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Assessment of Environmentally Minimum Water Level in a Mediterranean Lake Using Morphological, Hydrological and Biological Factors

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Abstract: Water resources management requires comprehensive and integrated approaches that jointly consider hydrological, ecological and social factors. The assessment of lakes' environmentally minimum water level is a critical tool for the sustainable management and protection of their ecosystems. This work combines the morphological, hydrological and biological factors of a Mediterranean lake (Lake Volvi, northern Greece) to assess its environmentally minimum water level. Initially, the morphological characteristics of the lake's bottom were analyzed, with consideration given to the protection of the lake's ecosystem and to the need to meet the water requirements for economic activities. Then, a hydromorphological analysis was conducted, relying on the surface water inflows to the lake from its hydrological catchment and the lake's water level -volume relationship. In addition, the water level requirements of the biological communities of macrophytes, benthic macroinvertebrates, and fish, as revealed after samplings were taken from the lake's littoral zone, are considered. Based on the above methodologies, the environmentally minimum water level of Lake Volvi is proposed to be lowered by as much as 35.8 m from February to May and 35.3 m from June to January in order to maintain the ecological integrity of the lake and the sustainable use of its water resources. The present study establishes a foundation for informed water resource management; however, ongoing research can improve methodologies and address emerging questions, fostering advancements in sustainable water management practices.

Keywords: ecological lake level; hydromorphological analysis; aquatic macrophytes; benthic macroinvertebrates; fish fauna; Lake Volvi

Citation: Doulgeris, C.; Ntislidou, C.; Petriki, O.; Zervas, D.; Nikolaidou, R.; Bobori, D.C. Assessment of Environmentally Minimum Water Level in a Mediterranean Lake Using Morphological, Hydrological and Biological Factors. *Sustainability* **2024**, *16*, 933. https://doi.org/10.3390/su16020933

Academic Editor: Hossein Bonakdari

Received: 28 December 2023
Revised: 18 January 2024
Accepted: 18 January 2024
Published: 22 January 2024

1. Introduction

Water resources require comprehensive and integrated approaches that jointly consider hydrological, ecological and socio-economic factors to guarantee environmentally sustainable, economically efficient and socially equitable management. Assessing the sustainable water level of a lake is a complex task that requires consideration of both environmental factors and ecosystem services. These services include essential aspects such as water supply, fisheries, nutrient cycling, climate regulation, flood control, recreation, tourism, and more, contributing significantly to human wellbeing and economic development. The assessment of lakes' environmentally minimum water level, i.e., the critical level below which no further withdrawal should occur, is a key factor in ensuring their ecosystems' sustainable management and protection. However, the impact of maintaining an environmentally minimum water level may vary across different segments of the community, presenting benefits to specific groups, such as fishermen or farmers utilizing water for irrigation, while potentially posing challenges for others. This recognition of divergent interests and potential conflicts underscores the intricate nature of water resource management, emphasizing the need for a comprehensive and balanced approach to address the diverse needs of both the environment and the community.

The methods for estimating minimum lake level could be categorized into lake morphology analysis methods [1–3], historical lake level methods [4–6], methods that combine a lake's hydrological and morphological features [7], habitat analysis methods and species–environment models [8–12]. The lake surface area method [1] defines a minimum lake level via the relationship of a lake's water level, area, and volume, with consideration given to the protection of ecosystems and the need to meet water demands. The hydromorphological method [7] combines a lake's hydrology and morphology by considering the water inflows from its hydrological catchment and water level–volume relationship. Wang et al. [13] applied six different methods to estimate the minimum water level in Lake Poyang (China) based on historical lake level data, analysis of morphological characteristics of the lake's bottom and the water level requirements of fish fauna. Bao et al. [14] analyzed the hydrological regime of wetland systems of Momoge (China) and proposed suitable water depths to favor the growth of phytoplankton, aquatic plants, benthic and fish fauna. Yi et al. [11] simulated the environmental conditions in a shallow lake, Lake Baiyangdian (China), using a habitat mathematical model of the common reed (*Phragmites australis*), relating water level fluctuation with reed growth to estimate the lake's minimum ecological water level.

Relationships between the development of aquatic macrophyte species and water level have been studied in plant physiology studies [15] which have investigated the optimal water depth for several aquatic plants. Keddy and Reznicek [16] reviewed the relationship between aquatic vegetation dynamics and water level fluctuations in the Great Lakes. The impact of water level changes on aquatic plant diversity has been evaluated in experimental plots [17,18], while the degree of water level fluctuations has been examined to achieve optimal plant diversity [19]. Van Geest et al. [20] conducted a large-scale study to match specific plant communities to specific water regime conditions. Beklioglu and Tan [21] reported changes in aquatic vegetation in five shallow lakes in Turkey after changes in their water regime conditions. Additionally, the degree of water level change and its duration are essential for plant communities [22]. Some studies in China moved a step further by evaluating the ecological preferences of aquatic plants concerning water regime conditions in order to establish optimum ecological conditions for aquatic ecosystems [8,23,24]. Moreover, prediction models of aquatic vegetation have been developed at different water levels [25]. Finally, aquatic plant seasonal water level preferences have been used to propose water level management plans for the protection and/or restoration of several wetlands in China [26–28].

The distribution and abundance of benthic macroinvertebrates in the littoral zone are determined mainly by habitat and available resources [29,30]. Other essential factors include lake morphology [31], the distribution and availability of phytoplankton [32], the density and biomass of macrophytes, organic matter [33–35] and water level fluctuations [36–39]. The impacts caused by water level fluctuations have been studied widely in different types of lakes [37,39]. Many studies have pointed out that water level fluctuation reduces the density, diversity and abundance of benthic macroinvertebrate assemblages and alters the taxonomic and trophic structure [40,41].

The requirements of the fish fauna community are systematically considered when determining the ecological flow in river systems, as, in many cases, the increase of fish stocks is also a goal [42]. Specifically, various aspects of the life history of a species of interest are examined, mainly regarding their reproduction strategies (e.g., spawning, fertilization, migration), diet, and behavior (habitat preference, larval–adult migrations). In lacustrine systems, however, and in contrast with the macrophyte and hydrogeomorphic parameters that are systematically considered when setting minimum water levels, studies that consider the ecological requirements of fish are scarce. Specifically, the determination of minimum water levels is based on expert judgment, so as to ensure the accessibility of fish to their breeding and feeding areas and the protection of those habitats (primarily concerning the structural complexity of the littoral zone, which provides crucial refuge for fish and comprises the most productive part of lacustrine ecosystems) [43,44].

Considering the above, it is clear that alterations in the macrophytic community may initiate cascading effects on the surrounding ecosystem, influencing both macroinvertebrate and fish fauna. The relationship between macrophytes and aquatic fauna is complex and can vary based on several factors, including the type of macrophytes, their abundance and the specific ecological conditions of the lake. Specifically, alterations in the distribution and abundance of macrophytes may indirectly impact these communities by changing critical factors, like habitats structure, shelters, food availability, and oxygen production. The structural complexity provided by macrophytes acts as crucial refuge and cover for both macroinvertebrates and fish, significantly contributing to their wellbeing and reproductive success. Consequently, fluctuations in the macrophytic community can result in indirect shifts in the dynamics of macroinvertebrate and fish fauna, underscoring the interconnected nature of these ecological components within the aquatic ecosystem. Understanding these relationships is crucial for effective lake management and conservation.

Ideally, the estimation of the environmentally minimum water level of a lake should consider both abiotic and biotic characteristics of the ecosystem. However, only a small number of case studies that combine methodologies to assess minimum water level in lakes appear in the literature. Moreover, the fluctuation of a lake's water level, and consequently the estimation of its minimum level, is highly related to the hydrological conditions of the lake's catchment that should also be considered. To address the above issues, the present study provides a multidisciplinary approach, combining morphological, hydrological and biological elements to determine the minimum water level required to maintain the ecological integrity of Lake Volvi, one of the largest natural lakes in Greece and one that has abundant flora and fauna. The five distinct methodologies analyze the lake's morphological and hydrological features, as well as the seasonal water level requirements of aquatic macrophytes, benthic macroinvertebrates and fish. In addition, results from the above methodologies are hydrologically evaluated to question whether the proposed minimum level is suitable for different hydrological conditions or not, as well as to determine whether the water potential of the lake's catchment is sufficient to raise the water level from the proposed minimum level to its maximum level every hydrological year.

2. Materials and Methods

2.1. Study Area

Lake Volvi is located in the water district of Central Macedonia, northern Greece. It has a surface area of 72.5 km^2 and holds a water volume of 911 hm^3 at the water level of 36 m a.s.l. Its average water depth is 12.5 m and its maximum depth is approximately 21 m. Lake Volvi is of tectonic origin [45], which explains its elongated shape, with a maximum length of 20 km and a width ranging from 2 to 6 km. At the beginning of summer, stratification of the lake commences (warm monomictic) [46], leading to anoxic conditions at the bottom, particularly in the deeper, eastern part of the lake. Lake Volvi outflows to River Richios, which in turn outflows to Strymonikos Gulf. Lake Volvi, along with neighboring Lake Koronia, is protected under the Ramsar Convention as a wetland of international importance (Lakes Volvi and Koronia | Ramsar Sites Information Service [47]). The lake also forms part of the National Park of Lakes Koronia-Volvi and Macedonian Temp. Their hydrological catchment drains an area of 2061 km^2, while the sub-catchment area of Lake Volvi is 1293 km^2 (Figure 1). The lake's catchment is sparsely populated, with 31,059 inhabitants distributed across 30 small villages.

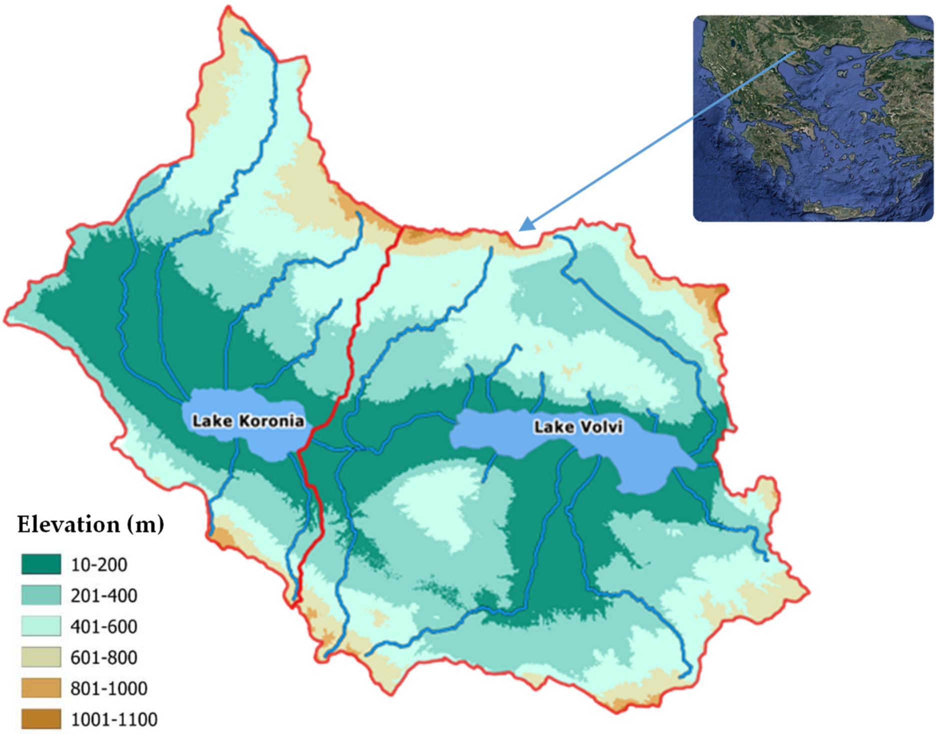

Figure 1. The hydrological catchment of lakes Koronia and Volvi. With red lines depicting the hydrological sub-catchment of each lake and blue lines depicting the key rivers.

The ecological quality of Lake Volvi faces a multitude of challenges. Volvi's water quality has been deteriorated by agricultural runoff, livestock waste, untreated or inadequately treated domestic sewage, and effluents from small food and dairy industries [48,49]. The intensive agriculture in the catchment area has also resulted in water quality degradation and a disruption of the lake's water balance [50,51]. Specifically, the increased nitrate load due to pesticide use has contributed to eutrophication of the lake. However, Antonopoulos and Gianniou [52] have spatially and temporarily analyzed the lake, modeling temperature, chlorophyll-α, phosphorus and dissolved oxygen for the period 2013–2015, and have concluded that Lake Volvi is not under eutrophication pressure, even though there appears to be a trend towards more intensive productivity.

The climate is characterized by mild winters and dry, hot summers, with an average annual temperature of 13.3 °C and an average temperature of the warmest month exceeding 22 °C [53,54]. The average annual precipitation for the period 1970–2000 was 519 mm. The rainfall of the driest month does not exceed 30 mm and is less than a third of the rainfall corresponding with the wettest month.

2.2. Datasets

Morphological, hydrological and meteorological data for Lake Volvi are available at the Greek Biotope/Wetland Centre (website for Nature and Biodiversity—http://www.biodiversity-info.gr/ (accessed on 5 May 2023)) and Malamataris [53]. The morphology of the lake's bottom is usually sufficiently expressed by the relationships between the lake's water level, surface area, and stored volume (Figure 2). The quality of level–area–volume data is crucial for estimating the lake's minimum level using a morphological or hydromorphological analysis, as well as to evaluate hydrologically the proposed environmentally minimum level. The water level in Lake Volvi fluctuates between 34.2 m and 37.5 m (a.s.l.), based on the data for the periods 1985–1994 and 2012–2021 (Figure 3). The minimum water level is usually observed during September–November, with an average value of 35.3 m, while the maximum level is observed in March–April, with an average of 36 m.

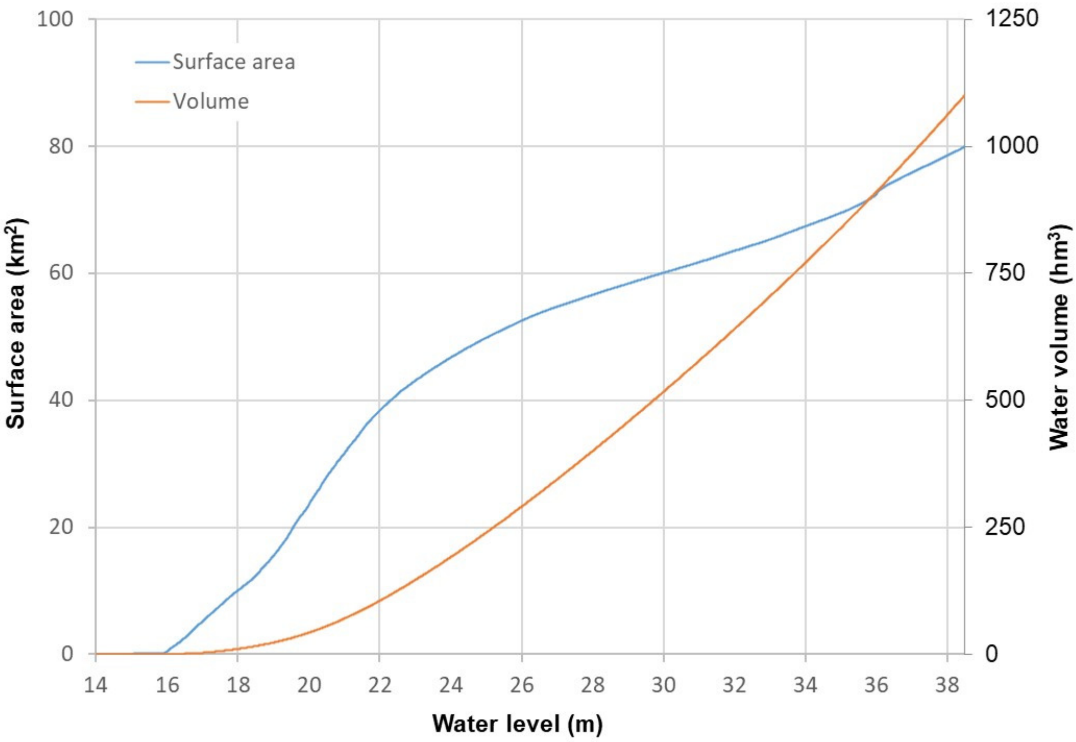

Figure 2. Water level–surface area–volume curves of Lake Volvi.

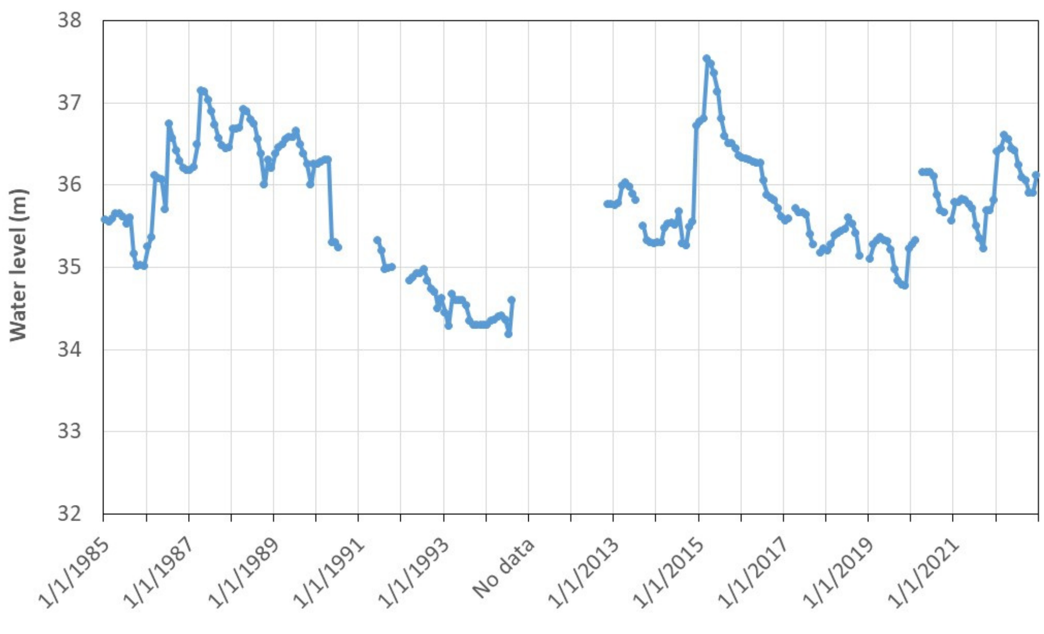

Figure 3. Water level fluctuation of Lake Volvi in the years 1985–1994 and 2012–2022.

Regarding the aquatic vegetation of Lake Volvi, the first systematic fieldwork was conducted by Papastergiadou in 1986 [55]. Sixteen different hydrophytic taxa were recorded, with *Najas marina*, *Trapa natans*, *Potamogeton lucens*, *Myriophyllum spicatum*, *Vallisneria spiralis*, *Potamogeton perfoliatus*, *Hydrocharis morsus-ranae* and *Ceratophyllum demersum* being dominant. The next comprehensive recordings of aquatic vegetation were conducted in 2013 and 2016 [56]. Vegetation sampling of 2013 recorded 13 taxa, dominated by *N. marina*, *C. demersum*, *M. spicatum*, *V. spiralis*, *P. perfoliatus*, *P. australis* and *Stuckenia pectinata*. Vegetation sampling during 2016 recorded 15 aquatic taxa, dominated by the same taxa as 2013.

Few data are available for the composition and abundance of benthic macroinvertebrates in Lake Volvi. A total of 54 taxa have been recorded in Lake Volvi over the last 30 years [57–61]. The most abundant families are Diptera and Oligochaeta, with 18 taxa and 15 taxa, respectively. Of these studies, only one focuses on the benthic macroinvertebrate assemblages of the littoral zone of Lake Volvi [59]. The rest mainly refer to the sublittoral and profundal zones of the lake.

Regarding the fish fauna, 28 species have been reported in the broader drainage area of Lake Volvi (including Lake Koronia and River Richios). Out of these, 8 species are endemic to the system or the Balkan Peninsula, 6 are introduced and 14 are native. Some of these species have almost disappeared or are found in very small populations, such as *Silurus glanis* and *Anguilla anguilla.*

2.3. Hydromorphological Analysis

2.3.1. Morphological Method

The morphological method applied to estimate Lake Volvi's environmentally minimum water level is the lake surface area method proposed by Shang [1]. The method defines a lake's critical water volume as that which corresponds to the inflection point of the surface area–stored volume curve. Based on this point, the minimum water level can be found, considering both the protection of ecosystems and the need to meet water demands and bearing in mind that a lake's surface area is an index for the protection of lake ecosystems [62] while its water volume is available to meet water demands of economic activities, such as irrigated agriculture. To solve the obvious conflict between ecosystem protection and the meeting of water demands, a multi-objective optimization model is applied. The first objective represents the maximization of lake surface area, considering that the biodiversity of a lake is favored as the lake surface area increases. The second objective represents the minimization of lake storage to meet the water requirements to the greatest possible extent. The transformation of the multi-objective optimization problem into a single objective problem is based on the ideal point method, which considers two non-negative weighted factors, (w_1 and w_2, where $w_1 + w_2 = 1$), and is written as: $\min \{w_1 v + w_2 [1 - s(v)]\}$, where s and v are the dimensionless surface area and volume, respectively. Weight w_1 minimizes stored volume to meet water demand and w_2 maximizes surface area to protect ecosystems. It has been demonstrated [63] that applying the method may lead to the rational estimation of the environmentally minimum water level when the ecosystem protection is favored against meeting water demands, i.e., $w_1 = 0.3$ and $w_2 = 0.7$. More details about the method are also given in [7].

2.3.2. Hydromorphological Method

The hydromorphological method [7] combines a lake's hydrological and morphological features. In particular, it considers the water inflows from a lake's hydrological catchment and its water level–volume relationship. To apply this method, three simple steps are followed. Initially, the surface water inflow to the lake is estimated, using a rainfall–runoff model for the lake's catchment, or alternatively, by considering the annual runoff as a percentage of annual rainfall. Then, a critical water volume is defined as the median volume of the annual water inflow time series (as estimated in the previous step). Finally, the minimum water level, corresponding with the volume that is equal to the maximum stored volume in the lake minus the critical volume, is determined, and can be easily found via the water level–volume relationship.

More specifically, to estimate the environmentally minimum water level in Lake Volvi, the lake's water balance and the rainfall–runoff relationship in its hydrological catchment were studied for the period 2015–2019 using the MIKE HYDRO Basin model and the NAM rainfall–runoff model [64]. The accuracy of modelling results was mainly verified based on the measured lake's water level. The above analysis found that the annual volume of surface water inflow to the lake from its hydrological catchment is estimated to be 7.5% of the volume of annual rainfall received by the lake's catchment. The surface water inflow to Lake Volvi (Figure 4) was estimated for a period of 30 hydrological years (1970/1971–1999/2000), given that a long timeseries of a sufficient number of meteorological stations were available for this period [53]. It should be mentioned that the surface water inflow to Lake Volvi is the determinant parameter of its water balance, as has been confirmed by hydrological modelling and analysis. Then, the critical water volume was found as the median value of the time series data provided in Figure 4, and, afterwards, the minimum water level was estimated based on the water level–volume relationship given in Figure 2.

Figure 4. Annual surface water inflow to Lake Volvi from its catchment for the hydrological years 1970–1971 until 1999–2000.

2.4. Habitat Types and Lake Bottom Granulometry

Important information to consider when deciding thresholds for water level fluctuations are shoreline habitat types and lake bottom granulometry. The data source for this information consisted of a previous extensive vegetation sampling in 2016, updated by field visits in 2023 for the current study in 20 sampling stations (Figure 5). More specifically, data were collected according to the Rapid Lake Habitat Survey Protocol (rLHS) created for Water Framework Directive monitoring samplings [65].

Ten out of seventeen habitats in the rLHS protocol were identified at the shoreline of Lake Volvi. The most common types found were emergent reed beds, open water areas and quaking banks (Supplementary Figure S1a). Absent types commonly found in other Greek lakes were tilled land, broadleaf/mixed woodland, broadleaf/mixed plantations and coniferous woodland. Regarding the shoreline substrate of Lake Volvi, the most common granulometry rank recorded was sand (0.06–2 mm), followed by gravel and stone (2–250 mm). In general, only a small number of areas were found to be dominated by silt, clay, mud or peat (Supplementary Figure S1b).

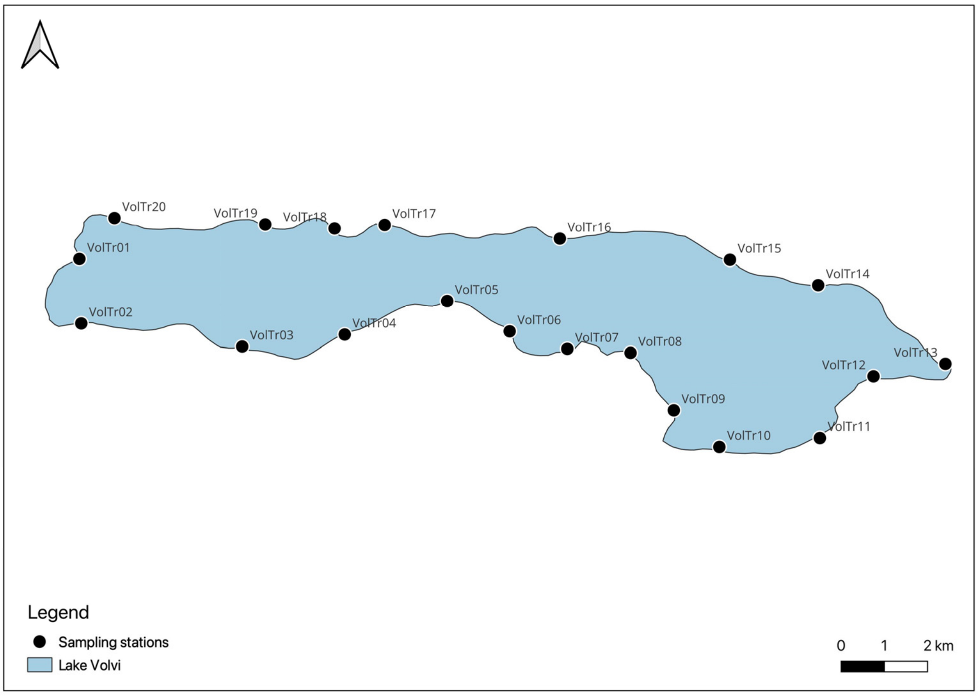

Figure 5. Distribution of the 20 sampling stations located in Lake Volvi, where habitat types and lake bottom granulometry were conducted. Samplings for macrophytes were conducted at stations VolTr02, VolTr03, VolTr04, VolTr05, VolTr08, VolTr10, VolTr11, VolTr15, VolTr17 and VolTr19. For benthic macroinvertebrates and fish, samplings were conducted at stations VolTr02, VolTr05, VolTr10, VolTr17 and VolTr19.

2.5. Biological Elements

2.5.1. Macrophytes

A complete survey of the composition, abundance and water depth distribution of macrophyte vegetation in Lake Volvi occurred in April 2023. The methodology used followed that of Zervas et al. [66], which, in order to acquire comparable data among the three periods, was also used for the samplings of 2013 and 2016 [56]. Ten out of the same twenty sampling stations of 2013 and 2016 were chosen to be revisited during 2023 (Figure 5).

Moreover, an extensive dataset of aquatic vegetation data from Greek lakes [56] was used to explore water level ecological preferences of macrophyte taxa found in Greece using field data. Specifically, this dataset contains 7464 vegetation sampling plots of aquatic macrophytes placed on depth gradients in 18 different Greek lakes, sampled between 2013–2016. From this dataset, sampling plots containing at least one taxon among those recorded in Lake Volvi were chosen and a fidelity measure analysis [67] was applied to statistically measure the probability of occurrence for each specific taxon in a particular water depth, weighted by abundance percentage values. At the resulting water depth, the range of occurrence for each taxon, with a confidence interval containing 50% of its probability of occurrence (between 25% and 75%), was chosen as a safe range that satisfies its water depth preferences. At the same time, a confidence interval containing 95% of its probability of occurrence (between 2.5% and 97.5%) was chosen as the absolute necessary for the survival of the taxon's population. The water depth preference ranges for each taxon, along with their population and spatial data collected from sampling (new vegetation survey and bibliographical data), were used to find the minimum seasonal water level required for the survival and continuity of the existing vegetation in Lake Volvi.

2.5.2. Benthic Macroinvertebrates

Benthic macroinvertebrates were sampled along separate transects from five stations in Lake Volvi biannually (October 2022 and April 2023) (Figure 5). Transects parallel to the shore at approximately 0.50 cm were conducted using a 250 mm × 230 mm, D-shaped pond net (0.9 mesh size) [68] according to the semiquantitative 3 min kick/sweep method [69]. All of the available microhabitats were covered proportionally. Benthic samples were sieved with a 500 μm mesh and fixed in 75% ethanol solution. Specimens were identified mainly at the family level (except for Ostracoda, Hydracarina, Araneae and Oligochaeta, apart from Tubificidae) using appropriate taxonomic keys [70].

The non-parametric Mann–Whitney test was applied using SPSS version 28 [71] to test whether there were differences in the benthic macroinvertebrate communities between the two sampling periods. Taxa were assigned to functional feeding guilds (FFG) based on dietary preferences as grazers and scrapers (GRA), miners (MIN), xylophagous taxa (XYL), shredders (SHR), gatherers/collectors (GATH), active filter feeders (AFIL), passive filter feeders (PFIL), predators (PRE) and parasites (PAR) according to Schweder [72]. Moreover, macroinvertebrates were classified into categories of locomotive capacity (LOC), hinged on the moving types as swimming/skating (LSS), swimming/diving (LSD), burrowing/boring (LBB), sprawling/walking (LSW), (semi)sessil (LSE), and others (e.g., climbing; LOT) following Schmedtje and Colling [73]. The feeding groups and locomotion type were estimated using ASTERICS software (version 4.0.4; Wageningen Software Labs 2005, Wageningen, The Netherlands). Finally, the water level fluctuation between the two sampling periods was determined using as metrics the diversity, abundance and composition of benthic macroinvertebrate assemblages, as well as the FFG and LOC traits [37,38,74].

2.5.3. Fish Fauna

Fish sampling was carried out in the littoral zone of Lake Volvi during the spring season 2023. Specifically, fish samples were collected at five stations (the same ones where benthic macroinvertebrate samples were collected) (Figure 5), using the method of electrofishing. During the sampling, an effort was made to "scan" all of the habitats found along the shoreline (such as areas near reeds, sandy or rocky bottoms) at an area larger than 150 m^2.

Furthermore, an extensive literature review was conducted to gather information on the biology and ecology of fish species, specifically focusing on their reproductive period and preferred reproductive substrate, diet and the habitat they prefer. The main source of information was the FishBase database. According to their preferred reproductive substrate, the species were classified as lithophilic (LITH), hyto-lithophilic (PHLI), phytophilic (PHYT), pelagophilic (PEL), ostracophilic (OSTR), psammophilic (PSAM), and ovoviviparous (NONE). Based on their diet, the fish species were categorized as omnivores, piscivores, benthivores, herbivores, and planktivores [75]. Finally, they were classified based on their preference for habitat as pelagic (PEL) and benthic (BENTH) species. For species with no available information, their classification was based on the preferences of the closest related species.

3. Results

3.1. Minimum Lake Level Based on Hydromorphological Analysis

The minimum levels for Lake Volvi, as estimated by the morphological and hydromorphological methods, are presented in Table 1. Regarding the morphological method, the minimum water level is estimated to be 32.5 m and the maximum water level at 36 m. This means that the water level could drop up to 3.5 m in a hydrological year, which apparently is an extremely high drop for the lake's water level. When the water level approaches this minimum level of 32.5 m, the lake's surface area decreases by 11% and the stored water volume by 26%, when compared with the corresponding maximum values. Applying the hydromorphological method, the minimum water level is estimated to be 35.3 m, meaning that the water level could drop by up to 70 cm during a hydrological year. In this case, when the water level is at the minimum level of 35.3 m, the lake's surface area decreases by only 3.2% and the stored water volume by 5.5%.

Table 1. Estimated minimum level in Lake Volvi using the morphological and hydromorphological methods.

	Morphological	Hydromorphological
Minimum level, m a.s.l.	32.5	35.3
Annual water level drop, m	−3.5	−0.7

3.2. Water Level Requirements of Biological Elements

3.2.1. Macrophytes

A recent vegetation survey of Lake Volvi in 2023 recorded the presence and estimated the abundance and positioning of 14 different taxa (in order of dominance: i. *N. marina*, ii. *Phragmites australis*, iii. *M. spicatum*, iv. *C. demersum*, v., *S. pectinata*, vi. *V. spiralis*, vii. *P. perfoliatus*, viii. *Cladophora* sp., ix. *Z. palustris*, x. *S. lacustris*, xi. *Potamogeton crispus*, xii. *Lemna minor*, xiii. *H. morsus-ranae*, xiv. *Salvinia natans*). Results of this vegetation survey, as well as three historic surveys for comparison purposes, are given in Supplementary Table S1. Among the recorded 14 taxa, 5 (iv, viii, xii, xiii and xiv) are pleustophytes, i.e., plants that are floating freely on the surface or below the surface of the water [76]; thus, there is no need to explore their water depth preferences. Among the rest of the recorded taxa, two (ii and x) belong to helophytes, i.e., rooted plants that have some parts of their bodies under the water level or in waterlogged soil and some parts emerging over the water line, while the remaining seven taxa (i, iii, v, vi, vii, ix and xi) belong to submerged hydrophytes, i.e., plants whose physiology is connected with living in the water column [76]; thus, all nine of these taxa are affected by water fluctuation.

Fidelity measures were calculated for the abovementioned selected nine taxa and their results are presented in Figure 6. Species *Zannichellia palustris* and *Schoenoplectus lacustris*, recorded exclusively in the shallow littoral zone of Greek lakes, showed the narrowest range of water depth tolerance; thus, they are considered the most sensitive taxa to water level fluctuations among those found in Lake Volvi. On the other hand, *S. pectinata*, *V. spiralis*, *N. marina* and *M. spicatum* were found covering a depth range of more than three meters in Greek lakes, thus they are considered water-level-fluctuation tolerant species.

Considering the water depth positioning of rooted macrophytes as recorded in Lake Volvi, in relation to the water-depth-range tolerance calculated for the same taxa through the fidelity measure analysis, water level fluctuation thresholds were identified to protect and sustain present macrophytic vegetation in Lake Volvi. These water level thresholds correspond to a minimum lake water level for period A (February to May), in which favorable conditions for the regeneration of last year's vegetation stands will occur, as well as a minimum water level for period B (June to January), in which favorable conditions for the development and reproduction of the new vegetation stands will occur. Conclusively, the macrophytic vegetation comparative study suggests a minimum water level threshold of 35.8 m a.s.l. (0.2 m lower than the maximum water level of 36 m) for Lake Volvi during period A, and a minimum water level threshold of 35.3 m a.s.l. (0.7 m lower than the maximum water level) for period B.

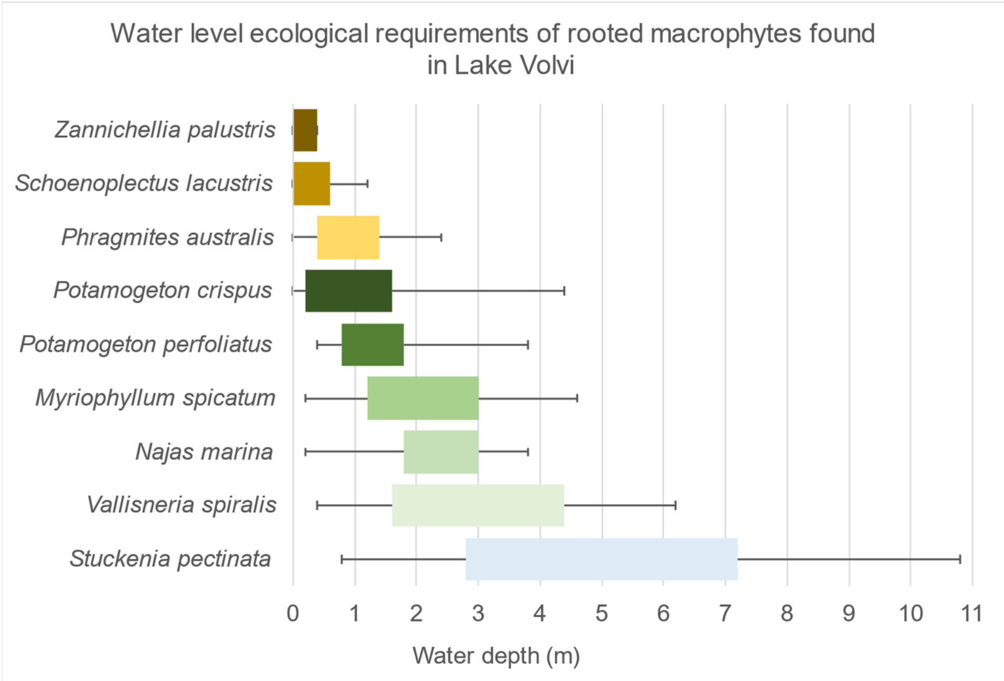

Figure 6. Summary of water level ecological requirements of the nine rooted macrophytes found in Lake Volvi (as calculated by fidelity measure analysis). Box plots show the confidence intervals containing the occurrences of 50% of each taxon's population in relation to water depth (between 25% and 75%), while their anchors delineate the confidence intervals containing the occurrences of 95% of each taxon's population in relation to water depth (between 2.5% and 97.5%).

3.2.2. Benthic Macroinvertebrates

A total of 21 benthic macroinvertebrate taxa were recorded in Lake Volvi during the two sampling periods. Specifically, Diptera, Ephemeroptera, Odonata, Trichoptera, Oligochaeta and Crustacea were observed in the samples in both periods. Diptera was the dominant taxonomic group at most stations. The highest number of benthic macroinvertebrate taxa was recorded in April 2023 at station VolTr02, while the lowest was recorded in October 2022 at station VolTr05 (Supplementary Figure S2a). Abundance was higher at all stations in April 2023 (Supplementary Figure S2b) compared with October, following the typical seasonal pattern. The highest value (1481 individuals) was recorded at station VolTr05, while the lowest (42 individuals) at station VolTr10 (Supplementary Figure S2b). The Mann–Whitney test showed that there was no statistically significant difference in the number of taxa between the two sampling periods ($p > 0.05$), but that there was a statistically significant difference in their abundance ($p < 0.05$).

Concerning the FFGs of benthic macroinvertebrates, the dominant group was the collectors group in both sampling periods (Supplementary Figure S3a), which is likely related to the fact that most sampling stations were characterized by coarse substrate material. Moreover, their presence is related with low water level fluctuations [77]. As for the LOCs, most of the taxa belonged to the (semi)sessil category, meaning that benthic macroinvertebrates have limited mobility (Supplementary Figure S3b), which may be attributed to the lack of significant water level fluctuations in Lake Volvi. The percentage of benthic macroinvertebrates that move in other ways, such as climbing (Supplementary Figure S3b), was also essential, indicating the presence of macrophytes.

During the sampling periods, the presence of sensitive indicators, such as Trichoptera, Ephemeroptera, and taxa with limited mobility, was noticed. Thus, it is recommended to maintain water level fluctuations depending on the period of the year. Specifically, it is suggested to retain the minimum lake level during period A (February–May) at 35.9 m (a.s.l.), 10 cm below the estimated maximum lake level of 36 m. During period B (June–January), it is proposed to avoid high water level fluctuations—for instance, higher than 40 cm—as a small change in water level (33 cm) results in compression of habitats [38]. These specific limits are acceptable for preserving the benthic macroinvertebrate assemblages in Lake Volvi.

3.2.3. Fish Fauna

Four out of the five sampling stations (stations VolTr02, VolTr05, VolTr10, VolTr19) have predominantly sandy bottoms (unstable substrates typically prevent walking and, therefore, hinder electrofishing) and are located near reed beds. Only station VolTr017 has rocky substrate with gravels. During samplings, specimens belonging to the species *Knipowitschia caucasica*, *Salaria fluviatilis* and *Cobitis strumicae*, which are benthic species (they prefer to stay close to the bottom), were captured (Supplementary Table S2). The species *C. strumicae* was caught only at station VolTr02, while the other two species were found across all stations. No other species were recorded. This is likely due to their habitat preferences.

Regarding their preferred substrate for reproduction, most of the species reported in the wider Volvi's drainage area were phyto-lithophilic (32%) and herbivores (25%), indicating the necessity of aquatic vegetation presence for egg adhesion during the reproductive period (Supplementary Table S2). Concerning their diet, most species are benthivores (35.7%) and omnivores (28.5%) (Supplementary Table S2). However, piscivores (17.8%) and planktivorous species (7.1%) are also present. Most fish species reproduce from spring to early summer, specifically in April, May, and June (Supplementary Table S2). Therefore, it is essential to maintain the water level at levels that allow fish to access their spawning grounds. It should be noted that, beyond the significance of the presence of "wet meadows" during this period for the reproduction of herbivore species, the connectivity between Lake Volvi and the River Richios throughout the year is crucial for the free movement of eels (mainly during spring, when mature individuals descend to the sea and young eels migrate to inland waters). The latter is achieved when the water level of Lake Volvi is higher than 36 m (a.s.l.).

Preserving the composition and abundance of macrophytes in the littoral zone of the lakes is crucial for the conservation of the ichthyofauna and, consequently, for ensuring the sustainability of fish stocks and the lake's fishery. Therefore, the assessed minimum level based on fish communities should not diverge significantly from that of macrophytes. In this context, it is recommended that, based on the water level requirements of fish fauna in Lake Volvi, the lake's minimum level should be maintained at an altitude close to 36 m a.s.l. (and higher if feasible) during period A (February–May). During period B (June–January), it is recommended to maintain the level at the highest possible level for the period to avoid severe "stress" in the system from water withdrawals.

4. Discussion

In this research, the environmentally minimum water level in Lake Volvi has been assessed by five distinct methodologies; two are associated mainly with morphological and hydrological data and analysis, and the other three with water level requirements of biological species. The first two methods (morphological and hydromorphological) are quite straightforward and provide unbiased estimations of the minimum lake level. However, they hardly consider the specific needs of biological species present in the lake. In addition, they estimate only one value of minimum lake level during the hydrological year without distinguishing and providing the minimum level in the wet and dry seasons. Nonetheless, the three methods associated with biological elements (macrophytes, benthic macro-invertebrates, fish) explicitly consider species' water level requirements to estimate the minimum lake level. Furthermore, they allow the estimation of different values of minimum lake level during the hydrological year, which is vital for bio-communities and useful for efficient lake management. However, they heavily depend on available data, which are often scarce or require demanding fieldwork to collect. In the present study, only the estimations provided by the analysis of the needs of aquatic macrophytes are substantiated and are based on long-term data, while the estimations based on benthic macro-invertebrates and fish fauna depend mainly on expert judgment.

The environmentally minimum water level in a lake is a decisive management measure that could promote sustainable management. Regardless of the methodology applied to estimate the minimum level, it should also be hydrologically evaluated, for two reasons. The first is associated with the management practices of a lake ecosystem that facilitate the ability of water managers to apply the same value to the proposed minimum level every year; however, the lake's available water potential differs significantly among wet and dry hydrological years, and, ideally, the minimum level could, or should, vary accordingly. As this is not feasible for practical reasons, the hydrological evaluation will exhibit how a lake's system will respond under different hydrological conditions if the measure of minimum level is implemented. The second reason is the necessity to verify that the water potential of a lake's catchment is sufficient to raise the water level from the estimated and proposed minimum to its maximum level. This is critical as it is essential to reach, or at least to approach, the maximum water level every hydrological year in order to keep the water balance for an ecosystem and ensure the renewal of a lake's water.

In this context, the minimum level proposed by the morphological and hydromorphological methods in Lake Volvi was evaluated in terms of the ability of the water level to rise from the proposed minimum to the maximum level based on surface water inflows from the lake's hydrological catchment. Specifically, it was assumed that, at the beginning of each hydrological year, i.e., on October 1st, the lake level is at its proposed minimum level. Then, using the surface inflows of each hydrological year, over a 30-hydrological-year period (1970–1971 to 1999–2000), the question of whether the water inflows into the lake from its catchment is sufficient to raise the lake level at maximum water level was tested. Based on the above hypotheses, it was found that, when the minimum level is estimated by the morphological method, the annual water inflow is insufficient to raise the lake level from the minimum to the maximum level for all of the hydrological years. On the contrary, when the minimum level is estimated by the hydromorphological method, the water inflow into the lake can raise the lake level to its maximum level for half of the hydrological years examined, thus ensuring the renewal of the lake's water. Meanwhile, for the rest of the years, the lake level approaches its maximum level satisfactorily. Practically, the analysis provided by the hydrological evaluation clarifies whether the minimum level proposed by the hydromorphological method can be safely applied by water managers. On the other hand, the morphological method estimates the minimum level at a very low, inapplicable water level for Lake Volvi. Doulgeris et al. [7] have reached similar conclusions by applying the hydrological evaluation to the environmentally minimum level of four other lakes, assessed by the morphological and hydromorphological methods.

Climate change is expected to have an impact on the hydrological regimes of lakes' ecosystems. This impact is mainly related to a decrease in rainfall and an increase in temperature, as well as in the combined effect of these changes on a reduction of lake catchment runoff [78,79], consequently altering the water level fluctuation. In this case, the minimum level in Lake Volvi may need to be reassessed by considering the new hydrological conditions and using, for instance, the hydromorphological method. Moreover, policymakers can incorporate climate resilience strategies into management practices, considering potential shifts in macrophytes distribution, benthic macroinvertebrate communities and fish behavior.

Taking advantage of the five methodologies applied in Lake Volvi, as well as the hydrological evaluation presented beforehand, we propose that the environmentally minimum water level should be up to 20 cm lower than the maximum level during February–May, i.e., up to 35.8 m a.s.l., as suggested by the water level requirements of biological elements, and up to 70 cm lower than the maximum level during June–January, i.e., up to 35.3 m a.s.l., as suggested by the hydromorphological method and the water level requirements of aquatic macrophytes. It should be mentioned that the maximum water level in Lake

Volvi, which is usually observed in March–April, may differ among hydrological years (dry/wet years) from the elevation of 36 m a.s.l. If the maximum level is close to this level, for example, between 35.7 m and 36.3 m, then, based on the morphological characteristics of the lake, the proposed minimum level for Lake Volvi could be safely used, i.e., up to 20 cm lower than the maximum level during February–May and up to 70 cm during June–January. However, if the maximum level differs significantly from the altitude of 36 m for a series of hydrological years, then it is proposed to redefine the minimum level for the new hydrological conditions in the lake's catchment.

Our study, investigating morphological, hydrological, and biological factors in Lake Volvi's environmentally minimum water level assessment, offers a comprehensive understanding of its ecosystem dynamics, guiding policies and management practices. This approach holds potential benefits for lakes confronting similar challenges, establishing a foundation for sustainable management. Additionally, our findings underscore the significance of adaptive policies tailored to specific ecosystems, proposing guidelines for setting environmentally minimum water levels. Policymakers could craft management plans prioritizing ecological preservation, particularly macrophytes, while considering socio-economic factors. This dual consideration ensures a holistic approach that aligns with broader sustainable water policies and adaptive strategies for the conservation and management of lakes. Moreover, policymakers can use this knowledge to develop ecosystem-based management strategies, which consider the entire ecological system rather than focusing on individual components in isolation.

However, despite offering valuable insights into sustainable water management for lakes, it is crucial to acknowledge inherent limitations. Firstly, our assessments rely on current environmental and ecological data, and, as environmental conditions may change over time, the applicability of our findings could be affected. Secondly, the complexity of ecosystems and their responses to stressors introduce uncertainties to our estimates. Additionally, socio-economic factors may present challenges, leading to potential gaps in our analysis of the impact on different community segments. It is important to recognize that our study provides a snapshot based on available data and methodologies; for example, post-2000 surface water inflow data were not available. Future research should strive to refine understanding by incorporating more extensive datasets, improving modeling techniques, and addressing the dynamic nature of ecosystems. By openly acknowledging these limitations, we aim to contribute to the ongoing scientific dialogue and encourage the further refining of methodologies for sustainable water management assessments.

Future research may refine our proposed environmentally minimum water levels through continuous monitoring and advanced modeling. Investigating the long-term impacts on ecosystem health and socio-economic dynamics, alongside the extension of this approach to diverse lakes, would enhance our understanding. Additionally, examining the potential impacts of climate change on the dynamics between macrophytes, benthic macroinvertebrate and fish can provide insights into the underlying ecological processes. Another interesting topic will be the examination of how people's lives, with all of their complexity, intersect with and influence economic activities and the production of goods and services. This is a compelling avenue for future exploration so as to understand the intricate relationship between human societies and their economic behavior.

To sum up, the present study establishes a foundation for informed water resource management, yet ongoing research can deepen understanding, improve methodologies, and address emerging questions, thereby fostering advancements in sustainable water management practices. For example, the proposed hydrological evaluation could act as a supplementary evaluation tool to any method that assesses the minimum water level in lake ecosystems. In addition, the relationship of the invaluable structural complexity provided by macrophytes as a crucial refuge for both macroinvertebrates and fish, is worthy of further study in terms of its contribution to the assessment of the minimum water level.

5. Conclusions

The environmentally minimum water level in Lake Volvi has been assessed by utilizing a state-of-the-art multidisciplinary approach combining morphological, hydrological and biological parameters. The combination of the five applied methods, namely, the morphological method, the hydromorphological method, and the three methods related to water level requirements of the bio-communities of macrophytes, benthic macroinvertebrates, and fish, suggests that the minimum lake level should be up to 20 cm lower than the maximum level of 36 m a.s.l during February–May and up to 70 cm lower during June–January.

Morphological and hydromorphological methods are quite straightforward and require available datasets of the lake's level–surface–volume curves, meteorological–hydrological time-series, and limited fieldwork. The morphological method estimates low values of minimum water level, and, as suggested by the advanced hydrological evaluation, should be avoided in practice. The hydromorphological method estimates the minimum level (only for the critical dry season) that conforms with the bio-communities' water level requirements and can thus be safely used in lake management. The analysis based on the macrophyte community seems to be more appropriate when seeking to suggest the minimum level, while suggestions based on fish and benthic macroinvertebrate depend on expert judgment and can be used adjunctively. However, in all cases of biological methods, the proposed minimum level is distinguished during the hydrological year, which is crucial for efficient lake management.

Overall, the development of efficient scientific methodologies for the critical issue of the environmentally minimum (or minimum or ecological) level of lakes, as well as the relevant legislation that ensures the proper management of lake ecosystems, is in its infancy. However, the scientific community and water managers are obliged to implement appropriate measures by which to protect the ecosystems of inland water bodies, considering also the need to meet the water requirements of economic activities in their catchment area. The present research study, carried out to estimate the environmentally minimum level in Lake Volvi, will contribute to this.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16020933/s1, Figure S1: Percent coverage of different (a) habitat types and (b) granulometry ranks at each of 20 vegetation sampling stations in Lake Volvi for the year 2016, updated in 2023; Figure S2: Number and abundance of benthic macroinvertebrate taxa at the sampling stations in October 2022 (Oct'22) and April 2023 (Apr'23) in Lake Volvi; Figure S3: Contribution (%) of (a) functional feeding guilds and (b) locomotive capacity of benthic macroinvertebrate taxa at the sampling stations in October 2022 (Oct'22) and April 2023 (Apr'23) in Lake Volvi; Table S1. Summary table of macrophytic vegetation composition in Lake Volvi, as recorded during three extensive sampling efforts in 1986 [55], 2013 and 2016 [56], as well as the results of the current sampling effort that took place in 2023 (in bold). For most recent samplings (2013, 2016 and 2023) the relative presence of recorded taxa is given in percentages of total sampling plots recorded; Table S2: Preferences of the fish species of Lake Volvi regarding their reproductive substrate, diet, habitat and reproductive period. LITH: lithophilic, PHLI: phyto-lithophilic, PHYT: phytophilic, PEL: pelagophilic, OSTR: ostracophilic, PSAM: psammophilic, OMNI: omnivores, INV: benthivores, PLAN: planktivores, HERB: herbivores, PISC: piscivores, PEL: pelagic, and BENTH: benthic. Jan: January, Feb: February, Mar: March, Apr: April, Jun: June, Jul: July, Aug: August, Sep: September, Oct: October, Nov: November, Dec: December.

Author Contributions: Conceptualization, C.D., C.N., O.P., D.Z. and D.C.B.; methodology, C.D., C.N., O.P. and D.Z.; validation, C.D. and D.C.B.; investigation, C.D., C.N., O.P., D.Z., R.N. and D.C.B.; resources, C.D.; data curation, C.D., C.N., O.P., D.Z. and R.N.; writing—original draft preparation, C.D., C.N., O.P., D.Z. and R.N; writing—review and editing, C.D., C.N., O.P., D.Z. and D.C.B.; supervision, C.D.; project administration, C.D.; funding acquisition, C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out by the Soil & Water Resources Institute (SWRI) of the Hellenic Agricultural Organisation (ELGO-DIMITRA) and funded by The Greek Natural Environment & Climate Change Agency (N.E.C.C.A.).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article or Supplementary Material. Other data are also available on request from the corresponding author.

Acknowledgments: The authors acknowledge the support provided by the Management Unit of Protected Areas of Central Macedonia, N.E.C.C.A.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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