion in a regional coastal aquifer in UAE

Mohammed S. Hussain[a,*], Akbar A. Javadi[a], Mohsen M. Sherif [b]

[a] *University of Exeter, Engineering Department North park road, Exeter EX4 6PH,UK*
[b] *UAE University, Civil and Environmental Engineering Department, Al Ain, P.O. Box: 17555, UAE*

## Abstract

In this study the vulnerability of the Wadi Ham aquifer, located in the Fujairah Emirate of the UAE, to seawater intrusion (SWI) is assessed using a 3D finite element (FE) model. The numerical model is developed based on available hydrogeological data in real scale. By simulation of the aquifer for the next 10 years and by maintaining the current rates of pumping (in year 2015), the progress of seawater intrusion in year 2025 is followed by further depletion in freshwater storage of the Wadi Ham aquifer. In order to control this problem, the model is subjected to a management strategy involving surface recharge of the aquifer with treated wastewater.

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*Keywords:* Numerical modeling; artificial recharge; seawater intrusion; treated wastewater

## 1. Introduction

In the last century, the use of surface water, as a desirable source of water, is increased in different domestic, industrial and agricultural sectors due to the its lower cost and ease of accessibility. However, the gradual population growth, land use changes and heavy urbanization have increased the pressure on this traditional source of water to the extent that it has led to the extraction of groundwater as alternative to surface water to cope with the scarcity of water resources [1]. In coastal regions, the groundwater as a primary or sole source of fresh water is continuously threatened by salinization due to lateral intrusion of seawater into the aquifer. The rate of inland SWI is accelerated

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* Corresponding author. Tel.: +44-1392-723909; fax: +44-1392-217965.
*E-mail address:* msh218@exeter.ac.uk

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due to the rapid disturbances that occur by pumping of groundwater [2]. Groundwater withdrawals for domestic, agricultural and industrial usage create a new hydraulic gradient; wherein the water level could be lowered to the extent that the piezometric head of fresh water body becomes less than that of the adjacent saline water body. This change in hydraulic gradient of aquifer accelerates the progressive landward invasion of the seawater toward the abstraction wells and consequently results in degradation of the chemical quality of abstracted water and surrounding groundwater followed by other problems such as decrease of fresh water availability, human health and ecosystem damage [2, 3].

Artificial recharge is one of the common methods to control the encroachment of seawater into coastal aquifer systems and thus to arrest further degradation of the groundwater quality. Nevertheless, it is mainly aimed at reducing flood flows, storing the water in aquifer, raising groundwater levels and relieving over-pumping [4]. The potential sources of water for recharge may be from surface water, pumped groundwater, treated wastewater, desalinated seawater or brackish water [5, 6]. Artificial recharge through injection wells has been suggested by Mahesha [7, 8] and Javadi et al. [9] as a suitable method for retardation of SWI in any geological condition of confined or unconfined aquifer. This positive potential of deep recharge barriers in repulsion of SWI has been analyzed by Luyun et al. [10] through experimental, analytical and numerical analysis. They concluded that the effectiveness of the recharge system is reduced if it is implemented farther and higher from the toe of saltwater wedge. The methodology has been assessed by Paniconi et al., [11, 12], Papadopoulou et al. [13], Allow [14] and Narayan et al. [1] for the range of global real case studies. Mahesha and Nagaraja [15] and Narayan et al., [1, 16] concluded that uniform natural rainfall can succeed in repulsion of saline wedge introduced by SWI. In an attempt to restore the inland piezometric heads around pumping wells during groundwater abstraction, Vandenbohede et al. [17] used an artificial recharge system using local ponds to feed the aquifer and to develop a safe or sustainable water extraction system against seawater intrusion problem. The efficiency of the aquifer recharge in controlling SWI using surface pond system has also been evaluated by Hussain et al. [5] for different scenarios and recommendations have been made for appropriate management strategies. The cost of providing high quality water (e.g. desalinated water) and its in-lieu delivery for recharging purpose is among the main limitations to the recharge barriers. In addition, unavailability of such water locally, especially in dry years or in the regions that suffer from scarcity of water, also restricts the use of hydraulic barriers. Therefore in recent years greater attention has been given to renewable sources of water such as treated wastewater as source of recharge to control seawater intrusion [e.g. 5, 9, 17, 18, 19-23]. The use of such reclaimed water that is usually stored in subsurface layers helps to satisfy a part of the water demand, control flooding and drought and protect the aquifer against the SWI.

The current work studies the control of SWI in an aquifer in the UAE using ponded treated wastewater. The country is characterized as low rainfall with limited resources of freshwater. It has been predicted that under the current rate of pumping these resources will be depleted in the mid of 20th century[24]. The region is also vulnerable to current climate conditions as precipitation comes more in the form of intense rain events followed by prolonged dry spells of the year. The utilization of reclaimed water or rain water through surface ponds can be easily followed in such areas that experience seasonal flood pulses. The excess surface water can be collected in pond systems all around the coastal areas aiming to control SWI beside their conventional role in management of floods. This study presents a 3D simulation of the Wadi Ham aquifer subjected to two different scenarios of recharge compared with another scenario of no management (pumping only). In the first management scenario continuous recharging of treated wastewater through a single pond system is considered for alleviation of SWI risks. However, in the second scenario, the general impacts from multiple ponds are studied.

## 2. Numerical Model

Spatial and temporal simulation of SWI will require the use of numerical methods to solve the nonlinear governing equations of flow and solute transport through porous media. The partial differential equation of the flow consists of flux equation for the water of variable density (Darcy's law) combined with the mass balance equation of the water. Similarly by combining the flux equation of the solute with its mass balance equation the generic mass balance equation of the dissolved salt transport (advection–dispersion equation) is obtained. The numerical solution of SWI is completed by coupling and solving these two governing equations of fluid flow and solute transport simultaneously using appropriate boundary and initial conditions [25, 26]. Consequently, a quantitative framework for analyzing the monitored data and assessing the responses of coastal aquifer systems to external stresses is provided. The challenges for studying and simulation of this variable density modeling approach are summarized by Simmons et al. [27], Diersch and Kolditz [28], Simmons, [29, 30] and Werner et al. [31].

In this study, the regional Wadi Ham aquifer is simulated using the finite element-based flow and solute transport model SUTRA (Saturated-Unsaturated TRAansport) developed by Voss [32]. The model employs hybrid finite-element and integrated-finite-difference method to solve the governing equations, which describe the variable-density groundwater flow and transport processes of either solute or energy in aquifer system under saturated-unsaturated conditions. SUTRA uses bi-linear quadrilateral elements in 2D and tri-linear hexahedrons elements in 3D. The implicit finite difference is predominately used for temporal, and thus for nodewise discretization of the non-flux terms (e.g. time derivatives and sources) of these balance equations. The values of such non-flux terms are assumed to be constant in the region occupied by each specified node (FE cell) in order to handle their nodewise calculations. In contrast, the modified version of standard Galerkin finite element method is used for the spatial approximations of the all other flux terms of the equations that are localized in elementwise norm. The SUTRA code solves the generic equations of Bear [33], which cover most types of known groundwater flow and transport problems. The general forms of these equations used in SUTRA are as follows:

Fluid mass balance equation:

$$(S_w \rho S_{op} + \varepsilon\rho \frac{\partial S_w}{\partial P})\frac{\partial P}{\partial t} + (\varepsilon S_w \frac{\partial \rho}{\partial C})\frac{\partial C}{\partial t} - \nabla.[(\frac{\mathbf{k}k_r\rho}{\mu}).(\nabla P - \rho\mathbf{g})] = Q_p \tag{1}$$

Solute mass balance equation:

$$\frac{\partial(\varepsilon S_w \rho C)}{\partial t} + \frac{\partial[(1-\varepsilon)\rho_s C_s]}{\partial t} = -\nabla.(\varepsilon S_w \rho\mathbf{v}C) + \nabla.[\varepsilon S_w \rho(D_m\mathbf{I} + \mathbf{D})].\nabla C] + \varepsilon S_w \rho\Gamma_w + (1-\varepsilon)\rho_s\Gamma_s + Q_p C^* \tag{2}$$

where: $S_w$ is water saturation [dimensionless]; ρ is fluid density [$M/L^3$]; ε is porosity [dimensionless]; $\rho_s$ is density of solid grains in solid matrix [$M/L^3$]; P is fluid pressure [$M/(L.T^2)$]; t is time [T]; C is solute mass fraction in fluid [$M_s/M$]; C* is solute concentration of fluid sources [Ms/M]; ∇ is divergence vector; **k** is solid matrix permeability (permeability tensor) [$L^2$]; $k_r$ is relative permeability to fluid flow [dimensionless]; μ is fluid viscosity [M/(L.T)]; g is gravity acceleration [$L/T^2$]; $Q_p$ is fluid mass source [$M/(L^3.T)$]; **I** is identity tensor [dimensionless]; **D** is dispersion tensor [$L^2/T$]; $C_s$ is specific concentration of adsorbate on solid grains [$M_s/M_G$]; **v** is velocity vector with components in i, j, and k directions [L/T]; $\Gamma_w$ is solute mass source in fluid due to production reactions [$M_s/(M_G.T)$]; $\Gamma_s$ is adsorbate mass source due to production reactions within adsorbed material itself [$M_s/(M.T)$]; $D_m$ is apparent molecular diffusivity of solute in solution in a porous medium including tortuosity effects [$L^2/T$]; $S_{op}$ is specific pressure storativity [$M_f/(L.T^2)]^{-1}$ and $S_{op} = [(1-\varepsilon)\alpha + \varepsilon\beta]$ ; α and β are porous matrix and fluid compressibility respectively [$M/(L.T2)]^{-1}$.

## 3. Study area

The study area is the lower alluvial plain of Wadi Ham catchment located in the Fujairah Emirate in the UAE. The available narrow valleys along the Hajar Mountains (Masafi Mountains) are the main sources to feed the catchment and the corresponding aquifer (Wadi Ham aquifer). The aquifer generally consists of recent Pleistocene Wadi gravels underlined by the fractured ophiolite rock settings. Fig. 1 shows the domain of Wadi Ham aquifer with the total area of 80.26 $km^2$ used in the numerical simulation. In order to prepare the 3D simulation model of the aquifer with the irregular geometry, the elevation maps and all the other information layers are prepared in the field scale using ArcGIS platform and in shape file formats and then imported into graphical interface of the SUTRA code. Fig. 1 illustrates the available hydrological/natural features and the applied boundary conditions. Hydrostatic pressure boundary condition with a constant head at the mean seawater level is used to define the coastline. The final numerical mesh has 48160 tri-linear hexahedral elements and 55990 nodes. The key input parameters are given in Table 1. The model is calibrated by defining an anisotropic and heterogeneous hydraulic conductivity field for the system. The permeability field is obtained using trial and error aiming at convergence of the calculated groundwater levels with the observed data. The available observed groundwater levels have been recorded for two stress periods from year 1989 to year 1994 and from year 1994 to year 2005 at 8 boreholes distributed over the model domain. The calculated groundwater levels at the end of years 1994 and 2005 show a reasonable agreement with the observed ones. Al Hyal, Ham and Al Hald are the main inflow boundaries, and Kalbha and Sharaah are the two main pumping wellfields on the site. The average flow rates from these hydrological/natural features that are used in the model are presented in Table 2. The assumed salinity of groundwater and inflow water is 250 mg/l. Also, 35700 mg/l and 100 mg/l salinity are assigned for seawater and rainwater respectively. Further details about the hydrogeological setting of the study area can be found in Sherif et al. [34].

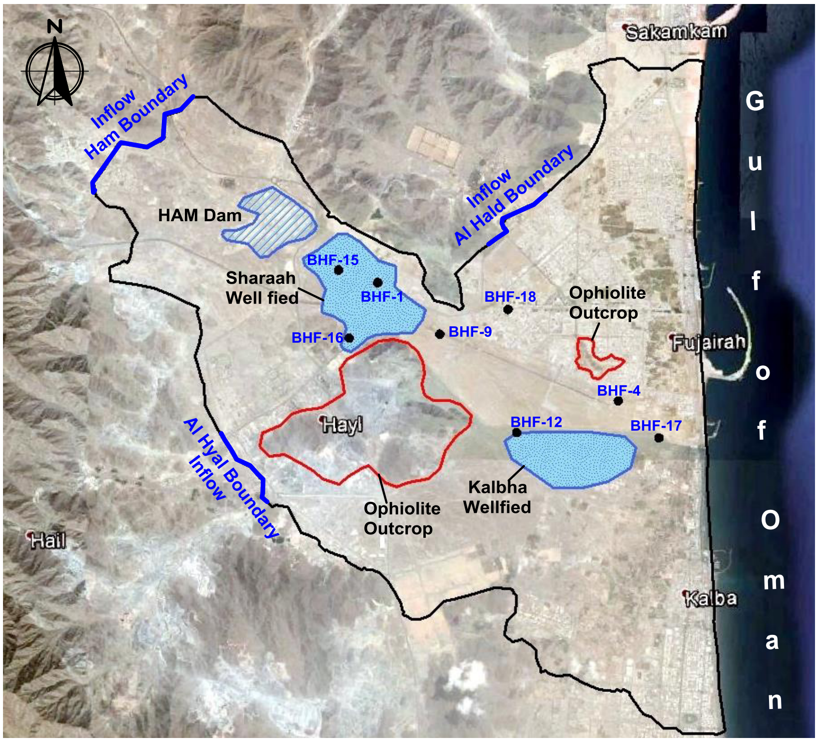

Fig. 1. Study area and the used boundary conditions.

Table 1. The parameters used in the model.

| | | |
|---|---|---|
| Dm | : coefficient of water molecular diffusion [$m^2$ /s] | $1.0\times10^{-9}$ |
| ε | : porosity [dimensionless] | 0.30 |
| g | : gravitational acceleration [m /$s^2$] | 9.81 |
| ρ | : density of seawater [kg/$m^3$] | 1025 |
| | : density of freshwater [kg/$m^3$] | 1000 |
| μ | : fluid viscosity [kg/(m.s)] | 0.001 |
| αL | : longitudinal flow dispersivity in horizontal directions [m] | 65 |
| | : longitudinal flow dispersivity in vertical direction [m] | 6.5 |
| αT | : transverse dispersivity [m] | 0.65 |
| Kv/Kh | : hydraulic conductivity anisotropy ratio | 0.1 |
| ∂ρ/∂C | : change of fluid density with concentration [kg/$m^3$] | 700 |

Table 2. Inflow and outflow rates defined in the model.

| | |
|---|---|
| Average annual precipitation | 0.20 m/year |
| Recharge factor | 0.4 |
| Infiltration rate from Dam | 0.02 m/day |
| Inflow | |
| Al Hyal | 850 $m^3$/day |
| Ham | 1450 $m^3$/day |
| Al Hald | 1100 $m^3$/day |
| Pumping | |
| Kalbha wellfied | 13600 $m^3$/day (from 1989 to 1994)<br>17200 $m^3$/day (from 1994 to 2005) |
| Sharaah wellfield | 3225 $m^3$/day (from 1989 to 1994)<br>2250 $m^3$/day (from 1994 to 2005) |

## 4. Results and discussions

In year 2005, the inland advance of 50% isochlor, measured at the aquifer bottom floor from the seaside, was 1375 m. This value is calculated along an arbitrary v section x-x passing through Kalbha pumping field (Fig. 2). By maintaining the simulation with the same hydrological settings for the next 10 years, the current condition of the flow and salinity for the year 2015 is obtained indicating a further 265 m progression of the 50% iso-concentration line. This remarkable encroachment would have led to additional depletion in freshwater sources; and therefore a management action seems necessary to protect the aquifer against SWI. In order to highlight the efficiency of the control measure using artificial recharge with treated wastewater, the model is subjected to three different stress conditions for the next coming 10 years. In the first case it is assumed that the current rates of pumping and rainfall will be maintained until year 2025. In the second case the effect of recharging through one surface pond (A) and in the third scenario the effects of three surface ponds (A, B and C) are considered to obtain the salinity distribution throughout the model, under the same pumping and rainfall rates used in the first scenario. In each of these 100 m×100 m artificial ponds the collected reclaimed water (with TDS of 1300 mg/l) is allowed to percolate into the aquifer with an average rate of 0.5 m/day.

The 50% iso-salinty contours of these three scenarios, progressing along the base layer of the model, are illustrated in Fig.2. The projections of the surface ponds' locations are also presented on this figure. In the 'no management' scenario, the system experiences a further intrusion of 220 m compared to the results of year 2015 on same x-x section. The positive role of recharging water to control SWI starts by percolation through the soil layers and reaching the water table. The recharged water enhances the seaward gradient of water table in the system by raisings the inland piezometric heads. This mechanism works as a countermeasure action against the inland encroachment of saltwater. In comparison to the no-recharge scenario the 50% iso-contour line will be pushed back in seaward direction by 290 m in the second scenario and 340 m in the third scenario along section a-a. The corresponding values of backward movement calculated in the second scenario are 550 m and 240 m along sections b-b and c-c respectively. Figs.3 and 4 show the comparison of the final results of the salinity distribution obtained in these scenarios at the end of year 2025 in vertical sections a-a and b-b respectively.

In this process, the low iso-salinity surfaces of the intruded saline water that are located in a shorter distance from the recharge system are more affected by infiltrated water and severely forced back to the sea. As pond B is located almost on top of the transition zone of saltwater wedge, and due to the divergent flow and mixing, the transient effects of recharge through this pond is spreading in all directions creating a halo of low salinity (closed contours of salinity with less than 10% concentration) in underlying depths surrounding the pond (Fig. 4d). These results clearly highlight the regional impacts of the recharge system to repulse the bulk movement of intruded saline water in this sandy aquifer followed by saving a considerable amount of freshwater/brackish water in the aquifer.

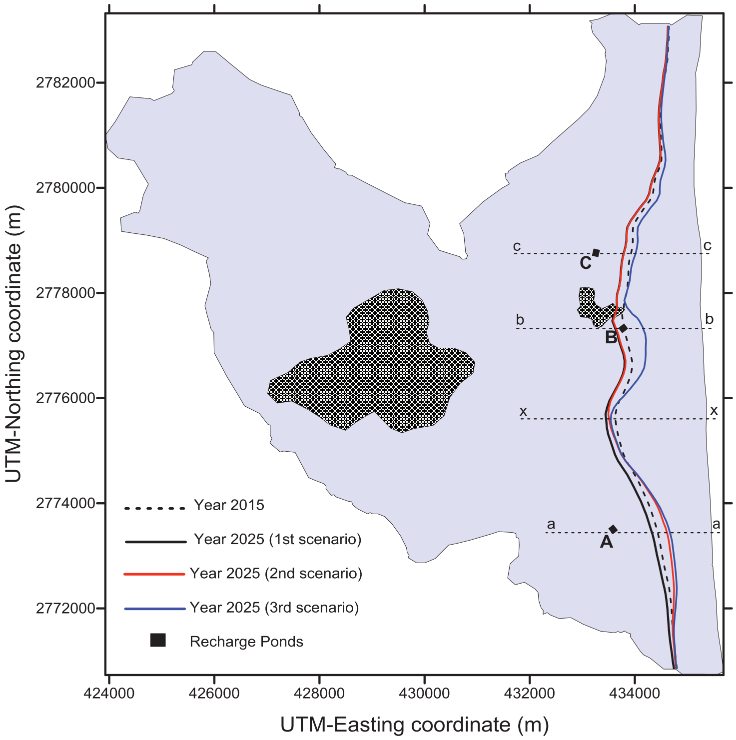

Fig. 2. Inland progress of 50% iso-concentration lines across the base of aquifer in XY plane.

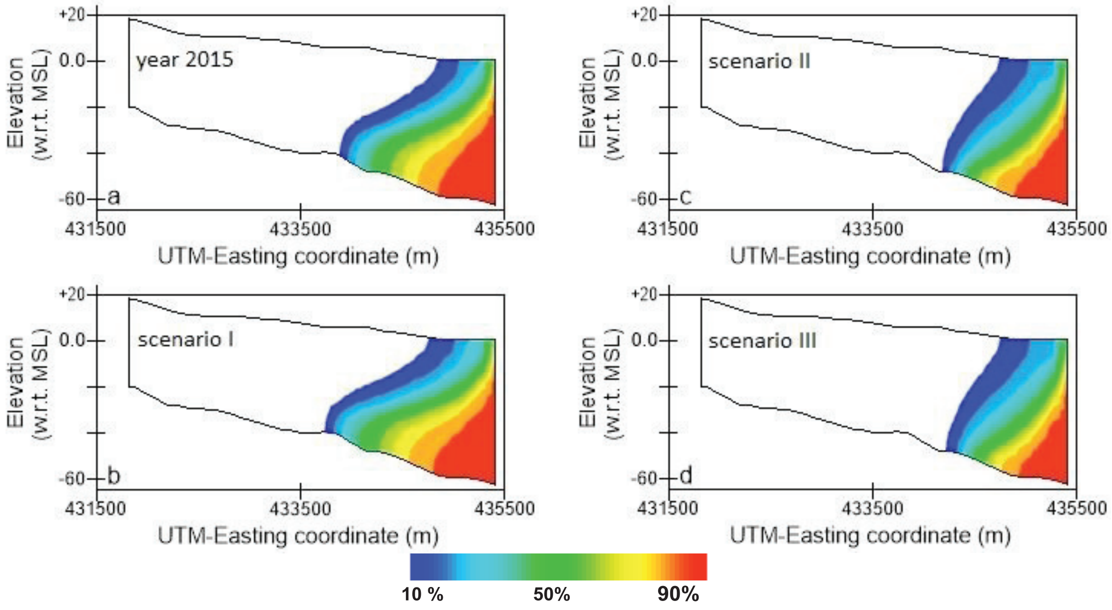

Fig. 3. Overall salinity (%) of the model in vertical sections taken along the cross-section *a-a* in all the simulated scenarios.

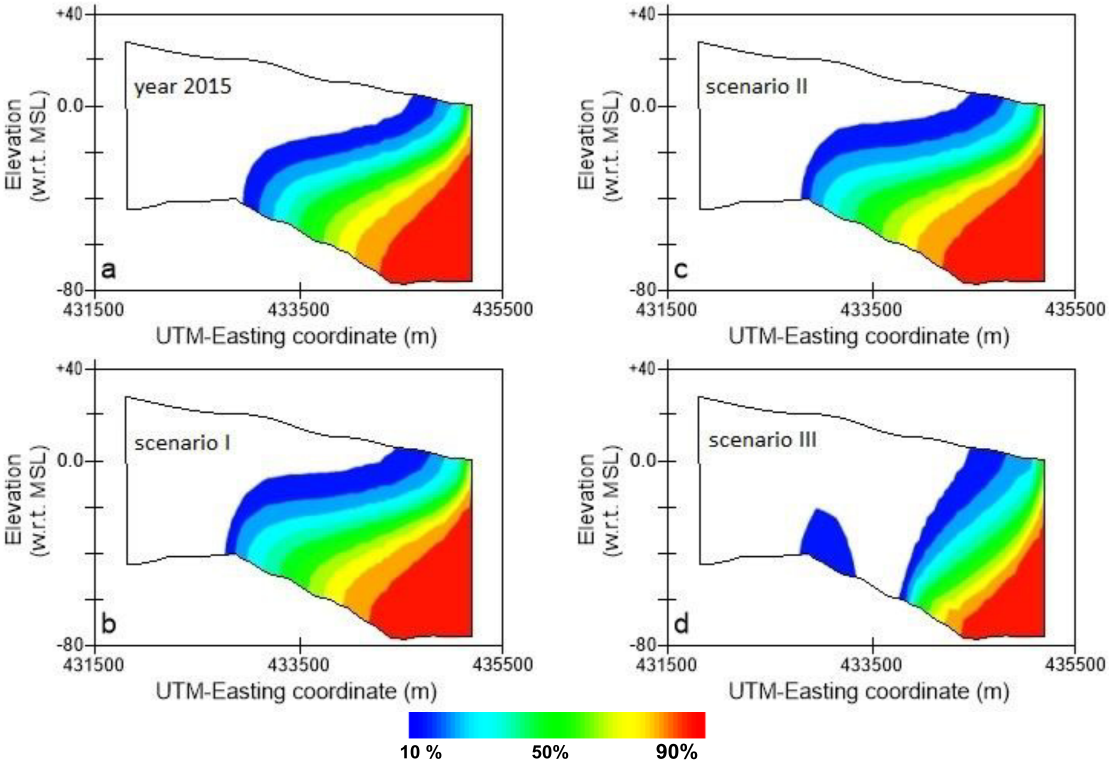

Fig. 4. Overall salinity (%) of the model in vertical sections taken along the cross-section *b-b* in all the simulated scenarios.

## 5. Conclusions

A numerical simulation was performed to outline the effects of artificial recharge, as a management policy, on inland advancement of saline water in the Wadi Ham aquifer in the UAE. The model was calibrated and used to simulate the future salinity levels of the aquifer in year 2025. In order to control the negative impacts of SWI, the system was subjected to management scenarios of artificial recharge using ponded treated wastewater in two different schemes and the results were compared with the no management scenario. It has been shown that a considerable reduction in salinity levels occurs throughout the aquifer owing to the application of the artificial recharge scenarios. Consequently a higher level of efficiency and a long term sustainability of the system would be guaranteed by designing several surface recharge basins in different locations of the study area. In addition, direct collection of the treated wastewater, rainfall and excess surface flow in these basins can be considered as reliable sources for recharging and feeding of the aquifer.

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