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Article

Recharge Assessment in Greek Karst Systems: Methodological Considerations and Implications

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Abstract: The recharge of karst aquifers is significant for the effective management of groundwater resources, and its estimation should be tailored to accommodate their specific hydrogeological characteristics. This study provides a two-step methodological approach for the determination of karst aquifer recharge. Initially, mean annual recharge rates were estimated in the karst system of Ziria (Southern Greece) utilizing the APLIS and modified APLIS methods in order to decipher which was the most suitable version for recharge assessments. The results indicated similar mean recharge rate values at 42.7% and 41.4%, respectively, but significant differences in the spatial distribution. The modified methodology emerged as a more accurate and realistic approach, mainly due to the incorporation of permeability assessments. The final phase of the methodological approach involved the application of modified APLIS in two additional karst hydrosystems, Planitero and Xiromero, while a quantitative cross-comparison of the recharge rates was obtained for a deeper understanding of the factors controlling the groundwater recharge process. In Ziria, recharge rates exhibit a relatively uniform distribution throughout the area, with a median value of 46.7%. Conversely, in Planitero, High recharge rates (60–80%) occupy 56.8% of the surface, while in Xiromero, Moderate recharge rates (40–60%) dominate, representing 53.4% of the land coverage. These variations underscore the spatial heterogeneity of recharge within the karst systems, highlighting the importance of considering local geological and hydrological conditions in its assessments. The methodological approach of this study is flexible and can be adapted to different karst sites for the determination of recharge regimes, contributing to the alleviation of the groundwater depletion issue.

Keywords: karst; groundwater recharge; geographic information systems; APLIS method

Citation: Nanou, E.-A.; Perdikaris, K.; Tserolas, P.; Zagana, E. Recharge Assessment in Greek Karst Systems: Methodological Considerations and Implications. *Water* **2024**, *16*, 568. https://doi.org/10.3390/w16040568

Academic Editors: Micòl Mastrocicco, Nerantzis Kazakis and Konstantinos Chalikakis

Received: 24 November 2023
Revised: 25 January 2024
Accepted: 27 January 2024
Published: 14 February 2024

1. Introduction

Groundwater resources play an immense role in today's society [1,2], since the universal demand for water supply is crucially increasing. The achievement of sustainable groundwater management is a pressing and often addressed issue due to its critical role in meeting basic human requirements [3]. The escalating need for freshwater, driven by global population growth and rapid urbanization, can cause groundwater reservoirs to face over-extraction and depletion, compromising their sustainability. Simultaneously, the issue of groundwater contamination has become extensive, with pollutants from agricultural runoff, industrial discharges, and improper waste disposal infiltrating aquifers.

Besides the ramifications that can arise from human activities, climatic causes may burden aquifers further, with dire impacts on their resources. In an era dominated by the pervasive effects of climate change, Earth's hydrological cycle faces unprecedented challenges with shifts in temperature regimes, alterations in precipitation patterns, and intensified extreme weather events. These climate-induced changes can cause direct and indirect repercussions on global reserves [4], disrupt traditional recharge mechanisms, and intensify water scarcity. The increasing occurrence of droughts may lead to changes in the water balance, while rising global temperatures contribute to heightened evaporation rates, further amplifying water scarcity in vulnerable regions. The challenges facing groundwater resources have reached a critical juncture, potentially influencing their global distribution in the future. This underscores the imperative to address numerous water-related issues in a sustainable manner. Groundwater depletion constitutes a universal concern due to the unbalanced abstractions in comparison to the natural recharge. Obviously, the study of groundwater recharge is quite challenging, especially in karst aquifers.

At the forefront of hydrological environments, karst aquifers provide high-quality groundwater that is utilized either for drinking water supply or irrigation purposes. Climate-induced shifts can cause severe repercussions, leading to both a degradation in the availability and a compromise in the quality of water resources [5–8]. At the same time, with distinct characteristics and processes, karst aquifers are able to provide substantial amounts of groundwater, often resulting in their overexploitation [9,10], in order to meet the water demands of the constantly increasing population.

In Greece, there are numerous carbonate massifs distinguished by a diverse array of geological, geomorphological, and hydrogeological features, leading to a substantial variation in the degree of karstification across the country. Over the last decade, increasing research efforts have been directed towards the characterization, protection, and sustainable management of native karst aquifers, highlighting their significant value as water sources in Greece [11]. Up to 80% of the domestic karst systems are defined by good groundwater quality and quantity conditions, while qualitative issues are recorded mainly in coastal aquifers on islands, represented by a percentage of 5% [12].

The viable management of groundwater use requires the aversion of resource depletion. Recharge is one of the most significant parameters to be assessed in order to sustain the overall effective function of an exploited aquifer. Its approximation is essential to evaluating the maximum volume of water obtainable and to avoid overutilization [13]. Stable isotopes [14–17], lump and spatial models (e.g., Karstmod, VarKarst, Modflow-CFP), as well as index-based methods (e.g., APLIS, KARSTLOP), are widely used in order to determine the recharge process in karst environments [11,18–24]. Due to the heterogeneity of porosity and permeability that transcends karst aquifers [25,26] and significantly affects many of their qualities, the quantification of recharge constitutes a challenging task. The APLIS method was developed by Andreo et al. [27] and later modified by Marin [28] for the estimation of the recharge rate, expressed as a percentage of precipitation. Its parametric methodology is based on a geographic information system (GIS) and was developed specifically for carbonate aquifers under Mediterranean climatic conditions. APLIS has been implemented as well as compared to several other methods by numerous researchers [29–32], while many modifications have been made since to accommodate varying circumstances [33–35].

In this research, we applied a two-step-based methodological approach. Initially, the efficiency of APLIS and its modified version were compared in the karst system of Ziria in Southern Greece. The quantitative comparison of the two methods showed that modified APLIS is more suitable for Greek karst systems. The next step was the application of modified APLIS at two additional karst sites, Planitero and Xiromero, located in Southern and Western Greece, respectively. A comprehensive examination of the method's performance was provided across distinct hydrogeological settings. The outcomes from all three study sites underwent statistical analysis in order to decipher the hydrogeological factors that influence the recharge process. To the best of our knowledge, this methodological approach was initially applied within this manuscript. Considering that groundwater recharge constitutes the most important parameter in the fight against groundwater depletion, this study contributes to the quantification and deeper understanding of the infiltration regime in karst hydrosystems.

2. Materials and Methods

2.1. Background Information and Geological Overview of the Study Sites

In the frame of this research, the recharge rate was estimated at three Greek karst sites. Similarities and differences are both present between the study areas in regards to the geological-topographical setting and the precipitation regime. From east to west, the aforementioned sites are: (a) Ziria, (b) Planitero, and (c) Xiromero.

The karst groundwater system of Ziria (EL0200220) was delineated in the framework of River Basin Management Plans [36] that were drafted according to the requirements of the 2000/60/EC Directive [37]. It is located in Northern Peloponnese, Southern Greece, approximately 45 km west of the city of Corinth, and covers an area of roughly 200 km^2. The aquifers of the system are formed within a large mountainous area of an almost circular extension known as Mount Killini or Ziria (2368 m.a.s.l.). A large karstic polje with an orientation of almost E-W is situated in the southern part of the study area, within which Stymphalia Lake was developed. The topography is rough, with often steep slopes, since the mountain occupies a considerable extent of the hydrological system. Ziria is primarily composed of Upper Triassic–Cretaceous and undifferentiated limestones and dolomites (Tripolis Zone) along with Cretaceous limestones (Olonos–Pindos nappe) that were thrust over the latter (Figure 1) [38,39]. The metamorphic bedrock of the area consists of quartzites, phyllites, and schists that mainly surface in the SW and NW regions. A substantial part of the karst system is covered by Quaternary deposits, including the polje, which, according to geoelectrical investigations [40], is mostly filled by impermeable clays.

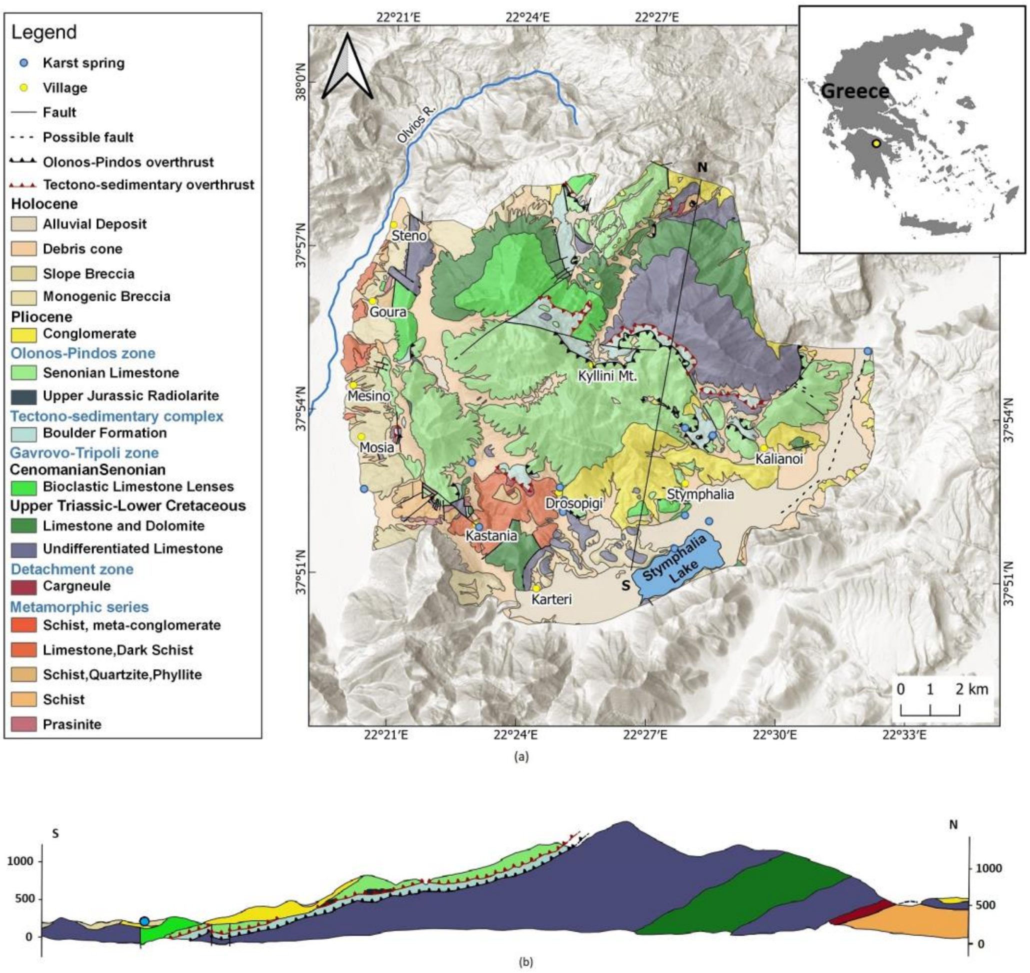

Figure 1. (**a**) Geological setting of the karst groundwater system of Ziria (modified by [38,39]), (**b**) Geological cross section (modified by [38]).

The karstification degree is prominent with the presence of many karstic landforms, such as dolines, swallow holes, and caves, while the recharge of the aquifers occurs in both diffuse and concentrated forms. The front of Stymphalia springs discharges one of the largest aquifers in the area and provides the drinking water supply for the cities of Corinth and Kiato. The groundwater of the system is also heavily used for irrigation purposes since large sections of the polje and the adjacent areas are being cultivated.

The aquifers of Planitero manifest within the Aroania (Chelmos) Mountains, which are located approximately 20 km west of Mount Ziria, so, due to their close proximity, the geological setting is very similar. This site constitutes a part of the much larger Ladon system (EL0100030), severed in order to include the recharge area of Planitero springs. It occupies 112 km^2 of land, and it is mainly composed of karstified carbonate rocks (Tripolis and Pindos zones) (Figure 2A) [38,41,42]. A considerable segment of the site is covered by Quaternary deposits, while there are outcrops of flysch and metamorphic bedrock. The aquifers discharge from a front of springs that supplement the Aroanios River. The presence of multiple faults and overthrusts makes the tectonic stress of the region indisputable. The resemblance between Ziria and Planitero is also evident in the steep terrain, with abrupt altitudinal inclinations and high elevations over 2300 m.a.s.l.

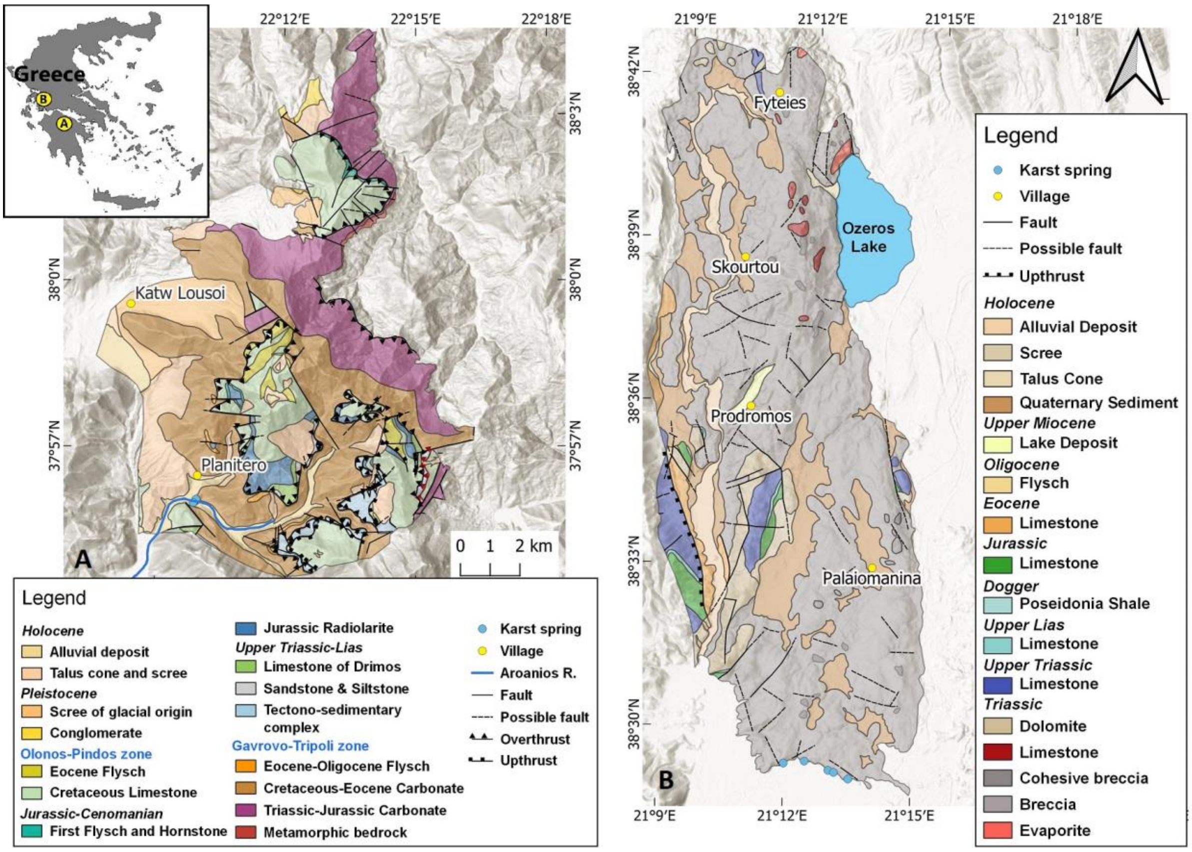

Figure 2. Geological setting of (**A**) Planitero (modified by [38,41,42]) and (**B**) Xiromero (modified by [43,44]).

Xiromero (approximately 170 km^2) is located in Western Greece and presents many dissimilarities compared to the other study sites. Like Planitero, it is also a delimited section of the Katouna–Lesini system (EL0400050), due to the emersion of evaporites in the northern part of the area, near Fyteies, functioning as a hydrological barrier. The aquifers are formed within the karstified Triassic breccia that prevail in the area and were developed by the fragmentation of adjacent Triassic limestones and dolomites (Figure 2B). They discharge from the Lambra–Agios Dimitrios front of springs, providing groundwater to accommodate the needs of adjacent villages. Quaternary deposits consisting mainly of clays and sandy materials, along with small outcrops of various limestones, complete the geological setting of the area [43,44]. Compared to the other study sites, the topography is much gentler, with altitudes not exceeding 510 m.a.s.l. Due to its location, Xiromero is also defined by greater rainfall amounts, since the precipitation pattern in Greece shows a general latitudinal decrease from west to east [45].

2.2. Application of the APLIS Method

The initial APLIS method [27] was applied in the karst system of Ziria, followed by the implementation of its modified version [28] in order to obtain a cross-comparison between the two adaptations. Modified APLIS was subsequently applied in the Planitero system, while in Xiromero the method was updated from Zagana et al. [29], with karst landforms emerging from remote sensing techniques derived from a more recent study [46].

In order to express recharge in mm/year, the percentage (%) maps resulting from modified APLIS were multiplied with the spatial distribution of precipitation in each study site. Precipitation data corresponding to time series spanning 30 years were collected from meteorological stations in the vicinity of the sites. The methodology employed for the spatial analysis considered the variation in precipitation according to elevation.

2.2.1. Assessing Recharge with APLIS and Modified APLIS in the Karst System of Ziria

APLIS estimates the mean annual recharge rate of carbonate aquifers. The assessed recharge originates solely from precipitation, and it is expressed as its percentage. The methodology behind APLIS also enables the acquisition of maps with the spatial distribution of the estimated recharge rates. To achieve that, the method proposes the combination of individual intrinsic variables that can potentially influence recharge in karst aquifers, such as Altitude (A), Slope (P), Lithology (L), Infiltration landforms (I,) and Soil type (S) [27]. The APLIS method was later modified by Marín [28], who introduced refinements such as the reclassification of slopes, adjustments to infiltration scorings, and the incorporation of a correction factor (Fh) that is associated with the permeability of the formation outcropping on the surface. To apply the method, the prior variables were developed as information layers within a Geographic Information System (GIS). Scoring values, ranging from 1 (minimum) to 10 (maximum), were then assigned according to the influence on recharge. All the map layers that were developed for the application of APLIS and modified APLIS in Ziria are depicted in Figures 3 and 4.

The altitude map (A) was derived from a Digital Elevation Model (DEM) of the country, which in turn originated the slope map (P) in percent rise as required by the method. The elevation in the study area ranges from 600 to 2368 m.a.s.l., and the altitude was classified in 6 sequences of 300 m intervals. The slopes span from 0%, mainly in the polje of Stymphalia, to over 100% on the steep inclinations of Mount Ziria. The scoring of the first two variables was attributed so that the higher the altitude, the greater the recharge due to the increase in precipitation, and the greater the slope, the lower the recharge into the aquifer [27] (Table 1). In both scenarios, the altitude map and its corresponding values remain consistent. However, the classification and scoring of the slopes differ in APLIS and its modified version, with the latter presenting an additional class.

Table 1. Scoring of the Altitude (A) and Slope (P) variables for the karst system of Ziria.

Scoring	1	2	3	4	5	6	7	8	9	10
Altitude (m)	-	-	(600–900]	(900–1200]	(1200–1500]	(1500–1800]	(1800–2100]	(2100–2400]	-	-
Slope (%)										
APLIS	>100	(76–100]	(46–76]	(31–46]	(21–31]	-	(16–21]	(8–16]	(3–8]	<3
Modified APLIS	>100	(65–100]	(45–65]	(30–45]	(20–30]	(15–20]	(10–15]	(5–10]	(3–5]	<3

Considering the lithological aspect (L), there are seven major units dominating the site that all received scoring based on imputes from previous studies [47,48] and field observations. All the carbonates received high scores due to their karstification degree and tectonic stress. The limestones of Tripolis are considered to be more karstified than the Cretaceous limestones of Pindos because the latter often intervene with thin layers of radiolarite [48], therefore they were attributed the values 10 and 9, respectively. The Quaternary formations exhibit fluctuations due to changes in grain size and composition, along with the presence of argillaceous materials. The alluvial deposits in the polje, along with the outcrop at the north-eastern part of the area, received lower values than the rest. Finally, the conglomerates were attributed a significantly higher score than what is proposed by APLIS since they are considered to be karstic [49].

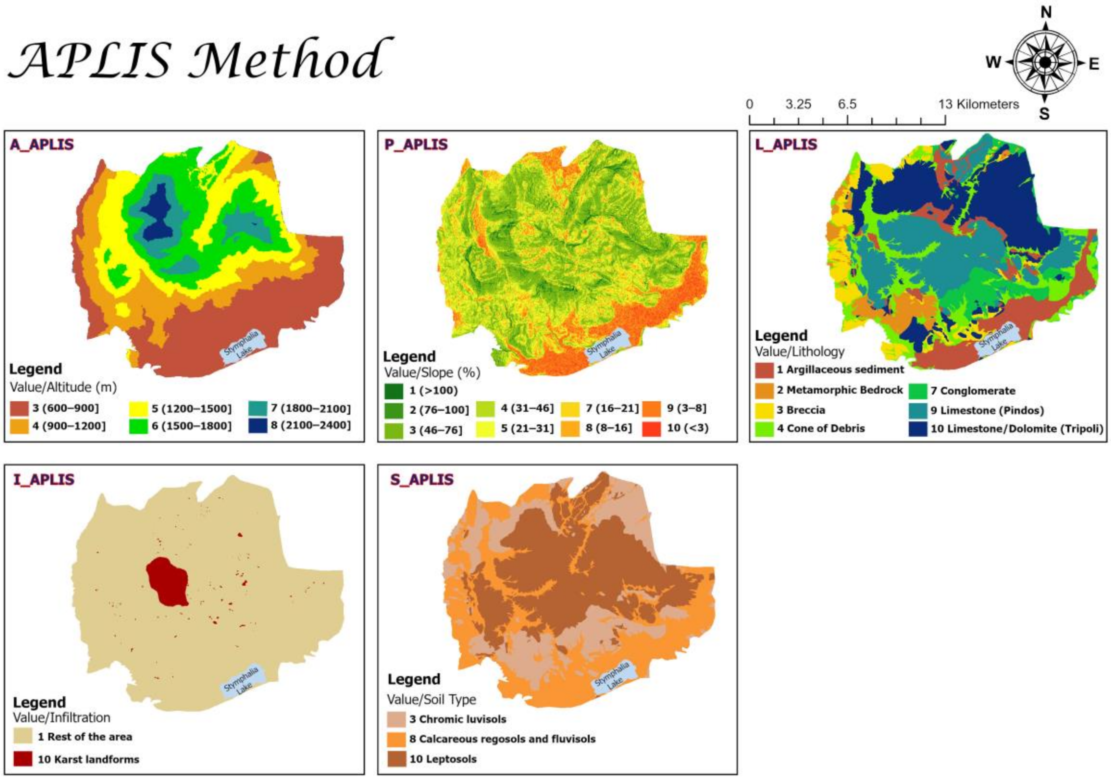

Figure 3. Maps of all the variables developed for the application of the APLIS method.

The areas of preferential infiltration (I) were located with remote sensing techniques, using aerial photographs and stereo pairs in Erdas Imagine 2010 software that enabled the three-dimensional representation of the system. Predominantly, these landforms were observed on the limestones of the Mountain, where the dominance of bare rocks and the absence of vegetation facilitated the clear delineation of such topographic depressions. On the Cretaceous limestones of Pindos, fields of dolines can be visually distinguished through satellite images and photographs, with no further assistance from remote sensing software. These landforms were collectively grouped rather than individually digitized, occupying, in such a way, a significant section of the limestones. Regarding this variable, APLIS provides only two rankings: a score of 10, which was attributed to the preferential infiltration landforms, and a score of 1, which was assigned to the rest of the system. Karst landforms that are filled with Quaternary sediments were assigned the lowest value (1), due to the method's limited scoring options. In modified APLIS, an additional intermediate value of 5 was introduced. It was received by the polje and other karstic features that are covered by various materials, as well as attributed to all the carbonate outcrops, in order to be distinguished from the non-carbonate formations.

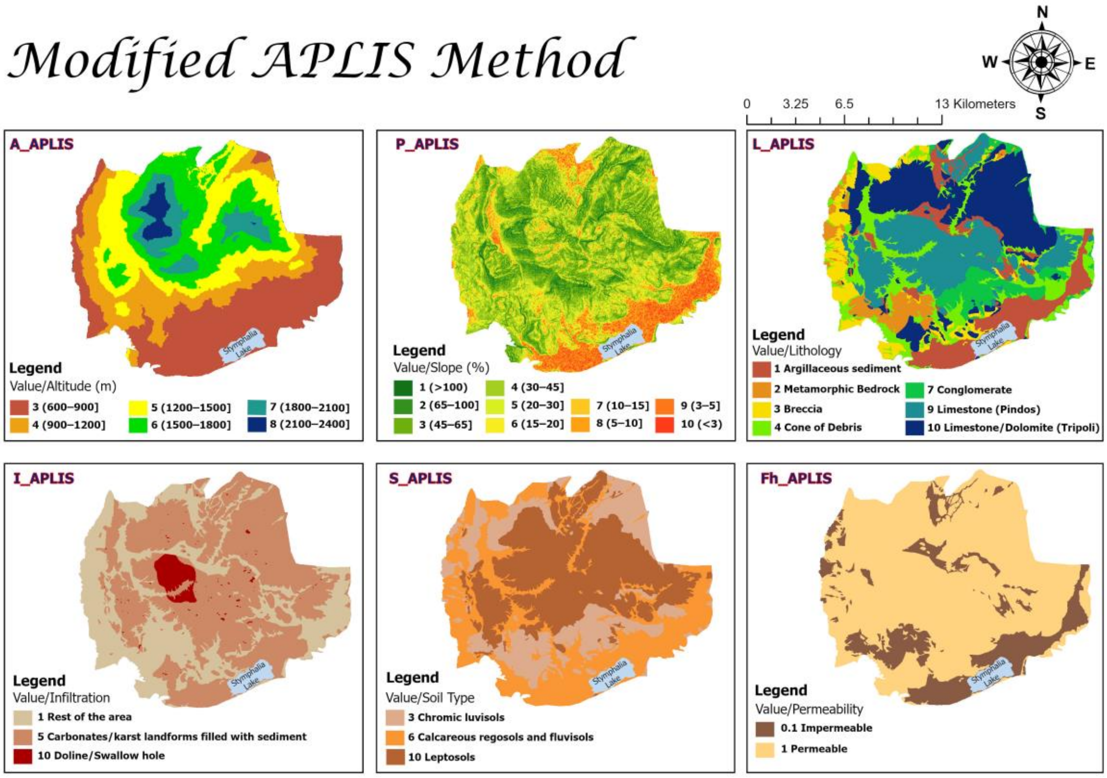

Figure 4. Maps of all the variables developed for the application of modified APLIS.

Due to the lack of specific soil data, the evaluation of the soil types (S) was based on the combination of information provided by different Soil maps [50–52]. A substantial section of the Mountain is characterized by exposed rock, devoid of soil and vegetation. Leptosols, assigned the highest value of 10, were designated as the soil type for limestone areas exhibiting minimal to no vegetation. Chromic luvisols were attributed to formations with denser vegetation, while calcareous regosols and fluvisols were predominantly assigned to Quaternary sediments. There are minimum scoring differences between the two methods.

For the estimation of the correction factor in modified APLIS, permeable formations such as carbonates, conglomerates, and most of the Quaternary deposits were identified with aquifer potential and were assigned the correction coefficient (Fh) 1. Impermeable formations like the metamorphic series and argillaceous sediments were assigned the value 0.1.

The reliability of the used data for the application of the methods is provided in the Supplementary Materials.

The scorings that were attributed to the rest of the variables for the application of modified APLIS are displayed in Table 2. For the estimation of the annual recharge rate and the creation of maps with its spatial distribution in both scenarios, the expressions of the original (1) and modified method (2) were utilized in ArcGIS 10.8 software:

$$R = (A + P + 3 \times L + 2 \times I + S)/0.9 \quad (1)$$

$$R = [(A + P + 3 \times L + 2 \times I + S)/0.9] \times Fh. \quad (2)$$

Table 2. Scoring values of the variables L, I, and S for the application of modified APLIS in Ziria.

Lithology (L)	*Scoring*	Infiltration Landforms (I)	*Scoring*
Argillaceous sediment	1	Rest of the area	1
Metamorphic bedrock	2	Carbonates/karstic landforms filled with sediment	5
Breccia	3	Doline/Swallow hole	10
Cone of Debris	4	**Soil Type (S)**	*Scoring*
Conglomerate	7	Chromic luvisols	3
Cretaceous Limestone (Pindos)	9	Calcareous regosols and fluvisols	6
Limestone/Dolomite (Tripoli)	10	Leptosols	10

2.2.2. Application of Modified APLIS to Planitero and Xiromero

The neighboring Planitero system presents many similarities to Ziria, and the values that were assigned to each variable are depicted in Table 3, while the scoring of the first two parameters (A and P) corresponds to Table 1.

Table 3. Assigned values to the variables of the modified APLIS for Planitero.

Lithology (L)	Scoring	Infiltration Landforms (I)	Scoring
Flysch/Argillaceous sediment	1	Rest of the area	1
Metamorphic bedrock	2	Carbonates/karstic landforms filled with sediment	5
Quaternary deposits	3	Doline	10
Talus Cone/Scree	4	**Soil Type (S)**	**Scoring**
		Chromic luvisols	3
Carbonates (Pindos Zone)	9	Calcareous regosols and fluvisols	6
Carbonates (Tripolis Zone)	10	Leptosols	10

The application of modified APLIS in Xiromero is thoroughly described in [29], while Table 4 presents the updated values that were attributed to each variable.

Table 4. Assigned values to the variables of modified APLIS for Xiromero—modified from [29].

Lithology (L)	Scoring	Infiltration Landforms (I)	Scoring
Quaternary Sediment	1	Rest of the area	1
Evaporites/non karstified limestones	2	Karstified Limestone/Breccia	5
Talus Cone/Scree	3	Doline	10
Alluvial Deposit	4	**Soil Type (S)**	**Scoring**
		Fluvisols	6
Dolomite	7	Calcareous Lithosols	6
Triassic Limestone/Breccia	9	Leptosols	10

3. Results and Discussion

3.1. Comparison of the Results That Each Version of the APLIS Method Provided in the Karst System of Ziria

The spatial distribution of recharge rates in Ziria reveals significant disparities when assessed by the original and modified methodologies. Considering the first case (Figure 5a), the recharge rates in the area are predominantly Low (20–40%) and Moderate (40–60%), while those identified as High (60–80%) and Very High (>80%) are in correlation with preferential infiltration zones or the presence of flattened slopes in carbonates. The annual recharge rate estimated by APLIS ranges from 16.6% to 85.5%, with a mean annual value of 42.7%.

In modified APLIS (Figure 5b), the spatial distribution of recharge has been significantly impacted by the introduction of the correction factor (Fh). Notably, the recharge rates in a substantial portion of the area, encompassing the polje and other outcrops of low-permeability materials, have been categorized as Very Low (<20%). Furthermore, there is a noteworthy shift in the recharge classification for carbonate outcrops in Mount Ziria, elevating them from the previous Moderate class (40–60%) to High recharge rates (60–80%) due to the additional value (5) in the preferential infiltration parameter that was attributed to all the carbonates. A similar upgrading is observed for conglomerates, transitioning from Low (20–40%) to Moderate (40–60%) recharge rates. Despite the significant divergence in spatial distribution compared to APLIS, the simultaneous expansion of formations with Very Low (<20%) and High (60–80%) recharge rates has resulted in a marginal alteration of the mean annual recharge rate, which has slightly decreased to 41.4%. With the modified version of APLIS, the recharge rate in the study area ranges from 1.6% to 85.5%.

The spatial distribution of the recharge rate resulting from both methods seems to be in unison for a significant part of the system classified as Low and Moderate, mainly referring to some of the Quaternary deposits and sections of the carbonates.

In a hydrological balance study carried out in the area, the infiltration coefficient was estimated at 51% for the carbonates of Mount Ziria, 35% for the conglomerates, 15% for the Quaternary deposits, and 2% for the tectono-sedimentary complex [53]. According to Röckel and Hötzl [49], on the other hand, the infiltration was roughly estimated at 50% for limestones and conglomerates since both of them are considered karstified, 20% for Quaternary gravels, and 4% for clays and marls. It is also suggested that, especially for the carbonate outcrops on Mount Ziria, 60% of infiltration can be expected because of the dominance of bare karst on vast areas.

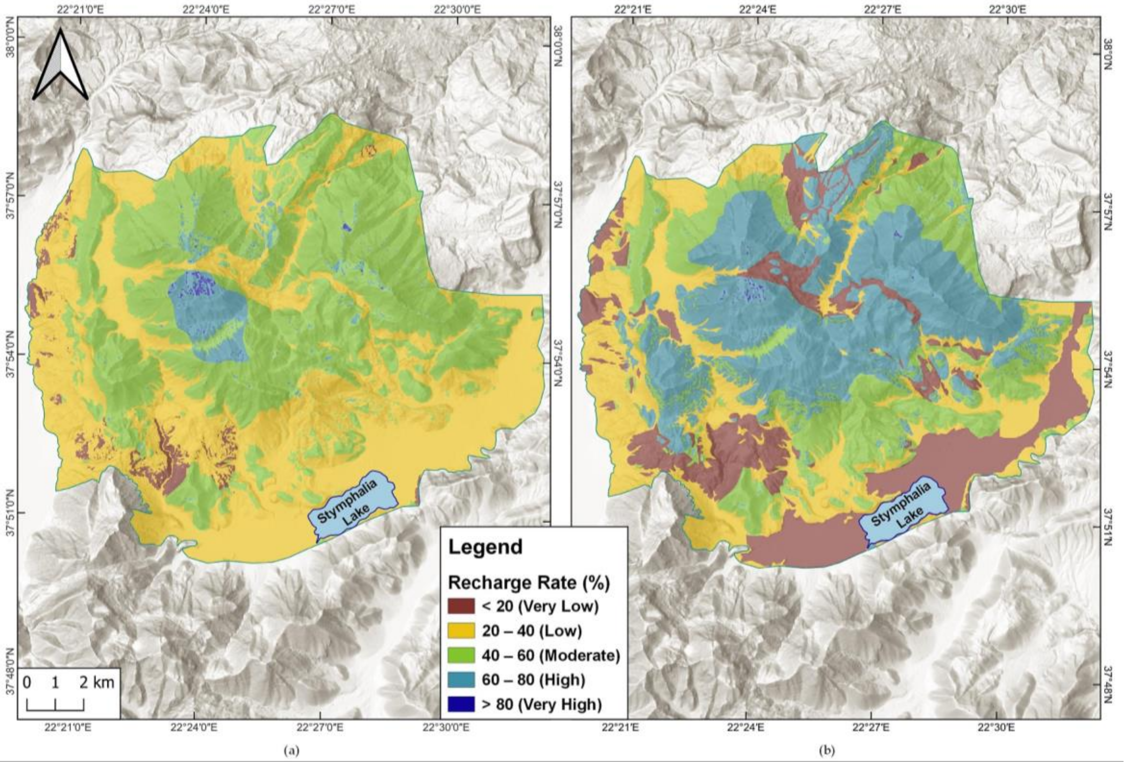

Figure 5. Spatial distribution of the annual recharge rate (%) in the karst system of Ziria utilizing (**a**) the APLIS method and (**b**) modified APLIS.

The inputs of these prior studies align more closely with the outcomes derived from modified APLIS, where, first and foremost, due to the correction factor (Fh), the areas of very low permeability and recharge below 8% can be recognized, contrary to the original methodology. In the alluvial deposits of the polje, along with the tectono-sedimentary complex, the recharge rates span between 1.6% and 3.5%. The percentages that are essentially identified in the conglomerates are in the range of 44–52%, while for the carbonates of Mount Ziria, they are 51–70%. In contrast, APLIS indicates different recharge rates for the same formations: approximately 16–28% for the alluvial deposits in the polje, 24–33% for the tectono-sedimentary complex, 35–42% for the conglomerates, and 44–64% for the limestones and dolomites. The highest percentage of recharge in both methods is 85%, but the range of 70% to 85% primarily refers to specific karstic landforms.

Data distribution and statistics contributed to the comparison between the two outcomes (Figure 6). In APLIS, the median recharge value is 38.9%, with 25% of the data falling below the threshold of 31.1% (representing the first quartile), while 75% of the data falls below the rate of 53.3% (corresponding to the third quartile). In modified APLIS, the median and first quartile values are 46.7% and 27.8%, respectively, while the third quartile stands at 62.2% (Figure 6a). The distribution of data within each recharge class appears to be more evenly distributed in the modified methodology. Conversely, in the original APLIS method, there is a noticeable deviation between the classes (Figure 6b). Low (20–40%) and Moderate (4060%) recharge rates dominate the area, collectively covering nearly 94% of the karstic system.

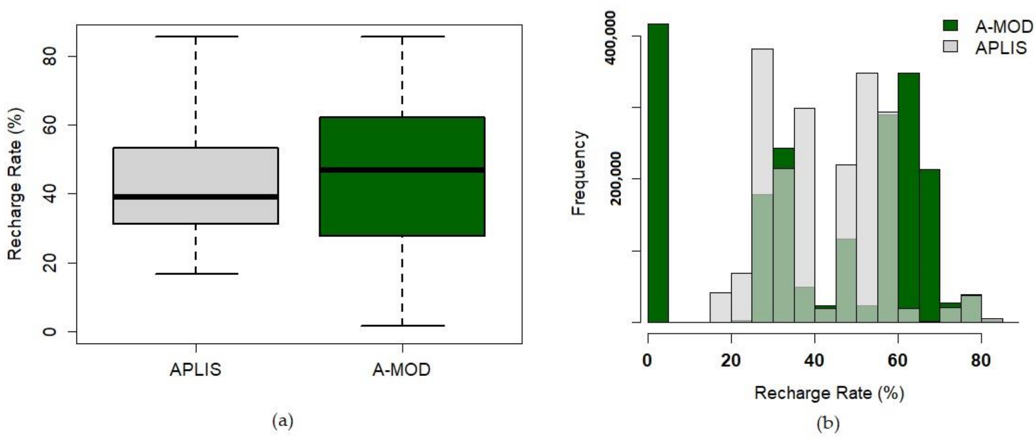

Figure 6. (**a**) Data visualization and comparison with boxplots; (**b**) Histogram with data distribution and range of values (A-MOD represents modified APLISand the light green color portrays areas of overlap).

In the modified methodology, High recharge rates (60–80%) appear to be the most prevalent, occupying 63 km^2 of carbonate sediments. There is a substantial difference between the methods regarding the Very Low (<20%) recharge class, where the variation in the two data volumes translates to 2.1% (APLIS) and 21% (modified) with respect to area coverage. In both methods, Very High (>80%) recharge rates are the least widespread, taking up an area of 0.5 and 0.25 km^2, respectively. Since the scoring of each variable corresponding to the karstic landforms of the mountain that primarily exhibit such a recharge class is exactly the same, the differentiation of the occupied surface between the methods is most likely due to the diverse classification of the slope factor (P).

To conclude, the modifications made to the APLIS method have significantly enhanced the accuracy of recharge rate estimations, leading many researchers to adopt the adapted methodology for their assessments. The attribution of additional values and the reclassification of specific variables have proven to be pivotal in shaping the final outcome. Modified APLIS distinguishes the infiltration landforms in three categories (1, 5, and 10), in contrast to the initial method, which has only two categories (1 and 10).

Consequently, the category with a score of 5 is more representative for many formations of the studied hydrosystem compared to the initial score of 1. The greater extent of the lowest recharge rates is due to the correction factor (Fh) that was introduced in the modified methodology and empowers users to provide a more precise permeability assessment for the geological formations. Inevitably, in the final map, extreme values of recharge rates (e.g., <20% and 60–80%) cover a greater area. Consequently, the mean annual value of the recharge rate estimated by the modified APLIS is lower than the initial method. The permeability factor has notably addressed the limitation of the original method, which could not estimate recharge rates below 8%. In non-permeable formations, APLIS estimated recharge rates between 16% and 33%, as it relied solely on the minimum attributed values of the lithological parameter. High elevations, flattened slopes, and thin soil coverage, however, can increase the recharge rate of an impermeable formation that receives high scores in all three categories.

Other researchers have also compared the two adaptations of the method. Espinoza et al. [34] applied APLIS and its modified version to a fractured karst aquifer in Peru, estimating the mean annual recharge rates at 48% and 24%, respectively, and emphasizing the key role of the correction factor in this differentiation. In another study, AHP, APLIS, and modified APLIS were implemented to evaluate the infiltration potential of the Roein Esfarayen Basin in Iran [54], with modified APLIS demonstrating the highest correlation coefficient (0.85) among the three methods, underscoring its efficacy in capturing and describing the complexities of recharge dynamics. Overall, the methodology behind modified APLIS consistently produces a more coherent and realistic portrayal of the recharge rate.

3.2. Statistical and Spatial Comparison of the Annual Recharge Rates in All Three Karst Sites Utilizing Modified APLIS

The estimation of the annual recharge rate was conducted using modified APLIS in both Planitero and Xiromero, resulting in maps illustrating its spatial distribution (as shown in Figure 7a,b).

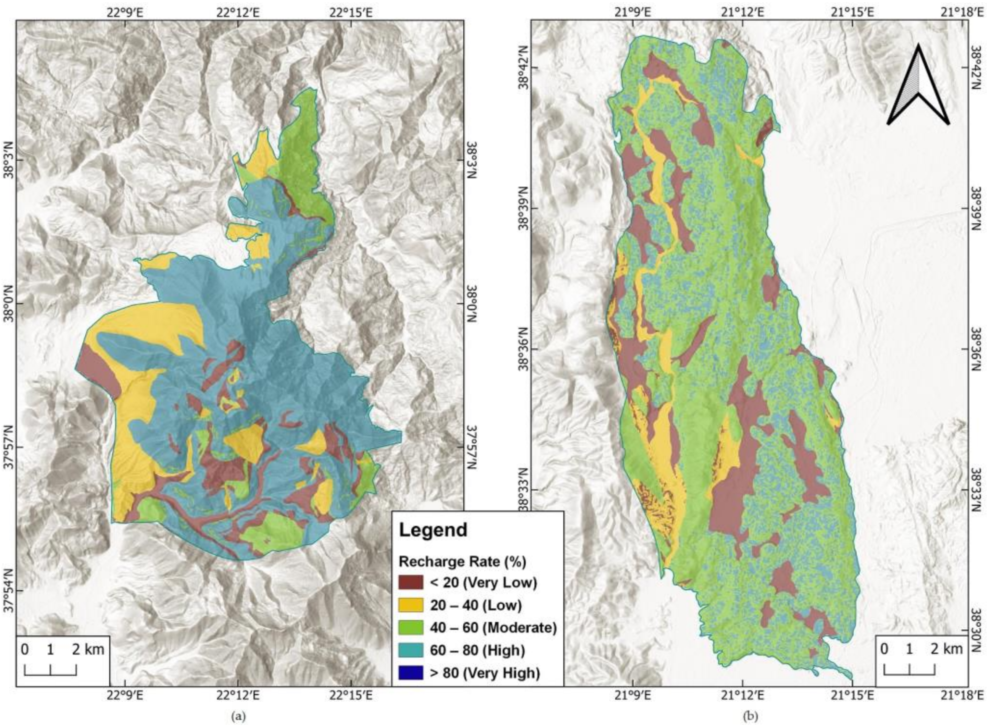

Figure 7. Annual recharge rate estimated with modified APLIS (**a**) in Planitero, Northern Peloponnese, and (**b**) in Xiromero, Western Greece.

In Planitero, recharge rates exhibit a broad range, spanning from 1.3% to 86.6%, with a mean value of 48.6%. Notably, the site is primarily composed of carbonate formations, which accounts for the prevalence of High recharge rates (60–80%) covering 62.7 km² of the total area (Figure 8a). A very small percentage, approximately 0.007%, is classified as Very High (>80%), mainly associated with infiltration landforms. Very Low (<20%) and Moderate (40–60%) recharge rates are nearly equally represented, encompassing 14.3 km² and 13.4 km² of the system, respectively.

The annual recharge rate in Xiromero ranges from 1.4% to 76.6%, with a mean annual value of 46.9%. It stands as the only site among the three that does not exhibit recharge rates that exceed 80% (Figure 7b). This differentiation can be attributed to the significantly lower elevations in the area, along with the absence of the highest lithological scoring (10). The dominant recharge class in Xiromero is Moderate (40–60%), occupying more than half of the entire surface (Figure 8a), and it is primarily associated with karstified breccia and limestone outcrops. High recharge rates (60–80%) correspond to 21.9% of the system, with a higher prevalence of this recharge class observed in both Ziria and Planitero.

A comparative analysis of all three sites (Figure 8a,b) reveals noteworthy distinctions in the annual recharge rates. In Ziria, apart from the Very High Class (>80%), recharge rates are much more evenly distributed throughout the area (median value 46.7%), since it is the only site that is not dominated by a specific geological formation. While Ziria and Planitero share several similarities, the range of recharge values in the latter is broader. The median and third quartile values are 62.2% and 64.4%, respectively, suggesting a tendency towards higher recharge values (Figure 8b). In contrast, the range of recharge rates in Xiromero is comparatively narrower, with the median value being 57.8% and the third quartile being 60%. These variations underscore the unique hydrogeological characteristics and geological formations of each system, which influence the distribution of recharge rates.

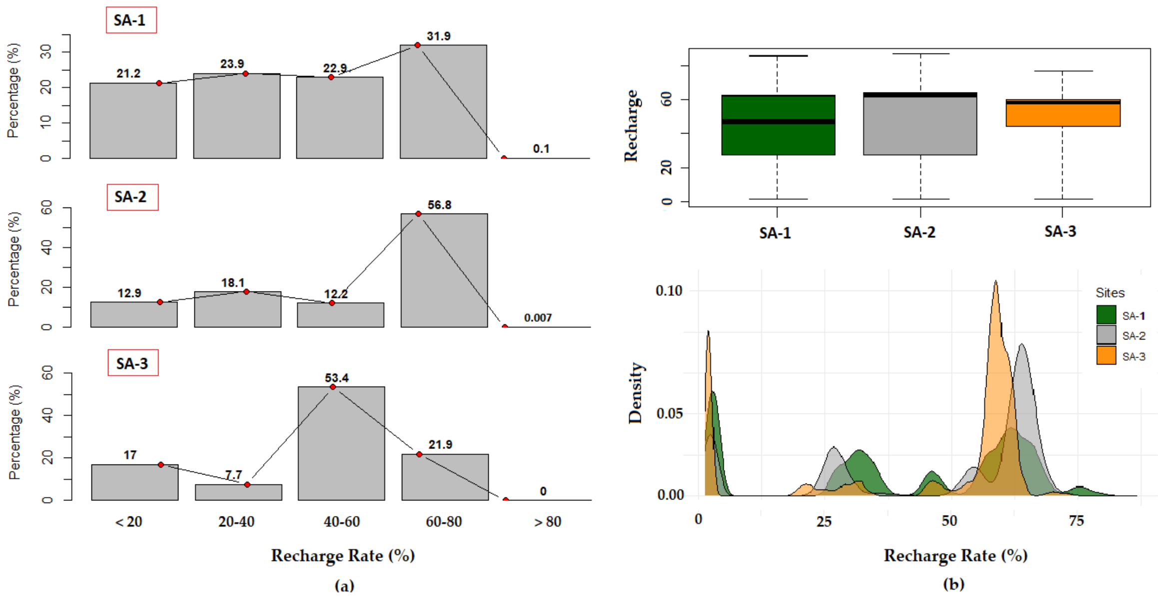

Figure 8. (**a**) Surface coverage of each recharge class in Ziria (SA-1), Planitero (SA-2), and Xiromero (SA-3), and (**b**) Boxplots illustrating the distribution of the annual recharge rate data in SA-1, SA-2, and SA-3 (**top**) and a density plot (**bottom**) showing its allocation between the sites.

The quantification of recharge in mm/year was accomplished by multiplying the spatial distribution of the assessed recharge rates (%) with precipitation (mm/year). Due to the close proximity of Ziria and Planitero, the same equation was utilized in order to convert contours into isohyets lines. In Ziria, recharge ranges from 13.7 to 1423.4 mm/year with a mean annual value of 498 mm/year, while in Planitero, due to the dominance of limestones and dolomites, the mean annual recharge is 618 mm/year. Xiromero does not exhibit Very High recharge rates (>80%), and the elevations in the area are considerably lower than in the other systems. However, due to the different precipitation regime in Western Greece, recharge in Xiromero spans from 13 to 852.5 mm/year, and the mean annual value is 439 mm/year.

Several methods and models have been developed over the years for the determination of aquifer recharge. The methodology behind APLIS provides reasonable results with an easy GIS-based application without requiring data that is difficult to acquire or not available, unlike many other approaches. It also enables the determination of the spatial distribution of recharge, something that separates it from many other methods. Its methodology has been widely used, so if it is necessary to have the spatial distribution of mean annual recharge rates, APLIS constitutes the most suitable method.

3.3. Implications/Limitations and Future Works

The estimation of recharge is a very intricate subject for karst environments due to their hydrogeological uniqueness. APLIS has yielded valuable insights, but it is essential to acknowledge the implications of this approach. The accuracy of the method heavily depends on the quality of input data and the attribution of scoring values, while it is not difficult to generate unreliable results. One major challenge arose from the assignment of values to the Soil types (S) within the study sites. The problem stems from the reliance on global and continental-scale soil maps that often provide generic and generalized data. This can introduce a level of uncertainty into the method, as local variations in soil characteristics may not be adequately represented. Consequently, the accuracy and reliability of the recharge assessment may be compromised, necessitating caution in interpreting the results and highlighting the need for higher-resolution local soil data for more precise assessments.

Another important consideration pertains to the variables Lithology and Preferential infiltration, which are of paramount importance in the expression of recharge assessment. The values assigned in Lithology in particular entail a degree of subjectivity, as they are left to the discretion of the user. This introduces a degree of user-dependent variability into the method, leading to variations in the outcomes based on individual judgment. It is crucial to communicate this inherent subjectivity, emphasizing that the accuracy of the recharge assessment is inherently linked to the quality and appropriateness of the values selected.

While the APLIS method is effective in mapping the spatial distribution of annual recharge within a given area, it exhibits a limitation in its capacity to estimate its temporal variability. This limitation stems from the inherent nature of the method, which predominantly focuses on spatial aspects, neglecting the intricate temporal dynamics of recharge processes and providing averaged annual values of recharge rates. Recharge in karst aquifers is not a constant phenomenon but can vary significantly over time, influenced by factors such as seasonal variations in precipitation, land use changes, and climate fluctuations. Kirn et al. [55] extended the spatial dimension of the method to include the aspect of time variance and concluded that APLIS tends to overestimate recharge in dry years and underestimate it in wet years.

APLIS is a promising method for assessing the mean annual recharge that has been applied to several karst aquifers under Mediterranean climatic conditions, yielding satisfactory results. Given the intricate nature of karst systems and the challenges associated with verifying recharge assessments, the adoption of a multi-method approach is essential. In the future, further research will be conducted in order to strengthen the premise of this ongoing project. A comparison of APLIS' results with lump simulation models is strongly suggested. The implementation of advanced modeling at the study sites will provide a more holistic view of recharge, aid in error reduction, and enhance the reliability of findings associated with APLIS as an individual technique. Sensitivity analyses and robustness testing will be conducted in order to assess the potential impact of varying the parameters on the method's results, and tectonic lineaments will be introduced as possible infiltration landforms. Discharge measurements and hydrograph analysis from the front of springs in the karst system of Ziria will contribute to the verification of the results. The determination of recharge rates on a hydrogeological basin scale is valuable for the understanding of karst aquifer functions. Nevertheless, we strongly suggest comparing the results with the hydrological component of infiltration at the hydrological basin scale [56]. This approach could better determine underground runoff, which is critically important in the groundwater extraction process for the sustainable water supply of the community. Future research will incorporate hydro-chemical data, high-frequency discharge measurements, and isotopic data from groundwater and rain.

4. Conclusions

The two-step methodological approach that was applied in this study revealed that the geological structure influences the recharge rates of a karst aquifer. The conclusions are summarized below:

- The discretization of formation permeability increases the reliability of recharge rate determinations.
- Modified APLIS, compared to the initial method, provided extended zones with Very Low (<20%) and High (60–80%) recharge rates.
- The modified APLIS method estimated a relatively lower recharge rate (41.4%) compared to the initial method (42.7%) in Ziria, mainly due to the imported parameter of permeability.
- The cross-comparison of the results between the different karst systems revealed that the coverage of karst aquifers determines the recharge rate.
- The highest mean recharge rate was estimated in the Planitero karst system (48.6%) due to the absence of coverage of the karstified rocks.

This study revealed that modified APLIS constitutes a flexible method for the estimation of karst aquifer recharge rates in the Mediterranean region. The quantification and spatial distribution of mean annual recharge rates can increase the accuracy of water balance estimations, which is a fundamental step for sustainable groundwater resource management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16040568/s1, Reliability of used data.

Author Contributions: Conceptualization, E.-A.N. and E.Z.; data curation and processing, E.-A.N., P.T. and K.P.; software, E.-A.N., P.T. and K.P.; writing-original draft preparation, E.-A.N.; writing–review and editing, E.-A.N. and E.Z.; supervision, E.Z.; funding acquisition, E.-A.N. All authors have read and agreed to the published version of the manuscript.

Funding: Part of the research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the HFRI PhD Fellowship grant (Fellowship Number: 684).

Data Availability Statement: The presented data are available on request from the corresponding author.

Acknowledgments: A section of this study has been presented at the 12th International Hydrogeological Conference held in Nicosia, Cyprus, in 2022.

Conflicts of Interest: The authors declare no conflict of interest.

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