doi.org/10.62683/SINARG2025.176

Research paper

THERMAL REGIME OF BOVAN LAKE

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Abstract

Bovan Lake is a significant water resource in southeast Serbia, used mainly for water supply, flood protection and recreation. The purpose of this study is to better understand seasonal variations in water temperature by examining the thermal characteristics of the lake at various depths within the intake tower. Water and air temperatures were recorded at five different heights within the intake tower, with hourly measurements taken from December 2020 to November 2021. The results revealed that there were notable seasonal oscillations in the temperature of the water, with upper layers undergoing more fluctuations than deeper levels. A strong correlation among air temperature and surface water layers signifies a considerable external climatic impact, but deeper layers show enhanced thermal stability. This analysis contributes to a better understanding of the thermal dynamics of Bovan Lake and can serve as a basis for more efficient water resource management.

Keywords: *Thermal Stratification, Monomictic Reservoir, Seasonal Variation, Vertical Mixing*

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1. INTRODUCTION

Thermal stratification of reservoirs and lakes is an essential process for both hydrology and ecology. Lake and waterway ecosystems, including their physical and chemical components, depend on temperature influences. Temperature influences how easily substances dissolve in water, affects biological activity, and causes the water to form thermal layers. This layering leads to uneven distribution of oxygen and nutrients and can also change the timing of chemical reactions in the water [1, 2]. Temperature regimes of lakes—where temperature is one of the primary determining parameters—are strongly influenced by climatic setting. Lakes located in temperate continental regions, particularly those with a monomictic regime, exhibit strong seasonal variation in thermal structure, governed by solar radiation, air temperature, and wind-driven mixing [3, 4].

Bovan Lake, geographically located in eastern Serbia, is an artificial reservoir. Monomictic lakes have a predictable stratification pattern in warm months with development of layering (e.g., thermocline) during summer stratification, and a full turnover in winter or early spring [3]. In this context, Bovan Lake is significant due to its role as a water supply source, but also as a multipurpose reservoir. Understanding the lake's thermal behavior is essential for hydrological and ecological planning. However, limited research has focused specifically on Bovan Lake with respect to vertical thermal dynamics and their temporal variation [5].

Climate change is increasingly altering the thermal dynamics of lakes and reservoirs across the globe. Changes in air temperature and the surface meteorological conditions in both space and time are impacting the timing, duration, and strength of thermal stratification in inland water bodies. Warm temperate monomictic lakes are very temperature-sensitive and show early warming and spring season thermal stratification onset dates and later stratification breakdown dates which reduces seasonal mixing. More recently, this phenomenon has been highlighted as a global pattern with many lakes experiencing increased thermal stratification duration, extended reduced frequency of full turnover, and increased atmospheric forced impacts to surface waters [6, 7]. These changes emphasize the importance of long-term and high-resolution temperature datasets, especially for reservoirs, such as Bovan Lake, with multiple ecological and hydrological roles.

This research paper adopts a systematic approach to analyze and interpret the seasonal dynamics of hourly water temperature in Bovan Lake, based on measurements taken from the intake tower between December 2020 and November 2021. The subsequent sections present a seasonal analysis of temperature variation and vertical stratification, as well as the influence of atmospheric conditions—particularly air temperature—on thermal behavior at depth. By identifying stratification phases and vertical gradients, this study contributes to a deeper understanding of the lake's thermal response to climatic forcing, providing support for improved reservoir management decisions. In addition, the study integrates recent insights on climate-induced thermal alterations observed in temperate-zone lakes, aiming to assess the potential vulnerability of Bovan Lake to ongoing climate change trends [6, 7].

2. STUDY AREA AND INPUT DATA

Bovan Lake is an artificial reservoir located in eastern Serbia, formed by damming the Moravica River between 1978 and 1984 to meet multipurpose demands, including regional water supply, flood control, and recreation. The reservoir lies within the Južna Morava River basin and holds a strategic role in local hydrological planning [5]. The dam structure is of the gravity type, and the resulting reservoir covers a surface area of approximately 4.10 km², with a total length of about 8 km and a maximum width of around 500 m. The deepest point, situated near the dam wall, reaches a depth of approximately 52 m [6].

The lake's morphology features a narrow, elongated profile with steep shorelines and a pronounced longitudinal depth gradient, which facilitates thermal stratification during warmer months. The surrounding catchment is predominantly rural, with limited urban development, which minimizes direct anthropogenic thermal input and allows for clearer detection of natural temperature dynamics [5, 6]. Given these physical and geographical features, Bovan Lake can serve as a representative site for studying thermal behavior in monomictic reservoirs exposed to seasonal climatic forcing.

The intake tower, positioned adjacent to the dam structure, provides a stable environment for systematic temperature monitoring. This vertical structure is equipped with submerged temperature sensors installed at four discrete water depth levels: T1 (238.5 m a.s.l.), T2 (243.5 m), T3 (248.5 m), and T4 (253.5 m), while an additional air temperature sensor (T5) is placed above the water surface. These sensors enabled continuous, high-frequency (hourly) temperature measurements over a full hydrological year, from December 2020 to November 2021, capturing both vertical and temporal dynamics of thermal stratification.

The collected dataset contains 6758 temperature readings per depth point, providing a robust basis for analyzing short-term fluctuations, seasonal trends, and depth-dependent thermal behavior. This high-resolution time series allows for a detailed examination of the lake's vertical temperature structure, and serves as a foundation for further investigation into mixing processes and surface–depth thermal interactions. The data also offer valuable insight for modeling responses to external drivers, particularly in the context of climate variability and reservoir management.

3. METHODS AND PROCEDURES

A year-long seasonal temperature dataset and time series was recorded at Bovan Lake (December 2020 - November 2021) using loggers placed at four depths of water (T1 = 238.5 m, T2 = 243.5 m, T3 = 248.5 m, T4 = 253.5 m) and an air logger located just above the water surface (T5). Each logger recorded hourly values, providing 6758 measurements per logger. Temperature was continuously recorded, allowing for a detailed view of how water temperature changed over time and at different depths throughout the seasons.

The original temperature data were, then, processed in part by descriptive statistics to summarize temperature behavior at each depth (mean, min, max, standard deviation, and interquartile range (IQR)). The original temperature data were, then, processed in part by descriptive statistics to summarize temperature behavior at each depth (mean, min, max, standard deviation, and interquartile range (IQR)).

Boxplots illustrated variability and central tendencies (boxplot indicators are for outliers, variability measures, upper and lower quartiles, and not min or max ranges) of each depth, with variability different across the depths, but more variability observed in the upper depths (T3 and T4) and less variability in the thermally stable lower layers (T1 and T2). Heatmaps provided a clear visual representation of stratification, mixing events, and how thermal layers changed over time.

Pearson correlation coefficients were calculated between air temperature and water temperatures at different depths to assess how temperature changes are related through the water column. The analysis showed that surface layers responded more strongly to atmospheric conditions, while deeper layers exhibited weaker correlations due to greater thermal inertia. Additionally, monthly average temperatures at each depth were used to track seasonal changes and identify the timing and strength of stratification.

All computations were performed using Python, employing libraries such as NumPy, pandas, seaborn, and matplotlib for statistical analysis and data visualization. Stratification patterns were assessed based on visual inspection of vertical temperature profiles and their temporal changes, rather than using a strict numerical threshold (e.g., >1 °C gradient). Although no formal criteria were enforced, transitions between stratified and mixed conditions were interpreted qualitatively by examining the layering and breakdown of temperature across depths. This approach allowed for capturing seasonal thermal dynamics in line with physical expectations and comparative trends observed in similar reservoir studies.

4. RESULTS AND DISCUSSION

Table 1. Descriptive statistics

	T1 238.5 m a.s.l.	T2 243.5 m a.s.l.	T3 248.5 m a.s.l.	T4 253.5 m a.s.l.	T5 air
count	6758	6758	6758	6758	6758
mean	9.04	11.51	12.62	12.058	14.33
std	4.11	5.91	7.40	8.13	9.32
min	4.07	3.32	3.66	-0.33	-7.14
25%	4.89	5.53	5.12	4.51	6.64
50%	8.70	11.43	11.76	10.16	13.30
75%	12.64	17.02	19.22	19.22	21.23
max	16.54	21.71	25.63	27.04	42.14

Descriptive statistics helped outline temperature patterns at all measured depths and confirmed consistent seasonal variation in air temperature. A total of 6758 hourly measurements was obtained for each depth (T1–T5), enabling a reliable statistical evaluation of the results. The mean temperature gradient exhibited the vertical angling, increasing from 9.04 °C at T1 (deepest layer) to 12.06 °C at T4 (surface layer) and the average air temperature at 14.33 °C (T5). The results indicate the influence of solar heating and weather conditions on the upper water layers. The standard deviation (std) values followed that same trajectory, ranging from 4.11 °C at T1 and 8.13 °C at T4 with the maximum variability at the surface. The air temperature had the largest std (9.32 °C) as well, indicative of extreme daily and seasonal variability associated with direct exposure to climate change forces. (Table 1.)

Extreme values (min-max) also indicated stratification and atmospheric influences. At T1, temperature range was between 4.07 °C and 16.54 °C, whereas T4 (shallowest) fluctuated from −0.33 °C to 27.04 °C, and from −7.14 °C to 42.14 °C for air. The inter-quartile range (IQR), derived by taking the difference between the 75th and 25th percentiles, describes the central spread of the values and closest degree of variability near surface: T4 (IQR ≈ 14.71 °C) and T1 (IQR ≈ 7.76 °C). These results corroborate that surface waters can be highly sensitive and respond more readily to external atmosphere forcing, with deeper layers being more thermally stable and to providing buffering capabilities, especially when warming or potentially stratification occurs, during colder periods. (Table 1.)

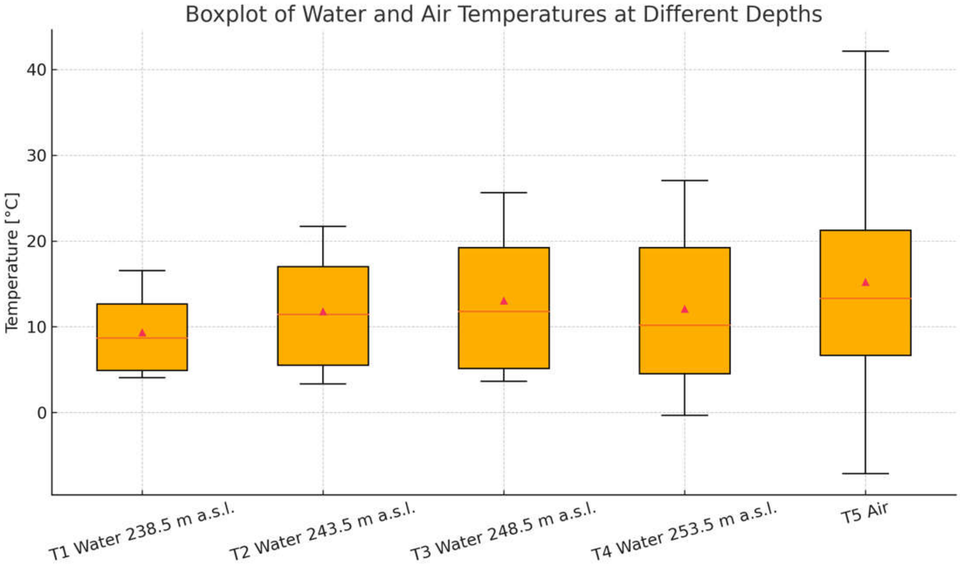

Figure 1. Boxplot of Water and Air Temperatures

The boxplot in figure 1 illustrates the distribution of temperatures in water and air for all measurements levels (T1–T5) through the minimum, 25th percentile (Q1), median, 75th percentile (Q3), and maximum values. The boxplot makes it clear that the upper layers (T3 and T4) have a wider interquartile range (IQR) of values indicating greater seasonal and instantaneous variability due to their direct relationship with the atmosphere. The deeper layer (T1) has a narrow interquartile range (IQR) and a small difference between minimum and maximum values, indicating strong thermal stability. Although the air temperature (T5) shows the widest overall temperature range—and thus the highest variability—the boxplot illustrates its role as a key external factor influencing the heating of surface waters. Overall, the boxplot shows that Bovan Lake has clear temperature differences between layers and noticeable seasonal changes, with deeper layers staying more stable and less affected by quick temperature shifts caused by weather conditions at the surface.

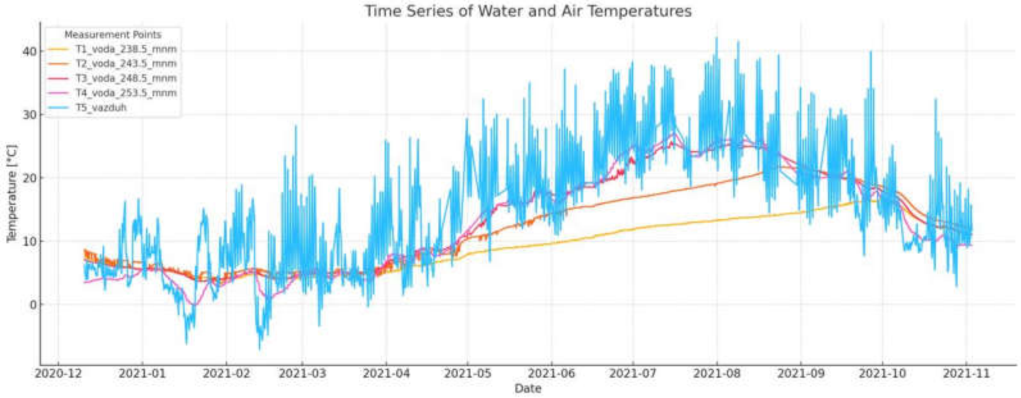

Figure 2. Time Series of Water and Air Temperatures

Figure 2. presents the time series representing hourly temperature data for the water at four depths (T1–T4) and air temperature (T5) collected in Bovan Lake from December 2020 to November 2021. This figure illustrates the seasonal trend of temperature with water temperature increasing gradually during the spring to peak summer months, then declining during autumn.

Air temperature (T5) fluctuated considerably in short spikes, demonstrating its high sensitivity to daily atmospheric conditions at all depths. Water temperature at depth smoothed out these spikes and took time to respond to air temperatures. The upper layers (T3 and T4) were more synchronic with air temperature and had more reciprocal influence from the atmosphere such as sun and wind; In contrast, the bottom layers (T1 and T2) showed slower temperature changes, indicating greater thermal stability.

This time progression also serves as temporal evidence for the onset and breakdown of thermal stratification. The divergence in surface and bottom temperature during the warming period (May - September) shows that thermal stability developed into stable stratification and the subsequent convergence of temperatures in winter or early spring (December - March) illustrates that stratification had ceased and mixing was taking place, which is the typical conditions for monomictic reservoirs. [1]

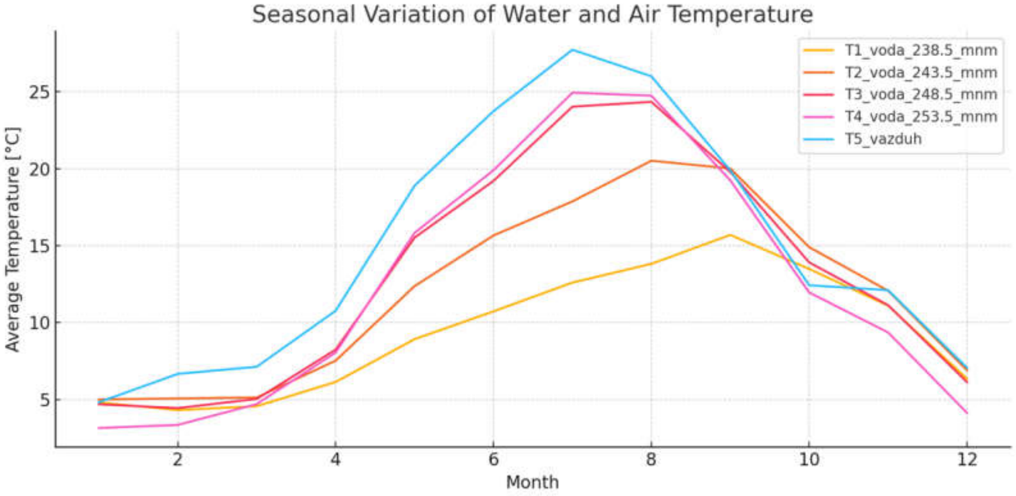

Figure 3. Seasonal Variation of Water and Air Temperature

Figure 3. shows the monthly average temperatures for water and air, showing clear seasonality. Temperatures rise steadily from March to July, reaching peak values in mid-summer. The surface water (T4) and air (T5) exhibit the highest average temperatures, with air temperature peaking at nearly 28°C and surface water around 25°C in July. Conversely, the lowest values are observed in January and February. This pattern clearly illustrates the influence of atmospheric conditions on the lake's thermal regime and confirms the existence of a stratified state during warmer periods.

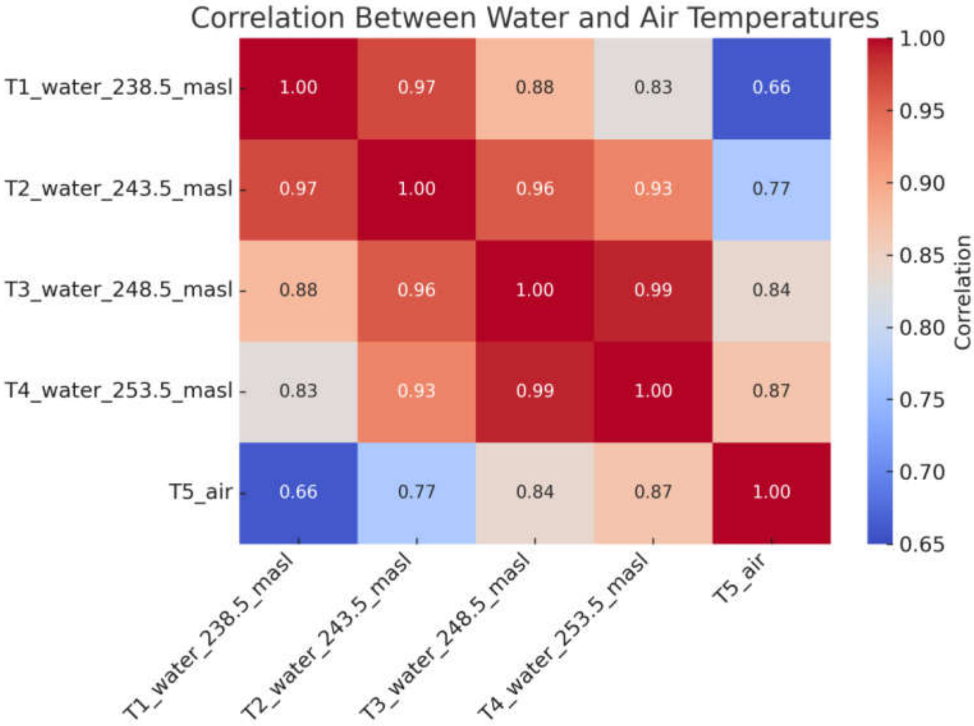

Figure 4. Correlation between water and air temperatures

The correlation matrix (Figure 4.) illustrates the Pearson correlation coefficients between air temperature (T5) and even versus water temperatures from three various deep positions below the body of water. As depth increases, the strength of the correlation decreases and vertically structured relationship is displayed, which indicates stratification in the water. The strongest pair-wise correlations were exhibited in shallow depth, T3 and T4 (r = 0.99). This indicates the water layers T3 and T4 behaved similarly thermally in the upper part of the lake when stratification was evident. The pair-wise correlation of air temperature (T5) to the bottom layer of water temperature (T1) suggests a weak correlation (r = 0.66).

This indicates similar short term thermal influence of atmosphere on the bottom layers of the body of water are insulated. Thermal response to atmospheric conditions has an inverse relationship with depth, since the surface water layers exhibit air-temperature heat exchange more dynamically throughout the year, while deeper water layers are thermally insulated.

The analysis confirms that Bovan Lake exhibits seasonally driven thermal stratification. Strong correlations between neighboring depths reflect stable vertical coherence in temperature profiles throughout the stratified period.

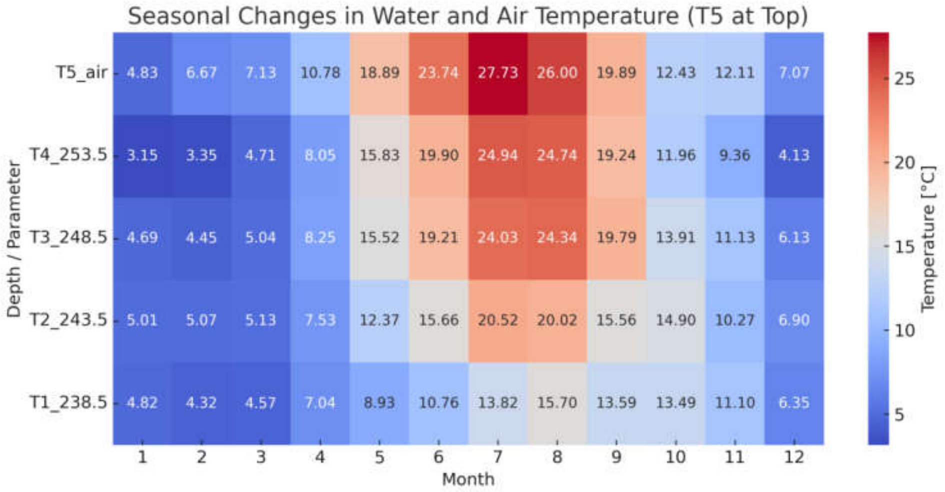

Figure 5. Heatmap of Seasonal Changes in Water and Air Temperature

Figure 5. shows the seasonal variation of mean monthly temperatures for air (T5) and water at four depths (T1-T4) in Bovan Lake for the year 2021. The patterns of temperature show an increase from January (mo. 1) until the peak in July and August (mo. 7-8) and then a decrease towards December. The air temperature (T5) peaked at a value of 27.73 °C in July while surface waters (T4) peaked just below, at 24.94 °C. The T1 and T2 had significantly lower temperatures and slower responses peaking from 18-20 °C.

The data reflects the observation of a stratified non-mixed regime throughout the summer months, meaning warmer and lighter water occupies the upper layers of the lake while cooler denser water remains near the bottom part of the reservoir. The smallest temperature amplitude exists at T1, the lowest depth measured, with mean monthly temperature values ranging from 4.82 °C in January to 17.82 °C in August. The highest amplitude is evident in the air temperature which indicates a seasonal forcing that is progressively decreased as depth increases.

In late fall, thermal regime shows signs of broken stratification as mean monthly averages begin to converge across all depths indicating the onset of vertical mixing. This pattern is typical for monomictic lakes that experience stratification during warmer seasons and fully mix during colder seasons. The clear layering of temperatures during summer, and convergence of monthly mean temperatures during winter is a strong visual representation to classify this reservoir, and show the reservoirs sensitivity to seasonal atmospheric variations.

The changes in temperature seen in Bovan Lake are very much in line with global patterns of lake warming and shifting mixing patterns. For example, increased stratification in the upper layers (T3 and T4) led to larger thermal gradients between the upper and bottom layers (T1 and T2) for a longer period of time during spring, summer, and early fall. In all cases, the continual stratification was similar to the patterns observed in temperate lakes where air temperatures increased and changes in solar radiation contributed to stronger and longer thermal stratification [7]. Additionally, the stable bottom layer (T1) temperatures during colder periods suggest reduced vertical mixing and decrease in total number of complete overturn events, similar to what occurs in warming conditions for monomictic reservoirs [8]. It is also noteworthy that the reasonable correlations between the air temperatures (T5) and the water temperature in the upper water layers has suggest, atmosphere forcing is Likely the largest driver of the vertical thermal structure gradient, as would be expected. Similarly, it is likely that Bovan Lake is exhibiting signs of early warming driven climate changes, which supports the need to continue monitoring functions of adaptive management.

4. CONCLUSION

This study provides a detailed assessment of the thermal regime of Bovan Lake using one complete year of hourly temperature data collected at four different depths, as well as atmospheric temperatures. The results indicated a clear seasonal stratification pattern with thermally stable layers developed during the summer and vertical mixing suggested during the colder months. These results suggest an overall monomictic thermal regime; stratification developed during the warmer seasons and the lake completely mixed at some point during the year. In monomictic systems, the final peak mixing period occurs typically during winter or early spring. However, multi-year observations may be needed to clarify and confirm truly monomictic status.

The surface water layers (T3 and T4) had more variability, a stronger correlation, and a stronger response to the atmospheric temperature (T5). The deeper layers (T1 and T2) resisted more variability, suggesting they are thermally insulated from short-term variability at the surface. Visual and statistical summaries (e.g., boxplots, heatmaps, line plots, and correlation matrices) provided evidence of a strong vertical temperature gradient and dynamic stratification and mixing over the yearly time scale. These thermal assessments provided a clearer picture of the thermal structure of the lake, its sensitivity to climatic and environmental drivers.

From a wider climate perspective, these trends in Bovan Lake are consistent with recent Global changes indicating that warming air temperatures are causing longer and more intense thermal stratification in lakes. A lesser degree of mixing in the cooler months and a stronger atmospheric influence at the surface suggest Bovan Lake may already be changing its thermal regime due to climate influences. These results demonstrate the necessity of continuing high-frequency monitoring and that future reservoir management plans need to more explicitly consider hydrological and hydroclimatic changes.

The findings may serve to facilitate local water resource management decisions, assist reservoir operations, or provide additional information to conduct environmental studies. Ongoing monitoring and expanded modeling and validation will allow for better characterization of long-term and extreme thermal behavior and to predict lake responses under a changing hydroclimatic environment.

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