Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 3, September 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I3/AF260313

Long-Term Limnological Assessment of Freshwater Ecosystems Under Climate Variability and Anthropogenic Environmental Changes

[1*] Ahmet Çelik, Türkiye Innovation and Industry Development Centre, Istanbul, Turkey.

[2] Derya Aydın, Türkiye Innovation and Industry Development Centre, Istanbul, Turkey.

Abstract: This study intended to examine long-term changes in the status of freshwater ecosystems due to climate variability and anthropogenic pressures on the environment through the use of physico-chemical, hydrological, nutrient, biological, and microbiological parameters. Freshwater ecosystems that have varying degrees of anthropogenic pressure were used for the assessment. Water temperature, dissolved oxygen, electrical conductivity, turbidity, nutrients, biochemical oxygen demand, chlorophyll-a, microbial indicators, and biodiversity were evaluated. Descriptive, trend, correlation, regression, and multivariate analyses were performed for climatic variables and anthropogenic pressure indices. Spatial and temporal differences were evident along the gradient of disturbance. Dissolved oxygen concentration ranged from 3.2 to 5.5 mg/L and from 6.2 to 8.1 mg/L; total nitrogen content rose from 0.32–0.86 to 1.28- 3.15 mg/L; and total phosphorus content increased from 0.02 to 0.08 and from 0.13 to 0.39 mg/L. Chlorophyll-a increased from 3.5 and 10.8 to 18.6 and 46.2 µg/L, suggesting higher levels of eutrophication. Biodiversity index decreased from 3.82 to 1.76, and microbial contamination increased from 45 to 1,850 CFU/100 mL. Total ecological state index changed from 91 at the reference sites to 42 at wastewater sites. These results show that climate variability and anthropogenic pressure are involved in the degradation of freshwaters together. This means that long-term monitoring of ecological condition, including environmental and biological indicators, is required for climate-resilient freshwater management and conservation.

Keywords: Freshwater Ecosystems; Limnology; Climate Variability; Anthropogenic Pressure; Water Quality; Biodiversity; Ecosystem Assessment.

(Submitted: May 22, 2026; Revised: July 02, 2026; Accepted: August 20, 2026; Published: September 30, 2026)

I. Introduction

Freshwater ecosystems form some of the most environmentally significant features of the global biosphere due to their role in supporting aquatic biodiversity, nutrient cycling, primary productivity, water purification, fisheries, agriculture, and human livelihoods. Despite the ecological and socioeconomic significance, the freshwater systems have been increasingly subject to climate variability and anthropogenic environmental stresses. Temperature changes in air and water, precipitation, droughts, floods, evaporation, and river discharges can impact the thermal regime, hydrologic connections, availability of habitats, nutrients, and biological productivity. River flow regimes, impacted by climate change, are of particular importance because the changes in the magnitude, timing, duration, and frequency of the flows can affect the ecological processes on multiple levels (Döll & Zhang, 2010). Freshwater organisms and communities are then subjected to changes in distribution, abundance, phenology, productivity, and interactions between species (Woodward et al., 2010). However, anthropogenic activities, including urban development, agricultural expansion, industrial development, waste disposal, land-use changes, water withdrawal, and nutrient enrichment, may significantly affect freshwater ecosystems.

When these two types of pressures appear at the same time, it may become challenging to determine the key causes of the observed changes in the ecology (Angeler et al., 2014; Mukherjee et al., 2023).

The aim of this research is to give a long-term limnological assessment of responses of freshwater ecosystems to climate variability and changes in the environment caused by humans. This research will try to determine the changes in the major physical and chemical parameters over time and study the connections between these parameters and climatic conditions as well as man-made pressures. Long-term observations

in ecology are especially helpful because freshwater ecosystems can demonstrate gradual changes, delayed response, seasonal changes, and even ecological transitions that cannot be adequately studied in short-term observations (Köhler, 2010). Ecological indicators can also help to organize the data on biodiversity, functioning of ecosystems, climate change, and human activities (Wang et al., 2021). The aim of this assessment is thus to build an all-embracing view of the development of the trajectory and environmental factors for freshwater ecosystems (Döll & Zhang, 2010).

While many studies have been carried out regarding climate change and anthropogenic influence on freshwater systems, a number of issues still require attention. First of all, many studies are focused on separate stressors and/or limited time periods of observations, which prevents identifying natural variation and environmental change (Mukherjee et al., 2023; Sidibe et al., 2026). Moreover, climate change and human influences could be interconnected in such a way that their interaction cannot be determined only through the examination of these factors separately. Besides, there are differences in the response of lakes and other freshwater ecosystems to the same environmental factors due to the existence of spatial variability (Wu & Sun, 2026). Another important issue that should be mentioned is the identification of historical variability and modern anthropogenic changes (García-Rodríguez et al., 2022).

This study makes a valuable contribution to the field of the evaluation of freshwater ecosystems undergoing the influence of both climatic and anthropogenic stresses by providing a comprehensive long-term perspective for its assessment. The study pays attention to the joint consideration of environmental and ecological indicators, which is more important than the separate consideration of particular variables. Such an approach may help detect long-term trends, environmental thresholds, and possible cumulative effects. The results can be applied in various fields, including freshwater ecosystem monitoring, conservation, and management.

The paper is organized as follows: Introduction (Section 1) provides background and purpose of the study; Literature Review (Section 2) describes the monitoring approach and stressors; Materials and Methods (Section 3) discusses sampling procedures and data analysis; Results (Section 4) gives spatial and seasonal trends along with ecological implications; Discussion (Section 5) explains results and their interpretations; and Conclusion (Section 6) highlights important management conclusions.

II. Literature Review

Long-term ecological monitoring is crucial in studying the dynamics of freshwater ecosystems since there may be huge differences between seasons or even years in the conditions of the environment. While short-term monitoring allows determining immediate perturbations, it may miss gradual shifts in baseline ecology, late biological responses, and long-lasting changes in the functioning of the ecosystem. Long-term ecological studies offer an opportunity to develop references, find environmental trends, discover anomalies, and assess ecosystem response to altered environmental drivers (Köhler, 2010). Freshwater ecosystems are especially sensitive to climatic change, as the effects of climate on organisms, populations, communities, food webs, and ecosystem function are mediated by temperature and hydrological factors (Woodward et al., 2010). The change in river flow under climate variability leads to changes in the timing and intensity of ecological processes, habitat availability, and nutrient/sediment transport (Döll & Zhang, 2010).

Ecological indicators have become increasingly appreciated as useful means of assessing the impacts on the freshwater environment. Indicators may incorporate various information related to aquatic biodiversity, ecosystem functioning, human impact, and climatic factors, which facilitates the overall environmental assessment (Wang et al., 2021). An indicator-based assessment method may enable the conversion of complex environmental observations into clear indicators of ecological condition and change. Vulnerable freshwater ecosystems have also been assessed with regard to their sensitivity, resilience, disturbances, and environmental stresses during the development of management measures (Angeler et al., 2014).

Climate Variability and Anthropogenic Environmental Pressures

The factors related to climate variability and anthropogenic activity usually overlap in freshwater systems. Temperature increases, changes in precipitation and runoff, droughts, floods, and modifications of the hydrologic regime could be associated with water pollution, intensified agricultural activities, urbanization, water withdrawal, habitat alteration, and eutrophication (Mukherjee et al., 2023; Hassan et al., 2019). These factors may influence water quality, biodiversity, productivity, and stability of ecosystems. Monitoring studies carried out in large freshwater bodies revealed the importance of long-term observations in studying changes caused by climatic and anthropogenic factors (Plisnier et al., 2018).

Modern studies give special attention to the development of indicators of changes caused by climate change in freshwaters. Such indicators could use physical, chemical, biological, and ecological characteristics of systems, providing thus a better understanding of changes compared to single parameters (Rose et al., 2023). Historical data obtained in the framework of paleolimnological studies could contribute to limnological observations by providing information on past periods beyond those studied in conventional monitoring studies (García-Rodríguez et al., 2022).

Emerging Evidence and Research Needs

According to recent research, the effects of environmental change on freshwater ecosystems can vary greatly across sites and different types of ecosystems. The spatial variation of ecological responses implies that the consequences of climate change and human activities cannot be viewed based on a unifying effect. In addition, the synergy of climatic changes and anthropogenic stressors may lead to increased ecological risks compared to the effect of each stressor individually (Sidibe et al., 2026). The same has been found for broader threats such as climate change, pollution, alteration of habitats, and resource overexploitation, which have been recognized as connected dangers that require combined methods of mitigation (Mukherjee et al., 2023; Hassan et al., 2019). Hence, an important direction of future research is related to the creation of assessment techniques that would combine climatic, hydrologic, physicochemical, and biological data. Therefore, existing literature clearly indicates the need for an approach that shifts from an independent examination of individual environmental factors to one which is more holistic in nature (Wang et al., 2021; Angeler et al., 2014; Rose et al., 2023; Woodward et al., 2010).

III. Materials and Methods

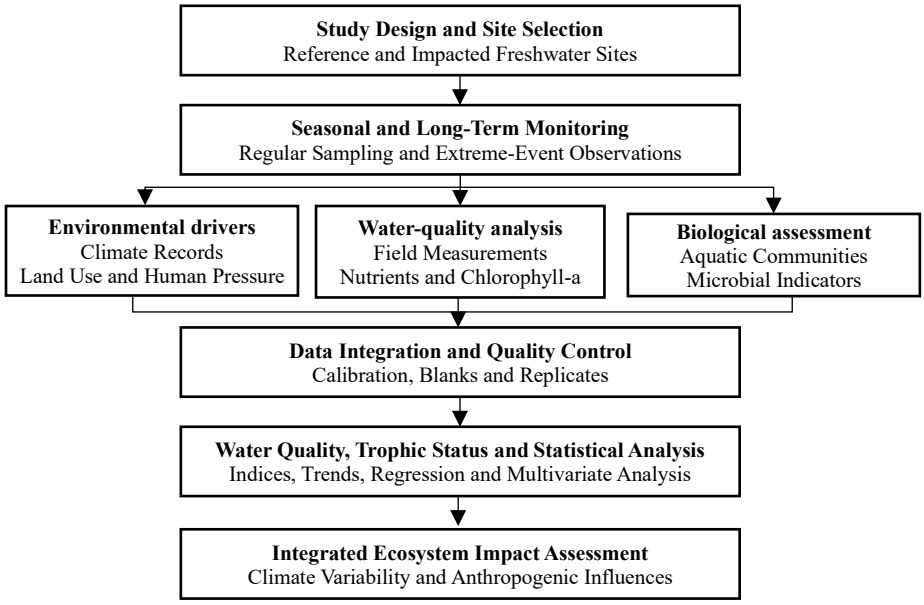


Figure 1: Integrated Methodological Framework for Freshwater Ecosystem Impact Assessment

Figure 1 represents the comprehensive methodological framework applied in the process of limnological evaluation. This process involves site selection, seasonal monitoring, data collection in the environmental, chemical, and biological context, quality control, water-quality modeling (regression, trend, multivariate), and ends with ecosystem impact evaluation under climate and human influences.

Study Design and Sampling

In this long-term limnological study, an analysis was carried out to determine how variations in climate and environmental pressures due to humans affect the characteristics of freshwater ecosystems. Freshwater ecosystems such as lakes, rivers, streams, and reservoirs, which differ in their hydrological characteristics and land use patterns, were chosen as study sites. Sampling stations were set up at sites where the freshwater ecosystems were relatively less disturbed, as well as those that are affected by human practices such as urbanization, agriculture, and industry.

Samples of water and field measurements were gathered on a recurring schedule through all of the important seasons. The objective was to include in the sample data the seasonal as well as any longer-term variations in the condition of the ecosystem. Other data collection was also done during times of extreme climate conditions such as rain, flooding, drought, and heat. GPS coordinates and other environmental characteristics were collected at each sampling location.

Climatic and Environmental Data

Long-term climatic records were collected through meteorological stations and credible climatic databases pertinent to the area under investigation. Air temperature, precipitation, relative humidity, and any other climatic variables were recorded on a monthly or seasonal basis. Climatic abnormalities were assessed in relation to the long-term averages. High temperatures, heavy precipitation, dry spells, and any other climatic extremes were recorded to ascertain if they have any effect on the process of the freshwater ecosystem.

Anthropogenic effects were determined using the information on land use, population density, agriculture, discharge of sewage, industrial effects, and other sources of disturbance in the environment. The characteristics of the surrounding land use for the sampling sites were determined using available geographic information systems (GIS), wherever necessary. The data were used to categorize the sampling sites on the basis of anthropogenic effects.

Physicochemical and Water-Quality Analysis

In situ measurements of various water-quality parameters were made during each sample collection event using calibrated water-quality instrumentation. These included measurements of water temperature, pH, dissolved oxygen, electrical conductivity, total dissolved solids, and turbidity that were carried out at each sample location. Secchi depth was used to measure water transparency. Samples were collected in sterilized, properly labeled flasks and transported to the laboratory under proper preservation conditions.

Parameters analyzed in the laboratory included major nutrients such as nitrate, nitrite, ammonium, total nitrogen, phosphate, and total phosphorus. Other parameters such as biochemical oxygen demand, chemical oxygen demand, total suspended solids, alkalinity, hardness, and major ions were analyzed as necessary for the purpose of the study. Chlorophyll-a was used to assess phytoplankton biomass and nutrient status. Analytical methods were standardized, and calibration, blanks, and replicates were performed in laboratory analyses.

Biological Assessment

Biological assessment was used alongside physicochemical analysis to gauge ecological status. Phytoplanktons, zooplanktons, benthic macro-invertebrates, and, when possible, aquatic macrophytes and fish communities were assessed through standard biological techniques. Taxa identification was done up to the lowest taxonomic level that was practically possible, while the species richness, abundance, diversity,

and evenness were estimated. The presence of pollution-sensitive and pollution-tolerant taxa was also taken into consideration.

Waterborne microorganisms were investigated where anthropogenic pollution was of specific interest. Water samples were examined for indicator organisms such as total coliforms and *Escherichia coli* using standard microbiological techniques. Microbial results were interpreted along with nutrient and physicochemical analysis to gauge possible impacts of domestic sewage and other anthropogenic effluents.

Assessment of Water Quality and Trophic Status

Water quality was assessed based on physical, chemical, nutrient, microbial, and biological indicators. The water quality index was determined through standardization and integration of chosen parameters in order to assess the overall status of water quality. Trophic status of water bodies was assessed based on nutrient concentrations, water transparency, and other indicators such as chlorophyll-a. Sampling locations were grouped depending on their trophic status and level of pollution.

Integration of biological and physicochemical parameters enabled differentiation of changes in water quality and ecological deterioration. Temporal variability of water and trophic indicators was compared among seasons, sampling locations, and years.

Statistical Analysis

Analysis of the obtained data involved performing statistical tests aimed at identifying seasonal trends and trends over the entire period of time under consideration, as well as revealing relationships between environmental factors and the response of ecosystems to those factors. Statistical measures were computed for all significant parameters. Seasonal differences and differences between sites and years were analyzed using appropriate parametric or non-parametric statistical tests. Trends over the entire period were revealed using regression analysis as well as non-parametric tests like the Mann-Kendall trend test with the Theil-Sen slope.

Correlation and regression analyses were conducted to reveal relationships between climatic factors and limnological parameters. Principal component and cluster analyses were applied to identify environmental gradients and group sites according to their environmental characteristics. If biological community data were available, multivariate analyses were used to find relationships between community composition and environmental factors.

Integrated Climate and Anthropogenic Impact Assessment

The final assessment brought together climatic, physicochemical, biological, and anthropogenic data sets to identify the key drivers of freshwater ecosystem condition. Variables such as temperature and rainfall were combined with measures of human impact such as land use change, nutrient pollution, wastewater discharge, and other forms of disturbance. The impacts of such variables on water quality and biological response were then quantified through correlational, regression, and multivariate analysis.

The process of integrating the information allowed for the determination of the long-term trends as well as their differentiation from short-term trends, both seasonal and those caused by extreme climatic events. The method was used for determining the state of health of freshwater ecosystems as well as the impacts of climate variation and human impact on limnology.

IV. Results

Spatial and Seasonal Variation in Water Quality

The results clearly indicated that there were differences in the water quality at sites subjected to varying degrees of anthropogenic impact. The reference sites tended to have relatively high values of dissolved oxygen while having low conductivity, turbidity, nutrient content, biological oxygen demand (BOD), and

chlorophyll-a concentration. Nutrient and organic contamination were high at the anthropogenically impacted sites. Seasonal differences were noted too.

Table 1: Representative Water-Quality Characteristics Across Different Levels of Anthropogenic Influence

Parameter	Reference Sites	Moderately Impacted Sites	Highly Impacted Sites
Temperature (°C)	24.1–27.3	24.8–28.5	25.2–29.4
Dissolved Oxygen (mg/L)	6.2–8.1	4.8–6.8	3.2–5.5
Electrical Conductivity (µS/cm)	120–310	280–560	490–920
Turbidity (NTU)	2.5–8.4	7.2–18.5	14.6–36.8
Total Nitrogen (mg/L)	0.32–0.86	0.71–1.64	1.28–3.15
Total Phosphorus (mg/L)	0.02–0.08	0.06–0.18	0.13–0.39
BOD (mg/L)	1.2–2.8	2.4–5.1	4.3–8.2
Chlorophyll-a (µg/L)	3.5–10.8	8.2–24.5	18.6–46.2

Table 1 shows progressive deterioration of water quality due to higher anthropogenic impact. The temperature increased from 24.1-27.3°C in reference points to 25.2-29.4°C in highly impacted points. Dissolved oxygen was reduced from 6.2-8.1 to 3.2-5.5 mg/L. Total nitrogen increased from 0.32-0.86 to 1.28-3.15 mg/L, and total phosphorus increased from 0.02-0.08 to 0.13-0.39 mg/L. BOD increased from 1.2-2.8 to 4.3-8.2 mg/L, which implies organic pollution is increasing. Chlorophyll-a also increased from 3.5-10.8 to 18.6-46.2 µg/L.

Seasonal and Long-Term Limnological Trends

The effects of climate variability on the features of freshwater ecosystems were observed for a long period of time, and it was noticed that temperature rise caused a decrease in dissolved oxygen level and an increase in phytoplankton production, while heavy rains caused an increase in turbidity level and transport of nutrients from the catchment area. Drought caused an increase in conductivity and dissolved materials. This was particularly so in areas where there was considerable anthropogenic influence.

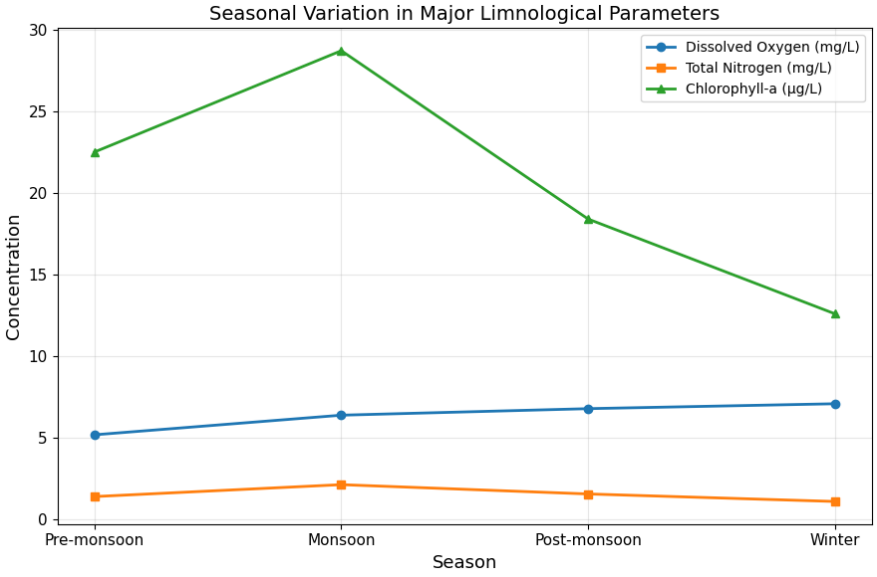


Figure 2: Seasonal Variation in Major Limnological Parameters

Figure 2 shows the seasonal variations in dissolved oxygen, total nitrogen, and chlorophyll-a. The amount of dissolved oxygen rose from 5.2 mg/L in the pre-monsoon season to 7.1 mg/L in winter, whereas the amount of total nitrogen peaked at 2.15 mg/L in the monsoon season against 1.12 mg/L in winter.

Chlorophyll-a showed a peak in the monsoon season, that is, 28.7 µg/L, whereas its lowest value was recorded in winter, i.e., 12.6 µg/L.

Biological and Ecological Responses

Biological evaluation revealed an increasing trend of structural change within communities on the disturbance gradient. Locations least disturbed had higher biological diversity and were more sensitive to pollution. The disturbed sites had a high abundance of pollution-tolerant organisms. High levels of chlorophyll-a and nutrients correlated with poor water clarity and declining ecology. Higher levels of microbiological parameters were noted at sites affected by wastewater.

Table 2: Integrated Ecological Condition of Freshwater Ecosystems

Site Condition	Water Quality Index	Trophic Status Score	Biological Diversity Index	Microbial Contamination (CFU/100 mL)	Overall Ecological Condition Score
Reference	91	18	3.82	45	91
Low Disturbance	84	31	3.45	120	84
Moderate Disturbance	72	48	2.91	380	72
High Disturbance	58	67	2.34	920	58
Wastewater Influenced	42	82	1.76	1,850	42

A decline in ecological quality is clearly evident in table 2 with the increase in anthropogenic activity. The water quality index dropped from 91 at the reference locations to 42 at the wastewater-affected sites, while the trophic state index increased from 18 to 82, depicting the increase in nutrient enrichment. The biological diversity index also fell from 3.82 to 1.76, while the microbial pollution rose from 45 to 1,850 CFU/100 mL.

Relationship Between Environmental Pressure and Ecosystem Condition

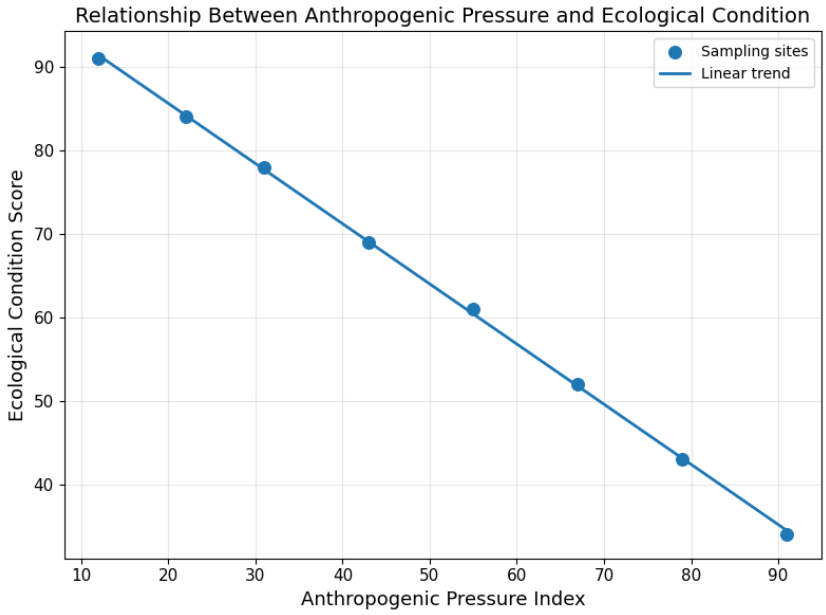


Figure 3: Relationship Between Anthropogenic Pressure and Ecological Condition

The relationship between climate-related parameters and anthropogenic activities influenced the response of ecosystems in the long run. The temperature had negative relationships with dissolved oxygen concentration and positive relations with chlorophyll-a concentration while precipitation was correlated with turbidity and nutrients. Factors such as urbanization, effluent discharge, and land use stress contributed to nutrient enrichment and organic pollution.

The inverse relationship between anthropogenic pressure and ecological condition is presented in figure 3. The increase in the anthropogenic pressure index from 12 to 91 resulted in a reduction in the ecological condition index from 91 to 34. Moderate anthropogenic pressure at 43, 67, and 79 was accompanied by ecological indices of 69, 52, and 43, respectively. This suggests that increased anthropogenic pressure results in worsening ecological conditions.

V. Discussion

Spatial, seasonal, and long-term impairment of freshwater ecosystems was demonstrated with increasing levels of climatic variability and anthropogenic impacts. Dissolved oxygen decreased from 6.2-8.1 to 3.2-5.5 mg/L, while total nitrogen increased from 0.32-0.86 to 1.28-3.15 mg/L and chlorophyll-a from 3.5-10.8 to 18.6-46.2 µg/L. Ecological condition score decreased from 91 at reference sites to 42 at wastewater-influenced sites.

This suggests that increasing nutrient enrichment, organic contamination, warming, and hydrological variability together result in deteriorating water quality and ecological health. The increase in trophic status score from 18 to 82 and decrease in biological diversity from 3.82 to 1.76 show increasing eutrophication and degradation of ecosystems.

Therefore, the significance of using both climatic and anthropogenic indices in freshwater monitoring should be highlighted.

These results cannot be used to draw conclusions regarding causal relationships among stressors or ecosystem responses outside of the sampling location and time period.

Longer monitoring records, remote sensing, continuous sensor data, paleolimnological analysis, and modeling should be applied in future research to predict the ecosystem response to different climate and management scenarios.

VI. Conclusion

Freshwater systems are now being subjected to the pressures of climate variation and anthropogenic environmental change, leading to the necessity for long-term and comprehensive limnological investigations. This study attempted to fill this gap in knowledge through the investigation of spatial, seasonal, and long-term variation in physico-chemical, nutrient, biological, microbiological, and ecological parameters in freshwaters with varying degrees of anthropogenic influence. The results showed that there was a significant degradation in the state of the ecosystem with increasing anthropogenic activity. Dissolved oxygen dropped from 6.2–8.1 to 3.2–5.5 mg/L, whereas total nitrogen rose from 0.32–0.86 to 1.28–3.15 mg/L and total phosphorus from 0.02–0.08 to 0.13–0.39 mg/L. There was an increase in Chlorophyll-a from 3.5–10.8 to 18.6–46.2 µg/L, indicating that there is more eutrophication. There was a reduction in biological diversity from 3.82 to 1.76, and an increase in microbial contamination from 45 to 1,850 CFU/100 mL. The overall ecological condition deteriorated from 91 in reference to 42 in wastewater. The anthropogenic pressure-ecological condition relationship deteriorated from 91 to 34 under increased pressure. Generally, the study shows that the factors of climate variation and human activities affect the stability of the freshwater ecosystem. Some of the important findings of the study include the need for monitoring, integrated ecological indicators, pollution prevention, climate management, and conservation.

References

[1] Wang, J., Soininen, J., & Heino, J. (2021). Ecological indicators for aquatic biodiversity, ecosystem functions, human activities and climate change. *Ecological Indicators*, *132*, 108250. https://doi.org/10.1016/j.ecolind.2021.108250

[2] Döll, P., & Zhang, J. (2010). Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, *14*(5), 783-799. https://doi.org/10.5194/hess-14-783-2010

[3] Plisnier, P. D., Nshombo, M., Mgana, H., & Ntakimazi, G. (2018). Monitoring climate change and anthropogenic pressure at Lake Tanganyika. *Journal of Great Lakes Research*, *44*(6), 1194-1208. https://doi.org/10.1016/j.jglr.2018.05.019

[4] Köhler, J. (2010). Long-term ecological research in freshwater ecosystems. In *Long-Term Ecological Research: Between Theory and Application* (pp. 179-187). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-90-481-8782-9_13

[5] Angeler, D. G., Allen, C. R., Birgé, H. E., Drakare, S., McKie, B. G., & Johnson, R. K. (2014). Assessing and managing freshwater ecosystems vulnerable to environmental change. *Ambio*, *43*(Suppl 1), 113-125. https://doi.org/10.1007/s13280-014-0566-z

[6] Mukherjee, S., Rizvi, S. S., Biswas, G., Paswan, A. K., Vaiphei, S. P., Warsi, T., & Mitran, T. (2023). Aquatic eco-systems under influence of climate change and anthropogenic activities: potential threats and its mitigation strategies. *Hydrogeochemistry of aquatic ecosystems*, 307-331. https://doi.org/10.1002/9781119870562.ch14

[7] Hassan, B., Qadri, H., Ali, M. N., Khan, N. A., & Yatoo, A. M. (2019). Impact of climate change on freshwater ecosystem and its sustainable management. In *Fresh water pollution dynamics and remediation* (pp. 105-121). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-13-8277-2_7

[8] Wu, D., & Sun, Y. (2026). Spatial variability of ecological shifts in lakes in response to anthropogenic activities and climate change over the past two centuries. *Limnology and Oceanography*, *71*(1), e70316. https://doi.org/10.1002/lno.70316

[9] Sidibe, G., Sumana, S. L., Shuaibu, A., & Xu, L. (2026). Assessing synergistic impacts of climate change and anthropogenic stressors on freshwater ecosystems. *Biodiversity and Conservation*, *35*(2), 65. https://doi.org/10.1007/s10531-026-03272-5

[10] Rose, K. C., Bierwagen, B., Bridgham, S. D., Carlisle, D. M., Hawkins, C. P., Poff, N. L., ... & Williamson, C. E. (2023). Indicators of the effects of climate change on freshwater ecosystems. *Climatic Change*, *176*(3), 23. https://doi.org/10.1007/s10584-022-03457-1

[11] García-Rodríguez, F., Costa, A. P. T., Frantz, A. M., Silva, C. F. M. D., Martins, K. P., Moraes, A. L., ... & Agostini, V. O. (2022). The combined use of paleolimnological and long-term limnological information to identify natural and anthropogenic environmental changes. *Acta Limnologica Brasiliensia*, *34*, e28. https://doi.org/10.1590/S2179-975X3322

[12] Woodward, G., Perkins, D. M., & Brown, L. E. (2010). Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1549), 2093. https://doi.org/10.1098/rstb.2010.0055

[13] Döll, P., & Zhang, J. (2010). Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, *14*(5), 783-799. https://doi.org/10.5194/hess-14-783-2010