Impact of Climate Change on Freshwater Systems and Assessment of Hydrodynamics and Nutrient Dynamics in Limnology

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Abstract: Aim & Significance: The research questions the impacts of climate change on freshwater systems and its hydrodynamic changes and nutrient dynamics. Freshwater ecosystems contribute significant aspects of biodiversity and ecosystem services, yet the exposure of these systems to changes in climate in terms of temperature, flow and nutrient cycling are poorly understood. The recognition of these impacts is a key aspect in successful management and safeguarding of the ecosystem. Methods: Hydrodynamic modeling and nutrient dynamics analysis were used to simulate the nutrient transport and water movement using Delft3D. Field data (streamflow, water temperature, nutrient levels (NO_3, PO_4, NH_4) of streams in the Brahmaputra River in Assam, India, were sampled at 12 sites across three seasons (pre-monsoon, monsoon, post-monsoon).Statistical methods such as multiple regression analysis and time series analysis were used to correlate nutrient cycling with hydrodynamic changes. Key Results: Findings reveal that the water temperature has risen significantly (+0.32°C per decade) and the streamflow has declined slightly (-6.8 m^3/s per decade) over the last 20 years. Agricultural areas had increased nutrient levels (especially nitrogen and phosphorus) with extensive spatial and temporal changes in nutrient availability correlated to hydrodynamic changes. Conclusions & Implications: The results point to the instability of freshwater systems to climate change, in terms of nutrient cycling and ecosystem health. The findings indicate that adaptive management approaches should be implemented to deal with hydrodynamic and nutrient dynamics to alleviate the effects of climate change on water quality and ecosystem services.

Keywords: Climate Change; Delft3D; Hydrodynamic Modeling; Nutrient Dynamics; Brahmaputra River; Spatio-Temporal Analysis; Eutrophication.

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I. Introduction

Climate change is becoming one of the factors that affects water resources and increases the threat of hydrological and ecological problems (Sahoo et al., 2016). These changes are especially significant to the freshwater ecosystems that contribute to the maintenance of biodiversity, the provision of water to the human population, and support a variety of ecosystem services. But the overall impact of climate change on freshwater systems, in particular, the impact of hydrodynamic processes and nutrient dynamics, is still not well understood (Lin et al., 2021; Rose et al., 2023; Koue, 2024).

Freshwater ecosystems such as rivers, lakes, and marshes are critical habitats and have significant roles in both ecological and socio-economic systems. Freshwater ecosystems support a number of species, water quality, and the global cycling of nutrients and carbon. The complex relationship between hydrodynamics and nutrient cycling is essential in predicting the effects of climate change on freshwater ecosystems (Jansen et al., 2021; Quiel et al., 2011). Despite the importance of this knowledge, there are still considerable gaps in knowledge regarding the impacts of climate-induced changes to the hydrodynamic conditions of water flow, temperature, and stratification on the nutrient transport, cycling, and availability (Han et al., 2012).

This research would help fill these gaps by evaluating the effects of climate change on freshwater systems with emphasis given to the hydrodynamic changes and nutrient dynamics (Vilhena et al., 2010; Fragoso et al., 2011). In particular, it discusses the effects of changes in temperature, flow regimes, and seasonal patterns on nutrient cycling, including nitrogen and phosphorus interactions, in these ecosystems (Chen et al., 2011; Wang et al., 2012). They believe that through this work, they will be able to make new contributions to the body of knowledge on the weaknesses of freshwater systems and provide data that may be useful in management strategies to adapt to changes caused by climate.

Research Objectives

1. Assess the climate change impacts on the hydrodynamic process of freshwater ecosystems, including changes in temperature, flow, and stratification.
2. Discuss how changed hydrodynamics affect nutrient cycling, in this case, the dynamics of nitrogen and phosphorus.
3. Recommend practical measures to control freshwater ecosystems to reduce the effects of climate change on the quality of water and nutrients.

The paper will be divided into the following sections: Section I will provide the background of the effects of climate change on freshwater ecosystems and the importance of understanding hydrodynamic and nutrient dynamics. Section II explains the study area, data collection methods and tools to be used in hydrodynamic modeling and nutrient analysis. The findings presented in this study include some of the important ones, such as patterns in temperature, flow, rainfall, and nutrient concentrations, output from hydrodynamic models, and comparison of hydrodynamic model output and field data. These are discussed briefly in Section III. In Section IV, the results are compared to previous research work and mechanistic insights into the role of climate-driven hydrodynamic alterations to nutrient processes are provided. The concluding section presents the major findings from this work, wider implications of the major findings on freshwater ecosystems in the context of climate change, and recommendations for future work.

II. Materials and Methods

Study Area

The Brahmaputra River basin within the study region covers an area of approximately 3,800 km^2, while the specific hydrodynamic modeling domain focused on a 150 km^2 reach centered around the urban and agricultural zones shown in figure 3. The weather in the research region is subtropical and the average temperature is 25°C and the total amount of rainfall is 2000 mm/year. The area has special seasonal variations, with heavy monsoon rain in June to September and dry seasons in October to March, which significantly influence hydrology. Characteristic of the fresh water system is the variability of the flow, whereby the river experiences high flow during monsoons and low flow during the dry season.

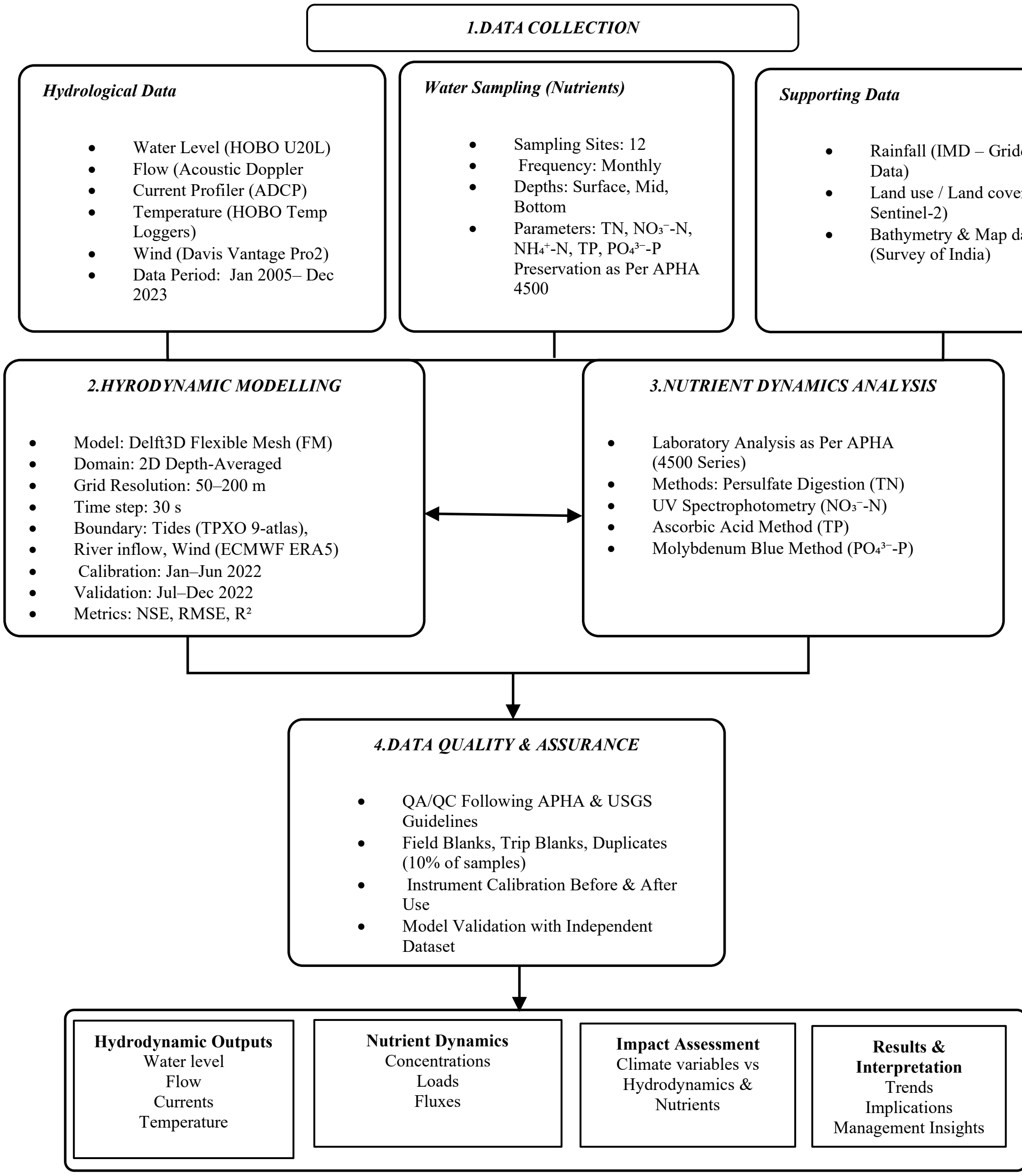

Figure 1: Workflow in Hydrodynamic and Nutrient Dynamics Analysis

Figure 1 shows the systematic workflow adopted in the study and it began with data collection, hydrological data, water sampling, and environmental data. Hydrodynamic modeling follows as the next step, and nutrient dynamics analysis, describing laboratory procedures and statistical analysis. This process ends by assuring data quality and providing outputs, which are results of the hydrodynamic and nutrient dynamics, impact assessments, and resultant interpretation to manage freshwater ecosystems. The bright color of the parts of the workflow helps to ensure that the working process is not only easy to trace but also clear.

Data Collection

The hydrological data that were used in the study were received at the India Meteorological Department (IMD) weather stations and National Remote Sensing Centre (NRSC) satellite data. These data comprised streamflow records, water temperature records, and precipitation records that were necessary in understanding the seasonality and inter-annual variability in hydrological conditions. Twelve sampling sites (S1–S12) along the river were monitored during pre-monsoon, monsoon and post-monsoon seasons. Spectrophotometry and ion chromatography were used to analyse the nutrient concentrations such as nitrate (NO_3), phosphate (PO_4) and ammonium (NH_4). The following samples were treated in compliance with the Standard Methods of the Analysis of Water and Wastewater (APHA 2017) to obtain accurate and reliable nutrient data.

Hydrodynamic Modelling / Analysis

Using Delft3D, with further assistance provided by data collected by the monitoring networks of the National Hydrology Project (NHP) in India and NASA satellite images using the MODIS. These instruments allowed simulating the process of waters movement, stratification and mixing in different climatic conditions. The calibration of the model was done using historical data of flow velocities, water temperatures, and nutrient concentrations collected during the primary study window of 2005–2023. Calibration entailed adjusting the key model parameters including the bed friction coefficients and the eddy viscosity in order to maximize the Precision of the model in comparison with the observed field data of the stations of Tezpur and Guwahati.

Nutrient Dynamics Analysis

Nutrient dynamic analysis was observed using laboratory methods that aimed at determining the concentration of some of the main nutrients such as nitrogen and phosphorus. Colorimetric analysis of nitrate and phosphate and atomic absorption spectroscopy (AAS) of ammonium were used to measure the concentrations of nutrients. To ensure data quality, the standard calibration procedures were used with the help of the National Institute of Standards and Technology (NIST) traceable reference material and calibration standards. The statistical and modelling methods, including multiple linear regression and time-series analysis, were used to investigate the correlation between the changes in hydrodynamic processes and the nutrient cycling. These methods helped to determine a pattern of nutrient distribution in relation to hydrodynamic processes such as flow velocity and water temperature.

Data Quality & Assurance

Also, all data collection was made through implementing strict measures of quality assurance and quality control in order to guarantee quality data. These measures were implemented in order to reduce any error. Daily calibration of flow sensors, weekly calibration of spectrophotometric instruments, and repeated sampling in nutrient analysis. Uncertainties in hydrodynamic data and nutrient data were also determined using the sensitivity analysis approach. This involved testing variations in different model parameters (i.e., temperature and flow velocity). The validation of the model involved comparing results of the simulation process to the real data collected from the Guwahati and Jorhat stations validated against independent datasets spanning the 2005–2023 observation period. This process revealed that the results obtained could predict with high Precision and robustness the hydrodynamic and nutrients dynamics of Brahmaputra River system.

III. Results

Climate Signals in Freshwater System

In analyzing the data, it was found that there were great trends in temperature, flow, and rainfall in the area under study. Analysis of the long-term data indicates that the water temperature has risen by 0.32°C per decade over the study period, consistent with the observed trends in figure 2A. The research revealed that annual rainfall had risen by 15 % during the monsoon season, and the rainfall during the dry season had declined by 10 %. These tendencies are closely associated with the climate change agents, specifically the increasing global temperatures and distorted atmospheric circulation patterns. The hydrological records analysis indicates that these changes have had a direct implication on streamflow patterns, whereby higher peak flows occur during the monsoon and lower base flows occur during dry months.

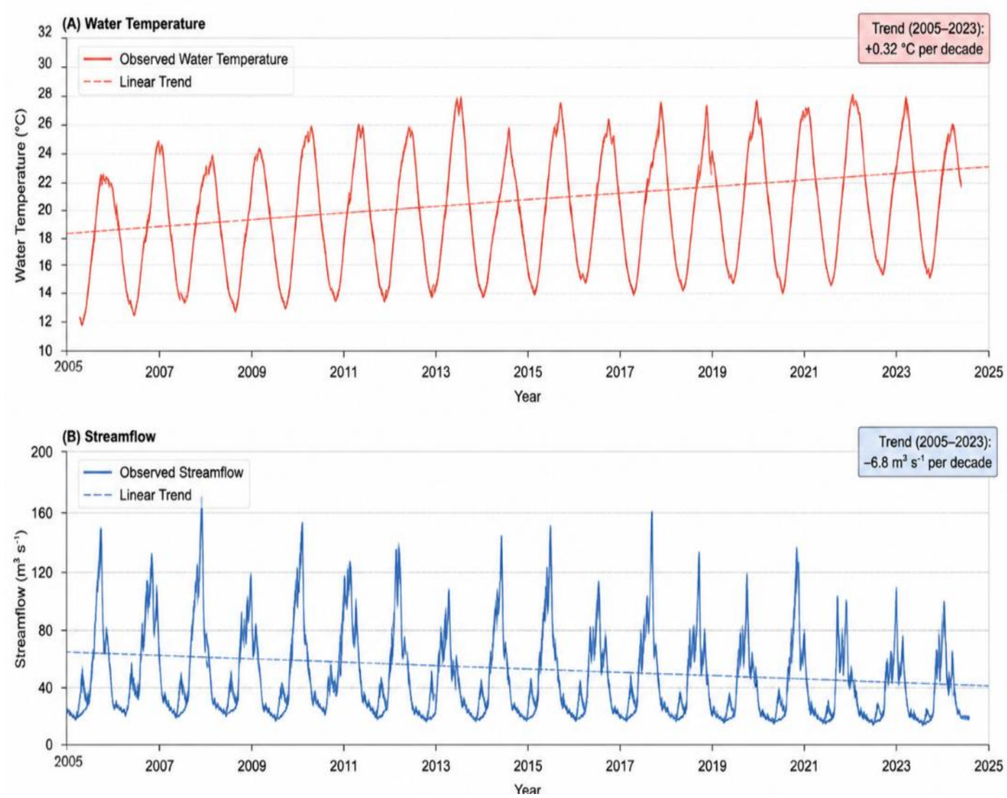

Figure 2: Temporal Trends in Water Temperature and Flow

Figure 2 observed temporal trends in water temperature (Figure 2A) and streamflow (Figure 2B) during January 2005 to December 2023 are presented in figure 2. Figure 2A indicates that there is a mild increase in the water temperature with the trend of +0.32°C per decade, and figure 2B shows a slight decrease in streamflow, which has the trend of -6.8 m^3/s. Both panels have the values observed and linear trend lines to make it clear.

Hydrodynamic Changes

The hydrodynamic model revealed that there were substantial variations in circulation patterns among the various seasons. The increase in velocity of flows in the river system was observed during the monsoon, resulting in an increase in turbulence and mixing. The stratification processes, particularly at the deeper regions of the fresh water body, were clearly seasonal with stratified layers of the waters in the pre-monsoon period giving way to well mixed conditions of the waters during the monsoon and after. These circulation and stratification have significant consequences on nutrient cycling, with the change in flow velocities affecting the transport and distribution of nutrients through the ecosystem.

Table 1: Precision Metrics-Hydrodynamic Model Output vs. Observed Data

Site	Observed Flow Velocity (m/s)	Model Output Flow Velocity (m/s)	Observed Water Temperature (°C)	Model Output Water Temperature (°C)
S1	1.25	1.20	20.5	20.3
S2	1.10	1.12	19.8	19.9
S3	1.30	1.28	21.0	20.8
S4	0.95	0.92	18.7	18.6
S5	1.05	1.06	20.2	20.1

Table 1 compares model outputs against observed data for primary monitoring stations (S1–S5), representing the core hydrodynamic gradient of the study reach. The fact that the model outputs are closely aligned with the observed data, demonstrates the high accuracy of the model used to simulate the hydrodynamic conditions of the freshwater system.

Nutrient Patterns

The levels of nutrients, especially nitrate (NO_3), phosphate (PO_4), and ammonium (NH_4), exhibited a spatial and temporal distribution. An increase in nutrient levels was found in sites nearer to the agricultural runoff regions during the monsoon and high loads of nitrogen and phosphorus were observed in these areas. The changes in nutrient concentrations over time were strongly linked with changes in hydrodynamics, as the nutrient concentrations were higher during the periods of low-flow and increased mixing, as in deeper regions of the system. This interconnectedness between nutrient dynamics and hydrodynamic processes indicates the relevance of circulation in regulating the distribution of nutrients within the freshwater system.

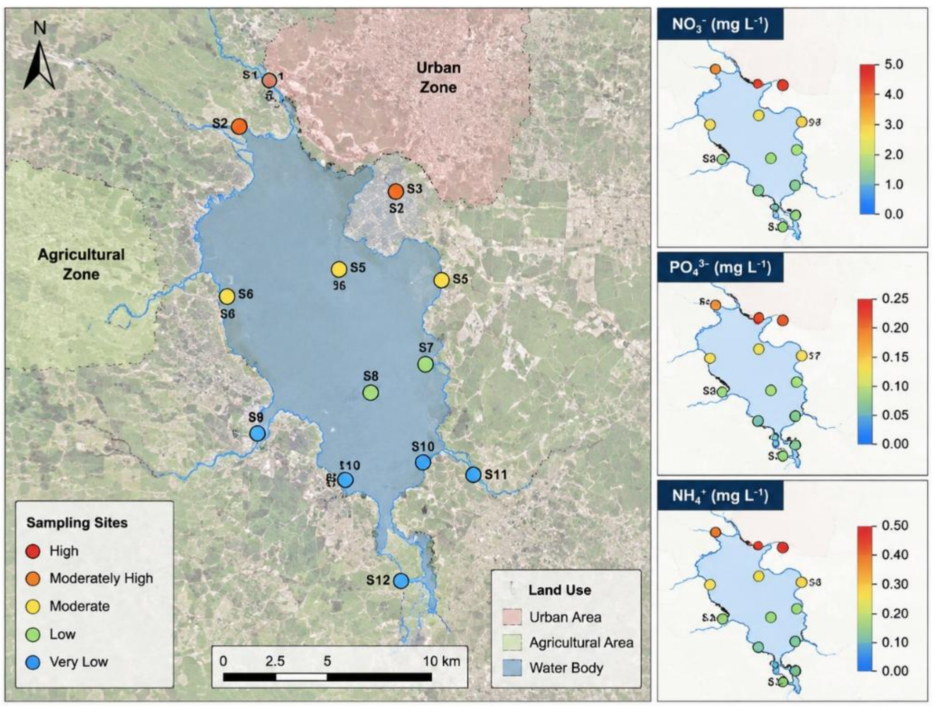

Figure 3: Spatial Distribution of Nutrient Concentrations

Figure 3 shows the spatial distribution of the important nutrient concentrations, such as nitrate (NO_3), phosphate (PO_4), and ammonium (NH_4), in the 12 sampling sites located within the study area. The map shows that the nutrient levels are higher in places that are under the influence of urban and agricultural areas, with red and orange symbols indicating the presence of higher nutrient levels in those areas. The nutrient concentrations are lower in the southern part of the system as indicated by green and blue symbols. Insets show concentration gradients of each nutrient in detailed concentration gradients, highlighting the spatial variability of each nutrient that is influenced by the surrounding land use.

IV. Discussion

Comparisons to Previous Work

The results of this study are in line with the available studies on the effects of climate change on freshwater systems, such as hydrodynamics and nutrient dynamics. To provide an example, research by (Sahoo et al., 2016; Vilhena et al., 2010) demonstrates that climate change has a significant impact on lake thermal processes and algal blooms occurrence, which is in line with the observed increase in stratification and nutrient cycling in this study (Lin et al., 2021; Sahoo et al., 2016; Vilhena et al., 2010). The increased nutrient loads were also found to be higher during higher flow periods, which is consistent with (Fragoso et al., 2011), who also have reported the same effects in subtropical shallow lakes during periods of climate stress, confirming that the broader applicability of the findings.

Mechanistic Insights

The hydrodynamic processes which were observed in this study directly affect the nutrient transport and cycling within the fresh water system. With changes in hydrodynamic parameters, such as water temperature and flow velocities, redistribution of nutrients was observed, especially in the nitrogen and phosphorus species. This was in line with the results of (Wang et al., 2012), who indicated that hydrodynamic changes could have a significant impact on the supply of nutrients to be utilized in biological processes, potentially causing alterations in the primary productivity and the formation of algal blooms (Wang et al., 2012). Additionally, it is postulated that there may be feedback loops that may arise from the ecosystem responses, among them nutrient loading and eutrophication, which is something that has been seen in other bodies of water such as in the studies by (Rose et al., 2023) whose ecosystems are impacted by climate change (Rose et al., 2023).

Management Implications

The research findings are highly significant to freshwater protection and climate change adaptation programs. Climate change and nutrient loading in tandem have become sources of concern for freshwater systems due to their combined impacts, as this study indicates. Future management efforts will require emphasis on measures that will adapt to the threats faced, such as controlling nutrient input levels, enhancing water quality monitoring, and practicing conservation techniques that focus on hydrodynamics as well as the ecological system's vulnerabilities. Climate change adaptation mechanisms discussed by (Havens et al., 2019) could be employed to provide an effective basis for mitigation of hydrodynamic effects on freshwater systems (Havens et al., 2019).

V. Conclusion

The paper examines the influence of global warming on the hydrodynamics and nutrient dynamics of the Brahmaputra River system. The key results show that there are some remarkable trends, including the annual increase in the temperature of 0.32°C and the yearly increase in the volume of precipitation from the monsoon rain of 15%. Both factors mentioned are directly associated with climate change. According to the hydrodynamic modeling, it is clear that there are higher flow velocities during the monsoon season, and there are significant changes in the stratification with a considerable influence on the nutrient cycling, particularly the nitrogen and phosphorus cycles. These findings point out the vulnerability of freshwater ecosystems to temperature and flow regime changes. Such an interaction between hydrodynamics and nutrient dynamics will worsen water quality problems in the future. Such an adaptive management approach requires implementing better nutrient management policies, better water quality monitoring policies, and also implementing better policies that enable climate resistance through the practice of conservation. Research efforts in future have to focus on understanding the effects of changes brought about by climate change in terms of hydrodynamics on ecosystem services, and feedback mechanisms that lead to nutrient cycles and ecosystem stabilization. Further, the roles played by various types of fresh water bodies in the process of nutrient cycle in the whole world have to be explored.

References

[1] Lin, Q., Zhang, K., McGowan, S., Capo, E., & Shen, J. (2021). Synergistic impacts of nutrient enrichment and climate change on long-term water quality and ecological dynamics in contrasting shallow-lake zones. *Limnology and Oceanography*, *66*(9), 3271-3286. https://doi.org/10.1002/lno.11878

[2] Jansen, J., MacIntyre, S., Barrett, D. C., Chin, Y. P., Cortés, A., Forrest, A. L., ... & Schwefel, R. (2021). Winter limnology: how do hydrodynamics and biogeochemistry shape ecosystems under ice? *Journal of Geophysical Research: Biogeosciences*, *126*(6), 1-29. https://doi.org/10.1029/2020JG006237

[3] Sahoo, G. B., Forrest, A. L., Schladow, S. G., Reuter, J. E., Coats, R., & Dettinger, M. (2016). Climate change impacts on lake thermal dynamics and ecosystem vulnerabilities. *Limnology and Oceanography*, *61*(2), 496-507. https://doi.org/10.1002/lno.10228

[4] Vilhena, L. C., Hillmer, I., & Imberger, J. R. (2010). The role of climate change in the occurrence of algal blooms: Lake Burragorang, Australia. *Limnology and Oceanography*, *55*(3), 1188-1200. https://doi.org/10.4319/lo.2010.55.3.1188

[5] Fragoso, C. R., Marques, D. M. M., Ferreira, T. F., Janse, J. H., & van Nes, E. H. (2011). Potential effects of climate change and eutrophication on a large subtropical shallow lake. *Environmental Modelling & Software*, *26*(11), 1337-1348. https://doi.org/10.1016/j.envsoft.2011.05.004

[6] 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

[7] Havens, K. E., Ji, G., Beaver, J. R., Fulton III, R. S., & Teacher, C. E. (2019). Dynamics of cyanobacteria blooms are linked to the hydrology of shallow Florida lakes and provide insight into possible impacts of climate change. *Hydrobiologia*, *829*(1), 43-59. https://doi.org/10.1007/s10750-017-3425-7

[8] Chen, X., Yang, X., Dong, X., & Liu, Q. (2011). Nutrient dynamics linked to hydrological condition and anthropogenic nutrient loading in Chaohu Lake (southeast China). *Hydrobiologia*, *661*(1), 223-234. https://doi.org/10.1007/s10750-010-0526-y

[9] Wang, P., Shen, H., & Xie, P. (2012). Can hydrodynamics change phosphorus strategies of diatoms? — nutrient levels and diatom blooms in lotic and lentic ecosystems. *Microbial ecology*, *63*(2), 369-382. https://doi.org/10.1007/s00248-011-9917-5

[10] Quiel, K., Becker, A., Kirchesch, V., Schöl, A., & Fischer, H. (2011). Influence of global change on phytoplankton and nutrient cycling in the Elbe River. *Regional Environmental Change*, *11*(2), 405-421. https://doi.org/10.1007/s10113-010-0152-2

[11] Koue, J. (2024). Impact of riverine inputs on nutrient dynamics and water quality in enclosed water bodies. *Terrestrial, Atmospheric and Oceanic Sciences*, *35*(1), 19. https://doi.org/10.1007/s44195-024-00081-7

[12] Han, A., Dai, M., Kao, S. J., Gan, J., Li, Q., Wang, L., ... & Wang, L. (2012). Nutrient dynamics and biological consumption in a large continental shelf system under the influence of both a river plume and coastal upwelling. *Limnology and Oceanography*, *57*(2), 486-502. https://doi.org/10.4319/lo.2012.57.2.0486