Ecology and Thermal Stratification Dynamics of Freshwater Lakes in the Kashmir Himalaya

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Abstract: ***Freshwater lakes of the Union Territory of Jammu and Kashmir (J&K) are ecologically and hydrologically important components of the western Himalayan landscape, supporting agriculture, fisheries, tourism and urban water supply across an altitudinal gradient of ~300 m to over 3,500 m. Despite decades of site-specific limnological study, there has been no coherent, comparative synthesis of stratification behaviour and trophic development for the region's main lentic systems. This paper (i) synthesises published physico-chemical, thermal and remote-sensing evidence for twelve representative J&K lakes covering high-altitude, forest, rural valley and urban valley settings; (ii) characterises the region's distinctive stratification regime, where stable thermal stratification is largely limited to the deeper rural lake, Manasbal, which behaves as a warm monomictic system stratified for eight to nine months of the year, whereas the majority of shallow, wind-exposed valley lakes remain polymictic; and (iii) proposes a Lake Ecological Integrity Index (LEII), a composite framework integrating trophic-state, stratification-stability and catchment-pressure sub-indices, illustrated here using literature-derived classifications. This synthesis confirms a consistent oligotrophic to hypertrophic gradient from high altitude lakes such as Gangabal and Nundkol, through rural and semi-urban lakes such as Manasbal, Wular and Anchar, to urban lakes such as Dal, Nigeen and Khushalsar. This gradient is driven primarily by a change in catchment land-use, untreated sewage influx, and macrophyte-mediated nutrient cycling. This is compounded by documented long-term shrinkage in open-water area in both Dal and Wular lakes. The research also analyses accumulating evidence that warming in the Himalaya is expected to deepen and extend stratification in deeper lakes, while increasing hypolimnetic hypoxia risk, producing a compounding interplay between eutrophication and climate-driven thermal change. The LEII framework aims to provide geographically comparable, multi-lake monitoring and prioritisation for conservation investment throughout J&K, supplementing single-lake assessments with a regionally uniform, extendable tool for lake managers and policymakers.***

Keywords: Lake stratification; Climate change; Composite index; Freshwater ecology

1. Introduction

Lakes are generally recognised as sentinel ecosystems for environmental change, combining catchment-scale hydrological, land-use and climatic signals into observable changes in thermal structure, nutrient status and biological community composition. Satellite observations and modelling studies are increasingly demonstrating that lake surface temperatures, ice-cover phenology and vertical mixing regimes are changing rapidly in response to global warming. Worldwide shifts from dimictic toward monomictic behaviour and, in some deep lakes, an increasing risk of permanent stratification have been reported in the literature. These lakes are regarded particularly vulnerable to such changes since very slight fluctuations in air temperature may change both the length of the ice cover and the severity and persistence of the summer stratification.

The Union Territory of Jammu and Kashmir is home to an exceptionally diverse population of freshwater lakes distributed along a steep gradient of altitude and land use: high altitude alpine lakes above 3,500 m (e.g., Gangabal, Nundkol, and Sheshnag); mid-altitude forest lakes (e.g., Nilnag); rural and semi-urban valley lakes (e.g., Manasbal, Wular, and Anchar); densely populated urban lakes in and around Srinagar (e.g., Dal, Nigeen, and Khushalsar); and a smaller set of sub-Himalayan lakes in the Jammu region (e.g., Mansar and Surinsar). They support snow-trout and carp fisheries, floating-garden horticulture, boat-based tourism, urban drinking-water supply and flood attenuation for the Jhelum river system, most notably at Wular Lake, which absorbs a large portion of the valley's monsoon and snowmelt flood peaks and is a Ramsar Wetland of International Importance."

An extensive limnological literature on Kashmir, dating back to the comparative multi-lake surveys of the 1980s, has documented the physico-chemical characteristics and progressive eutrophication of individual lakes, most intensively for Dal Lake and more recently for Wular Lake, using satellite-derived trophic-state indices. The literature consistently notes that stable thermal stratification is uncommon in the generally shallow lakes of the Kashmir Valley and is restricted mainly to the deeper rural lake, Manasbal . Most valley lakes are polymictic, macrophyte-dominated and subject to increasing nutrient loading from expanding urban and peri-urban catchments. But there are three holes. First, the stratification behaviour and trophic status have seldom been studied together in a single comparative framework throughout the whole altitudinal range of J&K lakes. Second, the relationship between climate-driven changes in thermal stratification and anthropogenic eutrophication, which is widely documented in the worldwide limnological literature, has not yet been explicitly included in evaluation of J&K lakes. Third, there is no composite, regionally consistent measure for prioritising J&K lakes for protection, similar to trophic-state indices used elsewhere.

This study attempts to tackle these issues in three ways. It integrates the current physico-chemical, limnological and remote sensing information for twelve typical J&K lakes into a single comparative analysis of stratification regime and trophic state. It places these results within the framework of the larger research on climate-driven lake mixing regime changes, to assess where Himalayan warming is expected to exacerbate current eutrophication stressors. Finally, it offers a Lake Ecological Integrity Index (LEII) that integrates the trophic-state, stratification-stability, and catchment-pressure sub-indices into a single, extendable index, here demonstrated using literature-based scores as proof of concept for future field-based validation.

2. Study Area

The study area comprises the lentic water bodies of the Union Territory of Jammu and Kashmir, which are situated mostly in the Kashmir valley, a broad intermontane floodplain of the Jhelum river, bordered by the Pir Panjal range to the southwest and the greater Himalaya to the northeast, and a few sub-Himalayan lakes in the Jammu division. The Kashmir Valley has moderate climate with monsoon shadow effect and considerable impact of winter western disturbances and spring snowmelt. The high altitude lakes over 3,500 m are under nival-glacial hydrological regime with several months of seasonal ice cover. The current paper considers twelve lakes along this gradient as illustrative case studies (Table 1). These include three high-altitude alpine lakes, one mid-altitude forest lake, five valley lakes ranging from rural to urban and one Ramsar-designated floodplain lake (Wular) and two Jammu area lakes.

Table 1: Representative freshwater lakes of Jammu and Kashmir considered in this synthesis. Altitude and depth values are approximate, compiled from the cited literature for illustrative cross-lake comparison and should be verified against primary bathymetric surveys before use in quantitative work.

Lake	Setting	Altitude (m a.s.l.)	Max. depth (m)	Mixing regime	Trophic status (literature-based)
Gangabal	High-altitude alpine	~3,570	~30 (approx.)	Seasonally ice-covered / dimictic	Oligotrophic
Nundkol	High-altitude alpine	~3,520	<10 (approx.)	Seasonally ice-covered	Oligotrophic
Sheshnag	High-altitude alpine	~3,590	n.a.	Seasonally ice-covered	Mesotrophic
Nilnag	Forest, mid-altitude	~2,280	shallow	Polymictic	Meso-eutrophic
Manasbal	Rural valley	~1,584	~13	Warm monomictic (stratified 8–9 months)	Mesotrophic, rising pressure
Wular	Rural valley (Ramsar site)	~1,580	3.6 (avg) / 5.8 (max)	Polymictic	Eutrophic (~57% of area, 2018)
Anchar	Semi-urban	~1,583	shallow	Polymictic	Eutrophic
Nigeen	Urban valley	~1,584	shallow	Polymictic	Eutrophic
Dal	Urban valley	~1,584	shallow (mean 3–4)	Polymictic	Eutrophic–Hypertrophic
Khushalsar	Urban valley	~1,584	shallow	Polymictic	Hypertrophic
Mansar	Jammu region	~740 (approx.)	moderate	Limited data	Eutrophic (TSI(TP) ≈70)
Surinsar	Jammu region	~680 (approx.)	moderate	Limited data	Eutrophic (TSI(TP) ≈61)

3. Materials and Methods

3.1 Literature synthesis

Evidence was compiled through a structured search of the peer-reviewed and grey limnological literature on J&K lakes, combining terms for individual lakes (e.g., “Dal Lake”, “Wular Lake”, “Manasbal”, “Anchar”, “Nigeen”, “Gangabal”) with limnological terms (“thermal stratification”, “trophic status”, “eutrophication”, “mixing regime”, “warm monomictic”). Sources included primary physico-chemical and biological limnological studies, satellite remote-sensing trophic-state assessments, palaeolimnological reconstructions, and institutional or agency reports on lake area change. For each lake, the following information was extracted where available: basin morphometry (altitude, area, depth), mixing/stratification regime, trophic classification, dominant pressures reported in the catchment, and any documented long-term trend in open-water area or nutrient concentration. Where a specific quantitative value (e.g., a Trophic State Index) was reported only in a secondary source, it is cited here as such, consistent with standard practice for cases where the primary study could not be independently verified.

3.2 The Lake Ecological Integrity Index (LEII)

To enable a regionally consistent comparison across lakes assessed by different authors using different methods and metrics, a composite Lake Ecological Integrity Index (LEII) is proposed, combining three sub-indices on a common 0–100 scale, where 100 represents maximum ecological integrity:

$$LEII = w_1 \cdot TSI + w_2 \cdot SSS + w_3 \cdot (100 - CPI) \qquad \text{(Eq. 1)}$$

where TSI is a Trophic State Sub-Index derived by mapping qualitative or quantitative trophic classifications reported in the literature onto a 0–100 scale (oligotrophic ≈ 85, mesotrophic ≈ 60, meso-eutrophic ≈ 50, eutrophic ≈ 35, hypertrophic ≈ 12); SSS is a Stratification Stability Sub-index reflecting whether a lake shows a predictable, well-documented mixing regime and the reported severity of hypolimnetic or bottom-water oxygen depletion; and CPI is a Catchment Pressure Sub-Index reflecting reported urbanisation, sewage influx, siltation, macrophyte encroachment, and any documented long-term decline in open-water area, scored so that higher values denote greater pressure. Equal weighting ($w_1 = 0.4$, $w_2 = 0.3$, $w_3 = 0.3$) is used here as a transparent, illustrative default; the framework is designed so that these weights can be revised once empirical, field-validated sub-index data become available for a larger lake sample.

It is important to state clearly that the LEII scores presented in Figure 2 are illustrative. They were computed from the qualitative trophic and pressure classifications reported in the cited secondary literature, using the mapping and weighting scheme in Eq. 1, and are intended to demonstrate the discriminatory behaviour of the proposed framework across a trophic gradient rather than to serve as validated, field-measured absolute scores. A harmonised, simultaneous field campaign across all twelve lakes, using standardised depth-profiling and nutrient-sampling protocols, is identified in Section 6 as the priority next step for empirically grounding the index.

4. Results

4.1 Stratification regime across Jammu and Kashmir lakes

Consistent with earlier comparative assessments, stable thermal stratification is uncommon among the Kashmir Valley's lakes, most of which are shallow (typically 3–6 m), wind-exposed, and macrophyte-dominated, and therefore behave as polymictic systems that mix intermittently throughout the ice-free season. Manasbal Lake is the principal exception: at a maximum depth of approximately 13 m, it is consistently reported as the only true warm monomictic lake in the Kashmir Valley, remaining thermally stratified for eight to nine months of the year with distinct epilimnion, metalimnion, and hypolimnion layers. Within the hypolimnion, dissolved oxygen has been reported to fall below 1 mg/L, accompanied by a clinograde pH profile, both indicative of a comparatively eutrophic bottom-water environment despite the lake's overall mesotrophic surface-water classification. Figure 1 summarises this contrast schematically, comparing an idealised Manasbal-type thermal and oxygen profile with that of a shallow, wind-mixed valley lake such as Dal or Anchar, in which temperature and dissolved oxygen remain comparatively uniform with depth.

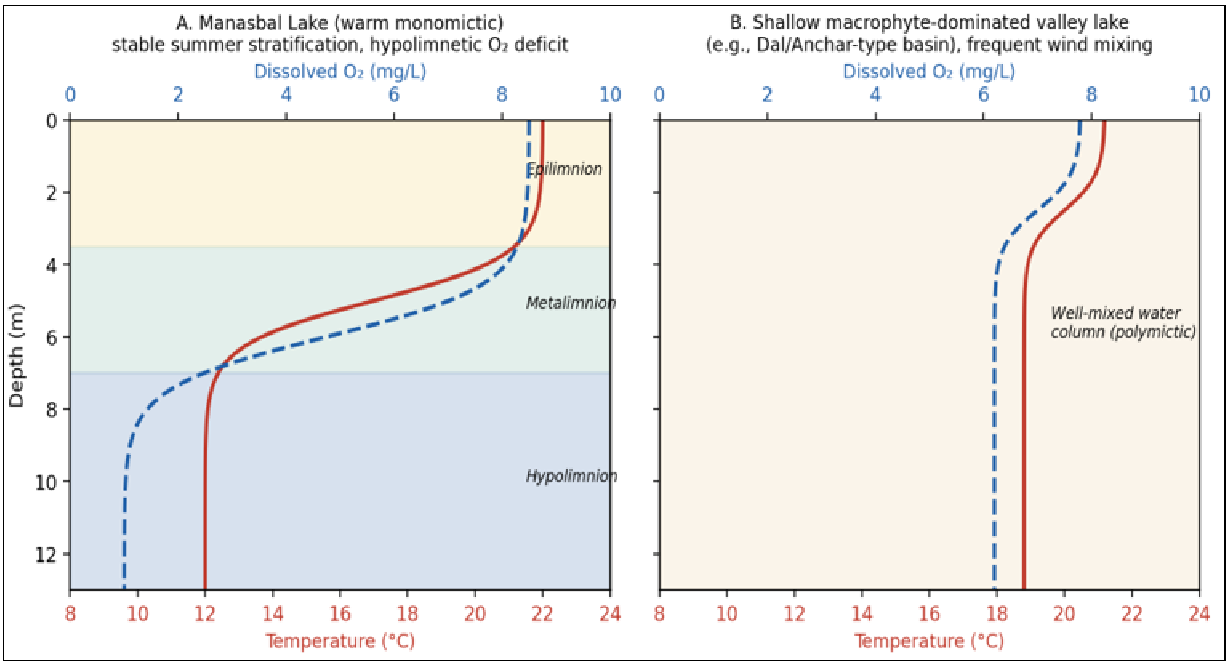

Figure 1: Schematic vertical thermal and dissolved- oxygen structure of a deep warm- monomictic Kashmir Lake versus a shallow polymictic Valley lake (illustrative profiles based on qualitative patters reported for Manasbal, Dal and Anchar Lakes; Yaseen & Bhat, 2021; Bhat et al., 2017)

4.2 Trophic gradient across the study lakes

The synthesised trophic classifications reveal a consistent gradient from oligotrophic high-altitude lakes to hypertrophic urban lakes (Figure 2). Gangabal and Nundkol, situated above 3,500 m with minimal catchment disturbance, are classified as oligotrophic. Sheshnag is reported as mesotrophic, while the mid-altitude forest lake Nilnag is described as moving toward a higher trophic state owing to nutrient influx from its catchment. Among the valley lakes, Manasbal remains broadly mesotrophic but is reported to be under increasing pollution pressure, particularly at littoral sites. Wular Lake, despite its scale and Ramsar status, was found to be approximately 57% eutrophic by area in a 2018 satellite-based assessment, with pollution linked to sewage, horticultural runoff, and sediment influx from willow plantations in its catchment. The semi-urban Anchar Lake and the urban Nigeen Lake are both classified as eutrophic, while Dal Lake- the most intensively studied lake in the region- has been reported to have progressed from a mesotrophic state several decades ago to an increasingly hypertrophic condition, with roughly a third of its area classified as severely degraded in a recent GIS-based assessment. Khushalsar, a smaller urban lake, is classified as hypertrophic. In the Jammu region, Mansar and Surinsar lakes have both been assigned Trophic State Index (TSI) values in the eutrophic range in a comparative western Himalayan lake study.

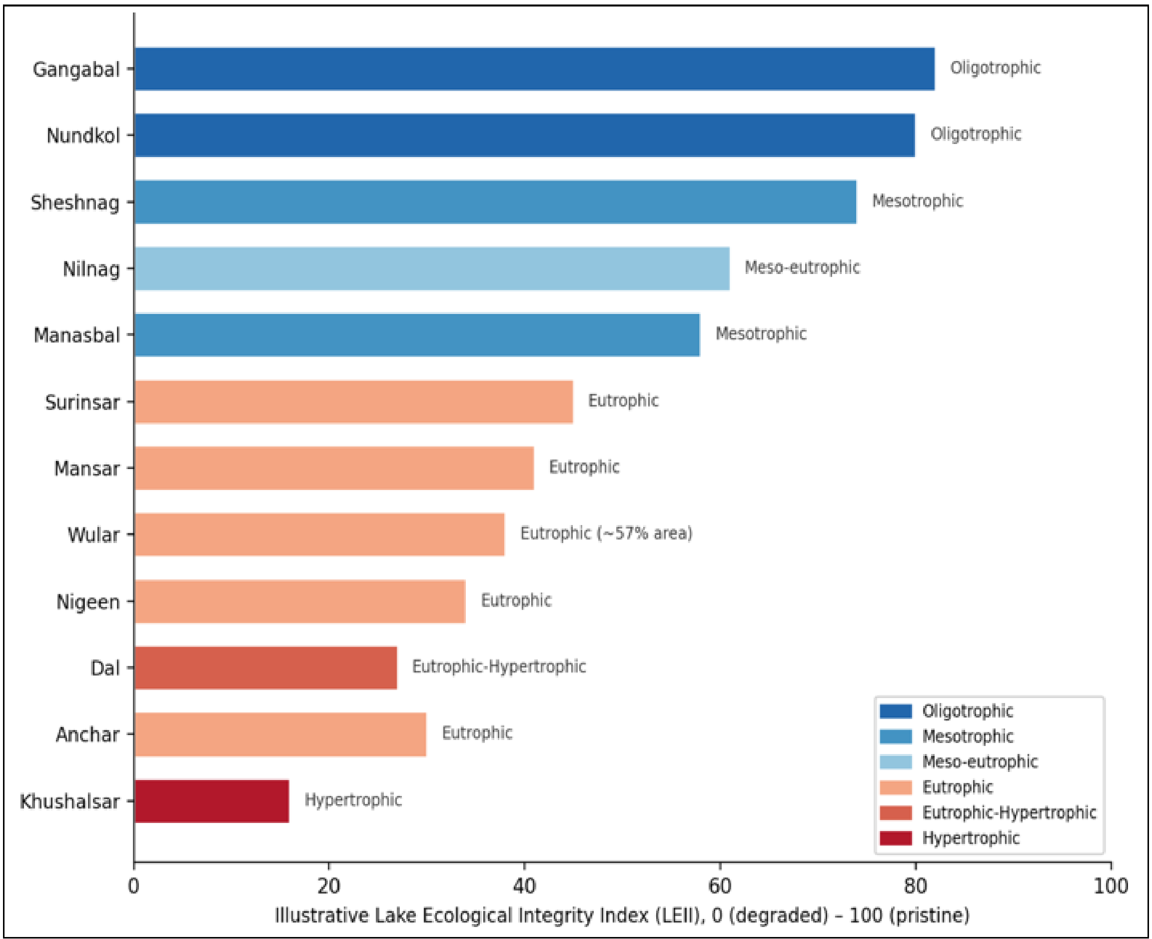

Figure 2: Trophic Classification and Illustrative composite lake Ecological Integrity (LEII) for major lakes of Jammu Kashmir, Synthesised from published trophic- state assessments (See Section 3 for sources and Eq. 1 for the LEII formulation)

4.3 Long-term area decline and cultural eutrophication

Beyond cross-sectional trophic classification, several studies document long-term declines in open-water extent that compound trophic degradation. Dal Lake's open-water area was reported to have declined from approximately 1,507 ha in 1911 to approximately 700 ha in 1984, with a corresponding increase in marsh area, reflecting decades of encroachment, sedimentation, and macrophyte expansion. Wular Lake has shown a comparable trajectory: satellite-based analyses indicate that its open-water area declined by roughly one-quarter between 2008 and 2019, alongside the 57% eutrophic-area estimate for 2018 noted above (Figure 3). A multi-proxy palaeolimnological reconstruction of Wular Lake sediments further shows that phases of enhanced macrophyte dominance and biogeochemical change have occurred over centennial to millennial timescales in response to past climatic shifts, indicating that the lake's present eutrophic trajectory is superimposed on a longer history of natural environmental sensitivity, now substantially accelerated by anthropogenic catchment pressure.

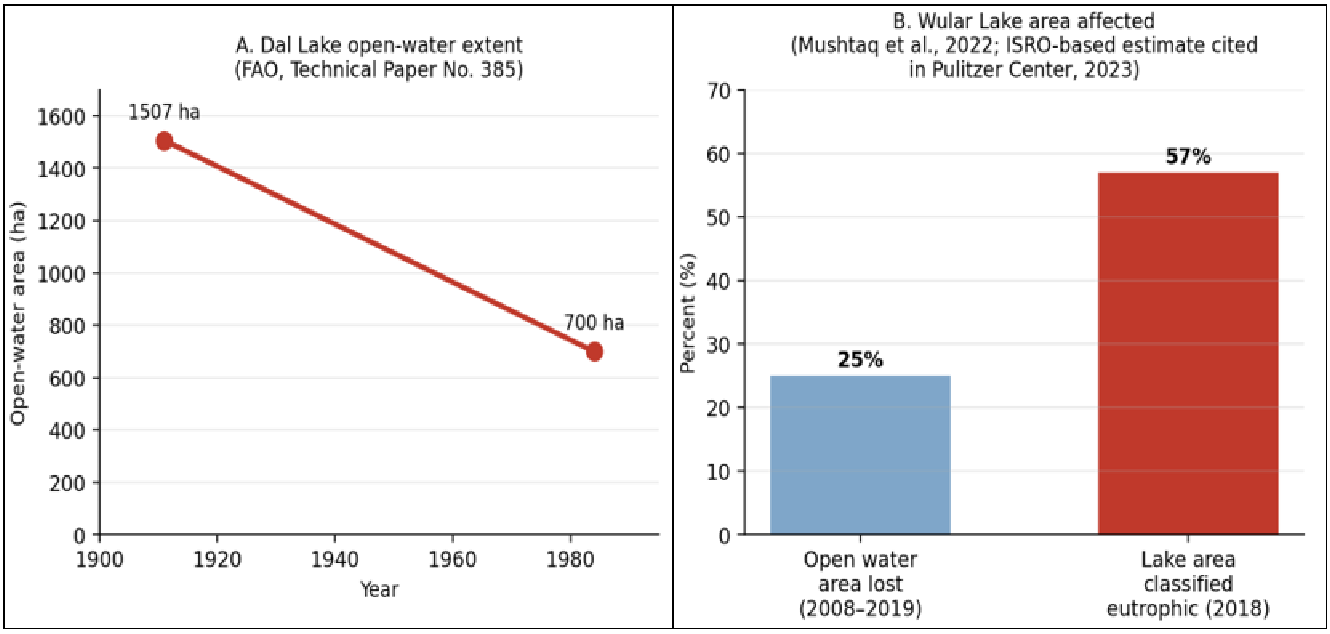

Figure 3: Documented decline in open water extent and expansion of eutrophic conditions in the two largest lakes of the Kashmir Valley

5. Discussion

The synthesis presented here confirms that trophic degradation, rather than thermal stratification, is the dominant limnological concern reported for most J&K lakes, reflecting their shallow morphometry and consequent exposure to complete wind-driven mixing. However, the regional and global literature on climate-driven changes in lake mixing regimes suggests that this picture may become more complex as Himalayan warming continues. Globally, lakes are increasingly shifting from dimictic toward monomictic mixing regimes, and a growing subset of monomictic lakes are projected to become effectively oligomictic or permanently stratified as surface warming and reduced ice cover increase thermal stability. Modelling studies of large, seasonally ice-covered lakes on the Tibetan Plateau similarly project earlier onset and longer duration of stratification, together with a shift toward warm monomictic behaviour, under continued warming. If comparable trends occur in Manasbal Lake- already the region's only confirmed warm monomictic system—a plausible consequence is a lengthening of the stratified period and a further intensification of hypolimnetic oxygen depletion, which would be expected to increase internal phosphorus loading from anoxic sediments and reinforce the lake's eutrophication trajectory even in the absence of any change in external nutrient inputs.

For the majority of J&K's shallow, polymictic valley lakes, the more immediate climate-related risk is unlikely to be a shift in mixing regime as such, but rather an amplification of existing eutrophication pathways through warmer growing-season temperatures, which favour faster macrophyte and algal growth, and through altered snowmelt timing and more erratic monsoon rainfall, which affect flushing rates and the delivery of nutrients and sediment from increasingly urbanised catchments. This compounding of climatic and anthropogenic drivers is consistent with the broader literature on lake vulnerability along altitudinal gradients, which finds that lakes at intermediate elevations precisely where most of the Kashmir Valley's lakes are situated- are often the most susceptible to regime change because they sit close to the thermal thresholds that separate stratified from well-mixed behaviour.

These findings carry direct management implications. First, lake restoration measures in J&K, such as mechanical de-weeding and dredging, have themselves been reported to reduce zooplankton populations and alter physico-chemical conditions, indicating that interventions designed to control macrophyte overgrowth can have unintended ecological costs that warrant more careful, lake-specific evaluation. Second, the concentration of severe eutrophication in urban and peri-urban lakes (Dal, Nigeen, Khushalsar, and increasingly Anchar and Wular) points to catchment-scale sewage interception and land-use control as a higher-leverage intervention than in-lake treatment alone. Third, the proposed LEII framework, once empirically validated, could support the kind of spatially explicit, multi-lake prioritisation that is currently difficult to achieve when each lake has been assessed using different indicators, sampling periods, and methods, and could be integrated into monitoring components of relevant state and national climate action frameworks.

This synthesis has several limitations that should be acknowledged. It draws on studies conducted at different times, using different methods, and with uneven spatial and temporal coverage across the twelve lakes, so the cross-lake comparisons in Section 4 should be read as indicative of broad trophic and stratification patterns rather than as precisely comparable measurements. The LEII scores presented in Figure 2 are, by design, illustrative rather than field-validated, and the weighting scheme in Eq. 1 has not yet been calibrated against independent ecological outcome data. Finally, several of the high-altitude lakes included here (Sheshnag, Nundkol) have been the subject of comparatively little recent limnological study, and their classification here relies on older or indirect sources.

6. Conclusion

Freshwater lakes across Jammu and Kashmir span an unusually wide ecological gradient, from near-pristine, oligotrophic high-altitude lakes to severely eutrophic and, in places, hypertrophic urban lakes, with a single confirmed warm monomictic system, Manasbal Lake, providing the region's clearest example of stable thermal stratification. The evidence synthesised here indicates that anthropogenic catchment pressure—sewage influx, land-use change, siltation, and macrophyte encroachment-remains the dominant driver of trophic decline across most of these lakes, but that climate-driven changes in thermal stratification represent an emerging and currently under-examined additional pressure, particularly for deeper lakes at risk of prolonged stratification and intensified hypolimnetic hypoxia. The Lake Ecological Integrity Index proposed here offers a transparent, extensible framework for bringing trophic state, stratification stability, and catchment pressure into a single comparative metric; its priority next step is empirical validation through a harmonised, simultaneous field campaign across a representative sample of J&K lakes, which would allow the illustrative weights and sub-index mappings used here to be replaced with field-calibrated values suitable for operational lake management and climate-adaptation planning.

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