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Analysis of the Drivers of Water-Level Changes in the Yamdrok Lake Basin During 2000–2023

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Abstract

Yamdrok Lake, a typical closed inland lake located in the southern Tibetan Plateau, is highly sensitive to climate change and human activities. Although previous studies have reported a declining lake-level trend, the mechanisms underlying the sharp decline since 2005 remain debated. In particular, the disturbance effects of human activities, such as pumped-storage hydropower operations, have not been rigorously characterized, and quantitative attribution under the combined influence of multiple factors remains limited. This study aims to systematically identify the drivers of lake-level changes in Yamdrok Lake during 2000–2023 and to quantify the relative statistical explanatory power of climate change and human activities on lake-level fluctuations using Shapley R^2 decomposition. We integrated 24 years of hydrological, meteorological, remote-sensing, and hydropower-operation data. Cumulative anomaly analysis, multiple linear regression, and Shapley R^2 decomposition were employed to establish an attribution model incorporating rainfall, evaporation, temperature, glacier meltwater, and hydropower operation intensity, represented by annual electricity generation. The relative statistical explanatory power of these factors with respect to interannual lake-level changes (ΔH) was quantified using Shapley R^2 decomposition for different periods, representing the proportion of variance in ΔH explained by each factor within the regression framework rather than absolute physical volumetric contributions, including hydropower-operation and non-operation periods. Results show that the annual mean water level of Yamdrok Lake declined significantly during 2000–2023, with a cumulative decrease of 5.1 m and an accelerated decline after 2005. The dominant controls shifted from an early rainfall–evaporation regime to a systematic water deficit dominated by rising temperature. Temperature increased significantly at a rate of 0.03 °C yr^{-1} ($p < 0.05$) and constituted the fundamental driver of the long-term lake-level decline. During the hydropower-operation period (2000–2014), the five factors jointly explained 84.51% of the variance in interannual lake-level changes, with hydropower operation intensity (32.32%), temperature (27.98%), and glacier meltwater (26.54%) being the three largest contributors in terms of statistical explanatory power. During the non-operation period (2015–2023), temperature consistently remained the most important individual contributor, accounting for 34.3–49.5% of the explained variance depending on whether missing glacier meltwater data for 2022–2023 were extrapolated or excluded from the analysis. Warming affects lake levels through two pathways: it directly enhances lake-surface evaporation and simultaneously promotes continuous glacier retreat within the basin. Glacier area decreased by approximately 30.5 km^2 between 2000 and

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2021, thereby weakening the long-term resilience of glacier-meltwater recharge. Consequently, the lake system has shifted from a dynamic balance toward a persistent state in which water losses exceed water inputs. Overall, lake-level changes in Yamdrok Lake represent the combined effects of progressive warming-induced water deficits and superimposed disturbances associated with hydropower operations. By extending observations to 2023 and incorporating dynamic glacier-area and hydropower-operation indicators, this study clarifies the temporal shift in dominant drivers, revises the previous interpretation that attributed lake-level decline primarily to reduced rainfall, and provides a scientific basis for lake-water-resource security assessment and climate-change adaptation on the Tibetan Plateau.

Keywords: lake-level change; driving mechanisms; Yamdrok Lake; pumped-storage hydropower station; Tibetan Plateau; Shapley decomposition

1. Introduction

Lakes, as integral components of the Earth's surface system, possess both ecological and resource functions and serve as critical hubs within terrestrial–aquatic coupled systems. Variations in lake area or water level essentially reflect the dynamic balance among water inputs, outputs, and storage within a catchment, making lakes highly sensitive to climate change and human activities [1]. Previous studies have shown that global warming alters physical processes, including shortened ice-cover duration, changes in mixed-layer structure, and enhanced evaporation. If rainfall and runoff recharge do not increase correspondingly, lake water bodies may be at risk of shrinkage [2]. Meanwhile, human activities, such as hydraulic engineering, irrigation water withdrawals, and land-use changes, can disrupt catchment water-balance structures, thereby intensifying or superimposing climatic effects [3]. Therefore, studies of lake dynamics can not only provide a fundamental basis for water-resource utilization, agricultural irrigation, urban and rural water supply, and ecological conservation, but also serve as a window for revealing the coupled mechanisms of climate change and human activities, thereby advancing our understanding of regional environmental change.

The Tibetan Plateau, widely known as the "Asian Water Tower," contains numerous lakes with extensive surface areas and is among the regions most sensitive to global climate change. The hydrological processes of its lakes provide important indicators of regional and global climate variability. In recent decades, closed-basin lakes in the central Tibetan Plateau have exhibited substantial and spatially coherent expansion; however, the underlying mechanisms remain incompletely understood. Studies have shown that, from 1976 to 2010, the surface area, water level, and water storage of six major lakes, including Siling Co, increased significantly, with the expansion accelerating markedly after 1999. Lei et al. reported that climate change, particularly increased rainfall and reduced lake-surface evaporation, was the principal driver of lake expansion, whereas the contribution of glacier meltwater varied according to glacier coverage across catchments [4]. Similarly, studies of abrupt water-level changes in Qinghai Lake have suggested that frozen-ground degradation and changes in evapotranspiration may be important drivers of water-balance fluctuations [5]. Previous research has also indicated that lakes in the interior and northern Tibetan Plateau have generally expanded significantly over recent decades in response to climate warming and altered rainfall patterns. This expansion has mainly been attributed to increased glacier and snowmelt induced by rising temperatures, together with changes in regional rainfall. For example, since the beginning of the twenty-first

century, inland lakes across the Tibetan Plateau have generally shown rising water levels and expanding surface areas [6]. This phenomenon has commonly been attributed to increased net water inputs resulting from accelerated glacier melt and enhanced rainfall under a warming climate [7]. In addition, reduced lake-surface evaporation associated with increased land-surface temperature and atmospheric humidity, as well as weakened solar radiation, has also been recognized as an important contributor to lake expansion [8]. Recent studies suggest that Tibetan Plateau lakes may continue to expand in the future, posing substantial threats to regional infrastructure and ecosystems. Integrated remote-sensing observations and model projections indicate that, even under low-carbon emission pathways, the surface area of endorheic lakes on the Plateau may increase by more than 50% (approximately 20,000 km^2) by 2100. Such expansion could inundate more than 1000 km of roads, approximately 500 settlements, and extensive grasslands and croplands, highlighting the urgency of implementing effective mitigation and adaptation measures [9].

However, not all lakes on the Tibetan Plateau exhibit a consistent expansion trend. Yamdrok Lake, a well-known inland lake in southern Tibet, displays a water-level variation pattern that differs from that of most lakes on the Plateau. Based on topographic maps and satellite remote-sensing data, Bian et al. [10] found that lake area within the Yamdrok Lake Basin decreased gradually between 1975 and 2006, primarily because warming-induced evaporation exceeded rainfall recharge. Chuduo et al. [11] conducted a systematic analysis of changes in the area of Yamdrok Lake from 1972 to 2010 and found an overall shrinking trend, with variations in rainfall identified as the principal cause. Using Landsat imagery and the normalized difference water index, Yang et al. [12] extracted lake-surface area information and showed that the areas of Yamdrok Lake, Kongmu Co, Bajiu Co, and Chen Co decreased, whereas those of Pumo Yumco and Duo Co expanded. This divergence was mainly attributed to an imbalance between intensified evaporation and insufficient rainfall recharge, while lake-surface evaporation and ice–snow meltwater were also considered non-negligible factors.

Historical observations and several previous studies have indicated that the water level of Yamdrok Lake has fluctuated and, in some periods, declined. These changes are associated with the particular balance among basin rainfall, evaporation, glacier-meltwater recharge, and human activities. Chuduo et al. [13], using hydro-meteorological data, found that the water level of Yamdrok Lake exhibited a fluctuating downward trend from 1974 to 2009, primarily driven by natural factors, including rainfall variability, rising temperature, and changes in evaporation, while human activities exerted relatively limited effects. Mima Tsering et al. [14], through cumulative anomaly analysis of rainfall and evaporation, found that water-level variations during 1974–2005 were mainly controlled by rainfall and evaporation, whereas human activities may have become the primary driver of lake-level decline after 2005. Tang et al. [15] analyzed water-level, rainfall, evaporation, and temperature data for the period 1974–2019 and concluded that the fluctuating decline in lake level was primarily associated with rainfall and other factors, including human activities. They further observed that the dominant influencing factors varied among seasons and time periods. Ye et al. [16] also identified rainfall and evaporation as the main drivers of water-level changes in Yamdrok Lake. Collectively, these studies suggest that decreasing or fluctuating rainfall, coupled with increasing lake-surface evaporation caused by rising temperatures, has resulted in water-level dynamics at Yamdrok Lake that differ from those of other lakes on the Tibetan Plateau.

Although previous studies have investigated water-level variations in Yamdrok Lake and their potential driving factors over different periods, substantial discrepancies remain among their conclusions. Moreover, existing research has primarily focused on the effects of changing climatic conditions on lake levels, while the impacts of human activities and glacier meltwater have received comparatively little attention. Consequently, a unified scientific understanding of lake-level changes in Yamdrok Lake and their physical mechanisms remains lacking. To address these gaps, this study employs cumulative anomaly analysis and multiple regression analysis to systematically investigate water-level trends in Yamdrok Lake during 2000–2023. The relative contributions of key climatic factors, including rainfall, temperature, and evaporation, as well as the electricity generation of the Yamdrok Hydropower Station, to hydrological changes in the lake are quantitatively assessed. The results are expected to provide an important scientific basis and reference for evaluating regional water-resource security and addressing the impacts of future climate change.

2. Materials and Methods

2.1. Data Sources

Yamdrok Lake is located in Gonggar County and Langkazi County, Shannan City, Tibet Autonomous Region, China, and is one of the largest closed inland lakes on the Tibetan Plateau. It extends from 90°08′ to 91°45′ E and from 28°27′ to 29°12′ N. The lake surface lies at an elevation of 4441 m above mean sea level (M.S.L.), and the basin covers an area of approximately 6100 km^2. All elevations in this paper are referenced to mean sea level (m a.s.l.). The lake is situated within an intermontane basin on the northern foothills of the Himalayas and is surrounded by perennial snow-covered mountains and glaciers, with peak elevations exceeding 7000 m a.s.l.

Yamdrok Lake has a surface area of approximately 569.37 km^2 and is the largest inland lake on the northern slope of the Himalayas. Together with Nam Co and Mapam Yumco, it is recognized as one of the three sacred lakes of Tibet. The lake has a mean water depth of approximately 23.6 m and a maximum depth of 60 m, with a lake-surface elevation of 4441 m a.s.l. The region has a mean annual temperature of 2.9 °C and mean annual rainfall of approximately 426 mm [17]. It is characterized by a semi-arid climate of montane shrub–steppe in southern Tibet. The lake basin is mainly underlain by continental clastic rocks of the Middle–Upper Jurassic, clastic rocks of the Upper Cretaceous, and Holocene coarse sand and silt deposits [18]. The Yamdrok Lake system also includes four associated lakes: Kongmu Co, Bajiu Co, Chen Co, and Pumo Yumco. The principal characteristics of the major lakes within the Yamdrok Lake Basin are summarized in Table 1. Lake water is mainly supplied by glacier meltwater and rainfall, with glacier meltwater accounting for approximately 16% of the total water input [19]. The basin location and configuration are shown in Figure 1.

Table 1. Parameters of the major lakes in the Yamdrok Lake Basin.

Name	Lake Surface Elevation (m a.s.l)	Lake Surface Area (km^2)
Yamdrok Lake	4441.0	569.37
Kongmu Co	4441.6	37.8
Bajiu Co	4506.0	30.1
Pumo Yumco	5010.0	293.7
Chen Co	4438.0	36.5

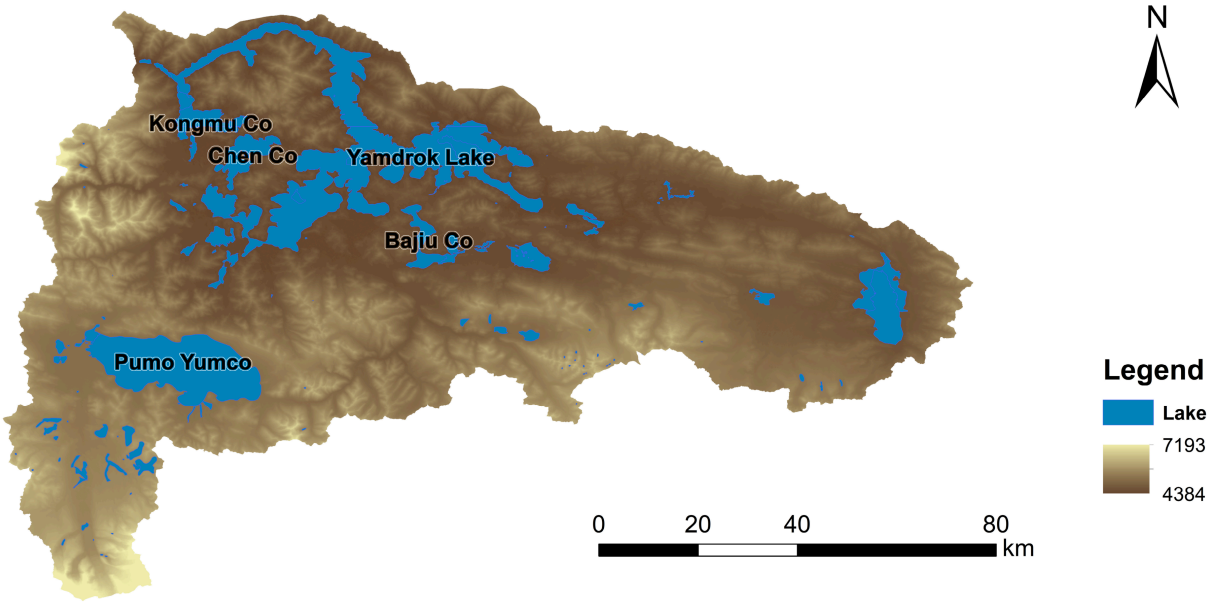


Figure 1. Map of the Yamdrok Lake Basin.

This study investigated lake-level variations using hydrometeorological variables, including rainfall, temperature, and evaporation. Meteorological data on rainfall and temperature for 2000–2023 were obtained from the Langkazi National Meteorological Station, located at an elevation of approximately 4454 m a.s.l. Lake-level and evaporation data for the same period were obtained from the Baidi Hydrological Station, located in Baidi Township, Langkazi County, at an elevation of approximately 4500 m a.s.l. Evaporation data were observed at the same station using a combination of 20 cm diameter evaporation pans and E-601 type evaporators, following the standard protocols of the China Hydrological Monitoring Standards. To ensure data consistency across the study period, evaporation measurements from the two types of equipment were harmonized using established conversion coefficients. The straight-line distance between the two stations is approximately 30 km. Given the sparse distribution of observational stations across the Tibetan Plateau, the use of data from nearby meteorological stations for hydrological analyses is common practice in this region. To address the spatial mismatch between the two stations, and following previous studies in the Yamdrok Lake Basin, meteorological observations from the Langkazi station were directly used to represent basin-scale climatic conditions, without corrections for distance or elevation, because both stations are located within the same climatic zone.

For rainfall data processing, daily rainfall values below 0.1 mm were treated as no-rainfall days. In addition, annual electricity-generation data from the Yamdrok Hydropower Station for 2000–2014 were incorporated into the analysis of lake-level changes. Lake-area data were derived from high-resolution multispectral Sentinel-2 imagery. Water bodies were extracted using the Normalized Difference Water Index (NDWI), and appropriate threshold values were applied. The extracted lake boundaries were subsequently refined through visual interpretation to ensure the accuracy of lake-area estimates. To minimize the influence of seasonal lake-level fluctuations, images with low cloud cover acquired during the relatively hydrologically stable late flood season, from October to December, were selected for lake-area extraction.

To address localized missing values in the historical meteorological and hydrological observation records, linear interpolation was applied. The interpolation procedure was implemented according to the physical meaning of each variable and the local geographical context. Specifically, daily rainfall records of "0" were retained because they represent

valid observations indicating the absence of rainfall. In contrast, for hydrometeorological variables with temporal continuity, such as evaporation, records of "0," invalid missing values, or anomalous values were treated as missing data and were filled by linear interpolation using valid observations from adjacent time periods. For the interpolated variables, the percentage of missing data was less than 5% for evaporation and less than 3% for lake level. The maximum continuous gap length that was interpolated was less than 7 days for both variables.

2.2. Research Methods

Hydrological trend variation was analyzed using lake water level as the target variable. A simple linear regression model was applied to assess trends in annual rainfall, temperature, and evaporation, with the statistical significance of the trends evaluated using significance tests.

$$y = w_0 + w_1 x \tag{1}$$

In Equation (1), where y denotes the hydro-meteorological factor, w_1 is the regression coefficient, x represents time, and w_0 is the intercept.

Changes in water level result from the cumulative effects of multiple years. Therefore, cumulative anomaly analysis was used to examine the relationships between individual factors and water-level variations, thereby providing a clearer characterization of their impacts on water-level change [20], as follows:

$$\Delta X(i) = \sum_{1}^{n} (X_i - \overline{X}) \tag{2}$$

In Equation (2), $\overline{X}$ denotes the long-term annual mean, X_i represents the value in the ith year, and $\Delta X(i)$ denotes the cumulative anomaly in the ith year.

Multiple linear regression was used to establish the relationships between the influencing factors and water level, as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p \tag{3}$$

In Equation (3), Y denotes the multi-year water-level series, β_p represents the regression coefficient(s), and X_p denotes the factors considered in the correlation analysis.

During the preparation of this manuscript, the authors used ChatGPT-5.6 for language polishing and proofreading. The authors have reviewed and edited all AI-generated output and take full responsibility for the final content of this publication.

3. Results

3.1. Characteristics of Climate Change

Analysis of the interannual variation in annual mean temperature during 2000–2023 indicates that, under intensified global warming, the annual mean temperature in the Yamdrok Lake region exhibited a significant increasing trend ($p < 0.05$), at a rate of 0.03 °C/a. The warming was particularly pronounced during 2013–2023, with an average annual increase of 0.0288 °C. The highest annual mean temperature, 4.6 °C, occurred in 2021, while the multi-year average was 3.7 °C. Monthly mean temperatures displayed clear seasonal variation, with the lowest values in winter and the highest values in summer.

Annual rainfall data for 2000–2023 were analyzed (Figure 2). The results indicate substantial interannual fluctuations in rainfall, characterized by alternating wet and dry years. The minimum annual rainfall, approximately 239.5 mm, occurred in 2009, whereas the maximum, 552.6 mm, was recorded in 2008. Linear trend analysis showed a non-significant decreasing trend in annual rainfall during the study period ($p > 0.05$), with an average decrease of approximately 1.63 mm/a. In terms of intra-annual distribution, rainfall was mainly concentrated from June to September, with July and August representing the peak rainfall months and monthly rainfall exceeding 100 mm. In contrast, the period from November to the following April constituted a prolonged dry season, during which monthly rainfall was extremely low and close to 0 mm in most months.

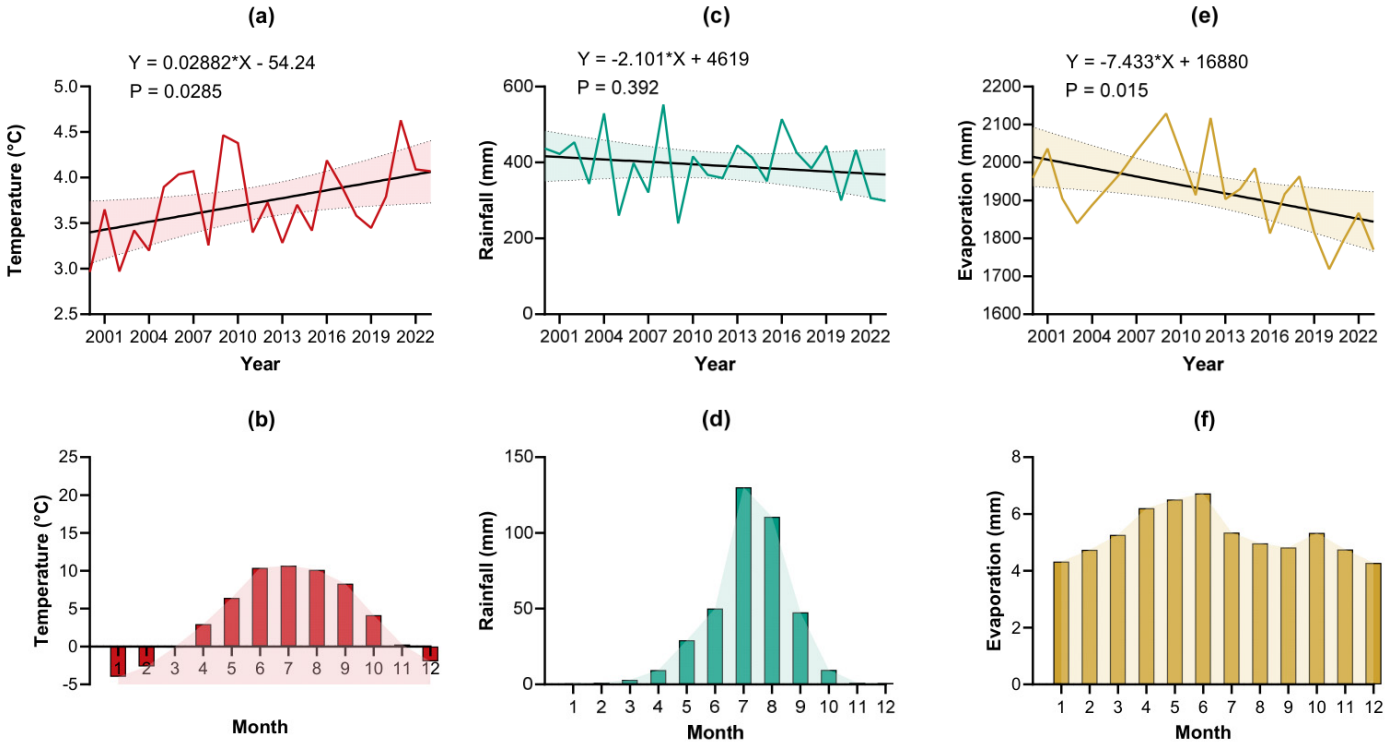


Figure 2. Interannual Variations and Seasonal Distribution of Temperature, Rainfall, and Evaporation During 2000–2023, (**a**) Annual mean temperature showed a significant increasing trend (Y = 0.02882X − 54.24, P = 0.0285); (**b**) Monthly mean temperature exhibited a unimodal distribution with the highest values in summer months; (**c**) Annual total rainfall showed no significant trend (Y = −2.101X + 4619, P = 0.392); (**d**) Monthly rainfall distribution was relatively uniform throughout the year with slight variations; (**e**) Annual total evaporation showed a significant decreasing trend (Y = −7.433X + 16,880, P = 0.015); (**f**) Monthly evaporation displayed a clear seasonal pattern with peak values during warmer months.

Annual evaporation, as observed using 20 cm evaporation pans and E-601 evaporators at the Baidi Hydrological Station, exhibited a significant decreasing trend ($p < 0.01$), declining by approximately 7.31 mm/a. Evaporation in most years fluctuated between 1800 and 2100 mm, with relatively modest interannual variability. This declining trend in observed evaporation occurred concurrently with a significant increase in temperature (Figure 2), presenting an apparent contradiction that is consistent with the well-documented "evaporation paradox" [21]. On the Tibetan Plateau, this phenomenon has been widely confirmed by multiple studies [22–24]. The decrease in pan evaporation is primarily attributed to a concurrent decrease in wind speed, which has been identified as the dominant factor, together with increasing vapor pressure and decreasing solar radiation. These changes collectively offset the enhanced evaporative demand driven by rising temperatures [23,24].

Monthly evaporation displayed a typical unimodal pattern: it gradually increased from low values in January, peaked in June–July, and subsequently declined toward December. Evaporation was lowest in winter (December–February), ranging from 4 to 5 mm; it increased rapidly in spring (March–May); reached its annual maximum in summer (June–August), with peak values of approximately 6–7 mm in June–July; and decreased during autumn (September–November), although remaining higher than winter levels.

3.2. Hydrological Variation Characteristics

The water level of Yamdrok Lake, the focus of this study, underwent substantial changes over the past two decades. As shown in Figure 3, the annual mean lake level exhibited a pronounced long-term declining trend from 2000 to 2023. During 2000–2004, the water level remained relatively high, reaching nearly 20 m at its maximum, which was substantially above the multi-year mean of approximately 16.8 m. After reaching its peak in 2004, the annual mean water level showed a persistent and significant decline.

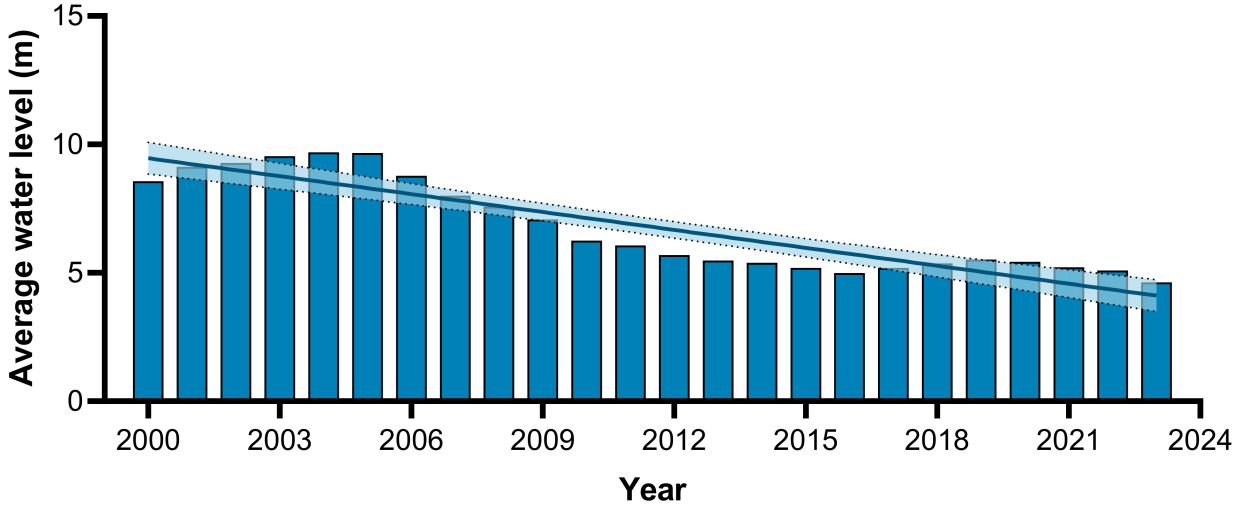


Figure 3. Annual changes in the water level of Yamdrok Lake during 2000–2023.

Although slight rebounds occurred in certain years, such as 2016–2018, the overall trend line clearly indicates a continuing decline in lake level. Since 2005, the water level has decreased sharply and has remained below the multi-year average since 2008. By 2023, it had fallen to the lowest level observed during the study period, representing a total decline of 5.1 m. All lake-level data used in the following analyses are annual mean water levels.

3.3. Hydrometeorological Correlation Analysis

Previous studies have demonstrated that rainfall is one of the major climatic factors influencing water-level variations in Yamdrok Lake. To preliminarily characterize the relationship between rainfall and lake-level changes, we compared the cumulative anomalies of lake water level derived from observations at Baidi Station with the cumulative anomalies of rainfall recorded at the Langkazi Meteorological Station for the period 2000–2023. The results are presented in Figure 4.

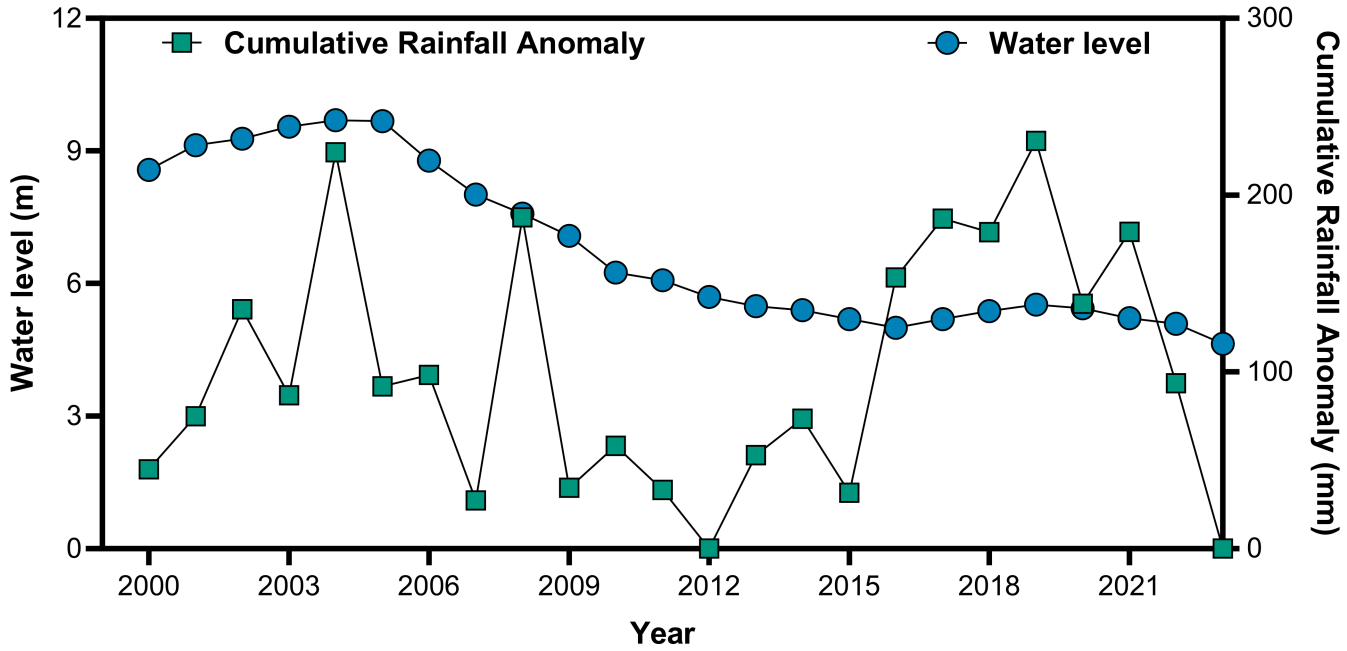


Figure 4. Comparison of Cumulative Rainfall Anomalies and Water Levels.

Overall, the cumulative anomalies of lake water level and rainfall exhibited relatively consistent variations during certain periods. In particular, the two variables showed relatively pronounced in-phase changes during 2000–2004 and 2019–2022, corresponding to periods of rising and declining lake levels, respectively. This finding suggests that variations in rainfall may have exerted a measurable influence on lake-level fluctuations during these periods.

However, the two variables did not remain consistent throughout the entire study period. A clear divergence between the cumulative anomalies of lake water level and rainfall occurred during 2005–2015, indicating that rainfall variability alone cannot fully explain the interannual fluctuations in the water level of Yamdrok Lake. This divergence may have resulted from the combined effects of multiple factors, including evaporation, glacial meltwater, runoff contributions from the catchment, disturbances associated with hydropower-station operations, and the lake's own water-storage and regulation capacity. Accordingly, rainfall is regarded in this study as one of the important factors affecting lake-level variations, rather than the sole controlling factor.

It should be noted that Figure 4 illustrates the correspondence between rainfall and lake-level variations based on cumulative anomalies at the interannual scale, and is primarily intended to identify their stage-specific co-variation over the multi-year period. Because lake-level responses to rainfall inputs may exhibit a certain time lag, the lagged relationship between rainfall and lake water level is further examined at the monthly scale in the following sections. This approach avoids conflating variations in interannual cumulative anomalies with intra-annual lagged responses.

As shown in Figure 5, a comparison of the cumulative evaporation anomaly and lake-level variations during 2000–2023 indicates that, before 2012, the two variables generally exhibited opposite trends: lake water levels declined as evaporation increased, and vice versa. However, after 2012, lake water levels continued to decrease despite a reduction in evaporation. This finding indicates that the decline in the water level of Yamdrok Lake cannot be explained by variations in evaporation alone.

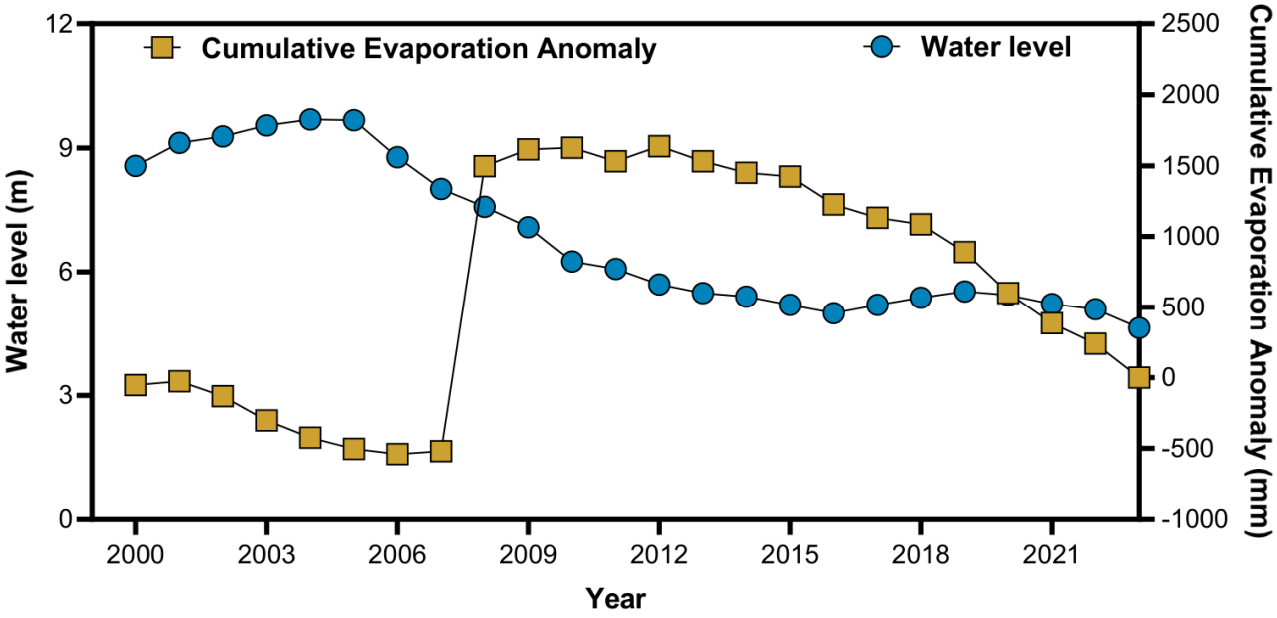


Figure 5. Comparison of cumulative evaporation anomalies and water levels.

As shown in Figure 6, the cumulative anomalies of lake water level and temperature exhibit a certain degree of correlation. During 2000–2004, the two variables displayed opposite trends: lake water levels increased while the cumulative temperature anomaly decreased. From 2005 to 2010, the cumulative temperature anomaly increased, whereas lake water levels continued to decline. As indicated in Figure 5, the cumulative evaporation anomaly also increased during this period, showing a trend broadly consistent with that of the cumulative temperature anomaly. These results suggest that temperature influences lake-level variations through its integrated effects on the lake's water-heat balance—including enhancing evaporative demand and driving glacier melt—rather than through a direct, one-to-one relationship with observed pan evaporation.

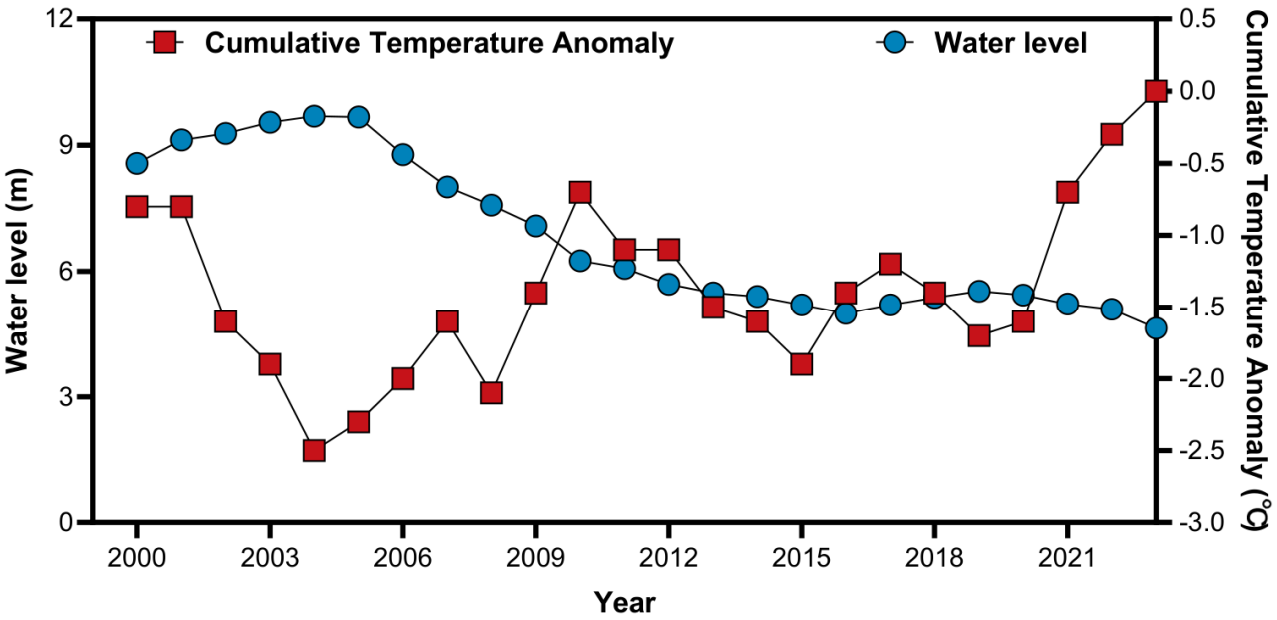


Figure 6. Comparison of cumulative temperature anomalies and water levels.

The cumulative anomaly series are used solely to visually illustrate the stage-specific fluctuation characteristics of individual variables and are not used for statistical inference

or attribution analysis. All quantitative conclusions regarding correlations and contribution rates are derived from stationarized data. To further investigate the response of interannual lake-level variations to meteorological factors, the difference in water level between adjacent years was calculated as the interannual water-level change, ΔH. Pearson correlation analyses were then conducted between ΔH and concurrent rainfall, evaporation, and temperature. The results are presented in Table 2.

Table 2. Correlation between water level and weather factors.

Influencing Factor	r Value	*p* Value
Rainfall	0.178	0.417
Evaporation	−0.313	0.146
Temperature	−0.494	0.017

The results show that the correlation coefficient between interannual water-level change and rainfall was 0.178 ($p = 0.417$), indicating a very weak and statistically insignificant positive correlation. The correlation coefficient between water-level change and evaporation was −0.313 (*p* = 0.146), indicating a weak but insignificant negative correlation. In contrast, water-level change was moderately and negatively correlated with temperature ($r = -0.494$, $p = 0.017$), which was significant at the 0.05 level. This indicates that, in years with higher temperatures, water-level changes were more likely to decrease or show a decline. This relationship may suggest that temperatures contribute to lake-level declines by altering the lake's overall water-heat balance, which includes increasing the potential for evaporation and accelerating glacier retreat, even when observed pan evaporation paradoxically decreases. Overall, however, the linear explanatory power of individual meteorological factors for water-level variation is limited, and none of these factors alone can fully explain the causes of water-level changes.

The correlation between rainfall and water level was found to be extremely weak and statistically non-significant at the annual scale, suggesting that rainfall alone cannot explain the interannual water-level variability within the current temporal resolution. However, given that previous studies identified rainfall as a dominant controlling factor, we hypothesized that the lake's hydrological response to rainfall may involve a certain time lag, ranging from several days to weeks. To test this hypothesis, we examined the mean monthly water level of Yamdrok Lake over the period 2000–2023 (Figure 7).

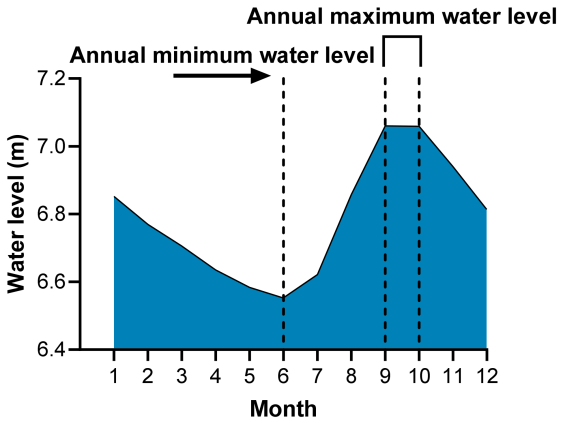


Figure 7. Annual changes in the water level of Yamdrok Lake. Downward arrows indicate annual maximum and minimum water levels, respectively.

The results reveal a pronounced seasonal cycle in the multi-year average water level. Specifically, the water level declines progressively from January to June, reaching its

annual minimum in June, then rises sharply from July onward, peaks during September–October, and subsequently recedes. This intra-annual pattern closely mirrors the seasonal distribution of basin rainfall and the associated hydrological response during the flood season. In the transition from spring to early summer, reduced rainfall coupled with enhanced evapotranspiration leads to a sustained decline in lake level. With the onset of the main rainy season, concentrated rainfall substantially increases water input, driving a rapid rise in lake level to its annual maximum. Following the retreat of the monsoon in late autumn and early winter, the water level gradually falls back. Collectively, these observations indicate that the seasonal evolution of the lake level is primarily governed by the regional monsoon rainfall, exhibiting a typical "low-water–high-water–recession" hydrological regime. Notably, the rainfall peak occurs in July–August, approximately two months ahead of the water-level peak, which clearly demonstrates a lagged response of Yamdrok Lake's water level to rainfall inputs.

3.4. Analysis of Anthropogenic Driving Factors

The above analysis indicates that rainfall, evaporation, and temperature cannot independently explain the causes of water-level decline, suggesting that other factors may also be involved. Water-level variation in Yamdrok Lake is a complex process influenced by multiple interacting factors. In addition to the natural regulation of water balance by meteorological factors, the lake water level may also be affected by hydropower station operation and scheduling, as well as glacier meltwater recharge. Therefore, this study further incorporates power generation and glacier meltwater volume as variables to quantitatively assess the combined effects of meteorological factors, glacier meltwater, and anthropogenic regulation on water-level changes.

Four 22.5 MW pumped-storage generating units and one 22.5 MW conventional hydropower generating unit were installed at the Yamdrok Lake Hydropower Station, giving a total installed capacity of 112.5 MW. The first of the four pumped-storage units began commercial operation in June 1997 [25], while Unit 5 was connected to the grid in December 2004. At full-load operation, the water flow rate required for electricity generation by a single unit is 3.16 m^3/s. As shown in Figure 8, electricity generation at the Yamdrok Lake Hydropower Station exhibited an initial increase followed by a decline during 2000–2014. From 2000 to 2006, annual electricity generation increased continuously and rapidly, rising steadily from 1.34×10^8 kW·h in 2000 to a historical peak of 6.55×10^8 kW·h in 2006. Beginning in 2011, annual electricity generation experienced a sharp decline. It dropped abruptly to approximately 1.44×10^8 kW·h in 2012, further decreased to approximately 3.91×10^7 kW·h in 2013, and ultimately fell to an extremely low level of only approximately 1.24×10^7 kW·h in 2014, approaching zero. The operation of the Yamdrok Lake pumped-storage hydropower station has bidirectional and stage-dependent effects on lake water storage. During periods of abundant water supply and low electricity demand in the Lhasa power grid, the station pumps water from the Yarlung Tsangpo River into Yamdrok Lake; during dry periods and peak-load conditions, water is released for electricity generation [26]. On the one hand, during electricity generation, lake water is discharged through the station, potentially reducing lake storage and causing a short-term decline in lake level. On the other hand, when the station pumps or diverts water from the Yarlung Tsangpo River into Yamdrok Lake, lake storage may increase. Therefore, the impact of the pumped-storage station on Yamdrok Lake cannot simply be regarded as continuous water loss; rather, it may enhance lake-level fluctuations through alternating water replenishment and discharge. Consequently, electricity generation or spillage volume alone cannot fully characterize the net effect of station operation on changes in lake water storage. The annual electricity generation and annual spillage volume used

in this study were obtained from operational statistics of the Yamdrok Lake Hydropower Station. Annual electricity generation primarily reflects the operational load and electricity-generation intensity of the station, whereas annual spillage volume is an annual statistical indicator provided by the station and may, to some extent, reflect variations in water discharge or operational water regulation. However, the specific statistical definition of "spillage volume" was not clarified in the original data. It is therefore uncertain whether this indicator includes only turbine discharge for electricity generation or also includes spilled water, overflow discharge, and other non-electricity-generation releases. Accordingly, this study does not directly equate spillage volume with turbine flow, net lake outflow, or net water consumption attributable to human activities; instead, it is used only as an indicator of the intensity of hydropower-station operational disturbance. Because annual data on pumped water volume, replenishment volume, and net water transfer volume for the Yamdrok Lake Hydropower Station are currently unavailable, this study does not estimate discharged water volume from electricity generation, nor does it quantitatively partition the net contribution of station operation to changes in Yamdrok Lake water storage. Therefore, electricity generation and annual spillage volume are used only to characterize the intensity and interannual variation in operational disturbance. Years with higher electricity generation and spillage volume may correspond to more intensive engineering regulation; however, the actual direction and magnitude of their effects on lake level still depend on the combined effects of concurrent water pumping into the lake, water discharge, spillage, and natural hydrological conditions. The relevant statistical results should thus be interpreted as the extent to which hydropower-station operational indicators explain part of the variability in Yamdrok Lake water-level fluctuations, rather than as physical contribution rates in a strict water-balance sense.

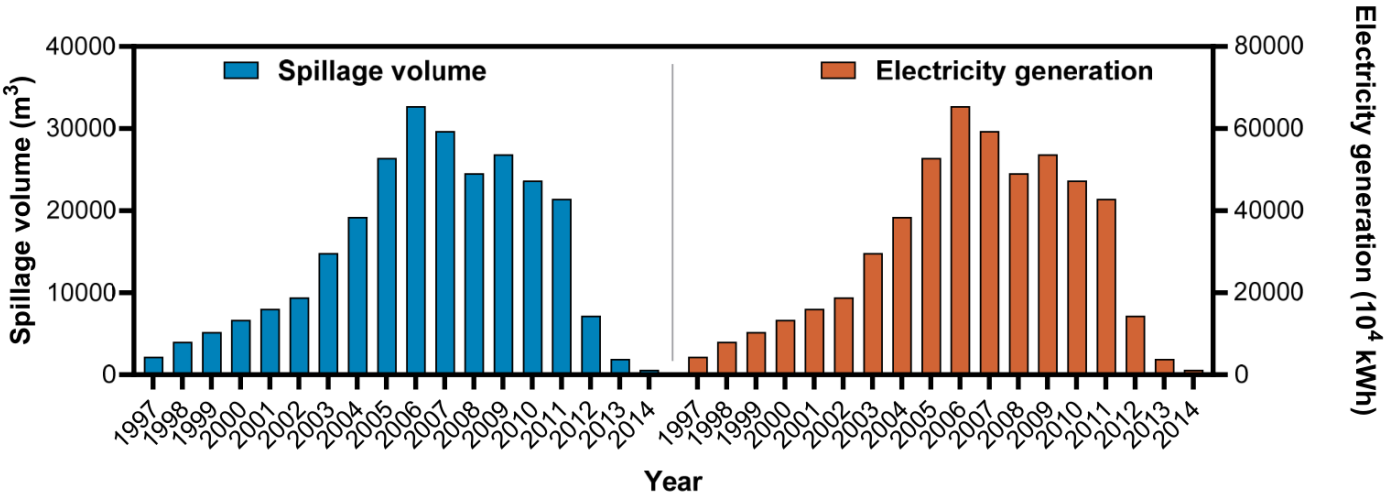


Figure 8. Electricity Generation and Spillage Volume of the Yamdrok Lake Hydropower Station, 1997–2014.

It should also be noted that the effects of Yamdrok Lake Hydropower Station operation on lake level do not depend solely on electricity generation, but are closely related to water diversion, pumping volume, and net water replenishment during station operation. As annual data on water diversion, pumping, and net replenishment for the Yamdrok Lake Hydropower Station during 2000–2023 are difficult to obtain, this study was unable to establish a water-balance-based model of the station's impact. Therefore, in the analysis of human activities, annual electricity generation is used only as an indirect proxy for the intensity of hydropower-station operational disturbance to examine its statistical relationship with lake-level fluctuations. The regression explanatory power of this variable

reflects only the statistical ability of electricity-generation-related operational disturbance to explain variability in lake-level fluctuations; it cannot be directly interpreted as the physical contribution of net water replenishment or net water consumption by the hydropower station to changes in lake level.

3.5. Glacier Meltwater Analysis

Given the glacier cover surrounding the Yamdrok Lake basin, glacier meltwater is an important source of recharge and has a non-negligible influence on lake-level variations. According to Zhao Yongli [27], the glacier area in the Yamdrok Lake basin decreased substantially by 58.45 km^2 between 1977 and 2012. Further monitoring of the core glacierized area on the western shore of Yamdrok Lake by Zhaxi Ouzhu et al. [28] showed that glacier area in this region decreased significantly by 18.57% between 1987 and 2021, with the temperature-driven retreat having continued to accelerate in recent years. This long-term and irreversible glacier-area retreat provides the basis for the dynamic decline in the meltwater-producing area in the present model. Therefore, although increasingly frequent recent extreme high-temperature events have sharply increased the ablation rate per unit area, the increase in total basin meltwater is physically constrained by the substantial reduction in the effective meltwater-producing area, i.e., the remaining glacier area. To avoid overestimation associated with the use of a single fixed glacier area in long-term hydrological simulations, detailed remote-sensing monitoring data on glacier-area changes on the western shore of Yamdrok Lake were used to construct a dynamic glacier-area series for the study area.

According to the above study, glacier retreat in the study area showed a distinct two-stage pattern. During 1987–2006, glaciers underwent a relatively stable retreat period, with a retreat rate of 0.37 km^2/a. During 2009–2021, however, glacier retreat accelerated, and glacier area remained continuously below its long-term average, with the retreat rate increasing to 0.88 km^2/a. Using the actual basin-wide glacier area of 195.91 km^2 in 2010, derived from the Second Chinese Glacier Inventory, as the absolute spatial reference, an annual continuous time series of glacier-area dynamics for the entire basin during 2000–2021 was reconstructed using proportional upscaling and piecewise linear interpolation. The results are presented in Table 3.

Table 3. Glacier Area in the Yamdrok Lake Basin During 2000–2021.

Year	Glacier Area (km^2)	Stage (a)	Area Change (km^2)
2000	207.07		
2001	206.32		
2002	205.57	2000–2005	−3.74
2003	204.83		
2004	204.08		
2005	203.33		
2006	202.58		
2007	200.94		
2008	199.31	2005–2010	−7.42
2009	197.67		
2010	195.91		
2011	194.15		
2012	192.39		
2013	190.63	2010–2015	−8.81
2014	188.86		
2015	187.10		
2016	185.34		
2017	183.58		
2018	181.82	2015–2021	−8.8
2019	180.06		
2020	178.30		
2021	176.54		

A degree-day factor (DDF) method was used to estimate glacier meltwater in the Yamdrok Lake basin. Because no locally observed DDF values are available for the study area, this study adopted a DDF of 10.97 mm·d^{-1}·°C^{-1} [29], based on findings from previous studies in the Yarlung Tsangpo River basin. The Yarlung Tsangpo River basin is geographically close to the Yamdrok Lake basin and shares broadly similar climatic conditions and glacier-ablation characteristics. The calculation results are shown in Figure 9.

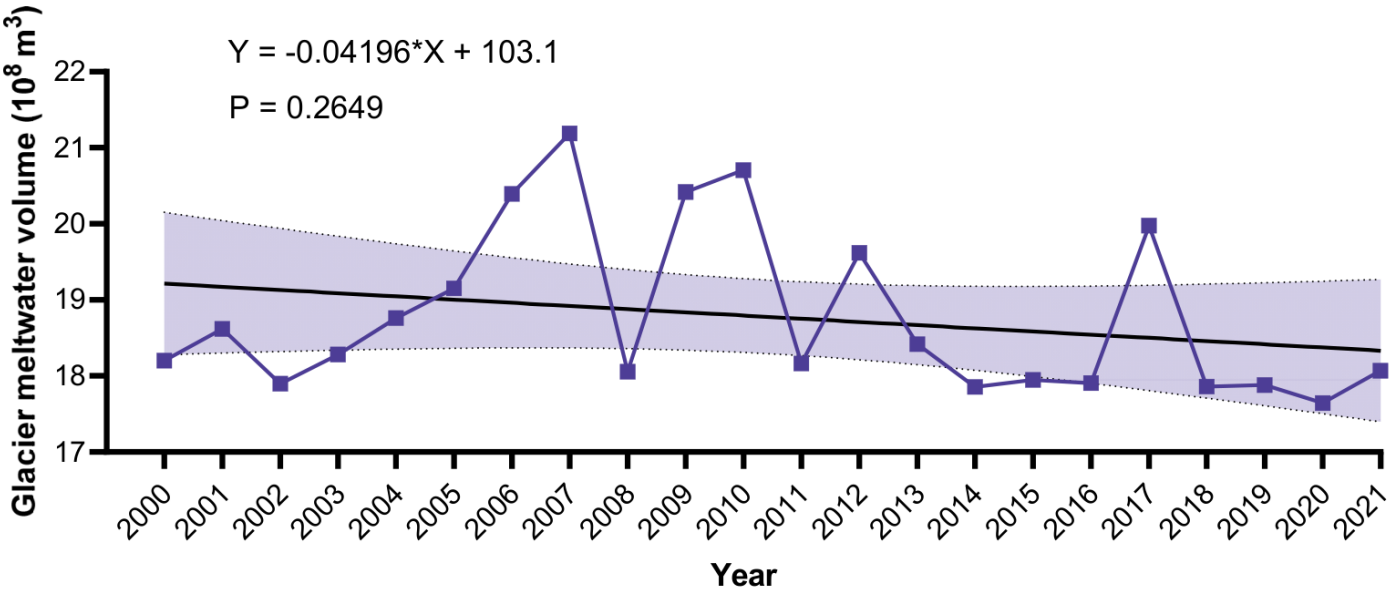


Figure 9. Glacier Meltwater in the Yamdrok Lake Basin, 2000–2021.

The results indicate that glacier meltwater in the Yamdrok Lake basin remained at a relatively high level during the study period, with annual meltwater volumes fluctuating approximately between 1.75×10^9 and 2.12×10^9 m^3. This demonstrates that glacier meltwater is a non-negligible component of water supply within the basin. Glacier meltwater exhibited pronounced interannual variability, with relatively high values occurring in 2006–2007, 2009–2010, 2012, and 2017, suggesting that enhanced glacier ablation in certain years may have exerted a short-term influence on lake recharge. Over the longer term, annual glacier meltwater in the Yamdrok Lake basin showed a slight declining trend from 2000 to 2021, with a trend slope of approximately -4.2×10^6 m^3/a. This result suggests that, under a warming climate, the contribution of glacier meltwater to lake recharge may exhibit distinct temporal stages. During the initial phase of warming, rising temperatures increase positive degree-days and intensify glacier ablation, thereby increasing meltwater recharge in the short term. However, as glacier area continues to retreat and ice storage is depleted, the volume of ice available for melting decreases, gradually weakening the capacity of glaciers to provide meltwater recharge in the later period. The generally lower glacier meltwater volumes after 2018 further indicate that the supporting role of glacier meltwater in lake recharge has weakened in recent years, which may consequently contribute to changes in lake level.

To further quantify glacier volume loss, we extracted glacier thickness change data from the High Mountain Asia Average Glacier Thickness Change from Multi-Sensor DEMs dataset [30] for glaciers within the Yamdrok Lake basin. A total of six glaciers (RGI50-13.26237–13.26247) were identified, with an average thickness change rate of -0.23 m/yr during 2000–2016. To estimate the total ice volume loss, we used the basin-wide glacier area of 195.91 km^2 for the year 2010 (Table 3), as this represents the approximate mid-point of the 16-year study period. Given the near-linear retreat of glacier area over the study period

(Table 3), using the mid-point area minimizes the overestimation that would result from using the initial glacier area (207.07 km^2 in 2000) and the underestimation that would result from using the final glacier area (Table 3). This approach yields an estimated ice volume loss of approximately -0.72 km^3 over the 16-year period. This independent estimate confirms that the glaciers in the Yamdrok Lake basin have been experiencing substantial ice depletion.

Over the longer term, annual glacier meltwater in the Yamdrok Lake basin showed a slight declining trend from 2000 to 2021, with a trend slope of approximately -4.2×10^6 m^3/a. While this trend might initially seem counterintuitive—as one would expect more melting with rising temperatures—it reflects a critical phase transition in the basin's glacier system. From 2000 to around 2012, glacier meltwater generally increased due to enhanced ablation driven by rising temperatures. However, as the glacier area has persistently shrunk (by approximately 30.5 km^2 between 2000 and 2021, as shown in Table 3), the area available for melting has substantially decreased. Consequently, the glacier system has passed a tipping point where the effect of a shrinking meltwater source area outweighs the effect of an increased melt rate per unit area, leading to a decline in total meltwater production in the latter half of the study period (post-2018). The independent ice volume loss estimate of approximately -0.72 km^3 from the NSIDC dataset further confirms this progressive depletion of the basin's ice reservoir. To extend the temporal coverage beyond 2016, we further examined the mass balance of Yanong Glacier, a well-studied glacier in the southeastern Tibetan Plateau (Parlung Zangbo Basin; [31]). Although it is located outside the Yamdrok Lake basin, its observed mass loss rate of -0.73 ± 0.13 m w.e./a during 1975–2015, with the rate doubling since 2000, provides important context for understanding the regional trend of glacier wastage, which is consistent with the substantial ice depletion we observed in the Yamdrok Lake basin.

For the missing glacier meltwater data in 2022 and 2023, we replaced the previously used linear trend extrapolation with a physically consistent degree-day factor (DDF) method. Because daily temperature data from the Langkazi meteorological station for 2022–2023 could not be obtained in time (they require a formal application to the China Meteorological Administration), we used the China meteorological forcing dataset v2.0 (CMFD 2.0; [32]) from the National Tibetan Plateau Data Center, which provides daily air temperature at $0.1° \times 0.1°$ spatial resolution. CMFD integrates observations from Chinese meteorological stations, including Langkazi station, through data assimilation, and has been extensively validated over the Tibetan Plateau. To ensure the reliability of the CMFD data for our study area, we validated the CMFD-derived temperatures against the Langkazi station observations for the overlapping period 2000–2021, which showed strong agreement ($R^2 = 0.92$, bias < 1 °C). For 2022–2023, we compared the CMFD-derived annual mean temperatures (4.80 °C and 5.20 °C) with the available Langkazi station annual means (4.09 °C and 4.07 °C), revealing a systematic positive bias of approximately 0.9 °C. We therefore applied a bias correction of -0.9 °C to all daily CMFD temperatures before calculating positive degree-days (PDD).

The bias-corrected PDD values were calculated as the cumulative sum of daily mean temperatures above 0 °C (PDD = $\sum T_i$ for $T_i > 0$ °C). The PDD was 2005 °C·day for 2022 and 1910 °C·day for 2023, substantially higher than the historical average (approximately 1000–1200 °C·day based on the 2000–2021 temperature record), reflecting the anomalously warm conditions in these two years.

Using the DDF method with a degree-day factor of 10.97 $mm \cdot d^{-1} \cdot °C^{-1}$, the estimated meltwater volumes were 3.88×10^9 m^3 (38.8×10^8 m^3) for 2022 and 3.70×10^9 m^3 (37.0×10^8 m^3) for 2023.

For the glacier area, we used the 2021 value (176.54 km^2; Table 3), which is the most recent observation available from our long-term glacier area time series. Given that the interannual glacier area change in this region is small (approximately 0.5–1.0% per year), the difference between using the 2021 area and the actual 2022–2023 area is negligible (<2%) compared to the DDF parameter uncertainty (±20%). This approximation does not materially affect the meltwater estimates or our main conclusions.

Sensitivity analysis with DDF varied by ±20% (8.78 to 13.16 mm·d^{-1}·°C^{-1}) resulted in meltwater variations of approximately ±20% (Table 4), confirming that the method is consistent and the conclusions are robust to DDF parameter uncertainty.

Table 4. Sensitivity analysis of glacier meltwater estimates to the degree-day factor (DDF) parameter.

Scenario	DDF (mm·d^{-1}·°C^{-1})	2022 Meltwater ($\times 10^8$ m^3)	2023 Meltwater ($\times 10^8$ m^3)
−20%	8.78	31.0	29.6
Baseline	10.97	38.8	37.0
+20%	13.16	46.5	44.3

3.6. Contribution Analysis of Factors Influencing Water-Level Variations

This study focused on the lake's hydropower-generation period, with 2000–2014 selected as the period for analyzing the factors influencing water-level variations. Hydropower development had already commenced during this period and may have affected lake-level fluctuations. Therefore, it was necessary to comprehensively consider the combined effects of climatic factors, glacier meltwater, and human activities on water-level changes. The annual water-level change was selected as the dependent variable, while rainfall, evaporation, temperature, glacier meltwater volume, and electricity generation were used as explanatory variables. A multiple linear regression model was constructed, and the Shapley R^2 decomposition method was further applied to quantitatively identify the relative contribution of each factor to water-level variations. Since the annual water-level change was calculated as the difference between the water level in a given year and that in the preceding year, the 1999 water-level data were additionally used as a baseline to enable calculation of the water-level change for 2000. The 1999 water level was used solely for calculating the annual water-level change in 2000 and was not included as a regression sample for the hydropower-generation period. Ultimately, the regression model covered 2000–2014, with 15 valid observations. Pearson correlation analysis showed that annual water-level change (ΔH) exhibited varying degrees of correlation with the influencing factors. In particular, annual water-level change was positively correlated with glacier meltwater volume, with a correlation coefficient of 0.4549, indicating that glacier meltwater had a certain positive effect on water-level variations. Correlations were also observed among the explanatory variables. Temperature showed a relatively strong negative correlation with rainfall (−0.6406) and a positive correlation with evaporation (0.5383), indicating interrelationships among climatic factors.

Figure 10 compares the observed annual water-level changes with the values predicted by the multiple regression model. As shown in the figure, the predicted results are generally consistent with the observed values in terms of the overall variation pattern, capturing the transition from predominantly positive to predominantly negative annual water-level fluctuations during the study period. From 2000 to 2003, both observed and predicted water-level changes were generally positive, indicating a rising water level during this stage. After 2004, annual water-level changes gradually decreased and remained negative from 2006 to 2010; the predicted values also captured this sustained decline reasonably well. After 2011, both the observed and predicted values showed a certain recovery trend,

indicating that the model had good skill in simulating the direction of water-level changes. Nevertheless, discrepancies remained between the predicted and observed values in certain years, particularly around 2001–2002, 2006–2007, and 2012. This suggests that the model has limited ability to explain anomalous fluctuations in individual years. Such discrepancies may be attributable to the small sample size, the limited capability of annual-scale data to characterize short-term hydrological processes, and the omission of other natural or anthropogenic factors from the model.

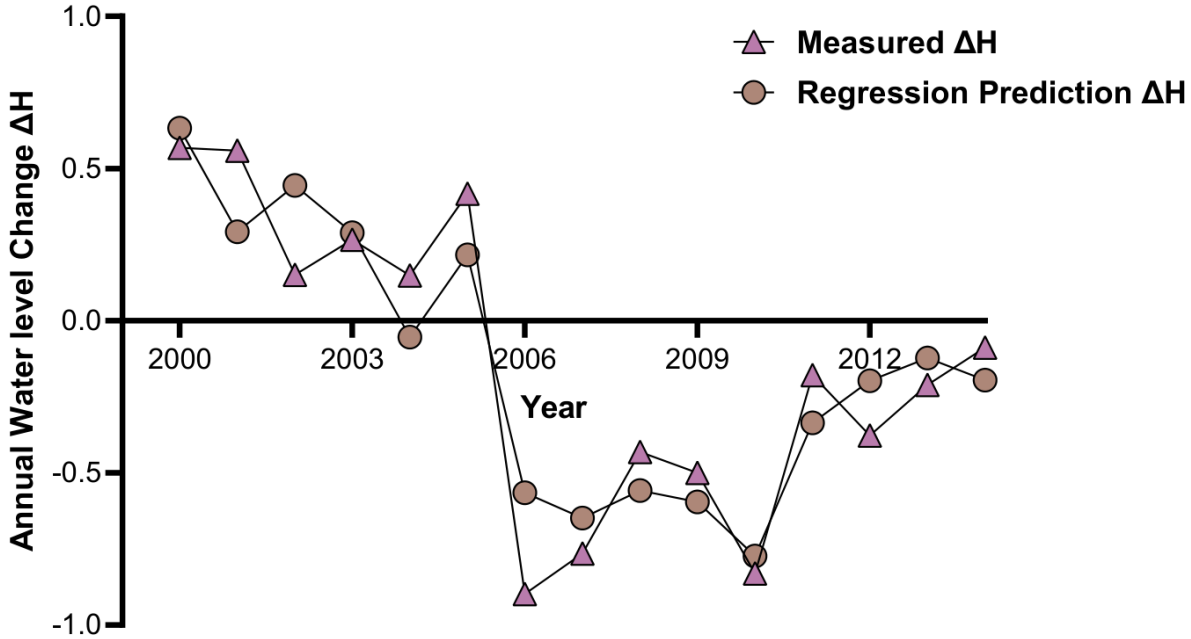


Figure 10. Comparison of Observed and Predicted Annual Water-Level Changes During the Hydropower-Generation Period.

The multiple linear regression results showed that the coefficient of determination (R^2) was 0.8451, indicating that rainfall, evaporation, temperature, glacier meltwater, and hydropower-station operational intensity (electricity generation) explained approximately 84.51% of the variation in annual water-level change during the hydropower-generation period. Although the model explained about 84.51% of the annual water-level variation, approximately 15.49% remained unexplained. This may be related to factors not fully incorporated into the model, including inflow and outflow runoff, lake storage regulation, groundwater exchange, and hydropower dispatching. In addition, the use of annual-scale data made it difficult to capture seasonal water-balance variations, which may also have constrained the model's explanatory power. The overall F-test yielded a p value of 0.0019, which is below 0.01, indicating that the model as a whole passed the significance test. However, none of the individual explanatory variables reached significance at the 0.05 level based on their individual regression coefficients. This may result from the short study period, the limited number of valid samples, and correlations among explanatory variables. In particular, the relatively strong correlation between temperature and glacier meltwater may reduce the statistical significance of individual regression coefficients. Therefore, rather than relying solely on regression coefficients to determine the contribution of each factor, this study further applied Shapley R^2 decomposition to quantitatively assess their relative contributions. It should be noted that the negative regression coefficients reported in Table 4 do not necessarily imply that all factors physically cause water-level declines. Since the dependent variable in this chapter is annual water-level change rather than absolute water level, and lake levels generally declined during the hydropower-generation

period, the signs of the regression coefficients reflect statistical relationships under the combined conditions of the study period. For factors with recharge implications, such as rainfall and glacier meltwater, their physical effects should still be interpreted in conjunction with the lake water-balance processes and hydropower-dispatching conditions during the generation period.

The Shapley R^2 decomposition results show substantial differences in the contributions of individual factors to annual water-level changes during the 2000–2014 hydropower-generation period. The factors were ranked by contribution as follows: hydropower-station operational intensity > temperature > glacier meltwater > evaporation > rainfall, with detailed results presented in Table 5. The contribution rates presented below are derived from the Shapley R^2 decomposition of the multiple regression model's explanatory power. They represent the relative statistical contribution of each factor to the explained variance of interannual water-level changes (ΔH), rather than absolute physical contributions to volumetric water loss. This distinction is particularly important for interpreting the hydropower operation intensity variable, as discussed in the table note.

Table 5. Contribution Analysis of Factors Influencing Water-Level Changes During the Hydropower-Generation Period.

Rank	Influencing Factor	Contribution Rate
1	Hydropower-station operational intensity	32.32%
2	Temperature	27.98%
3	Glacier meltwater	26.54%
4	Evaporation	9.07%
5	Rainfall	4.1%

Note: Hydropower station operational intensity is represented by annual electricity generation and reflects only the intensity of pumped-storage hydropower plant operations; it does not directly represent the net water loss of Yamdrok Lake. Its contribution rate is derived from the decomposition of the statistical model's explanatory power and should not be interpreted as the contribution of the power station to net water consumption. Contribution rates are reported to two decimal places; therefore, their sum may differ slightly from 100% because of rounding.

Overall, water-level changes in Yamdrok Lake during the hydropower-generation period were not controlled by a single factor, but rather resulted from the combined effects of climate variability, glacier-meltwater recharge, and pumped-storage hydropower plant operations. The Shapley R^2 decomposition indicates that hydropower-station operational intensity, temperature, and glacier meltwater were the three variables with the highest explanatory contributions in the model. This suggests that anthropogenic disturbance, changes in thermal conditions, and glacier-meltwater recharge are all closely associated with interannual water-level variations in Yamdrok Lake. In particular, changes in temperature may affect the lake water balance not only by influencing evaporation, but also indirectly by regulating glacier melting and, consequently, lake recharge. Glacier meltwater exhibited a positive effect on water-level changes, indicating that it remained an important source of water recharge to Yamdrok Lake during the hydropower-generation period.

It should be emphasized that the contribution analysis reflects the relative contributions of individual factors to the model's explanatory power within the current set of variables, rather than a strict attribution based on water balance. In particular, the contribution rate of hydropower-station operational intensity indicates a strong statistical association between power-station operating activities, as represented by annual electricity generation, and interannual water-level changes. However, it cannot be directly interpreted as indicating that hydropower generation caused an equivalent proportion of net water loss from Yamdrok Lake. Future studies could develop a net water withdrawal-and-release indicator using annual pumping volumes, discharge volumes, and power-station

dispatch data, thereby enabling a more accurate assessment of the actual effects of pumped-storage hydropower operations on water-level changes in Yamdrok Lake from a water-balance perspective.

To further analyze how the annual fluctuations in water levels during non-power station operation periods (2015–2023) respond to major climate factors, and to keep the time series consistent, we used updated glacier meltwater data from 2022 to 2023 (estimated using the DDF method); based on these nine years of data, we built a multiple linear regression model relating annual water level changes (ΔH) to rainfall, evaporation, temperature, and glacier meltwater. The Shapley R^2 decomposition results show that the contributions of each factor are 34.3% for temperature, 32.3% for glacier meltwater, 18.2% for evaporation, and 15.2% for rainfall. Temperature has the highest contribution, indicating it is the main factor explaining year-to-year water level changes during the non-power generation period; glacier meltwater and evaporation come next, with rainfall contributing relatively less. Considering that adding supplementary data may introduce some uncertainty, we also did a comparative analysis using the 2015–2021 data without the supplemented glacier meltwater to check the robustness of the main conclusions. The results are shown in Figure 11.

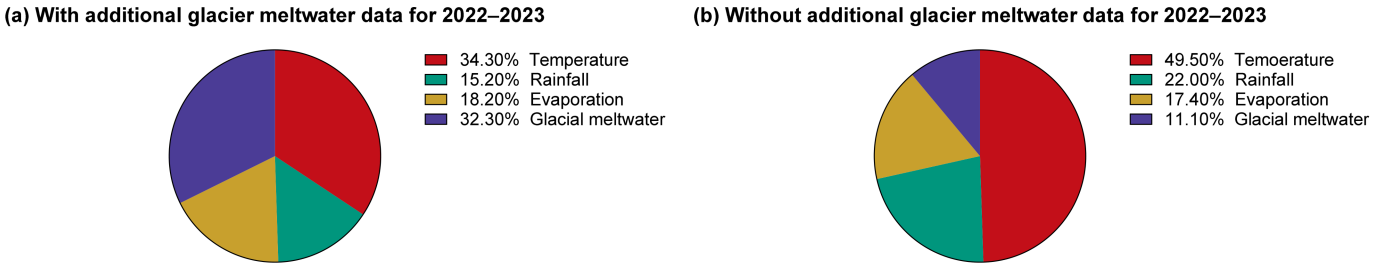


Figure 11. Comparison of the contribution rates of factors affecting interannual water level changes during non-power generation periods under different glacier meltwater data processing schemes.

A comparison of the two approaches reveals that interannual water-level changes during the non-generation period were jointly influenced by multiple factors, with temperature consistently exhibiting the highest relative contribution in both analyses. Using the 2015–2023 dataset with the 2022–2023 glacier meltwater values estimated by the DDF method, the model yielded an R^2 of 0.4543, indicating that rainfall, evaporation, temperature, and glacier meltwater collectively explained approximately 45.43% of the variation in interannual water-level changes. However, the overall model did not pass the significance test (p = 0.5683). The Shapley R^2 decomposition showed contribution rates of 34.3% for temperature, 32.3% for glacier meltwater, 18.2% for evaporation, and 15.2% for rainfall. A robustness test using only the observed 2015–2021 data (without the 2022–2023 values) yielded a higher R^2 of 0.5629, explaining 56.29% of the variation, but the model likewise did not reach statistical significance (p = 0.6831). Under this approach, the contribution rates were 49.46% for temperature, 22.05% for glacier meltwater, 17.38% for evaporation, and 11.11% for rainfall. Although the rankings of rainfall and glacier meltwater differed between the two approaches, temperature was consistently the factor with the largest contribution, while the contribution of evaporation remained relatively stable. These findings suggest that water-level variations in Yamdrok Lake during the non-generation period were sensitive to changes in temperature and associated hydrothermal processes. Given the extremely small sample sizes (n = 9 for the 2015–2023 analysis; n = 7 for the 2015–2021 robustness test), these results should be interpreted as exploratory rather than definitive. The lack of statistical significance is primarily attributable to the limited sample size, which constrains the statistical power of the regression analysis. Nevertheless, the interpolated

and non-interpolated analyses demonstrate a degree of consistency in identifying the main driving factors, suggesting that temperature change may be an important influence on interannual water-level fluctuations during the non-generation period, while glacier meltwater, rainfall, and evaporation jointly regulate the water-level change process. Future studies with longer observational records are needed to validate these exploratory findings.

4. Discussion

This study quantitatively estimated glacier meltwater only and did not further separate the effects of seasonal snowmelt and permafrost degradation on runoff processes. Seasonal snowmelt may affect runoff recharge during spring and summer, as well as its seasonal distribution. Permafrost degradation may alter the relative proportions of surface runoff and subsurface runoff by increasing active-layer thickness and changing soil infiltration capacity and groundwater recharge pathways. Owing to the lack of long-term observational data, the respective contributions of snow-cover and permafrost changes to the recharge processes of Yamdrok Lake cannot yet be quantitatively assessed. Future studies should integrate snow remote-sensing products, permafrost monitoring data, groundwater observations, and distributed hydrological models to further reveal the mechanisms through which glacier retreat, snow-cover change, and permafrost degradation affect runoff components and lake recharge under a warming climate.

Using independent glacier thickness change data from the NSIDC High Mountain Asia dataset [30], we estimated that the total ice volume loss in the Yamdrok Lake basin was approximately -0.72 km^3 during 2000–2016 (Section 3.5). This volumetric loss, combined with the 30.5 km^2 reduction in glacier area (Table 3), provides strong evidence that the basin's glacier system has transitioned from a phase of accelerated melting to a phase of source-area depletion. The declining meltwater production observed in the later period (post-2018) is therefore a direct consequence of this diminished ice reservoir, rather than a decrease in ablation intensity. Future research that integrates high-resolution remote sensing (e.g., SAR interferometry) and field measurements of glacier thickness would further improve the accuracy of glacier mass balance assessments.

Another important limitation of this study is that the attribution model did not explicitly account for seasonal snowmelt and permafrost degradation, both of which can influence runoff generation and hydrological connectivity in high-altitude cold regions. Seasonal snowmelt may modify runoff recharge intensity and its seasonal distribution, particularly during the spring and summer transition periods, potentially affecting the timing and magnitude of water inputs to the lake. Permafrost degradation, on the other hand, can alter the relative proportions of surface and subsurface runoff by increasing active-layer thickness, changing soil infiltration capacity, and modifying groundwater recharge pathways. These processes are particularly relevant in the Tibetan Plateau, where permafrost is widespread and has been experiencing significant degradation under climate warming. However, owing to the lack of long-term observational data on snow cover dynamics and permafrost conditions in the Yamdrok Lake basin, these processes could not be quantified within our current modeling framework. This omission may introduce uncertainties in our understanding of the full hydrological response, particularly regarding the subsurface flow components. Future research integrating satellite-based snow products, permafrost monitoring networks, groundwater observations, and distributed hydrological models is needed to better constrain their contributions to the water balance of Yamdrok Lake and to provide a more comprehensive assessment of the hydrological response to climate change in this region.

A noteworthy finding of this study is the simultaneous occurrence of significant warming (0.03 °C/yr, $p < 0.05$) and a significant decrease in observed pan evaporation

(–7.31 mm/a, $p < 0.01$) within the Yamdrok Lake basin during 2000–2023 (Figure 2). While this appears contradictory at first glance, it is a well-documented phenomenon in hydrological research, particularly on the Tibetan Plateau, commonly referred to as the "evaporation paradox" [21]. Zhang et al. [22] utilized data from 75 meteorological stations across the Tibetan Plateau during 1966–2003 and found that reference evapotranspiration decreased significantly at 47% of stations and pan evaporation at 38% of stations, despite a significant increase in temperature. Liu et al. [23] further quantified the contributions of individual climate factors, identifying decreasing wind speed as the dominant factor driving the decline in pan evaporation, followed by increasing vapor pressure and decreasing solar radiation. Xie et al. [24] reached a similar conclusion, showing that the positive effect of rising temperature on evaporation (+4.55 mm/a^2) was completely offset by the negative effects of wind speed reduction (–13.7 mm/a^2) and solar radiation decrease (–3.1 mm/a^2). Evaporation pan measurements represent the integrated result of multiple meteorological factors, including temperature, wind speed, relative humidity, and sunshine duration. While rising temperatures increase the atmosphere's capacity to hold moisture—thereby enhancing evaporative demand—the actual observed evaporation can decline if other controlling factors change in the opposite direction. Importantly, this observed "evaporation paradox" in the Yamdrok Lake basin is not an isolated finding. Tang et al. [15], in a comprehensive study of the same region using data from 1974 to 2019, also reported a decreasing trend in evaporation from the same hydrological station. The consistency between our results and this previous study strongly suggests that the decline in observed pan evaporation is a robust regional characteristic, rather than a data artifact. This finding does not weaken the role of temperature as a primary driver of lake-level decline. On the contrary, the contribution analysis in Section 3.6 identified temperature as the largest individual contributor to interannual water-level changes (27.98% during the hydropower-generation period and 34.3–49.5% during the non-generation period). This indicates that temperature drives lake-level decline through its integrated effects on the basin's water balance, rather than through a simplistic direct relationship with observed pan evaporation. Specifically, warming influences lake levels through two complementary pathways: (1) directly, by increasing evaporative demand, which enhances water loss from the lake surface and basin evapotranspiration; and (2) indirectly, by accelerating glacier retreat and reducing the long-term capacity for glacier meltwater recharge, as discussed in Section 3.5. Therefore, the "evaporation paradox" observed in this study does not undermine the conclusion that warming is the fundamental driver of the long-term water-level decline in Yamdrok Lake. Rather, it provides a more nuanced understanding of the complex hydrological response to climate change on the Tibetan Plateau.

Moreover, because annual data on the volume of water pumped or diverted from the Yarlung Tsangpo River into Yamdrok Lake are currently unavailable, the net water loss from Yamdrok Lake caused by pumped-storage hydropower plant operation cannot be accurately calculated. Therefore, annual electricity generation and annual spillway discharge in this study were used primarily as indicators of the intensity of engineering operational disturbance and should not be directly equated with net lake water loss. Future research should combine monthly power-station dispatch data, pumping volumes, turbine flow volumes, and lake-level observations to further quantify the specific impacts of pumped-storage hydropower operations on intra-annual water-level fluctuations and interannual water-level changes in Yamdrok Lake. It is important to reiterate that the contribution rates obtained from the Shapley R^2 decomposition represent statistical explanatory power rather than physical volumetric contributions. Because annual data on pumped water volume, net water transfer, and turbine discharge are currently unavailable for the Yamdrok Lake Hydropower Station, a physical water-balance-based attribution could not be performed.

The percentages reported in Section 3.6 and Table 4 should therefore be interpreted as the extent to which interannual variability in each factor statistically explains the variability in lake-level fluctuations, not as the proportion of net water loss or gain attributable to each factor. It should also be noted that the analysis for the power-generation period was based only on data from 2000 to 2014, yielding an effective sample size of 15, which is relatively small. Consequently, the regression coefficients of individual explanatory variables lack strong statistical significance. The model results are therefore more appropriate for identifying the relative contributions of different factors to interannual water-level variations than for drawing overly strong conclusions about the causal effects of individual variables. To reduce the influence of correlations among multiple factors on contribution assessment, this study employed Shapley R^2 decomposition to allocate the model's explanatory power, thereby improving the comparability of contribution rates among factors. In addition, observed glacier-meltwater data for the non-generation period were available only through 2021. If modeling were conducted exclusively using observed glacier-meltwater data, the analysis period would have to be restricted to 2015–2021. This would result in inconsistency between the temporal coverage of glacier-meltwater data and that of the other meteorological and hydrological variables, while further reducing the effective sample size. To balance time-series completeness and data reliability, two approaches were compared in this study. First, missing glacier-meltwater data for 2022–2023 were supplemented using linear trend extrapolation to maintain consistent time series for all variables over 2015–2023. Second, a robustness test was conducted using only the observed glacier-meltwater data for 2015–2021. Both approaches identified temperature as an important explanatory factor for water-level variation during the non-generation period, indicating that the conclusion regarding the prominent role of temperature is reasonably robust. Future studies should further validate these conclusions using longer time series and data with higher temporal resolution. In addition, water withdrawals for agricultural irrigation, domestic use, and tourism development may also affect the local water balance of Yamdrok Lake.

5. Conclusions

As one of the largest closed inland lakes on the Tibetan Plateau, Yamdrok Lake has experienced substantial water-level decline in recent decades. Using cumulative anomaly analysis and linear regression, this study investigated the causes of water-level decline in Yamdrok Lake during 2000–2023. The potential disturbance associated with hydropower station operation was also examined, and glacier meltwater was estimated. The main findings are as follows:

1. Climate-warming-induced hydrothermal imbalance is the fundamental driver of the long-term decline in Yamdrok Lake water level.** From 2000 to 2023, the lake level declined cumulatively by approximately 5.1 m, with an accelerated recession occurring after 2005. Temperature increased significantly at a rate of 0.03 °C yr^{-1} (*p* < 0.05) and was significantly negatively correlated with interannual water-level variation (*r* = −0.494, *p* = 0.017). On the one hand, warming directly intensified water loss through lake evaporation and basin evapotranspiration. On the other hand, it drove persistent glacier shrinkage within the basin, with glacier area decreasing by approximately 30.5 km^2 between 2000 and 2021. Consequently, glacier-meltwater recharge shifted from a phase of temporary enhancement during 2006–2012 to a weakening trend after 2018, followed by a sharp increase in 2022–2023 due to anomalously warm conditions. The updated 2022–2023 glacier meltwater estimates (3.88×10^9 m^3 and 3.70×10^9 m^3) are substantially higher than the historical average (1.89×10^9 m^3 for 2000–2021), reflecting the anomalously warm conditions in these two years. The relationship between rainfall and water level became markedly decoupled after 2005, suggesting that rainfall was no longer the dominant factor controlling long-term

water-level change. Fundamentally, the decline in Yamdrok Lake water level reflects a transition of the basin hydrothermal system from a state of dynamic balance to net water deficit under a warming climate, rather than a process that can be explained solely by reduced rainfall.

2. Pumped-storage hydropower operation represents an additional disturbance affecting water-level fluctuations, rather than a simple linear water-loss term.** During the power-generation period from 2000 to 2014, hydropower-station operational intensity, represented by annual electricity generation, accounted for 32.32% of the statistical explanatory contribution to interannual water-level variation, making it the single variable with the greatest explanatory power in the model for this period. This percentage represents the proportion of variance in ΔH (interannual water-level change) that is statistically explained by the interannual variability of electricity generation within the multiple regression framework, based on the Shapley R^2 decomposition. It does not represent the proportion of net lake water loss caused by hydropower operations. However, this contribution rate reflects the statistical association between the intensity of electricity-generation activities and water-level fluctuations; it does not indicate that water discharged for power generation caused an equivalent proportional net loss of lake water. The net effect of the power station depends on the difference between water pumped from the Yarlung Tsangpo River into the lake and water released for electricity generation. Because annual data on net pumping and discharge are unavailable, annual electricity generation should not be directly equated with lake water loss. Although large-scale power generation ceased after 2015, the lake level did not stop declining. Nevertheless, the variability of water-level fluctuations decreased substantially, further indicating that power-station operation primarily amplified interannual water-level variability rather than acting as an independent driver of the long-term declining trend. Therefore, the 32.32% contribution should be understood as a statistical indicator of temporal covariation, not a physical water-balance proportion.

3. The discrepancy between the present findings and previous studies identifying reduced rainfall as the primary cause mainly arises from differences in study periods and frameworks for identifying driving factors.** Previous studies were generally based on data from approximately 1970–2000. During that period, temperature increased relatively slowly, and the short-term regulatory effects of interannual rainfall variability on lake level could still mask the gradual cumulative effects of warming. Consequently, rainfall was identified as the most apparent driver. By contrast, the present study covers 2000–2023 and captures a critical transition period characterized by intensified warming after 2005, particularly after 2013, accelerated glacier retreat, and weakened rainfall regulation. This allows the longer-term, previously less apparent effect of temperature to become more evident. In addition, earlier studies generally lacked quantitative integration of glacier-meltwater dynamics and hydropower-station operation, making it difficult to identify shifts in driving mechanisms arising from the combined effects of multiple factors. The contribution ranking obtained in this study—hydropower-station operational intensity > temperature > glacier meltwater > evaporation > rainfall—should be interpreted as a ranking of the statistical explanatory power of these factors for interannual water-level variability during the specific period of 2000–2014, rather than as a ranking of their absolute physical contributions to the total water-level decline. The associated percentages represent the relative proportion of variance in ΔH that each factor explains within the multiple regression framework, based on the Shapley R^2 decomposition, rather than the proportion of volumetric water loss or gain attributable to each factor. This ranking reflects the strength of temporal coupling between fluctuations in each factor and lake-level fluctuations during that period. Climate warming, through increasing temperature and glacier retreat, provided the background for sustained water-level decline, whereas power-station operation imposed substantial intra-annual and

interannual disturbances on this underlying trend. Together, these processes shaped the evolution of Yamdrok Lake water level during 2000–2014.

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