



Groundwater Quality Analysis in Mygdonia Basin, Greece [†]

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Abstract: The objective of this research is the groundwater quality analysis in the Mygdonia basin (North Greece), where intensive agricultural activities take place. Groundwater sampling was carried out in May (17 samples) and in September (26 samples) for the years from 2013 to 2015. In situ physicochemical parameters (pH, EC, and T) were tested, whereas major ions (Ca^{2+} , Na^+ , Mg^{2+} , K^+ , NO_3^- , SO_4^{2-} , Cl^- , and HCO_3^-) were analyzed in the laboratory. Conventional statistical methods were applied for the classification of the groundwater hydrochemical type and the identification of the prevailing hydrogeological processes. Finally, some recommendations are presented for the protection of groundwater quality.

Keywords: aquifers; groundwater quality assessment; sustainable management; Mygdonia basin; North Greece

1. Introduction

Groundwater is critical for supporting human well-being and economic development. During recent decades, groundwater has been under increasing pressure and the threat of pollution due to agricultural and industrial activities, urbanization, and tourism development. In addition, the climate crisis will affect the parameters of the hydrologic cycle (increase in temperature, reduction of rainfall, droughts, floods) and, consequently, the natural recharge of the aquifers, alongside the quantity and quality of groundwater resources. In groundwater, dissolved ions and solids are always present. That defines its physical and physicochemical characteristics. When the concentration of pollutants is greater than threshold values, then it is unsuitable for irrigation and/or other uses.

The Mygdonia hydrologic basin consists of a rare complex of ecosystems, including the lakes, Koronia and Volvi, which constitute an important wetland system of high ecological and international importance (protected by Ramsar Convention), but over the years, a degradation, especially of Lake Koronia, has been observed [1]. The main causes of the water quality deterioration of Lake Koronia are the water withdrawals and the uncontrollable discharge of untreated domestic and industrial effluents [2,3].

This work investigates the groundwater quality of the Mygdonia basin. Conventional statistical methods, hydrogeochemical diagrams, along with data reduction methods, such as factor analysis, were applied in order to describe groundwater quality, classify samples according to their water type, and identify the prevailing hydrogeological processes that take place in the aquifers of the basin. Some proposals to improve the sustainability of groundwater resources in the Mygdonia basin are presented.

2. Study Area-Data Collection

2.1. General Characteristics

Mygdonia basin, covering an area of more than 2000 km² (650 km² in the lowland), is located in the Thessaloniki Prefecture, central Macedonia, North Greece (Figure 1). It



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is characterized by the typical Mediterranean and continental climate with wet (October–April) and dry periods (May–September). The mean annual rainfall is 585 mm, and the mean annual temperature is 13.5 °C [4].

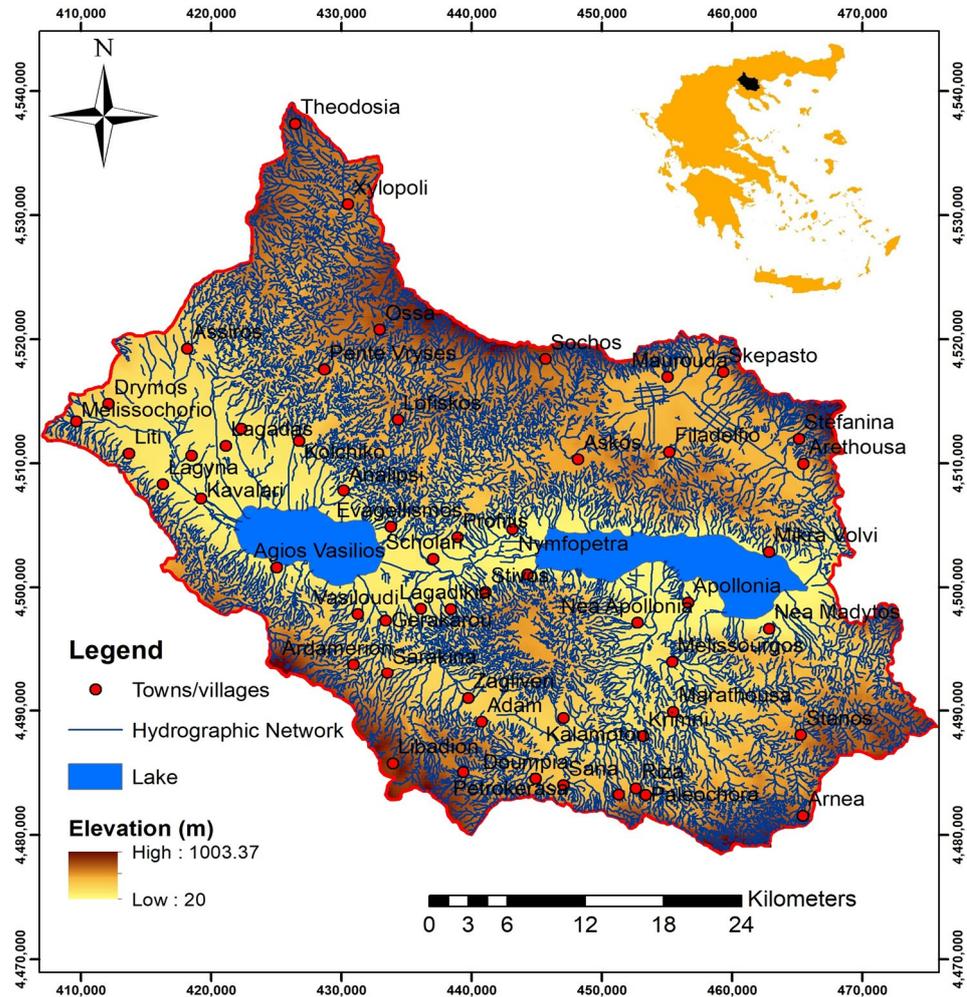


Figure 1. Morphological map of the Mygdonia basin. Map created by the authors based on free data derived by Copernicus (<https://www.copernicus.eu/el>, accessed on 16 January 2022).

From a geological point of view (Figure 2), as a tectonically active basin, the lowland of the Mygdonia basin is formed from recent unconsolidated materials consisting of sands, clay, and silty sand sediments [5]. The bedrocks are paleozoic gneisses, amphibolites, schists, marbles, and granitic intrusions of the Serbomacedonian massif [6].

Within the Quaternary deposits of lowland, aquifer systems are developed, including an unconfined shallow aquifer and deeper confined aquifers. The groundwater level is 0.7–43 m below the ground’s surface. Generally, the highest values are recorded in April (end of wet period) and the lowest in early October (end of dry period) [1].

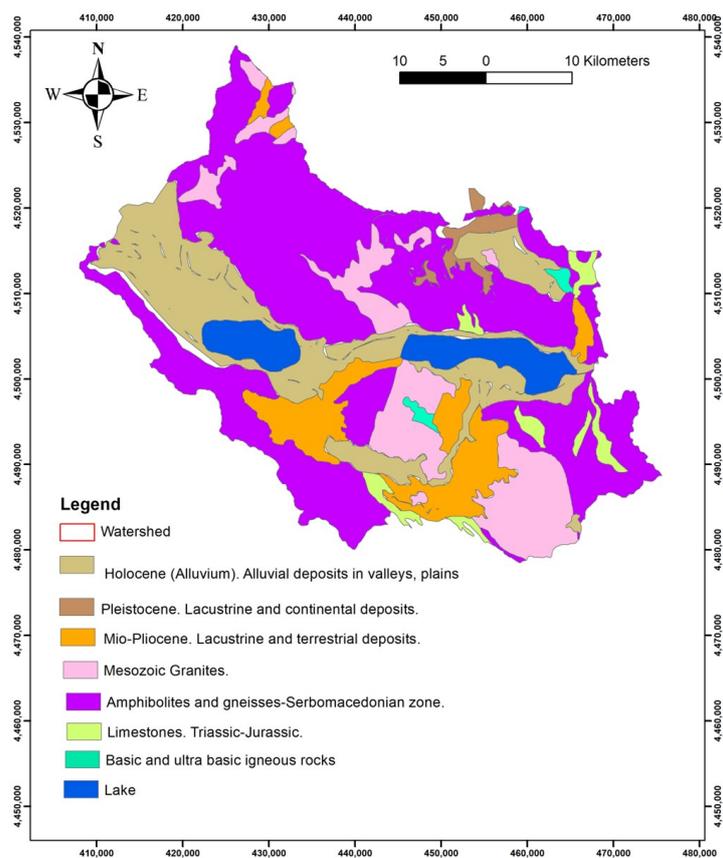


Figure 2. Geological map of the Mygdonia basin. (Adapted from Ref. [7]).

Groundwater recharge occurs through direct infiltration of rainfall, seepage from torrents, lateral subsurface inflows from mountainous areas, and return water flow from irrigation use [8].

2.2. Data Collection

Groundwater samples were collected during the wet (May) and dry (September) periods over the years from 2013 to 2015, showing similar results along with in situ measurements of the physicochemical characteristics. In this work, the results of the year 2014 are presented. The samples were analyzed in the Laboratory of Engineering Geology and Hydrogeology at the Aristotle University of Thessaloniki for eight major ions (Ca^{2+} , Na^+ , Mg^{2+} , K^+ , NO_3^- , SO_4^{2-} , Cl^- , and HCO_3^-). Sampling point locations aimed to cover the entire basin. Maps showing the spatial distribution of Electrical Conductivity (EC), temperature (T in $^{\circ}\text{C}$), and pH were created.

The AQUACHEM software was used to create Piper and Durov diagrams, and also the SAR (sodium adsorption ratio) value was calculated. Finally, factor analysis was applied in order to identify the main hydrochemical processes and uncover relationships between ions.

3. Results of Groundwater Quality Analysis

Summary statistics of the results of chemical analyses are presented in Table 1. The electrical conductivity (EC) mean values are equal to 916.5 $\mu\text{S}/\text{cm}$ for May and 889 $\mu\text{S}/\text{cm}$ for September. High values are attributed to the intensive agricultural activities, the existence of geothermal fields and human activities in the area. It is known that during the previous decades, many textile dyeing units operated in the area. The uncontrolled disposal of untreated waste in the channels resulted in the degradation of soil and groundwater resources.

Table 1. Descriptive statistics of pH, EC, and major ions for groundwater samples.

		μS/cm				mg/L					
		pH	EC	Na	K	Ca	Mg	HCO ₃	SO ₄	Cl	NO ₃
May-14	Mean	7.47	916.47	81.76	3.13	56.78	26.86	307.24	100.47	48.61	33.45
	Max	8.04	1971.00	240.00	5.90	96.00	67.90	580.00	280.00	234.00	110.00
	Min	7.07	444.00	16.00	1.70	20.40	10.00	216.00	26.00	8.00	0.40
Sep-14	Mean	7.49	889.04	66.97	3.03	54.68	33.45	302.31	76.28	38.94	36.00
	Max	8.04	2010.00	233.00	6.10	88.00	72.00	513.00	252.00	217.00	75.20
	Min	6.29	259.00	18.60	0.80	21.20	6.80	158.00	14.00	12.80	4.40

pH values range from 6.29 to 8.04, and groundwater temperatures range from 16.5 °C to 21.8 °C (Figure 3). The spatial variation and especially the high temperatures could be caused by the mixing of groundwater with geothermal fluids.

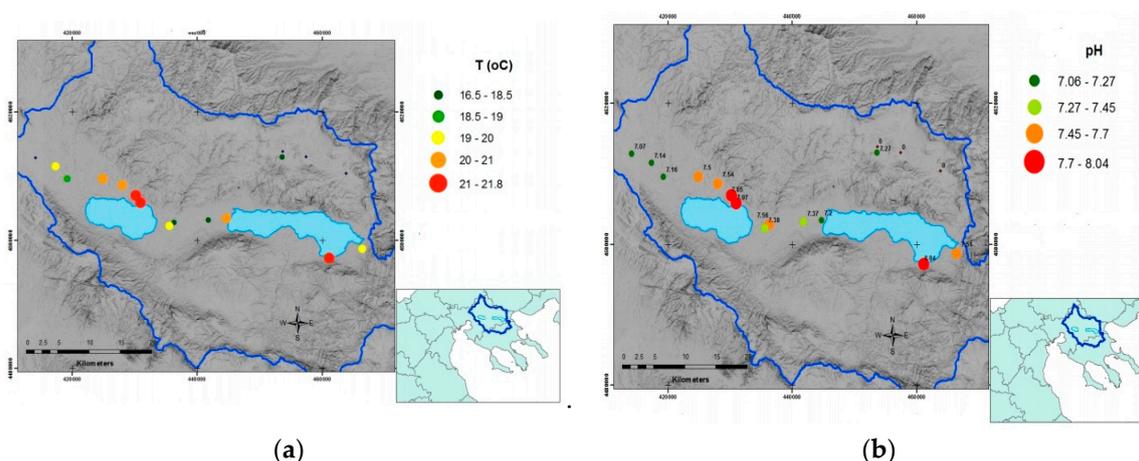


Figure 3. Spatial distribution for (a) temperature (T) and (b) pH for the period of May 2014. (Adapted from Ref. [1]).

A high percentage of the groundwater samples (25%) exceeds the maximum permissible limit for drinking purposes set by Directive 2006/118 EC, the Joint Ministerial Decision 39626/208/E130, and the Ministerial Decision 1811/2011 (Official Government Gazette 3322 B/2011). This is associated with the use of nitrogen fertilizers in agriculture. It is pointed out that the common fertilizers in the area contain nitrogen, phosphate, sulfate, and potassium.

Sodium values exceed the threshold value of 150 mg/L in seven out of forty-four samples. The high sodium values were recorded at boreholes close to the geothermal field and at livestock units. Groundwater quality regarding sodium could be affected by the geothermal fluids, and the use of salt in the livestock units could locally increase the sodium concentration in water samples.

Typically, the distribution of calcium (Ca²⁺) ions for the two sampling periods is shown in the maps of Figure 4, constituting a typical example given that calcium is one of the most important dissolved ions in water since the content of groundwater is directly linked to the geological environment through which the groundwater moves from the moment of its infiltration up to the entire period of its storage in the aquifer. Its highest concentrations are found in areas where water remains for a long time in the aquifer, as in the area between Koronia and Volvi lakes. High values of sulfates are locally recorded and should be attributed to the use of fertilizers and/or the mixing with geothermal fluids.

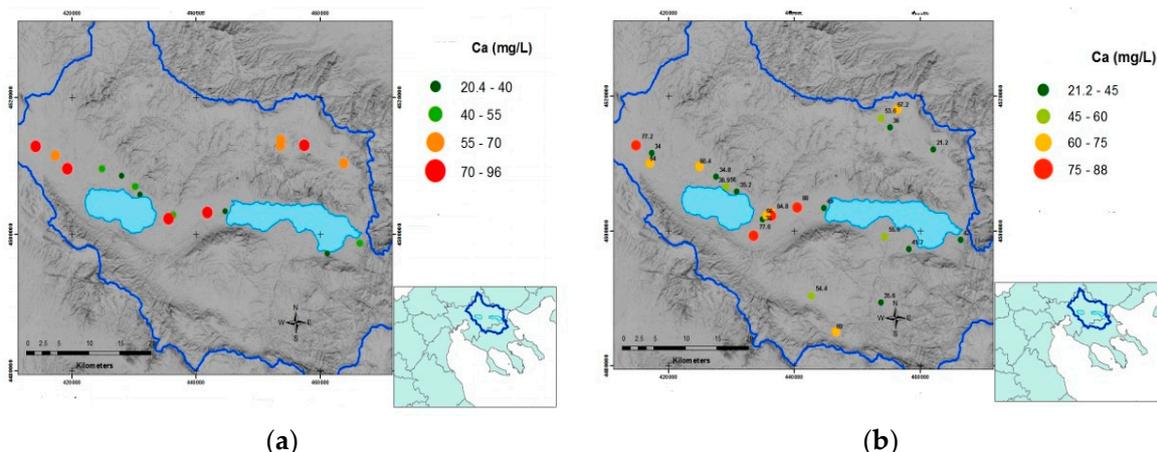


Figure 4. Distribution of Ca^{2+} ions in the Mygdonia basin in (a) May 2014 and (b) September 2014. (Adapted from Ref. [1]).

Hydrochemical diagrams were created, providing information about the water type. In Figure 5, Durov diagrams for both sampling periods were created, showing that all samples belong to bicarbonates in terms of anions. Regarding cations, samples belong to calcium and sodium, while based on anions and cations (square), several of them belong to bicarbonate, sulfate, and chloride. It is, therefore, concluded that the groundwater type is calcium-bicarbonate (Ca-HCO_3), while some samples are a mixture of different hydrochemical types of water [9].

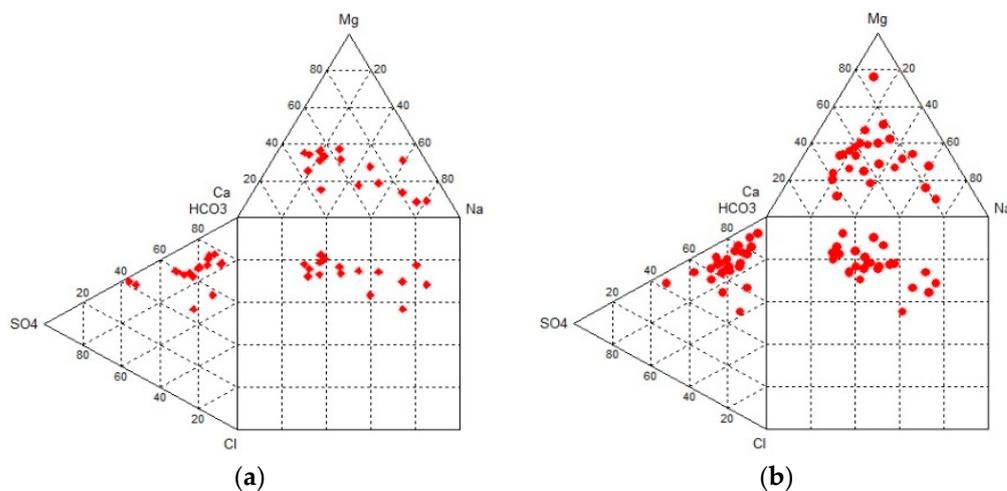


Figure 5. Durov diagrams including all samples from the Mygdonia basin in (a) May2014 and (b) September 2014 [1].

Concerning Piper diagrams, all samples regarding anions belong to bicarbonate, while in terms of cations, samples belong to calcium and sodium. Based on anions and cations (diamond), the majority belongs to the category of water coming from mixing processes with increased values of sodium. There are no dominant ions (Figure 6).

The SAR index proposed by the salinity laboratory of the US Department of Agriculture defines the degree of Na^+ adsorption by soil because this ion influences soil permeability [10]. SAR values range between 0.15 and 0.5, indicating that the water is suitable or permissible for irrigation use.

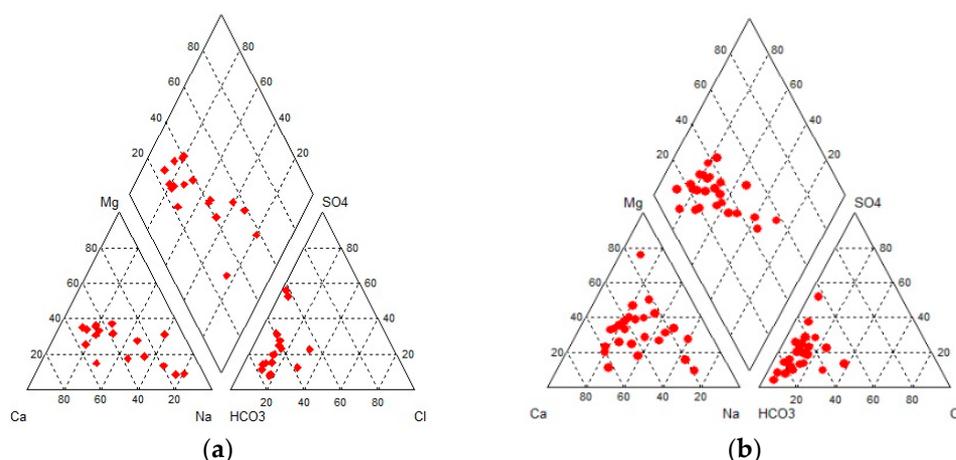


Figure 6. Piper diagrams including all samples from the Mygdonia basin in (a) May 2014 and (b) September 2014. (Adapted from Ref. [1]).

Statistical Analysis

Application of factor analysis [11–13] in all the chemical analyses of the period 2014–2016 showed that three factors, explaining 71% of the total variance, could describe the main hydrogeological and hydrochemical processes which take place in the Mygdonia basin. The first factor accounts for 32.6% of the total variance of the data and has high loadings on Mg, Na, EC, HCO_3^- , and Cl. This factor correlates to the mixing activities of water.

The second factor accounts for 21.5% of the total variance and exhibits high loadings with respect to calcium (dissolution of carbonates), and the third factor (16.8% of the total variance) shows high loadings on sulfate indicating an origin from fertilizers and/or geothermal fluids [14].

4. Conclusions and Discussion

Hydrochemical analysis was carried out to draw conclusions about the groundwater quality of the Mygdonia basin. From the analysis, a possible connection with geothermal fluids emerged. More specifically, regarding temperature values in some places, they were slightly increased (values up to 21.8 °C), which is probably connected to the existence of a geothermal field, while SO_4^{2-} appears elevated along the northern coastline of Lake Koronia, which may also be due to their mixing with geothermal fluids. Alongside, nitrate ions show high concentration values in the lowland part of the Mygdonia basin, probably due to the intense agricultural activity and use of fertilizers.

Based on Piper and Durov diagrams, it follows that the groundwater of the area has calcium and sodium as its main cations and bicarbonate as its main anion. That is, the dominant hydrochemical type of groundwater is Ca- HCO_3^- and mixing water types. Based on SAR values, the water is suitable for irrigation. Large numbers of samples exceeded the permissible upper limit of 50 mg/L (EU Council) for drinking water.

A set of measures, including monitoring (water quality, groundwater level, level of lakes, climatic data, water abstractions, etc.), should be applied for the protection of water quality and the sustainability of aquifers alongside the socio-economic development of the wider area. The application of rational fertilization waste-water treatment plants, as well as the delineation of protection zones around the boreholes and springs for water supply, will contribute to water quality protection.

Further investigation into the role of the geothermal field on groundwater quality should be implemented in the area of the boreholes in which high-temperature values were recorded. The continuous monitoring of groundwater quality characteristics is essential for the rational and sustainable management of groundwater in the Mygdonia basin.

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References

1. Devlioti, K. Hydrogeological Research and Groundwater Quality of the Mygdonia Basin. Master Thesis, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece, 2016; p. 128. (In Greek)
2. Ballas, L.G. Use of Fuzzy Rules in Water Resources Management-Application to the Volvi Hydrological Basin. Ph.D. Thesis, Aristotle University Thessaloniki, Thessaloniki, Greece, 2007.
3. Malamataris, D.; Kolokytha, E.; Loukas, A. Integrated hydrological modelling of surface water and groundwater under climate change: The case of the Mygdonia basin in Greece. *J. Water Clim. Chang.* **2020**, *11*, 1429–1454. [[CrossRef](#)]
4. Chantzi, P.; Dotsika, E. Mygdonia Basin (N. Greece) in the View of Isotope Geochemistry. In *Energy, Transportation and Global Warming, Green Energy and Technology*; Grammelis, P., Ed.; Springer International Publishing: Cham, Switzerland, 2016. [[CrossRef](#)]
5. Psilovikos, A. Paleogeographic Development of the Basin and Lake of Mygdonia (Lagada and Volvi Area, Greece). Ph.D. Thesis, Department of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece, 1977. (In Greek)
6. Mountrakis, D. *Geology of Greece*; University Studio Press: Thessaloniki, Greece, 1985.
7. Bornovas, J.; Rondoyanni, T. *Geological Map of Greece, Scale 1:500.000*, 2nd ed.; Institute of Geology and Mineral Exploration: Thessaloniki, Greece, 1983.
8. Nimfopoulos, M.K.; Mylopoulos, M.; Katirtzoglou, K. A qualitative-quantitative study of water and environmental pollution at the broader area of the Mygdonia basin, Thessaloniki, n. Greece. In Proceedings of the 6th Pan-Hellenic Geographical Conference of the Hellenic Geographical Society, Thessaloniki, Greece, 3–6 October 2002.
9. Mattas, C.; Kaklis, T.; Devlioti, K.; Vouvalidis, K. Groundwater qualitative characteristics of Mygdonia basin. Investigation of the pollution sources and suitability for human use. *Bull. Geol. Soc. Greece* **2016**, *L*, 854–864.
10. Tizro, T.A.; Voudouris, K. Groundwater quality in the semi-arid region of the Chahardouly basin, West Iran. *Hydrol. Process.* **2008**, *22*, 3066–3078. [[CrossRef](#)]
11. Voudouris, K.; Lambrakis, N.; Papatheodorou, G.; Daskalaki, P. An application of factor analysis for the study of the Hydrogeological conditions in Plio-Pleistocene aquifers of NW Achaia (NW Peloponnesus, Greece). *Math. Geol.* **1997**, *29*, 43–59. [[CrossRef](#)]
12. Voudouris, K.; Panagopoulos, A.; Koumantakis, J. Multivariate statistical analysis in the assessment of Hydrochemistry of the Northern Korinthia Prefecture alluvial aquifer system (Peloponnese, Greece). *Nat. Resour. Res.* **2000**, *9*, 135–146. [[CrossRef](#)]
13. Busico, G.; Cuoco, E.; Kazakis, N.; Colombani, N.; Mastrocicco, M.; Tedesco, D.; Voudouris, K. Multivariate statistical analysis to characterize/discriminate between anthropogenic and geogenic trace element occurrence in the Campania Plain, Southern Italy. *Environ. Pollut.* **2018**, *234*, 260–269. [[CrossRef](#)] [[PubMed](#)]
14. Poutoukis, D.; Ntotsika, E. Hydrogeochemical and isotopic investigation of the thermal bath water from Lagada and Volvi. In Proceedings of the 2nd Hydrogeological Congress, Patras, Greece, 24–28 November 1993; Greek Committee of Hydrogeology: Athens, Greece, 1994; Volume B, pp. 679–689. (In Greek)

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