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Lake pulses driven by glacier melting and climate variability

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The Tibetan Plateau is home to numerous glaciers that are important for freshwater supply and climate regulation. These glaciers, which are highly sensitive to climatic variations, serve as vital indicators of climate change. Understanding glacier-fed hydrological systems is essential for predicting water availability and formulating climate adaptation strategies. This study investigated the dynamic fluctuations in the water level of the Blue Moon Lake Valley (BMLV), supplied by meltwater from Baishui River Glacier No. 1 on Yulong Snow Mountain. We focused on the lake pulse phenomenon—subtle yet significant water level fluctuations that have often been overlooked in prior research. By employing fast Fourier transform (FFT), multivariate regression (MVR), and random forest (RF) models, we examined the interactions among glacier melt dynamics, climatic variables, and hydrological responses. Our analysis indicates that the rate of change (ROC) in the water level fluctuates between − 0.006 and 0.01 m/min, with a median ROC of − 7.24E−06 m/min, highlighting the significant variability influenced by glacier melt and precipitation. The maximum cumulative sum (CS) value of 0.09 m suggests a net increase in the water level, predominantly due to increased precipitation, decreased evaporation, and increased glacier melting. We demonstrate that temperature critically influences glacier melt rates and water level variations, alongside solar radiation, rainfall, atmospheric pressure, and wind speed. The ROC of Baishui River Glacier No. 1 melt ranges from − 0.0016 to 0.0015 m/min, reflecting substantial variation with significant downstream implications for water availability during dry seasons. The mean interval between consecutive glacier melt peaks is approximately 2.87 h, with a strong positive linear trend $R^2 = 0.99$, indicating frequent melt events. Conversely, water level peaks occur approximately every 6.5 h, with a strong positive trend $R^2 = 0.99$, indicating a slower recurrence rate. The transit time for meltwater from Baishui River Glacier No. 1 to BMLV is estimated at approximately 4.16 h. Additionally, we quantify the water flux from BMLV across various timescales, highlighting the substantial contribution of glacial meltwater. This novel study systematically examines the hydrological dynamics of BMLV. This study has the potential to reveal broader implications for water resource management, ecosystem dynamics, and climate change adaptation in regions dependent on glacier-fed lakes.

Keywords Lake pulse, Glacier melting, Baishui River glacier, Random forest, Multivariate regression

The Tibetan Plateau, known as the Third Pole of the World, hosts the largest concentration of land glaciers after Antarctica. The glaciers on the Tibetan Plateau deliver freshwater to downstream regions and play a critical role in the regional cryosphere[1–4]. Owing to their high altitude, these glaciers significantly influence climate variability. Current climate change is gradually altering their morphology, behaviour, elevation, melting rate, contraction, and thinning[3,5]. These changes impact downstream water resources, including both small and large freshwater lakes fed by these glaciers. Consequently, this impact directly and indirectly affects human populations, agriculture, ecosystems, and socioeconomic conditions[6]. Monitoring the mass balance of glaciers is necessary to assess the short- and long-term effects of climate change trends. In recent decades, glaciers across the Qinghai–Tibet Plateau, particularly temperate glaciers, have significantly retreated and lost mass due to global warming[6]. This loss was more noticeable in the southeastern region than in the northwestern region[7,8].

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These rapid changes not only impact local ecosystems and water resources but also affect agricultural and tourism activities[9]. Additionally, rising air temperatures lead to glacier melting and affect risks such as glacial lake outburst floods and debris flows, which can have serious socioeconomic, agricultural, and environmental implications[10,11]. Therefore, continuous and wide-ranging monitoring of glacier changes is essential for better managing these challenges in the context of current climate change issues. In addition, real-time monitoring of glacier melting, climate change, and water level fluctuations is important and can be effective for water resource management and natural disaster mitigation.

Lakes are formed globally by glacier melt, groundwater, rivers, and rainfall, which play key roles in human civilization and ecosystems. Glacier-fed lakes significantly contribute to the global hydrological cycle and serve as vital water sources[12–14]. Glacial meltwater lakes exhibit unique hydrological characteristics driven by dynamic fluctuations in water levels—which we refer to as 'lake pulses'—influenced by variations in glacier melt, precipitation, evaporation, and runoff. These cyclic, often diurnal, fluctuations reflect both immediate and delayed responses to melting events and climatic changes, particularly noticeable in glacier-fed lakes during warmer periods[15]. Lake pulses are critical for maintaining the ecological balance within lakes and their surrounding environments, influencing nutrient distribution, habitat availability, and the distribution of aquatic species[16]. These fluctuations drive ecosystem dynamics, influencing productivity and biodiversity. Glacier-fed lakes are crucial water sources for downstream communities, agriculture, and hydropower generation[17]. Monitoring lake pulses for subtle yet significant fluctuations in water levels provides valuable information for predicting water availability and managing water resources, particularly in regions heavily reliant on glacial meltwater, such as the mountains of Asia. Glacier melting rates are sensitive indicators of climate change, so studying lake pulses helps assess their effects on glacier dynamics, water resources, and ecosystems[15]. This novel evaluation elucidates the susceptibility of glacier-fed systems to evolving climatic conditions. Monitoring and analysing lake pulses is fundamental for maintaining the health and stability of these systems, ensuring ecosystem sustainability, and developing effective water management strategies. As climate change accelerates glacier melt, the study of lake pulses becomes increasingly imperative for predicting future impacts on water resources, ecological resilience, and downstream hydrological phenomena. By integrating field observations with advanced modelling techniques, hydrologists and related field researchers can better capture the complexity of lake pulses and their broader implications. This approach not only increases scientific understanding but also supports the development of informed policies and adaptive management practices for protecting these critical water resources in a changing climate.

Research in glacier-fed lakes, hydroclimatic fields and water resource management often relies on statistical techniques such as multiple linear regression or Spearman's rank correlation coefficient to identify the factors influencing glacial melting and water level fluctuations in lakes[18,19]. However, these studies have focused mainly on large lake systems such as the Great Lakes[18], or they have been conducted in regions such as China[19]. Nevertheless, a significant gap remains in research concerning the utilization of precise instruments such as RBR duet instruments to measure water level fluctuations in both small lakes such as Blue Moon Lake Valley (BMLV) and large lakes (e.g., Qinghai Lake) at the ground level. There is a significant gap in comprehensive hydrological, cryospheric, and climatic analyses needed to identify the drivers behind water level fluctuations in glacier-fed lakes and in ecosystems. Although documented shifts in temperature and precipitation patterns, as well as glacial melting processes in regions due to anthropogenic climate change, have already been analysed, these trends or their potential impacts on future water levels are projected.

Previous studies examining the responses of lake areas, water level variations, and climate changes have typically utilized qualitative analyses to identify influencing factors[20–23]. Other studies have employed linear fitting of climate data with lake water level changes for consistent periods[24]. While qualitative analyses can determine deterministic response trends between glacier melting, water level variations, and climate changes, they often lack precision regarding the magnitude of these responses. Earlier linear fitting analyses focused on the immediate, synchronous responses of glacier melting, water level changes, and climate changes, thereby overlooking any delayed effects[23]. This study aims to bridge the gap in quantitative analysis of the delayed responses of lake water levels to glacial melting and climate change. Specifically, the responses of the Baishui River Glacier No. 1 melting rate to BMLV basin dynamics and climatic variations are investigated. Importantly, the study also examines the delayed responses of lake area and lake pulse changes to climate shifts and glacier melting, areas that have undergone limited quantitative scrutiny. In this research, we employed peak time detection in glacier melting and water level fluctuation data to determine the delayed response of water level changes in the BMLV due to glacier melting and climate changes. This approach quantifies the time lag between glacial melting events and subsequent water level changes in the lake. By analysing these peak times, we can gain better facts and figures of the time scale influenced by glacier melting and its interaction with climate change. Therefore, this research seeks to address these gaps by integrating multiple parameters and utilizing precise instruments, such as RBRs, to measure water level fluctuations influenced by the melting of Baishui River Glacier No. 1 and climate variables in BMLV. This study is innovative in its high-precision, five-minute interval evaluations and then interpolated to one-hour, one-day, weekly, and monthly intervals for water flux and peak level time difference measurements. Following methodologies endorsed by previous researchers (Yi et al., 2015,Liang and Li, 2019, this study thoroughly investigates the factors influencing water level fluctuations in BMLV, thereby illuminating its hydrological dynamics and potential future trajectories. This study is creative in its integration of these factors, contributing high-precision evaluations and a detailed understanding of the primary causes and future implications of water level changes. Furthermore, this study aims to discover daily lake pulses through high-precision water level measurements; analyse the temporal relationships among glacial melting, precipitation, and water level fluctuations in lakes; and quantify the contributions of glacial melting and precipitation to water flux. Through these objectives, this research provides significant knowledge of the fluctuation patterns of water levels in BMLV with continuous time series at five-minute intervals, as well as the primary factors driving these fluctuations.

Study areas: Yulong Snow mountain and Blue Moon Lake Valley

Yulong Snow Mountain (YSM), located in the southeastern region of the Qinghai-Tibet Plateau at coordinates ranging from 27.16° to 27.66°N latitude and 100.15° to 100.33°E longitude, has significant geographical importance. It stands as the temperate glacier area nearest to the Equator on the Eurasian continent, excluding Indonesia's Chaya Peak. Spanning 35 km in length from north to south and 13 km in width from east to west, the YSM reaches its highest peak at an elevation of 5,596 m above sea level. As of 2017, the YSM boasted 13 glaciers covering a total area of 4.48 km^2. The elevation of these glaciers ranges from 5361 m above sea level in the accumulation region to 4,395 m above sea level at the glacier terminus (Fig. 1). The largest of these temperate glaciers is Baishui River Glacier No. 1, covering an area of approximately 1.32 km^2. Notably, this region serves as a convergence point for both the Indian monsoon and the Southeast Asian monsoon, as demonstrated by prior studies[25]. The YSM experiences distinct seasonal influences, with the southeast and southwest monsoons affecting it during the summer and autumn months, whereas the southern branch of the westerly belt impacts the region during the winter and spring seasons. The marked variation in vertical elevation within the YSM contributes to its remarkable biodiversity and diverse natural and cultural landscapes, playing a crucial role in providing essential cryosphere services. The presence of ice-and-snow landscapes holds immense cultural significance for Lijiang ancient town, which is recognized as both a world cultural heritage site and an intangible cultural heritage site. Furthermore, the utilization of ice and snow resources is closely intertwined with the economic and social development of a region. Over the period from 1980 to 2013, regional warming at the Lijiang Meteorological Station, situated at the base of the YSM, exhibited a warming trend of 0.3 °C per decade, as reported in several studies[9,26]. The distance between the YSM glacier and BMLV is estimated to be approximately 10 km.

Materials and methods

Data collection and integration

We utilized the RBR duet instrument, identified by serial number 214846 and equipped with firmware version 1.063, to collect time series water level data in the lake. Data collection commenced on August 28, 2023, in

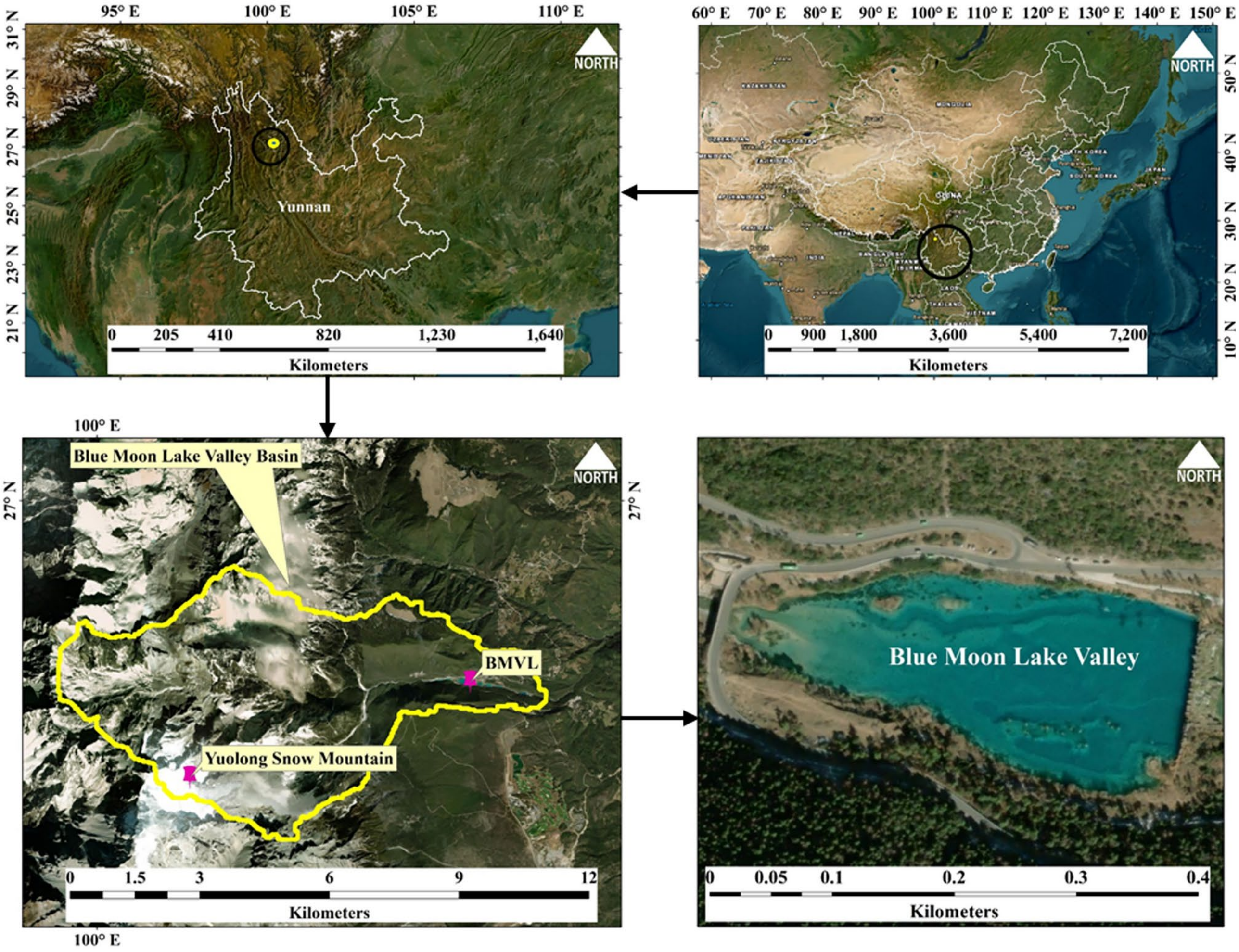

Fig. 1. Layout map of BMLV fed by Baishui River Glacier No. 1 on Yulong Snow Mountain, Lijiang, Yunnan District, China.

continuous logging mode, with the last recorded logger time occurring on October 8, 2023. The instrument recorded data across multiple channels, including temperature, water pressure, and water level, with a primary focus on collecting time series water level data in the lake. Measurements were taken at regular intervals, with a fixed 5-min gap between data points. Moreover, climate data acquisition involves a complex approach that integrates observational techniques, remote sensing technologies, and computational modelling[27,28]. This dataset is fundamental for discriminating climate trends, facilitating informed decision-making, and forecasting future alterations. Therefore, snow data and weather-related parameters, including temperature, relative humidity, atmospheric pressure, wind speed, precipitation, evaporation, and solar radiation, are monitored by ground-based weather stations on the Baishui River Glacier.1 at YSM (Fig. 2), which provides real-time information. To ensure precision and alignment with water level data, climate data were sourced from the station. A similar climate data time period was selected for synchronization.

Exploring wave height and periodicity in water level fluctuations in the BMLV

The study utilized time series data consisting of timestamps and water level measurements from the Blue Moon Lake Valley near the YSM glacier. Recorded at regular 5-min intervals from August 28, 2023, to October 8, 2023, the raw data underwent initial preprocessing to ensure uniformity and consistency for subsequent analysis. Peaks and troughs in the water level data were identified to characterize wave patterns, with wave heights computed based on these identified peaks and troughs via MATLAB's built-in functions. A visual representation of the water level data, including wave height, was subsequently generated.

Frequency domain analysis

To determine the frequency characteristics of the water level variations in the lake, the fast Fourier transform (FFT) method was employed. This method is widely utilized in hydrological studies[29–31] to analyse oscillatory movements, such as surface seiches, which represent periodic water level fluctuations[32,33]. The FFT transforms time-domain data into the frequency domain, enabling the identification of recurring patterns without the need to analyse the entire dataset. Through the FFT, an amplitude spectrum was obtained, revealing the main frequency components and periodic patterns in the data. This method is particularly useful for handling large datasets with different time scales and complex signals, providing a clear understanding of the frequency components and significant periodic patterns. By examining the amplitude spectrum, peaks corresponding to dominant frequencies were identified, allowing for a detailed evaluation of the periodic patterns in the water level data.

Exploration of temporal dependency

Autocorrelation analysis was conducted to explore the temporal dependencies within the water level time series. This technique calculates autocorrelation values across various lag times to evaluate the similarity between water levels at different time intervals. Autocorrelation function plots help visualize correlations between present and past water level values, revealing temporal patterns and trends. By measuring the correlation between a signal and its delayed copies over different lag times, autocorrelation analysis identifies repetitive patterns or cycles in the water level data, facilitating the detection of periodic fluctuations. This method is critical for analysing time series data, particularly for examining temporal dependencies and identifying periodicity[34]. It is especially beneficial for nonstationary signals, as it captures both short-term and long-term correlations. Statistical

Fig. 2. Snow and climate data station on Baishui River Glacier.1 at Yulong Snow Mountain, Lijiang, Yunnan District, China.

measures, including maximum, minimum, mean, and median values for both amplitude and autocorrelation, were computed to characterize the amplitude spectrum and autocorrelation of the water level data. Additionally, peak frequencies in the amplitude spectrum were identified, and the lag time corresponding to the maximum autocorrelation was determined, enhancing the understanding of the data's underlying characteristics.

Analysis of the rate of change and cumulative sum in the water level and climate parameters

Estimating the rate of change (ROC) in water level, glacial melting, and climatic parameters is essential for determining their temporal dynamics and contributions to environmental processes[35]. We analysed the ROC and cumulative sum (CS) for the water level and climate parameters, including temperature, rainfall, pressure, humidity, evaporation, wind speed, solar radiation, and glacier melting. A similar technique was used by Brun et al.[7]. By utilizing high-resolution time series data collected over two months at five-minute intervals, we calculated the ROC by determining the difference between consecutive data points and dividing by the corresponding time interval (Eq. 1). This allowed us to quantify the magnitude and direction of temporal variations for each parameter[35],[36]. Additionally, CS was computed by summing the ROC values over the observation period (Eq. 2), which provided the total net change and overall impact over time.

$$ROC_i = \frac{Parameter\ (t_{i+1}) - Parameter\ (t_i)}{Time(t_{i+1}) - Time(t_i)} \tag{1}$$

$$CS_i = \sum_{j=1}^{i} ROC_j \tag{2}$$

where $\mathrm{ROC_i}$ represents the rate of change for a parameter at the i^th^ time point, $\mathrm{Parameter}\ (\mathrm{t_{i+1}})$ is the value of the parameter at the $\mathrm{i+1}^{\mathrm{th}}$ time point, $\mathrm{Parameter}\ (\mathrm{t_i})$ is the value of the parameter at the $\mathrm{i^{th}}$ time point, $\mathrm{Time(t_{i+1})}$ is the time at the $\mathrm{i+1}^{\mathrm{th}}$ time point, $\mathrm{Time}\ (\mathrm{t_i})$ is the time at the $\mathrm{i^{th}}$ time point, CS_i represents the cumulative sum of the rate of change up to the $\mathrm{i^{th}}$ time point, and $\sum_{j=1}^{i} ROC_j$ is the sum of all rates of change values from (j = 1) to (j = i).

Rainfall event identification

Most of the previous studies investigated rainfall events and their impact on water level dynamics in the basin, given their significant influence on hydrological processes such as surface runoff, groundwater recharge, and water level fluctuations[5,37–39]. To identify these events, K-means clustering was applied to the rainfall records, following methodologies from recent literature[40–42]. Using the well-known K-means algorithm[40,43], the number of clusters was determined based on prior knowledge and domain expertise, resulting in the selection of two clusters for this analysis. The K-means algorithm effectively partitioned the rainfall data into distinct clusters, each representing unique precipitation patterns. This unsupervised machine learning technique was instrumental in identifying inherent patterns within the rainfall data[44]. The cluster centres were subsequently sorted, and a threshold based on the lowest cluster centre was defined to identify precipitation events. The time intervals with rainfall exceeding this threshold were classified as precipitation events, thus isolating periods of significant rainfall from the dataset. The impacts of these rainfall events on water level dynamics were analysed by comparing the mean water level during precipitation events with that during nonprecipitation periods. This comparison provided insights into the response of the water body to rainfall inputs, underscoring the influence of precipitation on water level fluctuations[42]. Additional statistical measures, including the highest, lowest, and average rainfall values, were calculated to ensure an overall overview of the variability and intensity of rainfall during the observed period.

Analysis of peaks and time differences in glacier melting and water levels

This section examines the temporal characteristics of peaks in glacier melting and water level data, as well as estimates the time differences between these peaks and their resultant impacts from glaciers to lakes. By identifying and analysing these peaks, we confirmed the periodicity and variability of the observed phenomena during the observation period. Initially, datasets containing hourly measurements of glacial melting and water level were prepared. Peaks in the glacier melting and water level data were identified by locating maximum values, and their timestamps were recorded via MATLAB 2024b. The time intervals between consecutive peaks for both glacier melting and water level data were subsequently calculated. This involved determining the difference in timestamps between each identified peak and its preceding peak. An analysis was then conducted to determine the overall peaks and indices in the entire dataset for both the glacier melting and water level data, revealing the distribution and magnitude of the peaks throughout the observation period. Linear regression analysis was performed to assess the trend in glacier melting and water level indices over time[45], confirming the long-term patterns and changes in peak occurrences and the impact of glacier melting on water level fluctuations. Furthermore, correlations were calculated between the time differences in glacier melting peaks and water level peaks to investigate the impact of glacier melting peak intervals on subsequent water level peak intervals. This analysis provided detailed information on the temporal dynamics of glacier melting and its influence on downstream water levels, elucidating the interconnectedness of these hydrological processes.

Exploring the impacts of glacier melting and precipitation on water level through multivariate regression analysis

The water level fluctuations in the Blue Moon Lake Valley are influenced primarily by glacier melting and precipitation. In this context, multivariate regression analysis (MVR) is an optimal technique for elucidating these relationships. MVR is a statistical method that examines the relationship between multiple independent variables and a single dependent variable[46]. Its significance lies in its ability to provide insights into how contributions from glacier melting and precipitation impact water level changes, which is crucial for effective water resource management, especially in glacier-fed regions where water availability is heavily dependent on environmental factors. MVR enables researchers to assess how changes in glacier melting and precipitation patterns affect water levels over time, as demonstrated in previous studies analysing hydrological processes and understanding the impact of climate change on water resources[42]. For this analysis, observational data encompassing water levels, glacier melting, and precipitation were utilized. First, the data were structured into a matrix format within the MATLAB 2024b environment, with each row representing a measurement instance and each column corresponding to a variable (either predictor or response). The fitlm function in MATLAB 2024b was employed to develop an MVR model for the dataset, with the water level designated as the dependent variable and glacier melting and precipitation as independent variables or predictors. Model performance was assessed through an examination of summary statistics, including coefficients, standard errors, t statistics, p values, root mean square errors (RMSEs), R-squared values, and the F statistic. These metrics provided significant information regarding the model's predictive efficacy and the significance of each predictor. To visualize the fitted model, scatter plots were generated to compare the observed and fitted water levels. Additionally, a residual histogram was created to gauge the model's goodness of fit. These visualizations facilitated an understanding of the model's performance and highlighted areas for potential improvement.

Assessing the impact and contribution of climate variables to glacier melting, water level, and water flux

This section analyses the contributions of various climate parameters to glacier melting, water level variations, and water flux. Numerous studies have confirmed the phenomenon of global warming and its consequential effect on glacial retreat, particularly on glacier runoff. This phenomenon has been observed globally and regionally, with notable examples in high mountain Asia, the Baishui River Glacier No.1 at YSM glaciers, and the Andes[9,26,47–50]. Additionally, ongoing climate change is accelerating the melting of glaciers, resulting in fluctuations in water levels in glacier-fed lakes and influencing flux patterns. These changes have significant implications for landscape dynamics, agricultural patterns, and natural hazard assessments[51,52]. Here, the aim was to determine the role and contribution of individual climate variables in influencing glacier melting, water level fluctuations, and water flux. Data for glacier melting, water level, and flux were individually collected along with the corresponding climate parameters. Minmax scaling was performed on the predictor variables to ensure uniformity in their ranges, preventing bias due to differences in variable magnitudes.

A random forest (RF) regression model was employed to quantify the importance of each climate parameter in predicting glacier melting, water level, and flux. The RF algorithm is widely utilized for classification, regression, and prediction because of its ability to capture complex relationships among input variables and mitigate the impact of outliers (Guo et al., 2016; Hartmann, 2022). One of the key advantages of RF is its ability to handle large datasets efficiently without being sensitive to overfitting and noise. Moreover, it can accommodate numerous variables without the need for variable deletion. Additionally, RF operates as an ensemble learning algorithm, supporting the combined performance of many decision trees for variable value prediction (Liu et al., 2012). Each decision tree within the RF model was constructed by using subsets of training samples with replacement, a process known as bagging. The model was trained using the scaled predictor variables and the corresponding data for each parameter. By utilizing 100 decision trees in the RF ensemble, the out-of-bag (OOB) predictor importance was evaluated to assess the relative contribution of each climatic variable. The RF model revealed the relative importance of climate parameters in influencing variations in glacier melting, water level, and flux. Feature importance scores were computed for each variable, indicating their contribution to explaining the variability observed in these parameters. Similar approaches have been utilized in previous studies[46,53]. After successful prediction, the RMSE was calculated as a performance metric representing the square root of the average squared differences between the observed and predicted values. Lower RMSE values indicate better predictive performance, demonstrating the effectiveness of the RF model in understanding the impacts of climate parameters on glacier melting, water levels, and flux dynamics.

Estimation of water flux in the BMLV

The determination of water flux (Q) is a critical aspect of hydrological studies, influencing water resource management and environmental planning. In this section, the water flux was computed via Eq. 3. The equation was derived from the principles of open-channel flow, specifically for the scenario where water flows over a dam or structure[54]. It incorporates the width of the flow, gravitational acceleration, and geometric characteristics of the flow to estimate the discharge or flux. This type of equation has often been developed through empirical methods and is particularly useful in hydraulic engineering and hydrology, where observed data can be used to establish relationships between different variables[55]. The use of such equations is common in hydraulic engineering for estimating flow rates in natural channels or artificial structures such as dams.

$$Q = M_o B \sqrt{2g} H^{3/2} \tag{3}$$

Here, Q = Flux of water, which is the volume of water passing through a cross-sectional area per unit of time. M_O is a constant with a value of 0.502. It was derived from empirical analysis or calibration based on specific

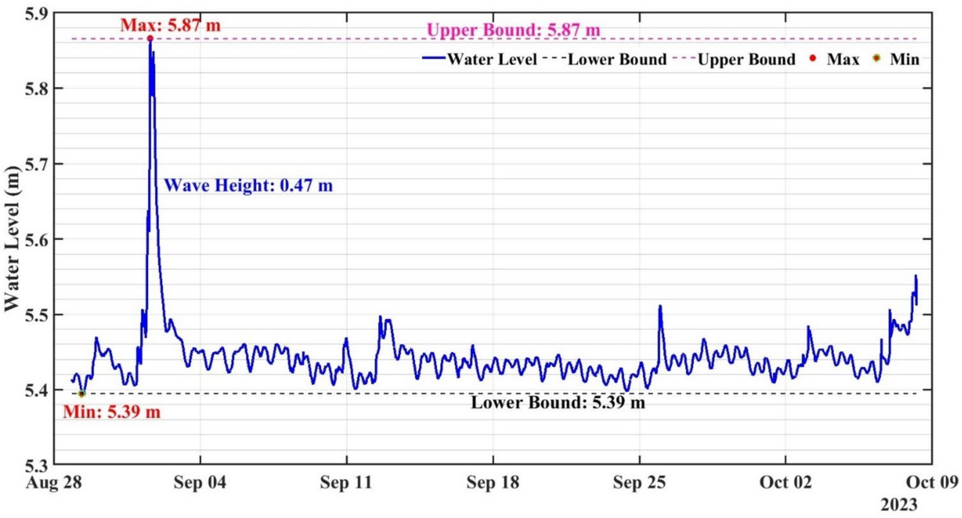

Fig. 3. Wave height fluctuations in the water level at the BMLV.

Parameters	Mean	Median	Minimum	Maximum	S-Deviation	Range
Glacier Melting (mm)	− 0.00005	0	− 0.004	0.004	0.002	0.008
Water Level (m)	5.44	5.43	5.39	5.86	0.040	0.47
Pressure (hPa)	582.50	582.66	580	585	0.97	5
Temperature (°C)	0.76	0.650	− 5.3	11.37	1.72	16.42
Rainfall (mm)	0.0004	0	0	0.068	0.002	0.06
S-Radiation (W/m^2)	126.91	1.26	− 6.52	1016	215.22	1,018.01
R-Humidity (%)	93.71	99.9	16.05	99.9	11.08	83.10
Windspeed (m/s)	1.187	0.96	0	5.485	1.15	5.39
Evaporation (mm)	0.01	0.011	0.004	0.014	0.0014	0.009

Table 1. Statistics of glacier melting, water level data, and climatic parameters.

characteristics of the lake. (B) denotes the cross-sectional width through which water flows. (g) is the acceleration due to gravity. (H) is the water height or head, measured from a reference level, usually the lake's surface. In the equation, ($H^{3/2}$) signifies that the relationship between water flux and water height is not linear but follows a power-law relationship.

Results

Wave height and periodic pattern analysis of water level fluctuations via autocorrelation and amplitude spectrum techniques

The analysis of wave height within the water level provides significant knowledge of the fluctuation patterns and dynamics of the lake. The maximum wave height observed was 0.47 m, indicating that the maximum amplitude of water level fluctuations occurred throughout the time series (Fig. 3). This metric is key for understanding the variability and intensity of wave motion within a lake, where higher wave heights suggest increased wave energy and potential wave-driven processes. The average water level was computed to be 5.44 m, representing the mean of fluctuations observed. The lower and upper boundaries of the water level, 5.39 m and 5.87 m, respectively (Table 1), represent the extremes within the dataset. These bounds provide context for the wave height metrics, delineating the minimum and maximum water levels recorded during the study period. The lower bound reflects the lowest water level reached, whereas the upper bound denotes the highest level attained, illustrating the natural variability and range of water level fluctuations in the lake.

Furthermore, the analysis of water level fluctuations in the lake via autocorrelation and amplitude spectrum techniques revealed distinct patterns indicating both periodicity and nonperiodicity. The dominant frequencies and their corresponding amplitudes in the amplitude spectrum suggested regular fluctuations over time, influenced by seasonal changes, glacial melting, climatic patterns, and hydrological processes. The maximum amplitude of 0.04 indicated significant fluctuations. The mean amplitude of 0.02 signified a moderate overall fluctuation level (Fig. 4a).

The maximum autocorrelation coefficient of 1.0 indicated a strong positive correlation between water levels at different time points, suggesting significant temporal dependence within the water level time series. Conversely, the minimum autocorrelation coefficient of − 0.11 suggested a weak negative correlation between certain time points.

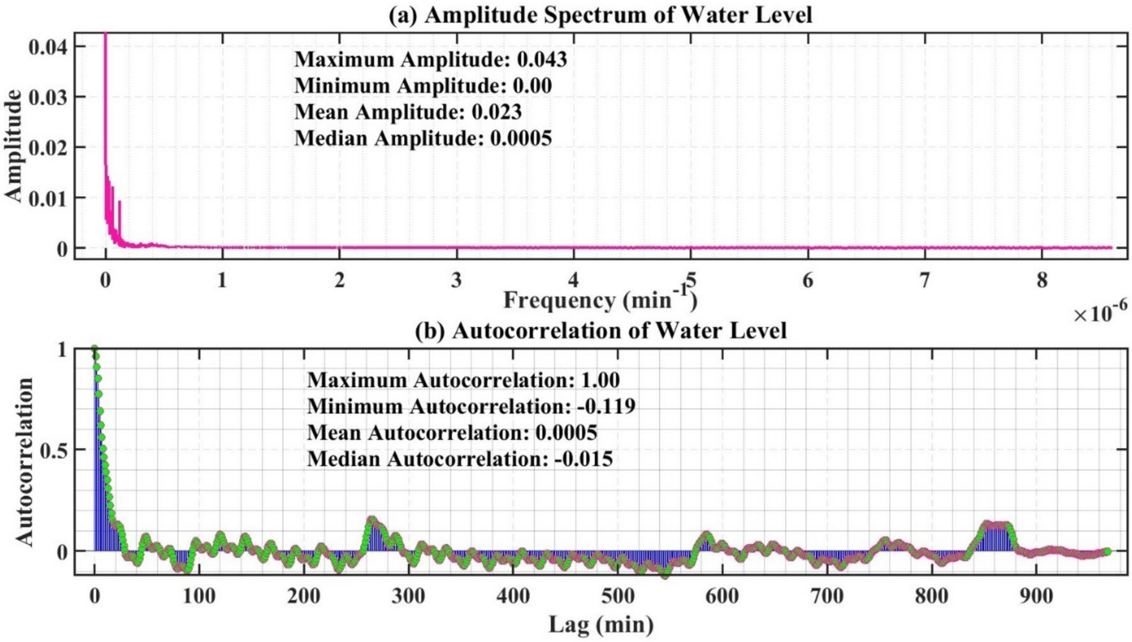

Fig. 4. **(a)** Amplitude spectrum showing the amplitude and frequency and **(b)** autocorrelation of the water level.

The mean autocorrelation coefficient of 0.0005 and the median autocorrelation coefficient of − 0.015 indicated a low average level of autocorrelation, with occasional periods of negative correlation (Fig. 4b).

Peaks in the frequency domain represented dominant frequencies, reflecting recurring patterns due to seasonal variations or environmental influences. Water level fluctuations in lakes are a natural phenomenon associated with climate variability[16]. Periodic fluctuations in the lake water level can reveal pulse-like behaviour, where sudden changes occur in response to external stimuli or events such as heavy rainfall, snowmelt, glacial runoff, or human activities affecting the lake's water balance. These periodic patterns, attributed to factors such as glacier melting rates, precipitation, seasonal variations, tides, or other environmental influences, enhance the understanding of water level fluctuation dynamics. Moreover, the presence of dominant frequencies and their amplitudes support understanding of the hydrological processes and environmental influences affecting BMLV.

Statistical analysis of glacier melting, water level, and climate parameters

This section presents the analysis of hydrological and environmental parameters recorded in the valley from August 28, 2023, to October 8, 2023 (Fig. 5a–i). These parameters reflected the complete characteristics of the environmental dynamics of the lake basin, particularly its correlation with glacial melting. Water level fluctuations occurred at an average depth of 5.44 m, with a minimum of 5.39 m and a maximum of 5.86 m (Fig. 5a and Table 1). Atmospheric conditions significantly influenced the basin, with the mean temperature recorded at 0.76 °C ranging from − 5.30 to 11.37 °C (Fig. 5b), which is consistent with findings from Wang et al.[56]. These fluctuations are attributed to glacial melting, which impacts the lake's temperature regime. Solar radiation averaged 126.91 W/m^2, with variations between − 6.52 W/m^2 and 1016 W/m^2 (Fig. 5e), highlighting the dynamic energy input into the melting rate and lake system. The atmospheric pressure remained stable (Fig. 5c), with a mean of 582.50 hPa, indicating consistent weather patterns during the observation period. The rainfall patterns revealed minimal precipitation (Fig. 5d), with a mean of 0.0005 mm and variability ranging from 0 to 0.06 mm (Table 1). The relative humidity averaged 93.71%, fluctuating between 16.05% and 99.9% (Fig. 5f). The average wind speed was 1.18 m/s (Fig. 5g), with moderate variability from 0 to 5.48 m/s, influencing the lake's surface dynamics, including evaporation and heat transfer. The evaporation rates had a mean of 0.01 mm, with a minimum of 0.004 mm and a maximum of 0.01 mm, and a standard deviation of 0.001 mm, indicating relatively stable evaporation (Fig. 5h) influenced by temperature, wind speed, and humidity. Glacial melting exhibited minor variations, with a mean value of − 0.00005 mm, fluctuating between − 0.004 mm and 0.004 mm, and a narrow standard deviation of 0.002 mm, indicating relatively consistent melting rates (Fig. 5i). These statistics suggest that stable evaporation and melting rates are influenced by temperature, wind speed, and humidity. Thus, these results confirm the interactions among glacier melting, water levels, atmospheric conditions, evaporation, and climatic variables, highlighting the complex interactions shaping the lake ecosystem, water resources, and ecological sustainability.

Hydroclimatic implications for BMLV: analysis of rainfall events and their impact

Figure 6 presents key findings related to rainfall events and water level fluctuations in the Blue Moon Lake Valley. The analysis employed a threshold of 0.00025 mm to distinguish between precipitation events and nonprecipitation events. The highest recorded rainfall occurred from September 1 to 3, 2023, with a value

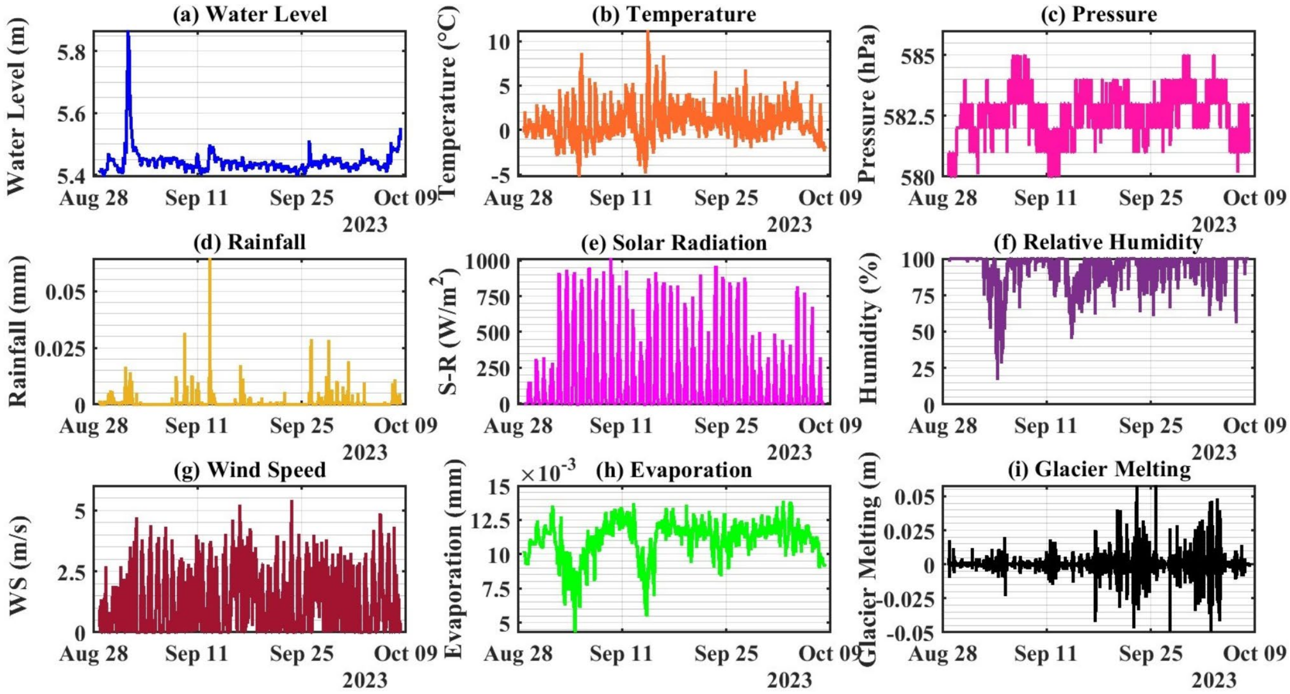

Fig. 5. All-inclusive display of water level data of BMLV and environmental parameters, including (**a**) water level, (**b**) temperature, (**c**) pressure, (**d**) rainfall, (**e**) S-radiation, (**f**) relative humidity, (**g**) wind speed, (**h**) evaporation, and (**i**) glacier melting.

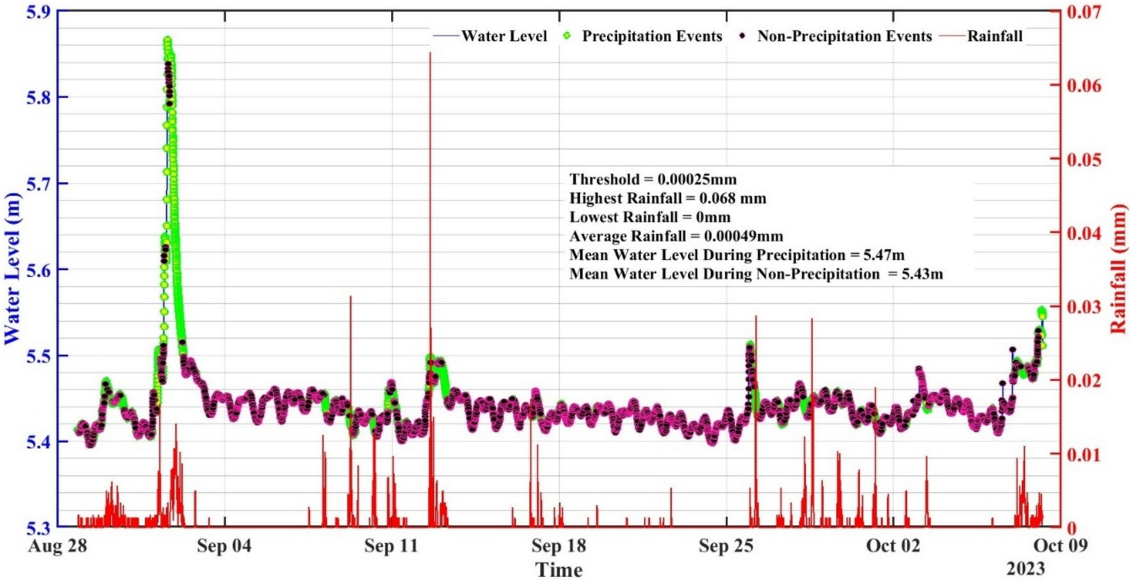

Fig. 6. Rainfall events and water level fluctuations in BMLV at five-minute intervals.

of 0.068 mm, resulting in a peak water level of 5.86 m, indicating overflow conditions during similar days. Conversely, the average rainfall across all events was 0.0004 mm. Furthermore, the mean water level during precipitation events was measured at 5.47 m, whereas the mean water level during nonprecipitation events was slightly lower at 5.43 m. These results highlight the hydrological response of the lake, indicating its sensitivity to climatic inputs during precipitation events. Overall, the identified threshold distinguished different rainfall events and provided information on the hydroclimatic dynamics of the area. With this technique, the analysed results are particularly relevant in the context of ongoing glacier melting trends, as increased precipitation can both regulate and contribute to water level fluctuations.

Estimation of the rate of change (ROC) and cumulative sum (CS) of the parameters

Glacier melting and climate parameters

From August to October 2023, the ROC of Baishui River Glacier No. 1 melting varied from – 0.0016 to 0.0015 m/min, indicating significant fluctuations (Fig. 7a). With a standard deviation of 0.0003 m/min, the melting patterns exhibited moderate variability (Table 2), impacting downstream water availability and streamflow. Glacial meltwater, which is vital during dry seasons, influences overall water availability, agricultural needs, and ecosystem health. It also maintains water levels in glacier-fed rivers and lakes. The fluctuations in Baishui River Glacier No. 1 melting, depicted by CS values ranging from – 0.0006 m to 0.014 m (Fig. 7b), highlight the dynamic nature of ice loss, which is influenced by various climate factors. The ROC for temperature ranged from – 0.74 to 1.01 °C/min, with a standard deviation of 0.08 °C/min, indicating significant fluctuations (Fig. 7c). Rapid temperature changes directly impact glacial melt and water flow into the lake, potentially increasing water levels. The CS of temperature showed an overall upwards trend, with positive values indicating net warming, ranging from – 0.99 °C to 2.29 °C (Fig. 7d). Rising temperatures can increase evaporation, alter rainfall patterns, and impact water availability and ecosystem sustainability. The solar radiation ROC ranged from – 67.17 to 62.03 W/m^2/min, indicating significant variations (Fig. 7k). Enhanced solar radiation accelerates melting, increasing water flow into the lake, whereas reduced radiation slows the melting process. Negative CS values indicate a net decrease in solar radiation, potentially reducing the energy available for glacier melting. The maximum CS value of 0.011 W/m^2 highlighted periods of high solar energy input, contributing to increased glacier melting (Fig. 7l). The range of CS values, from – 0.009 W/m^2 to 0.01 W/m^2, reflected variability in solar radiation patterns, influenced by seasonal variations and atmospheric conditions. The ROC for rainfall ranged from – 0.006 to 0.004 mm/min, with a median ROC of 0 mm/min, suggesting a slight decrease over time (Fig. 7e). The standard deviation of 0.00016 mm/min (Table 2) indicated moderate variability in rainfall patterns, influencing hydrological processes such as runoff and groundwater recharge. The negative CS values reflected a net decrease in rainfall, with the maximum CS value of 0.012 mm representing the highest cumulative rainfall observed (Fig. 7f). The dynamic nature of rainfall variations impacts water availability, agriculture, and ecosystem processes. The ROC for glacial melting (1.8E−06 m/min) is several orders of magnitude smaller than the ROC for pressure (1.65E−05 hPa/min), which indicates that changes in pressure have a minimal direct effect on the rate of glacial melting (Fig. 7g). The ranges for both the ROC and CS of pressure (0.656 hPa/min and 1 hPa, respectively) are much larger than the ranges for glacial melting (0.0030 m/min and 0.015 m, respectively) (Fig. 7h). This suggests that pressure can fluctuate significantly without causing proportional changes in glacier melting. The statistical parameters indicate that while pressure and glacial melting are related, the connection between them is relatively weak. Pressure does not appear to be a dominant factor driving the observed changes in glacier melting based on the provided information. The relative humidity ROC (Fig. 7o) ranged from – 5.60 to 4.87%/min, reflecting fluctuations in the atmospheric moisture content (Table 2). These variations significantly influence evaporation rates and the overall water balance in the basin. Higher relative humidity decreases evaporation, potentially increasing water accumulation and glacier melting, whereas lower humidity enhances evaporation, potentially reducing the melting rate. The range of CS values, from – 16.62% to 1.97E−14%

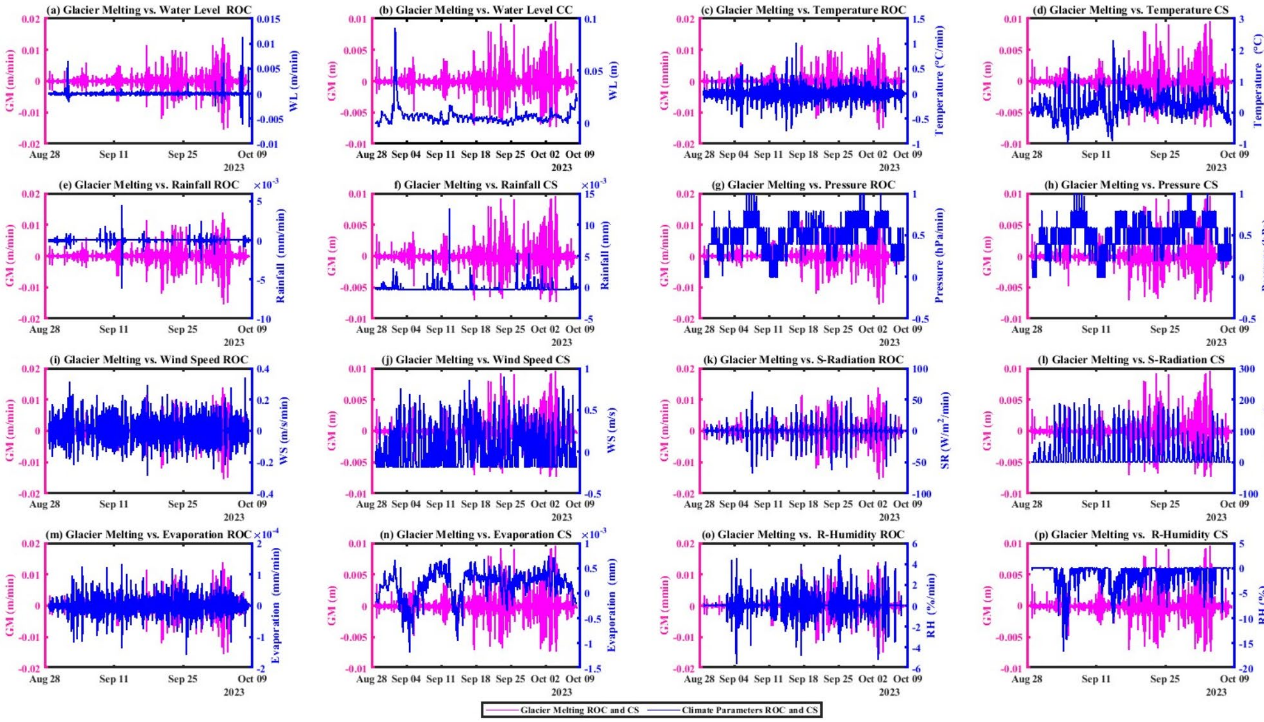
(a) Glacier Melting vs. Water Level ROC
(b) Glacier Melting vs. Water Level CC
(c) Glacier Melting vs. Temperature ROC
(d) Glacier Melting vs. Temperature CS
(e) Glacier Melting vs. Rainfall ROC
f) Glacier Melting vs. Rainfall CS
(g) Glacier Melting vs. Pressure ROC
(h) Glacier Melting vs. Pressure CS
(i) Glacier Melting vs. Wind Speed ROC
(j) Glacier Melting vs. Wind Speed CS
(k) Glacier Melting vs. S-Radiation ROC
(l) Glacier Melting vs. S-Radiation CS
(m) Glacier Melting vs. Evaporation ROC
(n) Glacier Melting vs. Evaporation CS
(o) Glacier Melting vs. R-Humidity ROC
(p) Glacier Melting vs. R-Humidity CS

Fig. 7. Glacier melting and climate parameters ROC and CS.

Parameters	Mean	Median	Minimum	Maximum	Standard deviations	Range
Rate of change (ROC) per minute						
Glacier melting (m)	1.8E−06	0	− 0.0016	0.0015	0.0003	0.003
Water level (m)	1.70E−06	− 7.24E−06	− 0.006	0.01	0.0002	0.01
Pressure (hPa)	1.65E−05	0	− 0.34	0.31	0.039	0.65
Temperature (°C)	− 2.60E−05	0	− 0.74	1.01	0.08	1.756
Rainfall (mm)	− 8.60E−09	0	− 0.006	0.004	0.00016	0.010
S-radiation (W/m^2)	4.09E−07	1.17E−03	− 67.17	62.03	5.58E+00	129.2
R-humidity (%)	3.67E−18	0	− 5.601	4.87	0.49	10.47
Windspeed (m/s)	− 1.60E−05	0	− 0.28	0.34	0.04	0.62
Evaporation (mm)	− 1.67E−08	− 6.67E−07	− 0.0001	0.0001	1.75E−05	0.0002
Cumulative sum (CS)						
Glacier melting (m)	0.006	0.005	− 0.0006	0.014	0.003	0.015
Water level (m)	6.04E−03	4.75E−03	− 0.003	0.09	0.008	0.09
Pressure (hPa)	0.4930	0.52	− 0.008	0.99	0.19	1
Temperature (°C)	0.2097	0.18	− 0.99	2.29	0.34	3.28
Rainfall (mm)	− 0.0002	− 0.0003	− 0.0003	0.01	0.0004	0.01
S-radiation (W/m^2)	− 7.75E−05	− 9.32E−05	− 0.009	0.01	0.0008	0.02
R-humidity (%)	− 1.237	− 7.29E−17	− 16.62	1.97E−14	2.21	16.62
Windspeed (m/s)	0.051	0.006	− 0.18	0.892	0.231	1.07
Evaporation (mm)	0.0001	0.0002	− 0.001	0.0007	0.0002	0.001

Table 2. Statistics of the water level, glacier melting, and climatic parameters of ROC and CS.

(Fig. 7p), highlights the dynamic nature of moisture conditions influenced by atmospheric circulation patterns and local topography. The wind speed ROC ranged from − 0.28 to 0.34 m/s/min, indicating fluctuations in air movement within the valley (Fig. 7i). The standard deviation of 0.04 m/s/min suggested moderate variability. Higher wind speeds increase evaporation by increasing moisture transfer from the glacier surface. Changes in wind speed also affect the temperature distribution within the valley, potentially influencing the Baishui River Glacier.1 melting rate. The maximum CS value of 0.89 m/s indicated periods of intense wind activity (Fig. 7j). Increased wind speeds accelerated the melting process of Baishui River Glacier No. 1, influencing water levels at BMLV. The ROC for evaporation exhibited small variations, ranging from − 0.0001 to 0.00013 mm/min (Fig. 7m), with a median ROC of − 6.67E−07 mm/min (Table 2), indicating a slight decrease. The standard deviation of 1.75E−05 mm/min suggested moderate variability. Higher evaporation rates lead to increased water loss, potentially lowering lake water levels (Fig. 7n). Conversely, lower evaporation rates reduce water loss, impacting the region's hydrological balance. The maximum CS value of 0.0007 mm indicated periods of intense water vapour loss, which could affect the region's water balance.

Water level and climate parameters
In terms of the water level, the ROC varied between − 0.006 m/min and 0.01 m/min, indicating fluctuations. The median ROC was − 7.24E−06 m/min (Table 2) suggested a general decrease, whereas the maximum ROC of 0.01 m/min highlighted significant short-term fluctuations (Fig. 8a). The standard deviation of 0.0002 m/min further emphasized this variability. Increased rainfall led to rising water levels, whereas decreased rainfall caused declines. Notable increases in water levels were observed during periods of sustained rainfall, such as from September 1 to September 3 and September 6 to 15, 2023 (Fig. 8e, f). Conversely, fluctuating rainfall from September 26 to October 3, 2023, also impacted water levels (Fig. 8f). Evaporation rates played a crucial role; high evaporation caused water loss, whereas low rates led to increases. Glacial melting significantly contributed to water levels, with periods of increased melting from September 16 to 25 and from September 28 to October 5, resulting in rising and fluctuating levels (Fig. 8a and b). The CS of water level changes confirmed overall trends, with positive values indicating a net gain in water level, suggesting that inflows (rainfall and glacial meltwater) exceeded outflows (evaporation and water withdrawals). The highest increase observed, with a maximum CS value of 0.09 m, was likely due to increased precipitation, reduced evaporation, and enhanced glacier melting. The range of CS values, from − 0.003 to 0.09 m, reflected variability in water level changes. Furthermore, it was visualized (Fig. 8a–p) and statistically analysed (Table 2) further revealing a strong relationship between glacial melting and various climate parameters that significantly influence water levels and availability in the basin. The observed data highlight the multifaceted connections and the need for wide-ranging monitoring and management strategies to sustainably manage water resources in the region.

Exploring the impacts of glacier melting and precipitation on the water level through multivariate regression analysis

The multivariate regression (MVR) technique was employed on combined glacier melting and rainfall data to understand their impacts on the water levels in a lake (Fig. 9a). The intercept value of 5.44 m indicated the estimated water level when both glacier melting and rainfall were zero. This provided a baseline for the analysis.

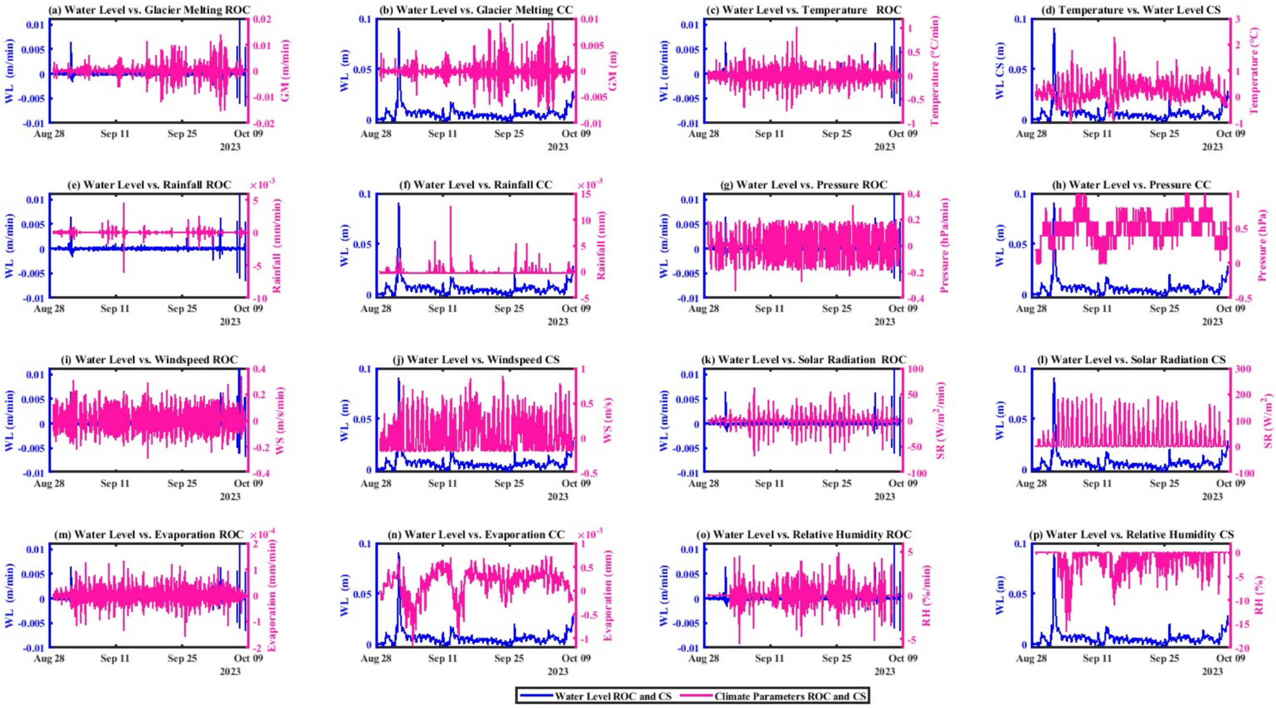

Fig. 8. Water level and climate parameters ROC and CS.

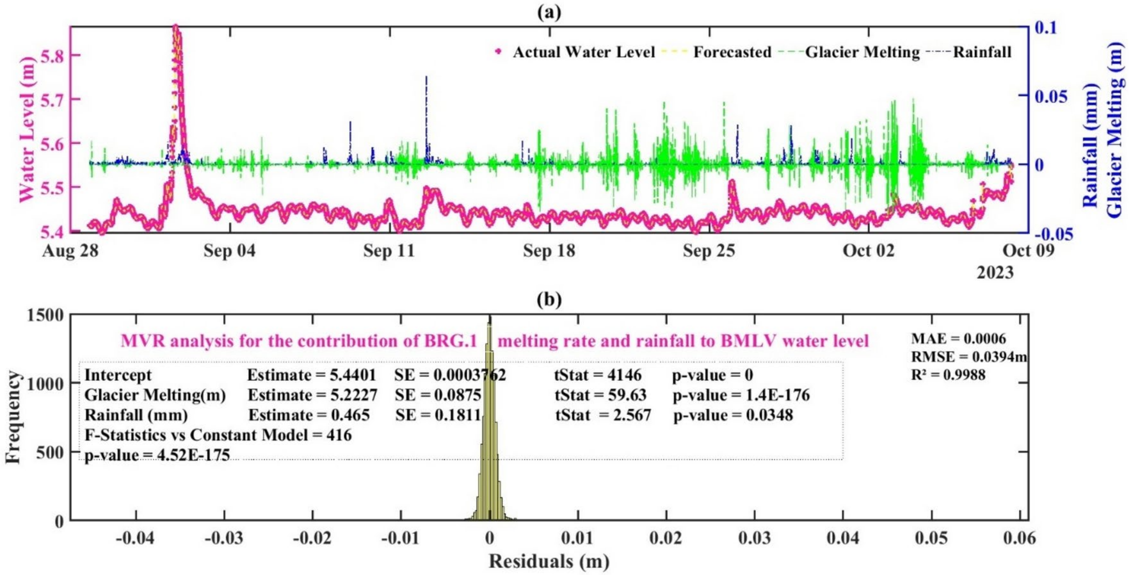

Fig. 9. Contribution of glacier melting and rainfall to water level (**a**) observed and fitted water level with glacier melting and rainfall (**b**) residual showing error in the observed and fitted water level.

The coefficient estimates (Estimate) demonstrated the effect of each predictor variable on the water level. The coefficient for glacial meltwater was 5.22 m, suggesting that for every unit increase in glacial meltwater, the water level increased by approximately 5.22 m. This effect was statistically significant, with a p value of 1.4792E−176, highlighting glacial meltwater as a crucial determinant of water level variations in a lake. Conversely, the coefficient for rainfall was 0.465 m, indicating that for every unit increase in rainfall, the water level tended to increase by approximately 0.465 m. This effect was statistically significant, with a p value of 0.034, indicating that while rainfall also positively influenced water levels, its impact was less pronounced than that of glacial melting. The RMSE of 0.039 m reflected the average deviation of the observed water level from the values predicted by the MVR model, indicating a reasonably accurate fit (Fig. 9b). A lower RMSE suggests that the model effectively

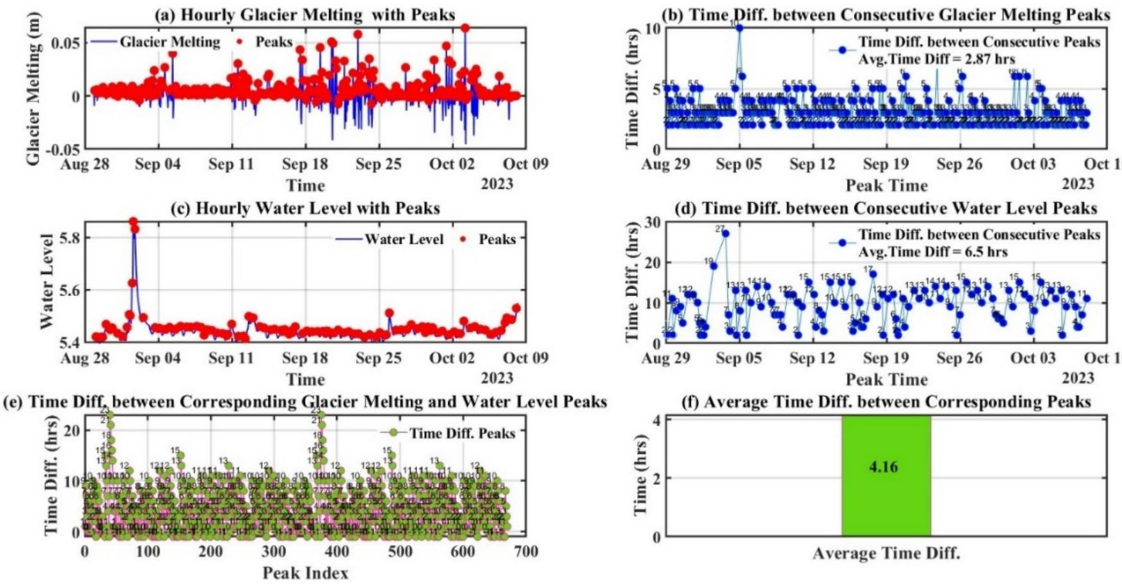

Fig. 10. Time difference between consecutive peaks of glacier melting (**a** & **b**) and water level (**c** & **d**) and the corresponding time difference between the glacier and the lake (**e** & **f**).

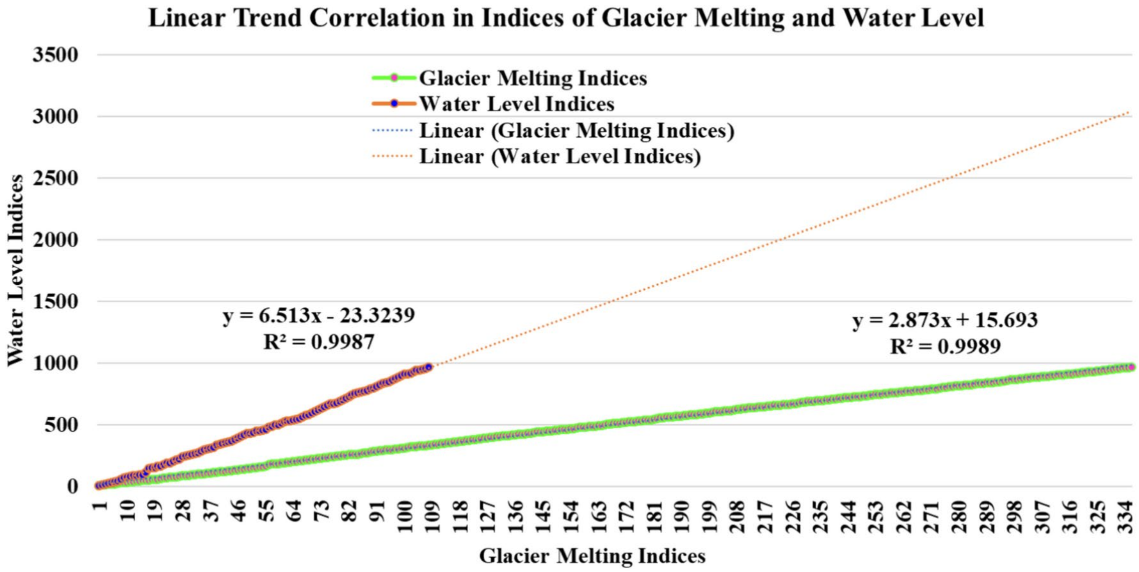

Fig. 11. Linear regression correlation between glacier melting and water level peak indices.

captured the variability in water levels based on the predictors used. This statistical validation confirmed the reliability of the model in explaining the observed impacts of water level, glaciers, and rainfall over the basin.

Hydrological analysis of the time lag and temporal dynamics of glacier melting and water level peaks

The average time difference between consecutive peaks in Baishui River Glacier No. 1 melting is approximately 2.87 h, indicating a rapid recurrence of glacier melting events (Fig. 10a and b). A linear regression analysis of the glacier melting peaks revealed a positive trend with an equation of $y = 2.873x + 15.693$. This suggests that, on average, the time between consecutive glacier melting peaks increased by approximately 2.873 h over time. The high R^2 value of 0.99 indicates an excellent fit of the linear model to the data, explaining approximately 99.89% of the variance in the glacier melting peak intervals (Fig. 11). Conversely, the average time difference between consecutive water level peaks (Fig. 10c and d) is estimated at approximately 6.5 h, indicating a slower recurrence than glacier melting events. The linear regression analysis of the water level peaks also revealed a strong positive trend, with an equation of $y = 6.513x—23.3239$ (Fig. 11). This suggests that, on average, the time between consecutive water level peaks increases by approximately 6.51 h over time. The high R^2 value of 0.99

indicates a good fit of the linear model to the data, explaining approximately 99.87% of the variance in the water level peak intervals.

These estimations demonstrate that although both glacier melting and water level fluctuations show positive trends over time, water level peaks typically occur at longer intervals than Baishui River Glacier No. 1 melting peaks do. This observation can be attributed to the time required for meltwater from the glacier to travel to the lake, resulting in delayed water level fluctuations. These delays, which are typically observed after 6.5 h, are due to varying climatic conditions and environmental parameters. The high R^2 values confirm the reliability of the linear models in accurately capturing the temporal patterns of peak occurrences in both datasets, confirming the robustness of the analysis. Additionally, the overall travel time for glacial meltwater to reach BMLV is approximately 4.16 h (Fig. 10e and f), with a distance of approximately 10 km. This travel time highlights the hydrological connectivity and the delay in peak water levels following glacial melting events. Understanding this time lag is critical for accurate water resource management on the downstream side and for predicting downstream impacts in the BMLV basin.

Calculation of water flux

We calculated water flux at different time scales ranging from five seconds to monthly. At the five-second scale, the immediate water flux was measured at 2.45 m^3/s. When interpolated to a five-minute scale, the average flux reached 10.818 m^3/min. On an hourly scale, the water flux was 1,766.38 m^3/hr, indicating the flow rate of glaciers melting into a lake and the water flux from the lake valley over shorter durations. The daily flux reached approximately 40,794.90 m^3/day, emphasizing the substantial daily contribution of Baishui River Glacier No. 1 melt water to the valley's water resources. Over a week, the cumulative water flux increased significantly to approximately 244,769.37 $m^3/week$, demonstrating sustained flow from the glacier with profound implications for valley hydrology and ecology. Interpolated to a monthly scale, the average flux was approximately 821,317.85 $m^3/month$, supporting long-term trends in glacial meltwater contributions to the valley as a continuous water source. These measurements highlight the critical role of glacial meltwater in sustaining the water resources of the valley.

Interpretation of the contributions of climate variables to glacier melting, water level, and water flux via the random forest model

The RF model was used to assess the impacts of climate variables on Baishui River Glacier No. 1 melting (Fig. 12a), water level (Fig. 12c), and water flux (Fig. 12e) in the Blue Moon Lake Valley. The findings confirmed how these parameters influence glacier melting, water level, and water flux, aiding in better water resource management and the prediction of climate change impacts[24]. Temperature emerged as the most influential variable in glacier melting, with a scaled contribution of 1.10. Higher temperatures accelerate Baishui River Glacier No. 1 melting by dictating the thermal conditions of glacier surfaces. Solar radiation closely followed with a scaled contribution of 1.08, as intense sunlight directly influences the energy balance of the glacier surface, enhancing the melting process. Evaporation, with a scaled contribution of 0.95 (Fig. 12b), impacts glacier melting by removing surface moisture, leading to increased melt rates. Relative humidity, with a scaled contribution of 0.64, indirectly affects glaciers by influencing air moisture levels; lower humidity levels could increase evaporation and sublimation rates, contributing to glacier melt. Pressure, with a scaled contribution of 0.32, influences weather patterns that affect glacier melting. Changes in atmospheric pressure also lead to temperature and precipitation variations,

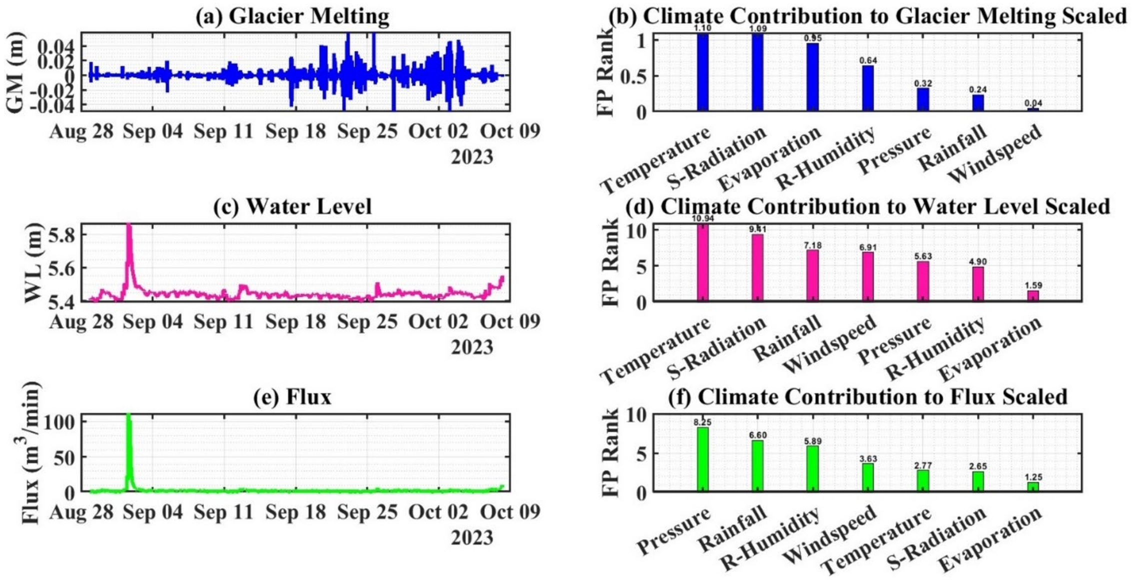

Fig. 12. Climate parameter contributions to Baishui River Glacier No. 1 melting (**a, b**), water level (**c, d**), and water flux (**e**, **f**)).

which impact the melt rate and increase water levels. Rainfall, with a scaled contribution of 0.24, directly adds precipitation over the glacier surface, enhancing melting, especially when the rain is warm. The wind speed, with a scaled contribution of 0.04, had a minimal impact on Baishui River Glacier No. 1 during the observation period. Although wind can contribute to sublimation and snow cover removal, its overall influence on the melting process was minor compared with that of other variables. This analysis highlights the diverse contributions of each climate variable to glacier melting, with temperature and solar radiation being the most significant drivers. Moreover, the RF model produced observed and predicted glacier melting data from climate parameters (Fig. 12b), demonstrating accurate predictions with an RMSE of 0.004 m (Fig. 13a).

Furthermore, the RF model revealed temperature as the most influential variable on water level fluctuations, with a scaled contribution of 10.947. This highlights the significant impact of temperature changes on hydrological processes such as glacier melting and evaporation rates, which directly and indirectly impact water level dynamics. Solar radiation closely followed, with a scaled contribution of 9.411, driving evaporation rates and influencing the water balance in aquatic systems. Rainfall ranked third, with a scaled contribution of 7.184 (Fig. 12d), directly impacting water levels in the lake by replenishing water resources. Atmospheric pressure ranked fifth, with a scaled contribution of 5.63, influencing weather patterns and precipitation levels. Wind speed, the fourth most influential variable, with a scaled contribution of 6.91, affects water levels through processes such as wind-driven waves and surface mixing. Relative humidity, with a scaled contribution of 4.907, indirectly influences water balance dynamics by affecting evaporation rates and atmospheric moisture content. Evaporation, identified as the least influential variable with a scaled contribution of 1.599, had a significant role in the water cycle but had a relatively minor direct effect on water level changes compared with precipitation and temperature during the study period. Additionally, the RF model produced observed and predicted water level data from climate parameters (Fig. 12d), demonstrating accurate predictions with an RMSE of 0.024 m (Fig. 13b).

When the water flux in the BMLV was analysed, pressure emerged as the most influential variable, with a scaled contribution of 8.25. Atmospheric pressure changes significantly influence wind patterns and surface water movement, impacting flux dynamics. Following pressure, rainfall had a scaled contribution of 6.6, directly impacting water volume and flux through direct inputs into the lake. Relative humidity, with a scaled contribution of 5.888, indirectly influences flux by affecting evaporation rates. Wind speed, contributing 3.63, drives surface currents and mixing, enhancing flux rates. Temperature, with a contribution of 2.77, influences evaporation rates and water density, affecting flux dynamics. Solar radiation, contributing 2.65, drives evaporation processes, impacting flux. Evaporation, with a contribution of 1.25, has a minor direct impact on flux but remains crucial for water balance. Overall, pressure and rainfall were the most significant drivers of lake flux according to the RF model. Finally, on the basis of the RF model, we developed observed and predicted water fluxes from climate parameters (Fig. 12f), which yielded accurate predictions with an RMSE of 0.084 m^3/min (Fig. 13c). These prediction data and plots support the dynamics of the Baishui River Glacier No.1, water level fluctuations and all water fluxes in the lake enhance the understanding of the phenomena among climate variables and water resources in the basin.

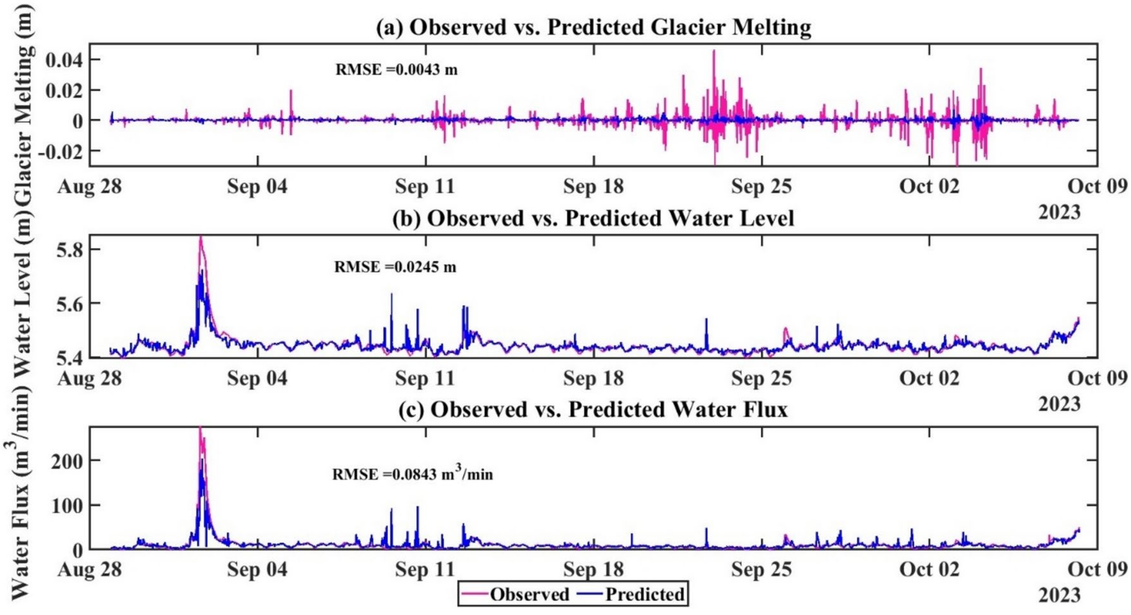

Fig. 13. Prediction of glacier melting (**a**), water level (**b**), and water flux (**c**) based on climate parameter scale ranks via the RF model.

Discussion

This study examined Blue Moon Lake Valley, a glacier-fed lake system, to understand its hydrological patterns, lake pulses, and implications for Baishui River Glacier melting, water level fluctuations, ecosystem behaviour, and water management. Prior research has also focused on the significance of these factors and phenomena[12–14]. Unlike other studies, our work places significant emphasis on the necessity of continuous lake pulse monitoring to grasp water availability and assess the impacts of climate change, which is supported by precise field data. These findings highlight the considerable influence of glacial meltwater, precipitation, temperature, and evaporation on water level fluctuations, necessitating sustained monitoring efforts[16]. These fluctuations, in turn, affect habitat availability and aquatic life, illustrating the interconnectedness of ecosystem processes in glacier-fed environments[17]. Additionally, we confirmed the susceptibility of glacier melting rates to climate change, stressing the need for proactive adaptation strategies[15]. Our analysis identified both periodic and nonperiodic patterns in BMLV water level fluctuations, emphasizing the complexity of the lake's water balance. Dominant frequencies and amplitudes suggest that recurring fluctuations are driven by seasonal changes, glacier melting, and climatic conditions[57]. For example, the maximum amplitude of 0.04 m and the mean amplitude of 0.02 m reflect the lake's sensitivity to environmental factors such as glacial melt, seasonal temperature variations, and precipitation levels. A detailed statistical analysis (Table 2, Fig. 7 & 8) demonstrated that fluctuations in temperature, solar radiation, atmospheric pressure, and wind speed directly impact glacier melt rates, which subsequently affect water inflow into the lake[58]. These parameters also influence evaporation and runoff, which are essential to the lake's water balance. Thus, the lake's water level is driven primarily by these interrelated climatic and glaciological factors. Similar findings were reported by Adrian[59], which lends further support to our conclusions. Throughout the observation period, the water levels fluctuated between 5.39 m and 5.86 m, with an average depth of 5.44 m, reflecting the dynamic water balance driven by glacier melting and atmospheric conditions. Significant variations in temperature, solar radiation, atmospheric pressure, precipitation, and wind speed were key drivers of the observed hydrological processes and ecosystem dynamics in the basin.

The observed fluctuations in water levels within BMLV reflect complex interactions among glacier melt, precipitation, and evaporation. The rate of change (ROC) of the water level revealed a median decrease of − 7.24E−06 m/min, indicating an overall declining trend in lake levels, although short-term fluctuations reached 0.011 m. These variations are closely linked to climatic and environmental drivers. Notably, intense precipitation events led to temporary increases in water levels, corroborating findings from other glacier-fed lakes ([7,16]). However, beyond the immediate rise in water levels, the broader implications of these fluctuations lie in their cumulative effects on downstream water availability, which is important for local agriculture and human consumption. The cumulative sum (CS) analysis confirmed the impact of these hydrological events, with a maximum CS value of 0.09 m during periods of increased precipitation and reduced evaporation. These results suggest that shifts in seasonal weather patterns, potentially exacerbated by climate change, are key drivers of hydrological variability in glacier-fed lakes. Similar trends are evident in other systems[15], highlighting the importance of long-term monitoring for water resource stability. For example, glacier melt has shown significant variability, with rates of change influenced by temperature, solar radiation, and precipitation. These fluctuations indicate not only a dynamic melt process but also the critical role that atmospheric conditions play in modulating glacier behaviour. Such variability directly impacts the volume and timing of water flow into the lake, with wider consequences for downstream water resource management and ecosystem services. Atmospheric pressure changes, ranging from − 0.34 to 0.31 hPa/min, also displayed moderate variability, and a maximum CS of 0.99 hPa indicated overall atmospheric stability. These stable conditions are important for maintaining consistent evaporation rates and influencing air circulation patterns, which in turn affect the lake's water balance. Temperature, another key factor, demonstrated fluctuations at the Baishui River Glacier No. 1 station ranging from − 0.74 to 1.01 °C/min. Such rapid temperature shifts are particularly critical in glacier-fed environments, where even slight temperature changes can result in accelerated melt, increased inflow into the lake, and subsequent changes in lake levels. The CS analysis revealed a consistent upwards trend in temperature, with implications for long-term water availability. This trend aligns with global warming projections by Liu et al.[60], supporting the need for adaptive strategies in water management. Solar radiation and its fluctuations from − 67.17 to 62.03 W/m^2/min played important roles in influencing both the melting rates and overall ecosystem productivity. Increased solar radiation accelerates glacier melt and evapotranspiration, impacting not only water availability but also photosynthesis and ecosystem dynamics in the basin. These findings are consistent with studies demonstrating the importance of solar energy in driving glacier-fed hydrological systems[61]. Similarly, the range of relative humidity (− 5.60% to 4.87%/min) suggests variability in atmospheric moisture, which directly influences evaporation rates and soil moisture, with wider consequences for the hydrological cycle. The observed fluctuations in wind speed and evaporation further show the interconnectedness of the lake's water balance. Wind-driven processes, such as wave formation, can influence surface evaporation, which in turn affects the lake's water levels. Evaporation rates, although exhibiting relatively small variations, still play a key role in overall hydrological dynamics, particularly in conjunction with temperature and wind speed changes.

The multivariate regression analysis highlights the critical influence of glacier melting and rainfall on water level fluctuations in the basin, with glacier melting showing a strong positive effect and a dominant driver. The significant positive effect of glacier melting (coefficient: 5.22 m, p value: 1.4792e-176) aligns with previous studies that highlighted the essential role of glacier-fed runoff in hydrological systems[7,16]). This finding is particularly relevant in the context of climate change, where accelerated glacier retreat could alter water availability patterns. Rainfall also contributed positively (coefficient: 0.465 m, p value: 0.034), albeit with a smaller impact than glacier melt did. This distinction suggests that while precipitation affects short-term fluctuations, glacial melt governs long-term water level dynamics, necessitating focused monitoring efforts on glacial processes for effective water resource management. The relatively strong model fit (RMSE: 0.039 m) further confirms the strength of these findings and provides reliable facts and figures for water management strategies in glacier-fed basins. The dominance of glacier melt in influencing water levels highlights the importance of anticipating melt patterns to ensure a sustainable water supply, especially as seasonal and annual glacier contributions may change due to warming temperatures[15]. Additionally, the results show the need to incorporate diverse environmental variables, such as soil moisture and temperature, into future models to capture the complex interactions influencing water availability. This aligns with other studies advocating for more comprehensive hydrological models[60,61].

Temporal analysis revealed distinct recurrence intervals for glacial melting and water level fluctuations, highlighting the intricate hydrological connectivity between the Baishui River Glacier No. 1 and the BMLV. The average interval of 2.87 h for glacier melting events illustrates the dynamic nature of glacier melting events in response to short-term climatic variations, particularly temperature and solar radiation changes during the late summer and early fall months. This pattern, combined with the gradual lengthening of intervals between water level peaks (average: 6.5 h), indicates that while glacier melt is rapid, the hydrological system delays peak water flow into the lake. This time lag of approximately 4.16 h, covering a distance of 10 km from the glacier to the lake, is significant for understanding the timing of water availability downstream. Accurate predictions of these delays are important for managing water resources and ecosystem health, especially during critical seasonal periods. Generally, the differing temporal patterns of glacier melting and water level fluctuations draw attention to the complexity of hydrological processes in glacier-fed environments. The gradual lengthening of intervals between significant water level fluctuations may signal changes in the frequency of meltwater contributions, potentially driven by border climatic shifts or glacier dynamics. Longer intervals between peaks could indicate reduced water availability, which impacts agriculture, human consumption, and ecosystem processes. These observations emphasize the importance of continuous monitoring to predict future trends and ensure water security in glacier-fed regions.

The analysis of water flux rates further illustrates the dynamic nature of the BMLV hydrological system. At the immediate timescale, the rapid rate of an average of 2.45 m^3/s at the five-second scale reflects the instantaneous response of the lake to glacial meltwater input. This high influx, when averaged over long timescales, results in sustained water contributions, such as 40,794.90 m^3/day, reinforcing the critical role of glaciers as major water sources for BMLV. The cumulative weekly and monthly fluxes highlight the consistent and substantial flow of glacial meltwater, emphasizing the importance of this input in maintaining the water level. These figures are important for forecasting water resource availability, particularly in light of potential future changes in meltwater volume due to warming temperatures.

The application of the random forest model revealed key climate variables influencing glacier melting, water levels, and water flux. Temperature emerged as the most influential variable across all analyses, indicating its role in accelerating glacier melting and driving hydrological processes. This finding highlights the vulnerability of glacier-fed systems to rising temperatures and the cascading effects on water availability. Solar radiation, evaporation, and relative humidity also significantly impacted glacier melting, indicating the multifaceted energy balance that governs ice loss. These interactions point to the need for integrated models that account for multiple environmental factors when predicting future melt rates and water availability. The RF model's results for water level fluctuations and flux further emphasize the complexity of climate-glacial interactions. In the case of water levels, temperature, solar radiation, and rainfall were identified as key drivers, indicating that both thermal and hydrological processes contribute to water level variability. For water flux, atmospheric pressure plays a central role in influencing wind patterns and surface water movement. This highlights the indirect but significant influence of atmospheric conditions on the hydrological dynamics of BMLV, reinforcing the need for comprehensive climate monitoring.

Limitations and recommendations

This study relies on the availability and comprehensiveness of collected data, which may be limited by factors such as accessibility, quality, and temporal coverage. The findings from this study may be context-specific to the Blue Moon Lake Valley, and caution should be exercised when applying them to other glacier-fed lake systems without considering their unique environmental settings. As a recommendation, the observation period should be extended to provide a more complete understanding of seasonal variability and long-term trends in hydrological processes, facilitating more effective analyses and predictions. Investing in enhancing data collection infrastructure and techniques, including advanced remote sensing technologies and expanded field observation networks, is essential for improving the quality, coverage, and spatial resolution of data. Encouraging collaboration among multidisciplinary teams, including hydrologists, climatologists, glaciologists, and ecologists, can provide better facts and figures of complex environmental systems and improve the accuracy of analyses. Establishing a sustained monitoring program to collect continuous data on climate variables, glacier dynamics, and hydrological parameters is vital for detecting trends, assessing long-term impacts, and informing adaptive management strategies. Conducting further research to investigate the limitations identified in this study and exploring alternative modelling approaches will contribute to advancing scientific contributions in the fields of glacier–lake dynamics and hydrology.

Conclusion

This study investigated the hydrological dynamics of the glacier-fed Blue Moon Lake Valley, showing the substantial impact of glacial melting on water level fluctuations, termed lake pulses. The findings show that temperature and solar radiation are key drivers of glacier melting and directly affect evaporation rates and water levels. The maximum observed amplitude of 0.043 m highlights the lake's sensitivity to climatic variations, including rainfall and atmospheric pressure. We found that glacier melting events occur approximately every 2.87 h, with water level peaks following a delay of approximately 4.16 h. This timing reflects the complexity of hydrological processes, which are influenced by subglacial hydrology and a distance of 10 km from Baishui River

Glacier No. 1 to BMLV. Furthermore, multivariate regression analysis revealed the significant role of glacier melting in shaping water levels, with rainfall also contributing positively but to a lesser extent. Additionally, water flux analysis revealed a continuous influx of glacial meltwater into BMLV, highlighting its essential role in maintaining hydrological balance. The random forest model identified temperature as the most influential factor affecting both Baishui River Glacier No.1 melting and water level fluctuations, with atmospheric pressure and rainfall also contributing significantly to water flux dynamics. This study significantly advances the understanding of the intricate dynamics between climate variables and hydrological processes in glacier-fed systems. The noticeable influence of glacial melting and rainfall on water level fluctuations highlights the need for integrated water resource management strategies in the face of climate change. This study clarifies how temperature and solar radiation affect glacier melt and systematically analyses water flow patterns. By understanding these mechanisms, we can better assess the resilience and vulnerability of these ecosystems. The findings and methods presented here are imperative for informing adaptive management practices and conservation strategies in glacial regions, especially as climate variability continues to increase.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. The authors declare no competing interests.

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Additional information

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