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Research Paper

Interannual variation and driving factors in area of the Zonag Lake basin on the Qinghai-Xizang Plateau*

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Abstract The Zonag Lake basin is situated in the hinterlands of the Qinghai-Xizang Plateau (QXP) and serves as a renowned calving ground for Tibetan antelopes. Zonag Lake is also a typical large inland lake on the QXP. Over the past three decades, the lake areas within the Zonag Lake basin have generally shown an expanding trend. However, different lakes therein have exhibited varying trend over time. Between 1988 and 1995, Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake all experienced shrinkage. After the 2011 breach of Zonag Lake, it continued to shrink, the downstream lakes, such as Kusai Lake, Haidingnor Lake, and Salt Lake consistently expanded. After the 2019 implementation of the Salt Lake drainage project, the water levels began to decline in 2020. The Zonag Lake basin has experienced an average annual precipitation of 308.5 mm over the past six decades, with a general upward trend in rainfall amounting to an average increase rate of 15.1%. The overall temperature within the basin has also been increasing, with a warming rate of 0.35 °C/10 a. This trend has become notably more pronounced since the beginning of the 21st century. Collectively, surface runoff (41.5%±2.3%) and lake precipitation (27.0%±1.5%) accounted for most of the total lake inflow, thus identifying atmospheric precipitation as the primary driver of lake expansion in the Zonag Lake basin. The meltwater from glaciers and permafrost was the secondary contributor, responsible for 24.0%±1.3% of the inflow.

Keyword: Zonag Lake area; expansion; precipitation; temperature

1 INTRODUCTION

The Qinghai-Xizang Plateau (QXP) is known as the “Asian Water Tower” and is a key source of water for major river civilizations in Asia, providing valuable water resources for downstream regions (Tang et al., 2019), while also serving as a vital ecological security barrier for China (Sun et al., 2012). With global warming, the QXP temperature and precipitation are increasing (Lutz et al., 2014; Zhang et al., 2016; Liu et al., 2025; Ouyang et al., 2025a), indicating an overall trend of humidification. Studies show that the rate of temperature increase in the QXP is 0.3–0.4 °C/10 a, which is twice of the global temperature increase rate during the same period (0.15 °C/10 a) (Chen et al., 2015; He et al., 2024). If the global temperature will increase by 1.5 °C in the future, the QXP region would experience a temperature rise of approximately 2.1 °C. This abnormal warming will accelerate glacier melting in the QXP and its surrounding areas (Kraaijenbrink et al., 2017; Li et al., 2020; Jiang et al., 2025; Ouyang et al., 2025b).

The QXP is home to many widely distributed

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lakes, covering a total area of approximately 50 000 km^2, accounting for approximately half of the total lake area in China (Zhang et al., 2019, 2020). Lakes on the QXP, which are minimally disturbed by human activities, serve as key objects to understand the mechanisms behind ecological and environmental changes in the high-altitude region (Zhang et al., 2022). Over the past five decades (1976–2021), the number of lakes in the QXP has increased by more than 30%, with the total area of the lakes increasing by over 25%. The volume of water stored in these lakes has increased by more than 160 billion t (Zhang et al., 2020, 2021). The magnitude of changes in lake water volume is related to water recharge sources and lake types. Generally, endorheic lakes tend to expand more considerably than exorheic lakes, and lakes with glacial feeding exhibit greater expansion than those without glacial feeding (Zhang et al., 2021). For instance, among the 300 lakes in the largest endorheic region of the QXP, the Qiangtang Plateau, approximately 90% are undergoing expansion and approximately 10% are showing signs of shrinkage, with most of the shrinking lakes located in the southern part of the QXP (Zhou et al., 2022).

The widespread lake expansion in the QXP is attributable to the combined effects of various environmental factors pertaining to global warming, mainly including rising temperatures, increased precipitation, glacier melting, permafrost degradation, and evaporation changes (Meng et al., 2012). However, the dominant factors considerably vary across different regions and time periods (Zhang et al., 2021, 2024). Previous studies reveal that the major expansion drivers differ among lakes, and that even the same lake may experience changes in the major drivers over time. For Nam Co (Lake), multiple studies have identified increased precipitation as the main source of water volume increase. Based on water balance estimates, Zhang et al. (2021) concluded that glacial meltwater contributed <30% to lake water increase from 1976 to 2019. Ma et al. (2012) and Lei et al. (2021) also reported precipitation change as the direct cause of Nam Co's expansion. Moreover, some studies haver primarily attributed the rapid expansion of Selin Co to accelerated melting of glaciers and snowpack due to rising temperatures (Song and Deji, 2023; Liu et al., 2024). Studies have suggested that the increased formation of glacial meltwater driven by global warming is the main cause of the recent rapid expansion of Nam Co (Wu et al., 2007; Zhu et al., 2010). This discrepancy partly stems from differences in the analyzed study periods. Liu et al. (2024) indicated that during 1976–2021, the area of Nam Co showed significant positive correlation with precipitation and temperature and that of Selin Co was primarily correlated with temperature. Therefore, the understanding of the hydrological processes of plateau lakes has been continuously deepening with increasing observational data and research. The response of a plateau lake system to climate change is complex and exhibits spatiotemporal specificity (Qiao et al., 2019). Therefore, research shall be conducted focusing on specific lakes, such as Zonag Lake that examined in this study. Zonag Lake was originally an independent endorheic lake. Its outburst drastically altered the regional drainage system, as the released water flowed downstream and connected several lakes in sequence. This process may eventually link Yanhu Lake to the headwaters of the Changjiang (Yangtze) River via the Qingshui River and the Chumar River (Chen et al., 2020). Current research on lake area changes and their driving mechanisms remains limited.

Lake expansion in TP triggers enhanced river erosion tens of kilometers downstream, with severe cases endangering lives and livelihoods up to hundreds of kilometers away (Cook et al., 2018; Zheng et al., 2021). Zonag Lake was a typical large lake (>50 km^2) in the QXP, until its size was drastically reduced by an outburst event. Zonag Lake in Hoh Xil experienced a breach in September 2011 (Zhang et al., 2021). After the breach, the possibility of dust release in the lake area increased, threatening the reproduction environment of the Tibetan antelope (Fan et al., 2023). The Kusai Lake, located in the heart of the Hoh Xil Nature Reserve, has experienced a marked rise in water level, leading to the overflow of lake water due to the continuous rise in water level. The outflow is greater than that of the Chumar River, the northern source of the Changjiang River (Yao et al., 2012), ultimately resulting in the connection of Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake (Liu et al., 2019). The Salt Lake has become a "recipient" of the basin, with a marked increase in lake basin area, posing threats to the Qinghai-Xizang Highway and Railway (approximately 16 km away). Therefore, studying the expansion of the Zonag Lake basin and clarifying the trend of regional lake expansion and the associated driving mechanisms, have considerable scientific values and practical significance for the protecting of the water ecological environment and the regional security of the QXP.

Yao et al. (2012) and Liu et al. (2016) used geographic information technology as well as mathematical and statistical methods to analyze the triggering factors of the Zonag Lake outburst. They found that one of the factors is possibly the rapid rise of lake level beyond its shores due to abundant precipitation in June–August, 2011. Liu et al. (2019) found that the recharge from melting ground ice caused by permafrost degradation in the Salt Lake area is the main reason for the lake's expansion. Yuan et al. (2022) used remote sensing image data, combined with field investigation and modeling methods, to study the causes of Salt Lake expansion, and found that an increase in precipitation was the main cause of the expansion from 2011 to 2018. Li et al. (2022) employed multisource satellite remote sensing technology and variable infiltration capacity model calculations, combined with correlation analysis, to show that the main factors affecting the expansion of the Salt Lake and Zonag Lake in various periods were different. Precipitation was dominant before 2014, while for 2015 to 2018, it was dominated by temperature, followed by precipitation. Furthermore, permafrost release and groundwater recharge accounted for more than half of the lake level increase.

The expansion of lakes in the QXP is influenced by the combination of multi-factors. Unfortunately, measurement data in the region are scarce. Most researchers had to analyze the trend of lake expansion and its causal factors via mathematical simulations. However, owing to the limitations of model adaptability and limited measurement data, the outcome are different in the main influencing factors. Many lakes are present in the QXP, and many main factors, such as atmospheric precipitation, glacial water retreat, and permafrost degradation, could lead to their expansion. The main factors affecting lake expansion vary in space and time. The Zonag Lake basin was selected as the primary research site due to its exemplary value in illustrating a complete glacial lake disaster cascade. First, the lake underwent the entire process from continuous expansion and overtopping erosion to a final outburst, providing a holistic natural laboratory for investigating such hazard mechanisms. Second, the outburst posed an immediate threat to critical infrastructure, most notably the Qinghai-Xizang Railway and Highway located merely 8 km^2 away, underscoring the urgent practical need for this research. Moreover, the systematic monitoring implemented since the event has generated a robust dataset, establishing a solid foundation for subsequent quantitative analysis. We collected the remote sensing data and meteorological and other observation data, with which we analyzed the area dynamics of Zonag Lake, Salt Lake, and Kusai Lake based on various factors of precipitation, temperature, and so on. The contribution of the different influencing factors to lake expansion was estimated based on the revealed lake expansion trend for the Zonag Lake basin and the relationship of this trend with water balance. Moreover, we provided a solution for mitigating lake expansion in lake expansion in the Zonag Lake basin by analyzing the underlying mechanism, to provide a reference for comprehensively analyzing the expansion mechanism of the QXP lakes.

2 STUDY AREA

The Zonag Lake basin is located in the western part of Zhiduo County, Yushu Tibetan Autonomous Prefecture, Qinghai Province, on the south side of the Kunlun Mountain Range, northeast of the Hoh Xil National Nature Reserve. Salt Lake is adjacent to the Qinghai-Xizang Railway, in average elevation of more than 4 600 m, and it is a subclass of closed depressions in the Cenozoic intermountain tectonic fracture basin in the southern part of the Kunlun Mountain Range (Guo et al., 2023). The mountainous terrain comprises mainly thaw-eroded high mountains, with year-round snow on the mountain tops, and strong modern cold weathering, perennial permafrost and thawing. The region features alpine arid climate, and the stratigraphy is mainly composed of Paleocene and Quaternary strata. The surface layer is alluvial gravelly-sandy (Dong, 2021), with a thickness of approximately 2 m. In the lower part, the Lower Pleistocene marl that characterized primarily by saline and gypsiferous lithology forms thick layers (Dong, 2021). The groundwater is mainly developed under the frozen layer of loose rock type (Guo et al., 2012). The northwestern part of the Zonag Lake basin comprises Zonag Lake, Kusai Lake, and Haidingnor Lake from west to east (Fig.1). The catchment area of Zonag Lake is 1 354 km^2, and the glacier area is approximately 21.97 km^2, accounting for 1.62% of the catchment area (Table 1). Zonag Lake is a famous calving ground of the Tibetan antelope, and it is also a typical large-scale inland lake in the QXP

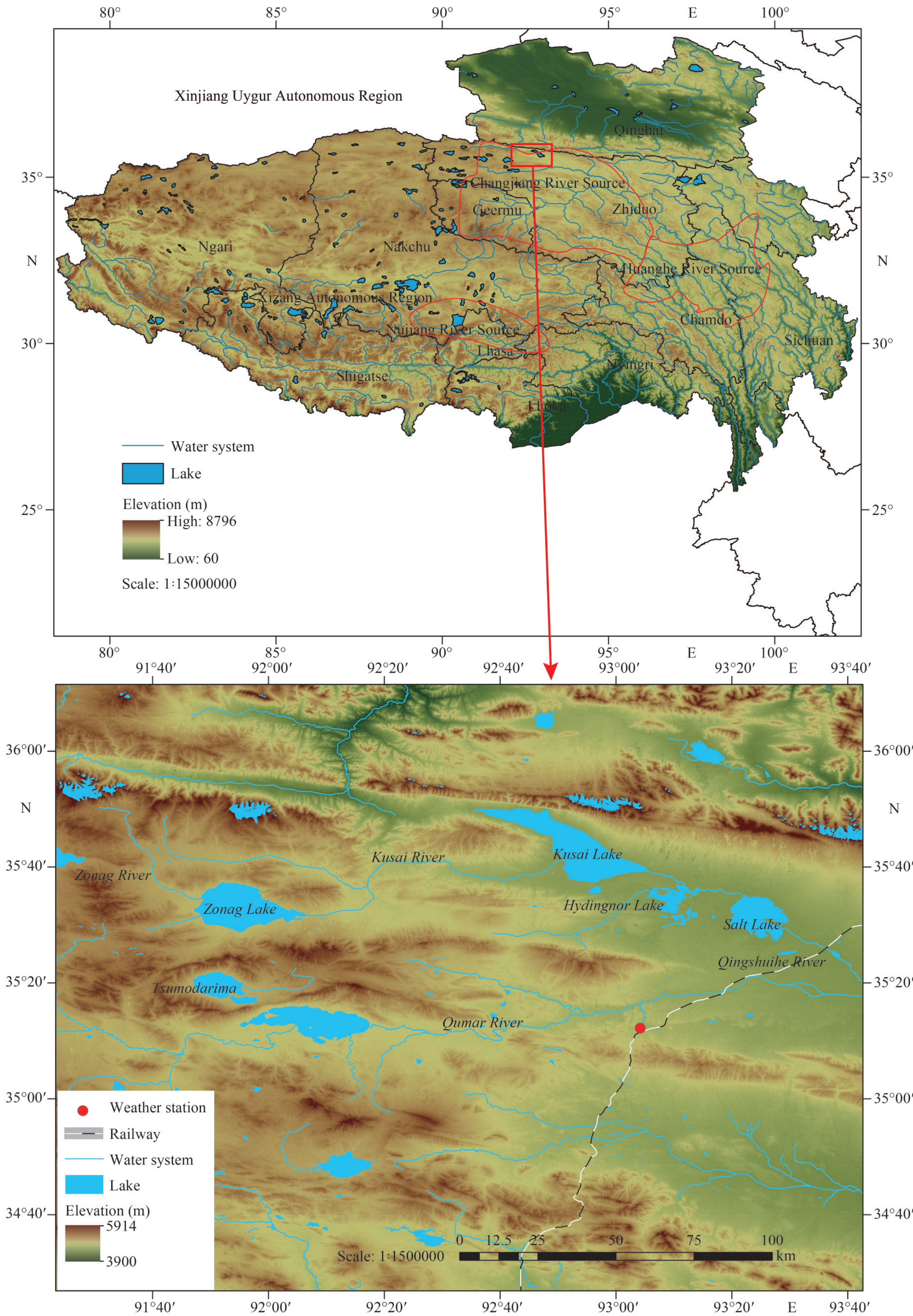


Fig.1 Location of the study area modified with ArcGIS 10.7 v software

Data source: Geospatial Data Cloud, CHN. https://www.gscloud.cn.

Table 1 Statistics of the Zonag Lake basin

Item	Zonag Lake	Kusai Lake	Salt Lake	Haidingnor Lake
Catchment area (km^2)	1 354	1 812	1 342	995
Glacier area (km^2)	21.97	37.73	7.09	–
Proportion of the glaciers area to catchment (%)	1.62	2.08	0.52	–

– denotes missing data.

(He et al., 2021). The catchment area of Kusai Lake is 1 812 km^2, and the glacier area is about 37.73 km^2 (Yao et al., 2012), accounting for 2.08% of the catchment area. After the 2011 collapse of Zonag Lake, Kusai Lake was the largest outflow lake in the Hoh Xil (Liang et al., 2025). The main recharge source of Zonag Lake before 2011 was regional precipitation and Kusai Lake River. The catchment area of Haidingnor Lake is 995 km^2, with no glacier distribution in the basin. The catchment area of Salt Lake is 1 342 km^2, and the glacier area is about 7.09 km^2, accounting for 0.52% of the catchment area (Fu et al., 2023). The geomorphology of the Salt Lake plain is mainly expressed as a plateau wide valley lake basin, with a gentle slope of approximately 0.2%, and the development of lakeshore multi-frozen grass swamps and hot thawing lakeshore ponds. The western part of the lake basin is adjacent to Haidingnor Lake, and the eastern part is separated from the Qingshui River, a tributary of the Chumar River (the northern source of the Changjiang River) by a low and gentle watershed (Chen et al., 2020).

3 METHODOLOGY

3.1 Meteorological and hydrological data source

Precipitation from the nearby weather station Wudaoliang (Fig.1), the research area is located in the remote Hoh Xil uninhabited area, and the nearest weather station is only meteorological station (Wudaoliang), which is about 37 km away from the Salt Lake. Observation data recorded here for more than 50 years are representative to a certain extent. Lake-surface evaporation represents the actual evaporation in the region. In the absence of direct evaporation records for the lake surface, the evaporation observation records in the watershed or a nearby meteorological station are multiplied by a conversion factor or an empirical formula was used to estimate the evaporation for the lake surface. Due to nil hydrological stations in the Zonag Lake basin and the difficult accessibility to the region, directly obtaining the flow rate of the lakes that feed into the Zonag Lake basin was nearly impossible. Therefore, the statistical significance of trends in the annual meteorological and hydrological timeseries was determined using the nonparametric Mann-Kendall (M-K) test, with a significance level of 0.05. Variation points were identified using the M-K sequential test. The intersection points of the forward sequence statistics (UF) and backward sequence statistics (UB) were taken as the variation point, provided it was located within the critical value range of ±1.96, corresponding to a significance level of 0.05.

3.2 Remote sensing data source

This study used Landsat series imagery comprising images obtained using Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI sensors, obtained from prior studies (Yao et al., 2012; Fu et al., 2023; Wang et al., 2023). All images, chosen from July to September with little or no cloud cover, were processed using the normalized difference water index (NDWI) to enhance water features and delineate lake boundaries based on the spectral contrast between the green and near-infrared bands. However, in practice, factors such as water turbidity, background terrain effects, and sensor-specific differences could influence the results. The threshold was empirically validated and consistently applied only when the automated classification showed strong agreement with the visual interpretation. An initial NDWI threshold of 0.15 (Zhang, 2019) was applied and then rigorously validated through visual interpretation of 100 randomly selected images for different years and lakes, which validated its high accuracy and consistency across the study area.

The corrected root mean square error (RMSE) was less than 1 pixel, and the data accuracy met the analysis requirements. The data predominantly encompassed the changes in lake area within the Zonag Lake basin over the past 30 years, as well as alterations in glaciers and evaporation associated with certain lakes of the basin. The results estimated based on the NDWI were compared with the “true values” and the area deviation percentage of each lake was calculated. The calculated average error for lake area extraction in the study area was approximately ±1.5%.

3.3 Analysis method

As the tail of the Zonag Lake basin, Salt Lake receives water from the upstream. Changes in the water volume of Salt Lake can reflect variations better than other lakes in the water volume of the Zonag Lake basin. Therefore, to quantitatively analyze the contribution of different influencing factors to lake expansion in the Zonag Lake basin, the water amount of the incoming and outgoing waters of Salt Lake was estimated using the water balance method (Zhu et al., 2010; Yuan et al., 2022; Fu et al., 2023) by Eq.1 below:

$$\Delta V=P+R_L+G-E, \quad (1)$$

where ΔV represents the change in lake water volume, P denotes lake precipitation (P=precipitation× lake area), R_L indicates precipitation surface runoff (R_L=watershed area×precipitation×runoff coefficient), G denotes glacial meltwater and permafrost, E indicates lake evaporation (E=evaporation×lake area).

4 RESULT

4.1 Change in area of the four main lakes in the Zonag Lake basin

4.1.1 Change in area of Zonag Lake

Most researchers have used remote sensing interpretation to analyze the area change dynamics of lakes in the Qinghai-Xizang region. We statistically integrated data from several sources (Fig.2) (Yao et al., 2012; Chen et al., 2021; Fu et al., 2023; Wang et al., 2023). The data indicate that the area of Zonag Lake decreased by 110.4 km^2 from 1988 to 2022, representing a total reduction of approximately 43%. The changes in area of Zonag Lake could be divided into five stages. The first stage (1988–1995) exhibited a trend consistent with that of other lakes in the QXP; a low shrinkage rate of 0.32 km^2/a. In the second stage (1996–2010), the lake area experienced a gradual increase, with an expansion rate of 1.08 km^2/a. The third stage (2011–2012) marked a sharp decline in the lake area, with a reduction of 57.9 km^2/a. In the fourth stage (2013–2018), the lake surface area remained largely unchanged and stabilized. In the fifth stage (2019–2020), the lake area again exhibited a shrinking trend, with a decrease of 1.84 km^2/a.

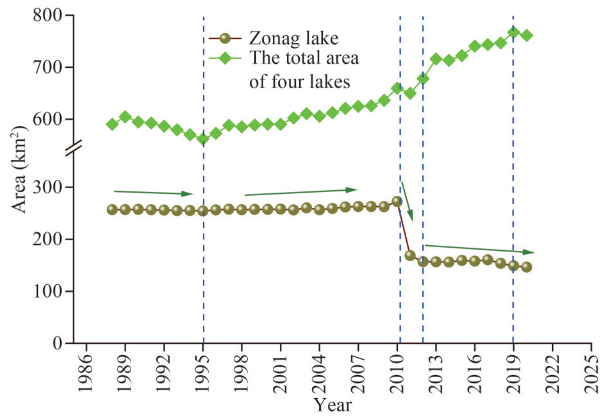


Fig.2 Interannual variation in area of Zonag Lake and four lakes

4.1.2 Change in area of Kusai Lake, Haidingnor Lake, and Salt Lake

From 1988 to 2020, the area of Kusai Lake increased by 78 km^2, indicating an expansion of nearly 30.5%. Meanwhile, the area of Haidingnor Lake increased by 33.45 km^2. Before 2011, the area of Haidingnor Lake was similar to that of Salt Lake. The area of Salt Lake increased by 184.2 km^2, indicating an expansion of approximately 575%. All the three lakes showed a gradual shrinkage trend, albeit with differing rates. The expansion of these three lakes comprised five stages (Table 2). In the first stage (1988–1995), the shrinkage rate of Salt Lake was the highest (Fig.3). In the second stage (1996–2010), the areas of the three lakes gradually increased, with the expansion rate varying over time. The main reason for expansion in this stage was that the amount of incoming water was larger than that of outgoing water. In the third stage

Table 2 Changing rates in area of the four lakes in Hoh Xil at different stages (km^2/a)

Name of the lake	First stage (1988–1995)	Second stage (1996–2010)	Third stage (2011–2012)	Fourth stage (2013–2018)	Fifth stage (2019–2020)
Zonag Lake	0.32	0.77	-57.9	-0.03	-3.69
Kusai Lake	-0.36	1.84	24.3	-0.22	-4.88
Haidingnor Lake	-1.89	1.33	13.2	0.20	1.00
Salt Lake	-2.30	1.18	29.7	9.90	-1.73

(2010–2011), the areas of the three lakes increased at different rates, of which Salt Lake showed the highest rate of expansion throughout the study period. This phenomenon was mainly triggered by an outburst event of Zonag Lake (Fig.2), leading a large volume of water to flow downstream and feed the other lakes (Yao et al., 2012; Xie et al., 2020; Fu et al., 2023). In the fourth stage (2012–2018), the areas of Kusai Lake and Haidingnor Lake showed no significant changes, whereas Salt Lake recorded a progressive expansion of 9.9 km^2/a. In the fifth stage (2019–2020), although Haidingnor Lake exhibited slight expansion, all other lakes showed shrinkage.

4.2 Meteorological change in the Zonag Lake basin

4.2.1 Precipitation

We collected precipitation data of the past 60 years recorded in the Wudaoliang Meteorological Station and analyzed the precipitation changes in the Zonag Lake basin. The average annual precipitation in the Zonag Lake basin was 308.5 mm (Table 3), which is significantly lower than the average annual precipitation in the source area of the Changjiang River source area (351.5 mm) (Zhou et al., 2022). The year of lowest annual precipitation (136.3 mm) was in 1984, and the largest year of highest precipitation (479.6 mm) was in 2018 (Fig.4). The overall trend of precipitation in the study area increased at 23 mm/10 a in 1961–2020, but the precipitation decreased at 13.1 mm/10 a for the period 1961–1979. During 1980–2020, precipitation increased significantly at 35 mm/10 a.

The analysis on interdecadal precipitation changes in the study area revealed a decreasing trend before the 1970s and an increasing trend in the late 1980s. Compared with the precipitation in the 1960s, the average annual precipitation increased by 15.1% in the 21st century. The precipitation increased most significantly by 22.4% during 2000–2009, while the precipitation increased by 40.8% during 2010–2019 and 35.5% in the last three years.

The M-K test was conducted to analyze the precipitation timeseries in the study area (Fig.5). The UF statistics revealed an overall trend. From 1960 to 2000, the UF curve fluctuated around zero, indicating no significant trend in precipitation in the QXP. After 2000, the UF statistic showed a sustained increase, indicating a rising trend in annual precipitation. This post-2000 upward trend reached a significance level of 0.05 as the UF value approached or exceeded the critical value of 1.96. An intersection point between the UF and UB curves occurred around 2000 within the critical zone (±1.96), indicating a change point. Consequently, precipitation shifted from an insignificant trend to a statistically significant increase after this change point.

4.2.2 Temperature

The data obtained from the Wudaoliang Station, the regional temperature has showed an increasing trend in the last 62 years (1961–2023), with a warming rate of 0.35 °C/10 a (Fig.6), which is nearly twice the global temperature increase rate of the same time period, and is comparable to that of the QXP as a whole (Chen et al., 2015). Interdecadal changes in the temperature showed that the average temperature was the lowest in the 1960s, increased in the 1970s, decreased in the 1980s, began to increase again in the 1990s, and finally increased considerably in the 21st century. This shows that the study area exhibits large interdecadal variations in temperature, and the analysis of the overall trend of temperature changes requires long-term temporal meteorological monitoring.

The M-K test method was used to conduct a mutation test on the changes of the air temperature in the study area (Fig.7). The intersection of the UF and UB curves above the 1.96 threshold in 2001 indicates that the temperature in the study area exhibited a statistically upward trend throughout the entire study period, with a notable intensification occurred around 2001. The annual mean temperature increased by 0.79 °C from -5.5 °C before the abrupt change (1961–2001) to -4.29 °C after the abrupt change (2001–2019), indicating a significant warming trend in the Zonag Lake basin after 2001.

Glaciers (particularly large ones) exhibit a lag period of approximately 10–20 years in their

Table 3 Precipitation in the Zonag Lake basin in different decades

Decade	1961–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2019	2020–2022	Mean
Mean annual precipitation (mm)	268.1	260.5	271.3	291.0	328.1	377.6	363.2	308.5
Compared with the precipitation in the 1960s (%)	–	-2.8	11.9	8.5	22.4	40.8	35.5	15.1

– denotes missing data.

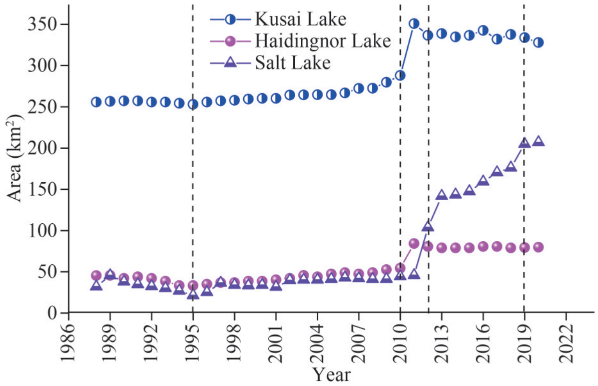


Fig.3 Interannual variation in areas of Kusai Lake, Haidingnor Lake, and Salt Lake

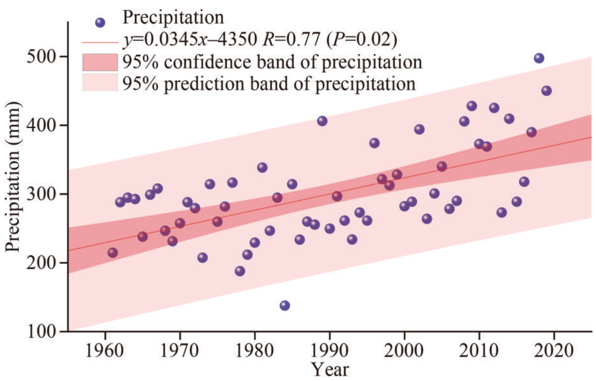


Fig.4 Interannual precipitation variations in the Zonag Lake basin (Wudaoliang Meteorological Station)

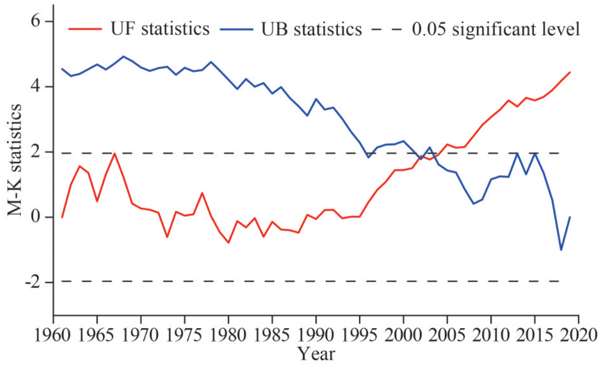


Fig.5 M-K test results for annual average air precipitation in the Zonag Lake basin

response to climate change (Su et al., 1999). The lag period for large glaciers on a global scale is approximately 8 years (Ding, 1995). Concurrently, the thermal state of permafrost systems demonstrates considerable lags (Liu and Zhang, 2013; Yin et al., 2023). Therefore, analyzing these lags observed after the abrupt temperature change since the 21st century is crucial.

Approximately 10 years after the abrupt

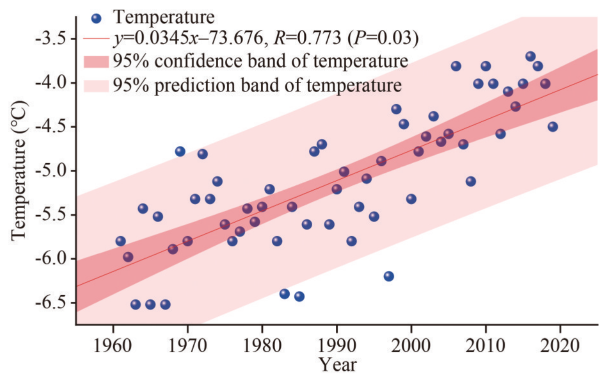


Fig.6 Interannual temperature variations in the Zonag Lake basin

Data source: the Wudaoliang Station.

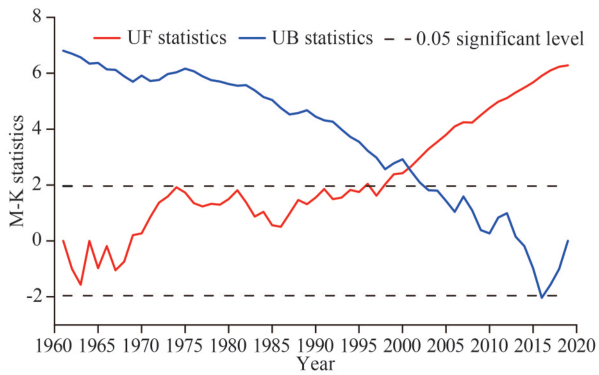


Fig.7 M-K test results of annual average air temperature in the Zonag Lake basin

temperature change of 2000–2001 (i.e., around 2010–2011), the expansion of Zonag Lake led to its outburst and the water volumes of all four lakes in the basin showed significant increasing trends (Fig.2), which was likely associated with the lagged responses of glacier and permafrost systems (Ding, 1995; Su et al., 1999; Liu and Zhang, 2013; Yin et al., 2023). Consequently, changes in the hydrological system that are currently being observed—including lake interconnections and shifts in source contributions—may not solely be the product of contemporaneous climate conditions but may represent a "delayed response" to the abrupt temperature change that occurred at the beginning of the 21st century. This understanding is crucial for predicting the long-term evolution of the regional water cycle in the future.

5 DISCUSSION

5.1 Analysis of the causes of lake expansion

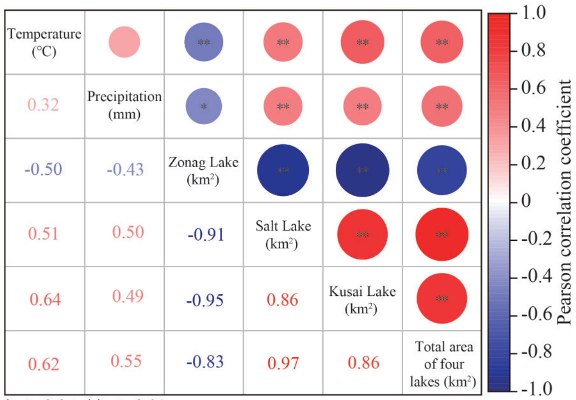
As shown in Fig.2, before the 2011 outburst of Zonag Lake, the area change of lakes in the study area was divided into two stages. In the first stage (before 1995), all the four lakes in the Zonag Lake basin showed a slight shrinkage trend, and all the lakes were in closed state. The main reason for the shrinkage of the lakes was that the amount of water into the lakes (e.g., precipitation, snow and ice melting, and permafrost regression) was lower than that exiting from the lakes (e.g., evapotranspiration). In the second stage (during 1995–2010), all the four lakes slight expansion trend similar to that in the central and northeastern parts of the QXP (Sun et al., 2018; Zhang et al., 2020). The main reason for the expansion of the lakes was that the amount of water entering the lakes was higher than the amount of water exiting the lakes because Zonag Lake, Kusai Lake, Haidingnor Lake, Salt Lake were in a closed state. The inflow was greater than the outflow. This was mainly due to an increase in atmospheric precipitation (Fig.3), coupled with a significant warming trend , which led to the melting of glacial permafrost in the region (Sun et al., 2018; Zhang et al., 2022) and further increased the inflow of water into the lakes. The areas of Kusai Lake and Zonag Lake were similar in this stage, and their expansion rates were nearly twice that of Zonag Lake. This was mainly because the area covered by glaciers around Kusai Lake was 1.7 times of the area of Zonag Lake, and the area of waterlogged area was 1.4 times of that of Zonag Lake (Liu et al., 2019). The warming and humidification occurred in the study area, during which temperature increased, resulting in more glacial meltwater and precipitation runoff sinking into Kusai Lake than into Zonag Lake. The catchment area of Salt Lake was 0.7 times of that of Kusai Lake, and the glacier area of the Salt Lake basin was only 20% of that of Kusai Lake (Table 2). Thus, the recharge of Salt Lake through precipitation and glacial meltwater may be considerably lower than that of Kusai Lake during this stage. The expansion rate of Salt Lake was similar to that of Kusai Lake, probably because lake area of Salt Lake was considerably lower than that of Kusai Lake and the change was more significant.

Significant changes in the areas of the four lakes were observed after the 2011 outburst of Zonag Lake. In 2011, Zonag Lake showed a sharp shrinkage trend: the lake area was reduced by nearly 38.14%. This was mainly because the two heavy precipitation processes before August 22, 2011 and the continuous precipitation process that occurred afterward caused a large amount of water leak-out from Zonag Lake (Xie et al., 2020; Li et al., 2022). Meanwhile, the area of Kusai Lake increased by 21.82% after receiving the lake water from the collapse of Zonag Lake. This was mainly due to the continuous inflow of water from Zonag Lake, which led to the connection of Kusai Lake with the downstream Haidingnor Lake and Salt Lake at the southeast side (Yuan et al., 2022), decreasing the water volume of water in Kusai Lake. Subsequently, Salt Lake and Haidingnor Lake showed a significant increasing trend in water volume, in which the area of Haidingnor Lake increased by approximately 50% in 2013 and that of Salt Lake increased by approximately 209%. After its collapse, Zonag Lake continued to show a slow shrinkage trend, which was mainly because its late lake collapse mechanism was similar to the glacial lake collapse. In particular, the water of the permafrost weir first flowed out slowly through the small ditches within the permafrost. Subsequently, the flow of water facilitated the melting of the ground ice and accelerated the soil erosion (Ding et al., 2021), which further decreased the lake's water storage capacity.

Salt Lake, also known as the tail of the Zonag Lake basin, receives inflow from upstream channels, basin precipitation, glacier- and permafrost-derived meltwater, and other sources. Its hydrological changes were complex, particularly during 2013–2019, when the lake exhibited a pronounced increasing trend in the water level. Meanwhile, after 2019, the area of Salt Lake showed a slight decreasing trend, and the area shrinkage of the lake area in this stage was the result of the human implementation of the Salt Lake Conducting and Discharging Project (He et al., 2021). Under this project, the water of Salt Lake is discharged to the downstream Qingshui River, which merges into the Chumar River, the northern source of the Changjiang River. Our research covers the period after the collapse of Zonag Lake and the implementation of this drainage project. Some previous studies focused on earlier periods. The dominant hydroclimatic mechanisms in different periods may differ.

5.2 Effect of precipitation on lake expansion

Correlation analysis (Fig.8) revealed significant correlation between lake area and precipitation in Zonag Lake. This result was attributed to the expansion of Zonag Lake with increasing of precipitation and the occurrence of a rout. The later stage due to the rout was gradually cut with the downstream of water flow. Water overflow



*: $P \le 0.05$; **: $P \le 0.01$

Fig.8 Correlation analysis of lake area with precipitation and temperature

Red circles indicate positive correlation; blue circles represent negative correlation.

contributed to the downstream melting of the ground ice and the erosion of soil (Ding et al., 2021), which in turn led to a further decrease in the lake area.

From 1988 to 2010, Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake in the Zonag Lake basin were independent lakes. Before 1988–1995, these lakes in the Zonag Lake basin showed a slight shrinkage trend, which is consistent with the results reported by Zhu et al. (2010). From 1995 to 2010, the lakes in the Zonag Lake basin showed a slow expansion trend, with an expansion rate of less than 1.5 km^2/a. Moreover, the order of the expansion rate increase was Kusai Lake (1.84 km^2/a)>Haidingnor Lake (1.33 km^2/a)>Salt Lake (1.18 km^2/a)>Zonag Lake (0.77 km^2/a). The catchment area and expansion rate of Salt Lake were similar to those of Haidingnor Lake. Regional precipitation was the main factor contributing to lake expansion in the Zonag Lake basin during this stage.

From 2011 to 2015, the total area of Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake increased by approximately 100 km^2 (16% increase in the total lake area, compared with that in the period before 2010). Further, the average increase in precipitation in the basin was approximately 19.1% (compared to the period before 2010), indicating that lake expansion of the lakes was influenced by precipitation during this period. From 2016 to 2019, all water resulting from lake expansion was released to the Salt Lake via the overflow. Consequently, the area of Salt Lake increased by approximately 50 km^2 compared to that in 2012–2015. In this period, changes in the glacier area around the Zonag Lake basin were similar to those observed in 2012–2015 (Fu et al., 2023); however, precipitation increased significantly in 2016–2019. Thus, an increase in precipitation within the Zonag Lake basin was the main contributor to the expansion of the Salt Lake.

5.3 Impact of warmer temperatures on lake expansion

As shown in Fig.6, air temperature was significantly positively correlated with the areas of Salt Lake, Kusai Lake, and the three lakes within the Zonag Lake catchment. This result was due to an increase in the amount of water released from nearby glacier melting, snow, and ice melting, and increased permafrost degradation due to an increase in regional air temperatures. Thus, air temperature is an important driver of Zonag Lake expansion. A comparison of changes in the lake areas of Haidingnor Lake and Salt Lake before 2011, indicated high similarity (R=0.82). Furthermore, there was no glacier in the catchment area of Haidingnor Lake, whereas some glaciers were distributed in the catchment area of Salt Lake. Hence, before 2011, glacial meltwater contributed less to the expansion of Salt Lake, and was not a major factor causing lake expansion.

From 2011 to 2015, the total areas of Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake increased by about 100 km^2 (16% increase in the total lake area compared with the period before 2010); the temperature increased by about 1.1 ℃; and glaciers degraded by approximately 4.13 km^2 (6.2% decrease in the area), suggesting that the expansion of the lakes in this period was affected by glacier retreat. From 2016 to 2020, the total area of Zonag Lake basin, Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake lakes increased by about 56 km^2 (16% increase in the total lake area compared with that in 2011–2015), temperature increased by about 0.19 ℃ , and glaciers did not degrade (no changes in the area), indicating that lake expansion in this stage was mainly influenced by precipitation. In the warm and humid environment, glacial permafrost degradation accelerated, and the lake water volume of the QXP increased significantly by about 8 Gt/a, of which glacier and permafrost melting contributed approximately 26% (Zhang et al., 2017a) and permafrost degradation contributed approximately 10% of the lake water volume in the inland area of the QXP (Zhang et al., 2020).

This comprehensive analysis shows that the main factors dominating the expansion of regional lakes in the Zonag Lake basin differed in different time periods. During the period 1961–2020, lake expansion was driven primarily by precipitation, except for the years 2011–2015, when the combined effects of precipitation and glacial meltwater jointly controlled the expansion.

The lake connectivity in the Zonag Lake basin has disrupted the original independent watershed patterns, resulting in the formation of a unified, larger catchment area. The hydrological processes after the connection are as follows. The outflow from upstream lakes has become a key source of recharge for downstream lakes, leading to the convergence of water and salts into the terminal Salt Lake. This may trigger shoreline erosion and morphological adjustments in the downstream lake basins (Xie et al., 2020) while causing a potential gradual freshening trend in the downstream Salt Lake (Fu et al., 2023). The rise in lake water levels accelerates permafrost degradation in surrounding areas, and changes in permafrost conditions reduce the stability of lake shores and basins (Wang et al., 2022a). Furthermore, elevated water levels altered the hydraulic connection between lake basins and adjacent aquifers, potentially enhancing lakewater-groundwater exchange and influencing regional groundwater flow paths and recharge patterns. Lake expansion inundates grasslands, converting terrestrial ecosystems into aquatic ecosystems (Du et al., 2018), which may impact habitats and migration routes of wildlife, such as the Tibetan antelope.

5.4 Quantifying the impact of different factors on lake expansion

The harsh environmental conditions in the Zonag Lake basin limit field survey access. Only Salt Lake is situated near the Qinghai-Xizang Railway, and even there, on-site measurements can only be conducted during specific time periods. Before 2020, no field measurements were performed in the study area, and no hydrological monitoring data were obtained. Therefore, this study considers the Salt Lake as the research object (based on the principle of water balance), adopts the monthly measured water level and overflow data of Salt Lake in 2020, and estimates the change in the quantity of water flowing in and out of the lake in 2020 based on the principle of water balance. Lake characterization indicates that the underlying rock and soil are fully saturated and overlain by continuous permafrost, resulting in minimal infiltration that can be considered negligible. The study area is uninhabited, and there is no information about groundwater. Permafrost is well developed and very thick, and groundwater recharge is limited; hence, the contribution of groundwater recharge was not considered. The lakes in the study area are recharged mainly through land precipitation recharge, lake precipitation, glacial meltwater, and permafrost meltwater. The flow of water out of the lakes mainly includes lake evaporation and outflow.

5.4.1 Lacustrine water dynamics in the Zonag Lake basin (ΔV)

Because Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake were connected before the 2019 Zonag Lake water flowed into Kusai Lake through overflow. Thus, Kusai Lake received incoming water from Zonag Lake and then overflowed into Haidingnor Lake, which expanded and then eventually entered Salt Lake. Based on the analysis of remote sensing data, the lake areas of Haidingnor Lake, Zonag Lake, and Kusai Lake are basically unchanged. After the implementation of the guide drainage project, the area of Salt Lake did not change significantly in 2019–2020. Therefore, the amount of water drained from the Salt Lake is basically the amount of water added to the lakes in the Zonag Lake basin

The flow of the Salt Lake drainage system is primarily monitored in real time using a radar wave online flow measurement system. The flow was verified and checked against data obtained from manual surveys (using current meters or Acoustic Doppler Current Profiler). The volume of water discharged to the downstream through the Salt Lake drainage project in 2020 will be 467 million m^3.

5.4.2 Recharge flow from precipitation-generated surface runoff (R_L)

According to the measured data obtained from the Wudaoliang Station, precipitation in the Zonag Lake basin was 428 mm in 2020 and the atmospheric precipitation was calculated as 2.029 billion m^3. Because a portion of precipitation is lost as surface runoff that flows into neighboring rivers and lakes, the total precipitation cannot be fully considered as lake-recharge input. Wang (2022) analyzed the annual runoff coefficient of the Changjiang River source area based on the measured runoff data from 1961 to 2018, and the surface precipitation data of the basin during the same period via mutation using the M-K method and sliding *t*-test. The results show that the 5-year sliding mean value of runoff coefficient in the Changjiang River source area ranged from 0.19 to 0.32 during 2007–2018. The average runoff coefficient value was 0.246. Therefore, in this study, to better reflect the actual condition, the regional runoff coefficient and amount of precipitation recharge were used to calculate the actual runoff volume, which was 499 million m^3.

5.4.3 Lake precipitation recharge (P)

Calculated from the 2020 lake areas of Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake as well as the regional measured precipitation, the lake surface precipitation of Salt Lake was 326 million m^3.

5.4.4 Estimation of lake evaporation (E)

Given that the total area of river water bodies within the study area is very small compared with the total lake area and most rivers are seasonal, their contribution to evaporation was disregarded compared with those of the major components, such as lake evaporation and glacial meltwater. Therefore, the effect of ignoring their contribution on the overall evaporation estimation was within an acceptable range. Fu et al. (2022) applied the Penman-Monteith equation to analyze potential evapotranspiration trends from 1960 to 2019 in the Salt Lake, reporting a multi-year average of 813 mm and an increasing rate of 10.8 mm per decade. In contrast, in this study, we employed a more direct and lake-specific evaporation measurement. Specifically, we adopted the lake water evaporation rate of 850 mm reported by Xie et al. (2020), which was derived from field monitoring during 2016–2017. This value lies within the range (733.1–877.4 mm) identified by Fu et al. (2022) and aligns closely with their long-term average, supporting its plausibility. Although based on short-term monitoring, the magnitude of this evaporation rate reflects the regions typical long-term evaporative characteristics, thereby lending support to its use in multidecadal scale analyses. By combining this evaporation rate with the 2020 surface areas of Zonag Lake, Kusai Lake, Haidingnor Lake, and Salt Lake, the total surface evaporation of Salt Lake was estimated to be 647 million m^3 in the 2020.

5.4.5 Estimation of glacial and permafrost meltwater (G)

Using $G=\Delta V+E-(P+R_L)$, the glacial and permafrost meltwater volume in the Zonag Lake basin was estimated to be 289 million m^3 in the 2020.

Based on the relationship between each of the aforementioned recharge sources and the total lake inflow, it was estimated that water recharge through land after atmospheric precipitation (R_L) (Fig.9), P, and G accounted for 44.8%, 29.2%, and 25.9%, respectively, of the total recharge. Atmospheric precipitation (R_L+P) accounted for 74.0% of the total recharge, representing dominant factor controlling the lake expansion in the Zonag Lake basin. E and lake drainage (LP) accounted for 58.1% and 41.9%, respectively, of the lake outflow in the 2020.

5.5 Sensitivity analysis

The water balance model used in this study did not include the groundwater term, which constitutes a source of uncertainty. In lakes in the Qinghai-Xizang Plateau, the exchange between groundwater and lake water is complex. There may be groundwater that replenishes lakes (especially in permafrost degradation areas). Similarly, there may be lake seepage processes that replenish groundwater (Zhang et al., 2013; Wang et al., 2022c). Given the lack of relevant observations in this area, the direction and magnitude of its net flux are difficult to determine. Future research needs to consider this aspect through geophysical exploration or the establishment of coupled surface water-groundwater models. Sensitivity analysis was performed in this study to assess the impact of ignoring the presence

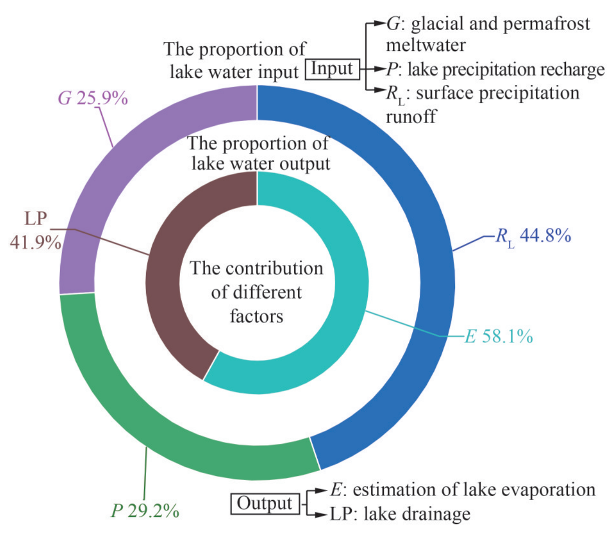


Fig.9 Contribution proportion of various factors to inflow and outflow in the Zonag Lake basin in 2020

The contribution of groundwater was not taken into account.

of groundwater on conclusions.

In high-latitude permafrost regions, active layers are very shallow and the hydraulic connection between surface water and groundwater is weak (Cheng et al., 2019). Zhang et al. (2017b) estimated that groundwater in the inland areas of the Qinghai-Xizang Plateau contributes approximately 12% to the water volume of lakes. Wang et al. (2022b) used SBAS-InSAR technology to estimate lake water changes in the Selin Co basin from 2017 to 2020. They found that the contribution of subsurface glacial meltwater in the basin to the increase in the lake water volume was approximately 10%. Therefore, in this study, a groundwater contribution of 5%–15% was assumed and considered in the water balance model to quantitatively incorporate the impact of groundwater on final results. Results were obtained by setting four groundwater contribution levels (0%, 5.0%, 7.5%, 10%, and 15%; Table 4). The results show that glaciers and permafrost accounted for approximately 22.0%–25.9% of the lake inflow and precipitation accounted for 63.0%–74.0%. Through error analysis, the contribution of rainfall runoff was found to be 41.5%±2.3%, that of lake-surface precipitation was 27.0%±1.5%, and that of glaciers and permafrost was 24.0%±1.3%.

According to relevant studies, the contribution of glacial and permafrost meltwater to lake expansion is approximately 12% and 13% in the inner QXP (Zhang et al., 2021), which is comparable to the estimated 20% contribution in the Hoh Xil Lake Basin (Liang, 2022). The meltwater contribution to lake water recharge calculated in this study (24.0%±1.3%) is consistent with these previously reported values, thereby supporting the reliability of our findings. Precipitation contributes 67%–75% to Selin Co in the QXP (Tong et al., 2016) and 74% to endorheic lakes in the QXP (Zhang et al., 2021). Therefore, our conclusion is consistent with previous results, verifying the rationality of our analysis.

Table 4 Different contributions of groundwater considered in the sensitivity analysis and their effects on the contributions of other factors

Case	Groundwater (%)	Runoff (%)	Glacier+ permafrost (%)	Lake precipitation (%)
Baseline	0.0	44.8	25.9	29.2
Case 1	5.0	42.6	24.6	27.8
Case 2	7.5	41.5	24.0	27.0
Case 3	10.0	40.4	23.3	26.3
Case 4	15.0	38.1	22.0	24.9
Mean	7.5	41.5	24.0	27.0
RSD	5.0	2.3	1.3	1.5

5.6 Study limitation

The study area is located in the remote Hoh Xil uninhabited area and is sparsely populated. The environment is harsh, and the investigation is difficult. The severe lack of data due to the uninhabited nature in the region poses a major challenge. As a result, certain parameters (such as runoff coefficient) were derived from nearby study sites and were not locally calibrated. This could be a source of uncertainty for our quantitative estimates. Although the water balance method was used to estimate the contributions of different impact factors in this study, the following deficiencies remain. Owing to the lack of relevant monitoring data, the contribution of groundwater and permafrost meltwater to lake expansion was neglected in this study, which might lead to the overestimation of the proportion of some contributing factors. Notably, the lack of regional data currently prevents precise quantification of the individual contributions from glaciers and permafrost. In future research, we will enhance field observations and develop an integrated hydrological model that incorporates both glacial and permafrost processes to better elucidate their separate and synergistic roles in the lake water cycle. In addition, evaporation of the lake was mainly considered, while the evaporation of the surrounding river water was not considered, thus the amount of the lake water might be overcalculated. In general, because the trend of lake expansion in the QXP is obvious, but the phenomenon of lake outburst is rare, the understanding of the driving mechanism of lake expansion is still insufficient. Hence, further research is needed.

Because the study area is an uninhabited zone, it is difficult to obtain high-precision data on the distribution and properties of seasonal permafrost. The study area is mostly continuous, with stable permafrost systems (Cheng et al., 2019; Daout et al., 2020; Ran et al., 2021). This study was based on the water balance method and estimated the contribution of permafrost and glacial meltwater to lake water recharge by subtracting the difference between the total outflow (lake-surface evaporation+discharge) and the lake-surface precipitation recharge and runoff recharge. Finally, considering different permafrost types may lead to more refined results, which will be a critical direction for future research.

5.7 Implication

Notably, lake expansion in the Zonag Lake basin shows a steadily increasing trend, leading to direct and distinct risks for Tibetan antelope habitats and the Qinghai-Xizang Railway. This situation differs from the more hydrologically constrained expansion seen in basins such as Selin Co. This uniqueness is critical for formulating targeted conservation policies. Based on our spatiotemporal analysis of lake expansion and its projected inundation areas, we identified potential threats to the critical calving and migration grounds of the Tibetan antelope around Zonag Lake. We proposed to establish buffer zones and ecological corridors in the northeastern part of the basin, which is less susceptible to inundation. We also recommended a dedicated monitoring system combining satellite imagery and in situ gauges to track lake water-level changes and shoreline dynamics toward the railway. On one hand, a diversion embankment is being built on the water-adjacent side of the Qinghai-Xizang Railway to divert lake water overflowing from Salt Lake to nearby Qingshui River. On the other hand, we suggested to build cofferdams at a certain distance away from the water-facing side of the railway embankment to prevent embankment erosion by high-salinity lake water. The prediction and assessment of the maximum future discharge volume of the Zonag Lake basin should be conducted. If necessary, the existing channels should be expanded. In addition, channel slopes and energy dissipation facilities (such as concrete or stone lining) shall be reinforced to prevent the rapid flow from eroding and damaging them. In addition, multiple levels of drainage outlets and backup channels shall be set up at different elevations along the shore of Salt Lake so that water can be discharged in time when the lake water rises to different levels. In complex conditions, backup discharge channels or networked drainage patterns shall be constructed.

6 CONCLUSION

This study quantitatively revealed the driving factors affecting lake expansion in the Zonag Lake basin through the analysis of remote sensing data and regional meteorological information, and combined with statistical analysis and level-balance calculations. The main conclusions of the study are as follows.

In the past 30 years, the lake area in the Zonag Lake basin has shown an overall expansion trend, but different lakes had various trends over time. After the collapse of Zonag Lake in 2011, Zonag Lake has been shrinking. The other lakes have shown different expansion degrees. The expansion of the Salt Lake has been curbed by implementing the Salt Lake drainage project in 2019. The lake area started to decrease in 2020, and stabilized subsequently.

Except for the years 2011–2015—when the four lakes in the Zonag Lake basin were affected by the joint influence of precipitation and glacier meltwater—the expansion of the four lakes in the Zonag Lake basin in the other years was mainly affected by precipitation. Atmospheric precipitation (surface runoff and lake precipitation) was the key factor driving lake expansion, and glacier and permafrost melting was the secondary factor. Lake evaporation was the major reason of lake water loss in the Zonag Lake basin.

7 DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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