SIMULATION OF VARIABLE-DENSITY GROUNDWATER FLOW AND TRANSPORT IN THE COASTAL AQUIFER OF THE PYRGOS AREA (GREECE)

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ABSTRACT

This study presents an application of the SEAWAT code to simulate three-dimensional, variable-density groundwater flow and transport in the coastal unconfined aquifer developed in the alluvial deposits of Alfeios River in the Pyrgos area. After the drainage of the Mouria Lake in 1960's, located in the low-lying area of the aquifer along the coast, water table drawdown and groundwater quality deterioration associated by enormous electric power consumption annually are observed due to the pumped drainage of the aquifer. The SEAWAT code was used to simulate the variable-density groundwater flow under the existing hydrologic stresses and to predict the long term future development of the aquifer under scenarios which include restoration of the Mouria Lake and energy saving.

1 INTRODUCTION

Salt water intrusion is a significant problem in coastal aquifers, which often are in hydraulic continuity with sea, wetlands, estuaries (Langevin et al., 2005) and agricultural drainage systems (Simpson et al., 2011). Groundwater flow in coastal aquifers is dominated by the fluid variable density caused by the spatial and temporal variations of salt concentration. In that case, numerical simulation of groundwater flow and transport should take into account the significant vertical flows and the disperse transition zone between salt water and freshwater. Existing modeling studies, on a vertical two-dimensional profile, include the tidal influence on seawater intrusion and submarine groundwater discharge from coastal aquifer with a mildly sloping beach (Mao et al., 2006), and the effect of human activities and the sea level rise (Giambastiani et al., 2007) as well as the effect recharge wells and subsurface flow barriers (Luyun et al., 2011) on seawater intrusion in unconfined coastal aquifers. Among existing full three-dimensional modeling studies we may mention the study of Oude Essink (2001), who focused on the groundwater salinity distribution and the consequences of sea level rise in coastal groundwater system in The Netherlands. Also, Paniconi et al. (2001) studied the effects of pumping, artificial recharge and natural infiltration on seawater intrusion in a coastal aquifer in Tunisia and Langevin (2003) investigated the regional-scale submarine groundwater discharge to a marine estuary.

This study presents the full three-dimensional modeling of the coastal phreatic aquifer, developed in the alluvial deposits of Alfeios River in the Pyrgos area of Western Peloponnisos, Greece. Significant part of the aquifer is the low-lying area of the former Mouria Lake with land surface elevation below sea level. Mouria Lake has been drained in 1960's to provide land for agriculture. Due to the pumped drainage of the aquifer water table drawdown and groundwater quality deterioration are observed along with poor agricultural production of the reclaimed land and enormous electric power consumption. The SEAWAT code was employed to simulate the density dependent groundwater flow under the existing hydrologic stresses for a period of four decades to approximate the current situation. The SEAWAT code was also employed to predict the long term future development of the aquifer and the area under scenarios which include restoration of the Mouria Lake in part of its original area or nearly complete restoration of the lake and a parallel energy saving.

2 STUDY AREA

The study area is located in Peloponnisos and especially on the north-western bank of the Alfeios River estuary and on the north of Kyparissiakos Gulf, as shown in Fig. 1a.

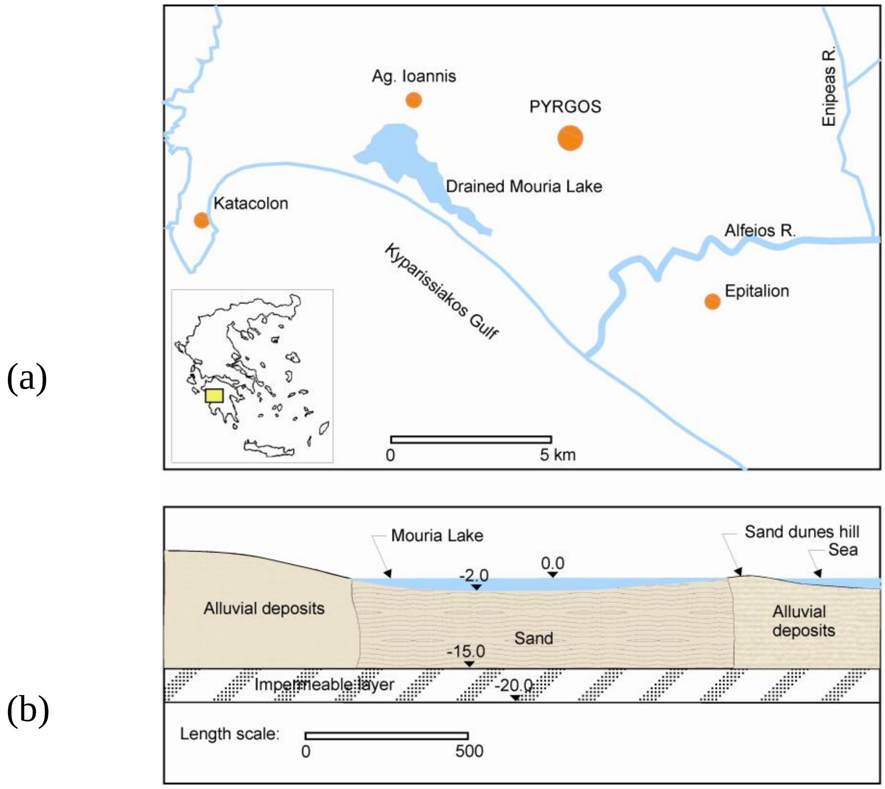

Figure 1. (a) Geographical location of the major Pyrgos area including the area of the former Mouria Lake; (b) Cross-section of the Mouria Lake zones indicating the geological texture used herein for simulations.

It is between the NW-SE trending fault south of Pyrgos town, which appears as the hydraulic boundary of the aquifer to the north, and the coastline. It includes the low-lying area along the coast, with soil surface elevation below the sea level, which was the former Mouria Lake. The lake covered an area of approximately 6.5 km^2 and was extended about 2.5 km on the north up to the boundaries of the Community of Ag. Ioannis. It was separated from the sea by a 200-m strip of sand dunes forming a small hill. The whole length of Mouria Lake was 8.2 km approximately. On the north-western boundaries of the lake and up to the roots of the nearby hills there was a marsh named "Casta", which acted as a buffer zone absorbing nutrients and other pollutants from the water feeding the lake. The lake has been drained in 1960's after the construction of a system of drainage canals and land drainage pumping stations, to provide land for agriculture. The recharge of the aquifer is mainly owing to the infiltrated rainfall water and to the lateral seepage from Alfeios River. Measurements of piezometric head in the low-lying area after the drainage of the Mouria Lake show drawdown of the water table, negative hydraulic gradients and salt water intrusion. The groundwater quality has been deteriorated not only because of salt water intrusion but also due to anthropogenic contamination.

3 NUMERICAL SIMULATION

3.1 Governing equations

The finite difference SEAWAT_v4 model (Langevin et al., 2007) was used to simulate the three dimensional, variable-density groundwater flow and transport in the coastal unconfined aquifer of the Pyrgos area (Fig. 1). The SEAWAT_v4 code, which is a combined version of MODFLOW (Harbaugh et al., 2000) and MT3DMS (Zheng and Wang, 1999; Zheng, 2006) codes, is also able to simulate simultaneous solute and heat transport with the combined effects of concentration and temperature on variable-density flow. Furthermore, SEAWAT_v4 is able to simulate the effects of fluid viscosity variations, commonly caused by temperature variations, on groundwater flow.

In our case, the saltwater intrusion problem was considered as a variable groundwater flow problem in which the fluid density is a function only of salinity, as in previous versions of SEAWAT. Temperature and viscosity variations are also not represented. Therefore, for the isotropic and heterogeneous aquifer, the equation of variable-density groundwater flow which is solved may be written in a form similar to that of previous versions of SEAWAT as follows:

$$\nabla\cdot\left[\rho\mathbf{K_o}\left(\nabla h_o+\frac{\rho-\rho_o}{\rho_o}\nabla z\right)\right]=\rho S_{s,o}\frac{\partial h_o}{\partial t}+\vartheta\frac{\partial\rho}{\partial C}\frac{\partial C}{\partial t}-\rho_s q_s' \qquad (1)$$

where, ρ is the fluid density [ML^{-3}], ρ_o is the fluid density [ML^{-3}] at the reference concentration (freshwater), h_o is the hydraulic head [L] in terms of the reference fluid (freshwater), $\mathbf{K_o}$ is the equivalent freshwater hydraulic conductivity [LT^{-1}], $S_{s,o}$ is the specific storage [L^{-1}] in terms of equivalent freshwater head, C is salt concentration [ML^{-3}], ϑ is porosity [-], t is time [T], x_i is the ith orthogonal coordinate [L], and q_s' is a source or sink flow rate [T^{-1}] of fluid with density ρ_s [ML^{-3}]

In SEAWAT_v4 the flow equation and the equation which describes solute transport in the aquifer must be solved jointly. The MT3DMS version 5.2 which has been implemented in SEAWAT_v4 has the ability to simulate simultaneously both heat and multi-species solute transport due to similar forms of solute and heat transport equations. In our case of salt water intrusion in a coastal aquifer, for simplicity, heat transport as well as chemical reactions are not simulated. In addition it is considered that the main components of natural salt do not interact with the solid matrix and a retardation factor may be omitted from the governing equation. Finally the solute transport equation which the IMT process actually solves in our case may be written in the following form.

$$\frac{\partial(\theta C)}{\partial t} = \nabla\cdot(\theta\mathbf{D}\cdot\nabla C) - \nabla\cdot(\mathbf{q}C) - q'_s C_s \tag{2}$$

where C_s is the salt concentration [ML^{-3}] of the source/sink flux q'_s, **D** is the hydrodynamic dispersion coefficient tensor [L^2T^{-1}] and **q** is the specific discharge [LT^{-1}].
The equation of state, which relates fluid density to salinity, may be written as

$$\rho = \rho_o + \frac{\partial\rho}{\partial C} C \tag{3}$$

where $\partial\rho/\partial C$ is the slope of the linear relation between fluid density and salinity, which has an approximate value of 0.7 for salinities ranging between freshwater and seawater (35 kg/m^3). With these values density varies linearly between 1000 kg/m^3 for freshwater and 1024.5 kg/m^3 for seawater.

In the solution procedure followed for all the simulations the coupling between flow and transport is explicit and the variable density water table corrections are added. Internodal conductance values used to conserve fluid mass are calculated using an upstream weighted algorithm. Flow is solved using the Pre-Conditioned Conjugate Gradient (PCG) package. The advective term of the solute transport equation is solved using the third order Total Variation Diminishing (TVD) scheme and the remaining terms are solved using the Generalized Conjugate Gradient (GCG) solver with the SSOR pre-conditioner.

3.2 Hydrogeologic properties

Major hydrogeologic data for the proposed three-dimensional model were obtained from the investigations and the two-dimensional model developed by Karapanos (2009). The horizontal two-dimensional groundwater flow was simulated by Karapanos (2009) using the Flowpath II software (Evsicov et al., 1998) in order to establish a reliable hydrogeologic balance. The model grid was consisted of a single layer of 200 m×200 m cells in the horizontal plane. Two zones of different hydraulic conductivities were considered. In the area of the drained Mouria Lake, due to the presence of finer alluvial deposits, lower values of hydraulic conductivity were observed than the hydraulic conductivity values observed in the rest of the aquifer area. Finally, the hydraulic conductivity values were obtained from model calibration conducted for unsteady-state flow conditions and for a storage coefficient (specific yield) S=0.2. The values of 300 m/d and 600 m/d were found for the zone of the drained Mouria Lake and for the rest of the aquifer area, respectively. These values were also adopted for the three-dimensional model we present herein. The NW-SE trending fault of the complex fault system in the Pyrgos area was considered as the boundary of the three-dimensional model in N-NE and the Alfeios River as the SE boundary. The NW boundary, perpendicular to the coastline, was considered as a no flow boundary. Since the unconfined aquifer is lying on a horizontal impervious layer 15 m below sea level, it is considered that the aquifer extents SW along the beach slope up to the sea depth of 15 m, which is approximately at a distance of 2 km from the coastline.

3.3 Discretization

Aquifer discretization aimed to represent its three-dimensional structure and in addition to obtain acceptable accuracy of the simulation results with reasonable computational effort. Each cell of the constructed finite-difference model grid is 100 m×100 m in the horizontal plane, which is considered sufficient according to the total volume and extent of the aquifer. The grid consists of 91 rows and 146 columns. Since much more finer vertical resolution is required for an accurate simulation of the variable density flow, the model grid was designed having 6 layers. Due to the mildly sloping beach and the irregular boundaries of the aquifer only 30,835 cells (≅39%) out of 79,716 are considered as active cells. The top elevation of layer 1 is variable to approximate the land surface elevation. The bottom of layer 1 is set at the elevation of 1 m below sea level. The cells of layer 2 were designed to have a uniform thickness of 2 m (i.e. uniform volume of 100 m×100 m×2 m), while each one of the rest four layers was designed to have a uniform thickness of 3 m (i.e. uniform volume of 100 m×100 m×3 m). It becomes apparent that model cells in layer 1 have variable thickness and volume. For model cells within the drained Mouria Lake the top elevation of layer 1 is set to 1.0 m, while for model cells in the vicinity of the NE boundary is set to 12 m. Consequently, the cells thickness in layer 1 varies between 2 m to 13 m. The bottom elevation for the cells of layer 6 is 15 m below sea level, on the impervious base.

3.4 Boundary conditions

The recharge of the aquifer from its N-NE boundary was derived by Karapanos (2009) on the basis of water table contour maps. From the western section of the boundary (red cells in Fig. 2) the recharge is estimated as 24,800 m^3/d. The next section west of Pyrgos town (green cells in Fig. 2) is considered as a boundary of high recharge which is estimated to be 195,200 m^3/d. After a short section SW of Pyrgos town which is considered as impermeable boundary the next section (blue cells in Fig. 2) up to the Alfeios River is also considered as a boundary of lateral recharge which is estimated to be 88,000 m^3/d. These recharge data were converted to be used with the WELL package of the MODFLOW code, which is applied to assign injection wells to the cells of each column of the above recharge boundary sections. According to the salinity of the groundwater measured in boreholes in the vicinity of the above boundary section, the salt concentration of the water recharging the aquifer was estimated as 0.65 kg/m^3, 0.45 kg/m^3 and 0.40 kg/m^3, respectively. The SE boundary, which is the Alfeios River, was considered as a boundary of constant head varying linearly from 0 m at the estuary to 1 m at a distance of 5 km upstream and then varying also linearly up to 8 m for the next 5 km.

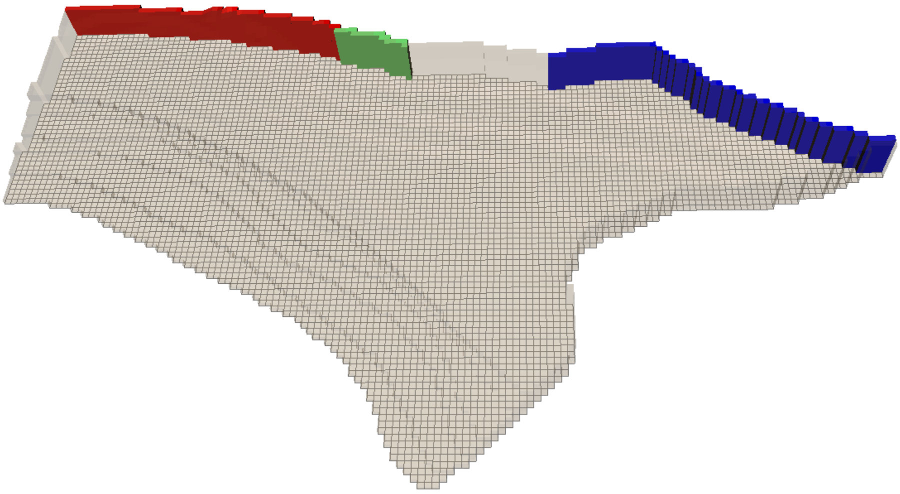

Figure 2. Illustration of the aquifer three-dimensional discretization, the prescribed flux boundaries and the 100 m×100 m grid in the horizontal plane at the bottom of the 6th layer (vertical exaggeration = 30×).

The salt concentration of the Alfeios River water was considered of being 0.27 kg/m^3 according to the measurements of Iliopoulou-Georgoudaki (2003) and Karapanos (2009).

It is also considered that the aquifer is constantly recharged throughout the year due to rainfall infiltration and irrigation water losses which was estimated to be 0.001 m/d. The salt concentration of the recharge water was estimated to be 0.2 kg/m^3.

At the SW boundary, which is the coastline and the sea bottom up to the sea depth of 15 m at approximately 2 km from the coastline, the constant head was set equal to zero because any tide effects were considered negligible and the salt concentration was set to 35 kg/m^3.

In addition the effective porosity is considered as 35%. The longitudinal dispersivity a_L was set equal to 1 m and the ratio of transverse to longitudinal dispersivity was 0.1. For the particular problem the molecular diffusion coefficient for porous media was taken equal to 10^{-4} m^2/d (Schnoor 1996, Batchelor 2000, Oude Essink 2001).

For the simulations which include the functioning of the existing drainage system the DRAIN package of the MODFLOW code was applied to take into account the interaction of groundwater with the main drainage canal and to quantify groundwater discharge towards the drain, which is aligned nearly parallel to the coastline at a distance varying between 450 m and 1,250 m. The discharge is computed assuming that the water level in the canal is maintained lower than the sea level by pumping the excess water to the sea. The drain conductance values required by the DRAIN package were obtained from calibration using the trial and error method. They were adjusted in order to reach a best fit between the computed discharge and the measured discharge from the drainage pumping stations, which is 25,299,000 m^3/year (Georgiadis et al. 1998).

For the simulations which include restoration of the Mouria Lake, the head in the area of the former lake was set equal to the sea level and the salt concentration of the water of the lake was set to 15 kg/m^3 according to the maximum value of salinity measured in the lake before its drainage in the 1960's (Georgiadis et al. 1998).

4 RESULTS OF NUMERICAL SIMULATIONS

Three dimensional numerical modeling of the Pyrgos coastal phreatic aquifer was conducted in order to analyze human interventions which could affect seawater intrusion and the long-term future development of the aquifer area. The following three scenarios were simulated.

i) The simulation of variable-density flow under the existing hydrologic stresses in which the pumped drainage of the aquifer is significant.

ii) The simulation which include the nearly complete restoration of the Mouria Lake to represent the groundwater flow mechanism of the past.

iii) The simulation for the case of restoration of the Mouria Lake in about 57% of its original area which nowadays seems to be the most feasible scenario of the lake restoration.

For all the simulations, the aquifer initially was assumed to be filled with seawater and the water table was assumed to be horizontal throughout the aquifer with its height at the sea level. The aquifer was subject to recharge which caused the rising of the water table height and the flushing of the seawater towards the sea. The simulations were conducted for a time period of 15,000 d. The simulated water table heights agree with the results of the long-term simulations of Karapanos (2009).

In all the three examined scenarios variations in head and concentration were found to be negligible after 5,000 d. At the end of the 15,000 d simulations the computed mass budget shows the following:

a) For the complete restoration of the Mouria Lake it was found that 18% of the aquifer recharge rate is owing to the constant head boundary of the Alfeios River. The aquifer discharges through the constant head boundaries of the beach bottom, the lake bottom and the lower part of the Alfeios River estuary.

b) When part of the Mouria Lake is restored simulation results show that the aquifer recharge rate due to infiltration and irrigation water losses is increased for about 7.3% in the not restored area of the former lake and only slightly (≅1.1%) from the constant head boundary of the Alfeios River. In this case 15.5% of the recharge rate for the entire aquifer is owing to constant head boundary of the Alfeios River.

c) The simulation of the existing situation, with the pumped drainage system in operation, shows that 27% of the aquifer recharge rate is owing to the constant head boundaries, which is 50% higher than the corresponding recharge rate for the complete restoration of the Mouria Lake. This is attributed to the increased hydraulic gradients towards the main drainage canal along the coastline which also enhance intrusion of seawater into the aquifer. It should be noted that in this case aquifer recharge is also increased due to rainfall infiltration and irrigation water losses in the area of the former Mouria Lake. Recharge rate for the entire aquifer was found increased for about 9.5%. Accordingly it was found increased the discharge rate of the aquifer towards the beach bottom and Alfeios River estuary, and towards the main drainage canal. It was found that 24% of the aquifer discharge rate takes place through the pumped drainage system.

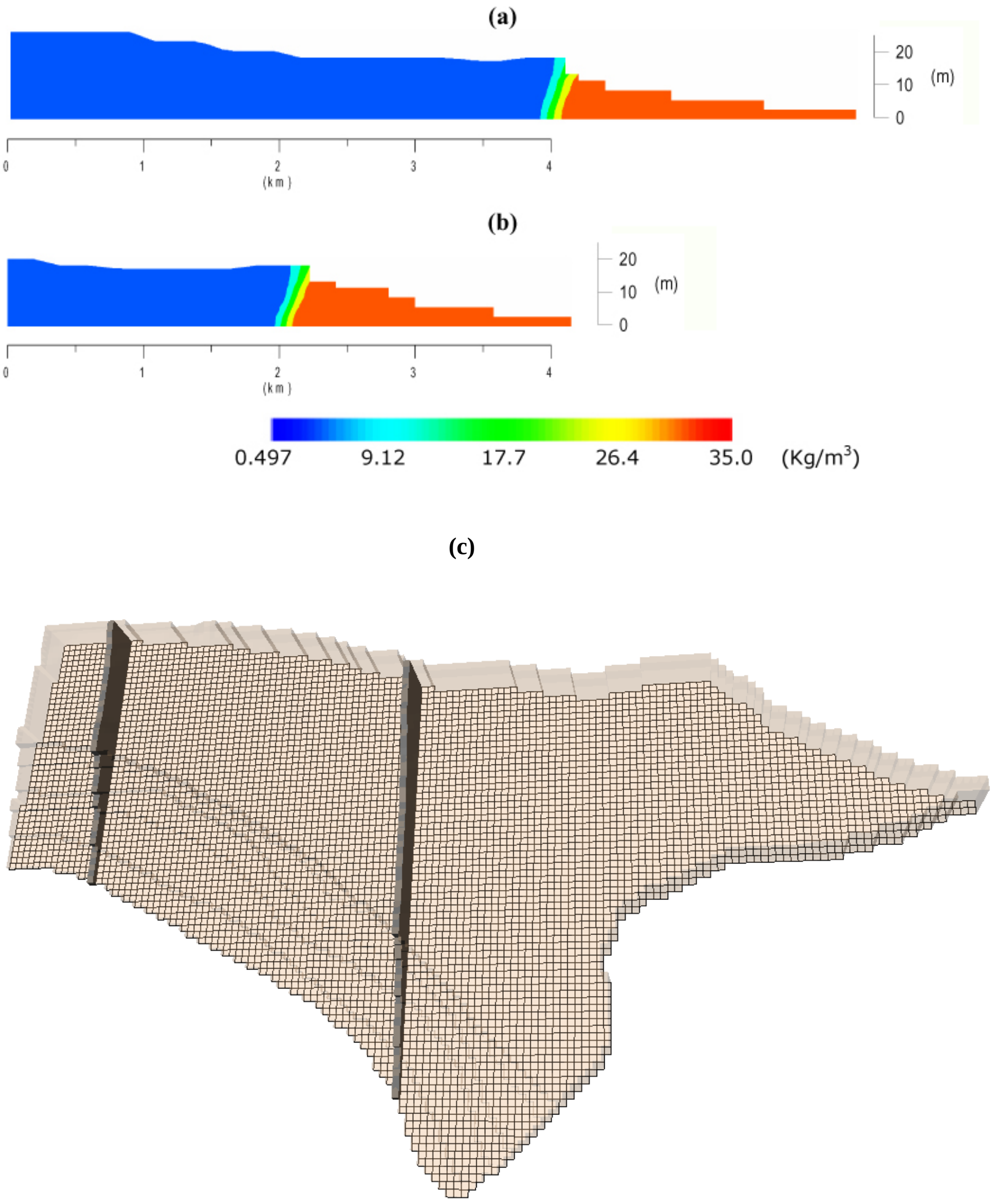

Figure 3. Vertical cross-sections through columns (a) 66 and (b) 16 showing the transition zone as defined by salt concentration after 15,000 d operation of the pumped drainage system and (c) the 16 and 66 columns in the three-dimensional grid.

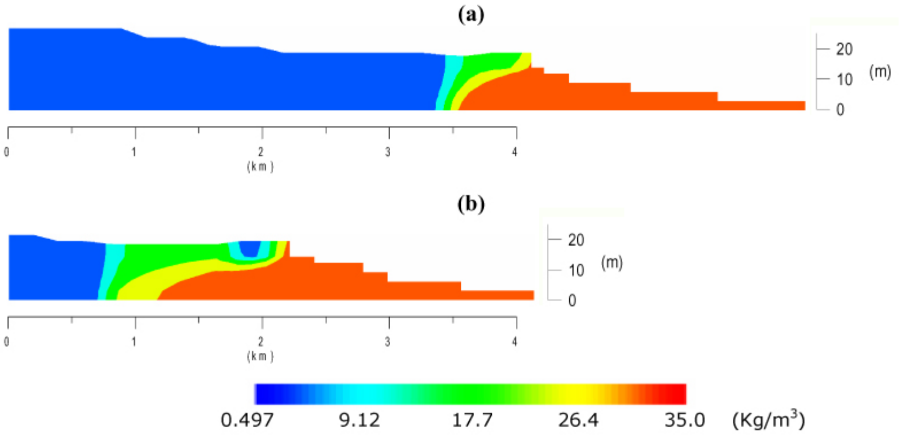

Figure 4. Vertical cross-sections through columns (a) 66 and (b) 16 showing the transition zone as defined by salt concentration after 15,000 d from the complete restoration of the Mouria Lake.

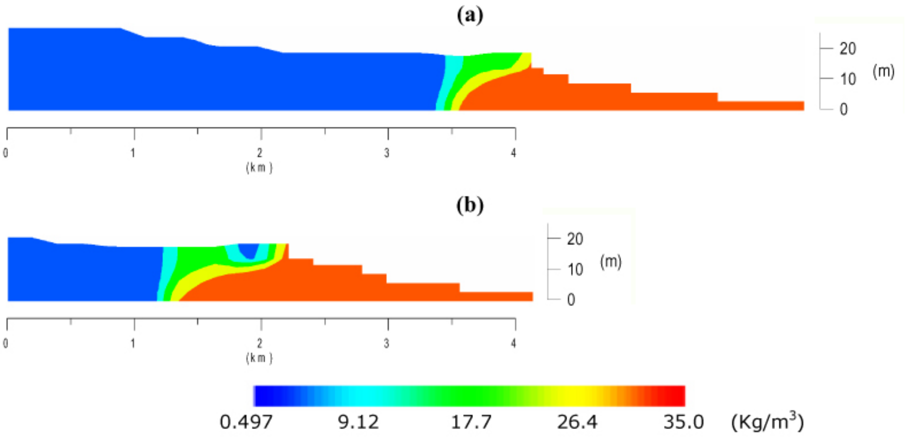

Figure 5. Vertical cross-sections through columns (a) 66 and (b) 16 showing the transition zone as defined by salt concentration after 15,000 d from the restoration of the Mouria Lake in part of its original area.

The simulated seawater intrusion to the aquifer for the three examined scenarios is shown in Figs. 3 through 5. Fig. 3 depicts the seawater intrusion for the first simulated scenario. The advancement of the salt wedge at the bottom of the aquifer and the transition zone underneath the coastline are shown in two vertical cross sections at the end of the simulation. It appears that due to the large amount of recharge mainly from the NE boundary of the aquifer, the seawater intrusion and the transition zone which have a width of about 200 m does not affect the rest of the aquifer. This result is in agreement with field observations of Karapanos (2009) who found low salinity values (<1 kg/m^3) in the vast majority of the observation wells. Figs. 4 and 5 show that large transition zones were formed underneath the area occupied by the restored lake, at the end of the simulation, and in every case are in accordance with the width of the lake in every vertical cross section.

CONCLUSIONS

The SEAWAT code has been used to simulate the mixing of freshwater and seawater in a phreatic aquifer and the development of the transition zone as a result of hydrodynamic dispersion. The simulation results imply that the salt water intrusion at the coastline boundary is restricted to a distance of 200 m, which corresponds to the sand dunes zone. The pumped drainage system removes considerable amount of water with a significant energy consumption, which is approximated to 670 MWh per year. In case of lake restoration the transition zone is restricted underneath the area occupied by the lake and it does not affect the major area of the aquifer. The partly lake restoration was found to be equally effective to the complete lake restoration regarding the salt water intrusion.

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