Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.21550

99 (2017) 49–58
December

Saltwater intrusion management using the SWI2 model: application in the coastal aquifer of Hersonissos, Crete, Greece

Athina Pappa[a,*], Zoi Dokou[b], George P. Karatzas[c]

[a]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands, email: atpappa@hotmail.com*
[b]*Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA, email: zoi.dokou@uconn.edu*
[c]*School of Environmental Engineering, Technical University of Crete, Chania, Greece, email: karatzas@mred.tuc.gr*

Received 20 December 2016; Accepted 25 July 2017

ABSTRACT

This work assesses the effectiveness of different methods of saltwater intrusion management in a coastal aquifer. The study area is Hersonissos, near Heraklion, Crete, Greece, where saltwater intrusion is a significant threat for the sustainability of the local groundwater resources. The saltwater intrusion phenomenon was simulated using the MODFLOW program coupled with the SWI2 package, to calculate the hydraulic heads in the area and to estimate the position of the seawater intrusion front. Various saltwater intrusion management methods were examined such as the artificial recharge of the aquifer with reclaimed wastewater, the optimization of the pumping rates of the supply wells and the extraction of saltwater at locations where the problem is more acute, indicated by the thickness of the intrusion zone. The above management options are evaluated individually and in combination, to assess their relative and joint effect in managing the saltwater intrusion problem in the area.

Keywords: Saltwater intrusion; Coastal aquifer; Groundwater management; Numerical modeling

1. Introduction

Coastal aquifers are important freshwater resources especially in arid or semi-arid regions, where population, economic activity and tourism often concentrate. Crete is the largest island in Greece, with significant influence on the economy that has seen a significant increase in urban and touristic activities, over the past 30 years. As a result, the majority of the population has become concentrated in coastal areas and in many cases the infrastructure required to support this type of economic development is not adequate. Hersonissos, which is the coastal aquifer of interest in this work, is located in the central-northern coast of the island, near Heraklion. Most of the activities and infrastructure in the area, related to tourism, agriculture and industry, are located near the coast and are very water intensive. The main source of water in the region is the coastal aquifer, which is exploited by abstraction wells, exacerbating the naturally occurring saltwater intrusion problem.

The process of saltwater intrusion is a serious problem in many coastal aquifers; therefore, there is a great need for models simulating this phenomenon accurately. Numerical codes have become a powerful tool for the simulation and management of saltwater intrusion [1]. One of the most widely used codes is SEAWAT, which allows the coupled modeling of solute transport and variable-density groundwater flow [2]. The governing equations of flow and solute transport are solved numerically using MODFLOW and MT3D, respectively. SUTRA is another model used for the simulation of saturated–unsaturated, variable-density groundwater flow and solute transport that combines the finite element and the integrated-finite-differences method for the solution of the coupled equations [1]. The FEFLOW

---

* Corresponding author.

Presented at the conference on Efficient and Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016, Chania, Greece, June 1–4, 2016.

model is also a variable-density model that simulates both the saturated and unsaturated zones and provides a finite-element subsurface flow and transport modeling system [3]. Variable-density models, such as those described above are very computationally demanding. An alternative, less computationally expensive way of studying the saltwater intrusion problem without the use of density-variable models is by using the groundwater-modeling program MODFLOW [4] coupled with the SWI2 package [5]. The SWI2 package allows the simulation of three-dimensional, vertically integrated, variable-density flow without the need to discretize the aquifer vertically. It requires fewer model cells, because each aquifer can be represented as a single layer model and, as a result, it requires less computer time and memory for the calculations.

The use of MODFLOW-SWI2 has been limited since it is a relatively new package. It has been coupled with a stochastic inverse model (gradual conditioning method) and applied to simulate the transient movement of the freshwater–seawater interface in a two-aquifer synthetic case study [6]. It has also been used in a few field applications; to establish the chance of the upward movement of saline water in Northern Kenya [7], to examine the effect of climate change on the depth of the freshwater–saltwater interface in Casco Bay, Maine [8], and for studying the saltwater intrusion overshoot based on published parameters from field settings for four aquifers [9].

The management of saltwater intrusion is a challenging process which requires adequate hydrological knowledge, awareness of the local environmental and social conditions and the ability to account for climate change and governmental policies [1]. Common methods of saltwater intrusion management are to reduce coastal evapotranspiration, to reduce freshwater discharge into the sea, to increase aquifer recharge through other sources, like wastewater injection or infiltration through artificial recharge ponds, or to treat part of the saltwater pumped from the aquifer using desalination technologies [10].

Artificial recharge has been proposed by Johnson et al. [11], Asano and Cotruvo [12] and Bouwer [13] in Los Angeles, as a method to inhibit saltwater intrusion. Crook et al. [14] proposed the use of reclaimed wastewater for replenishing groundwater. An alternative solution is the pumping of saltwater from the intrusion zone as proposed by Kacimov et al. [15]. In this method, the saltwater pumping wells are positioned in areas where the problem is more acute, in order to attract the saltwater front toward the sea and away from the freshwater pumping wells located inland, as proposed by Sherif and Hamza [16] for an aquifer in India. Dokou et al. [17] and Karterakis et al. [18] have used an optimization–simulation method to maximize groundwater withdrawal rates while inhibiting the saltwater intrusion front at locations closer to the coast, at Hersonissos aquifer. Similarly, the optimization of pumping rates has been considered in several works for different case studies: for the coastal aquifer of Malia in Crete [19] and for a coastal aquifer in the island of Kalymnos in Greece [20,21].

In this paper, the current extent of saltwater intrusion at the Hersonissos aquifer was simulated using MODFLOW combined with the SWI2 package. Using the calibrated model, management scenarios for controlling saltwater intrusion were proposed and evaluated. These methods include (a) artificially recharging the aquifer with water from the local wastewater treatment plant, (b) extracting saltwater near the coast and (c) optimizing existing pumping rates by using a groundwater management optimization model. The above management options are evaluated individually and in combination, to assess their relative and joint effect in managing the saltwater intrusion problem in the area.

2. The study area

2.1. Area characteristics

The Hersonissos aquifer is located in the northern coast of Heraklion, 25 km from the city of Heraklion in Crete, Greece (Fig. 1). The Hersonissos basin covers an area of about 18 km^2 and stretches for 3.8 km in the W–E direction and for almost 4.7 km in the N–S direction. Hersonissos has about 10,500 permanent residents, engaged mainly in tourist services or agricultural activities. Due to these activities, water demand is high during the summer period, in particular, leading to high pumping rates that cause massive drops of hydraulic heads. As a result, the existing seawater intrusion problem is exacerbated and the sustainability of this coastal aquifer is jeopardized.

2.2. Hydrogeology

The basin is mainly covered by karstified limestones of variable hydraulic conductivity and marls, whereas alluvial deposits of high permeability can be found along the coastal line. The hydraulic conductivities for the main geological formations, specified based on the geological map of the area [22] (Fig. 2), are presented in Table 1.

It was assumed that these geological formations are uniform in the vertical direction of the model. This coastal aquifer is karstified; because of this, its regional conductivity values are difficult to establish and may vary within wide ranges. The hydraulic characteristics of such aquifers are influenced by the extreme values of permeability and by the presence of permeable channels and of extended conduit/cavern networks with unknown spatial distribution. To overcome these difficulties, the karstic system was simplified and modeled as an equivalent porous medium. In this approach, the spatial variations in the hydrogeological properties of the rock mass are averaged over a representative elementary volume in order to define their values at the macroscopic level. It was also assumed that the vertical conductivities are equal to one-tenth of the horizontal by applying an anisotropy factor of 0.1, a typical assumption for groundwater models [23].

2.3. Meteorological data

Hersonissos has a temperate Mediterranean climate with a mean temperature of approximately 19°C. Winters are mild, with January and February being the coldest months. Snowfall is rare and, therefore, not taken into account in this work. Sunshine is vivid all year round, with the warmest months being July and August. The rainy season extends from October to March.

According to the hydrological study of the north of the province of Heraklion [22], about 47% of the study area is permeable and the infiltration rate at these permeable areas

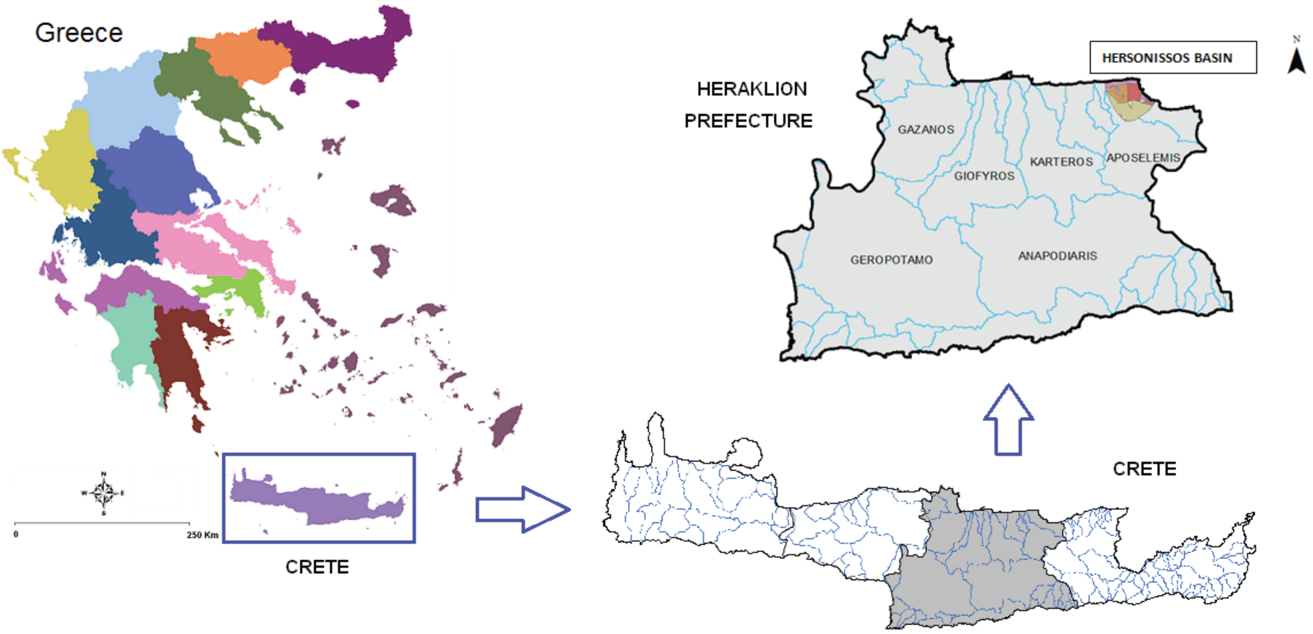

Fig. 1. The island of Crete in Greece and the location of the Hersonissos basin (modified from [17]).

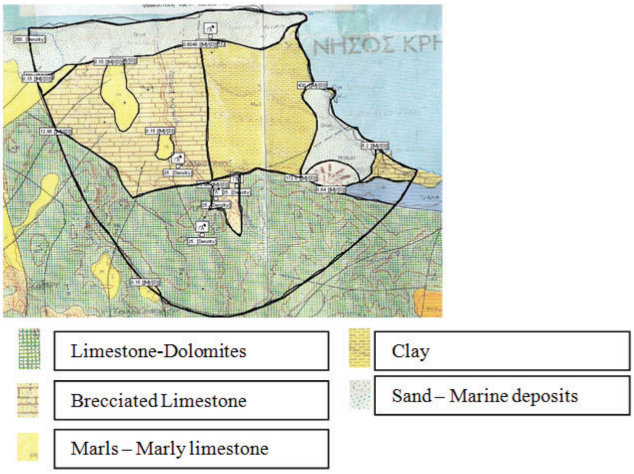

Fig. 2. Geological map of the study area [18,22].

Table 1
Hydraulic conductivities for the geological formations in the study area [22]

Bedrocks	Hydraulic conductivities (m/d)
Limestone–dolomites	12.96
Brecciated limestone	5.2
Marls–Marly limestone	0.15
Clay	0.6048
Sand–marine deposits	430

is about 23%. The semi-permeable areas cover 22% of the study area and the infiltration rate at the semi-permeable areas is 11%. The precipitation rate in the area is 483 mm/year and is considered to be evenly distributed over the model domain. The amount of groundwater recharge for the permeable and semi-permeable areas is calculated as follows: 47% × 23% × 483 mm/year = 52 mm/year for the permeable and 22% × 11% × 483 mm/year = 12 mm/year for the semi-permeable areas. The total recharge is, therefore, estimated to be 52 + 12 = 64 mm/year.

3. Methodology

Simulation models were used in the work for the assessment of possible solutions to the saltwater intrusion problem [24]. As a starting point, a conceptual model was first constructed and then solved by using numerical modeling [25]. The processing of the model data was performed by using mfLab [25,26], an open-source environment that enables the interface of the groundwater modeling code of MODFLOW with Matlab.

3.1. The MODFLOW program

MODFLOW is a freely available United States Geological Survey modular three-dimensional finite difference groundwater-flow code, which is used worldwide for providing numerical solutions to the partial differential equation of groundwater flow. The study area is discretized into a grid of rectangular blocks and the solution of the equations follows directly from each block's mass balance and Darcy's law. Using this block-centered finite differences model, the computation of the hydraulic heads is performed at the centre of each block or cell, while the flows are computed at the block interfaces [4].

MODFLOW solves the partial differential equation that describes the movement of water in the subsurface by using finite differences:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \tag{1}$$

where K_{xx}, K_{yy}, K_{zz} (L/T) are the values of hydraulic conductivity along the x, y, z coordinate axes, h (L) is the potentiometric head, W (T^{-1}) is the volumetric flux per unit volume representing sources and sinks of water, with $W < 0$ for flow out of the groundwater system and $W > 0$ for flow into the system, S_s (L^{-1}) is the specific storage of the porous material and t (T) is the time [4].

3.2. Seawater intrusion package for MODFLOW

The seawater intrusion (SWI2) package for MODFLOW 2005 allows for the simulation of vertically integrated, variable-density groundwater flow and seawater intrusion estimation. The main advantage of using SWI2 is the significantly reduced computational time, compared with models that couple variable-density flow and contaminant transport. SWI2 adopts the Dupuit approximation (resistance to vertical flow is neglected and there is no vertical head gradient) and is able to simulate multiple aquifers; each aquifer (represented as a single layer model) is discretized vertically into zones having different densities. As a result, numerical simulations using the SWI2 package require far fewer cells than dispersive solute transport simulations [5].

A simplified derivation of the horizontal, vertically integrated, variable-density groundwater flow is presented here for the calculation of the flow in specific zones, assuming an aquifer with a horizontal top and bottom, which contains two fluids of different density at zone 1 and zone 2 (Fig. 3). In order to find the discharge (Q_1) for zone 1 between the two observation wells, a and b, shown in Fig. 3, the following equation is used:

$$Q_1 = -K\bar{b}_1 dy\frac{(h_b - h_a)}{dx} \tag{2}$$

where $\bar{b}_1$ is the average thickness of zone 1 between wells a and b (L), dy is the aquifer width vertical to flow, h_b is the freshwater head at the top of the aquifer at well b (L), h_a is the freshwater head at the top of the aquifer at well a (L) and dx is $x_b - x_a$ (L).

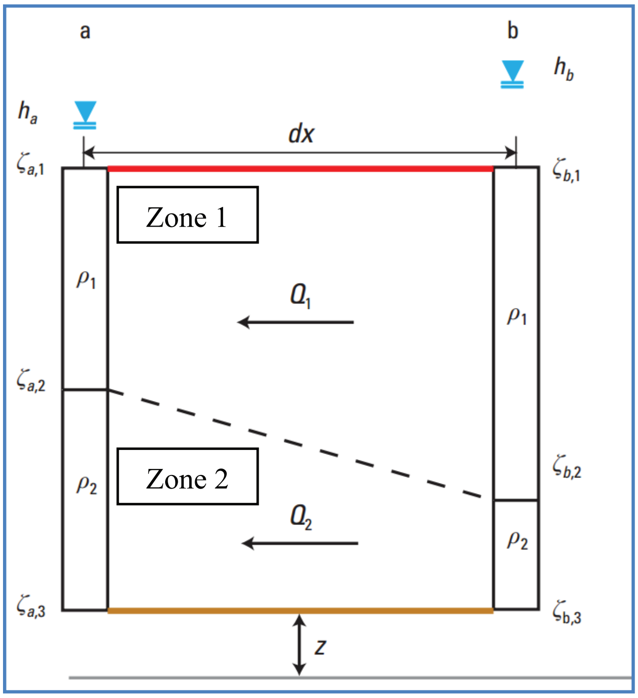

Fig. 3. Horizontal aquifer with two zones (zones 1 and 2) between wells a and b [5].

Similarly, the discharge between the two wells for zone 2 is:

$$Q_2 = -K\bar{b}_2 dy\frac{\left(\hat{h}_{b,2}-\hat{h}_{a,2}\right)}{dx} \tag{3}$$

where $\bar{b}_2$ is the average thickness of zone 2 between wells a and b (L), $\hat{h}_{b,2}$ is the calculated freshwater head at zone 2 at well b (L) and $\hat{h}_{a,2}$ is the calculated freshwater head at zone 2 at well a (L).

To calculate the average freshwater head for zone 2 at well b ($\hat{h}_{b,2}$) the following equation can be used:

$$h_f(x,y,z) = h(x,y) + \int_z^{\zeta_1} \nu(z,y,z')dz' \tag{4}$$

where ν is the dimensionless density, $\nu = \frac{\rho+\rho_f}{\rho_f}$ with ρ representing the fluid density (M/L^3) and ρ_f is the density of freshwater (M/L^3) and ζ_n representing the elevation of the interface (L) at the top of zone n.

Based on the above, the average freshwater head for zone 2 at well b is given by:

$$\hat{h}_{b,2} = h_b + \nu_1\left(\zeta_{b,1}-\zeta_{b,2}\right)+\frac{1}{2}\nu_2\left(\zeta_{b,2}-\zeta_{b,3}\right) \tag{5}$$

Also, for calculating the average freshwater head for zone 2 at well a, $\hat{h}_{a,2}$:

$$\hat{h}_{a,2} = h_a + \nu_1\left(\zeta_{a,1}-\zeta_{a,2}\right)+\frac{1}{2}\nu_2\left(\zeta_{a,2}-\zeta_{a,3}\right) \tag{6}$$

The calculated average freshwater heads in zone 2 at the two wells refer to the vertical midpoint of that zone, and as a result the $\hat{h}_{a,2}$ and $\hat{h}_{b,2}$ differ at elevations at the two wells. This poses the risk of having nonzero discharge at no-flow conditions. To avoid this risk, the heads need to be adjusted to the same vertical elevation (datum) by modifying Eq. (4). In addition, hydrostatic conditions are assumed within the entire aquifer. This results in Eq. (7):

$$\hat{h}_{w,2} = \bar{h}_{w,2} + \nu_2\left(z_{w,2}-z_0\right) \tag{7}$$

where $\bar{h}_{w,2}$ is the average freshwater head at zone 2 at well a or b (L), $z_{w,2}$ is the elevation of the vertical midpoint of zone 2 at well a or b (L) and z_0 is an arbitrary datum (L).

This arbitrary datum, z_0, can take any value. In case $z_0 = 0$, Eq. (5) reduces to:

$$\hat{h}_{b,2} = h_b + \nu_1\left(\zeta_{b,1} - \zeta_{b,2}\right) + \frac{1}{2}\nu_2\left(\zeta_{b,2} - \zeta_{b,3}\right) + \frac{1}{2}\nu_2\left(\zeta_{b,2} + \zeta_{b,3}\right) \quad (8)$$

or more simply:

$$\hat{h}_{b,2} = h_b + \nu_1\left(\zeta_{b,1} - \zeta_{b,2}\right) + \nu_2\zeta_{b,2} \quad (9)$$

Similarly, Eq. (6) can be written as:

$$\hat{h}_{a,2} = h_a + \nu_1\left(\zeta_{a,1} - \zeta_{a,2}\right) + \nu_2\zeta_{a,2} \quad (10)$$

Combining Eqs. (2), (3), (9) and (10), the total discharge of the aquifer shown in Fig. 3 can be written as:

$$\begin{aligned} Q = Q_1 + Q_2 &= -K\bar{b}\mathrm{d}y\frac{(h_b - h_a)}{\mathrm{d}x} \\ &- K\bar{b}_2\mathrm{d}y\frac{\left\lfloor \nu_1\left(\zeta_{b,1} - \zeta_{a,1}\right) - \nu_1\left(\zeta_{b,2} - \zeta_{a,2}\right) + \nu_2\left(\zeta_{b,2} - \zeta_{a,2}\right)\right\rfloor}{\mathrm{d}x} \end{aligned} \quad (11)$$

where $\bar{b}$ is the average thickness of the aquifer between wells a and b and

$$R = -K\bar{b}_2\mathrm{d}y\frac{\left\lfloor \nu_1\left(\zeta_{b,1} - \zeta_{a,1}\right) - \nu_1\left(\zeta_{b,2} - \zeta_{a,2}\right) + \nu_2\left(\zeta_{b,2} - \zeta_{a,2}\right)\right\rfloor}{\mathrm{d}x} \quad (12)$$

where R stands for the pseudo-source term.

So, the implementation of SWI2 at this coastal aquifer is based on the computation of the surface elevation values (ζ) [5].

3.3. The groundwater management model

The groundwater management (GWM) model is a tool for groundwater management used in combination with MODFLOW. The GWM model uses the response matrix approach in order to solve different types of linear, nonlinear and mixed-binary linear groundwater management problems. Each problem consists of decision variables, an objective function and constraints [27].

By using GWM it is possible to find the optimal pumping rates at current extraction wells, for which the saltwater intrusion front will retreat at a certain location, while meeting at least part of the irrigation and drinking water needs of the region. For unconfined aquifers, the optimization problem of determining the optimal pumping rates is nonlinear, due to the nonlinear change of the hydraulic head in response to pumping. This kind of problems can be solved using a sequential linearization approach. More specifically, GWM solves the nonlinear problem by repeated linearization of the nonlinear features of the management problem, where response coefficients are recalculated at each iteration. The first-order Taylor series expansion for hydraulic head is assumed to be accurate for each sequential linear program, but in contrast to the linear case, the vector of base flow rates changes at each iteration [27].

The sequential process is repeated until two convergence criteria are met: (a) the change in flow rate values from the prior iteration to the current iteration becomes less than a fraction of the magnitude of the flow rate at the current iteration and (b) the change in the objective function value becomes less than a specified fraction of the magnitude of the objective function value.

The solution is based on the simplex algorithm and the mathematical expression of the optimization problem is given by:

$$\begin{aligned} &\max \sum Q_i \\ &\text{s.t.} \\ &h_j \geq h_{\min} \\ &Q_i \leq Q_{i\max} \\ &Q_i \geq 0 \end{aligned} \quad (13)$$

where Q_i represents the pumping rate at well i, h_j is the hydraulic head at a control point j and $h_{\min}$ is the minimum hydraulic head needed to avoid saltwater intrusion, i is the number of pumping wells and j the number of constraint locations (control points) representing the saltwater intrusion front. The upper limit on well pumping rate, $Q_{i\max}$, is set equal to the currently used one for every well, representing the maximum capacity of the well.

4. Results

In order to compute the saltwater intrusion in the study area, the existing abstraction wells must be taken into account [28]. The locations of these active wells, which belong to the municipality of Hersonissos, are presented in Fig. 4 and their pumping rates are given in Table 2.

The elevation of the saltwater zone interface above the model bottom is shown in Fig. 5.

Due to the abstraction, saltwater is clearly attracted inland, reaching the water supply wells. As a result, the extracted water is a mixture of freshwater and saltwater, with the salinity varying from well to well, depending on the distance from the sea, the geology of the area and the local natural recharge.

Given the nature of seawater intrusion, the management of a coastal aquifer involves the decision of an acceptable ultimate landward extent of the seawater front and the calculation of the amount of freshwater discharge necessary to keep it in that location. The risk of seawater intrusion clearly limits the extent to which a coastal aquifer can be used for water supply, but the amount of extracted water can be increased by using an optimal management scheme. To this end, various management scenarios and their impact on the amount of water that can be safely extracted from the aquifer are presented in the following sections.

4.1. Scenario 1: injection of treated wastewater

One of the techniques used to counteract saltwater intrusion is the replenishment of the aquifer using injection wells. For this scenario, it is assumed that the replenishment is performed with treated effluent from the local wastewater treatment plant [12–14]. Such injection wells should be placed as far as possible from the extraction wells, in order to maximize the flow path and prolong the residence time of the recharged water. This would allow the adequate breakdown of pathogens and toxic substances and the dilution by mixing of the recharged water with the freshwater of the aquifer [12]. However, due to the karstic nature of the aquifer, shortcuts may occur and travel times cannot be easily predicted. So, the applicability of the idea of using injection wells with treated wastewater needs to be adequately tested in the field and extensive monitoring should be performed in order to check if the recovered water can meet the quality standards of Greek legislation.

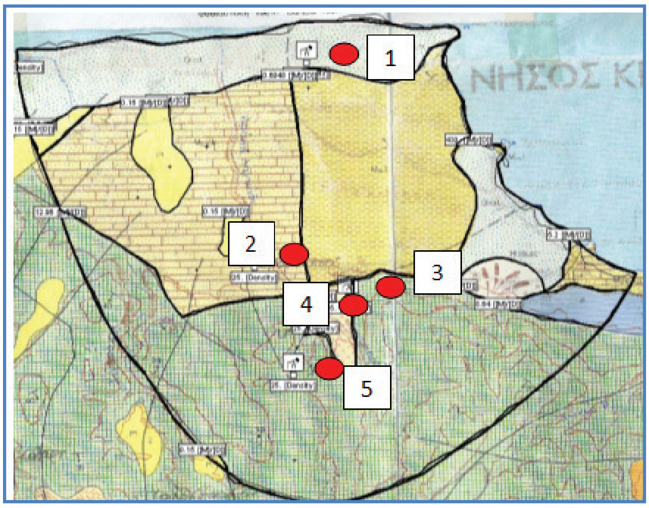

Fig. 4. Locations of abstracting wells [22].

Table 2
Pumping capacities of abstracting wells active in the area [22]

Well	Pumping rates (m^3/d)
1	1,800
2	2,520
3	576
4	520
5	146

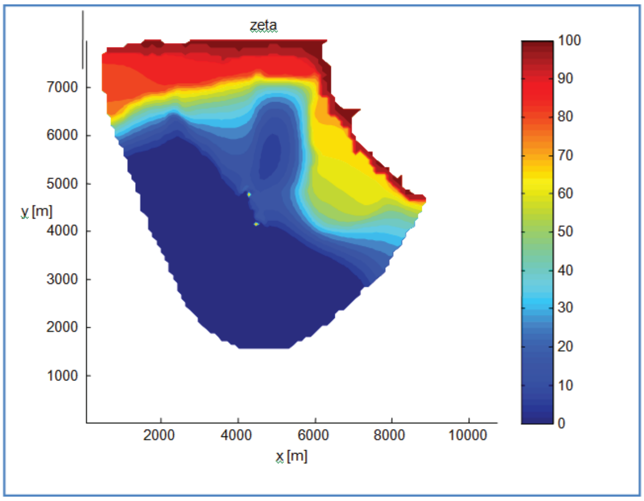

Fig. 5. The elevation of the saltwater zone interface above the model bottom with active abstracting wells [29].

The wastewater treatment plant at Hersonissos has a capacity of 500 to 3,400 m^3/d, currently used for irrigation and fire protection purposes. It is assumed that 1,000 m^3/d of treated water, that can be stored, will be available for injection [30], which corresponds to 1,000 m^3/d × 365 d/year = 365,000 m^3/year. The rest of the effluent will be used for irrigation and fire protection.

Since there is no information about the specific use of this water, the replenishment of the aquifer with water from the treatment plant will only be examined as a potential scenario. However, the model can be used to study the extent to which saltwater intrusion is hindered by injecting 1,000 m^3/d of water, using a single well located close to the coast in the eastern part of the aquifer. Results for this scenario are shown in Fig. 6(b) [29]. A significant reduction of the saltwater intrusion zone due to the injection of water can be observed. The saltwater zone was reduced from about 60 to 40 m near the injection well, especially in areas with low hydraulic conductivity.

4.2. Scenario 2: saltwater extraction

Another method for hindering saltwater intrusion is the use of wells for extracting saltwater from the aquifer [15,16]. In this scenario, the existing pumping wells were kept operating at their current capacities. The saltwater was pumped from the aquifer using five wells located in the northern part of the study area where the intrusion problem is most severe. An extraction capacity of 1,000 m^3/d was considered for every well [29]. The results for this scenario are shown in Fig. 6(c).

The use of these saltwater extraction wells inhibits the intrusion in the north (coast) and reduces the intrusion zone up to a maximum of 20 m. This methodology could be further investigated by determining the optimal number, as well as placement, of the extraction wells by using optimization algorithms.

4.3. Scenario 3: optimized pumping rates

The optimization of the initial pumping rates was chosen as another method for alleviating the saltwater intrusion problem. The GWM software was chosen for determining the optimal rates required to retract the saltwater intrusion front to the specific position marked with a red line in Fig. 7 [17]. Since the Hersonissos aquifer has a depth of 100 m, the critical hydraulic head value for preventing saltwater intrusion is 102.5 m, based on the Ghyben–Herzberg approach.

The calculated pumping rates for hindering saltwater intrusion at the chosen location depicted in Fig. 7 are presented in Table 3.

The purpose of this optimization is to increase the hydraulic head at the saltwater intrusion front to values above a specific threshold. By taking a closer look at Fig. 7, it is clear that pumping well 1 is located far from the intrusion

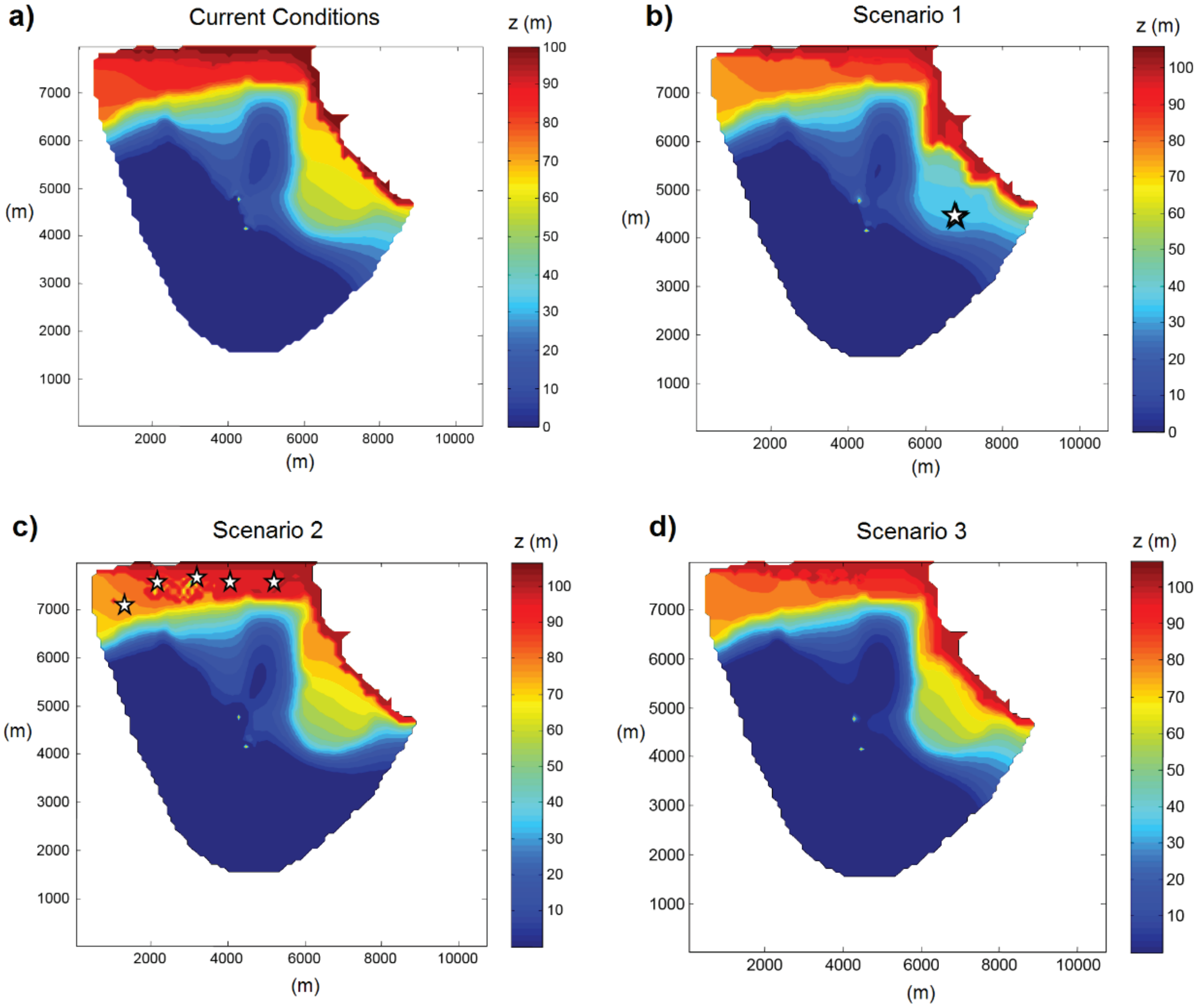

Fig. 6. Seawater intrusion zone under (a) current pumping conditions; (b) scenario 1: water injection (recharge well marked by an asterisk); (c) scenario 2: saltwater extraction in the northern part of the area (extraction wells marked by asterisks) and (d) scenario 3: using optimal (reduced) pumping rates [29].

front. Therefore, it is not surprising that its pumping rate is not reduced after applying the optimization. Although well 1 affects the saltwater intrusion phenomenon in the study area, it does not directly influence the retraction of the saltwater front that has already reached the wells located inland. However, it is important to note that the quality of the water pumped from this well would be very low, with salinity levels over the desirable limits for drinking or irrigation purposes, making its use questionable.

The results for scenario 3 are shown in Fig. 6(d). By applying these optimized pumping rates at the existing wells, the saltwater intrusion problem is alleviated in the northern and northeastern coastal parts of the study area. With this method, the saltwater intrusion front retracts almost 500 m away from the pumping wells located in the central part of the study area and a 10% reduction of the saltwater interface elevation is achieved at locations near the coast.

4.4. Scenario 4: combination of solutions

Various combinations of the previous methods were also considered in order to test their cumulative effect on saltwater intrusion. The results for the combination of the methods applied in scenarios 1 and 2 – one well injecting reclaimed wastewater and five wells pumping saltwater – are shown in Fig. 8(b). By combining these two methods, a 20% decrease in the depth of the intrusion zone was achieved in the northern part of the study area. A significant improvement is observed in the eastern part of the study area, where the injection well is located, where the thickness of the intrusion zone was reduced from about 60–70 to 40 m.

Results for the combination of the methods applied in scenarios 1 and 3 – one injection well and optimized pumping rates for existing wells – are presented in Fig. 8(c). In this case, the elimination of the intrusion zone in areas close to the pumping wells located inland is significant, since, the toe has

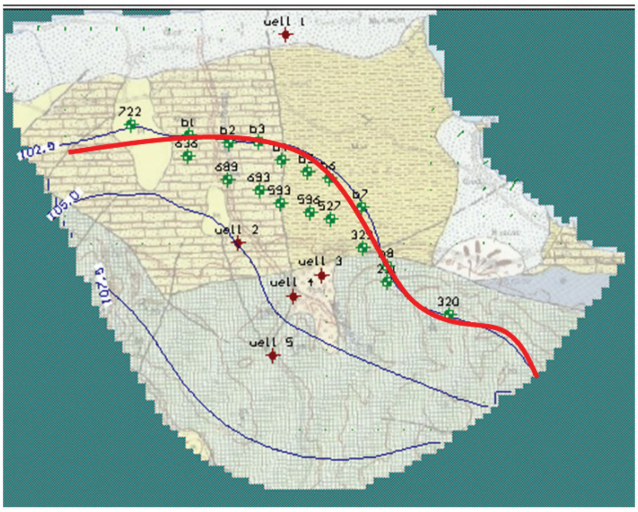

Fig. 7. Saltwater intrusion toe position (red line) for optimized pumping capacities.

Table 3
Optimized pumping rates [17]

Pumping well	Initial pumping rates (m^3/d)	Calculated pumping rates using GWM (m^3/d)	Pumping reduction percentage (%)
1	1,800	1,800	0
2	2,520	42	98
3	576	576	0
4	2,520	2,520	0
5	146	146	0
ΣQ_i	7,562	5,084	33

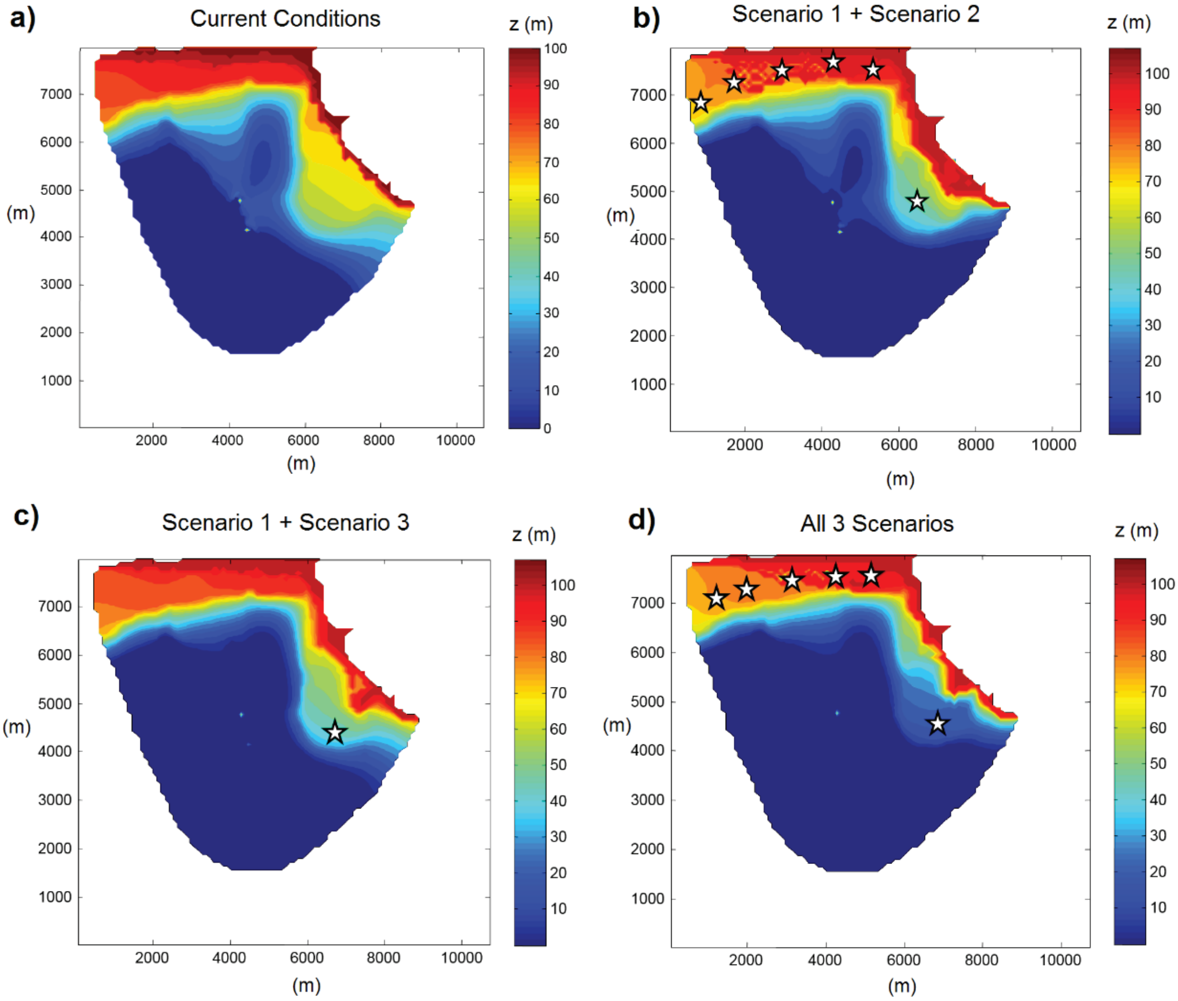

Fig. 8. Seawater intrusion zone under (a) current conditions, (b) the combination of the methods in scenarios 1 and 2, (c) the combination of the methods in scenarios 1 and 3 and (d) the combination of all three methods.

been moved about 1 km away from the wells located in the central part of the study area. An improvement of approximately 30% is observed in the eastern part. However, in the northern part where the problem is more acute, the problem of saltwater intrusion does not change significantly, a mere reduction of about 10% of the saltwater interface elevation is achieved.

The simultaneous application of all three methods considered in scenarios 1, 2 and 3 yielded significantly improved results as shown in Fig. 8(d). The front of the intrusion zone is pushed away from the wells by about 1.5 km and the thickness of the zone decreases by almost 80% in the eastern part. The problem remains more pronounced in the northern part, where a decline of about 20% is achieved in the saltwater interface elevation. Therefore, by implementing a combination of the above methodologies, the saltwater intrusion front is restricted to locations closer to the coast and the water quality of the inland wells can be protected.

5. Conclusions

The exploitation of water from the existing pumping wells in the area of Hersonissos in Crete exacerbates the natural phenomenon of saltwater intrusion, thereby deteriorating the quality of the abstracted water and jeopardizing the sustainability of this coastal aquifer. The modeling of the saltwater intrusion phenomenon performed here, demonstrated that the seawater intrusion front is approaching existing water supply wells and has already reached at least some of them. By adopting a "business as usual" approach, the problem will aggravate, with saltwater intrusion spreading further inland over time. Different counteraction methods were tested through simulations. The injection of treated wastewater for the replenishment of the aquifer would improve the situation. However, with this method, the quality of the effluent and its subsurface changes and the breakdown of pathogens are issues that must be addressed.

The estimation of the maximum freshwater amount that can be safely extracted from this vulnerable aquifer is of great importance. For this reason, the method of optimizing the existing pumping rates was applied. It is a low cost method, since it only requires adapting existing capacities to the calculated optimal ones, but limiting the freshwater amounts available to the public cannot be adopted without ensuring alternative freshwater resources. Its main benefit is the immediate application of the new pumping rates, but also the possibility of their adjustment according to local needs. However, the fact that the capacity of one well in the study area must drop dramatically, by almost 98%, may raise social objection, and therefore, could be deemed infeasible, if no additional water supply is secured.

Another promising method of alleviating the seawater intrusion problem is the extraction of saltwater from specific locations near the coast. This method requires drilling new wells, an action associated with installation and operating costs, but does not require changes in the present freshwater pumping regime of the area, making it a more attractive solution.

The combination of the three methods can provide a significant improvement of the results by hindering the intrusion front toward the coast and away from the inland wells. However, further research is also necessary with respect to the hydraulic properties of this karstic aquifer, in order to reduce the uncertainty of the model results.

References

[1] A.D. Werner, M. Bakker, V.E. Post, A. Vandenbohede, C. Lu, B. Ataie-Ashtian, C.T. Simmons, D.A. Barry, Seawater intrusion processes, investigation and management: recent advances and future challenges, Adv. Water Resour., 51 (2013) 3–26.

[2] W. Guo, C.D. Langevin, User's Guide to SEAWAT: A Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow, Water Resources Investigations Report, United States Geological Survey 6, 2002.

[3] M.G. Trefry, C. Muffels, FEFLOW: a finite-element ground water flow and transport modeling tool, Ground Water, 45 (2007) 525–528.

[4] A.W. Harbaugh, MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—The Ground-Water Flow Process, US Department of the Interior, US Geological Survey, Reston, VA, USA, 2005.

[5] M. Bakker, F. Schaars, J.D. Hughes, C.D. Langevin, A.M. Dausman, Documentation of the Seawater Intrusion (SWI2) Package for MODFLOW, US Geological Survey Techniques and Methods, Book 6, Chapter A46, 2013, 47 p.

[6] C. Llopis-Albert, J.M. Merigó, Y. Xu, A coupled stochastic inverse/sharp interface seawater intrusion approach for coastal aquifers underground water parameter uncertainty, J. Hydrol., 540 (2016) 774–783.

[7] E. Luedeling, A.L. Oord, B. Kiteme, S. Ogalleh, M. Malesu, K.D. Shepherd, J. De Leeuw, Fresh groundwater for Wajir—ex-ante assessment of uncertain benefits for multiple stakeholders in a water supply project in Northern Kenya, Front. Environ. Sci., 3 (2015) 16.

[8] M. Guiang, M.R. Allen, Increased Risk of Groundwater Contamination due to Saltwater Intrusion Driven by Climate Change in Casco Bay, Maine, Oak Ridge National Laboratory, TN, Oak Ridge, 2014.

[9] L.K. Morgan, M. Bakker, A.D. Werner, Occurrence of seawater intrusion overshoot, Water Resour. Res., 51 (2015) 1989–1999.

[10] G.H.O. Essink, Improving fresh groundwater supply—problems and solutions, Ocean Coastal Manage., 44 (2001) 429–449.

[11] T. Johnson, E. Reichard, M. Land, S. Crawford, Monitoring, Modelling, and Managing Saltwater Intrusion, Central and West Coast Groundwater Basins, Los Angeles County, California, First International Conference on Saltwater Intrusion and Coastal Aquifers—Monitoring, Modelling, and Management, Essaouira, Morocco, 2001.

[12] T. Asano, J.A. Cotruvo, Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations, Water Res., 38 (2004) 1941–1951.

[13] H. Bouwer, Artificial recharge of groundwater: hydrogeology and engineering, Hydrogeol. J., 10 (2002) 121–142.

[14] J. Crook, T. Asano, M.H. Nellor, Groundwater recharge with reclaimed water in California, Water Environ. Technol., 2 (1990) 42–49.

[15] A.R. Kacimov, M.M. Sherif, J.S. Perret, A. Al-Mushikhi, Control of sea-water intrusion by salt-water pumping: coast of Oman, Hydrogeol. J., 17 (2009) 541–558.

[16] M.M. Sherif, K.I. Hamza, Mitigation of seawater intrusion by pumping brackish water, Transp. Porous Media, 43 (2001) 29–44.

[17] Z. Dokou, M. Dettoraki, G.P. Karatzas, E.A. Varouchakis, A. Pappa, Utilizing successive linearization optimization to control the saltwater intrusion phenomenon in unconfined coastal aquifers in Crete, Greece, Environ. Model. Assess., 22 (2017) 115–128.

[18] S.M. Karterakis, G.P. Karatzas, I.K. Nikolos, M.P. Papadopoulou, Application of linear programming and differential evolutionary optimization methodologies for the solution of coastal subsurface water management problems subject to environmental criteria, J. Hydrol., 342 (2007) 270–282.

[19] G.P. Karatzas, Z. Dokou, Optimal management of saltwater intrusion in the coastal aquifer of Malia, Crete (Greece), using particle swarm optimization, Hydrogeol. J., 23 (2015) 1181–1194.

[20] I. Athanasakis, Z. Dokou, E. Mathioudakis, P. Stratis, N. Vilanakis, Combining stochastic optimization and numerical methods-software for the pumping management of coastal aquifers: case study of a rectangular homogeneous aquifer, Int. J. Math. Models Methods Appl. Sci., 9 (2015) 727–732.

[21] A. Mantoglou, Pumping management of coastal aquifers using analytical models of saltwater intrusion, Water Resour. Res., 39 (2003).

[22] Hydrogeological Study of Northern Heraklion, Project of Ministry of Infrastructure, Institute of Geology and Mineral Exploration, Crete Branch, 1996.

[23] M.P. Papadopoulou, E.A. Varouchakis, G.P. Karatzas, A Study of the Complex Karstification Phenomenon in Nature: An Analysis of the Flow in a Fractured Medium in Crete, Proc. 10th International Conference on Environmental Science and Technology, Kos Island, Greece, 2007.

[24] L.F. Konikow, Use of Numerical Models to Simulate Groundwater Flow and Transport, US Geological Survey, 1996.

[25] T.N. Olsthoorn, User Guide for mfLab, 2013.

[26] T.N. Olsthoorn, mfLab Code, 2013, Available at: https://sourceforge.net/projects/mflab/

[27] D.P. Ahlfeld, P.M. Barlow, A.E. Mulligan, GWM—A Groundwater-Management Process for the U.S. Geological Survey Modular Ground-Water Model (MODFLOW-2000), US Department of the Interior, US Geological Survey, 2005.

[28] N.N. Kourgialas, Z. Dokou, G.P. Karatzas, G. Panagopoulos, P. Soupios, A. Vafidis, E. Manoutsoglou, M. Schafmeister, Saltwater intrusion in an irrigated agricultural area: combining density-dependent modeling and geophysical methods, Environ. Earth Sci., 75 (2016) 1–13.

[29] A. Pappa, T.N. Olsthoorn, Z. Dokou, G.P. Karatzas, Simulation and Management of Saltwater Intrusion at a Coastal Aquifer in Crete, Greece, Second EWaS International Conference, Chania, Crete, Greece, 2016.

[30] K.P. Tsagarakis, G.E. Dialynas, A.N. Angelakis, Water resources management in Crete (Greece) including water recycling and reuse and proposed quality criteria, Agric. Water Manage., 66 (2004) 35–47.