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ARTIFICIAL RECHARGE OF COASTAL AQUIFERS USING TREATED WASTEWATER TO CONTROL SALTWATER INTRUSION

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ABSTRACT

This paper investigates the efficiency of artificial recharge of aquifers with treated wastewater using a surface basin (pond) system to control seawater intrusion (SWI) in coastal aquifers and to increase their safe yield. First a hypothetical case study of an unconfined aquifer is simulated. The effects of the artificial recharge system on inland advancement of saline water in a real case study (Wadi Ham aquifer in the UAE) are outlined in another application. The numerical model of the Wadi Ham aquifer is developed based on the available hydrogeological data in real scale. The 3D variable-density flow and transport numerical models of both case studies are solved using the finite element method. The transient progress of saline water before and after the recharge event is presented in both case studies. Both systems initially suffered from aggressive inland encroachment of saline water due to pumping. However, by implementation of the recharge pond, the treated wastewater starts to infiltrate towards the groundwater table and consequently it helps to alleviate the saltwater intrusion. The results highlight that lower equi-concentration lines are generally more sensitive to recharge and abstraction events.

Keywords: *seawater intrusion; numerical modelling; coastal aquifer; artificial recharge; treated wastewater*

1. Introduction

In coastal areas, usually, there is a relatively small hydraulic gradient of subsurface flow toward sea. But the small density gradient between the seawater and freshwater forces the seawater to penetrate into aquifer and then mixing occurs with the inland freshwater sources. Saltwater intrusion is a serious problem that continuously threats the quality of the groundwater storage in these areas. The groundwater withdrawals can accelerate the rate of saltwater intrusion by disturbing the natural hydrostatic equilibrium state between these two fluids [1]. In order to maintain the seaward hydraulic gradient against SWI a hydraulic barrier should be planned. The artificial recharge approach which is the main focus of this paper is among the most popular techniques that can achieve this. Generally it aims at reducing flood flows, storing the water in aquifer, raising groundwater levels, relieving over-pumping and finally improving water quality and suppressing the saline water [6]. The great potential of this approach in repulsion of intruded saline wedge has been suggested by a number of researches [1-4].

The quality and quantity of the recharge water, the cost and the source of providing the high-quality water for recharge especially in the areas that suffer from scarcity of water and also the operational cost of the recharge system are the factors that should be taken into consideration in the design of recharge systems. Using desalinated seawater is costly and could be difficult to justify. Therefore, application of reclaimed water (treated wastewater) can be highlighted as a reliable strategy with low economic cost and high environmental benefits. The current work attempts to simulate the 3D patterns of evolution of controlling SWI in both hypothetical and real cases of unconfined aquifers using ponded treated wastewater. A density dependent finite element model SUTRA (Saturated-Unsaturated TRAnsport) [5] is used for numerical simulation of both aquifers. The SUTRA code is a FE-based numerical model that employs hybrid finite element and integrated finite difference methods to solve the governing equations of flow and transport processes of solute or energy in aquifer systems. The background information about the SUTRA code and some of its applications in optimal modelling of different SWI management measures can be found in recent papers of the authors [1,8].

2. First Application: Hypothetical Aquifer

The first application is a 3D hypothetical aquifer with 300 m length, 100 m width and 40 m depth (Figure 1). The domain is discretized into 24000 elements and 26691 nodes. Hydrostatic water heads of 24.5 m and 24.0 m are assigned to the left and right sides of the domain respectively to represent the freshwater and seawater boundaries of the simulated unconfined aquifer, where an unsaturated layer overlying a saturated layer. The van Genuchten model [9] is used for simulation of unsaturated flow through top layer. The system is subjected to continuous pumping of 430 m^3/day implemented by the local production well screened at coordinates (70, 40, 15) m. The main input data used for the simulation model include: the coefficient of water molecular diffusion of 1.0×10^{-9} m^2 /s; fluid viscosity of 0.001 kg/(m.s); porosity of 0.35[dimensionless]; transverse and longitudinal dispersivities of 0.5 m and 5.0 m respectively; permeabilities of 1.0×10^{-12} m^2 and 5.0×10^{-11} m^2 for the top and bottom layers; solute mass fractions of 0.0357 and 0 for seawater and freshwater, and densities of 1025 kg/$m^3$and 1000 kg/m^3 for seawater and freshwater respectively.

3. Second Application: Wadi Ham Aquifer, UAE

The second application is the Wadi Ham aquifer located in Fujairah emirate in the UAE country. Figure 2 shows the domain of the Wadi Ham aquifer with the total area of 80.26 km^2 used in the numerical simulation. The figure also illustrates the available hydrological/natural features and the boundary conditions. A hydrostatic pressure boundary condition with a constant head at the mean seawater level is used to define the coastline. The 3D model is generally an anisotropic and heterogeneous system based on hydraulic conductivity field defined through calibration process. The final numerical mesh has 48160 tri-linear hexahedral elements and 55990 nodes. The details about the hydrogeological setting and 3D modelling of this study area can be found in [7-8] where a considerable amount of SWI is reported as the current condition of this aquifer and more specifically due to continuous groundwater withdrawal from available production well located close to the coastline that intensifies the inland encroachment of saltwater.

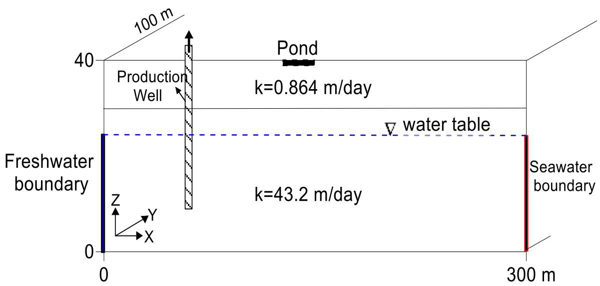

Figure 1: Geometry and boundary conditions of the hypothetical model

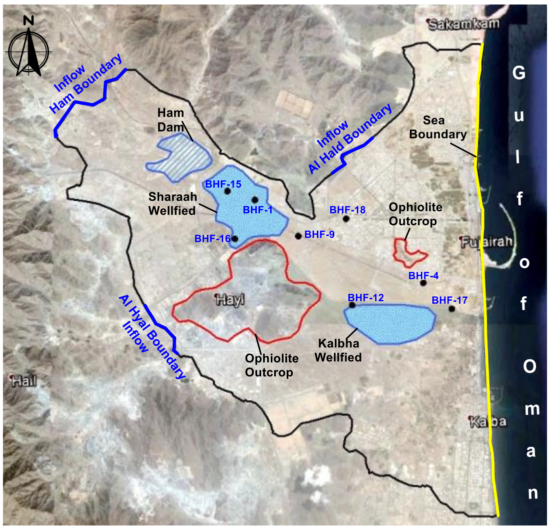

Figure 2: Boundary conditions of Wadi Ham aquifer

4. Results and Discussion

Figure 3 shows the equilibrium salinity distribution of the considered hypothetical aquifer in the first application that is obtained under applied abstraction rate (430 m^3/day) and without any management action. The average inland advancements of the toes of the 10%, 50% and 90% salinity contours along the bottom boundary of the aquifer, measured from the seaside boundary, are 241 m, 232 m and 133 m respectively. These remarkable ingression trends lead to depletion in freshwater sources and thus an essential management action seemed to be necessary in order to protect the aquifer against

SWI. Therefore the system is then subjected to one classical scenario of groundwater management involving artificial recharge of aquifer using the ponded water. However the treated wastewater as an economic and environmentally safe source of water is suggested here and used in a pond to feed the aquifer. The recharge is implemented by an artificial surface pond (40m×10m ×1m) centred at coordinates (150, 65, 39)m. The recharge pond replenishes the aquifer with 1.0 m constant head of water. The corresponding average rate of recharge directly under the pond (calculated by SUTRA) is 0.39 m/day. The transient advancements of 10%, 50% and 90% iso-concentration lines in the reverse direction toward the sea are the evidence of the success of the recharge system to repulse the intruded saline water where the saltwater-freshwater interface will migrate back towards the sea by 8 m, 82 m and 53 m for this set of contour line respectively. This process is followed by recovering a considerable amount of freshwater in the aquifer. The transient variation of the 50% iso-concentration line during the recharge stress period (measured at the bottom boundary from the seaside in the XY plane) is presented in Figure 4. It can be seen that the amount of SWI mitigation is significant in regions away from the pumping well. Also, the retreat of seawater in the central area of the coastal zone is mostly attributed to the positive potential of the recharge system.

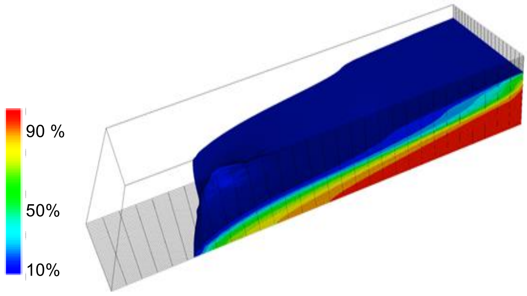

Figure 3: 3D salinity map (%) of hypothetical example prior to recharge process

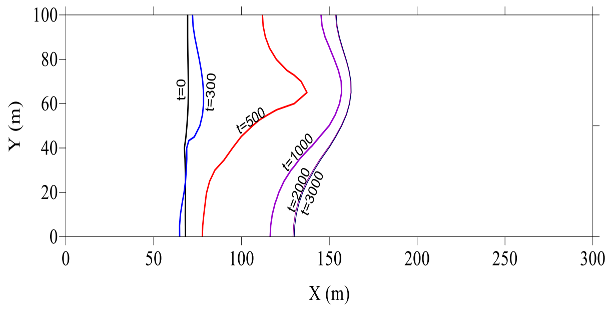

Figure 4: Transient progress of the 50% ischolar across the base of aquifer in XY plane

In the second example, the current condition of flow and salinity in the Wadi Ham aquifer (as a real-world case study) is first obtained. Figure 5 shows the current 3D distribution of salinity throughout this aquifer, pointing out the levels of contamination that are threatening the Kalbha production wells. In the numerical experiment conducted to control SWI in this aquifer, the system is again subjected to an assumed planning of artificial recharge using treated wastewater. For this purpose and by maintaining the current pumping rates (in year 2015) for the next 10 years, three recharge ponds (A,B and C) are assumed in the model to continuously feed the aquifers with an average rate of 0.5 m/day. The 50% iso-salinity contour for this control approach progressing along the base layer of the model is illustrated in Figure 6 and it is compared with the corresponding case with no-management strategy. The projections of the surface ponds' locations are also presented in the figure. In the no-management scenario (first scenario), the system experiences a further inland intrusion of 220 m compared to the results of year 2015 on X-X section. The recharged water subsequently 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 first (no-recharge) scenario, the 50% iso-contour line will be pushed back in seaward direction by 340 m along section a-a in the second (surface recharge) scenario. 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.
In general, there are some limitations in implementing of this scenario of the control methods. Direct application of recharge by ponding or spreading is not applicable in confined aquifers or even relatively thick unconfined aquifers. Under these circumstances, a deep injection by recharge wells may satisfy the design criteria in confined systems. In addition, the application of treated wastewater with large quantities to recharge aquifers requires further attention in terms of sustainability of the host aquifer, and health, environmental and economic risks.

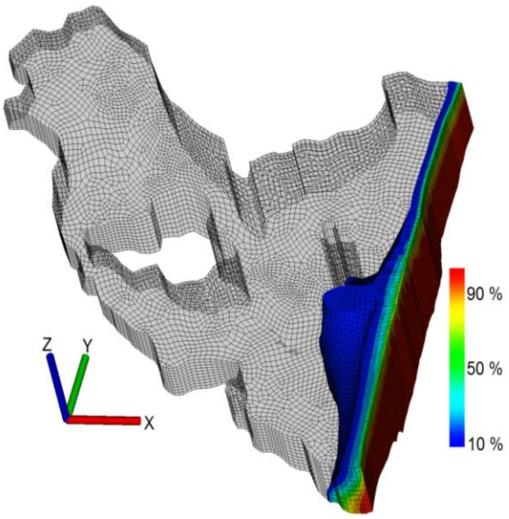

Figure 5: Current condition of salinity distribution (%) in Wadi Ham aquifer

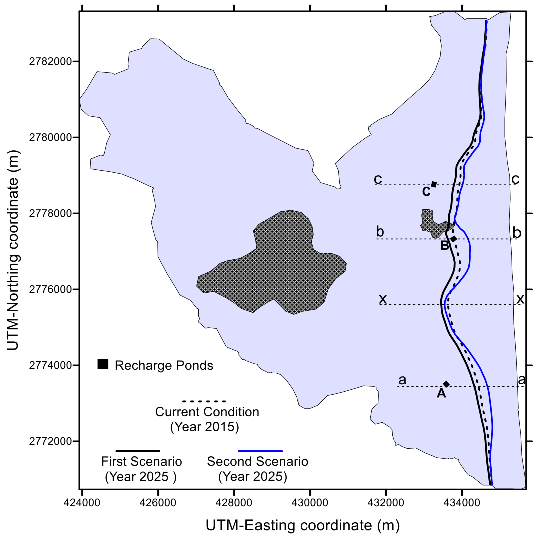

Figure 6: Inland progress of 50% iso-concentration lines across the base of Wadi Ham aquifer

5. Conclusions

3D numerical simulations were performed to outline the effects of the artificial recharge on general inland advancement of saline water into both hypothetical and real-world examples of coastal aquifers. It was shown that a considerable decrease in salinity levels occurs in the aquifers owing to the application of the recharge scenario. This is because the recharged water enhances or maintains the seaward gradient in the system by raising the inland piezometric heads. Therefore, the design of the simple recharge basins to feed the aquifer by collecting the treated wastewater and/or storm water can be considered as an efficient countermeasure against saltwater intrusion and could guarantee the long term sustainability in small unconfined aquifer systems.

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