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Lake Morphometry and its Effect on Aquatic Vegetation under the Influence of Eutrophication in Kashmir Waters

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Abstract

The morphology plays a major role in a lake system's water quality. The lacustrine structure and function has been shown to be significantly influenced by lake morphology. The current paper aims to examine the relationship between the physico-chemical criteria of water and aquatic macrophyte distribution. Over the course of a year (September 2022-Oct 2023) data on the morphology, aquatic vegetation and water quality of two lakes was collected. To identify potential correlations between lake morphology features, key water quality parameters and macrophytes distribution, statistical and ordination analysis was carried out. Principal component analysis (PCA) was applied in order to distinguish the key morphological parameters and water quality parameters while Redundancy Analysis (RDA) was used in order to estimate possible associations between the macrophyte distribution and the morphology of the lakes. The results revealed significant correlations between the lake catchment area and total phosphorus concentration. The Lake catchment and depth key variables showed the strongest influence on the lake discrimination in the PCA results, followed by Schindler's ratio. The RDA findings suggested that several macrophyte species may be grouped together in shallower lakes. The volume and depth of the lakes are characterized by a larger number of macrophytes. The RDA between hydrophyte data and water quality parameters revealed that the first three axes explained 84.97% of the species-environment relationship and 36.08% of the variance in the species data.

Keywords: Dal lake, Manasballake, morphological parameters, PCA, RDA, aquatic macrophytes

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Introduction

Lake morphology is one of the key elements affecting the trophic status, physico-chemistry, productivity and distribution of aquatic organisms. The lacustrine structure and function has been shown to be significantly influenced by lake morphology. In particular, along with large-scale climatic variables (temperature, rainfall), and productivity, lake morphology has a significant impact on the composition of lake fish communities (Brucet et al., 2013). The parameters that are related to nutrient cycling and water chemistry include lake area, lake volume, maximum depth and average depth. The parameters that are related to nutrient cycling and water chemistry include lake area, lake volume, maximum depth and average depth. Lake habitats exhibit diverse characteristics due its morphometry impacting abiotic factors such as light, oxygen concentration, nutrient levels and pH. Quantifying lake morphology involves using morphometric metrics that depict the shape and size of lake basins. Deeper lakes have a thicker surface layer, which determines photosynthetically available irradiance, nutrient cycling efficiency, and organism vertical distribution (Cole, 1994). On the other hand, smaller and shallower lakes, are strongly influenced by wind-induced sediment re-suspension, which causes significant changes in their water chemistry and geochemical cycles. Average depth is a key factor in controlling lake productivity. Furthermore, the shape of the lake can be linked to bottom dynamic conditions (Ambrosetti & Barbanti, 2002a). According to Ambrosetti & Barbanti (2002b), the slope of the littoral zone significantly affects the biomass and distribution of submerged macrophyte communities. A gentle slope in the littoral zone allows the deposition of fine materials and can modulate the action of the waves in favour of the growth of aquatic macrophytes. Investigations have been done into how various lake processes are affected by the relative size and shape of lake basins. The dynamics of mixing, hydrology, sedimentation (Blais & Kalff, 1995), dissolved organic carbon content, the biomass of submerged macrophytes and primary productivity (Fee, 1980) are a few of these processes.

Lake catchment is also an important element in determining water chemistry as it affects the nutrient inputs. There are studies demonstrating the relationship between the different land uses of catchment areas and water quality (Fraterrigo & Downing, 2008), while other studies have shown the influence of hydrology and geology in the catchment on the nutrient transport capacity.

The morphology, hydrography, and catchment characteristics of a water body can affect the speed and nature of shifts in aquatic vegetation patterns due to nutrient enrichment. While eutrophication unfolds similarly in shallow and deep lakes, there is widespread acknowledgement that shallow lakes exhibit greater resilience to these changes compared to deep lakes (Scheffer et al., 1994). Shallow lakes experience a swifter turnover of nutrients lost through sedimentation, with sediment release contributing proportionately more to nutrient concentration than external loads (Sas, 1990). Consequently, it is anticipated that very shallow lakes, characterized by a restricted water volume, would undergo faster nutrient enrichment compared to deep lakes, even under similar anthropogenic influences. Additionally, shallow lakes demonstrate heightened sensitivity to trophic interactions, particularly the top-down control exerted by grazing zooplankton (Jeppesen et al., 1997). Many studies examining the relationships between environmental factors and aquatic biota patterns consider both unaffected and impacted lakes. In lakes influenced by human activities, anthropogenic pressures disrupt the natural diversity of biological assemblages, and vegetation patterns are predominantly shaped by nutrient availability (Heegaard et al., 2001). Conversely, in ecosystems free from human impacts and typically characterized by lower trophic levels, the physical and morphological characteristics of a waterbody play a crucial role in determining natural patterns in aquatic vegetation. As macrophyte distribution is strongly influenced by water depth and light penetration, the maximum lake depth affects, among other factors, the potential area covered by plants. This study aims to investigate whether and how changes in lacustrine vegetation along the water eutrophication gradient differ significantly among distinct morphological lake types.

The aim of the current paper was to examine the possibility of using morphological descriptors by investigating the relationship of these parameters and physicochemical criteria of water quality and aquatic macrophytes parameters as well. Apart from lake area, lake volume, average and maximum depth,other parameters such as average depth to maximum depth ratio, relative depth, development of volume and Schindler's ratio was used in our analysis.

Materials and Methods

Study area: Data on vegetation, morphology and water quality from shallow and deep lakes was surveyed for a period of one year (September 2022 - Oct 2023) at five different sites, representing various morphometrics as well as a wide spectrum of water quality (Fig. 1). Dal Lake is situated to the northeast of Srinagar, the summer capital of Jammu and Kashmir at an elevation of 1583 meters above sea level, within the coordinates of $34^{0}5'$-$34^{0}6'$N and $74^{0}8'$-$74^{0}9'$E longitudes. Meanwhile, Manasbal Lake is approximately 32 km north of Srinagar (34°152 N, 74°402 E), with an elevation of 1584 meters above sea level. Average and maximum depth, lake volume and catchment area are presented in Table 1.

Environmental variables: The following physicochemical variables were measured monthly for one year at each survey site during the monitoring year: Depth, dissolved oxygen, water pH, nitrate nitrogen,

Table 1. Geographic location, altitude, and morphological descriptors of the studied lakes

Lakes	Latitude	Longitude	Altitude (m a.s.l)	Mean depth (m)	Relative depth (m)	Max depth (m)	D v	Catchment area (km$^{2)}$	Volume *10^6 m^3
Dal lake	$34^{0}5'$-$34^{0}6'$N	$74^{0}8'$-$74^{0}9'$E	1583	1.46	0.11%	5.7	0.73	316	9.83
Manasbal lake	34°152 N	74°402 E	1584	4.55	0.63%	12	1.12	33	12.8

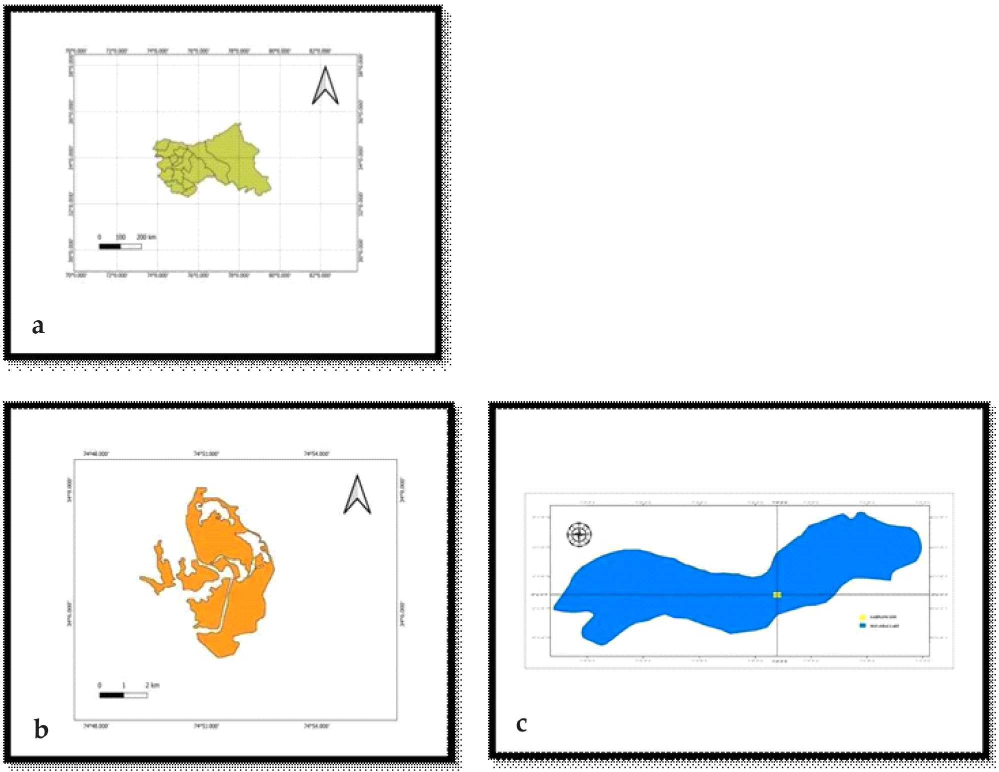

Fig. 1. Location of the studied lakes in Kashmir; (a) Map of Jammu and Kashmir (b) Dal lake c) Manasbal lake

Total nitrogen, and Total phosphorus. All the analyses of the samples were carried out as per the standard methodology of APHA (2012) and Adoni et al. (1985).

Macrophytic study: The field survey procedure for macrophytes involved the transect method/random quadrat method (Misra, 1968). Within the littoral of each lake variables such as the maximum colonisation depth, the mean vegetation coverage and the relative cover of all the aquatic and emergent plant communities (stands) were determined. Identification was performed using standard taxonomic keys (Cook, 1996; Kumar, 2009).

Lake Morphometry: Lake Morphometry parameters such as Relative depth, mean depth, maximum depth Schindler's ratio and Development of Volume were calculated.

Results and Discussion

Total phosphorus showed significant positive correlations with the catchment area in both lakes (Fig. 2). It could be interpreted as a strong influence of the catchment area on phosphorus inputs in the lake. As a result, in smaller catchments, land use near the shore is more important than in larger catchments, where nutrient loading is affected by the entire catchment (Buck et al., 2004). The total phosphorus concentration in Dal Lake might be attributed to the widespread use of phosphate fertilizers in agricultural activities and sewage pollution from the catchment areas. Phosphate fertilizers and organic manure are prevalent in agricultural areas which results in the transport of soil laden with various fractions of total phosphorus in Dal Lake (Solim & Wanganeo, 2008)

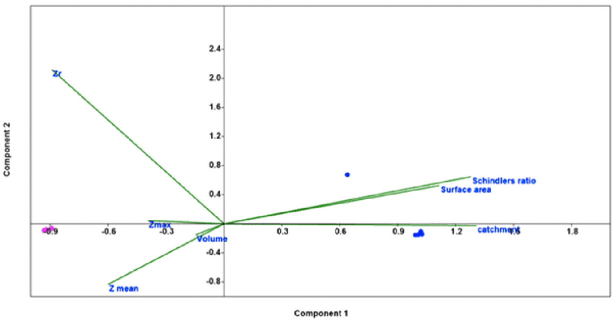

Fig. 2. PCA ordination plot showing the positioning of lakes along morphological parameters (vectors)

Ordination analysis: Principal components analysis (PCA) is a technique that uses the dependencies between variables to represent high-dimensional data in a more tractable, lower-dimensional form without losing too much information. The first two PCA components on morphometric data explained 98.7% of the data variance (Table 2). According to the results of PCA as well Schindler's ratio was correlated negatively with Secchi depth reflecting the influence and importance of the catchment area on the lakes. Overall, we can postulate that catchment influence and relative depth are quite important factors regarding their effects on lakes' water chemistry and quality. The nutrient loadings linked to catchment area size likely impact the trophic state of lakes. Results indicate that a larger catchment area, relative to lake depth, exerts a stronger influence on water quality, particularly transparency and nutrient levels. Notably, the morphometry of shallower lakes plays a more significant role in influencing their water quality. In terms of relationships between morphology and aquatic macrophytes, our findings suggest that lake area and catchment size may not have a discernible effect.

The positive loadings on Ammonia, Nitrate, Orthophosphate, and Total phosphorus might be linked to agricultural runoff from the catchment area. While positive loadings on ammonia and phosphorus are also related to the discharge of partially treated wastewater from the inefficient STP. Positive loadings of Orthophosphate, Nitrate, Total Phosphorus and Ammonia clearly demonstrate that both lakes have high concentrations of nutrients, which are responsible for modifying the water chemistry and turning both lakes eutrophic. According to many authors, higher phosphorus readings indicate nutrient enrichment of lakes due to eutrophication (Welch, 1980). The lime-rich rocks in the catchment region are associated with positive loadings on calcium hardness. The positive loadings of chloride are mainly due to seasonal fluctuations in dilution, solubility, and oxidation and also the presence of chloride in the lakes indicates organic pollution, implying that pollution is mostly caused by the outflow of domestic wastes. A strong positive contribution on air temperature, water temperature, and pH, and a negative contribution on the D.O. was represented on PC2. In lakes, the inverse connection between temperature and dissolved oxygen is a natural phenomenon (Solanki et al., 2010). Wetzel (1975) investigated the link between air and water temperature, concluding that water temperature corresponds to air temperature. PC3 explained positive loadings on depth and transparency. The positive loading on depth is due to the melting of snow, which resulted in an increase in water volume, and hence it is closely associated with transparency. The positive relationship of Total hardness and Magnesium hardness might be associated with the geology of the lake's catchment, which is linked to the lime-rich rocks in the catchment area. pH was positively involved in water quality variations and negatively on free CO_2. The high rates of photosynthesis by autotrophs, which result in enhanced carbon dioxide consumption, are responsible for the positive pH loading (Bini et al., 2010).

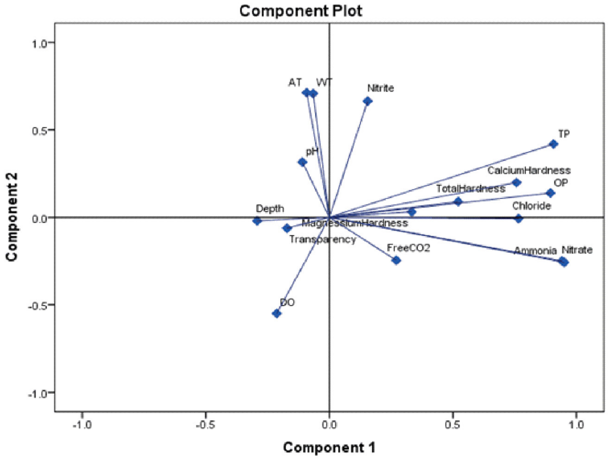

Fig. 3. Principal components analysis ordination diagram for Dal and Manasbal lakes on the basis of studied Physico-chemical parameters

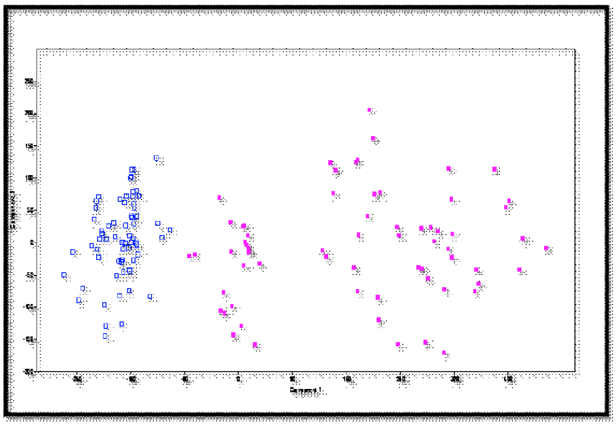

Fig. 4. Bi-variate plot between Dal Lake and Manasbal Lakes

Table 2. Eigen value and percentage of variance explained by two principal components (PC's) for Dal and Manasbal Lake for studied lake morphometry parameters

Components	Eigen value	% of Variance	Cumulative
PC1	5.70445	81.49	81.49
PC2	1.23035	17.57	98.7

Table 3. Eigen value and percentage of variance explained by each of the five principal components (PC's) for Dal and Manasbal Lake for studied variables

Components	Eigenvalue	% of Variance	Cumulative %
PC1	5.83	36.44	36.44
PC2	3.91	24.38	60.82
PC3	1.95	12.21	73.03
PC4	1.36	8.55	81.58
PC5	1.08	6.76	88.34

The PCA plot illustrates a rise in Lake catchment from the left to the right along the first component and an increase in mean depth from the top to the bottom along the second component (Fig. 2). The deepest water body stands out in the right quadrant, while the shallower one is located in the bottom-left quadrant. Additionally, there's a noticeable clustering of Lake Manasbal on the right, seemingly linked to Schindler's ratio and surface area vectors (Fig. 3).

To determine the variance of physico-chemical parameters between two water bodies. The first five components in the PCA analysis together explained 88.43% of the total variation, with Eigenvalues 5.83, 3.91, 1.95, 1.36 and 1.08 respectively (Table 3). PC1 explained 36.44% of the total variance and high positive loadings contribute towards Orthophosphate, Total phosphorus, Calcium hardness, Ammoniacal-nitrogen, Chloride, Nitrate-nitrogen, and Total hardness whereas, D.O, Depth, and Transparency had a negative contribution to this component. PC_2 explained 24.38% of the variance and showed high positive loadings towards Air temperature, Water temperature, pH, and negative loadings on DO, Chloride, Free CO2, Ammoniacal nitrogen, and Nitrate-nitrogen. The bivariate plot of the PC1 and PC2 extracted from the principal component analysis of water quality parameters from Dal and Manasbal Lake showed slight intermixing of some parameters (Fig. 4).

Relationships between aquatic macrophytes, lake morphology and water quality: The results of the RDA between the lake morphology and hydrophytes showed that the first 3 axes explains 33.5% of the variance of species data and the 83.89% of species-environment relation. Z mean, volume, and Z max

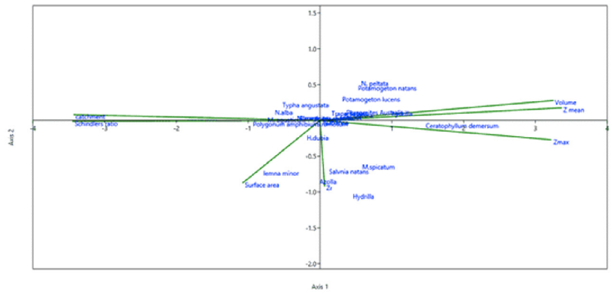

Fig. 5. RDA ordination bi-plot revealing the relationships between morphological parameters and aquatic macrophytes

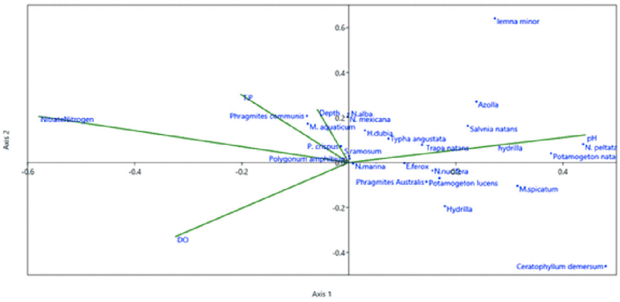

Fig. 6. RDA ordination bi-plot revealing the relationships between water quality parameters and aquatic macrophytes

revealed the strongest correlations on axes 1. According to the results, the volume and depth of the lake are characterized by a larger number of macrophytes (Fig. 5). The plot graph indicates a correlation between max depth and Ceratophyllum, implying a preference for deeper lakes compared to other hydrophytes. The RDA results show that the first 3 axes explain 36.08% of species variance and 84.97% of the species-environment relationship, as illustrated in (Fig. 6). The depth and volume of the lakes were the parameters which presented strong relations with the axes of redundancy analysis and seemed to be associated with most macrophyte species. Volume development presents higher values in shallow lakes with flat bottoms. Therefore association of many aquatic macrophyte species with the volume parameter could be interpreted as a preference of macrophytes for shallow lakes with gently sloped littoral. On the other hand, the deeper lake presented associations with few macrophytes. In Dal Lake, the maximum density was recorded for submerged species (*C.demersum* and *Myriophyllum spicatum*) followed by free-floating (*Lemna minor* and *Azolla cristata*). The maximum density for submerged species could be due to water depth, transparency and nutrient availability in the lake as water depth has a substantial impact on the establishment, development and dispersion of submerged vegetation and also low water levels have a larger impact on submerged flora. While at Manasbal Lake similar pattern was followed with a maximum number of individuals recorded for *C. demersum* and *M. spicatum* and a minimum for *Najas marina* and *Euryale ferox*. The maximum number for *C. demersum* can be attributed to the increasing water depth of the lake with which the internode shoots of *C. demersum* also elongate, which is consistent with earlier research by Zhu et al. (2012). The minimum number of *N. marina* in the lake's shallowest and lowest-fetch zone implies that light conditions were adequate for the seed development of this submerged macrophyte (Chambers, 1987) and also because the seedling development of this species is successful on the soft sediments (Forsberg, 1965). The minimum number for *Eurale ferox* might be due to anthropogenic stress and also because rooted floating-leaves are not well suited to very soft sediments, their heavy seeds might sink to a depth that prevents their germination (Barrat-Segretain, 1996). The positive loadings on Nitrate-nitrogen and Total phosphorus were strongly correlated with *Phragmites communis, Myrophillum aquaticum, Polygonum amphibium*. This is due to macrophyte distribution and development linked to nutrient-rich environments, notably nitrate and phosphate, which have been shown to favour macrophyte growth. For submerged macrophytes, water depth is the most critical element in determining seedling establishment and growth. The capacity of these plants to adapt to a variety of circumstances is demonstrated by their rapid development (Burlakoti & Karmacharya, 2004). The positive loading on *Myriophyllum aquaticum* shows that the species invades shallow water bodies that are prone to disturbances, such as repetitive and frequent water level variations. As pH is closely connected to bicarbonate concentrations, an essential source of inorganic carbon for photosynthesis and submerged species development, pH may have a significant impact on some species (Catling et al., 1986). Total phosphorus and nitrate concentrations were reported to have the greatest impact on the first axis, which was positively linked to emergent and free-floating leaved plants. Emergent and floating-leaved plants are commonly seen under eutrophic conditions, and life forms are known to represent the abundance of different trophic states (Nurminen & Horppila, 2009).

Conclusion

This study elucidated the substantial impact of lake morphometry on the distribution of aquatic macrophytes and overall water quality in selected lakes of Kashmir. Our findings underscore the critical role of morphological parameters, such as catchment area, depth, and volume, in shaping the physicochemical environment and, consequently, the ecological dynamics of aquatic vegetation. The positive correlation between catchment area and total phosphorus concentrations highlights the influence of watershed characteristics on nutrient dynamics and eutrophication processes. Moreover, the significant relationships identified through PCA and RDA analyses provide an understanding of how lake morphology can guide the management and restoration of aquatic systems. These insights are invaluable for the formulation of targeted and effective lake management strategies that aim to enhance water quality while preserving or enhancing biodiversity.

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