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Groundwater modeling and management in a complex lake-aquifer system

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Abstract In this paper, the hydrogeologic analysis and the development of a numerical model for the simulation of a complex system of aquifers in Northern Greece are presented. The study area faces a severe environmental danger as the unsustainable water consuming practices have resulted in negative water balance and severe water shortage. Based on field data and in-situ measurements carried out by several research groups during the last 30 years, a conceptual model is developed, that alters what scientists believed to date as far as the hydraulic communication between the shallow and the deep aquifer, as well as the lake-aquifer interaction are concerned. Based on the assumptions of the conceptual model, a numerical model has been developed in order to investigate the regional groundwater flow in the aquifers. The Modflow program has been used for its implementation. The results have verified firstly that a marginal hydraulic contact between the 2 aquifers is permitted, and secondly that the assumed relation between the lake's water volume and the aquifer's water table fluctuations is practically negligible. The dramatic decrease in the lake's water reserves by 90%, as the model results show, is mainly due to the reversing of the torrent-aquifer interrelation. Finally, the model is used as a management tool for the restoration of the aquifer as well as of the lake.

Keywords Groundwater flow · Conceptual models · Numerical modeling · Lake-aquifer interaction · Koronia lake · Aquifer restoration · Lake restoration

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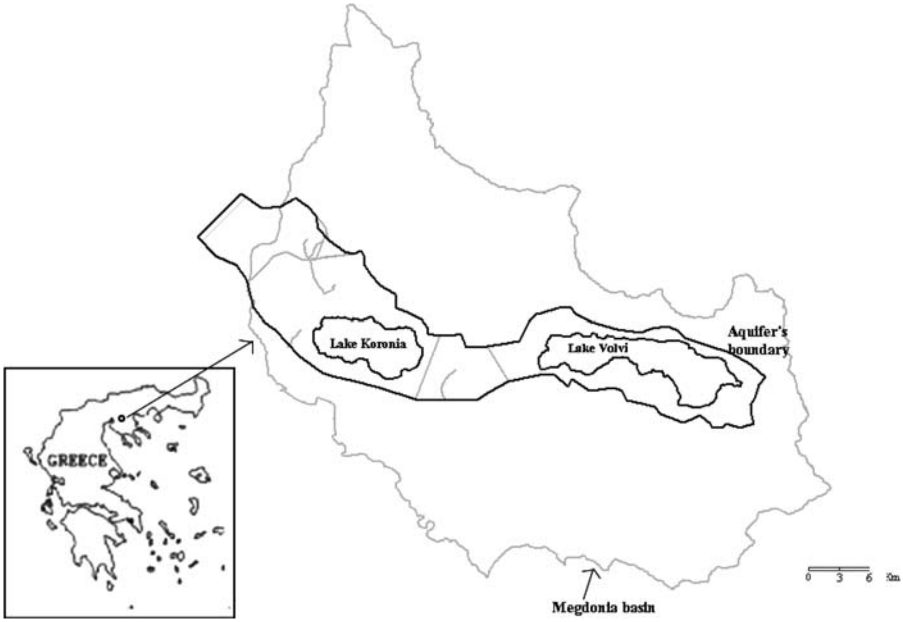

Fig. 1 Location map of the study area – The Megdonia Basin and the underlying aquifer

1. Introduction

Lake Koronia belongs to the hydrologic basin of Megdonia, in Northern Greece, which is part of an interrelated water resource system, also including Lake Volvi, as can be seen in Figure 1. Lake Koronia is one of the most important wetlands in Greece and a typical example of the impacts that unsustainable water resources management might have. Owing to the absence of an integrated water resource management plan in the area, the water resources of the lake, as well as the surface and groundwater resources of the hydrologic basin, were unable to cover the needs of the water consuming agricultural and industrial activities, resulting in negative water balance and severe water shortage. In particular, as far as the lake is concerned, during the last 20 years there has been a dramatic decrease in the water reserves by 90%, threatening the existence of this environmental resource. The plain part of the basin of Megdonia, shown in Figure 2, covers an area of 570 km^2 and is roughly delimited through the 200 m isoline. This isoline follows the surface boundary between the sediment deposits and the crystalline schists, which form the basement rocks of the basin of Megdonia. The western part of the basin consists of the plain (269 km^2) and the western hilly area (13 km^2) of the sub-basin of lake Koronia (total area 282 km^2) as well as of the sub-basin of Scholarion with a plain area of 93 km^2. The eastern part of the basin forms the sub-basin of lake Volvi and has a total plain area of 220 km^2 (Figure 2).

The underlying aquifer and its interaction with the lake play a critical role in the state of this water system (Figure 1). Several major studies have been carried out on the surface and groundwater hydrology of the sub-basin Lake Koronia over the past decade. These include comprehensive and wide ranging studies by the Prefecture of Thessaloniki, the Ministry of Environment, Natural Resources and Public Works, the IGME and the Aristotle University of Thessaloniki.

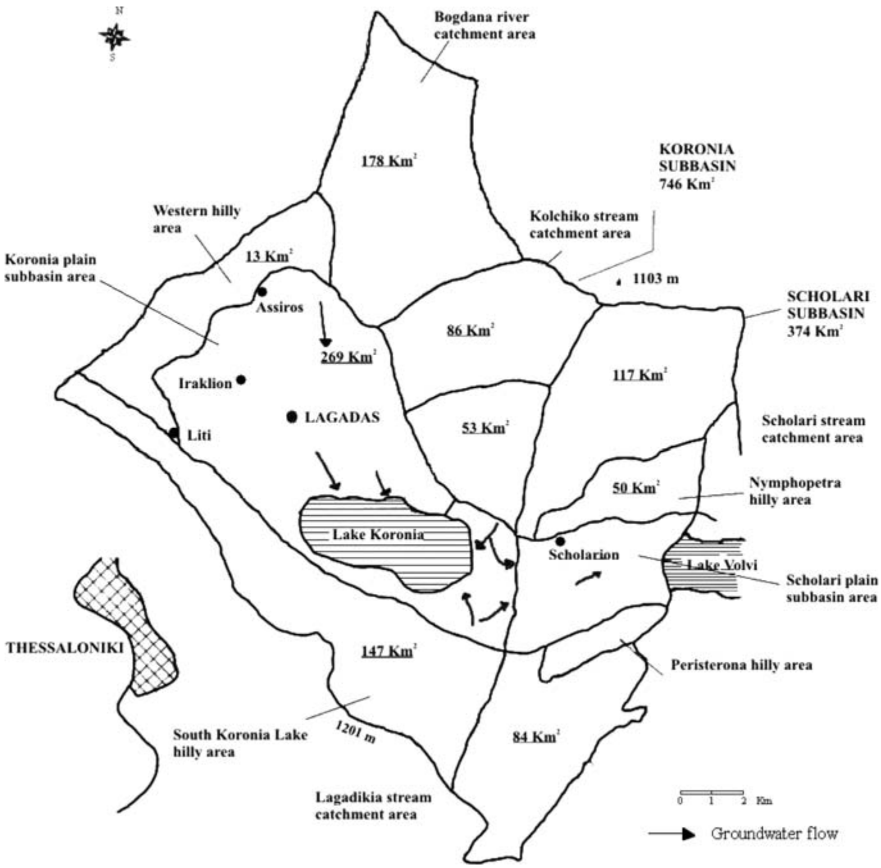

Fig. 2 The western part of Megdonia Basin

All former studies referring to the hydrogeologic conditions in the study area have been taken into consideration in the present study and especially those by BRGM (BRGM, 1972), Vatseris (Vatseris, 1992), and Knight Pielson (Knight, Pielson, Karavokyris and Partners, 1998).

However, in general data is limited and severely restricts a comprehensive understanding, especially as far as the hydrogeologic environment is concerned. In fact, as this study will show, all former studies have reached the false conclusion, that there is no hydraulic contact between the shallow and deep aquifers while the interaction between the lake and the aquifer also remains unclear.

In order to carry out the present study, the Institute of Geology and Mineral Exploration (IGME) collected new field data and carried out in-situ measurements. This involved the following tasks (Veranis *et al.*, 2002):

- periodic measurements of the piezometric surface for the period 1997–2001 in 66 pumping wells.
- registration of 500 pumping wells and evaluation of the stratigraphic data from their lithologic sections.

- hydrolithologic mapping and tectonic analysis with the help of satellite pictures and aerial photographs.
- drilling of 7 new pairs of deep boreholes (200–300 m) with hydraulic isolation of the shallow aquifers (0–70 m) and pumping tests for the estimation of the hydraulic parameters (k, T, S) in the deep aquifers.
- geophysical investigation of the surface to calculate the thickness of the sediments and logging in pumping wells.
- hydrochemical analysis to determine the quality of groundwater.
- grain size analysis of samples from the pumping wells in order to calculate the "efficient porosity".
- acquisition and evaluation of meteorological and hydrological data, in order to recalculate the water mass balance.

The aim of this study is the geologic-hydrogeologic analysis with emphasis on the hydrogeologic characteristics of the shallow and deep aquifers, as well as the development of a numerical model, which will simulate the groundwater flow field, calculate the groundwater mass balance, predict the future state of the system and eventually will be used as a management tool in future restoration attempts of this water system (Mylopoulos *et al.*, 2003).

2. General description of the study area

2.1. Geomorphologic characteristics

The hydrologic basin of Lake Koronia consists of the sub-basins shown in Figure 2. Until 1985 the lake's water surface covered an area between 45 km^2 and 49 km^2. Yet during the past years it has been decreasing constantly covering in 2002 an area of only 25 km^2. The water reserve of the lake decreased respectively from 200×10^6 m^3 in 1985 to 20×10^6 m^3 in 2002.

2.2. Geologic and tectonic structure

As shown in Figure 3, the western part of the Megdonia graben consists of the plain areas of the sub-basins of Lake Koronia and Scholarion while the eastern part consists of the plain area of the sub-basin of Lake Volvi. The basement rocks in the western part consist of metamorphic rocks of the Paleozoic age Serbo-Macedonian massif (two-mica gneisses, amphibolites), as well as of the Mesozoic age Circum Rhodope Belt (phyllites, quartzites, clay-schists, marbles and granites). The sedimentary rocks that fill the region are divided in the Pre-Megdonian and Megdonian system, as it can be seen in Figure 4 (Psilovikos, 1977).

According to the geological map the sub-basins of Lake Koronia and Scholarion consist of: *Black clays-1*, located at the bottom of the Lake Koronia with a thickness between 10 and 40 m. A second strata of *black clays*, about 5–15 m thick, lies at a depth between 30 and 80 m and extends from the east of the town of Lagada area to the west coast of the Lake Volvi area. These black clays correspond to the bottom of the Megdonia old-lake, (Figures 3 and 4), (Veranis and Katirtzoglou, 2002). Intercalations of sands, silt, red clays, pebbles and mixtures of them are located in the central part of the sedimentary basin, while intercalations of red-clays with mixtures of pebbles and sands are located in the western part and in the periphery of the sedimentary basin (Psilovikos, 1977).

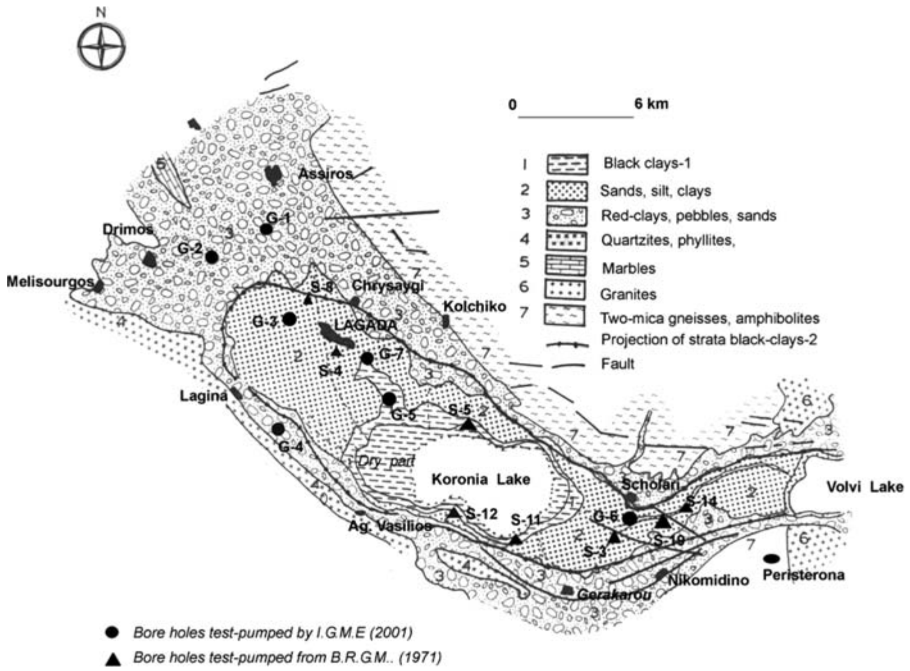

Fig. 3 Geologic map of the study area

Metamorphosed rocks are interrupted by neotectonic faults directed mainly from NW to SE, E-W, NE-SW, N-S. The discontinuities of the hard rocks are related to the tectonic activities in the Megdonia basin and result in increases of the hydraulic conductivity of the hard rocks in several positions (Mercier *et al.*, 1979). According to the geophysical study performed by BRGM (1972) and IGME (Thanasulas, 1983), there is a horst to the east of Scholarion, attributed to these faults. Considering that the groundwater flows along the main axis of the plain area, which is parallel to the direction of the main faults, we conclude that there are no significant obstacles to groundwater movement due to vertical movements of the faults.

2.3. Surface hydrology and water mass balance

According to prior estimations, until 1985 the water balance in the sub-basin of Lake Koronia was positive with a surplus of 37×10^6 m^3/year (Knight *et al.*, 1999). Almost the total of the runoff from the streams of the hilly-mountainous area reached Lake Koronia causing an overflow of the lake. During the past 20 years this overflow has stopped as surface runoff is mostly percolating to cover the groundwater deficit caused by water consumption. As a consequence only small water quantities (6×10^6 m^3/year) reach today Lake Koronia.

This study reevaluates the water balance in the plain and the western part of the hilly area of the sub-basin of Lake Koronia. The parameters used to calculate the water balance are described below.

2.3.1. Precipitation

Monthly rainfall data from the station of Lagadas, which is at an altitude of 110 m, were used. In order to calculate the water balance we used the mean annual precipitation for the period

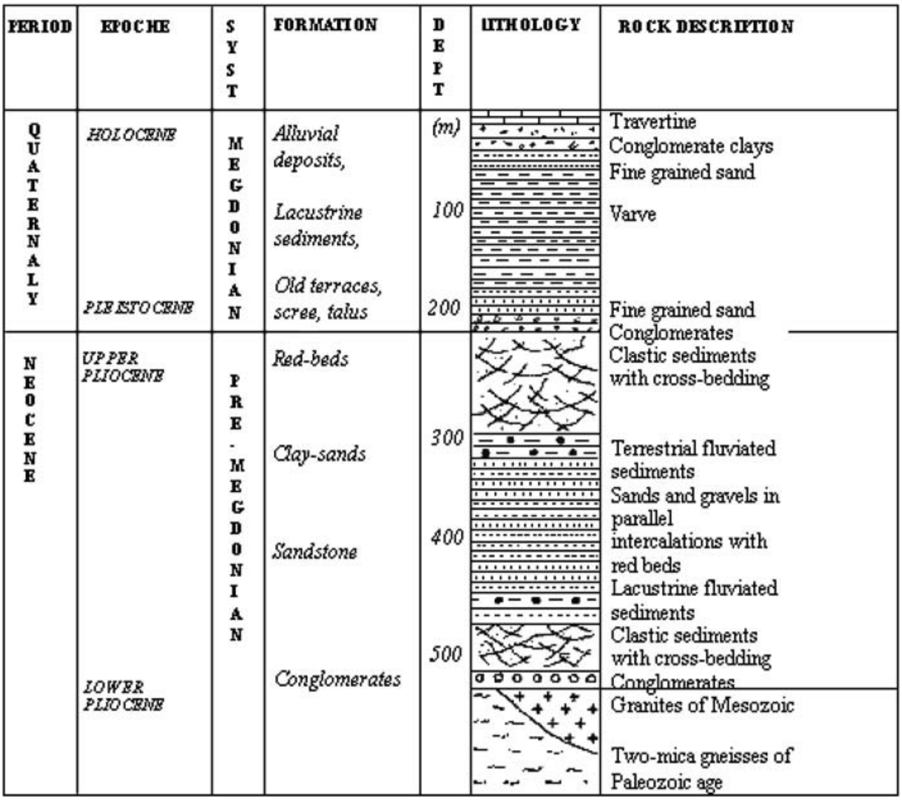

Fig. 4 Simplified stratigraphic column of the Megdonia sedimentary basin

1997–2001 which is 531 mm/year. Data for this time period were derived from the piezometric studies as well as from individual baseflow measurements in the streams. The total amount of precipitation in the plain and western hilly area of the sub-basin of Lake Koronia (the lake surface is excluded) is, for the same time period: $P_{\text{plain}} = 136.4 \times 10^6\ \text{m}^3/\text{year}$.

2.3.2. Evapotranspiration

When calculating the evapotranspiration, several parameters are taken into consideration, such as precipitation, temperature, sunlight, vegetation etc. For the sub-basin of Lake Koronia there are no data concerning sunlight, hence the evapotranspiration is calculated using the Turk-formula (Turk, 1961).

$$E = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \tag{1}$$

where: E = actual evapotranspiration, P = annual precipitation index ($P = 531\ \text{mm}$), $L = 300 + 25\text{T} + 0.05\text{T}^3$ and T = mean annual temperature in °C.

For the plain and the western hilly area of the sub-basin of Lake Koronia, with a mean annual temperature of $T = 14.9\,^\circ\text{C}$, the actual evapotranspiration is calculated as $E_{\text{plain}} =$

468.6 mm which corresponds to 88% of the precipitation. Accordingly, using the Thornthwaite formula (Thornthwaite, 1948), the potential evapotranspiration is calculated to be 420 mm/year, which corresponds to 82% of the precipitation. When inserting in the calculations the value derived from the Turk-formula ($E = 468.6$ mm/year), the mean annual evapotranspiration in the plain and in the western hilly area of the sub-basin of Lake Koronia is $E_{\text{plain}} = 120.4 \times 10^6\,\text{m}^3$.

The amount ($P_{\text{plain}} - E_{\text{plain}} = Q_{\text{plain}}$) available for runoff and percolation on a yearly basis is: $Q_{\text{plain}} = 16 \times 10^6\,\text{m}^3$, which corresponds to 12% of the total precipitation. In the plain area surface runoff is negligible (less than $1 \times 10^6\,\text{m}^3$/year) and appears only after intense rainfalls.

2.3.3. Surface and groundwater inflow from the hilly and mountainous area

The hilly and mountainous area of the hydrological sub-basin of Lake Koronia covers a total area of 464 km^2 with a mean altitude of 475 m, and contains the torrents' sub-basins to the north, west and south of the plain area. Data concerning the torrents' baseflow were acquired from on site base flow measurements in the torrents. The measurements were performed in the period 1997–2001, on a weekly basis and concerned the flow rate at two positions for each torrent: one at the boundary between the mountainous and the plain area and a second one near the lake. The results show that a mean annual amount of $14.75 \times 10^6\,\text{m}^3$/year percolates for this period along the streambeds in the plain, and only $6 \times 10^6\,\text{m}^3$/year reaches the lake.

Owing to the lack of meteorological data, an exact water balance calculation for this area is not possible. An estimation was performed instead, concerning the total available water amount for runoff and percolation. From the data of Lagadas station the following equation arises:

$$Y = 0.1533x + 477.54 \tag{2}$$

which results in a very poor correlation ($R^2 = 0.2$) between precipitation and altitude. On the contrary, a better correlation exists between altitude and temperature ($R^2 = 0.87$):

$$Y = -0.0049x + 15.744 \tag{3}$$

Equation (2) gives a mean annual precipitation of 550 mm for the years '97–'01, which in turn gives a mean precipitation in the hilly and mountainous areas of the sub-basin of Lake Koronia: $P_{\text{h\&m}} = 255.2 \times 10^6\,\text{m}^3$/year. According to the Turc formula, for a mean annual temperature of 13.4 °C (taken from Eq. 3) the evapotranspiration is: $E_{\text{h\&m}} = 218.3 \times 10^6\,\text{m}^3$/year, giving a total available water amount for runoff and percolation: $\text{P}_{\text{h\&m}}\text{-E}_{\text{h\&m}} = 36.9 \times 10^6\,\text{m}^3$/year. Subtracting the amount measured at the streams ($14.7+6 = 20.7 \times 10^6\,\text{m}^3$/year), a mean annual amount of $16.2 \times 10^6\,\text{m}^3$ is left. This volume is considered to be groundwater inflow as it comes from the transformed substratum of the hilly and mountainous areas, percolates laterally and enriches the loose aquifers of the plain (Katirtzoglou, 2001; Veranis and Katirtzoglou, 2001b).

2.3.4. Return flow from irrigation

In the saturated zone, the most significant return flow comes from irrigation and it is estimated to be between 4 and 5 $\times$ 10^6 m^3/year, which corresponds to a 10% of the total amount used for irrigation purposes.

2.3.5. Groundwater outflow

Outflow towards the sub-basin of Scholarion has been taking place during the last years, and it is estimated to be between 3 and 5 $\times$ 10^6 m^3/year. A more detailed discussion of groundwater outflow can be found in the section of hydrogeology.

2.3.6. Consumptions

Consumptions regard irrigation, industrial use and water supply.

1. Irrigation: According to local authorities, over 3000 wells are currently pumping in the study area, mostly from the shallow aquifers (20–60 m), to irrigate 17.5 acres of crops (mostly clover, corn, vegetables, tobacco and cotton). The majority are illegal, which means that they are not recorded in any official documents, a fact that makes it difficult to specify their exact locations and pumping rates. Thus, in order to estimate the water demand for irrigation, the irrigated areas were separated based on the kind of cultivation, according to the land use information that was collected from the local municipalities. The water demand calculations were based on the evapotranspiration conditions in the area and the soil parameters of the cultivations, and gave an annual amount of 42 $\times$ 10^6 m^3.
2. Industrial use: Twenty industries are located in the plain of the sub-basin of Lake Koronia, which pump water from the deep aquifers. Water consumption to cover their needs mounts up to 8 $\times$ 10^6 m^3/year.
3. Water supply: According to data collected from the local municipalities, 3 $\times$ 10^6 m^3 are required, to cover the water supply needs of the 28.000 permanent residents.

The total amount of outflow due to consumption and groundwater outflow is estimated to be 49 $\times$ 10^6 m^3/year.

2.3.7. Inflow-Outflow

Based on prior calculations, the mean total amount of inflow due to percolation, irrigation return flow and surface as well as groundwater inflow is 55.4 $\times$ 10^6 m^3/year.

Following the solution of the water balance equation with a mean annual precipitation value in the Lagadas station of 531 mm/year, the inflow (for the time period 1997–2001) is 57.7 $\times$ 10^6 m^3/year and the outflow is 58 $\times$ 10^6 m^3/year (Table 1). Consequently, 0.3 $\times$ 10^6 m^3 are subtracted every year from the permanent water reserves. This amount is practically negligible and does not justify the annual fluctuation of the piezometric surface. Comparing the results of the piezometric study to the evaluations of the water balance, we conclude that the annual losses from the permanent water reserves are underestimated when solving the water balance equation. This is mainly due to the fact that there are insufficient data, which leads to miscalculations.

2.4. Hydrogeology

As it has already been mentioned, there are two groups of geologic formations, namely the rocks and the loose sediments of the plain area. In the rocky formations, water circulates through the faults and the permeability varies significantly, depending on the extent and the fragmentation of the rocks. According to the microtectonic observations (Kilary method) performed in 1994 (Demiris, 1994), the hydraulic conductivity coefficient (K) along the faults is estimated to be between 2.3×10^{-6} m/s and 7.1×10^{-7} m/s. From the water supply wells that have been drilled in the crystalline schist formations of the hilly area, it has been found that the groundwater flowing through the faults at a depth greater than 30 m is under pressure, having rates between 10 and 25 m^3/h. The aquifers of the plain area are being recharged by this groundwater through lateral percolation.

As far as the hydrogeological conditions in the plain area are concerned, the stratigraphy in the whole sub-basin, as it can be concluded from the 6 new boreholes drilled during the present hydrogeologic study, is composed of alternating layers of clay, sand, pebbles, silt and compounds of them. The percentage of clay in a formation is the main factor determining whether the formation will be characterized as an aquifer or not. Apart from the central area of the sub-basin, where black clay can be found, in the rest the lateral stratigraphic correlation, even between neighboring boreholes, is often impossible owing mainly to the rapidly changing sedimentary environment. Through the observation of the lithological sections of the boreholes, a higher participation of red clays can be found towards the sub-basin's margins.

In the formations till a depth of 80 m, in the central part of the sub-basin, there are black clays, which indicate the existence of a lake deposit. In order to identify black clays traced in the lakeshore area and on the bottom of the lake, 11 shallow boreholes (19–25 m) were drilled. The in-situ pumping tests have shown that the hydraulic conductivity coefficient of the black clays traced in the dried-out part and the lakeshore area is very small and not greater than 10^{-9} m/sec.

Shallow aquifers are considered those which are found at a depth of no more than 60 m, and are partially phreatic and partially confined. Their state can change at places according to the season, being confined during the wet period and phreatic during the dry period because of the groundwater level's drop. The storativity coefficient values derived from several pumping tests (Table 2), show that the shallow aquifers are in between a confined and a phreatic state. The shallow aquifers are being exploited mostly for irrigation purposes through approximately 3000 wells.

Deep aquifers are found at depths between 60 and 450 m. The part of the basin where black clays are found, can be considered as the separating impermeable or semi-permeable layer between the deep confined and the shallow confined or phreatic aquifers. In the remaining part of the basin, which extends from the central part to the margins, the corresponding separating boundary is the layer of red clays.

Although all former studies in the area have concluded that there is no hydraulic contact between the shallow and the deep aquifers, the present study, having a better picture especially of the deep aquifers because of the 6 new deep boreholes, has come to the opposite conclusion. In fact, along the vertical stratification of the basin, several red clay beds can be found making it thus difficult to distinguish a particular layer. The red clay beds are of limited extent and consist of red clay, sand and gravel mixtures. Thus, a direct hydraulic conduct between the deep and the shallow aquifers can be assumed. The deep aquifers are being exploited mostly for irrigation, water supply and industrial purposes through approximately 500 wells.

Table 1 Water mass balance in the Koronia's lake plain area

Inflows ($\times 10^6$ m^3)			Outflows ($\times 10^6$ m^3)	
Direct Surface percolation in the plain area P_{plain}-E_{plain}:		16	To Scholarion aquifer:	4*
From hilly and mountainous area	Streambed Percolation	14.7		
	Torrents to Lake	6	Withdrawals	54*
	Lateral groundwater inflow	16.2*		
Returns from irrigation		5*		
Total		57.7		58

Note. *estimated amount

Table 2 The hydraulic parameters of the aquifers

	K (m/sec $\times 10^{-5}$)	T (m^2/sec $\times 10^{-3}$)	S $\times 10^{-3}$	Q/S$_w$ (m^3/h.m)	Source
Shallow aquifers	34.0–61.3	5.1–9.2	6.1–12.0		(BRGM, 1972)
Shallow and deep aquifers	0.7–9.0	0.51–6.3	1.3–5.1	0.5–7.4	(BRGM, 1972) and (Demiris, 1994)
Deep aquifers	1.02–7.48	0.16–5.69	0.79–4.53	0.27–5.4	(Veranis–Katirtzoglou, 2001)

2.5. Hydraulic parameters

The hydraulic parameters of the aquifers were estimated based on results of the pumping tests carried out in the shallow and deep boreholes during the periods 1970–71 (BRGM) and 2001 (IGME) respectively. The first study has determined the aquifer's geometry through a set of geophysical measurements and has measured the hydraulic conductivity coefficient *K* and the storativity coefficient S through pumping tests, which have been performed at 11 points in the upper aquifer. IGME, in order to cover needs of the present study, has carried out a relevant set of pumping tests at 7 different points in the deep aquifer.

2.6. Piezometric heads measurements

Three sets of piezometry data are currently available. One from the period 1970–71 (BRGM, 1972), one from the period 1991–1992 (Vatseris, 1992), and one from the present study (1997–2002, IGME) which includes the 7 new boreholes operating with hydraulic isolation of the first 50–70 m in order to exclude, as far as possible, the shallow aquifers from groundwater withdrawal. From what has been already mentioned, it can be deduced that the two aquifers present a uniform piezometric surface. If Φ_{1i} is the shallow aquifer's hydraulic head at the point i and Φ_{2i} the deeper aquifer's head at the same point, then the difference $\Phi_{1i} - \Phi_{2i}$ varies between 0 (at the majority of the sub-basin's area) and + 3 m (to the east of Lagadas'

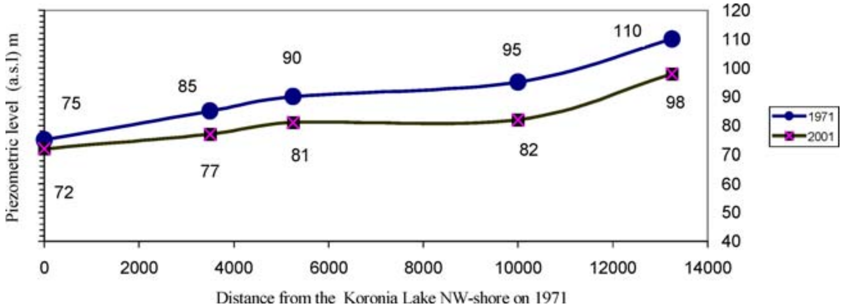

Fig. 5 Depth of the piezometric level along the main axis of the plain of the Koronia Lake sub-basin area for the years 1971 and 2001

area), while in the area to the east of the lake it is −2 m. Even in the area where there are industrial wells pumping only from the deep aquifer at high extraction rates, and therefore the difference $\Phi_1 - \Phi_2$ is very high, reaching even 20 m, after 2–3 months of no pumping activity, the difference becomes negligible. This remark confirms the hypothesis of hydraulic contact between the two aquifers.

From the first set of observations (‘70–‘71) an artesian zone was found to the west and northwest of the lake, which now has disappeared because of the water table’s drop. This drop can be seen in terms of mean values in Figure 5 along the main axis of the plain area (lake-northwest direction). From 1971 to 2001 in the area around the lake the head loss was 2–4 m, 7–9 m at Lagada’s area (4 km from Lake), 11–13 m at Iraklion (6 km from Lake), and near the national road of Liti-Assiros 12–15 m (approximately 10 km from Lake). The total mean aquifer’s drawdown in Lake Koronia sub-basin for the period ‘71–‘96 is 5 m (0.2 m/year) (wet period). For the next years, as recent observations show, this drop has been doubled as it rises to 2.5 m for a 5year period (‘97–2001, 0.5 m/year), as a consequence of the intensification of pumping activities. The higher head losses occur in the areas with intense exploitation of the deep aquifer, such as the industrial zone to the northwest, or areas with poor transmissivity, such as the sub-basin’s margins. The difference between the aquifer’s level underneath the lake (72–74 m) and the lake’s surface (69–70 m) confirms the poor lake-aquifer interaction.

Finally in the eastern part, over the Scholarion horst, there is a groundwater limit formed by the water that percolates through the 2 surface torrents. This area is practically functioning as a boundary separating Lake Koronia from the aquifer of Scholarion sub-basin. As one can conclude from these observations there is a continuous head loss along this boundary through the years (from 77 m in 1971 to 74 m in 1991 and to 71.5 in 2001), proportional to the loss in the rest of the aquifer.

Examining the seasonal water table fluctuations (wet-dry period), as they resulted from the latest observations, they are higher at the sub-basin’s margins and at the western-northwestern part than in the central plain area. For example, in the year 2000 the mean value of this fluctuation was 4.5 m at the margins and the western-northwestern part, while in the center it was 3.6 m. According to the hydrogeological analysis of the previous chapter, this difference could be even higher, given the different hydrogeologic properties of the 2 formations. Yet, the intense pumping activity in the sub-basin’s center causes such a drop to the water table that a period of at least 2–3 months is required for the water table to recover.

3. Groundwater simulation model

3.1. The conceptual model

According to previous studies in the area, a shallow and a deep aquifer exist. These were thought to be separated by a single, practically impermeable layer of clay, which covered the entire sub-basin's area at a certain depth. Yet, the latest hydrogeological research of this study proved that it is not a single clay layer but rather equitant layers of clay, sand, silt and compounds of them, one beneath the other, with black clay being the critical formation separating the aquifers. Hydrogeologically speaking, as can be concluded from the existing lithological sections, there are 3–7 different aquifers between the depths of 50 and 300 m which are composed by sand, silt and gravels mixed with a little clay.

This alteration is practically equivalent to a 2-layer aquifer system, separated by a third impermeable layer of black clay. Both aquifers are functioning with similar mechanisms and both are being recharged within the sub-basin's boundaries. The top one is mostly unconfined, having a depth varying between 40 and 60 m, and consists of lake deposits separated by wedges of clay. This aquifer is being recharged directly through surface precipitation. The deeper aquifer, on the other hand, is confined, with a depth ranging from 100 to 300 m, and is being recharged through the torrent precipitation and lateral groundwater volumes flowing through the fragmented formations bounding the aquifer. Furthermore, there must be an indirect hydraulic continuity between the 2 aquifers as their piezometry's similarity implies. The above assumptions are shown in Figure 6, which represents the system of aquifers in a cross-section.

In order to simulate the black clay bed hydrogeological behavior, the system of aquifers is separated into 3 layers in the cross-section and 3 zones with different hydraulic conductivity values in the plane, as is shown in Figure 7. The black clay layer exists only in the intermediate zone of the second layer, separating thus the shallow from the deep aquifer. In the area of the other two zones, there is no definite separation between the two layers and a direct contact of the 2 aquifers is supposed. The complex stratigraphy is thus approached by the heterogeneity of the hydraulic parameter fields (Peck *et al.*, 1988).

The lake's bed is practically impermeable, as the latest pumping tests have shown ($K = 10^{-9}$ m/s). Thus, the contact between the lake and the aquifer, which theoretically depends

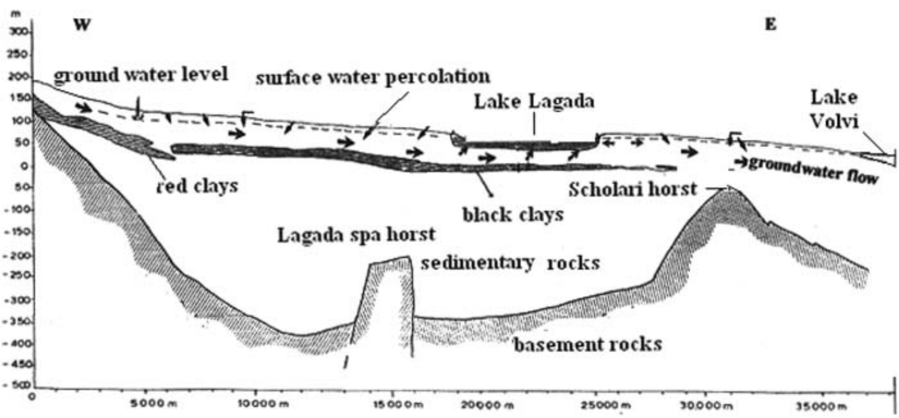

Fig. 6 Conceptual representation of the system of aquifers in a cross-section

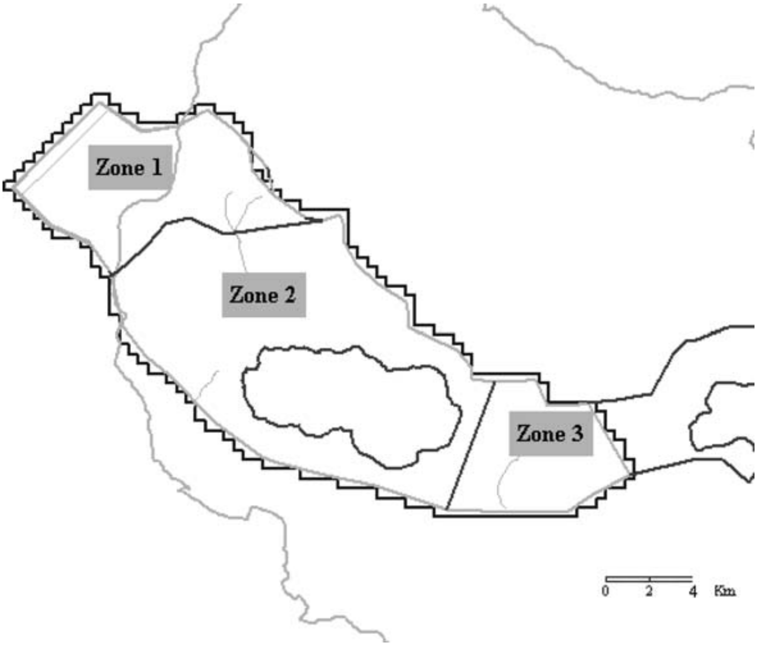

Fig. 7 Different hydraulic properties zones

on the aquifer's water table level, has to be rather poor and not critical for the lake's water level.

For the simulation of the Scholarion horst, a specified, time variant, head condition can be used, which, according to the computed heads of the adjacent cells to the west, will determine whether there is an outflow from the aquifer towards the adjacent aquifer of Scholarion sub-basin through this boundary, or vice versa.

3.2. Development of the model

The development of a quasi-three-dimensional simulation model of Lake Koronia sub-basin aquifer was based on the assumptions and principles of the conceptual model. The Modflow computer code, developed my McDonald and Harbaugh (1988), has been used in the present study. It is a well documented and tested, easy to use code for developing multi-layered, finite difference simulation models of complex geological systems. Its modular structure consists of a main program and a series of highly independent subroutines called modules, each dealing with a specific feature of the hydrogeologic system to be simulated. The division of the code into modules makes the program flexible and permits the user to examine the specific hydrogeologic features of the model independently.

The governing equation for the three-dimensional transient flow in a heterogeneous and anisotropic aquifer, that Modflow solves, is:

$$\frac{\partial}{\partial x}\left(K_x x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z z \frac{\partial}{\partial z}\right) - W = SS \frac{\partial h}{\partial t} \quad (4)$$

where: K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z axes, which are assumed to be parallel to the major axes (Lt^{-1}) h is the hydraulic head (L), W is the source-sink term (t^{-1}), Ss is the specific storage (L^{-1}); and t is time (t).

3.2.1. Boundary conditions

According to the preceding assumptions (Figures 6 and 7), the boundaries of the present modeling study were determined by reviewing the available hydrogeologic data, and are shown in Figure 8.

The lateral boundaries, as well as the deep aquifer's bottom are impermeable, except of the lateral inflow of groundwater through the faults of the surrounding rocks. This inflow takes place along the N-NW boundary and at the SE of the lake and has been simulated by the steady influx assumption (Neumann type condition). The exact mechanism of this inflow, such as intrusion surfaces (length and depth) and rates, is not known with certainty. Instead, a small number of head observations near these surfaces is available, and a mean annual inflow rate approximation (16.2×10^6 m^3) can be derived from the sub-basin's volume budget, for the last 5 years. The exact rate was part of the model's calibration process (within a range from 10 to 20 million m^3/year).

The lake is simulated as a specified, time variant (wet-dry period), head boundary condition (Dirichlet type condition), in which the hydraulic head remains equal to 70 m during the wet period and falls to 69.5 m during the dry period, representing the mean level of the water surface of the lake during the past years (Hunt *et al.*, 2003). The conductance, a Modflow parameter that characterizes the lake-aquifer interaction, was set to 3.5×10^{-6} m/d, a value corresponding to a mean $K_z = 10^{-9}$ m/s and a lakebed with an average of 25 m thickness, values that were derived from the recent observations in the lakeshore's area.

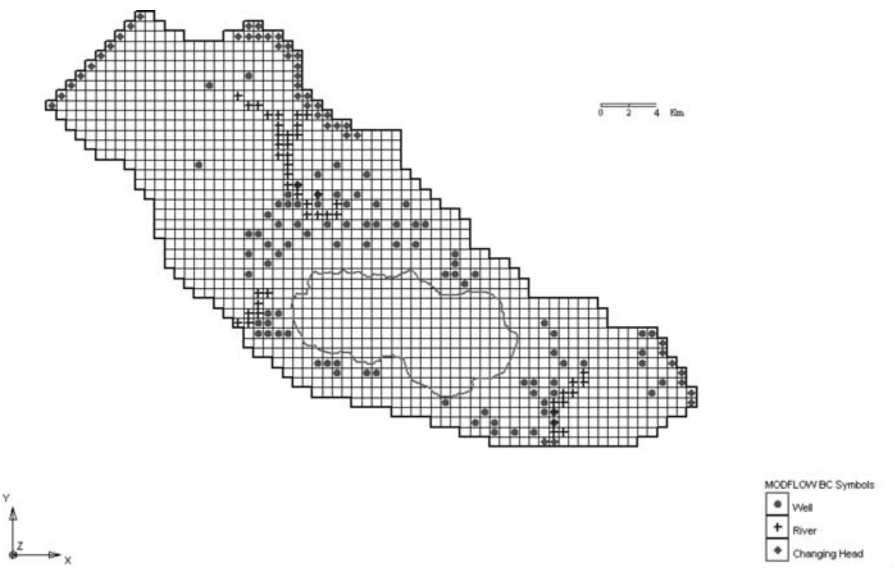

Fig. 8 Finite difference grid and boundary conditions of the study area

The study area has been discretized into an orthogonal grid of 44 rows, 67 columns and 3 vertical layers, with a grid spacing of 500 m (Figure 8). This spatial discretization has been found to be adequate in view of the available data and the computational time. Furthermore, such a grid spacing, given the time step chosen for the solution, meets the requirements for numerical stability maintaining the Courant number below 1, even in areas with intense pumping activity. The resulting network consists of 5.896 cells, covering an area of 282 km^2.

In the vertical direction, two layers simulated the two aquifers, having variable thickness depending on the surface and the Scholarion horst. A third intermediate layer has been used to simulate the dividing impermeable formation, with an indicative thickness of 10 m.

3.2.2. Hydraulic parameters fields

The hydraulic parameter data fields have been determined based on the measurements of Table 2. A spatial interpolation method (Shepard's method) has been used to produce each parameter's data field and assign a value to each cell. The storativity coefficient S, has been introduced into the model in the form of specific storage Ss and specific yield Sy, depending on whether the aquifer is confined or unconfined, according to the computed hydraulic head level. For the Sy an estimated value 0.08 for a mean representative effective porosity parameter is given.

A leakance term in the intermediate layer 2, denotes the existence of black clay bed in zone 2 (leakance $= 1 \times 10^{-9}$ l/s) and the direct contact of the shallow and deep aquifers in the rest zones 1 and 3 (leakance $= 1 \times 10^{-3}$ l/s).

3.2.3. Aquifer's recharge

Recharge has been estimated by quantifying the surface water bodies that enter the aquifer directly through rainfall percolation, through the torrents' beds and the lake. The value for the direct rainfall percolation in the plain area has been estimated based on the hydrology as discussed above and set to 16 m^3/year. As far as the recharge coming from the streambeds and the lakebed percolation is concerned, it has been entered using the conductance parameter, which combines a mean vertical hydraulic conductivity of their geological substrate (1×10^{-5} m/s for the torrents, 1×10^{-9} m/s for the lake) with the water level in these streams.

3.2.4. Withdrawals

All three types of withdrawal wells exist in the sub-basin: water supply wells covering the needs of the approximately 30,000 inhabitants, industrial wells for the 20 industries of the region, and a large number of wells (about 3000), mostly around the lake, for the irrigation of the 17, 500 acres of crops. The uncertainty concerning the exact total annual withdrawal rate of the latter led us to consider irrigation pumping as another parameter-target of the model calibration. The relevant wells in the model are extracting, mostly from the shallow aquifer, a mean annual total volume, which ranges between 35 and 45×10^6 m^3. All the other wells (urban supply and industrial) are deeper and less powered (known total rate: 11×10^6 m^3 annually).

3.3. The model's calibration

A combination of the BRGM and the IGME pumping test data at a total of 18 different points of the study area, provided the information regarding the aquifer's hydraulic parameters. The relation between the number of the hydraulic parameter's measurements and the errors in the output of groundwater models – especially in cases where groundwater conditions are complex – has been frequently discussed in the literature (Davis and Dvoranchik, 1971; Iman & Helton, 1988; Peck *et al.*, 1988). Additional errors in the model's output are due to the fact that parameters often have to be estimated since there aren't any on site measurements. Although both the model chosen to represent the spatial variation of a parameter (uniform domain or uniform zones, or heterogeneous domain) as well as the method of averaging values within a zone or domain are important, the critical factor in most models seems to be the small number of measurements. In the present study, in order to define the values of the parameters a combination of the zoning method (the 3 zones of Figure 7) and of the method of spatial interpolation within each zone, from local measurements, has been used. The Value of Information Analysis could provide a means for quantifying the reduction of uncertainty from additional measurements (Freeze *et al.*, 1987) but this is beyond the scope of this study. Furthermore, it seems most improbable, for the time being, that additional on site measurements may be performed in our study area. Thus, the observations of the hydraulic parameters (K, T and S) were considered to be the "least uncertain" of the entire simulation procedure, compared to other parameters, and within the accuracy limits set for the model, as they have at least resulted from on site pumping tests. On the contrary there is a great uncertainty regarding the vertical leakance of the intermediate layer, which reflects the uncertainty regarding the interaction of the 2 layers. In other words, what remains to be proved is the conceptual model hypothesis about clay's intermediate function in the system. In addition, other sources of uncertainty that make the modeling process difficult are the annual rates of lateral inflow (from 10 to 20 million m^3), the outflow to the east towards the Scholarion sub-basin's aquifer (from 3 to 5 million m^3), and the exact volume extracted from the irrigation wells (from 35 to 45 million m^3). Their values have resulted from estimations rather than on site measurements, and are therefore subjected to the calibration process. The alternative values that have been used in the calibration process for these parameters have been taken from the water mass balance equation used in the Hydrology section.

The model's calibration is based on the existing 66 hydraulic head observations at different points of the aquifer, for the years 1997 and 2000 (wet-dry period value/year), as well as the wet period of 2001, which are the only available data in the region, as far as piezometry is concerned (Figure 9a). Considering as an initial condition the 1996–1997's hydraulic head distribution (wet period) a trial and error procedure was adopted to calibrate the model. The aim was to achieve a good match between computed and observed heads for the remaining 4 available head distribution fields (1997 dry, 2000 wet and dry and 2001 wet), by adjusting, after each simulation, the above inflow and outflow rates, as well as the vertical leakance term of the intermediate layer. Additional runs were also made for the final adjustment of the hydraulic conductivity field, for both aquifers. The procedure caused a refinement of several interpolated local values of K at the vicinity of observations with high differences between computed and observed heads, and determined the final boundaries of the 3 zones of Figure 7.

Several runs were made in order to obtain an acceptable fit with the observed values for the 5-year period ('97–'01). Finally the calibration process has resulted in the final form of the model which has produced the minimum possible root mean square error (RMSE), which is the average of the squared differences between all the observed and the relevant simulated

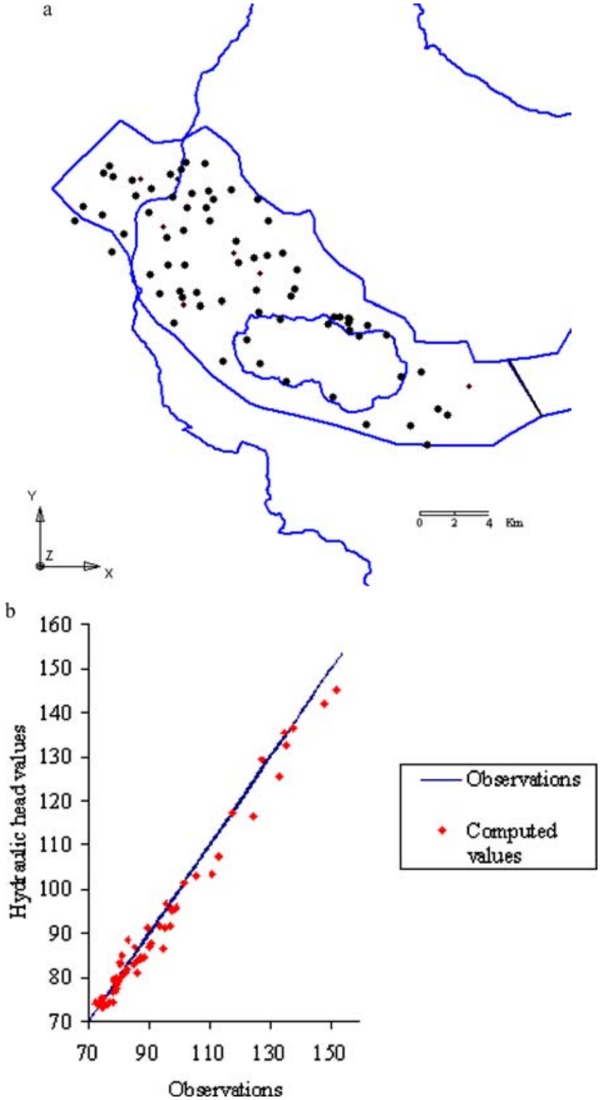

Fig. 9 (a). the 66 hydraulic head observations; (b). Computed versus observed head values for each observation point (wet period 2001)

heads. The RMSEs of the initial and final runs, for each of the 4 head distribution fields are given in Table 3. The decrease in RMSE indicates the significant improvement compared to the previous runs, especially compared to the starting point assessments. The piezometry of the deep aquifer, as computed by the model for the wet period of 2001 is shown inFigure 10.

The relationship of computed versus observed values for each observation point and for the latest data set (2001) is illustrated in the plot of Figure 9b. High deviations from the diagonal line occur mostly in the NW area, due to the high local hydraulic gradients, which demand a very detailed grid for their simulation. It is notable that if we exclude this particular area, the RMSE in the remaining field is reduced to less than 1 m values.

Table 3 Comparison between first and final runs of the model

	RMSE – First run	RMSE – Final run	% RMSE – reduction
97 dry	3.8	1.6	58
2000 wet	6.1	2.4	61
2000 dry	5.7	2.3	60
2001 wet	6.9	2.8	59

Fig. 10 Simulated heads (in meters) of the deep aquifer, for the wet period of 2001

4. Results of the model for the period 1997–2001

A careful examination of the hydraulic head distributions as simulated by the model for the period 1997–2001 makes it clear that the main direction of the groundwater flow is parallel to the sub-basin's main axis, following the N,NW-S,SE direction in the sub-basin of the lake and the *W-E* direction in the area of the lake (Figure 10). In the N-NW part of the aquifer (zone 1), where there is also the lateral inflow, there is an intense densification of the equipotential lines, caused by the high values of the hydraulic gradient (14‰–17‰). In the center (area of Lagadas till the lake as well as in the area near the lake (zone 2)), the hydraulic gradients decrease (2.2‰), and therefore the calculated values match the measurements very good.

Table 4 Groundwater mass balance, calculated by the model

Inflows ($\times 10^6$ m^3)		Outflows ($\times 10^6$ m^3)	
Through lateral boundaries	13.66	To Scholarion aquifer	3.43
Torrents percolation	14.75	To Koronia Lake	0.35
Surface percolation	17.32	Withdrawals	49.5

Finally in the eastern part, the presence of the Scholarion horst as a boundary to the east becomes obvious. Groundwater flow is being separated in two directions, mainly in the direction *E-W* from Scholarion till the lake, and in the direction *W-E* in the area to the east of Scholarion, sending thus an amount of 3–5 million cubic meters annually to the adjacent aquifer of Scholarion sub-basin, as the model has calculated.

In the largest part of the aquifer, except of the areas where there is intense pumping, the hydraulic heads of the 2 aquifers (shallow – deep), as computed by the model, coincide. Yet, even in the areas where they don't, the differences are not bigger than a few meters. These can be better understood (besides the existence of a black clay bed between the 2 aquifers) by taking into consideration the different kind of pumping in the 2 aquifers. The shallow one is being pumped by a large amount of drills, evenly distributed throughout the plain, which pump only during the dry period. In the deep one on the other hand there are fewer drills, which pump by far a larger volume (industry and water supply) and throughout the whole year, causing thus more intense pressure cones in the area.

Figures 11a,b, present the change in time (1997–2001) of the computed hydraulic head at 10 different observation points of the aquifer. These points can be seen in Figure 11c.

4.1. Groundwater mass balance

The groundwater mass balance, as the model has calculated it, can be seen in Table 4. An annual deficit of approximately 7.5×10^6 m^3 is calculated which is extracted by the non-renewable storage and yields the mean annual piezometric drop of 0.5 m.

Regarding the lake's volumetric budget, for the same period (1997–2001), the very poor groundwater recharge yields a marginal equilibrium strongly dependent on the industrial waste inflow (8×10^6 m^3) and the annual precipitation. For a less wet year the lake will be completely dried out (e.g. with a 480 mm/year precipitation, a 4–5 $\times 10^6$ m^3 deficit is created in a water system that bears currently a water volume of 15–20 $\times 10^6$ m^3).

5. Prediction of future conditions – The model as a management tool

The calibrated model is used for predicting future conditions of water levels. Owing to the meteorological uncertainty, regarding mainly future rainfalls, three hypotheses referring to a 5-year period were inserted into the computational process:

(a.) the next 5 years a repetition of the past decade's rainfalls will occur ("mean 1" assumption),
(b.) each future year will have the same mean precipitation with the mean annual precipitation over the last 20 years, equal to 515.1 mm ("mean 2" assumption), and
(c.) a succession of the 5 driest between the last 20 years will occur for the next 5 years ("dry" assumption).

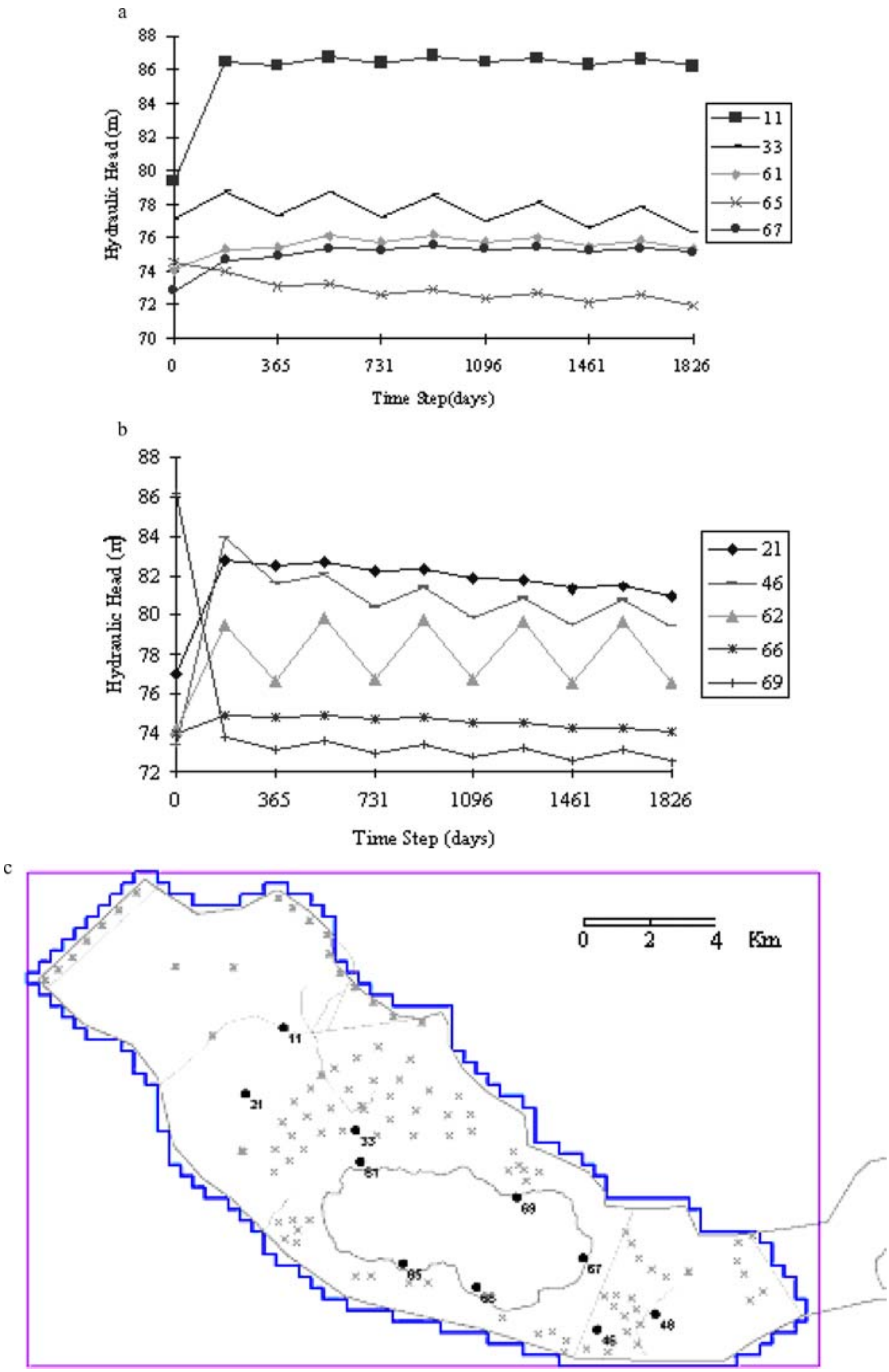

Fig. 11 (a). and (b). Change in time ('97–'01) of the computed hydraulic head at 10 different observation points of the aquifer, (c). Position of the observation points

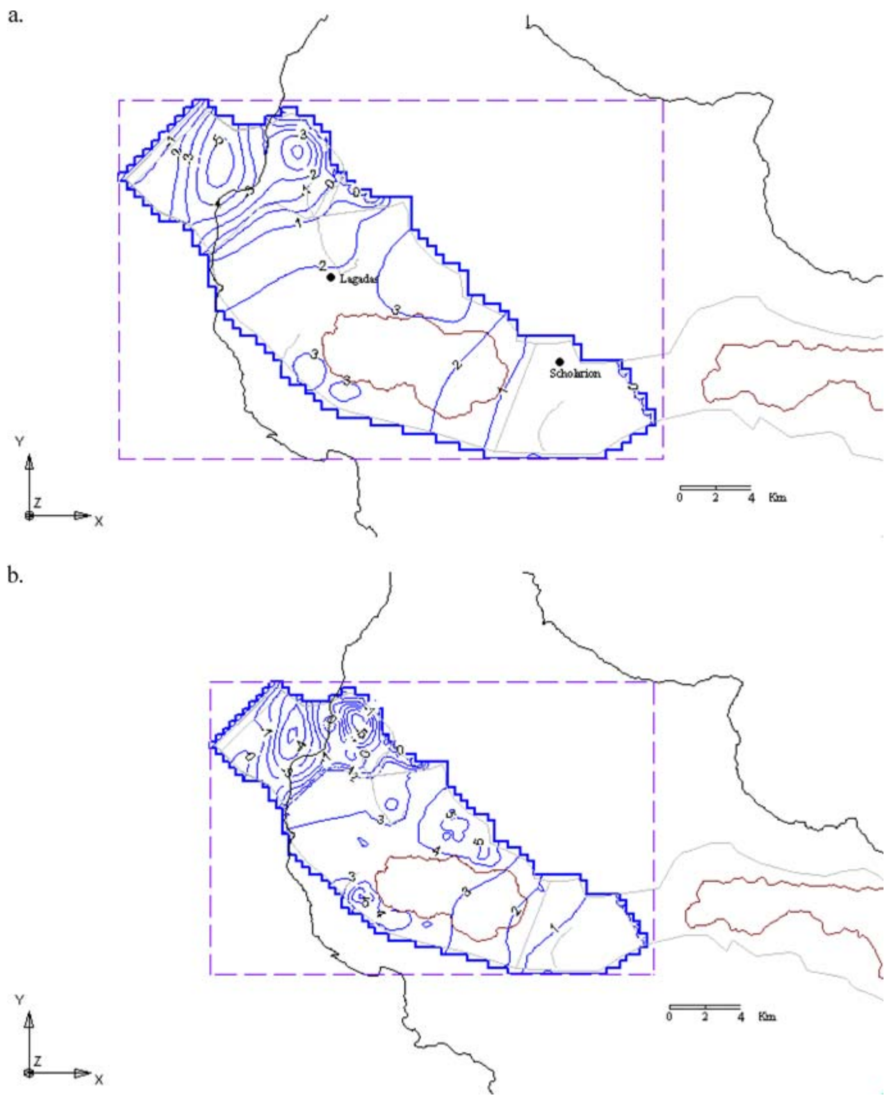

Fig. 12 (a). Hydraulic head losses (in meters) within 5 years. Do nothing scenario ("mean 1" assumption), (b). Hydraulic head losses (in meters) within 5 years. Do nothing scenario ("dry" assumption)

For case "a" the results show that the negative balance between replenishment of water resources and their consumption continues (7.5 million m^3 for a mean hydrological year) causing a cone of depression all over the aquifer with drawdown values varying between 2 m at Lagadas (to the NW of the lake), 4.5 m underneath the lake to the west, falling to 2 m at the east of the lake. A drawdown map for this case is shown in Figure 12a. Almost the same results are given for case "b". For the "dry assumption" (case "c", Figure 12b) the situation appears, as expected, even worse, with a mean drawdown's increase of 4 m throughout the

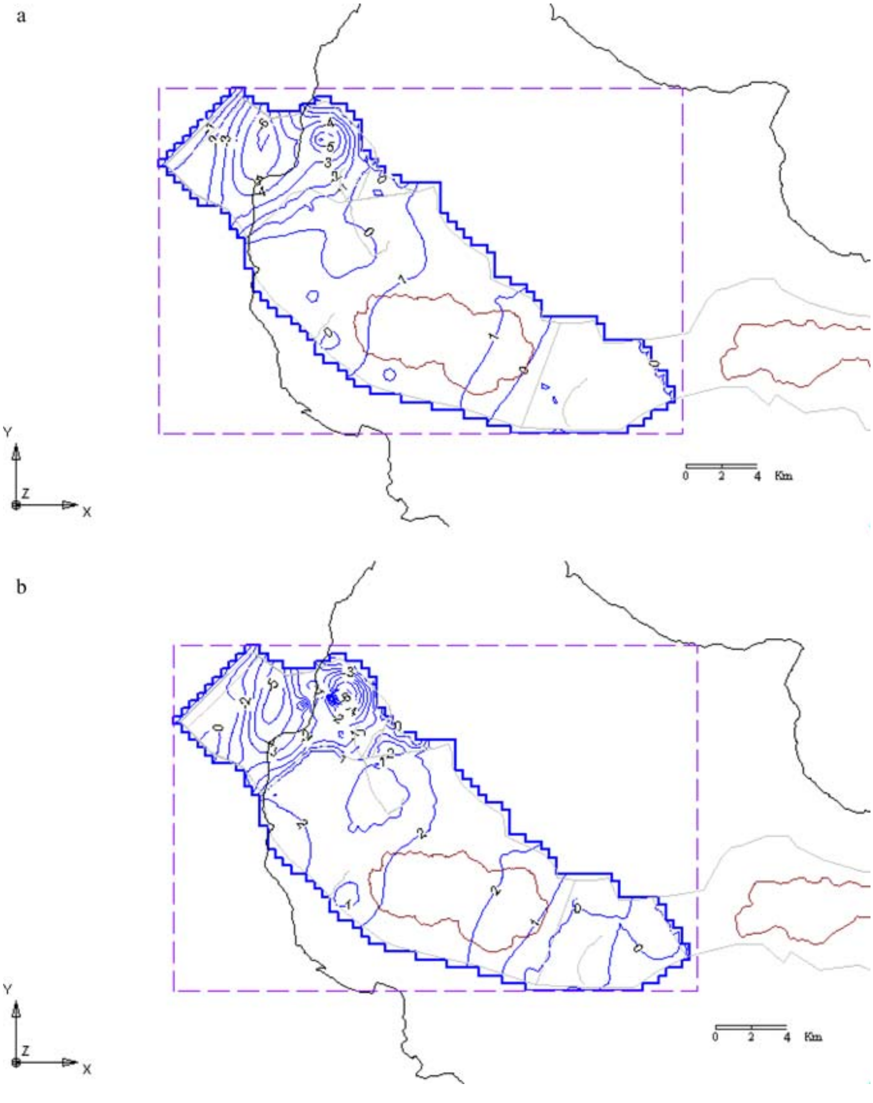

Fig. 13 (a). Hydraulic head losses (in meters) within 5 years. Decrease of the irrigations pumping per 7.5 m^3/year scenario ("mean 1" assumption), (b). Hydraulic head losses (in meters) within 5 years. Decrease of the irrigations pumping per 7.5 m^3/year scenario ("dry")

entire aquifer and a maximum drawdown of 11 m to the north of the lake (a mean annual drawdown of 1.5 m over the entire aquifer and a mean deficit of 16 million m^3/year).

As expected, the corresponding lake water budget in all 3 cases is even more discouraging, proving that there is a serious danger threatening the sole existence of a very significant ecological system.

In order for the project to comply with the concepts of integrated approach and sustainable management, several complementary measures needed to be taken. Therefore, combinations of the above-mentioned scenarios with water saving in the agricultural sector, in the form of a

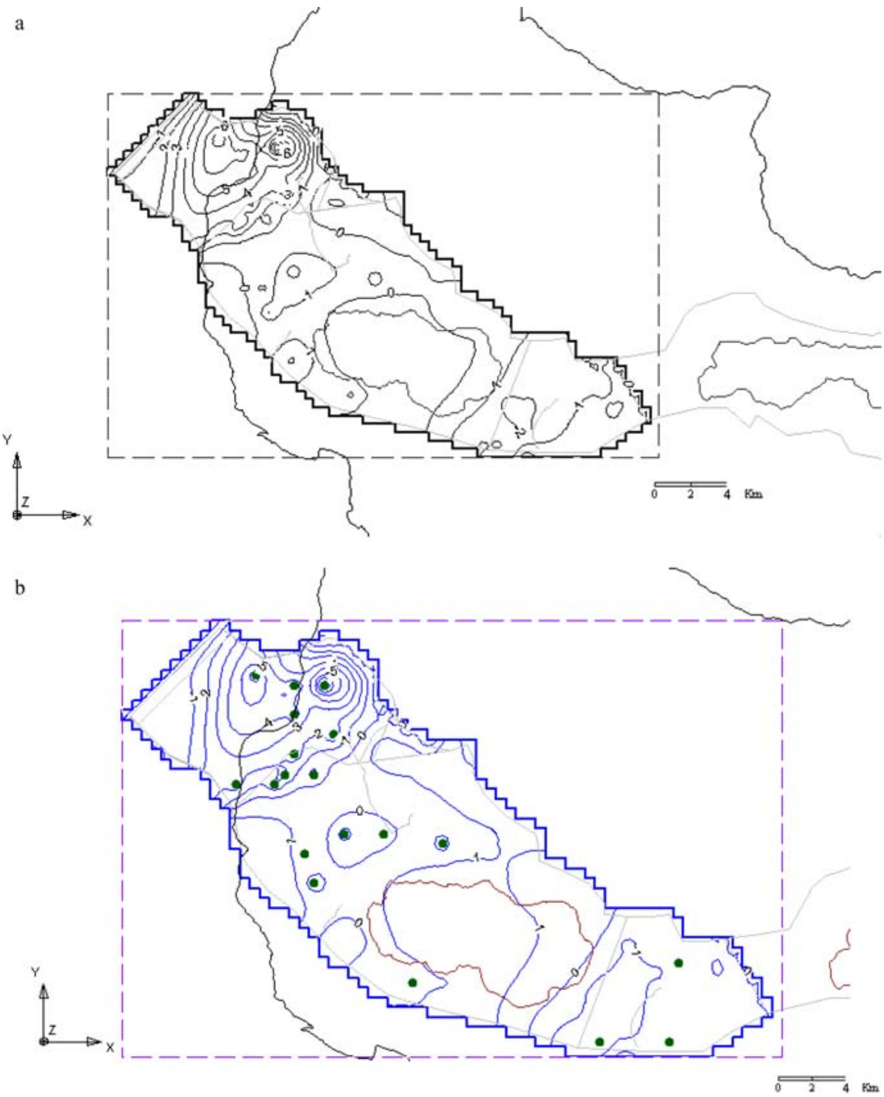

Fig. 14 (a). Hydraulic head losses (in meters) within 5 years. Decrease of the irrigations pumping per $15\,m^3$/year scenario ("mean 1" assumption), (b). Hydraulic head losses (in meters) within 5 years. Decrease of the irrigations pumping per $15\,m^3$/year scenario ("dry")

decrease of pumped water were examined, in order to restore the water balance. This decrease could be placed within a general framework of policies which the State intents to implement in order to preserve the aquifer and the Lake of Koronia. Two new sets of scenarios resulted from this combination, namely one set where the decrease is 7.5 million m^3 (equal to the annual groundwater volumetric deficit), concerning thus the safe yield concept, and another one, where the decrease is 15 million. It should be noted that in both cases the decrease was simulated by the model through a uniform decrease of the recharge rate of the wells, and not through a decrease of the amount of the wells.

For the first scenario (decrease of 7.5×10^6 m^3) and the "Mean I assumption" the results are shown in Figure 13a. As can been seen in this figure, the head loss decreases significantly and varies between 0 and 1 m in the area between Lagadas and the lake, where there is the most intense pumping. The state of the rest of the aquifer, as can be seen in Figure 13a, corresponds to that of the former scenario, whilst the mean piezometry is elevated per 2 m in the entire aquifer. The total water balance at the end of the 5 years confirms the above-mentioned observations, showing a total deficit over the entire decade of 3 million (about 0.6 million per year). Based on the fact that the annual deficit was 8 million, it becomes obvious, that a profit of 7.5 million per year would lead to an almost well balanced volumetric budget.

The same scenario combined with the extreme "Dry assumption" shows as expected more intense head losses and holds gloomy prospects for the future of the aquifer (Figure 13b). The head loss in the area of Lagadas and the lake reaches 2 m and becomes equal to 0 m in the area of Scholarion. The total water balance at the end of the 5 years shows a total deficit of 53 million (10.5 million/year).

The above-mentioned scenario is a quite realistic one, which has been proposed to the Ministry of Agriculture and has good chances of being implemented. Nevertheless this scenario will just stabilize the current state of the aquifer in the future, without taking any measures for the aquifer's rehabilitation. In this direction another set of computations was performed, regarding a decrease of 15 million/year. Although its implementation is considered to be most improbable, at least for the next years, the scenario was developed in order to provide a full picture of the managerial perspectives of the area.

As can be seen in Figure 14a ("mean I assumption"), this scenario could lead to a partial inversion of the aquifer's fate, as in almost the whole field there is a piezometry elevation (indicated by negative isocurves) instead of drop. This elevation will lead the aquifer in the next 5 years to the condition it was 5 years ago. A probable continuation of this water preserving policy in the future could lead the aquifer to a total rehabilitation. Even in the extreme "dry assumption" scenario the head losses do not exceed 1 m in the intense pumping area (Figure 14b).

6. Conclusions

The hydrogeological framework and the numerical simulation of the aquifer system presented in this study have proved that the basic assumption of all previous studies regarding the interaction between Lake Koronia and its underlying aquifers is false.

Previous theories agreed there is a definitive distinction between the shallow and the deep aquifer, which are separated by a fully impervious bed. What is really the case is that there is an alteration of shallow aquifers until the depth of 60 m and below that, until the basement rocks, the deep aquifers. They are both separated by black and red clay beds, which do not constitute a uniform impervious layer so that a hydraulic contact between the several aquifers is permitted. At the plain's area boundaries there is an increased participation of red clays constricting groundwater flow while along the elongated axis of the plain area the participation of red clays reduced in favor of more permeable formations (sand and clay) along with black clays which denote the lake's deposition. These black clays are in fact forming the impermeable or semi-permeable bed that separates the deep from the shallow aquifers. Its extension though, doesn't reach the aquifer's lateral boundaries permitting thus a marginal hydraulic continuity between the deep and the shallow formations. This explains the very small differences between their piezometric heads (deep-shallow).

The second false assumption concerns the lake-aquifer interaction. The hydraulic conductivity measurements on the lake's bottom prove that the believed dependence of the lake water volume on the aquifer's water table fluctuations is practically negligible. The true reason of the lake's water reduction (during the last 20 years it has been reduced to 10% of its volume), as the model results show, is the reversing of the torrents-aquifer interaction. Years ago the high level aquifer's groundwater was seeping into the torrents, which, in turn, were recharging the lake. Today, because of the aquifer's drawdown the torrents lose their water to the groundwater system through the permeable sediments of the plain area. Thus, the main water resource of the lake has disappeared creating the very likely danger of the lake's complete drying.

In general, the present situation of the Lake Koronia sub-basin forms a complex water resource problem with environmental, social and economic consequences. During the past 20 years the increasing water demand has resulted in a 90% reduction of the lake's water deposits and a standard drop of the aquifer's water table of 0.5 m/year, at least during the last 5 years. According to the model's predictions the negative water balance will continue and will be even greater, as long as the present water consuming activities will not change through the implementation of an integrated water resources management plan in the area. An improvement through a decrease of pumping per 7.5×10^6 m^3 (an amount equal to the safe yield) would only stabilize the present situation. On the contrary, a further reduction would lead to a gradual restoration of the aquifer to its former condition.

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