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GROUNDWATER FLOW MODELLING OF THE ALLUVIAL AQUIFER IN THE MOURIA AREA, SW GREECE

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Abstract

The objective of this paper is to study the impact of a reflooding of the former Mouria Lake on the hydraulic state of the Pyrgos area. The hydrogeological data acquired through field work were combined with the volumetric budget and the hydrological data from the entire Alfios River catchment in order to build the conceptual and numerical model of the groundwater flow system, which confirmed the hydraulic state before the drainage of the Mouria Lake. The model was also used to predict the future hydraulic state in case stresses change. For this purpose, Flowpath II, a numerical groundwater flow model, was used to evaluate the impacts of groundwater exploitation in the alluvium unconfined aquifer that is developing in the Holocene deposits. Due to the connection of the aquifer with the surface drainage canals near the coastal zone, the conceptual model was built upon irrigation data, rainfall data, and pumping rate data from the pumping stations that drain the area of the former Mouria Lake. These data were inserted in the model which was calibrated using a 24-month set of piezometric measurements. The simulation results show that the groundwater level before the drainage of the lake was 2m higher than the present situation and the same scenario will happen in case of reflooding the drained lake. Today, the pumping stations keep the groundwater level near the sea level throughout the hydrological year.

Key words: *groundwater modelling, unconfined aquifer, conceptual model, piezometric measurements.*

1. Introduction

The Mouria Lake, located in Western Peloponnese, was drained for cultivation during the late 60's. Today the c. 600-ha large former Lake and the surrounding area is used for cultivation and grazing. The sediments filling the drained Mouria Lake are Holocene alluvial deposits while gravel and sand dominate in the surrounding area (Fig. 1a). The eastern, western and northern margins of the study area consist of lagoonal sediments, while a sand barrier system and marine deposits constitute the southern margins (Streif, 1980).

The irrigation needs for cultivation are covered by the use of water from Alfios River, which is distributed through water canals in the area of 48 km^2. Deep wells (20-50m) have been abandoned in the last decade because of the deterioration of the water quality, while majority of the wells that appear in the unconfined aquifer (approx.10m) are of little use.

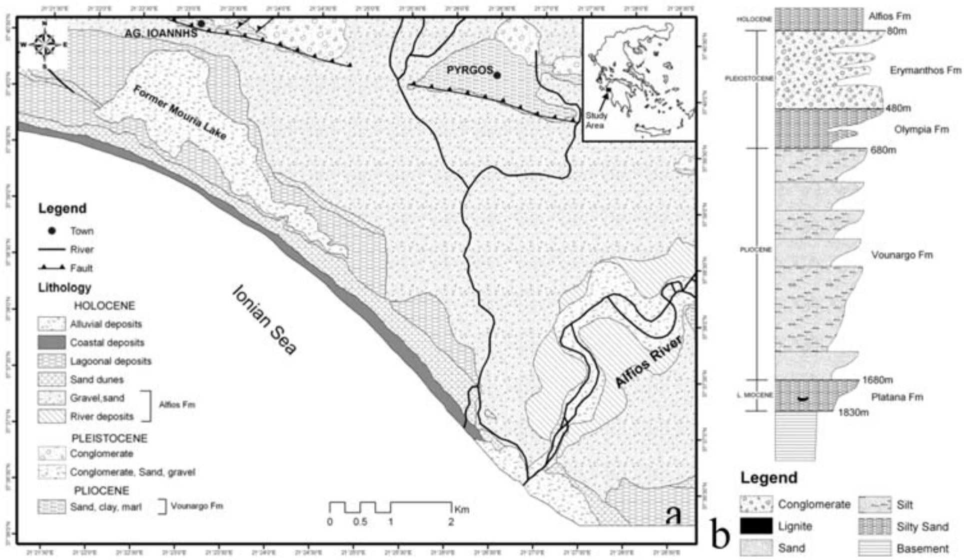

Fig. 1: (a) Geological map and (b) stratigraphy of the study area (Streif, 1980).

The aim of this study is to build a conceptual model that will represent the present conditions based on hydrological, lithological and hydrogeological data and to set up the numerical model of the unconfined aquifer that simulates the groundwater flow in the area of Pyrgos. The basic objective of the model is to confirm the hydraulic state and estimate the volumetric budget of the study area that represents the input and output volumes of water in the unconfined aquifer, in order to predict future heads in case stresses differ in the future (e.g. drought periods) and to investigate the potentiality of re-flooding the entire former lake, based on the results of the present study.

2. Geological – hydrogeological setting

The study area is part of the Pyrgos basin (Hageman, 1976, Koukouvelas et al., 1996) and consists of two sedimentary systems. The lower part consists of the marine-lacustrine Platana and Vounargo formations (Fm) (Fig. 1b). An overall coarsening-up trend characterizes both formations. The Platana Fm was deposited during the Late Miocene. Higher up, the lacustrine and marine sediments of the Platana Fm are interdigitated basinwards with the overlying Vounargo Fm, which is the major lithological unit in the Pyrgos basin (Kamberis, 1987). The upper sedimentary system consists of three formations. At the bottom, the 200m thick Pliocene Olympia Fm is a coarsening-up fluvio-lacustrine succession overlain by the 400m thick Erymanthos conglomerates, with sediment supply from the north. On top of this system the 80m thick Middle Pleistocene-Holocene Alfios Fm is exposed in the low-land area of the Pyrgos basin.

The lower coastal zone of the Pyrgos area is covered by Holocene alluvial deposits (Alfios Fm) in which an unconfined aquifer is developed. The aquifer is mainly recharged by the direct infiltration from precipitation in the rainy period and irrigation in the dry period, as well as lateral leakage along the Alfios riverbed. Piezometric measurements conducted in the Mouria area suggest that the underground water moves from the north-east area to the coastal zone while the hydraulic gradient varies from 0.1‰ to 8‰, with the mean value at 2.8‰ (Fig. 2). The lower values are near Alfios

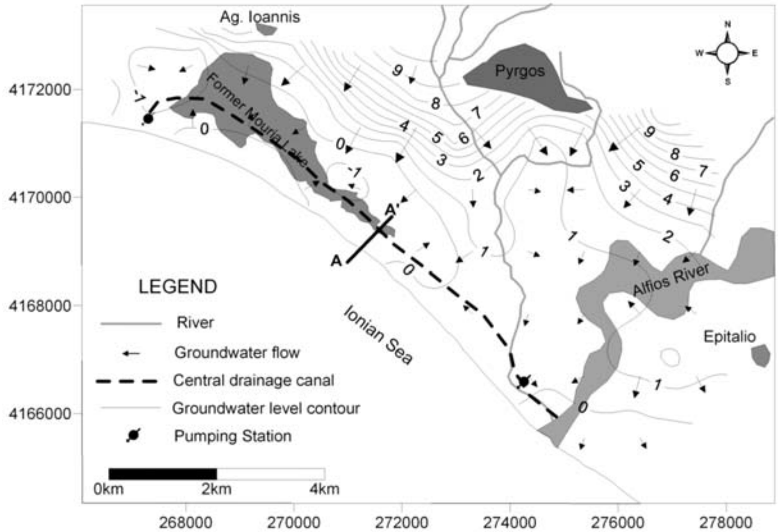

Fig. 2: Piezometric map of the unconfined aquifer at the Mouria area (June 2006).

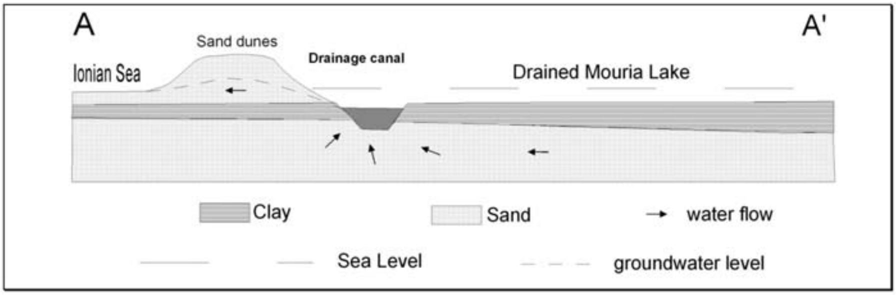

Fig. 3: Hydrogeological cross section of the line A-A' shown in figure 2.

River which indicates that sediments with higher hydraulic conductivity dominate in that area and there is increased recharge from the river to the aquifer. Near the coastal zone there is negative hydraulic gradient and seawater intrusion caused by the pumping stations that lead surface water and part of the underground water to the sea. The two pumping stations are located at the west and east edge of the drained Mouria lake and are used to drain the former lake area through drainage canals (Fig. 2&4). Due to the depth of the canals (approx. 4-5m), there is connection with the aquifer resulting in the drawdown caused by the use of pumping stations (Fig. 3).

3. Numerical Simulation

3.1 Conceptual model

The development of the model that simulates the groundwater flow in the area of Pyrgos was produced following the steps according to Anderson and Woessner (1992). The conceptual model was conducted using geological, hydrological and hydrogeological data that were collected during field work and is based on three coverages.

The first coverage describes the hydraulic conductivity of the unconfined aquifer and its spatial distribution. The study area was divided into two areas with different hydraulic conductivities. The second coverage includes the quantity and the distribution of the recharge data based on both rainfall and irrigation data. According to the hydrological balance in the Alfios River catchment, the volume of water that infiltrates and recharges the alluvial unconfined aquifer is 20% of irrigation and rainfall data (Karapanos, 2009). The third coverage includes streams and rivers that recharge the aquifer by lateral leakage (e.g. Alfios River) or cause a drawdown due to the use of pumping stations (e.g. drainage canals).

3.2 Description of the model – Creating the Grid

The well known Flowpath II software (Evsikov et al., 1998) was selected for the simulation of the unconfined aquifer in Pyrgos area, which resolves the three-dimensional groundwater flow equation (Rushton and Redshaw, 1979) using the finite differences arithmetical method (Anderson and Woessner, 1992). This method demands that the study area should be divided in cells with dimensions x, y and z. The grid that was produced divides the aquifer in cells 200x200m and consists of rows, columns and single layer in z axis.

The 45 km^2 study area is divided into 1209 cells. The NNE boundary of the aquifer consists of the Plio-Pleistocene deposits of Vounargo formation and Pyrgos fault zone (Fig. 4). Alfios River is the SE boundary of the simulation area, where the heads vary linearly. The NW boundary is parallel to a flow line and is simulated as no-flow boundary, while the SW boundary is the sea shore, which is a constant head equal to zero throughout the year. The base of the aquifer is a clay layer that is found in all lithological sections and is impermeable, with a mean elevation of -15 m. Since the aquifer is unconfined, it is not necessary to insert the elevation of the top of the aquifer. As regards the streams and the drainage canals, these were inserted in the model and proved to be significantly important toward the volumetric budget. The hydraulic conductivity was calculated through pumping tests to be 600 m/day in the simulation area while there is a zone of 300 m/day in the area of the former lake due to the existence of less permeable sediments (clay). Recharge rates were calculated to be 20% of the water from rainfall plus irrigation for each month, expressed as m/day as shown in table 1.

3.3 Initial – boundary conditions

According to the ASTM (D5609-94) standards there are 3 conditions: specified head condition, specified flow condition and variable head condition. The boundary conditions in the unconfined aquifer of Pyrgos were determined according to the geological and hydrogeological setting of the area.

According to the piezometric maps and the field work, the NE section of the aquifer extends parallel to Pyrgos fault zone and is simulated as a variable head boundary (Fig. 4). Across this boundary there is limited flow as the Pyrgos fault zone and the neogene deposits of Vounargo formation seem to be a hydraulic boundary. However, in order to simulate the amount of water coming in the aquifer from this zone, a recharge area has been used in which the input of water has been calculated using the hydraulic gradient, expressed as recharge rate, equal to 0.02 m/day (Fig. 4). At the west part of the town of Pyrgos along the fault zone, there is an influx zone that was simulated with a recharge rate of 0.61 m/day. Similarly, in the east part of Pyrgos town, the influx was simulated as recharge rate of 0.055 m/day. The NW boundary of the aquifer is simulated as a no-flow boundary as it is parallel to the flow lines, with no input or output of groundwater across this boundary. A no-flow boundary is also found at the south part of Pyrgos town because of the impermeable sediments of Vounargo formation.

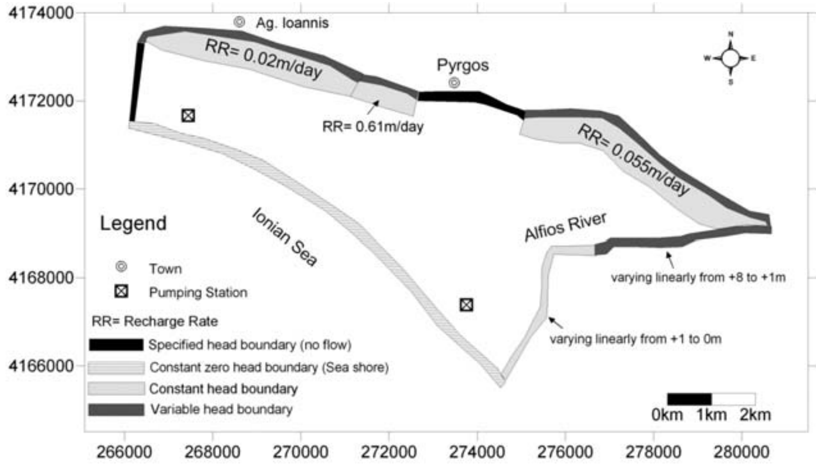

Fig.4 : Simulation grid at the Mouria area.

The SE boundary of the aquifer is Alfios River, simulated as variable head boundary, as the water level varies throughout the year especially towards the inner land. The head varies linearly from +8 m to +1 m, as it is found that the hydraulic head in that area (Epitalio Bridge) is constantly +1 m throughout the year (Karapanos, 2009). This happened throughout the period 2006-2007 that piezometric measurements took place and is attributed to the extensive use of pumping stations near Alfios River and the coastline that keep groundwater level to a certain level (Fig. 4). Thus, from that point until the Ionian Sea, the lower part of the river was simulated as constant head boundary varying linearly from +1 m to 0. The west boundary of the aquifer is the Ionian Sea simulated as constant head equal to zero.

The volume of water that is pumped from the drainage canals to the sea was simulated as negative hydraulic head at the central drainage canal that develops along the coastline. Because of the constant use of the pumping stations in order to maintain a certain water level to the canals, the hydraulic head is constantly below zero throughout the year. The volume of water pumped by the wells in the unconfined aquifer is minor and therefore not considered in the model, compared to the excessive volume of water pumped by the pumping stations. This volume is simulated by the model as constant negative hydraulic heads in the central drainage canal.

3.4 Calibration of the model

In the present study the trial and error method was used in order to calibrate the model and find the parameters that simulate better the aquifer. The evaluation of calibration is performed by the use of the Mean Error (ME), the Mean Absolute Error (MAE) and the Root Mean Square (RMS) (Anderson and Woessner, 1992).

Initially, the model was calibrated based on the piezometric measurements of June 2006 which is assumed to be the mean annual groundwater level and is representative for the two year simulation period. The aim of this calibration is to estimate the values of hydraulic conductivity as the other parameters remain the same and are known. The data used for the separate recharge zones were calculated according to the rainfall and irrigation data to be 0.00007 m/day for the whole area. The simulation was done in transient state conditions and the storativity value equals 0.2 (S=0.2) according to pumping tests.

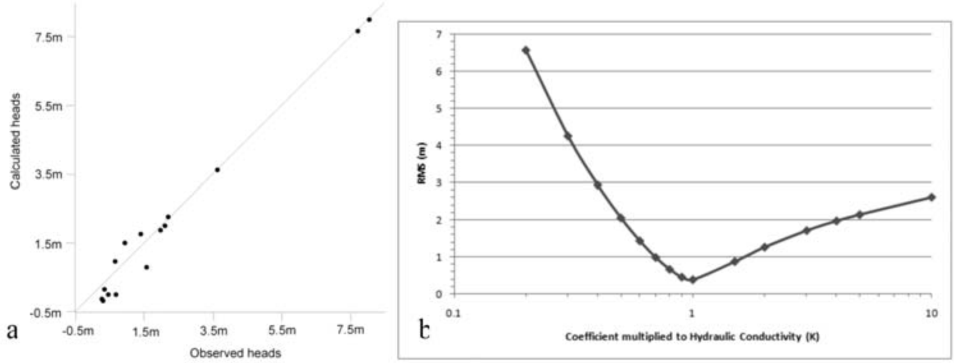

Fig. 5: (a) Correlation of the computed and the observed values, (b) Sensitivity analysis.

Table 1. Recharge rates based on rainfall and irrigation data.

Month	Irrigation (m)	Rainfall (m)	Summary (m)	Infiltration (20%) (m)	Recharge Rate m/day)
June 06	0.01246	0	0.01246	0.00249	0.00008
Sept 06	0.00807	0.0805	0.08857	0.01771	0.00059
Dec 06	0	0.0771	0.07710	0.01542	0.00051
Mar 07	0	0.0612	0.06120	0.01224	0.00041
Jul 07	0.01470	0	0.01470	0.00294	0.00010
Oct 07	0.00173	0.2351	0.23683	0.04737	0.00158
Dec 07	0	0.1033	0.10330	0.02066	0.00069

The RMS and MAE values are considered to be reasonable as they are MAE = 0.3 m and RMS = 0.38 m (Fig. 5a).

3.5 Sensitivity analysis

The sensitivity analysis is aimed to prove that the chosen parameter values play a very important role and are not randomly chosen. Thus, several values were used for the two zones of hydraulic conductivity and their impact was checked by the use of RMS (Fig. 5b). The model completed several simulations for 15 different pairs of conductivity values and results show that the lower RMS value is achieved only by the use of the conductivity values for which the model was calibrated.

3.6 Validation of the model

The uniqueness of the results of the model is achieved by the validation of the model. The results of the simulation are checked when new stresses are used toward a new set of observed heads. The validation of the model was done in transient conditions where S=0.2 and different recharge rates were used according to rainfall and irrigation data as shown in table 1.

Throughout the different simulations, the RMS error varies from 0.38 to 0.73 and the MAE from 0.30 to 0.63. Hence the model can simulate the groundwater system with good fit to the observed data and can be used to extract safe results about the volumetric budget and to predict future heads in different stresses.

Table 2. Volumetric budget for the case of September 2006.

Input	Infiltration	Alfios leakage	Summary
Percentage (%)	84.17	15.83	100
Output	**Underground runoff**	**Drainage canals**	**Summary**
Percentage (%)	14.32	85.68	100

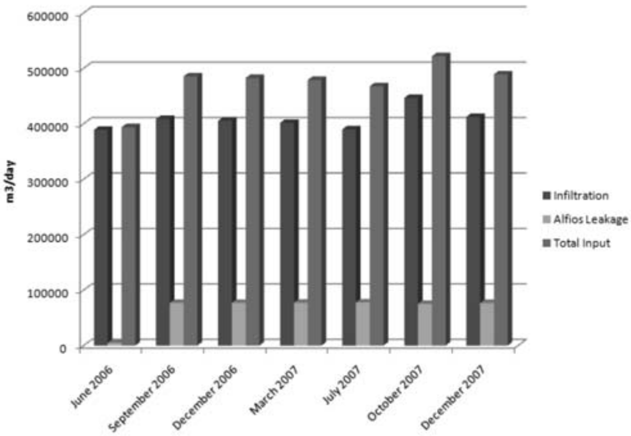

Fig. 6: Variation of the input in the unconfined aquifer.

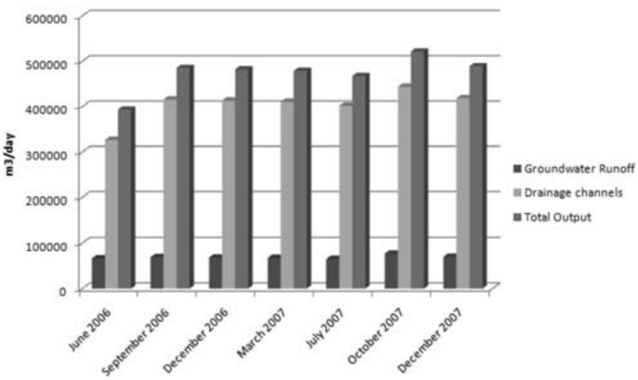

Fig. 7: Variation of the output in the unconfined aquifer.

3.7 Volumetric budget

One of the main objectives of the model is to estimate a reliable volumetric budget and estimate the volumes of water entering and departing from the aquifer. In the study area the volumetric budget is reflected by the following equation:

Direct Infiltration (20% of the Irrigation data + Rainfall data) + Alfios river Input = Groundwater output + Drains (from the drainage canals).

The direct infiltration was calculated as 20% of the volume of water coming from the rainfall and irrigation. The lateral leakage along the riverbed is calculated from the model by the use of the heads

Table 3. Volumetric budget in December 1990.

Input	**Infiltration**	**Alfios leakage**	**Summary**
Percentage (%)	81.96	18.04	100
Output	**Underground runoff**	**Drainage canals**	**Summary**
Percentage (%)	12.93	87.07	100

Table 4. Volumetric budget for recharge rate equal to 0.00008 m/day.

Input	**Infiltration**	**Alfios leakage**	**Summary**
Percentage (%)	90.34	9.66	100
Output	**Underground runoff**	**Drainage canals**	**Summary**
Percentage (%)	93.03	6.97	100

Table 5. Volumetric budget for recharge rate equal to 0.002319 m/day.

Input	**Infiltration**	**Alfios leakage**	**Summary**
Percentage (%)	94.13	5.87	100
Output	**Underground runoff**	**Drainage canals**	**Summary**
Percentage (%)	88.38	11.62	100

in nearby wells and the piezometric maps. The results for the simulation period of September 2006 are shown in table 2 as an example while the overall results are in figures 6 & 7.

As shown in table 2 for the case of September 2006, 15% of the underground water comes from Alfios River through lateral leakage while the rest 85% comes from direct infiltration of the rainwater during the winter period and the irrigation water during the summer period.

Drainage canals play a very important role in the area as they lead 85% of groundwater to the sea while the rest 15% is underground runoff towards the sea. The same results appeared when different recharge rates were inserted in the model showing that the drainage system at the former Mouria Lake keeps groundwater level at a certain level near the sea level throughout the hydrological year.

According to the results presented through the histograms in figures 6&7 for different recharge rates throughout the years 2006-2007, the largest amount of input and output groundwater was recorded during October 2007, because of the high level of precipitation (235.1 mm) in that month.

3.8 Prediction of the model

One of the advantages of the model after its calibration and validation is the simulation of the aquifer in different stress periods. In the study area, the aquifer is constantly recharged throughout the year even in the summer period because of the infiltration of water used for irrigation. So the scenario that was checked was that of heavy rainfall. The highest value of precipitation recorded for the Pyrgos area in the last 30 years was 347.8 mm in December 1990. This value equals to a recharge rate of 0.002319 m/day. The results in case the same scenario happens again in the future, are presented in table 3.

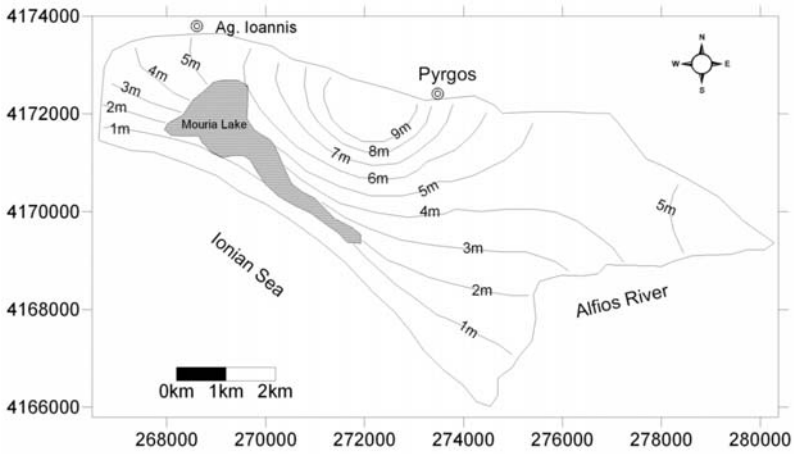

Fig. 8: Piezometric map of the study area before the drain of the Mouria Lake during the low water period.

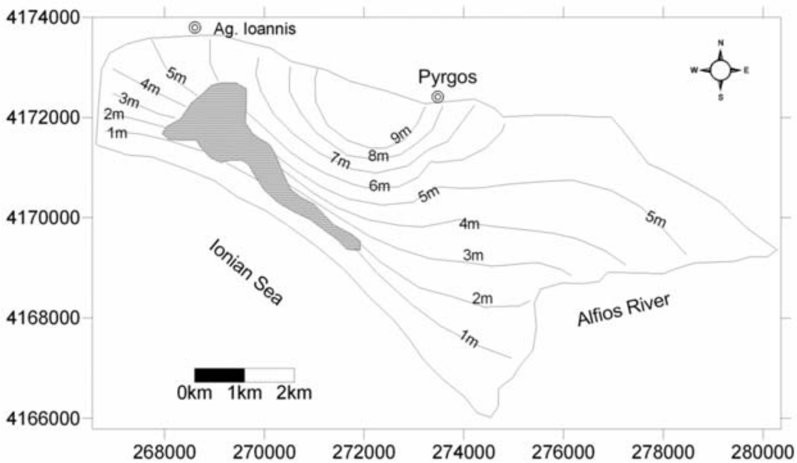

Fig. 9: Piezometric map of the study area before the drain of the Mouria Lake during the high water period.

Another hypothesis made, was that of simulating the aquifer before the drainage of the Mouria Lake that took place in 1960's, as the plans for future reflooding demand it. The lake surface was simulated as constant zero head surface without the drainage canals. The initial recharge rate inserted was 0.00008 m/day which is the lowest value recorded and secondly 0.002319 m/day, that is the maximum value. The results of the simulation for these two hypotheses are shown in tables 4&5 and figures 8&9 respectively.

Results indicate that the role of drainage canals is significant for the study area, as in the past decades before the drainage of the Mouria Lake the groundwater level was 2 meters higher and the lateral leakage from Alfios River was 10% less than the present situation.

4. Conclusions – Results

The numerical simulation of the alluvial aquifer in Pyrgos area was conducted using Flowpath II software. The results were very satisfying regarding both the simulation of the piezometric surface and the reliable volumetric budget. According to this, 15% of the aquifer water derives from lateral leakage from Alfios River, while 85% derives from infiltration of the rainwater during the winter period and irrigation water during the summer period. The drainage canals play a very important role in the area as they lead 85% of the groundwater to the sea and the rest 15% is underground runoff towards the sea. Additionally, the prediction of the aquifer's piezometric surface and balance in case stresses change, was checked by the use of the model.

In the study area the aquifer is constantly recharged throughout the year even during the summer due to the water use for irrigation. According to heavy rainfall scenario, 18% of the aquifer water will derive from Alfios lateral leakage, while 82% from infiltration of the rainwater during the winter period and irrigation water during the summer period. Another hypothesis made was that of simulating the aquifer before the drainage of the Mouria Lake that took place in 1960 's. Results show that the role of drainage canals is significant for the study area as in the past decades the groundwater level was 2 meters higher, scenario that will happen again in case of reflooding the lake. According to the volumetric budget, the lateral leakage from the Alfios River was decreased 10% in relation to the present situation.

5. Acknowledgments

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