Numerical Prediction of the Efficacy of Treated Wastewater Recharge to Impede Seawater Intrusion in the Coastal Aquifer of Gaza − Palestine

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ABSTRACT: The ongoing depletion of the coastal aquifer in the Gaza strip due to groundwater overexploitation has led to the process of seawater intrusion, which is continually becoming a serious problem in Gaza, as the seawater has further invaded into many sections along the coastal shoreline.

Prediction of the future behaviour of the seawater intrusion process in the Gaza aquifer is thus of crucial importance to safeguard the already scarce groundwater resources in the region. In this paper the coupled three-dimensional groundwater flow and density-dependent solute transport model SEAWAT, as implemented in Visual MODFLOW, is applied to the Gaza coastal aquifer system to simulate the location and the dynamics of the saltwater–freshwater interface in the aquifer in the time period 2000-2010. A very good agreement between simulated and observed TDS salinities with a correlation coefficient of 0.902 and 0.883 for both steady-state and transient calibration is obtained.

After successful calibration of the solute transport model, numerous management scenarios schemes are examined to maintain the ground water system and to control the salinity distributions within the target period 2011-2040. In the first, pessimistic scenario, it is assumed that pumping from the aquifer continues to increase in the near future to meet the rising water demand, and that there is not further recharge to the aquifer than what is provided by natural precipitation. The second, optimistic scenario assumes that treated surficial wastewater can be used as a source of additional artificial recharge to the aquifer which, in principle, should not only lead to an increased sustainable yield of the latter, but could, in the best of all cases, revert even some of the adverse present-day conditions in the aquifer, i.e., seawater intrusion. This scenario has been done with three different cases which differ by the locations and the extensions of the injection-fields for the treated wastewater.

The results obtained with the first (do-nothing) scenario indicate that there will be ongoing negative impacts on the aquifer, such as a higher propensity for strong seawater intrusion into the Gaza aquifer. This scenario illustrates that, compared with 2010 situation of the baseline model, at the end of simulation period, year 2040, the amount of saltwater intrusion into the coastal aquifer will be increased by about 35 %, whereas the salinity will be increased by 34 %. In contrast, all three cases of the second (artificial recharge) scenario group can partly revert the present seawater intrusion. From the water budget point of view, compared with the first (do nothing) scenario, for year 2040, the water added to the aquifer by artificial recharge will reduces the amount of water entering the aquifer by seawater intrusion by 81, 77 and 72 %, for the three recharge cases, respectively. Meanwhile, the salinity in the Gaza aquifer will be decreased by 15, 32 and 26% for the three cases, respectively.

Keywords: Gaza coastal aquifer, Seawater intrusion modeling, SEAWAT, Artificial recharge.

1 INTRODUCTION

Groundwater is the most precious natural resource in the Gaza Strip and it is the only source of water supply for domestic, agricultural, and other use in the area. Hydrological data reveals that, over the years, the Gaza coastal aquifer has been overexploited from heavy groundwater pumping to meet municipal and agricultural demands, which increased from 136 MCM (million cubic meters) in year 2000 to 174 MCM in year 2010 (PWA, 2010a). This increased demand cannot be balanced anymore by natural aquifer replenishment from precipitation (Sirhan and Nigim, 2002). As a result of this over-exploitation, the water

levels across most of the coastal aquifer have dropped significantly, with values going up to more than 12 m below the mean sea level in some areas. Such large groundwater level declines have led to increased sea water intrusion and a subsequent deterioration of the freshwater quality, as the chloride concentrations have exceeded the safe drinking threshold value of 250 mg/l recommended by WHO guidelines. Besides that, some of the wells are already been closed due to the increase of chloride concentration (PWA, 2001).

Nowadays, the groundwater situation in the Gaza region has become even more disastrous, so that endeavours to forestall imminent future deficiencies problems and to restore and/or maintain the sustainability of the Gaza groundwater system for now and the near future are becoming extremely urgent. Under these circumstances, appropriate ground water management policies are essential for preventing further aquifer overdraft. Identification of such policies requires first an accurate simulation of dynamics of the ground water system in response to various hydrological, meteorological, and human impact factors. Numerical modelling is the indispensable tool to achieve this objective, therefore a definite answer to see that seawater intrusion is not possible anymore, or will have partly been reverted by that time can only be given after application of a density-dependent flow and transport model.

In the present paper the coupled three-dimensional groundwater flow and density dependent solute transport model SEAWAT as implemented in Visual MODFLOW is applied to the Gaza coastal aquifer system to simulate the location and the dynamics of the saltwater–freshwater interface in the aquifer in a time-dependent mode.

The main objective of the present paper is then to carry out an integrated numerical resources management analysis for the Gaza coastal aquifer. Thus, once the numerical groundwater flow model has been set-up and calibrated, various groundwater impact scenario schemes for the near future target period 2011-2040 are simulated, in order to understand the aquifer behaviour, i.e. the changing of the salinity distribution in the long-term. In particular, in order to possibly restore positive conditions of the Gaza aquifer's mass balance and to revamp its depletion and deteriorations, groundwater management scenarios for artificial recharge of groundwater by reclamation wastewater are numerically investigated.

2 STUDY AREA

2.1 *Physiogeographic and hydro-climatic conditions*

Palestine is composed of two-separated areas, the Gaza Strip and the West Bank. The Gaza Strip area is part of the Palestinian occupied territories, located at 31°25'N, 34°20'E. It is a very small area located at the eastern coast of the Mediterranean in southwest Palestine. The Gaza Strip is bounded by the 1948 cease-fire line by Israel in the north and east and by Egypt in the south and by the Mediterranean Sea in the west (Figure 1). Its length is 40 km, while its width varies between 6 km in the north to 12 km in the south, comprising a total area of 365 km². With more than 1.84 million inhabitants living in this small area, the Gaza Strip is one of the most densely populated areas in the world, with an average population density of 4,930 person/km², which is bound to increase tremendously in the future, as the annual growth rate is 3.2% (PCBS, 2000).

The climate of Gaza is a transitional one between an arid tropical climate in the south, with an average annual rainfall of 200 mm/year that increases to 400 mm in the temperate and semi-humid climate of the Mediterranean coast in the north, with mild winters and dry, hot summers (PWA, 2001). Most of the rainfall occurs in the months October to March in the form of thunderstorms and rain showers, but where only a few days during these wet months are actually rainy days. As the potential evaporation in the Gaza strip is of the order of 1300 mm/yr, it becomes clear that the rejuvenation of water resources in the region is rather low (PWA, 2000). In fact, the coastal groundwater aquifer is not only the sole source of fresh water, but the only source of water supply in the region at all.

Figure 1. Location of the Gaza strip study area.

2.2 *Hydrogeology*

The coastal aquifer covers an area of about 2000 km2 and extends along some 120 km of the Mediterranean coastline from the Gaza Strip in the south, where its width is about 20 km, to Mount Carmel in the north, with of only 3-10 km (Figure 2 left panel). Under natural conditions, the groundwater flow in the Gaza Strip is generally directed from east to west towards the Mediterranean sea (Mercado, 1968). This means that part of the recharge of the Gaza section of the groundwater aquifer occurs on the territory of Israel in the east.

   The geology of the aquifer system that extends along the coastal plain of the Gaza Strip is of the Pliocene-Pleistocene age consists mainly of marine deposits of sandstone, calcareous siltstone and red loamy soils. With regard to the hydrogeology, the aquifer system can be subdivided near the coast into four separate sub-aquifers, A, B1, B2, and C, which all together form a largely unconfined and confined/unconfined multi-aquifer system in the western part of the aquifer area (PEPA, 1996) (Figure 2 right panel). Marine clay layers (aquiclude) with a thickness of 20 meters separate these sub-aquifers and extend from the shoreline to about 2-5 km inland.
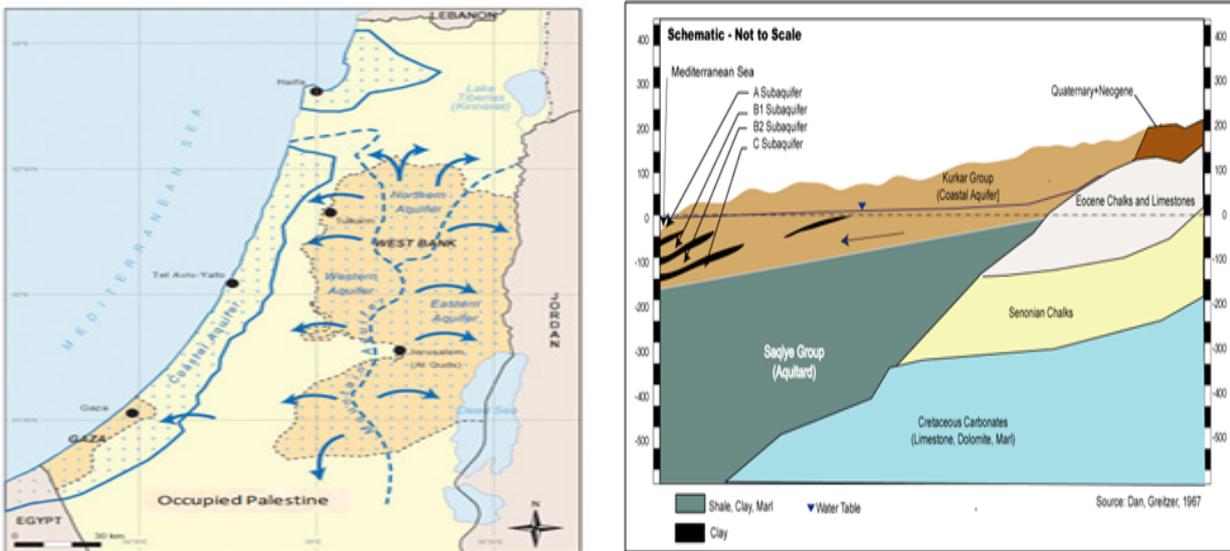

Figure 2. Coastal aquifer with groundwater flows (left) and Hydrogeological EW-cross section through the aquifer (right) (adapted from PWA, 2003).

3 MATHEMATICAL THEORY AND SETUP OF THE SOLUTE TRANSPORT MODEL

3.1 *Governing equations*

The density-dependent groundwater flow equation

The groundwater flow equation for variable density flow can be written in terms of this fresh water head, as follows (Langevin *et al.,* 2003):

$$\frac{\partial}{\partial x}\left[\rho k_{fx}\left\{\frac{\partial h_f}{\partial x}\right\}\right] + \frac{\partial}{\partial y}\left[\rho k_{fy}\left\{\frac{\partial h_f}{\partial y}\right\}\right] + \frac{\partial}{\partial z}\left[\rho k_{fz}\left\{\frac{\partial h_f}{\partial z} + \left(\frac{\rho - \rho_f}{\rho_f}\right)\frac{\partial z}{\partial z}\right\}\right]$$

$$= \rho S_f \frac{\partial h_f}{\partial t} + \theta \frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t} - \rho_s q_s \tag{1}$$

where:

h_f, equivalent fresh water head [L].
k_{fx}, k_{fy}, k_{fz}, equivalent freshwater hydraulic conductivities in the three coordinate directions [LT^{-1}].
ρ, density of native aquifer water [M/L^3]
ρ_f, density of freshwater [M/L^3].
S_f, specific storage in term of equivalent fresh water head [L^{-1}].
C, solute concentration [M/ L^3].
θ, effective porosity (dimensionless).
ρ_s, density of water entering from a source or leaving through a sink [M/L^3].
q_s, volumetric flow rate of sources or sinks per unit volume of aquifer [T^{-1}].

The solute transport equation

The solute transport equation is the same for variable-as for constant-density flow and transport, i.e. (Zheng and Bennett, 1995).

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \cdot \nabla C) - \nabla \cdot (vC) - \frac{q_s}{\theta} C_s + \sum_{k=1}^{n} Rk \tag{2}$$

where:

C, salt concentration [ML^{-3}].
D, hydrodynamic dispersion coefficient [L^2/T].
v, fluid velocity [L/T]
q_s, flux of source or sink (T^{-1}).
C_s, solute concentration of water entering from sources or sinks [M/ L^3].
θ effective porosity (dimensionless).
R_k, rate of solute production or decay in reaction k of *n* different reactions [M/(L^3 $*$T)], which in the present application of pure saltwater transport is set to zero.
D, hydrodynamic dispersion tensor, defined as D = Dm + D*, where Dm and D* are the coefficients of mechanical and molecular dispersion, respectively [L^2/T], the former being related to the linear fluid velocity v [L/T] through Dm = f (v, A$_L$, A$_T$), where A$_L$ [L], A$_T$ [L] are the longitudinal and transversal dispersivity, respectively.

Equation of state relating density to concentration

The variable density flow equation (1) is coupled in two ways to the transport equation (2). Firstly by the second term on the right-hand side of Eq. (1) which represents the change of fluid mass due to the change in solute concentration *C,* and, secondly, by the direct effect of *C* on the density *ρ* appearing on the left side of the subsequent equation.

The empirical (linear to first order) relation between the density *ρ* of saltwater and concentration *C,* also called an *equation of state*, was developed by Baxter and Wallace (1916) and can be written as

$$\rho = \rho_f + EC \tag{3}$$

where:

E= $d\rho/dc$ is the empirical relation between the density and salt concentration, and which has a value of E= 0.7143 for salt concentrations ranging between zero and that of seawater. With Eq. (3) the groundwater flow equation (1) is coupled to the solute transport equation (2).

3.2 SEAWAT model set-up for the Gaza coastal aquifer

3.2.1 Set-up of the solute transport module

As the basic conceptual structure of the groundwater flow model part of SEAWAT is essentially identical to the MODFLOW model, the conceptual model setup of SEAWAT for the Gaza coastal aquifer, as implemented in Visual MODFLOW, relies directly also on that of the original MODFLOW groundwater flow model set-up (Sirhan and Koch, 2013a). This means also that the calibration results of the constant-density MODFLOW-2000 model, as well as the main internal and external hydrologic sources and stresses, will be incorporated with only minor adjustments into the SEAWAT-2000 variable-density model, to simulate the transient dynamics of the saltwater-freshwater interface in the Gaza coastal aquifer.

3.2.2 Boundary conditions

The boundary conditions for the solution of the solute transport equation in the model domain are already assigned in the conceptual Gaza aquifer groundwater flow and solute transport model. These are, namely, constant concentration (Dirichlet) boundaries in the west (coastline), with a constant salt concentration equivalent to that of seawater (see subsection below), and Neumann boundary conditions in the east, with a specified salt concentration (see Figure 3 for details):

- Dirichlet boundary-conditions with a constant salt (TDS) concentration of that of seawater, i.e. C=C_0 = 35,000 mg/l (salinity) are set in all layers for all cells along the Gaza coastline.
- Neumann boundary conditions with a TDS of 250-1100 mg/l (salinity) are assigned in all layers for all cells at the eastern boundary.

The salinization due to the infiltration of contaminant water from the surficial recharge (rainfall) is neglected, because of its very small effect, compared to the main source of salinity i.e. seawater intrusion.
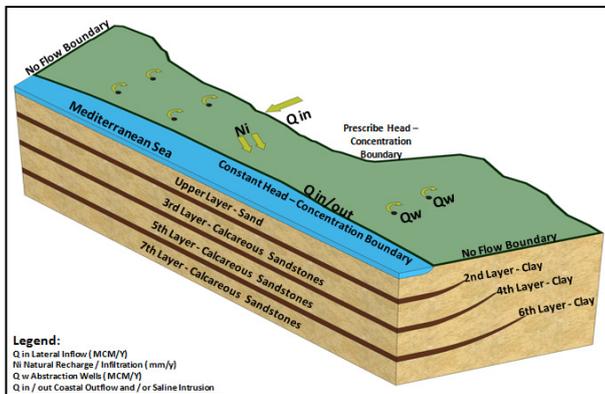

Figure 3. Schematization of the conceptual model of the Gaza coastal aquifer (Sirhan and Koch, 2013a).

3.2.3 Initial conditions

For the transient variable-density groundwater flow and solute transport simulations, which cover a time period of 2001-2010, initial conditions for chloride concentrations distributed across the model area must be set. In the present application the simulated chloride concentrations for year 2000, as obtained during the steady-state calibration of the model, are assigned as initial condition for the transient simulation.

In fact, SEAWAT model requires the concentrations of total dissolved solids (TDS) which, by virtue of the equation of state (Eq. 3), determines the density of the saline fluid, rather than the chloride concentrations. Therefore, the latter are linearly converted to TDS, by assuming that seawater has a chloride concentration of 19,800 mg/l and a TDS value of 35,000 mg/l (Parker *et al.*, 1955). This means then also, that the SEAWAT-computed concentration output is discussed in terms of total salinity, not chloride concentrations.

3.2.4 *Calibration and model results*

Following the usual approach in groundwater flow and transport modeling (e,g. Anderson and Woessner, 1992; Kresic, 1996), both steady-state and transient calibrations for the solute transport modul, of SEA-WAT, wherefore chloride concentrations measured biannually in the 2000-2010 time period at 51 wells distributed across the model area (see Sirhan and Koch, 2013a,b; Sirhan, 2014) are used as calibration targets, have been carried out. More exactly, as in the SEAWAT- model, the TDS salinity is required, and all chloride concentrations are converted to equivalent TDS- salinity, prior use in the subsequent processing.

In addition to the aquifer parameters already calibrated in the groundwater flow model (Sirhan and Koch, 2013a), the dispersivities for the sub-aquifers and aquitards (clay) layers are adjusted by trial and error in the transient calibration of the SEAWAT solute transport model. For simulation the location and the dynamics of the saltwater–freshwater interface in the aquifer in the time period 2000-2010 a very good agreement between simulated and observed TDS salinities with a correlation coefficient of 0.902 and 0.883 for both steady-state and transient calibration is obtained (Figure 4).
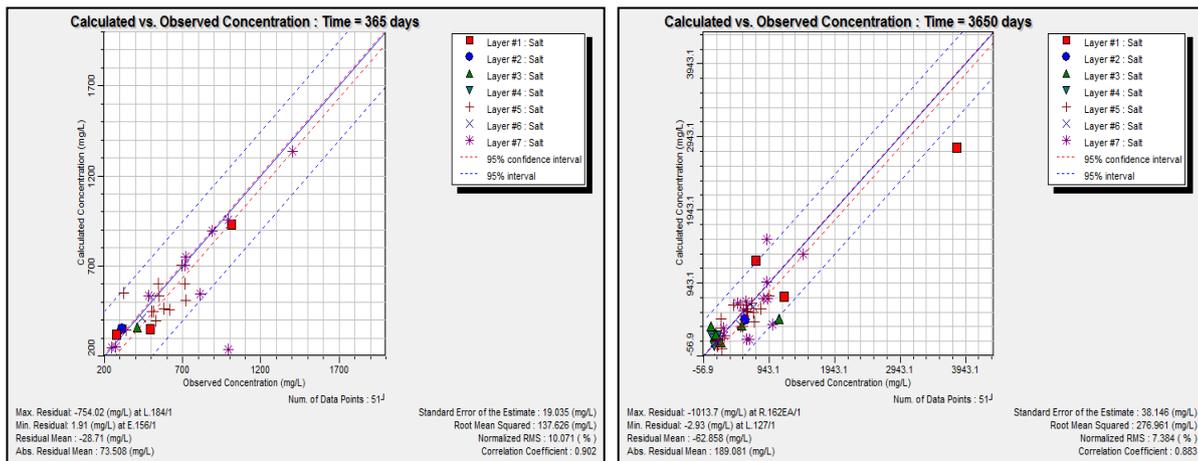

Figure 4. Scatterplot of steady-state year-2000 (left) and transient year-2010 (right) SEAWAT- calculated over observed salinity concentrations for the various layers of the model with summary of statistics.

4 PREDICTIONS OF THE VARIOUS MANAGEMENT SCENARIOS

Summarizing the results of various future groundwater management scenarios for the Gaza coastal aquifer of the previous sections, it is clear that all three artificial recharge cases are more or less able to forestall, or even to remedy, the presently existing adverse aquifer conditions, namely, low groundwater heads and high salinity by the end of the target simulation period, year 2040 as shown in Figure 5 and 6. The positive effects of this second (recharge) scenario groups become even more striking, when compared with the first (do-nothing) management scenario which is the most critical one, as it assumes ever-increasing groundwater extraction in the coming 30 years.
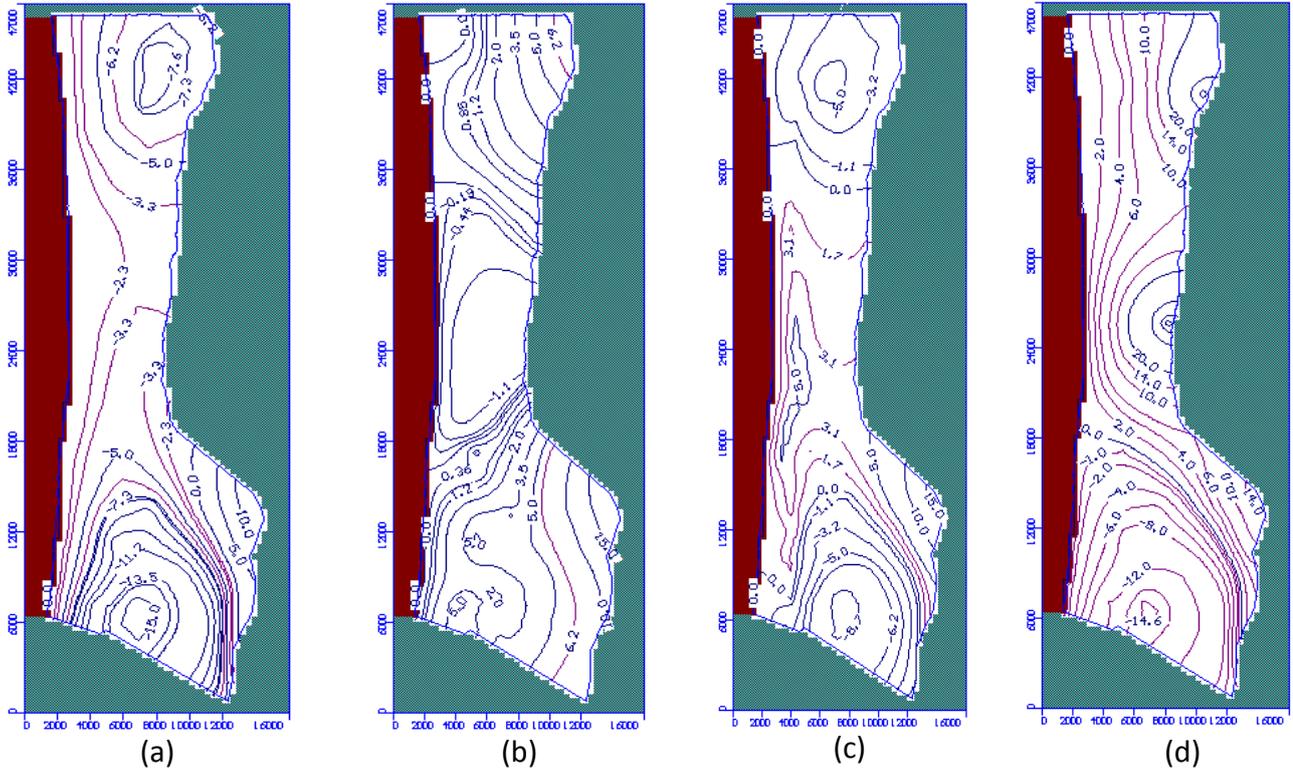
Figure 5. Year-2040 head for 1st scenario (a), compared with 2nd scenario of 1st case (b), 2nd case (c) and 3rd case (d).
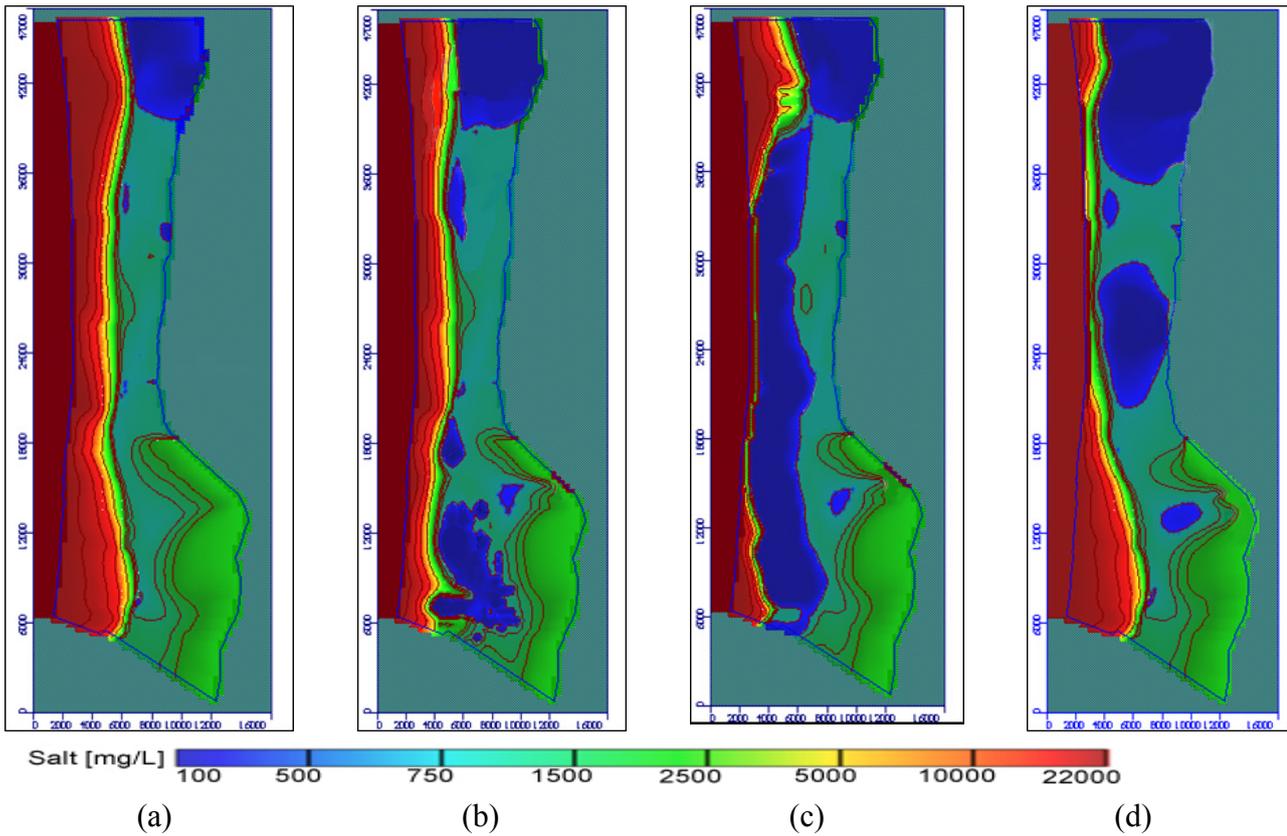

Figure 6. Year-2040 salinity for 1st scenario (a), compared with 2nd scenario of 1st case (b), 2nd case (c) and 3rd case (d).

As a matter of fact, the first (do-nothing) scenario illustrate that at the end of the simulation period, year 2040, the amount of saltwater intrusion into the coastal part of the aquifer increases by about 35 %, meanwhile the salinity will be increased by 34 %.

In contrast, all three cases of the second (artificial recharge) scenario group can partly revert the present seawater intrusion. From the water budget point of view, compared with the first (do nothing) scenario, for year 2040 the additional water to the aquifer by the artificial recharge reduces the amount of water entering the aquifer by seawater intrusion by 81%, 77% and 72 %, for the three recharge cases, respec-

tively (Figure 7). Moreover, the artificial recharge reduces the saltwater-polluted (salinity) in the Gaza aquifer by 15%, 32% and 26% for the three cases respectively.
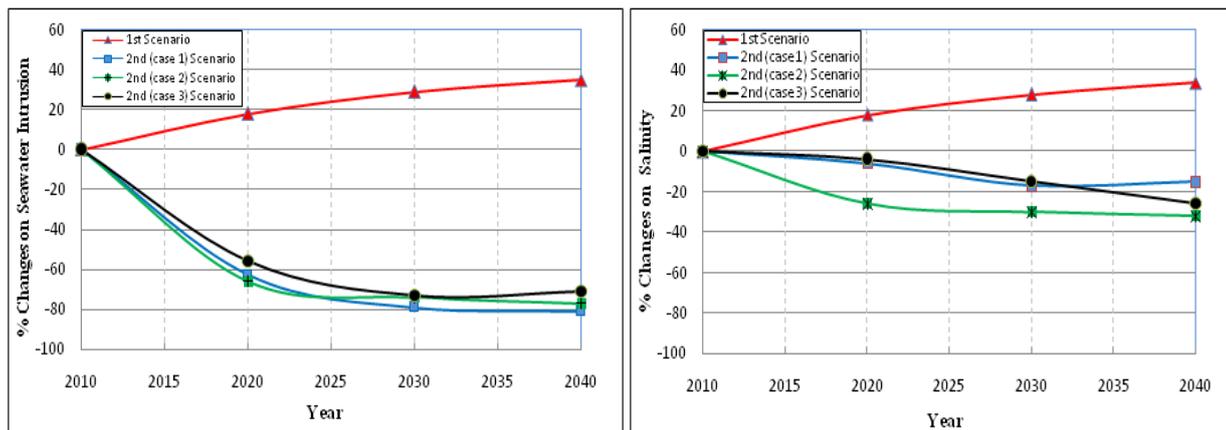

Figure 7: Percentile changes of amount of the seawater intrusion (left) and salinity (right) under the various schemes.

5 CONCLUSIONS

As a matter of fact, the results of the numerical modeling with the artificial recharge scenarios indicate that there is some success in aquifer recovery that may forestall or remedy the adverse aquifer conditions, such that the presently existing saltwater intrusion is partly been reverted by the end of simulation period in year 2040.

The estimated hydraulic heads show that the 1st case of the second artificial recharge scenario is the best option for achieving the aquifer remediation in the long-term in terms of groundwater levels restoration. Meanwhile, the 2nd case of the second (artificial recharge) scenario is the best option in term of reducing the salinity (TDS) in the long-term, while the 3rd case would be the second effective option in reducing aquifer salinity (see Figure 7).

The results obtained from the simulated three cases of the second (artificial recharge) scenario can promotes and guide the Palestinian Water Authority (PWA) for taking further decisions on the adoption of a long-term strategic plan of artificial recharge to control the future seawater intrusion in the Gaza coastal aquifer.

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