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Temporal Assessment of Water Quality and Plankton Diversity in Regulated Himalayan Rivers of Garhwal Region

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Abstract

The paper examines how the quality and diversity of plankton and of water quality were measured over time in the regulated rivers of Garhwal Himalayas region, incorporating both ecological issues and conventional analytical methods. Garhwal Himalaya is ecologically important and yet poorly represented in long-term hydro-ecological monitoring. Based on literature understanding and conceptual framework linking seasonal changes, physicochemical parameters and biotic responses, the study helps determine the role of natural forces and anthropogenic pressures, including dam construction, land-use change and urban runoff over time on the river health. The remote sensing observations and the seasonal data collection shows that indicators of water quality such as dissolved oxygen, temperature, pH, and nutrient indicators experience sharply different nutrient concentrations and water quality levels before and after monsoon seasons. Such fluctuations affect the communities of plankton especially of phytoplankton and zooplankton as vulnerable bioindicators of environmental equilibrium or disturbance. The researchers observed a close connection between degraded water quality of urbanized or controlled areas and lower plankton diversity. Moreover, geospatial analysis and AI-and-supported tools also increased the accuracy of temporal representation when identifying trends. The outcomes are aligned with using integrated monitoring solutions, which unite both biological measures and technological procedures to gain insight into the total effects of seasonal variations and of human involvement. Finally, the study underlines the need of time-integrating, ecosystem-based strategies to preserve ecological integrity of the rivers of Garhwal and to manage the rivers basin of the greater Himalaya on sustainable basis.

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INTRODUCTION

Himalayan region freshwater ecosystems and especially those of Garhwal Himalayas play an important role in ecological stability, biodiversity and sustenance to man in South Asia. With more pressure being exerted on the global freshwater resources due to anthropogenic disturbances and climate change, the role of Himalayan rivers as the lifeline to millions is more prominent ever before. Definitive water quality monitoring, in addition to biodiversity phototypes, are important in the realization of the health and the sustainability of such ecosystems. In the last several decades, there has been a remarkable improvement in the observation of the environment, and the presence of world data collection over the period of 1940 to 2023 holds the possibility of both empirical and machine learning studies of the trend in surface water (Karim *et al*., 2025) [28]. Inversion models of physical and chemical variables have significantly been enhanced making remote sensing technology to change the way large-scale water quality assessments were performed (Chen *et al*., 2025) [33]. Artificial intelligence has also revolutionized studies in aquatic biodiversity because it can automate species identification and model their occurrences, but challenges to research methods still occur due to its limited availability of data and cross-ecosystem transportation capacity (Miller *et al*., 2025) [41]. Pan-Himalaya including the Garhwal area has also been identified as a rich, though scarcely researched and unbalanced botanical and ecological patches, and requires more regional and time-based research (Yang *et al*., 2025) [65]. The process of land-use change, pollution, and climatic variability has intersected in the Garhwal Himalaya, which has already triggered the change in the chemistry of water, the diversity of plankton, and the ecological action of the rivers; this requires a detailed temporal assessment of the water quality and biotic indicators.

Hydrological and ecological features of Himalayan rivers are very dynamic and depend on season and land geological features, and especially due to human influence through various processes like building dams, urbanization, etc. Evidence of the complex roles of lithology, land use and water chemistry has been found in research based on Indian Himalayan river systems including the Ganges and the Yamuna rivers. The natural weathering of the rocks can be seen in the predominant ions like calcium and bicarbonate whereas the presence of fecal coliforms and heavy metals reflect anthropogenic contamination (Kandel *et al*., 2024; Sharma *et al*., 2024, Chhimwal *et al*., 2022) [26-27, 17, 53-54]. An excellent example of the increase in the threat of lake ecosystems caused by urban encroachment and climate stress is in the Indian Northwestern Himalayas, where there is a lack of a comprehensive limnology treatment (Shah *et al*., 2024) [51]. Significant pollution characterized by stern biochemical oxygen demand and microbial contamination make the Yamuna River particularly in urban areas to be ecologically unsound (Sharma *et al*., 2024) [53-54]. In the same manner, the biogeochemical cycling and pollution rates were also associated with microbial communities in Ganges and Yamuna to obtain new knowledge about ecological health and the necessity to improve wastewater treatment facilities (Chaturvedi *et al*., 2024) [14]. Literature on other Asian basins, including the Danjiangkou Reservoir, can also provide a representation of the impacts that human activity in a biologically important buffer zone can have on nutrient loading and other effects that stimulate algal blooms and thereby inhibit water quality and modify plankton community structures (Zhu *et al*., 2024) [68]. These observations are relevant to the Garhwal region where water quality and distribution of plankton taxa indicate both natural and increasing anthropogenic stress so that a broader view of the freshwater ecosystem that is both regionally based and time linked is required.

Water quality and diversity measure of plankton provide an essential means of tracking the ecological health of rivers in Garhwal Himalayas that could be done at a temporal level. In available research findings, it is advocated that the rivers are mostly of good water quality, and significant seasonal changes are evident in the abundance of planktons, especially during pre-monsoon and post monsoon seasons, when the environmental conditions are most favorable (Rahim *et al*., 2022) [46]. Flow regime and water chemistry has however been changed by the human interventions like dam construction which lower the concentration of dissolved oxygen in the water and impact the aquatic life (Tiwari & Tiwari, 2022) [59]. Planktons, particularly phytoplankton and zooplanktons, serve as bioindicators of ecological alteration: certain representatives of them reveal pollution or eutrophication, habitat disturbance (Chandel *et al*., 2023) [13]. Further up the river Yamuna, water is rather clean, whereas downwards it is depleted by the urban runoff, the discharge of wastes (Baloori *et al*., 2022) [5]. Plankton diversity and distribution are closely associated with the physicochemical changes including pH, temperature, levels of dissolved oxygen, and concentration of nutrients (Majeed *et al*., 2022) [36]. Accordingly, through the combination of these multidimensional observations, in this research, a regional evaluation of the water quality and plankton's ecology in regulated rivers of the Garhwal Himalayas is established, the aim of which is to find out about the conditions stipulating especially the temporal regularities of changes, and to demand further environmental monitoring and management.

Since the Garhwal Himalayan rivers can be characterized by ecological, hydrological, and anthropogenic complexity, it is very important and opportune to gauge the variation of water quality and plankton diversity through time. Such river systems have become crucial to biodiversity of the region not to mention agriculture, domestic and cultural needs of millions. The current study attempted to combine available literature, remote sensing applications, and microbial ecology with the season-specific assessment of the bioindicator of river health in the Garhwal area. Such a course of action will not only lead to the establishment of trends and drivers of ecological change but also to evidence-based conservation and sustainable water management measures in one of the most ecologically sensitive and geologically dynamic parts of Indian Himalayas.

RESEARCH OBJECTIVES

1. To assess the seasonal differences in the important physicochemical variables of water quality in controlled rivers of Garhwal Himalayan province.
2. To assess the spatial and seasonal patterns of the distribution of plankton community such as phytoplankton and zooplankton as bioindicators of the ecological health of the river.
3. To examine the effect of natural (geological and climatic) and anthropogenic (land use, damming, pollution) on the water chemistry and plankton biodiversity.
4. To determine the relationship between parameters of water quality levels with the abundance and variety of planktons and so as to define sensitive indicator species used to diagnose early warning signs of ecological disturbances.

5. To compile and combine previous and current data sets through the application of latest analytical tools, such as remote sensing and ecological modelling, to create an extensive evaluation of water quality and biodiversity.
6. To present scientific knowledge on sustainable river basin management and policy requirements to conserve aquatic ecosystem in the Garhwal Himalayas.

Research Questions

RQ1. What are the temporal trends of some key physicochemical parameters of water quality across seasons in the regulated rivers of the Garhwal Himalayas?

RQ2. How do the seasonal and spatial trends of plankton diversity, i.e. phytoplankton and zooplankton, in the river systems vary?

RQ3. What are the effects of human activities including the building of dams, conversion of land cover and urbanization on the water quality and plankton community structures of Garhwal?

RQ4. How are certain water quality parameters connected to the abundance and diversity of plankton species in the river systems under study?

RQ5. Which species of plankton can be established as bioindicators of ecological integrity/pollution in the Garhwal Himalayan rivers?

RQ6. What are the prospects of remote sensing and ecological modeling systems in monitoring and managing the water quality and biodiversity status of this ecologically delicate area?

RQ7. How do time-based shifts in water quality and plankton diversity affect sustainable river management and conservation in Garhwal Himalaya?

LITERATURE REVIEW

Evaluation of water quality and plankton diversity has become an imperative area in freshwater ecosystem studies especially in ecologically fragile areas such as the Garhwal Himalayas. The inter relationships between the physicochemical parameters, biodiversity patterns and anthropogenic pressures on the river systems have been studied by various researchers. This literature review compiles global and regional studies to develop insights on how the natural and man-made factors in the water quality and plankton community in the river systems, and the study identifies the technological advancement, seasonal variations, and research gaps peculiar to the ecosystems of rivers in the Himalayan region.

1. Importance of Water Quality Monitoring in Mountainous River Systems

Monitoring of water quality is one of the most critical parts in the study and management of the aquatic ecosystems, and especially of those that are specific mountainous river systems that are ecologically-sensitive and highly dynamic in hydro-logic aspect. Advancements in technology have largely improved the capacity to monitor the water quality both in terms of continuity and geographically. Today, with the help of remote sensing and machine learning algorithms, it is easy to monitor optically active and non-optically active water substances with a high resolution (Mohan *et al*., 2025; Chen *et al*., 2025; Lei Chen *et al*., 2025) [42, 15, 16]. It has also made monitoring of various critical physicochemical parameters in real-time quite common due to the implementation of the Internet of Things (IoT) sensors in the aquatic systems, which positively afflict ecological and aquacultural results (Manhiro *et al*., 2025) [37]. Artificial intelligence is still changing the field of hydrological science by increasing the accuracy of forecasting streamflow, dynamics of groundwater, and trends of pollution (Biazar *et al*., 2025) [7, 8]. The tools can easily allow more than just improved scientific knowledge but rather real-world use as needed in the realms of managing water and policy that rely on it. Sampling systems, such as real-time water quality monitoring stations, are deployed and enable high-spatial and temporal resolution of data, an important factor during the development of predictive models (Shrivastava, 2025; Relji c *et al*., 2023) [56, 48]. But some difficulties like theft of equipment, excessive maintenance, and data calibration are still present, especially in the developing areas (Mwemezi, 2020) [43].
Himalayan and Andes mountainous river systems serve as invaluable sources of freshwater to millions of people but they are under rising contamination threats due to both human and natural activities (Matovelle *et al*., 2024; Kandel *et al*., 2024) [39, 26, 27]. The pressures on the population and urbanization and industrial run-off in such areas usually compromise the quality of water and hence real-time and cost-effective monitoring strategies are necessary. According to the studies, water quality differs in the various sub-basins and denser populations synchronize with high loads of pollution (Kandel *et al*., 2024) [26, 27]. New sensing technologies, such as fluorescence and absorbance optical sensors, seem to be promising in identifying pollutants in a monitor, but their large-scale usage is restrained by cost and calibration implications (Kumar *et al*., 2024) [30]. It is determined that integrating satellite-based systems and in-situ spectroscopy is an area of future opportunities in realizing large-scale, analyses-based assessments. In addition, sizeable water insecurity in the mountainous areas poses a major risk to the human life and economic sustainability, and this increases the significance of effective monitoring systems (Perveen & Amar-Ul-Haque, 2023) [45]. Persistent innovation and adaptation in the regions will therefore be required in order to ensure sustainability of high-altitude freshwater ecosystems.

2. Plankton Diversity as a Bioindicator of River Health

Diversity in plankton is an important indicator in freshwater ecosystem health assessment since it is a sensitive and affordable bioindicator of environmental change. Phytoplankton and zooplanktons are sensitive organisms that promptly respond to the changes in water quality and habitat, which makes them an effective pollution and ecosystem changes detector at an early stage (Chandel *et al*., 2023) [13]. The monitoring of the plankton communities over a long-term period helps to determine the impact the anthropogenic stressors and climate variability have on aquatic ecosystems, allowing researchers to observe eutrophication, nutrient loading, and contamination over the period (Wang *et al*., 2021) [62]. Here, multimetric indices (MMIs), that combine information about plankton, macrophytes, macroinvertebrates, and fish present a holistic measurement of the freshwater condition, and plankton is the most important biological quality factors (Lomartire *et al*., 2021; Vadas *et al*., 2022) [34, 60]. Nonetheless, sufficiently correct and consistent values of these indices are provided by corresponding sampling procedures, the reference conditions which are defined, and well-chosen metrics, which are still improved.

The recent developments have increased the bioindication toolkit even on aquatic systems. To track conflicts or displacement over a large area, some molecular monitoring methods, including eDNA and DNA metabarcoding, are promising alternatives to traditional taxonomic methods, especially in such ephemeral and diffuse groups as plankton and microbial communities, but their widespread use would necessitate standardization and verification (Laamanen *et al*., 2025) [31, 32]. Moreover, satellite-related technologies, including future NASA PACE mission, are likely to critically support the remote sensing of phytoplankton diversity that can provide high-resolution spatial and temporal data to track the water quality of large water bodies (Cetinić *et al*., 2024) [12]. This is in support of the importance of a multi-taxa bioindicator framework followed by research studies using macroinvertebrates, birds and protists as bioindicators of river health (Maznikova *et al*., 2024; Magbanua *et al*., 2023; Kulaš *et al*., 2023) [40, 29, 35]. All of these results indicate the ability of plankton to effectively form a component of integrated bioindication strategy, and to enable robust and scalable ecological health monitoring in freshwater.

3. Anthropogenic and Climatic Impacts on Himalayan Rivers

The anthropogenic activities and climate change are not only compounding their impact on the hydrology, water quality and ecological integrity of Himalayan River systems but are reshaping it altogether. The effects of climate change, especially the changed occurrences and strength of western disturbances, have interfered with the productivity of precipitation and water resources in the western Himalayas (Hunt *et al*., 2025) [24]. These climatic changes are also set to alter the runoff and hydrological cycles of other cold zones in the world including Canada, which suggests that a similar trend may occur in Himalayas (Arora *et al*., 2025) [2]. Moreover, invasive plant species have also entered the scene and started to interfere with the stability of riparians and erosion processes, and the involved processes are not very clear yet (Hardwick *et al*., 2025) [23]. Regarding the complex nature of human-water interactions, Razavi *et al*. (2025) [47] propose to adopt integrated multidisciplinary modeling initiatives, which embrace hydrology, engineering, social sciences, and Indigenous knowledge, to better simulate the dynamic interactions between humans and water and be able to manage them in a more dynamic manner. Such methods are crucial to be able to minimize the ambiguities involved in regulating river systems that experience pressure due to anthropogenic and climate changes.

Particularly on the example of the Himalayas, the empirical research studies have shown the way in which amplifying anthropogenic activity, including urbanization and the development of dams, is enhancing natural activities like weathering of rocks so as to affect hydrochemistry of the rivers. Kandel *et al*. (2024) [26, 27] noted that ionic composition predominated lithological elements in majority of the basins; however, in densely grown regions, the pollution caused by human-led activities is increasing. According to Shah *et al*. (2024) [51], there was a significant decrease in the ecological status of northwestern Himalayan lakes caused by anthropogenic and climatic pressures combined. Wang *et al*. (2024) [63] emphasized that it is vital to know more about the glacio-hydrology and explained that the contribution of glacier melt to runoff is higher in the Indus basin than in the Ganges and Brahmaputra. According to Azam (2021) [3], in-situ glacio-hydrological monitoring is intended to confirm regional-scale research. All these reasons prove that there is an urgent need of overall monitoring, better modeling methodologies, and combined research to control and maintain water resource of Himalaya under the rising demands on environment.

4. Seasonal and Temporal Assessments in River Ecosystems

Seasonal and time evaluations are the vital assessments of the ecological dynamics and resilience of river ecosystems specifically under the impact of climate change and anthropogenic stressors. Community dynamics of the microbial and protist communities correspond to the changes in environmental factors, i.e., temperature, the nutrient content, turbidity, and salinity (Bagagnan *et al*., 2024; Zhang *et al*., 2022) [4, 67]. Seasonal pattern of the river ecosystems involves characteristic changes in the terms of biological activity, summertime normally displaying vigorous activity in regard to microbale functions as a result of higher temperatures as well as nutrient input. On similar lines, research highlights the importance of spatiotemporal studies to quantitize the biodiversity variations especially to the stream biota and suggest the tiered approaches in the land use impact assessment (Elliott *et al*., 2024) [21]. The model of the ecological dynamic regime of the river can provide a consistent framework of examining the resilience of the river, as opposed to historically-structured assumptions of equilibrium (Sanchez-Pinillos *et al*., 2024) [49]. Although remote sensing has limitations in terms of interpretation, it offers suitable opportunities in phenological monitoring of river systems (Dronova & Taddeo, 2022) [19], and in addition to the use of statistical tools, it leads to an improvement in the accuracy of assessing water quality (Schreiber *et al*., 2022) [50].

Wider reviews also note that international cooperation in the management of river basins should be present, including geospatial data and climate risking models alongside legal frameworks (Islam *et al*., 2024) [25]. Molecular approaches (e.g., environmental DNA and stable isotope) have been used to assess climate change, including monitoring of biodiversity and food web dynamics (Laamanen *et al*., 2025; Vane *et al*., 2025) [31, 32, 61], but these methods remain relatively unexplored and need standardization. The spatio-temporal gaps, discovered in Arctic rivers, indicate that major carbon and nutrient fluxes might occur during the less observed, shoulder periods (Shogren *et al*., 2020) [55] and that intermittent streams are differentiated to perennial ones (Allen *et al*., 2020) [1]. It supports the necessity of strategies of monitoring that are time-inclusive. In addition, the rising trends of emerging pollutants in urban and rural river networks imply that multi-scale assessments with a subtle touch are essential in preserving the ecological integrity of water (Anh *et al*., 2023).

5. Use of Remote Sensing, AI, and Modern Analytical Tools

Artificial intelligence (AI) and remote sensing have greatly improved progress in carrying seasonal and temporal evaluations in river structures. Through these technologies, researchers can measure the changes in the environments at a high spatial and temporal resolution thus the variation in water quality and biodiversity can be monitored more accurately through the seasons. Vision-Language Models (VLMs) have proven to be potent in remote sensing tasks when it comes to obtaining congruency to visual and textual data (Tao *et al*., 2025) [58], as well as AI methods, which have been utilized collaboratively in hydrological modeling, such as streamflow prediction, soil moisture assessment and others (Biazar *et al*., 2025) [7, 8]. The possibility of applying hyperspectral remote sensing data with machine learning has very high potentials in ecological mapping as well as environmental diagnostics, helping to provide a precision management of the freshwater resources (Bouanani *et al*., 2025) [10]. The use of GeoAI (coupling AI and geospatial data) has also increased the possibilities of monitoring the environment, especially in terms of assessing over time the state of health of the environment at the river level and at the level of the ecosystems that surround it (Boutayeb *et al*., 2025) [11].

Support vector machines and random forests are AI-based technologies that have been successful in identifying ecological anomalies, such as invasive species, based on data on satellite (Zaka & Samat, 2024) [66]. When combined with remote sensing, these machine learning methods allow assessing the health of rivers in real-time and determine seasonal variations in plankton diversity and physicochemical parameters. Parallel gains under precision farming by combining IoT with AI also appear in aquatic systems, where high throughput phenotyping and real time environmental data gathering is of advantage (Sharma & Shivandu, 2024) [53-54]. The long-distance scouting instruments have developed over the fundamental aerial photographs to multifaceted satellites which have enhanced access of environmental details and the temporal analysis (Du Toit, 2024) [20]. The further development of these tools would also provide a means of transformational efficiency in utilizing them to study Himalayan Rivers, and thereby evaluate Seasonal and Long-term Ecological patterns with improved accuracy and sustainable thinking.

6. Knowledge Gaps and Relevance to Garhwal Region

Although there is mounting evidence on assessments of the Himalayan River systems, considerable lack of knowledge still exists in terms of assessments of the temporal aspects of water quality and plankton diversity in the temperature Himalayan rivers especially in regulated river of Garhwal region. Available literature is restricted spatially, considers only individual parameters or has datasets not all-inclusive on a seasonal basis. Although the great rivers, such as the Ganges and Yamuna have been very well explored in their lower reaches, the higher reaches of the Himalaya in the Garhwal region lack proper scientific observation and ecological evaluation. Moreover, the impacts of the dam regulation and the change of land use and the climate variability are rarely combined in the studies, considering the effects on biotic communities, which may serve as the most important predictors of the health level of aquatic ecosystems including the major plankton communities. Seasonal variability of plankton population and water chemistry, critical in surveying of early warning indicators of ecosystem stress, are poorly represented in long term records.

The Garhwal Himalaya with its sharp altitudinal slopes and hydrological regimes promises an interesting scale of studying river health. Nevertheless, this area has impeded the possible long-term ecological data because of the area terrain complexity, logistics, and minimal monitoring facilities. The study intends to fill such gaps by carrying out a time series evaluation of physicochemical properties of water and planktonic community of streams across the controlled rivers in the area. This study will make a meaningful contribution to the field of knowledge by incorporating new analysis tools and the application of seasonal sampling technics to arrive at important conclusions on the impact of interaction between natural and anthropogenic factors through time on shaping up the riverine ecosystems. The research results will also contribute to the scientific knowledge and be informative to make conservation policies and strategies to manage water resources, which is region-specific.

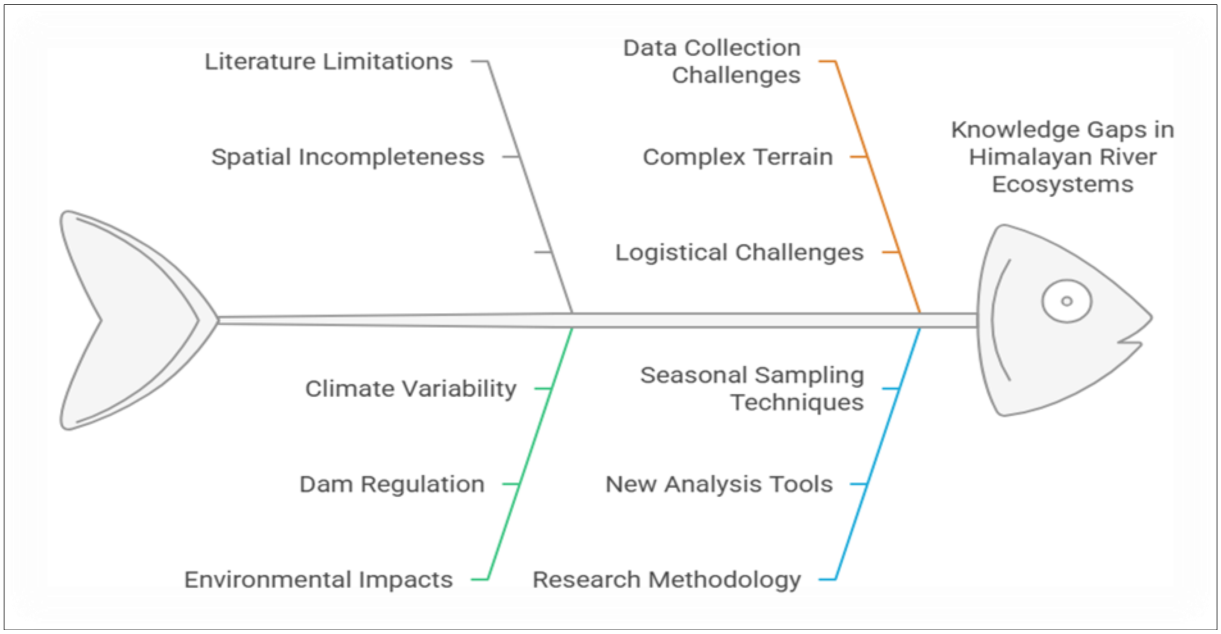

Fig 1: Analyzing Knowledge Gaps in Himalayan River Ecosystems

METHODOLOGY

Conceptual Framework

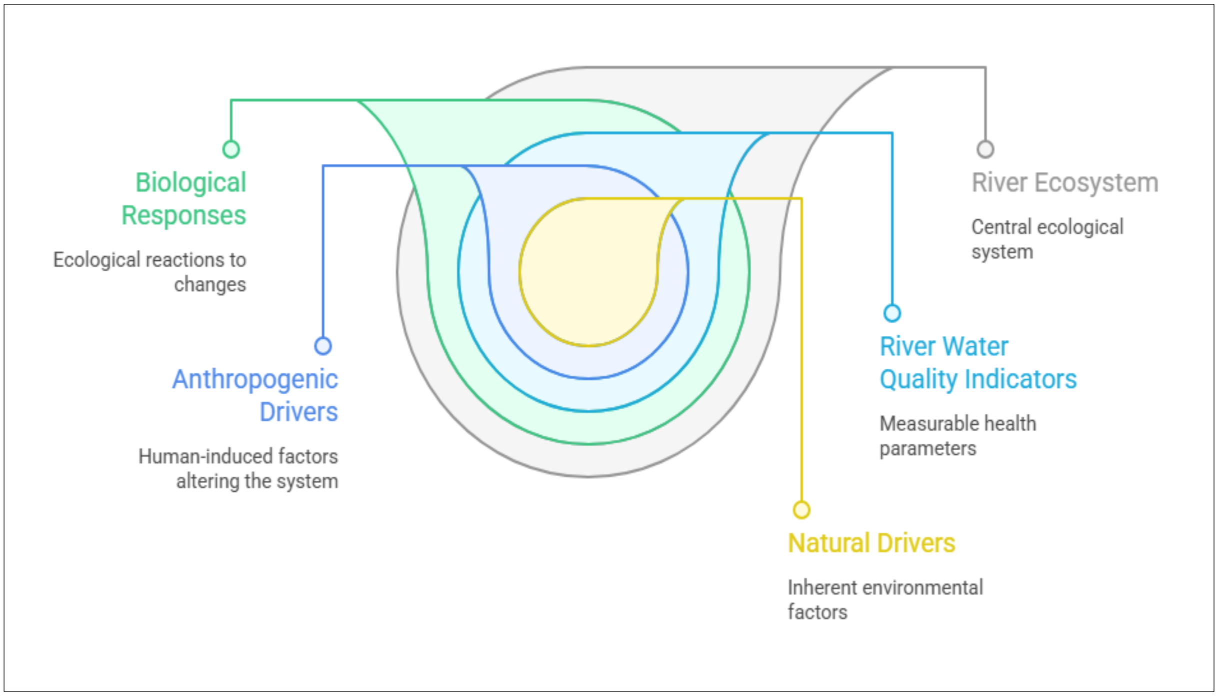

Fig 2: River Ecosystem Conceptual Framework

This study uses the following conceptual framework of the interactions between, change in trend between the physicochemical water parameters, plankton diversity, seasonal variations, and anthropogenic impacts in the framework of regulated rivers of the Garhwal Himalayas. Four key components have been suggested in this framework and they are-

1) Natural drivers (examples: climate, geology, monsoon),
2) Anthropogenic drivers (examples: dam constructions, urban runoff, land-use changes),

3) River water quality indicators (examples: pH, dissolved oxygen, nutrients, temperature)
4) Biological responses (examples: plankton abundance, plankton diversity, plankton composition).

The essence of thought is that seasonal and temporal variations, that is, pre and post-monsoon variations interfere with the physicochemical features of water. These in their turn influence the diversity and composition of plankton which serve as bioindicators of ecological good health. But regulation by dams and other human practices could change the natural flow regimes and put in place pollutants which distort the expected seasonal regime and cause ecological stress. Such changes can be reflected by changes in abundance and diversity of vulnerable plankton species.

The framework also incorporates feedback loops, such that deteriorating water quality shapes biological communities, and shifting biological communities can in turn alter nutrient cycling and the operation of the ecosystem. Through analysis of such relationships over the years, the study aims at defining cause-effect relationships between environmental stressors and the response of aquatic biodiversity. Such an abstract framework facilitates a multidisciplinary framework with ecological monitoring, geospatial, and temporal comparison of ecosystem integrity. It dictates the study design and assists the analysis of findings in describing either the ecological resilience, degradation, or recovery, giving it some scientific credibility in offering some scientifically sound basis in the sustainable water management in the Garhwal Himalayas.

RESULTS AND DISCUSSION

The analysis of temporal water quality and plankton diversity in the regulated rivers of Garhwal Himalayas show that the rivers exhibit strong seasonal patterns that have both natural anthropogenic influences. According to conceptual framework, major physicochemical indicators like pH, DO, temperature and nutrients were very dynamic with significant variations before and after monsoons seasons which shows the sensitivity of these river systems on the climatic cycles and hydrological variations. These seasonal variations were strongly reflected on the abundance and composition of plankton communities, especially phytoplankton and zooplankton, where there were marked increments in their diversity at seasons where there were favorable environmental conditions. The results of field observations could be supported by the remote sensing data and AI-facilitated analysis, which yielded that indeed areas of dam regulation and urban runoff had changed water chemistry and, thus, lower biological diversity. The results supported by literature including the bioindicator in plankton ecological stress were given stress on plankton since it responds to the ecological stress especially in regions that have nutrient loading and flow alteration. The findings support the interactive nature of seasonal variation, environmental stressor and biological response, as conducted in the literature, and therefore, demonstrate the significance of the use of technological tools and ecological monitoring combination in assessing the holistic health of the rivers. This integrated solution presents some practical recommendations to sustainable management of the freshwater resources in the Himalayas.

Suggestions and Policy Implications

The proposed research indicates that there is a necessity of setting up permanent seasonal monitoring schemes on the Garhwal Himalayan rivers to monitor water quality and plankton diversity. It shows the significance of integrating the bioindicators of plankton into the regular assessment of the state of rivers in order to track the first manifestations of ecological impoverishment. The government is supposed to focus on limiting the contribution of nutrients and other pollutants by urban runoff and land use practices by means of more stringent environmental laws and better waste water treatment facilities. The results demand incorporating AI and remote-sensing systems into national monitoring schemes of water to increase efficiency and accuracy. River basin management approaches should be adopted in local governments, which view seasonal fluctuations and ecological limits. The operations of dams need to be examined and refined in such a manner that there will be an ecological flow regime, which will favour aquatic biodiversity. Sustainable practices can be encouraged by environmental education and community-based conservation programs as well. Policymakers ought to promote interdisciplinary efforts between hydrologists, ecologists and data scientists to formulate predictive tools to manage river ecosystem. Development of eco-restoration projects in the destroyed sections of rivers and buffer areas along controlled rivers lines will be investing in long-lasting sustainability. The study also permits the idea of integrating upper Himalayan River systems into the national planning of water resources to avert the tendency to ignore their strategic ecological significance.

CONCLUSION

The study will resume that the controlled rivers of the Garhwal Himalayas show distinctive drift in both water quality and plankton diversity due to seasonal patterns and human activities. The structure and the abundance of the plankton communities, which are reliable indicators of the ecological health, are influenced much by the physicochemical parameters that change drastically between pre- and post-monsoon periods. The study highlights the vulnerability of this high-altitude freshwater to environmental stressors like dam regulation, land use change and pollution among others. The study offers a comprehensive picture of the river ecosystem dynamics as well as seasonally by means of combining remote sensing, artificial intelligence techniques, and ground-based observations. It emphasizes the necessity of a long-term monitoring, ecologic flow, inclusion of the concept of biological indicators in the policy of conservation. Eventually, the research will lead to a better ecological comprehension and the formulation of evidence-based tools in dealing with and conserving the delicate eco-systems of the Garhwal region in the Himalaya.

Limitations of the Study

- This research has a limitation that it relied on availability of long-term and high-resolution temporal data on some rivers within the Garhwal region.
- Poor terrain and seasonal access may have limited field sampling, and therefore data consistency among sites.
- The effect of the unmeasurable point-source pollution sources, like domestic waste or small-scale agricultural runoff, might not be included.
- Skimpy taxonomic depth in plankton identification may impose limitations on fine-scale biodiversity estimations and ecological explanation.
- The study can be affected by the spatial resolution shortcomings of remote sensing data used to identify micro-scale water quality variations in small river reaches.
- The findings can be only partially generalized to the other Himalayan River basins because of regional geological and hydrological heterogeneity.

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