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Using groundwater flow simulation of the Chania Plain area to propose a proper irrigation plan

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Abstract: The objective of this work was the simulation of groundwater flow at the aquifer of the Chania plain area in Crete, Greece. This area is dominated by irrigated olive and citrus trees with high water demands during the dry period. In the present study, the three-dimensional Princeton Transport Code (PTC) model was employed in combination with the pre-post processor model ArgusOne, which has been developed specifically to simulate groundwater flow and solute transport. PTC employs a unique splitting algorithm for solving the fully three-dimensional equations, which significantly reduces the computational burden. For the model calibration, a simulation time of two years (1998 - 2000) was considered. The model was calibrated using hydraulic head data. In order to quantify the accuracy of the calibration process, a statistical analysis was performed between the simulation results and the corresponding groundwater field data. In addition, for the study area, the irrigation needs in a yearly basis were estimated based on a common irrigation amount for olive and citrus trees (period between May to September). Finally, using the simulation results the effects of saltwater intrusion are discussed and a proper irrigation plan is proposed based on crop requirements.

Key words: groundwater flow; irrigation wells; PTC model

1. INTRODUCTION

Aquifers are the primary source of freshwater for both human needs and crop production. For the majority of the agricultural production areas, groundwater is remaining the ultimate source of freshwater, since it is generally less prone to pollution compared to surface water. Aquifers are constantly recharged by rainwater seepage and continuously feed reservoirs (Siebert et al., 2010).

The water resources around the world are under increasing pressure due to the rapid population and economic growth. As a result of the continuous increase in the water demand for human and agricultural needs, an accurate mapping and characterization of the aquifers is necessary. For an accurate aquifer characterization and simulation, an extensive analysis is needed with field-testing and data gathering.

The application of finite difference and finite element methods to groundwater flow equations has allowed complex and real world systems to be simulated (Bear and Verrujit, 2012). Numerical simulation models have provided a framework for conceptualizing and evaluating aquifer systems (Gorelick, 1983). Various numerical models have been developed for groundwater simulations, such as the Finite Element subsurface FLOW system (FEFLOW) (Diersch, 2005), the Groundwater Modeling System (GMS) (Xiaobin, 2003) and USGS MODular groundwater Flow model MODFLOW (McDonald and Harbaugh, 1988), etc.

In the present study, the well-known Princeton Transport Code (PTC), a groundwater flow and contaminant transport simulator (Babu et al., 2002), was used to simulate the dynamics of a freshwater coastal aquifer located at the Chania Plain. The simulation of groundwater resources leads to effective irrigation management plans that can enhance the agricultural productivity especially in small Mediterranean agricultural watersheds (Kourgialas et al., 2015).

2. STUDY AREA

The study area is the Chania Plain domain, located in the Chania Prefecture in western Crete, Greece. The study area extends from the White Mountains (Lefka Ori) to the coastline, including the city of Chania and the river basins of Tavronitis and Keritis, with coordinates 35.4° to 35.5° North latitude and 23.8° to 24.1° East longitude. The coastline of the Chania Prefecture is over 350 km long and the study area has a total catchment of 2320 km^2 (Figure 1). Agriculture is a significant part of the area's economy, and agricultural land occupies a large portion of the area (600 km^2) from which 105 km^2 are considered as irrigation land (Nikolaidis and Karatzas, 2010). The climate is sub-humid Mediterranean with humid and relatively cold winters and dry and warm summers. The average annual precipitation is about 665 mm of which over 95% occurs between October and May (Chartzoulakis et al., 2001).

The main geological formations in the study area, are classified based on their permeability (Figure 1) (Nikolaidis and Karatzas, 2010):

- Granular non-alluvial deposits of small to very small permeability (P3)
- Granular alluvial deposits of ranging permeability (P1)
- Miocene deposits of moderate to low permeability (P2)
- Karstic formations of high to moderate permeability (K1)
- Impermeable formations of small to very low permeability (A1 & A2)

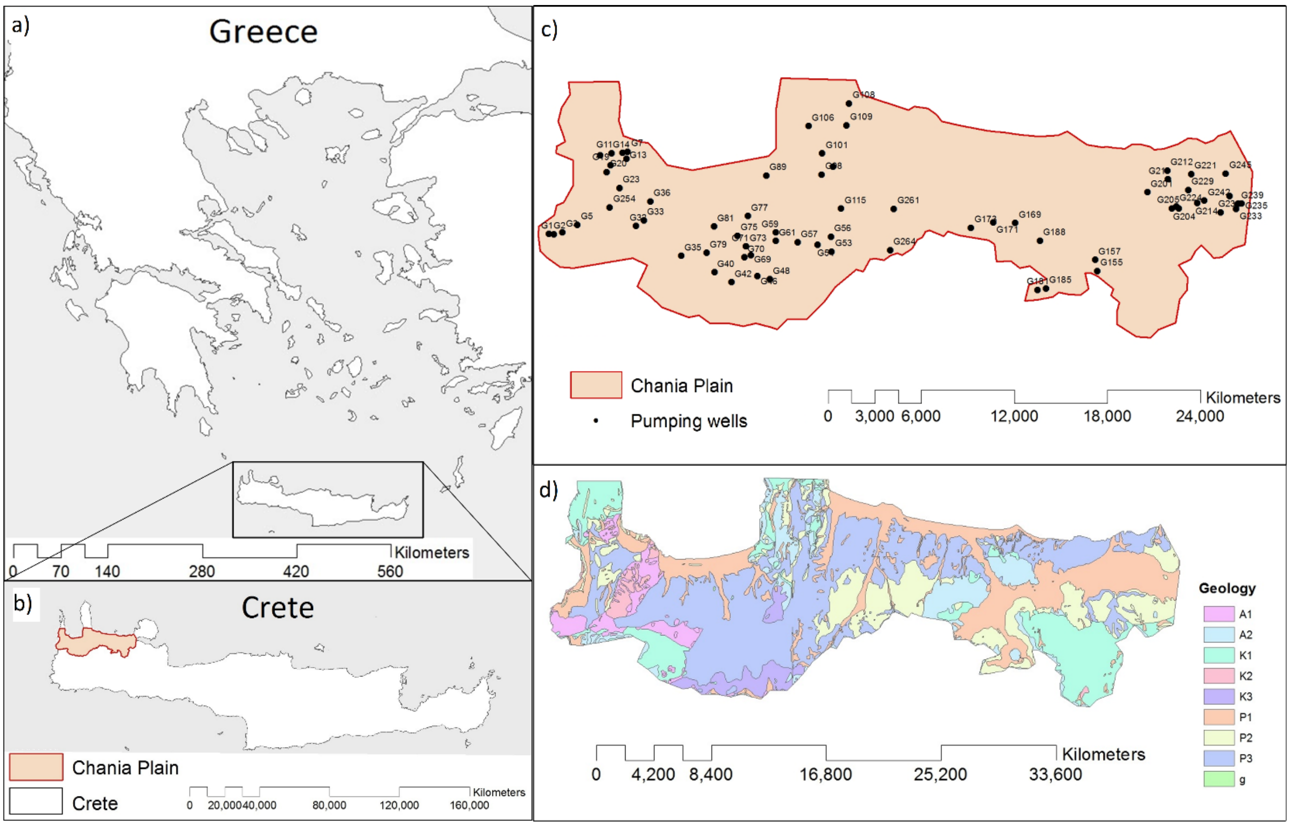

Figure 1. Location of Chania Plain: a) Greece, b) Crete, c) Chania Plain with the pumping well locations and d) the hydrogeology, of the study area.

3. MATERIALS AND METHODS

3.1 Princeton Transport Code (PTC) model set-up

In order to simulate groundwater flow in the study area, the Princeton Transport Code (PTC) model was applied. PTC is a plug-in extension for the ArgusONE graphical pre- and post-processor software suite. PTC uses a system of partial differential equations to calculate groundwater flow according to hydraulic head h (Eq. 1), using a combination of finite-element and finite-difference methods, and groundwater Darcy velocity in three-dimensions x, y and z (Eq. 2, 3 and 4, respectively):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-S\frac{\partial h}{\partial t}+Q=0 \tag{1}$$

$$V_x=-K_{xx}\frac{\partial h}{\partial x} \tag{2}$$

$$V_y=-K_{yy}\frac{\partial h}{\partial y} \tag{3}$$

$$V_z=-K_{zz}\frac{\partial h}{\partial z} \tag{4}$$

The above system of equations is a result of combining Darcy's law and Conservation of Mass Law. The PTC model has also the ability of contaminant transport calculations (Babu et al. 2002).

The PTC – ArgusONE model has been designed to be fully compatible with GIS (Geographical Information System) files. The model domain outline, the polygons describing the area geological formations with corresponding hydraulic conductivities, the well locations, the initial heads and the pumping rates were imported into the model using shapefiles. An important parameter needed to be determined is the aquifer depth. From the ground survey data presented by Lionis and Perleros (2001), a bottom layer with a depth of 100 m below sea level was considered. A brief description of the model input parameters is given in Table 1.

Table 1. Model input

Parameter	**Model input**
Mesh Type	Triangular
Water table iterations	50
Convergence Criterion	0.0001
Number of Layers	3
Number of Stresses	4
Total Stress time	180 days
Total Time steps per stress	40
Total Simulation Time	720 days

The simulation time was set to two years based on the available data for the time period from April 1998 to April 2000. According to the hydrogeological study presented by Lionis and Perleros (2001), the bottom layer of the aquifer comprises mostly of limestone, the middle layer of marls and the upper layer consists of the geological formations presented in the hydrolithologic map of Figure 1. The hydraulic conductivity values used were 0.015 m/d for granular non-alluvial formations, 100 m/d for granular alluvial deposits (mainly located near the coastline), 0.15 m/d for miocene deposits, 86.4 m/d for karstic formations and 0.00024 m/d for flysch deposits (impermeable formations).

A Dirichlet boundary condition (BC) of fixed hydraulic head equal to 100 m was applied along the coastline to simulate the sea boundary. At the southern boundary of the region, Neumann conditions (specified flux) were applied in order to represent the in-flows from the mountains and from aquifers adjacent to the model domain (constant flows 1 and 2 in Figure 2). Pumping wells were also represented by Neumann boundary conditions with zero pumping rates during wet seasons (all the wells are used for irrigation purposes) and 114,492 m^3/d during dry seasons (in total). The pumping well locations are presented in Figure 2. The finite element mesh generated for the area consisted of 6275 triangular elements (Figure 2).

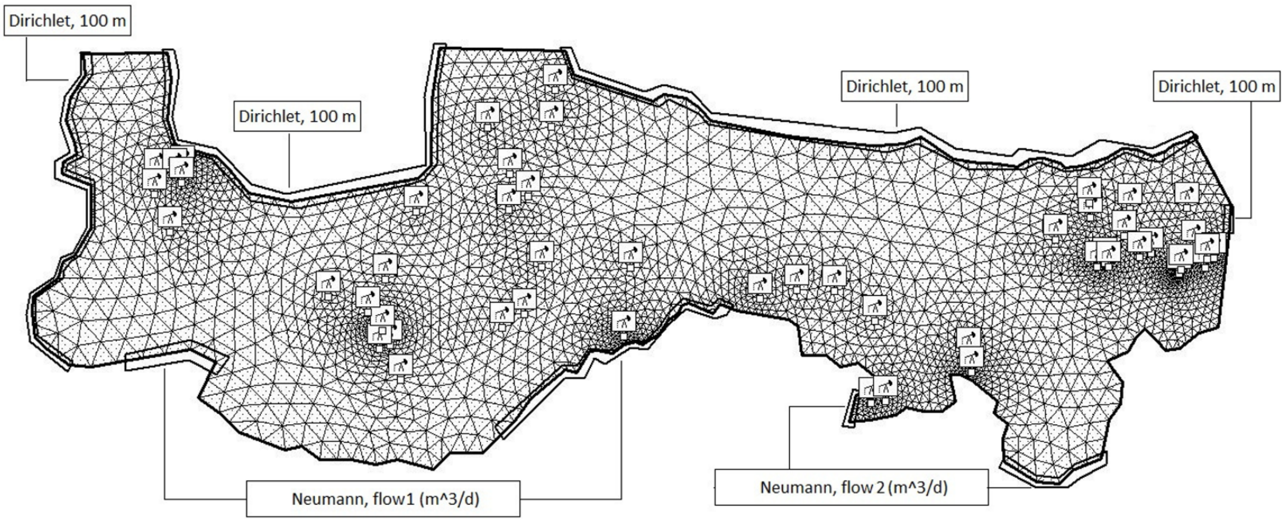

Figure 2. Model domain with the lateral in-flows.

3.2 Calibration process

A calibration processs was performed estimating the groundwater flows from the adjacent basins (south boundary conditions) and comparing the measured hydraulic head values with the observed heads from well-data. The model was calibrated for the time period Apr. 1998 – Apr. 2000 based on the available hydraulic head data of 70 wells. Two statistical indicators were employed in order to determine the fit of the model results to the observed measurements. These indicators were the Root Mean Square Error (RMSE) and the coefficient of determination (R^2). Values of RMSE close to zero indicate a perfect fit. Regarding the coefficient R^2, a value equal to 1 indicates a perfect fit between simulated and observed data (Abramowitz and Stegun, 2012).

4. RESULTS

4.1 Calibration results

The calibration was performed manually by adjusting the inflows from the southern boundaries until the model results were in good agreement with the observed data (hydraulic heads). The calibration values with the best match between field data and simulation results were equal to 5000 m^3/d and 1750 m^3/d for flow 1 and equal to 200 m^3/d and 70 m^3/d for flow 2, for the wet and dry periods, respectively.

During the calibration process, the majority of the wells show a good agreement between simulated and observed values while few wells had not such a good agreement. This behavior was explained considering that some wells must be pumping water from a separate, impermeable or leaky aquifer, which is not included in the present model. In addition, it was observed that in the area marked by the circle in Figure 3, the geological formations of moderate permeability (P2) are dominating and the hydraulic conductivity value inserted into the model was too low to adequately represent the real conditions. Therefore, during the calibration process the hydraulic conductivity value of the porous formation P2 was increased to 20 m/d, in order to succeed a better much between simulated and observed hydraulic head values. Both modifications to the formations' hydraulic conductivities were within the typical values of such formations found in the literature.

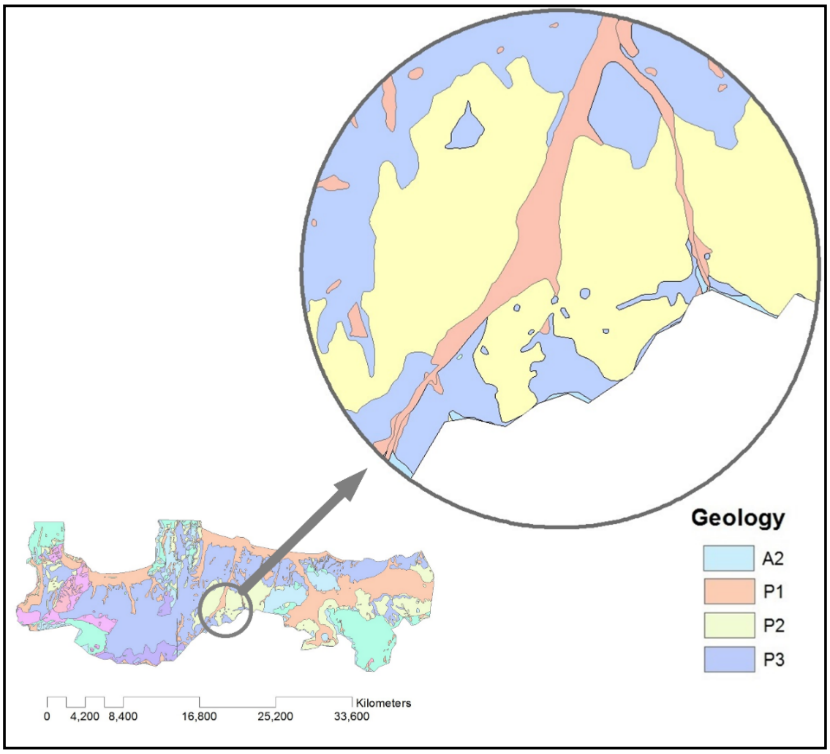

Figure 3. Area of higher hydraulic conductivity

The good correlation between field measurements and the simulation results is shown in Figure 4, for the calibration period. Moreover, in this figure a statistical indicator is presented verifying the good agreement. The correlation coefficient (R^2) is approximately equal to 0.987, the Root Mean Squared Error (RMSE) is equal to 3.3, an acceptable value according to Anderson et al. (2015).

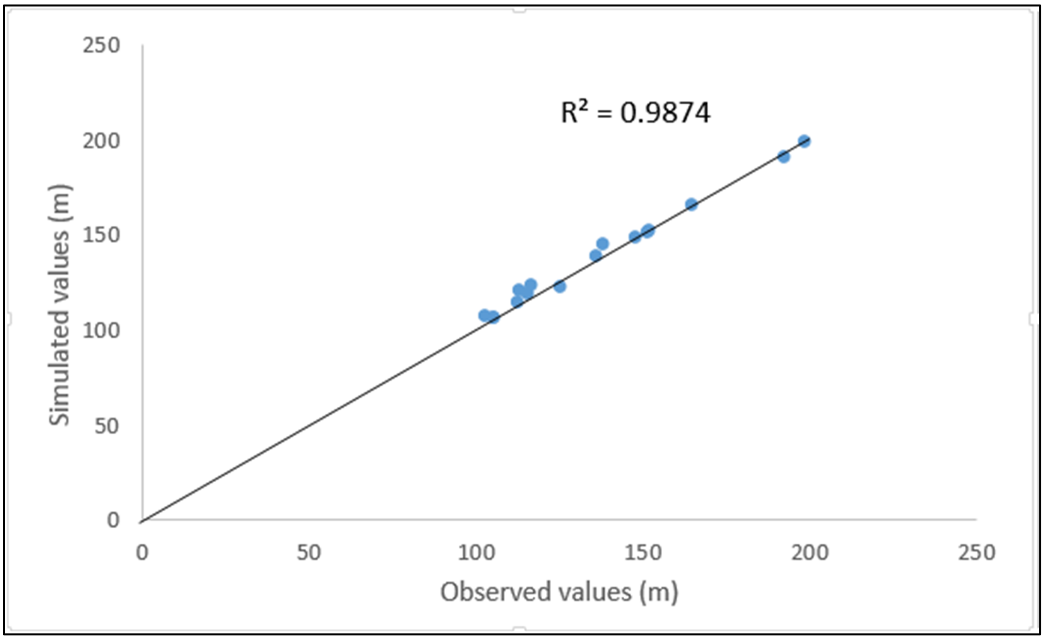

Figure 4. Observed vs. Simulated hydraulic heads values, and the 1:1 line.

4.2 Two-dimensional maps model results

The PTC model results are shown in Figure 5 for the dry and the wet season, respectively.

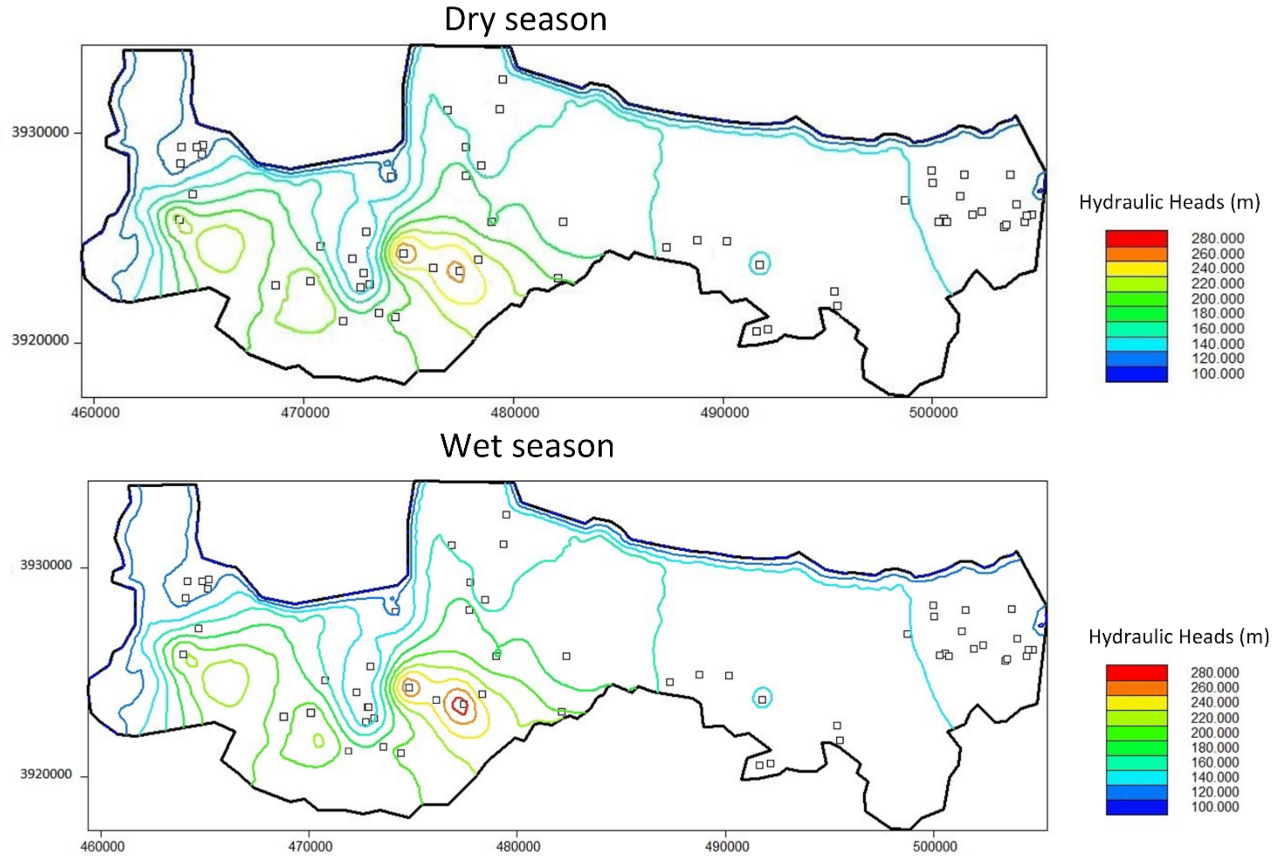

Figure 5. Simulated hydraulic heads for the dry and the wet season

Based on Figure 5 it can be easily verified that all pumping locations, remain safe from saltwater intrusion (saltwater interface at 102.5 m based on Ghyben-Herzberg equation for a given aquifer depth of 100 m) for both wet and dry seasons. The wells located in the western part of the region, near the coastline, could be potentially affected in the future, in the case of an extended dry period with increase pumping rated. It is also observed, that the hydraulic heads do not decrease significantly during dry season. This is partly due to the short time period of modelling, as well as the large domain area. Thus, one may presume that the pumping wells do not pose a significant threat to the aquifer regarding saltwater intrusion. More detailed modeling focused on a local scale might reveal local problems due to saltwater intrusion that cannot be captured by this large scale model.

For the study area, an appropriate common irrigation amount for olive and citrus trees (period between May to September) is around 250 mm and 450 mm per 10^3 m^2 of agricultural land, respectively (Kourgialas and Karatzas, 2015). From the irrigated land of 105 km^2, in the study area, 70% consists of olive trees while the rest of citrus. Thus, the irrigation needs in a yearly basis can be estimated to be $18 \cdot 10^6$ m^3 and $14 \cdot 10^6$ m^3 for olive and citrus trees, respectively. Taking into consideration the above findings (with the total irrigation needs to be $32 \cdot 10^6$ m^3/year, while water abstraction for irrigation to reach $42 \cdot 10^6$ m^3/year) the proposed modeling approach could be used by local authorities in order to organize a proper groundwater abstraction irrigation plan for a sustainable agricultural and urban development.

5. CONCLUSIONS

In the present work, a simulation of the groundwater flow in the Chania Plain aquifer was performed using the Princeton Transport Code. The data used for model calibration was from April 1998 until April 2000. Based on the simulation results, at the west side of the domain the hydraulic heads are higher, verifying the correct placement of the majority of the pumping wells. In addition, there was insignificant differentiation between the wet and dry stresses, despite the increase of pumping rates during the dry period. Therefore, the pumping wells do not affect significantly the hydraulic characteristics and the behaviour of the aquifer's physical system.

Due to high irrigation demands in the Chania Plain there is a large number of pumping wells in order all agricultural needs to be satisfied. The effectiveness of the model development is significant, allowing the local authorities to properly control the pumping effects at any well location, by means of running additional model scenarios in order to avoid potentially harmful well placements.

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