ORIGINAL ARTICLE

Interpretation of groundwater hydrographs in the West Thessaly basin, Greece, using principal component analysis

S. Seferli[1] · K. Modis[1] · K. Adam[1]

Abstract

The scope of this work is to elucidate the use of principal components analysis (PCA) as a tool to interpret the areal distribution of various types of ground water level fluctuation patterns within the Western Thessaly basin in Greece. In this area, intense water abstraction takes place during the last decades to cover the needs of agricultural activities and has impacted the ground water regime. Interpretation of ground water level measurements with PCA would allow stake holders involved in water management to closely monitor the aquifers piezometry, through the identification of certain target wells within larger groups of monitoring wells. In the present study, the application of the above methodology on existing monitoring data revealed nine representative monitoring wells in a total of 62. These target locations can be measured in the long term, allowing the collection of reliable water level data and thus the sustainable monitoring of the aquifers.

Keywords Ground water hydrographs · Principal component analysis · Overexploitation · West Thessaly basin · Geostatistics

Introduction

Measurements of water levels in monitoring wells or piezometers are an integral part of any groundwater investigation. The water level data that are obtained from field measurements can then be used to plot hydrographs of hydraulic head versus time, which are subsequently used to evaluate the response of the ground water system to either natural or manmade activities over time at the location of that monitoring station (Winter et al. 2000). Subsequently statistical methods can quantitatively summarize all the data collected over space and time during the course of a project (Modis and Sideri 2013), providing the basis to better understand the various types of water level fluctuation patterns within a study area. Statistical analysis of available water level data can also provide the basis to optimize and effectively reduce the number of monitoring locations without jeopardizing the accuracy of compiled information in the long term.

To analyze water level data and reveal patterns in such large datasets, an analytical procedure to lower the dimensionality of the problem is required. Principal component analysis (PCA) is intended to establish a series of factorial variables that summarize all the hydrological information. This is the most widely used method of multivariate data analysis due to the simplicity of its algebra and its straightforward interpretation. PCA is used to identify the important components that explain most of the system variance. Moreover, PCA focuses on providing a representation of a multivariate data set using the information that is contained within the covariance matrix, so that the extracted components are mutually uncorrelated. In addition, the principal components have the important property that successive components explain the maximum residual variance of the data in a least-squares sense.

This kind of analysis aiming to provide some basic insights into the similarities and dissimilarities in patterns of water level fluctuations so as to select wells for long-term monitoring was first applied by Winter et al. (2000). Moon et al. (2004) applied PCA to analyze water table fluctuation to estimate groundwater recharge using also the corresponding precipitation records. More recently, Upton and Jackson (2011) combined groundwater hydrographs into a small number of groups displaying similar patterns of fluctuations,

✉ S. Seferli
seferlimatina@gmail.com

1   School of Mining and Metallurgical Engineering, National Technical University of Athens, Zografou, 157 80 Athens, Greece

for which one representative hydrograph can be modeled. Zhang (2012) also used the same methodology to conclude that the distribution of precipitation, abstraction for irrigation and water table depths were the main factors determining the hydrograph patterns and their distribution.

A similar type of analysis was performed in the present study to examine the behavior of a series of monitoring wells in West Thessaly basin, Greece (Fig. 1). This basin is the larger part of the Thessaly plain where the most

important aquifers for water supply are found in the region. Its importance is notable, due to the fact that the Thessaly basin has high irrigation water demands covered mostly by wells, given the limited reservoir infrastructure. This intense pumping has led to water overexploitation that has caused land subsidence (Marinos et al. 1995, 1997) and ground deformation (Modis and Sideri 2015) which has caused damage to infrastructure in some areas (Fig. 2).
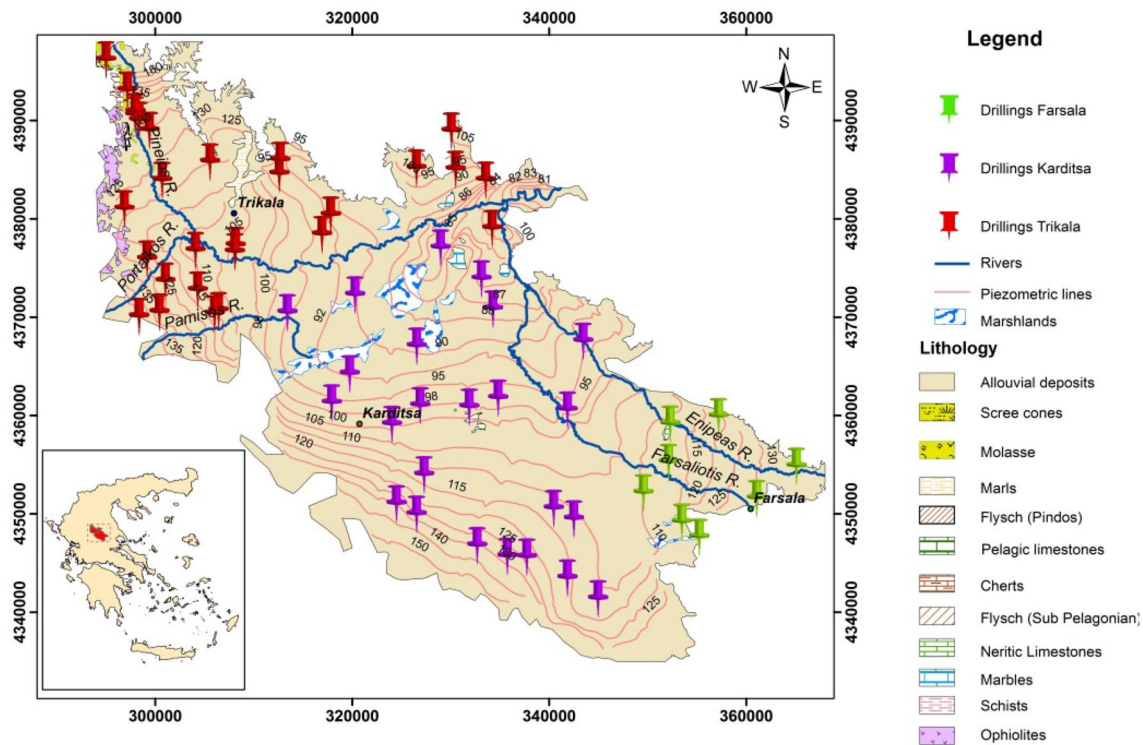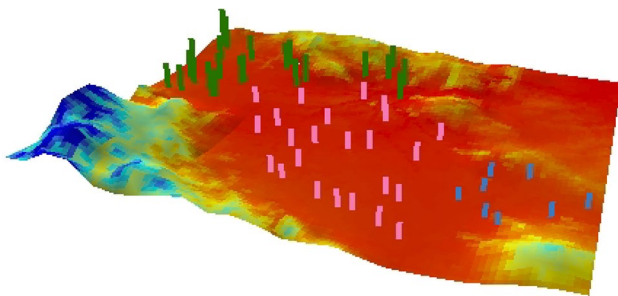

Fig. 1 Geological and piezometric map of the West Thessaly basin

Fig. 2 Damages due to land subsidence in West Thessaly basin. The cracks in the stonework on the left photo by Apostolidis and Georgiou (2007) evolve, despite the repairs even 8 years after, as seen in the right photo taken by the authors (2015)

Fig. 3 Location of the West Thessaly basin

Fig. 4 DTM of West Thessaly basin showing the classification of data in three groups according to topography

Site description

The Thessaly basin is a lowland area in Central Greece (Fig. 3), with an area of about 4520 km², which is mainly drained by the Pinios River. The basin is subdivided by a group of hills into two sub-basins, the Western and the Eastern one. These sub-basins contain sediments and metamorphic rocks that form high-yielding aquifers.

The study area is located in the West Thessaly basin, which has subsequently been subdivided into three smaller areas. The first area is located in the Farsala region (Fig. 4) and contains the lowland area surrounding the Agios Georgios, Farsala and Stavros villages. The second area is located in the S–SW part of the basin which includes the wider Karditsa prefecture area and contains a lot of semi-rural and urban areas. The third area includes the largest part of the Western Thessaly basin and is crossed by Pineios and its major tributaries, the Pamissos and Portaikos rivers.

The lithostratigraphy of the area includes three major units. The sedimentary rocks (limestones, clastic formations, flysch) belong to sub-Pelagonian, Western Thessaly and Pindos units, while the metamorphic rocks (marbles, gneisses, and schists) form part of the Almopia (metamorphic Pelagonian) unit. Nevertheless, the majority of the surface formations are Mesohellenic molassic formations, alluvial deposits of Holocene age and conglomerates (Papanikolaou 1986). The alluvial deposits of the Western Thessaly basin constitute a system of unconfined shallow aquifers which extend in the upper layers. In the deep permeable layers, successive confined-artesian aquifers are developed (Marinos et al. 1995, 1997). This system, in addition to the infiltrated surface water, is supplied through lateral water infiltration from karstic aquifers in alpine carbonate formations that outcrop along the margins of the basin.

Groundwater level dataset

Throughout the Western Thessaly basin, several water wells were drilled during recent decades, to examine the hydrogeology of the area (Kallergis 1970; Sogreah 1974) and to monitor the long-term variations of ground water levels in an area where intense water abstraction takes place for the irrigation of agricultural lands. The data compiled consist of discrete measurements of the water levels in monitoring wells over a period of 22 years (April 1993–August 2014) for the Farsala area, 20 years (July 1974–November 1993) for the Karditsa area and 23 years (April 1983–June 2005) for the Trikala area. Measurements at all sites were taken on a monthly basis. The number of wells used for this study was 8 for the Farsala area, 24 for the Karditsa area and 30 for the Trikala area. A minimum of 240 water level measurements were taken at each well during the study period.

A digital terrain model (DTM) of the study area with the location of the monitoring wells examined is given in Fig. 4. As shown in this model, the three sites analyzed in the present study are located in lowlands of similar elevations, allowing thus the interpretation and comparison of available ground water level data.

Methods

PCA was used to reveal temporal patterns in the available water level data. The goal was to determine a few uncorrelated linear combinations of the original hydrographs that can then be used to summarize the data set without losing much information. PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations/

measurements of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The number of principal components is generally less than or equal to the number of original variables.

PCA quantifies the relationship between variables by computing the covariance matrix for the entire data set. The original data matrix is then decomposed into a scores matrix and a loadings matrix (Fig. 5) by calculating the eigenvectors and eigenvalues of the covariance matrix. The scores are a measure of the temporal similarity between the observed pattern of water levels for a given date and each principal component. The loadings matrix contains the projections of the original variables to the principal components axes and thus can be visualized as a measure of spatial similarity between the water level variables and each principal component.

Furthermore, another outcome of PCA is that, by plotting the random variables as vectors in their new subspace spanned by the principal components, it is possible to examine their cross correlations and locate potential groups that may share similar characteristics. This ability was extensively used in this study to determine a few hydrograph patterns that would describe the general patterns of groundwater level fluctuations over a 20- to 23-year period for each study area.

Results and discussion

Principal component analysis was selected for this study because it provides an unbiased and efficient tool that could facilitate the analysis of the thousands of water level measurements compiled within the monitoring program conducted in the areas under study. The goal was to determine a limited number of hydrograph patterns that would describe the general patterns of water level fluctuations over a 20- to 23-year period for each site. Furthermore, by determining

the extent to which hydrographs at individual well locations relate to the statistically computed hydrographs, the spatial distribution of hydrograph patterns could be mapped throughout the area of each of the three sites. As reported in previous studies (Winter et al. 2000; Lafare et al. 2016), this type of analysis would be useful in comprehending the response of the ground water system to natural processes, such as the distribution of recharge, human activities, such as ground water abstraction for irrigation, as well as indicating the relationship of water level fluctuations to differences in permeability of the geologic units.

The analysis of the monitoring data of the three areas under study and their respective variance versus the principal components are shown in Table 1.
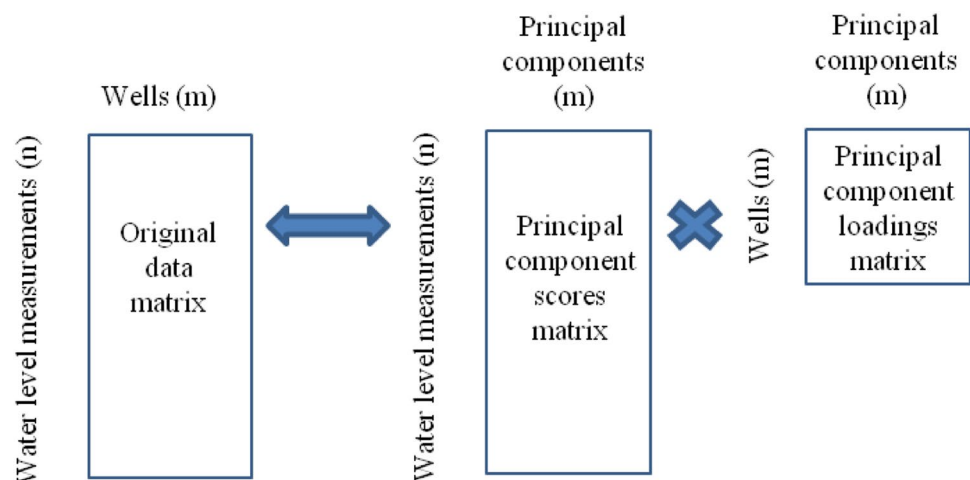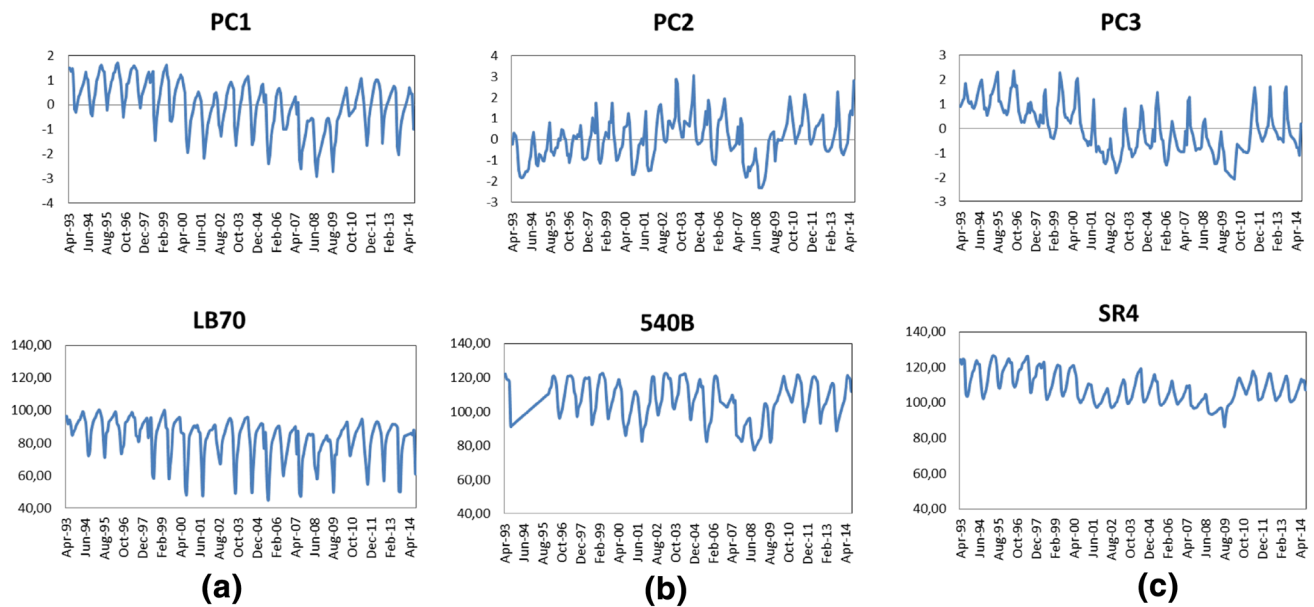
Farsala area

For the Farsala area, the monitoring data collected from eight wells during the 23-year monitoring period were analyzed. For these data, the first principal component (FA-PC1) accounted for 73% of the variance in the water level data (Table 1). A hydrograph of component scores related to FA-PC1, which is a graphical representation of this variance in the data, is shown in Fig. 6a. Hydrographs using this principal component are herein referred to as scores hydrographs. The second principal component (FA-PC2) accounted for 13% of the variance in the water level data (Table 1). A scores hydrograph for FA-PC2 is shown in Fig. 6b. The third principal component (FA-PC3) accounted

Table 1 Percentage of variance explained by the first three principal components

Principal components	1	2	3
Farsala	73	13	10
Karditsa	78	5	4
Trikala	65	8	6

Fig. 5 Schematic diagram of PCA transformation of water level measurements (modified from Winter et al. 2000)

Fig. 6 Component scores plot and hydrographs of representative monitoring wells for the three principal components in the Farsala area

for 10% of the variance in the water level data (Table 1) and the respective scores hydrograph for FA-PC3 is shown in Fig. 6c.

A plot of the component loadings for each well as they relate to FA-PCl versus FA-PC2 and FA-PC3 (Fig. 7) indicates that for the Farsala area, the monitoring wells can be classified into three groups. Wells LB70, PZ11 and PZ46 that present high loadings on FA-PCl and low loadings on FA-PC2 and FA-PC3 on the lower right side of the diagram are designated as group 1. Hydrographs of actual water levels for one of these wells, i.e., LB70 (Fig. 6a), clearly reveal the close relationship of these actual hydrograph patterns to the scores hydrograph for FA-PC1 (Fig. 6a). Hydrographs show an inverse U-shaped seasonal pattern, reflecting smooth water discharge conditions in the monitored aquifers.

By contrast, wells 540B and SR6 that have high loadings on FA-PC2 and low loadings on FA-PC1 and FA-PC3 which are seen on the upper left side of the diagram (Fig. 7) are designated as group 2. A hydrograph of actual water levels in one of these wells, i.e., 540B (Fig. 6b) indicates the close similarity of this hydrograph pattern to the scores hydrograph for FA-PC2 (Fig. 6b). In contrast to the first group, these boreholes show more flashy seasonal patterns indicating a quick respond to recharge. However, over the longer term, these hydrographs show a 10-year rising trend before stabilizing, suggesting that in this area water abstraction remains lower or is balanced with the recharge of the aquifer.

A third group consisting of wells 445YEB, LB119 and SR4 has relatively high loadings on FA-PC3 and moderately high loadings on FA-PC1 and FA-PC2. Hydrographs

of actual water levels for one of these wells, i.e., SR4 (Fig. 6c) indicate some similarity with the characteristics of the scores hydrographs for FA-PC3 (Fig. 6c). In fact, they show a similar type of seasonal response with that of the second group. Nevertheless, as far as long-term variations are concerned, they follow a similar trend to group 1, with an initial—10 years—long declining trend which then stabilizes.

Figure 8, which shows the locations of the well groups in relation with the major geological formations found in these areas, can be used to elucidate the causes of the actual hydrograph patterns. For example, as shown in Fig. 8, for wells of group 1 the monitored water table is located in alluvial formations. Additionally, as seen in Fig. 1, these wells are found downstream of the Farsala watershed. Due to the above conditions, water table fluctuations reflect more seasonal and longer term recharge conditions. In contrast, groups 2 and 3 are found upstream of Farsala watershed and the water table is developed within limestone. As a result, water table fluctuations in these wells are abrupt and they respond promptly to aquifer recharge. Groundwater recharge is seen to generally balance or occasionally exceed irrigation water abstraction as suggested by the long-term trend of ground water level variation. Finally, the differences in long-term behavior between boreholes of group 2 and the other two groups might be explained due to their vicinity to wetlands, as indicated in Fig. 9, and the hydraulic connection of the monitored aquifer with other water bodies encountered within the neighboring karst areas.
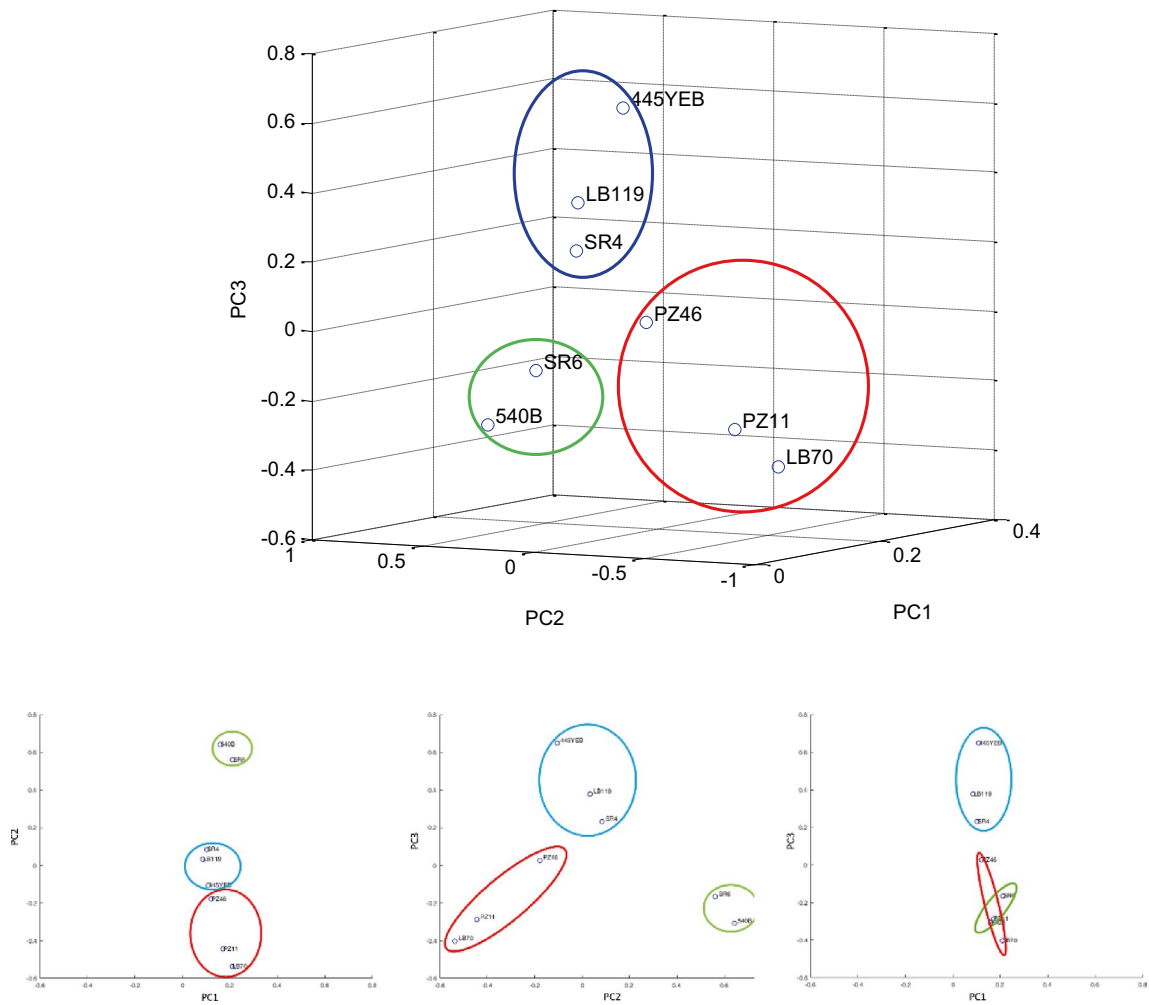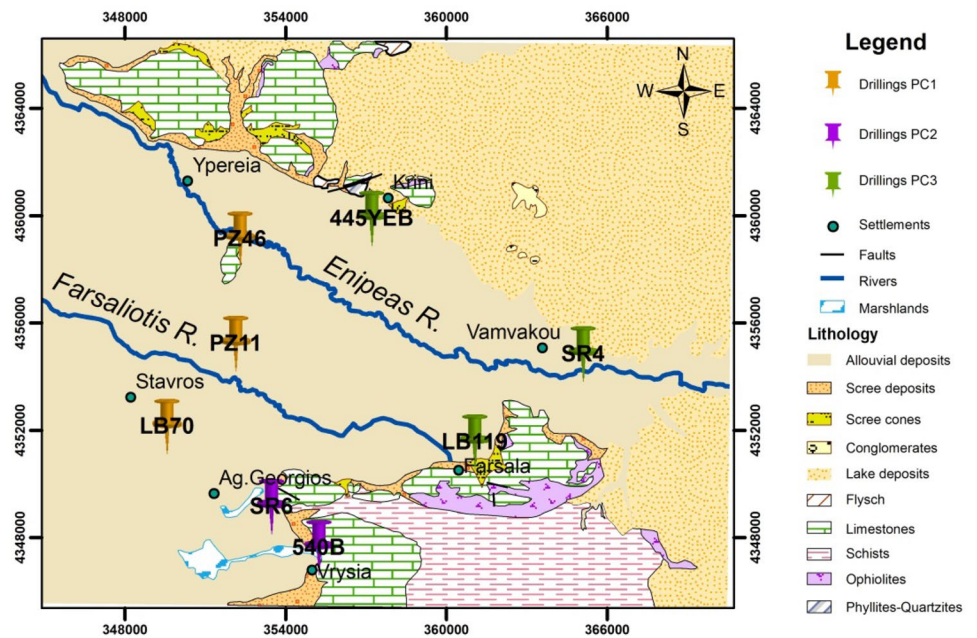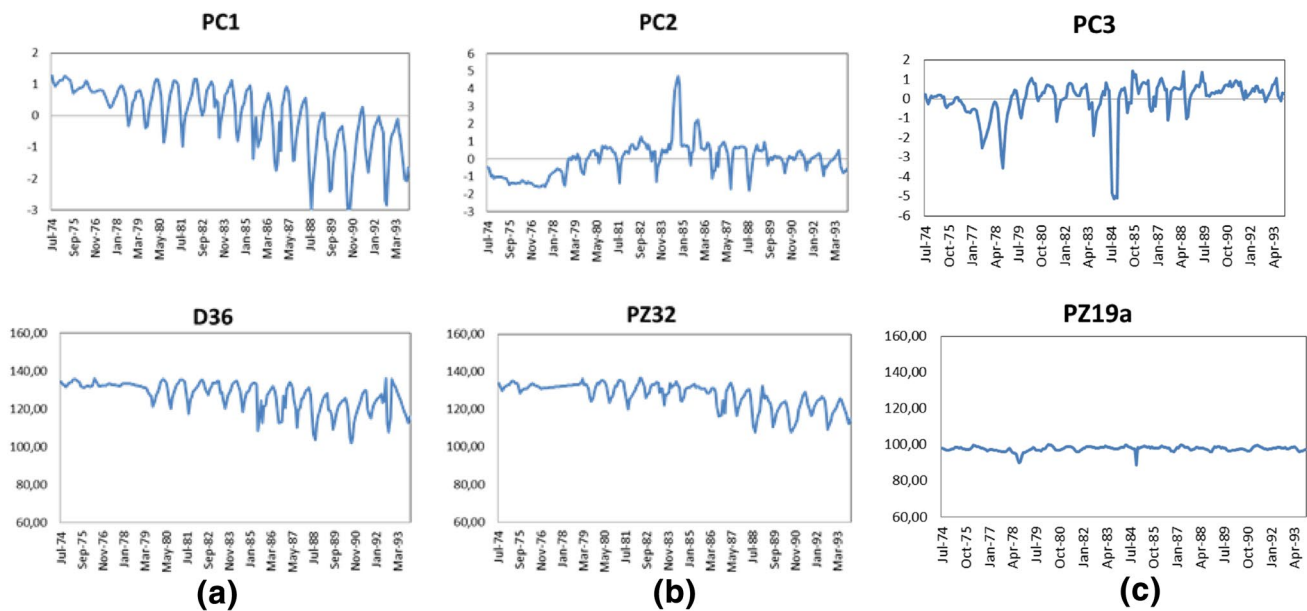
Fig. 7 Plot of component loadings for each well in Farsala related to the three principal components

Fig. 8 Configuration of the geo-
logical formation on the land
surface and areal distribution of
well groups in Farsala

Fig. 9 Component scores plot and hydrographs of representative monitoring wells for the three principal components in Karditsa

Karditsa area

A data set of 24 wells that had been monitored for a period of 20 years was analyzed for the Karditsa area. For this area, the first principal component (KA-PC1) accounted for 78% of the variance in the water level data (Table 1). A scores hydrograph for KA-PC1 is shown in Fig. 9a. The second and third principal component (KA-PC2) (KA-PC3) accounted for 5% and 4%, respectively, of the variance in the water level data (Table 1). Score hydrographs for KA-PC2 and KA-PC3 are shown in Fig. 9b, c respectively.

A plot of the component loadings for each well as they relate to KA-PCl versus KA-PC2 and KA-PC3 (Fig. 10) indicates that in the Karditsa area most of the wells also fall into three groups. Wells A2, D30, D36 and SR13 that present high loadings on KA-PC1 and low loadings on KA-PC2 and KA-PC3 on the lower right side of the diagram are designated as group 1. Hydrographs of actual water levels for one of these wells, i.e., D36 (Fig. 9a) indicate the close relationship of these actual hydrograph patterns to the scores hydrograph for KA-PC1 (Fig. 9a). A continuous long-term decline is detected in the average water level in the wells of this group.

By contrast, wells D37 and PZ32 that have high loadings on KA-PC2 and low loadings on KA-PC1 and KA-PC3 on the upper left side of the diagram (Fig. 10) are designated as group 2. A hydrograph of actual water levels in one of these wells, i.e., PZ32 (Fig. 9b) indicates the close relationship of this hydrograph pattern to the scores hydrograph for KA-PC2 (Fig. 9b). In contrast to

the first group, these hydrographs show a more or less stabilized long-term trend, while their seasonal behavior is characterized by strong biennial water level fluctuations.

A third group consists of wells G403, G407, G408, G503, G504, G505, G506, PZ19a and SR11 that have high loadings on KA-PC3 and moderately high loadings on KA-PC1 and KA-PC2. Hydrographs of actual water levels for one of these wells, i.e., PZ19a (Fig. 9c), present some of the characteristics of the scores hydrographs for KA-PC3 (Fig. 9c). In fact, they show a similar type of seasonal response to the second group, with the exception of two sudden drops in 1978 due to the drought and the 1984 where aquifer overexploitation was recorded.

A map of the location of the well groups and of the underlying lithologies shown in Fig. 11 can be used to further elucidate the causes of the actual hydrograph patterns. For example, as shown in Fig. 11, in almost all the wells examined the water table is located in alluvial formations. Additionally, borehole loggings indicate mostly clay and gravels in groups 1 and 2, while in group 3 more clay and sand are encountered (Hydroerevna 1973; Kallergis 1970). On the other hand, all the wells classified in groups 1 and 2 are found upgradient of Karditsa, as shown in Fig. 1. Due to the above conditions prevailing in this area, it seems reasonable that in the third group of wells, the average water level is relatively stable. By contrast, the biennial pattern of water level fluctuations shown by groups 2 and 3 cannot be attributed strictly to the prevailing geological conditions, but it may have to be related with the impacts of anthropogenic activities.

Fig. 10 Plot of component loadings for each well in Karditsa related to the three principal components
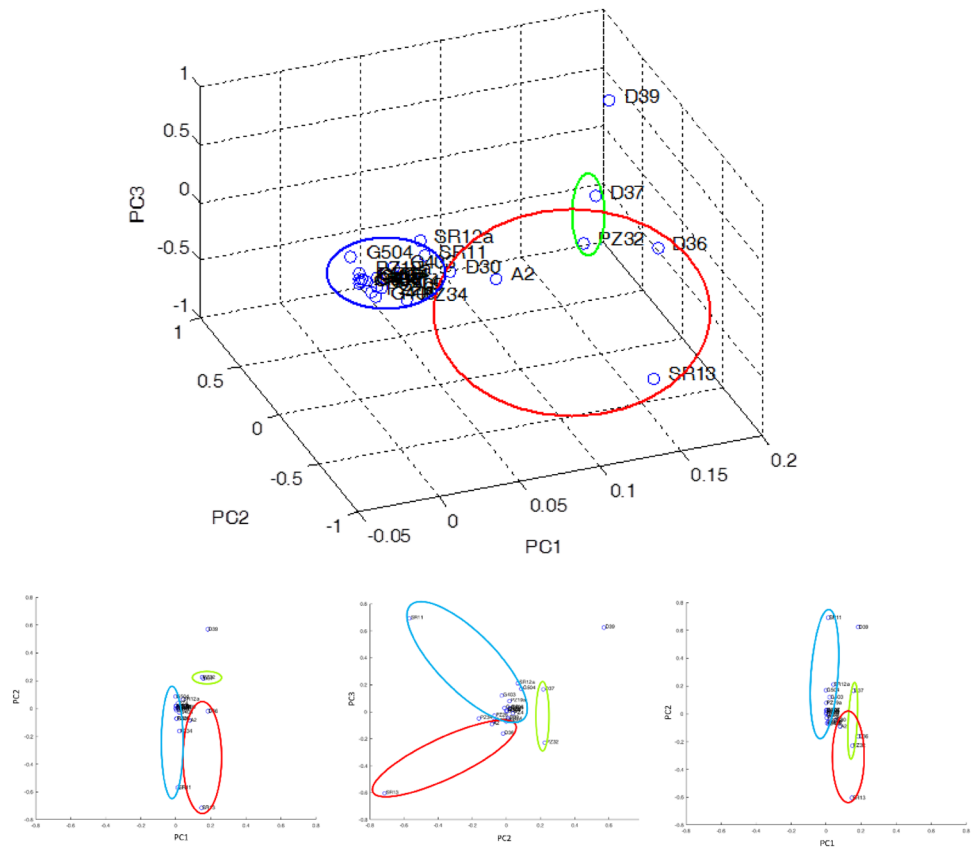
Fig. 11 Configuration of the geological formation on the land surface and areal distribution of well groups in Karditsa
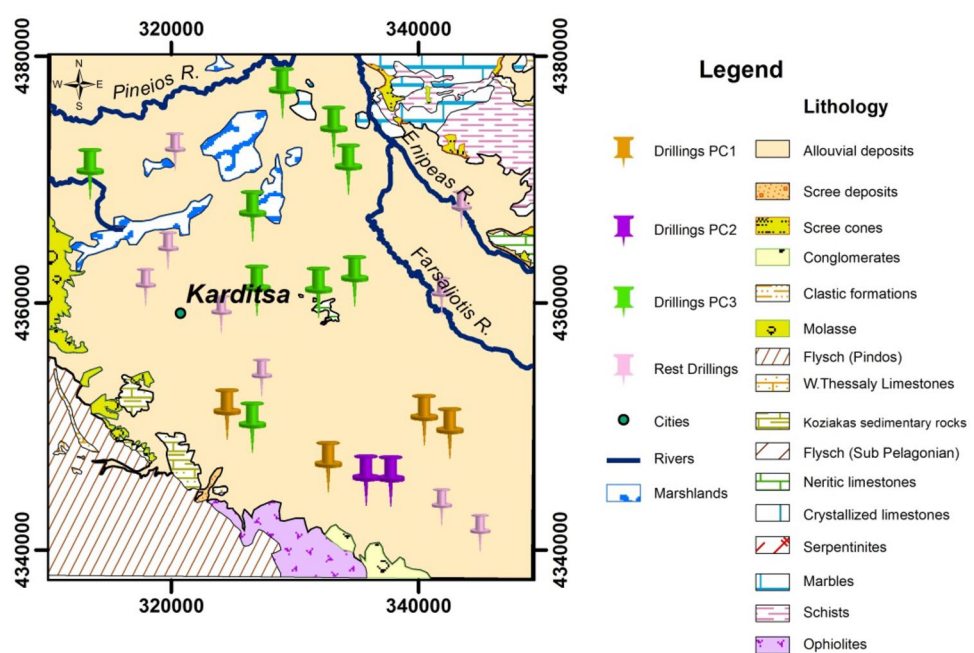
Trikala area

For the Trikala area, data from thirty (30) wells that had been monitored for a period of 23 years were examined. In this area, the first principal component (TR-PC1) accounted for 65% of the variance in the water level data, the second principal component (TR-PC2) accounted for 8% of the variance and the third principal component (TR-PC3) accounted

for 6% of the variance in the water level data (Table 1). Scores hydrographs for TR-PC1, TR-PC2 and TR-PC3 are shown in Fig. 12.

A plot of the component loadings for each well as they relate to TR-PC1 versus TR-PC2 and TR-PC3 (Fig. 13) indicates that again in the Trikala area the wells may be grouped into three groups.

Wells D1, D22, D25, D27, 174, PZ54, PZ57, SR92 and TB20 that have high loadings on TR-PC1 and low loadings on TR-PC2 and TR-PC3 on the lower right side of the diagram are designated as group 1. Hydrographs of actual water levels for one of these wells, i.e., TB20 (Fig. 12a), indicate that there is a close relationship of these actual hydrograph patterns to the scores hydrograph for TR-PC1 (Fig. 12a). A continuous long-term decline is detected in the average water level in the wells of this group.

At the other extreme, wells 25, 112T, 3a, 84T, D10, D16, D21, D5, G402, G405, G501, P2, PZ1, PZ28, PZ3, PZ30, PZ55 and PZ70 have high loadings on TR-PC2 and low loadings on TR-PC1 and TR-PC3 and plot on the upper left side of the diagram (Fig. 14). This grouping of wells is designated as group 2. A hydrograph of actual water levels in one of these wells, i.e., PZ1 (Fig. 12b), indicates the close relationship of this hydrograph pattern to the scores hydrograph for TR-PC2 (Fig. 12b). In contrast to the first group, they show a trend of initially increasing water levels which then generally stabilize over the longer term.

A third group consists of wells PZ17, PZ18, D2 that have relatively high loadings on TR-PC3 and moderately high loadings on TR-PC1 and TR-PC2. Hydrographs of actual water levels for one of these wells, i.e., PZ17 (Fig. 12c), indicate some characteristics of the scores hydrographs for TR-PC3 (Fig. 12c). In fact, they show some types of seasonal response characterized by cycles which repeat every 3–4 years.

A map of the areal distribution of the well groups identified in Fig. 14 and the respective geological formation recorded on the surface of these areas can be used to develop insight into the causes of the actual hydrograph patterns. For example, as shown in this figure, the examined water table is located in alluvial deposits at almost all wells of group 2, while groups 1 and 3 are located near bedrock formations. Additionally, borehole loggings indicate mostly clay and gravels in groups 1 and 3, while in group 2 more clay and sand are encountered (Hydroerevna 1973; Kallergis 1970). On the other hand, all wells classified in groups 1 and 3 are found upstream of Trikala watershed, as shown in Fig. 14. Due to the above conditions prevailing in this area, it is concluded that in the second group of wells, the average water level is generally stable. By contrast, the pattern of water level changes seen in group 3 cannot be attributed strictly to the prevailing geological conditions, but it may be related to the influences of anthropogenic activities.

Conclusions

The West Thessaly basin contains an important groundwater resource that has been subjected to excessive groundwater abstraction which in turn has caused damaging land
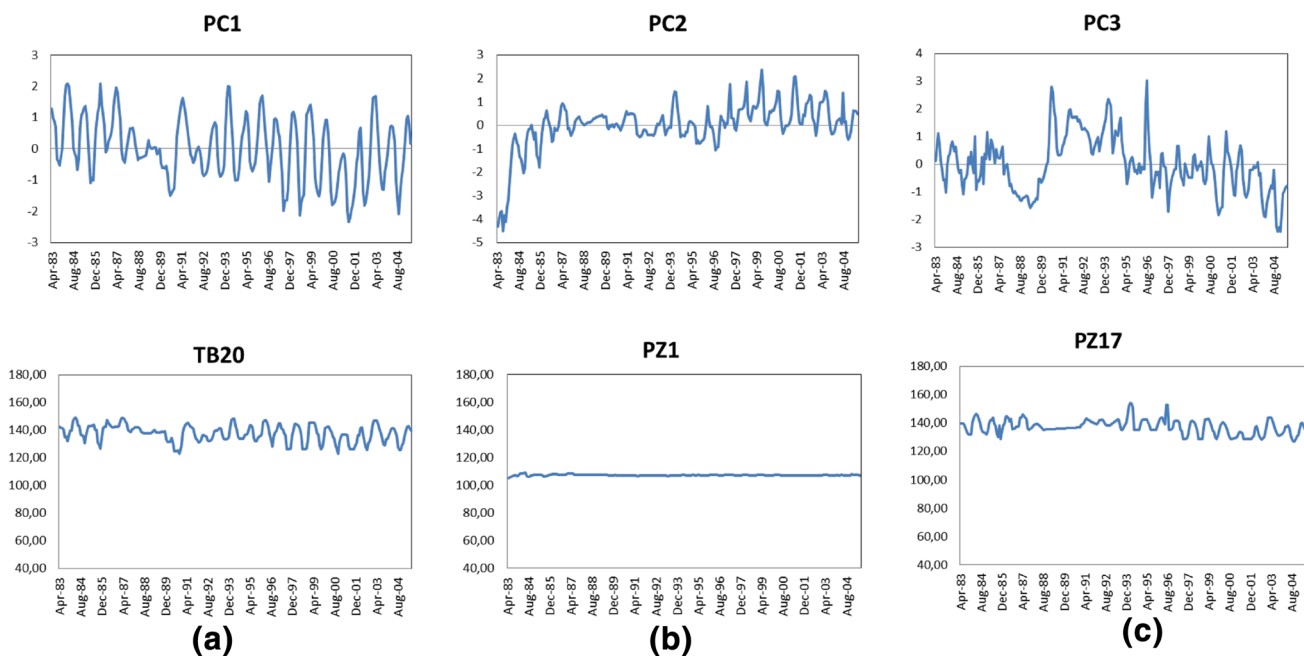

Fig. 12 Component scores plot and hydrographs of representative monitoring wells s for the three principal components in Trikala
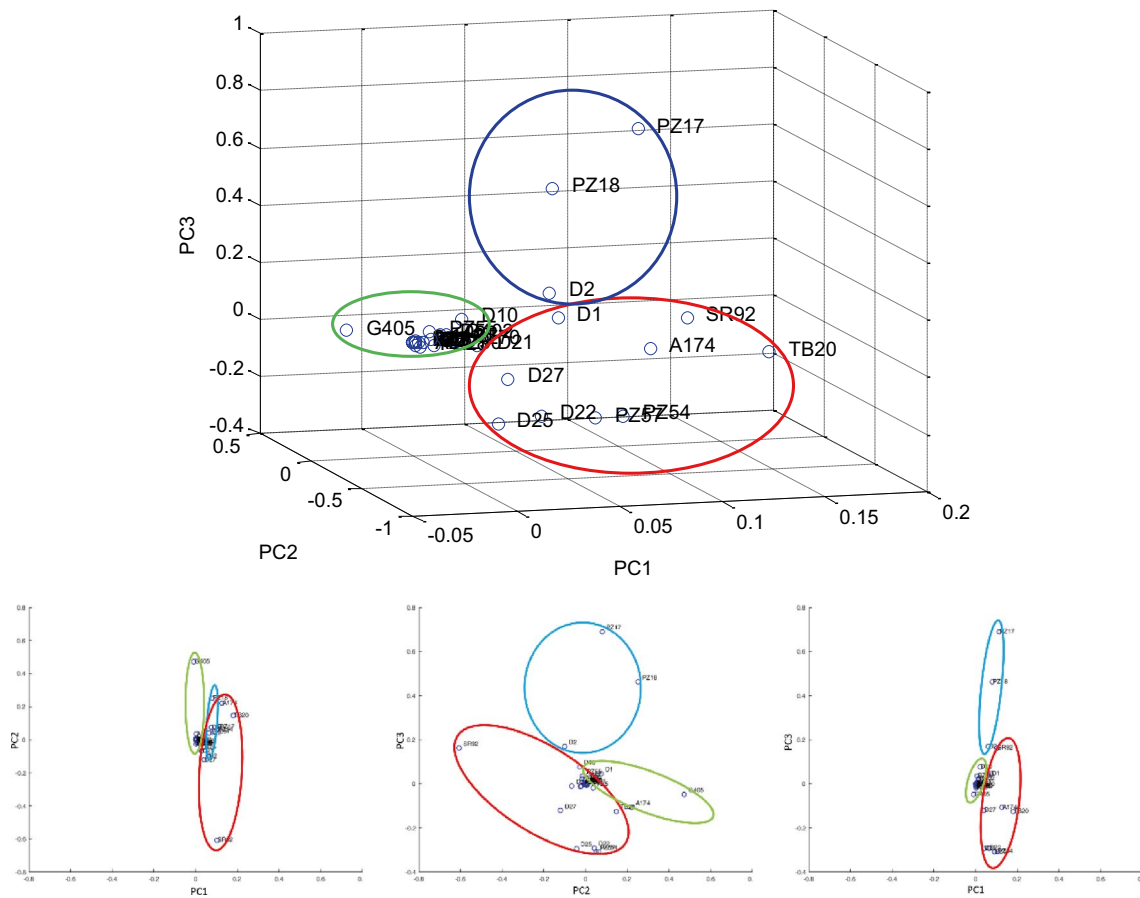
Fig. 13 Plot of component loadings for each well in Trikala related to the three principal components
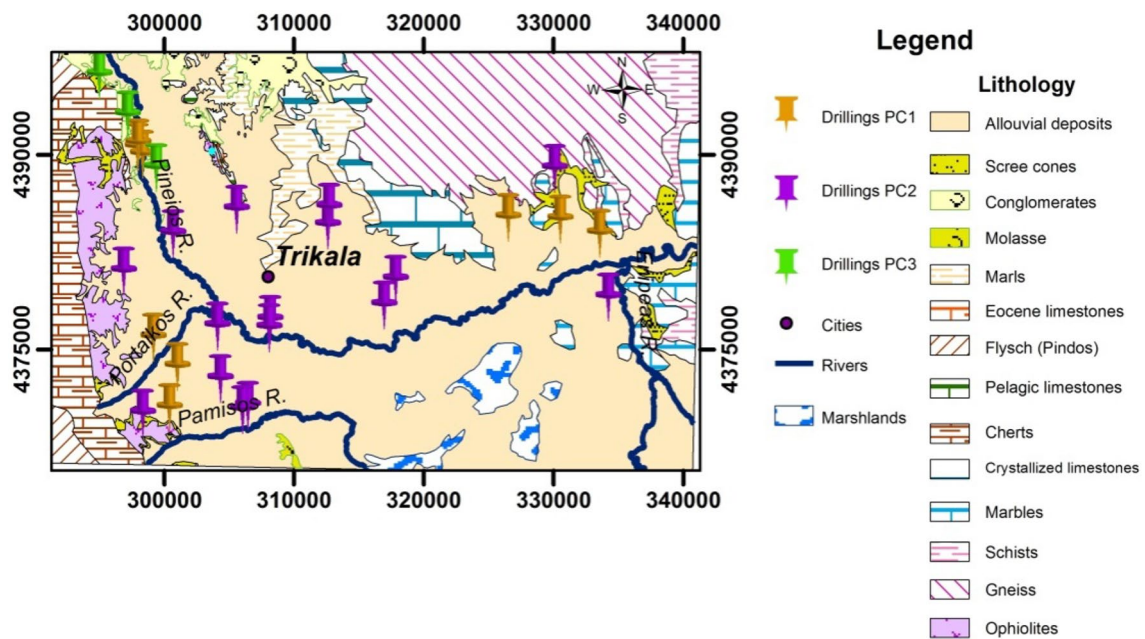

Fig. 14 Configuration of the geological formation on the land surface and areal distribution of well groups in Trikala

subsidence. Based on these factors and the results of the water level assessments undertaken in this study, it is concluded that regulatory authorities in the region will need to implement a suitable groundwater monitoring program to assess and, ultimately, to manage the decline of water levels in the area.

The first step in developing a strategy for managing water level declines in the area will be to develop suitable allocation limits based on a sound water balance.

To develop such a water balance, the following information will be required: reliable meteorological data, monitoring of the flows of the Pineios river and its tributaries and continuous monitoring of ground water levels at appropriate locations in the two sub-basins.

These data would allow sustainable allocation limits for both groundwater and surface water resources to be developed that could be adapted for changes in annual rainfall in the region. These data can then be compared with the water volumes that are currently abstracted from surface and groundwater ensuring that appropriate measures, both preventive and mitigation, are applied for the sustainable management of the water resources in this area.

The application of the PCA to hydrographs from 62 monitoring wells recorded in the period 1974–2014 revealed the existence of distinct temporal patterns in the available water level data that allowed wells to be classified into groups with a similar behavior. This behavior was further analyzed based on the geological and hydrogeological conditions encountered in the above areas, taking also into account the borehole logs of the examined monitoring wells. Then, it is possible to identify certain target wells one from each of the above well groups that could be selectively monitored in the long term, allowing the sustainable monitoring and the collection of reliable groundwater level data.

Based on the findings of the present study, it is concluded that the application of the PCA method, combined with the hydrogeological evaluation of the hydrographs recorded, allows the significant reduction in the number of wells to be monitored in the Thessaly area without jeopardizing the accuracy of the water model prediction. More specifically, as concluded in this study, groundwater level can be continuously monitored in only 9 instead of 62 monitoring wells in the three sub-basins of the West Thessaly area, so as to allow the competent water authorities to compile the necessary, representative data for the sustainable water management in this region.

Although this study has focused on the optimization of groundwater monitoring in three sections of the West Thessaly basin (namely, the Farsala, Karditsa and Trikala sub-basins), the principals developed here could be extended to other parts of the West and East Thessaly basins.

Compliance with ethical standards

References

Apostolidis E, Georgiou H (2007) Geotechnical research of the surface ground ruptures in Thessaly basin sites, recording and documentation. Institute of Geology and Mineral Exploration. Athens **(unpublished report; in Greek)**. https://scholar.google.com/scholar?q=Apostolidis%2C%20E.%2C%20%26%20Georgiou%2C%20H.%20%282007%29.%20Geotechnical%20research%20of%20the%20surface%20ground%20ruptures%20in%20Thessaly%20basin%20sites%2C%20recording%20and%20documentation.%20Institute%20of%20Geology%20and%20Mineral%20Exploration%20%28IGME%29%2C%20Unpublished%20report%20%28in%20Greek%29

Hydroerevna (1973) Ministry of National Economy—general direction of agriculture. Execution of 200 boreholes for the groundwater development in Thessaly **(Unpublished report, Athens, Greece)**. https://scholar.google.com/scholar?q=Ministry%20of%20National%20Economy%20-%20General%20Direction%20of%20Agriculture.%20%281973%29.%20Execution%20of%20200%20boreholes%20for%20the%20groundwater%20development%20in%20Thessaly%2C%20Unpublished%20report%2C%20Athens%2C%20Greece

Kallergis G (1970) Hydrogeological investigation of Kalambaka basin (Western Thessaly). Institute of Geology and Mineral Exploration (IGME), vol XIV, no 1. Athens, pp 1–197. https://doi.org/10.12681/eadd/0308

Lafare A, Peach D, Hughes A (2016) Use of seasonal trend decomposition to understand groundwater behavior in the Permo-Triassic Sandstone aquifer, Eden Valley, UK. Hydrogeol J 24:141–158

Marinos P, Thanos M, Perleros V, Kavadas M (1995) Water dynamic of Thessaly basin and the consequences from its overexploitation. In: Proceedings of the 3rd Hydrogeological Congress. Heraklion **(in Greek)**. https://scholar.google.com/scholar?q=Marinos%2C%20P.%2C%20Thanos%2C%20M.%2C%20Perleros%2C%20V.%2C%20%26%20Kavadas%2C%20M.%20%281995%29.%20Water%20dynamic%20of%20Thessaly%20basin%20and%20the%20consequences%20from%20its%20overexploitation.%20Proceedings%20of%20the%203rd%20Hydrogeological%20Congress%2C%20Heraklion%2C%20Crete%20%28in%20Greek%29

Marinos P, Perleros V, Kavadas M (1997) Deposited and karsic aquifers of Thessaly plain. New data for the status of their overexploitation. In: Proceedings of the 4th Hydrogeological Congress. Athens **(in Greek)**. https://scholar.google.com/scholar?q=Marinos%2C%20P.%2C%20Perleros%2C%20V.%2C%20%26%20Kavadas%2C%20M.%20%281997%29.%20Deposited%20and%20karsic%20aquifers%20of%20Thessaly%20plain.%20New%20data%20for%20the%20status%20of%20their%20overexploitation.%20In%20Proceedings%20of%20the%204th%20Hydrogeological%20Congress%2C%20Athens%20%28in%20Greek%29

Modis K, Sideri D (2013) Geostatistical simulation of hydrofacies heterogeneity of the West Thessaly aquifer systems in Greece. Nat Resour Res 22(2):123–138

Modis K, Sideri D (2015) Spatiotemporal estimation of land subsidence and ground water level decline in West Thessaly basin, Greece. Nat Haz 76(2):939–954

Moon S, Woo N, Lee K (2004) Statistical analysis of hydrographs and water-table fluctuation to estimate groundwater recharge. J Hydrol 292:198–209

Papanikolaou D (1986) Geology of Greece (in Greek), Eptalofos Publications, National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment. Athens, pp 136–138, 147–151, 157

Sogreah SA (1974) Groundwater development project of the plain of Thessaly. Republic of Greece, Ministry of Agriculture, Directorate General of Agricultural Development and Research Land Reclamation Service, Athens. https://scholar.google.com/scholar?q=SOGREAH%20SA%20%281974%29.%20Groundwater%20development%20project%20of%20the%20plain%20of%20Thessaly.%20Republic%20of%20Greece%2C%20Ministry%20of%20Agriculture%2C%20Directorate%20General%20of%20Agricultural%20Development%20and%20Research%20Land%20Reclamation%20Service%2C%20Athens

Upton A, Jackson R (2011) Simulation of the spatio-temporal extent of groundwater flooding using statistical methods of hydrograph classification and lumped parameter models. Hydrol Process 25:1949–1963

Winter TC, Mallory SE, Allen TR, Rosenberry DO (2000) The use of principal component analysis for interpreting ground-water hydrographs. Ground Water 38(2):234–246

Zhang RG (2012) Groundwater hydrograph patterns in north China plain during 1982–1986 interpreted using principal component analysis. Adv Mater Res 356–360:2320–2324