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Research on lake water level and its response to watershed climate change in Qinghai Lake from 1961 to 2019

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Lake water level reflects the dynamic balance of water input and output/loss and is a sensitive indicator of climate change and variation. Studying the relationship between the closed Qinghai Lake water level and watershed climate change is important for understanding regional climate change and its impacts on the lake. The objective of this study was to investigate changes in Qinghai Lake water level/area and environmental factors during 1961–2019, using ground-based measurements data, hydrological balance model and statistical methods. The results revealed two primary phases: during the first phase (1961–2004), the lake water level lowered by 0.80 m/decade ($p < 0.01$), while in the second phase (2004–2019), it rose markedly by 1.80 m/decade ($p < 0.01$). The lake area increased in April and September between 1990 and 2019, but since 2004 the increases have been more significant. Air temperature near the lake during 1961–2019 warmed by 0.39°C/decade and precipitation increased by 17 mm/decade. Annual river runoff increased at 14.3 mm/decade from 1961 to 2019, however, runoff decreased (–6.8 mm/decade) during the first phase from 1961 to 2004 and increased significantly (84.7 mm/decade) during the second phase from 2004 to 2019. The increases in precipitation and river runoff were the predominant factors contributing to lake water level rises and area expansion, while a decreasing lake water level and area reduction corresponded to reduced precipitation and river runoff and increased evaporation. As a sensitive indicator of regional climate change, the fluctuations of lake water level and surface area provide a comprehensive reflection of climate change in the Qinghai Lake watershed.

KEYWORDS

lake water level, lake area, water balance, climate change, Qinghai Lake

1 Introduction

Climate change has significantly affected river and lake hydrological processes in many regions of the world. The hydrological processes in cold regions, such as the Tibetan Plateau (TP) and the high latitudes, are very sensitive to climate change (Yang et al., 2010; Wu et al., 2019; Zhang et al., 2019a; Zhang et al., 2019b). There are approximately 1,400 lakes with water surface areas greater than 1 km² over the TP and these are primary water resources besides glaciers and rivers (Lehner and Döll 2004; Zhang et al., 2014a; Zhang et al., 2019c). Lakes are extremely sensitive to climate, responding rapidly to environmental changes in their catchment (Adrian et al., 2009). During recent decades, lakes in TP have experienced significant changes, including fluctuations in lake water level and lake surface area (Wang et al., 2008; Zhang et al., 2014b; Zhang et al., 2020). The relatively limited human activities in TP mean

fluctuations in lake water level offer a clear indicator of climate change. Qinghai Lake is within a large, closed basin and lies in the northeastern TP within a transitional zone between the East Asian and Indian monsoons and the Westerlies (An et al., 2017; Wang et al., 2019). The unique geographical location of Qinghai Lake makes it one of the sensitive regions to climate change in TP (Liu et al., 2011; Zhang et al., 2014a).

Many studies have reported a severe decrease in the water level and surface area of Qinghai Lake over the past few decades. During 1959 to 2000, the water level of Qinghai Lake experienced a 3.35 m decline (Li et al., 2007). Studies also showed that Qinghai Lake was significantly shrinking and provided abundant sediments for aeolian erosion (Li et al., 2004; Sun et al., 2008; Yi et al., 2010; Wang et al., 2013; Fang et al., 2019). However, some lakes in TP have significantly increased in water level and surface area since 2000 (Liu et al., 2009; Duo et al., 2010; Zhang et al., 2011; Kropáček et al., 2012; Lei et al., 2013; Zhang et al., 2020), indicating that lakes in TP have the characteristics of rising water level and increasing surface area in the 21st century when climate change gradually intensifies. Lake storage and water level showed an increasing tendency in the wet years (Shen et al., 2005). Studies of water level changes using remote sensing data for 74 lakes showed that the levels of 62 (84%) lakes rose from 2003 to 2009, including Qinghai Lake (Zhang et al., 2011). Because many lake basins in TP include glaciers in their catchments, it has been hypothesized that the increase in glacier melt water has contributed significantly to the growth of inland lakes (Yao et al., 2007). However, some lakes without glacier contributions have also expanded significantly in recent years, which indicates that other climatic factors—such as precipitation increases and lake evaporation decreases—may also affect recent lake growth (Liu et al., 2009a). Changes in precipitation, temperature, evaporation, and permafrost are potential factors influencing the water levels of Qinghai Lake (Lee et al., 2011). Regional climate changes such as temperature and precipitation have been reported to directly impact the water level of Qinghai Lake (Qin and Huang, 1998). Qinghai Lake is the largest inland closed lake in China. It is located in the confluence area of East Asian monsoon, Indian monsoon and Westerly wind, and is very sensitive to climate change (Li et al., 2007; An et al., 2017). Qinghai Lake is a closed lake with only inflow but no outflow. It is an ideal place to study the impact of climate changes on the lake water body. Studying the relationship between Qinghai Lake water level and watershed climate change is important for understanding regional climate change and its impacts on the lake.

Previous studies have in general, used relatively short periods of data records for water level and surface area. Moreover, it is not clear which is the key factor that has caused Qinghai Lake hydrology to change so dramatically over time. Insufficient data of precipitation, river runoff, water level, and area data mean the attribution of lake change and variation for Qinghai Lake is poorly understood. To fill this knowledge gap, this study aimed to investigate changes and variabilities of Qinghai Lake level and area from 1961 through 2019 using the updated datasets of *in-situ* measurements and satellite remote sensing images. The results will provide reliable data and knowledge for local and regional water resources assessment, evaluation of climate change, environmental protection, and socio-economic developments.

2 Materials and methods

2.1 Study area

Qinghai Lake is located in a semi-arid and cold region of the northwestern TP, at an elevation of 3,194 m (Figure 1). From 1961 to

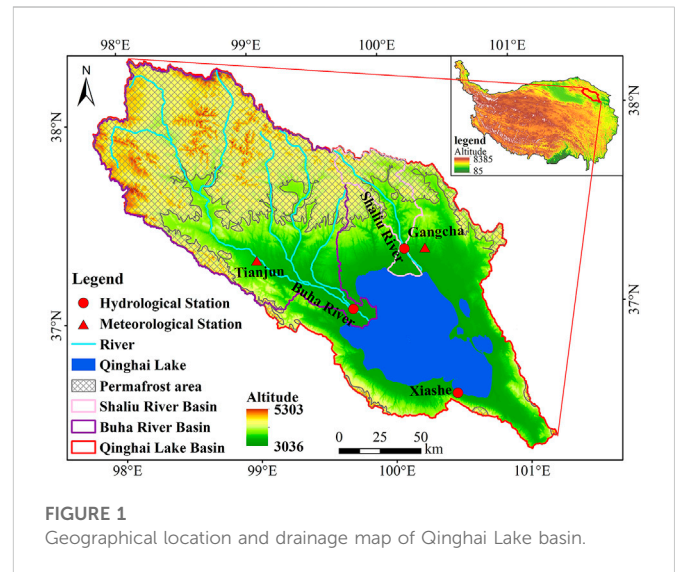


FIGURE 1
Geographical location and drainage map of Qinghai Lake basin.

2019, mean annual air temperature was -0.6°C and annual precipitation was 367 mm. More than 80% of annual precipitation falls as rain from May to September (Xu et al., 2007). The average water depth, lake surface area, lake water volume, and entire basin drainage area of Qinghai Lake are approximately 21 m, 4,591 km² (2019), $85 \text{ m}^3 \times 10^9 \text{ m}^3$, and 29,660 km², respectively (Li et al., 2007). The lake surface is ice-covered from mid-December to late March (Cai et al., 2019; Dong et al., 2019). There are more than 40 rivers (some seasonal) flowing into Qinghai Lake, but most are relatively small and intermittent. The largest river in Qinghai Lake basin is the Buha River, with a runoff accounting for almost 50% of the total runoff to Qinghai Lake; the Shaliu River is the second largest river with a discharge accounting for 14.5% of the total runoff (Li et al., 2007). Water consumption by humans is responsible for only 1% of the evaporation loss of the lake and has little effect on lake water level change (Li et al., 2007). Most of the lake catchment is covered by grazing land, alpine shrubs, and meadows (Zhang et al., 2014a). There are not many glaciers in the basin (Qin and Huang, 1998), except a small one in the upper Buha River basin (Colman et al., 2007). There is a large range of permafrost regions, comprising approximately 42% of the total basin area (Cao et al., 2019). The entire lake basin experiences seasonal freezing and thawing.

2.2 Datasets and methods

The datasets used in this study are from ground-based measurements and satellite remote sensing images. Meteorological data, such as daily mean air temperature and daily precipitation, were collected from TianJun (TJ) and GangCha (GC) meteorological stations within Qinghai Lake basin during 1961–2019 (Figure 1), and monthly and annual mean air temperature and precipitation were calculated from daily data. The mean meteorological conditions in Qinghai Lake basin are reflected by the average value from the two meteorological stations. The lake water level was obtained by measuring 5 min with bubble water level gauge and the data were calibrated at the XiaShe hydrological station on the south shore of the lake. Discharges of Buha and Shaliu rivers were measured from hydrologic stations during 1961–2019 (Figure 1). These data have

been quality controlled by hydromet services; annual data were derived from monthly or daily data. Evaporation was estimated by the Penman-Monteith Equation, daily ET_0 was calculated for two stations by means of the FAO 56 p.m. equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (1)$$

where ET_0 is reference evapotranspiration rate (mm d^{-1}), T is mean air temperature ($^{\circ}\text{C}$), R_n is the net radiation at the surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G is the soil heat-flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), μ_2 is the wind speed at a height of 2 m (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $(e_s - e_a)$ is the saturation vapor pressure deficit (VPD) (kPa), Δ is the slope of the vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), and γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

Satellite remote sensing images were used in this study to examine lake surface area changes. Landsat image series are the most widely used data for lake surface area monitoring because of the high spatial resolution, long availability, and free access (Pekel et al., 2016; Sheng et al., 2016; Verpoorter et al., 2014). Spatial resolution of selected images is 30 m. Data for April and September were used to represent the dry and wet season in Qinghai Lake watershed, respectively; if data were unavailable in April or September, data from May or October were selected. In order to better reflect the characteristics of lake water level and area changes in dry season and wet season, satellite data in April and September were used. The normalized difference water index (NDWI) (McFeeters, 1996) was applied to distinguish water from land with the Otsu method (Otsu, 1979). Because Landsat data were unavailable and discontinuous from 1972 to 1989, images from 1990 to 2019 were selected to explore variation of the lake area.

Qinghai Lake is a closed catchment, thus the hydrological balance model for Qinghai Lake can be expressed as follows:

$$\Delta H_{sim} = P + R - E \quad (2)$$

Where ΔH_{sim} is annual water level variation (mm), P is annual precipitation (mm) over the lake, R is river runoff, and E is annual evaporation (mm) from lake. ΔH_{obs} can be calculated from observation data:

$$\Delta H_{obs} = \sum_{i=1}^N ((H_i - H_{i-1}) + (H_{i+1} - H_i) + \dots + (H_{N-1} - H_N)) \quad (3)$$

Where H_i and H_{i-1} are the lake water level at i th month and $(i-1)$ th month, $N = 12$, respectively.

Long-term hydro-climatic changes have been determined by a linear trend analysis (Li et al., 2000). Pearson correlation analyses (two-tailed) and statistical significance tests were used to assess the associations among climatic and hydrological variables. The ΔH_{sim} results were compared with the ΔH_{obs} data by using three different criteria—mean absolute error (MAE), root mean square error (RMSE), and coefficient of correlation (?)—as based on the following equations:

$$MAE = \frac{1}{N} \sum_{i=1}^N |(Y_s)_i - (Y_o)_i| \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N [(Y_s)_i - (Y_o)_i]^2} \quad (5)$$

$$R = \frac{\frac{1}{N} \sum_{i=1}^N [(Y_s)_i - \bar{Y}_s][(Y_o)_i - \bar{Y}_o]}{\sqrt{\frac{1}{N} \sum_{i=1}^N [(Y_s)_i - \bar{Y}_s]^2} \times \sqrt{\frac{1}{N} \sum_{i=1}^N [(Y_o)_i - \bar{Y}_o]^2}} \quad (6)$$

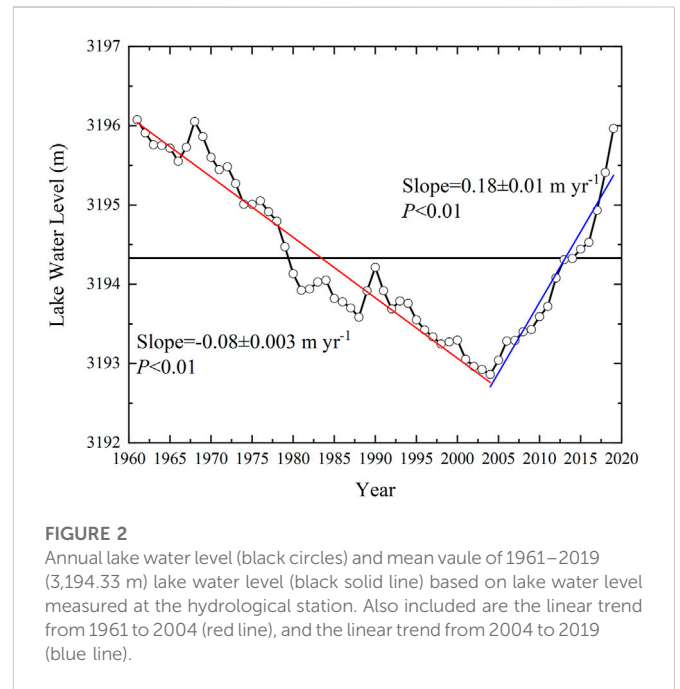


FIGURE 2
Annual lake water level (black circles) and mean value of 1961–2019 (3,194.33 m) lake water level (black solid line) based on lake water level measured at the hydrological station. Also included are the linear trend from 1961 to 2004 (red line), and the linear trend from 2004 to 2019 (blue line).

$$\bar{Y}_s = \frac{\sum_{i=1}^N (Y_s)_i}{N} \quad (7)$$

$$\bar{Y}_o = \frac{\sum_{i=1}^N (Y_o)_i}{N} \quad (8)$$

Where Y_s and Y_o are simulated and observed data, respectively, and N is the sample size.

3 Results

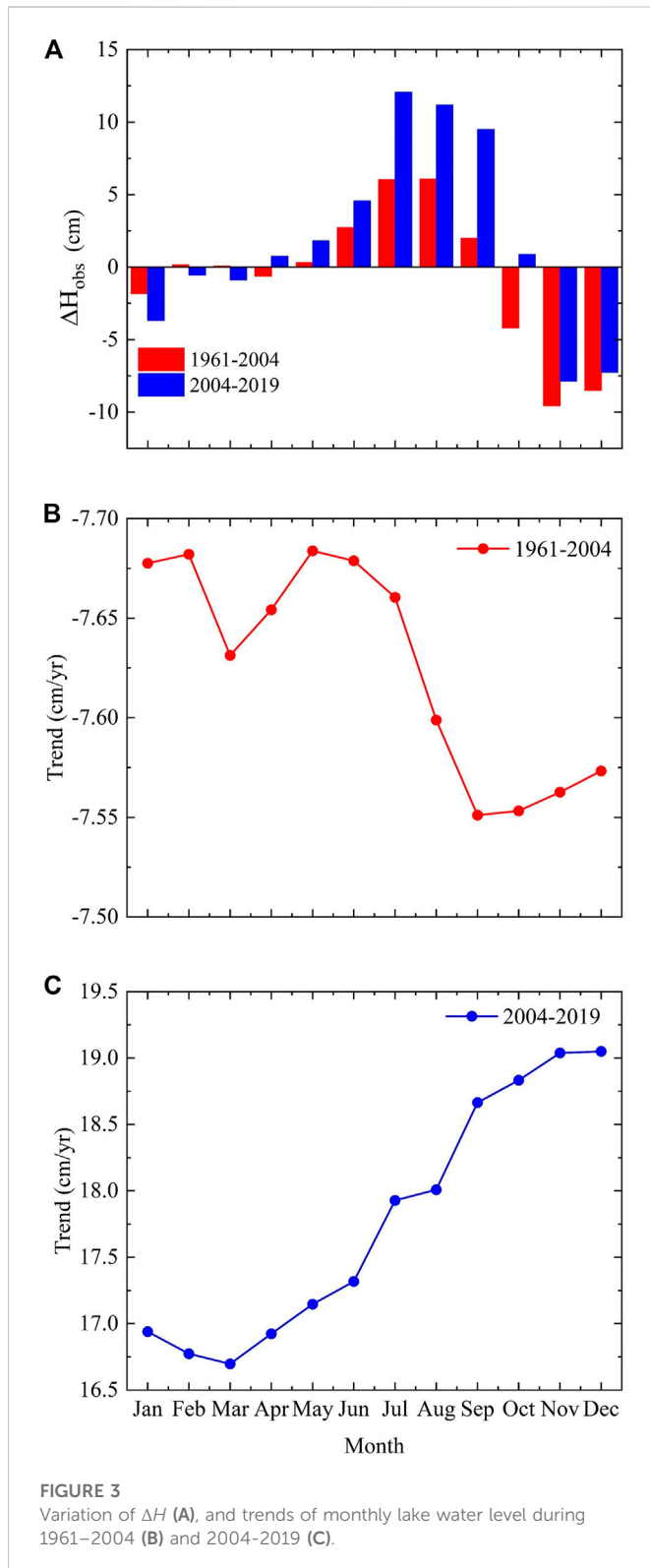
3.1 Changes of lake water level

3.1.1 Inter-annual changes

Long-term water level data reveals two phases of change from 1961 to 2019 (Figure 2). During the first phase from 1961 to 2004, the lake water level decreased, on average by 0.80 m/decade. The lake water level was 3,196.10 m in 1961 and 3,192.86 m in 2004, which is a decline of 3.24 m in 43 years. Within this first period, there were fluctuations in the lake water level. These fluctuations included two major increase events—one in the late 1960s and one in the late 1980s (Figure 2)—with the largest increase of 0.33 m in 1989. Conversely, the largest annual decline in water level was 0.34 m in 1980. Major decline events occurred in the early 1960s, from the early 1970s through the late 1990s, and from the early 1990s through the mid-2000s (Figure 2).

During the second phase (2004–2019), the lake water level increased dramatically and continuously with relatively weak oscillations. On average, the lake water level increased by 1.80 m/decade, which was approximately 2.25 times greater than the decreasing rate during the first phase (Figure 2). The lake water level was 3,192.86 m in 2004 and 3,195.97 m in 2019, an increase of 3.11 m in 15 years. The largest increase was 0.48 m in 2019 (Figure 2).

Over the 58 years of recorded data, there were 25 years when the annual lake water level was above the 1961–2019 mean value



(3,194.33 m), although it has not yet returned to the original level recorded in 1961 (Figure 2). There were 34 years when the annual lake water level gradually decreased to less than 3,194.33 m in each year until 2013, before persistently increasing to more than 3,195.00 m again in 2018, close to the lake water level of 1962 (Figure 2). Overall,

the water level showed a continuous increasing trend, which accelerated since 2013 with a rate of about 2.72 m/decade (Figure 2).

3.1.2 Seasonal change

The average monthly lake water level change revealed a general rise from May to September and a decrease from October to April during the first phase (1961–2004) (Figure 3A). During the second phase (2004–2019), the water level rose from April to October and declined from November to March (Figure 3A). The increase in lake water levels from April to October during the second phase (2004–2019) was significantly greater than that of the first phase (1961–2004) (Figure 3A). The rise in lake water level predominantly occurred in summer, while the decline mainly occurred in autumn, winter, and early spring. Monthly records of lake water levels show a low water level period from October to April, and a high water level period from May to September (Figure 3A).

The rates of monthly lake water level change during the two phases were different. The lake water level exhibited a significant downward trend with an average decreasing trend of 7.60 cm/year for each month during the first phase (Figure 3B). Although the difference among monthly lake water level declining rates was small (~ 0.13 cm/year) during the first period, high magnitudes of water level lowering occurred in February and May, while the lowest magnitude was in September (Figure 3B). The lake water level showed an obvious upward trend with an average increasing rate of 17.8 cm/year during the second phase (2004–2019) (Figure 3C), approximately 2.3 times the absolute magnitude of the first phase. The highest was in November and December (19.10 cm/year) and the lowest in March (16.70 cm/year) (Figure 3C). From February through April, lake level changes were relatively small (Figure 3A), owing to minimum river runoff and snowfall, and weeks to months of lake ice cover.

3.2 Lake area changes

Lake water surface area was obtained by using satellite remote sensing data. Available Landsat images from 1990 to 2019 were used to obtain the lake surface area in April and September for each year. Fluctuations in lake water surface area were synchronous with the variation in lake water level in April (Figure 4A) and September (Figure 4C) from 1990 through 2019. During 1990 to 2019, the lake water surface increased by approximately 203.40 km² in April with an increasing rate of 44.70 km²/decade, and by approximately 237.40 km² in September with an increasing rate of 47.80 km²/decade. However, since 2004, the increases in lake water surface area have been more significant with increasing rates of 174.50 km²/decade and 182.70 km²/decade for April and September, respectively. Lake water level and lake surface area from 1990 to 2019 showed a strong positive correlation, with a coefficient of 0.98 for April and 0.99 for September, respectively, and $p < 0.01$ (Figures 4B, D). The extremes in lake water surface area and water level do not always fully agree each other, and this is mainly owing to the difference in coastal slopes around the lake.

I and II present the first phase (1961–2004) and the second phase (2004–2019), respectively. The first phase (I) of lake area is 1990–2004, and the second phase (II) is same as other variables.

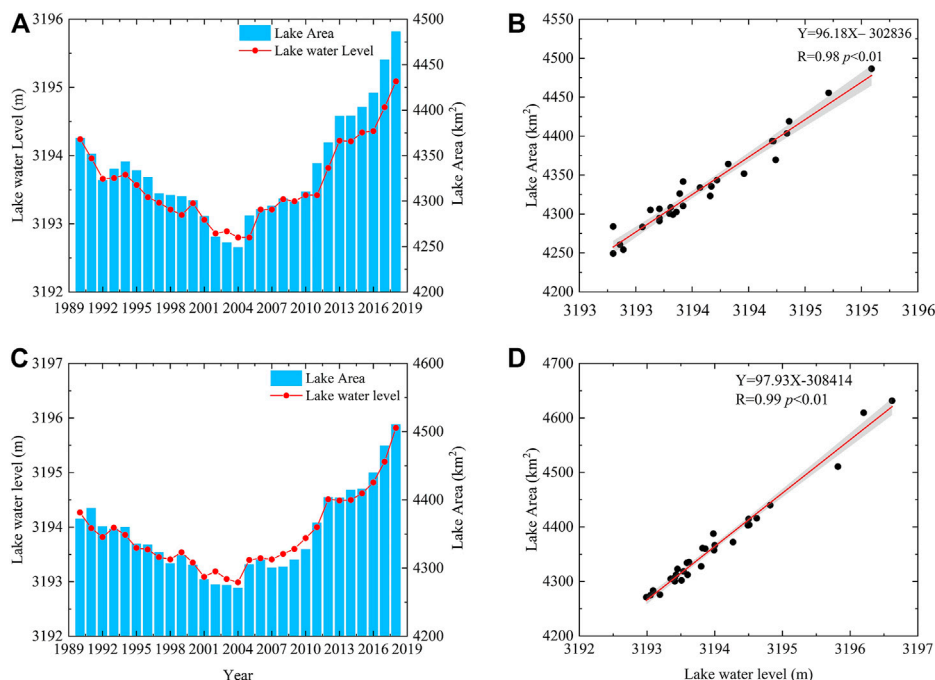


FIGURE 4 Variation of monthly lake water level and surface area for April (A) and September (C), and linear correlations between lake water level and surface area for April (B) and September (D).

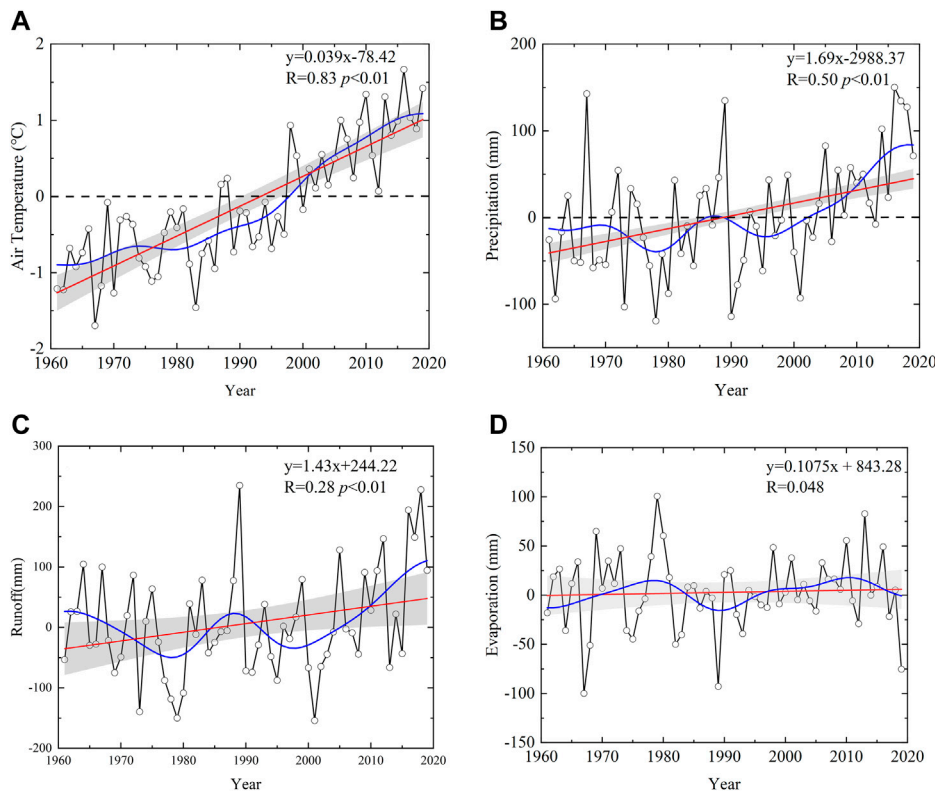


FIGURE 5 Anomalies of mean annual air temperature (A), precipitation (B), river runoff (C), and lake surface evaporation (D) with respect to the 1981–2010 mean in Qinghai Lake basin from 1961 through 2019. The 1981–2010 mean air temperature was -0.3°C , precipitation was 376.3 mm, river runoff was 280.9 mm, and evaporation was 924.4 mm, respectively. Also included are individual annual anomalies (black lines with open circles), the linear trend from 1961 to 2019 (red lines), the Fast Fourier Transform smoothing (blue lines), and 0.95 confidence interval of linear trend (gray shading).

TABLE 1 Statistics of factors affecting the water balance of Qinghai Lake.

Factor	Phase	Mean	Trend (per decade)	Standard deviation
Temperature (°C)	I	-0.80	0.30	0.60
	II	0.60	0.50	0.50
Precipitation (mm)	I	359.00	3.00	57.80
	II	432.20	62.40	52.70
Runoff (mm)	I	266.40	-6.80	76.20
	II	343.60	84.70	90.40
Evaporation (mm)	I	844.60	0.08	38.60
	II	851.10	-16.10	37.00
Lake Water Level (m)	I	3,194.40	-0.80	1.00
	II	3,194.00	1.80	0.90
Lake area (km ²)	I	4,317.20	-80.20	36.60
	II	4,376.10	178.60	89.80

I and II present the first phase (1961–2004) and the second phase (2004–2019), respectively. The first phase(I) of lake area is 1990–2004, and the second phase(II) is same as other variables.

3.3 Response of Qinghai lake water level to climate change

Changes in lake water level are affected by many factors, such as precipitation, river runoff, evaporation, and air temperature. The effect of precipitation on lake water level includes two aspects: first, rain falls directly onto the lake surface, and thus lake water level rise; second, precipitation falls across the lake basin, generates river runoff, and then flowing into the lake. Air temperature records showed that precipitation varied from -1.99°C to 1.37°C from 1961 to 2019, with an overall mean of -0.43°C . There is a strong warming tendency of $0.39^{\circ}\text{C}/\text{decade}$ during 1961–2019 over the Qinghai Lake basin (Figure 5A). Precipitation records from 1961 to 2019 showed that precipitation varied from 257 to 527 mm, with an overall mean of 378 mm. There were large inter-annual fluctuations and a weak increasing tendency of approximately 16.90 mm/decade during 1961–2019 over the Qinghai Lake basin (Figure 5B). However, precipitation showed a slight increase of 3.00 mm/decade, with large inter-annual variability during the first phase (1961–2004), while a continuously increasing tendency was detected during the second phase (2004–2019) with an increasing rate of 62.4 mm/decade (Table 1), approximately 21 times that of the first phase. The increase in precipitation during the second phase alone contributes approximately 35% of the lake water level rise. More specifically, precipitation decreased by about 250 mm from the late 1960s through the late 1970s (Figure 5B), while the lake water level declined by approximately 200 cm (Figure 2). During the second phase, precipitation exhibited a gradual increase from approximately 250 mm around 1990 to approximately 525 mm in the late 2010s (Figure 5B). However, the lake water level only started to rebound around the mid-2000s (Figure 2), more than a decade after the precipitation began increasing (Figure 5B).

River runoff in Qinghai Lake basin exhibited large inter-annual fluctuations (127–516 mm) with a weak increasing tendency over the entire study period (1961–2019) (Figure 5C). River runoff tended to decrease during the first phase (1961–2004) at a rate of $-6.80\text{ mm}/\text{decade}$, and markedly increased during the second phase (2004–2019)

at a rate of 84.70 mm/decade (Table 1). The decrease in river runoff during the first phase alone can partially explain the decline in lake water level (Table 1). Simultaneously, the marked increase in river runoff from the early 2000s through the end of the record period contributed substantially to the rise in lake water level.

Evaporation exhibited an inconspicuous upward trend in the period of 1961–2019 (Figure 5D; Table 1). The two phases of evaporation exhibited different tendencies. During the first phase, evaporation displayed a weak increasing trend, on average, by 0.80 mm/decade from 1961 to 2004. In contrast, evaporation in the second phase (2004–2019) showed a decreasing trend, and the decreasing rate was approximately 16.10 mm/decade after 2004 (Table 1), about 20 times that of the first phase (0.80 mm/decade) (Figure 5D; Table 1). The substantially decreased rate of evaporation during the second phase contributed significantly to the rise in lake water level. Consequently, the decrease in lake water level (Figure 2) during the first phase was predominantly because of the decrease in river runoff, relatively little evaporation loss, and little or no contribution from precipitation change. The rising lake water level during the second phase (Figure 2) corresponded to increasing precipitation (Figure 5B) and river runoff (Figure 5C), and decreasing evaporation (Figure 5D). More specifically, changes in precipitation and river runoff were essentially in the same trends as shown by the smoothed curves using the low-pass filters (Figures 5B, C), while evaporation showed an opposite trend (Figure 5D) and air temperature showed a relatively weak linkage (Figure 5A).

Changes in water balance for Qinghai Lake were evaluated by using observed and calculated values (Figure 6A). Calculated water level changes essentially capture the major changes from *in-situ* measurements. Further analysis was conducted by using simulated values against the ground-based measurements (Figure 6B) and showed that the observed and simulated values were closely related, with $R = 0.91$ (Figure 6B). These results demonstrated that the simulated lake level changes were reliable and could be used for further investigation of the Qinghai Lake basin hydrology.

Major climate variables have a substantial impact on lake water level changes, and thus lake hydrological processes. Overall, changes in

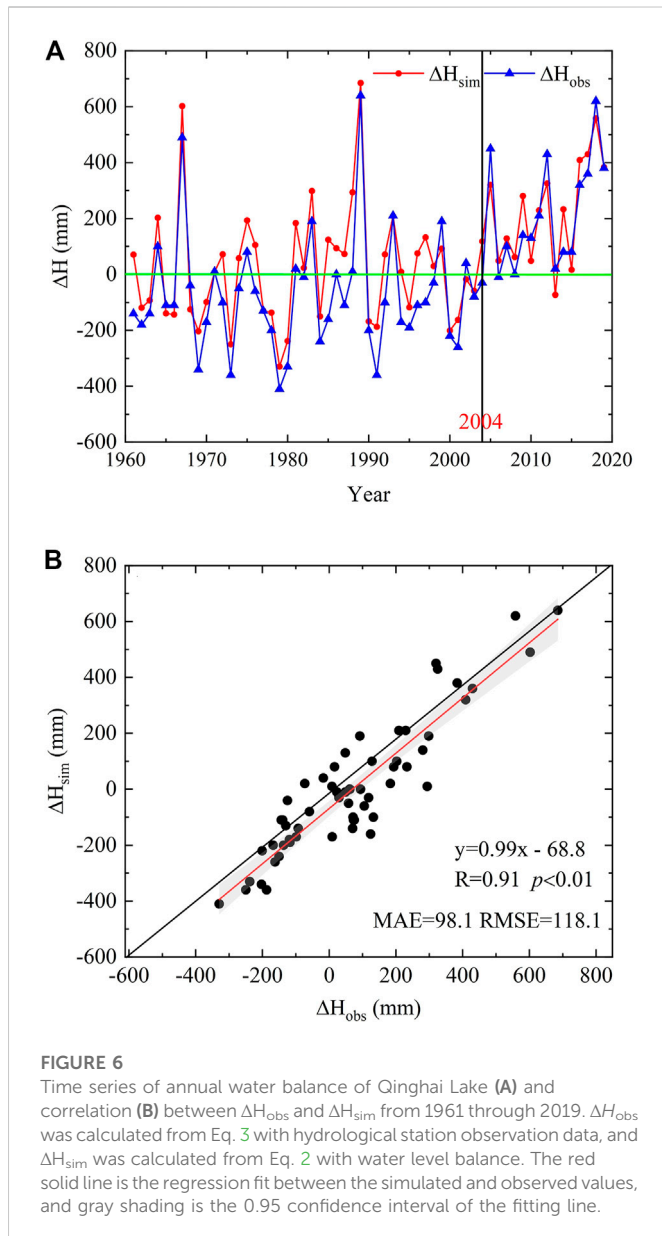


FIGURE 6
Time series of annual water balance of Qinghai Lake (A) and correlation (B) between ΔH_{obs} and ΔH_{sim} from 1961 through 2019. ΔH_{obs} was calculated from Eq. 3 with hydrological station observation data, and ΔH_{sim} was calculated from Eq. 2 with water level balance. The red solid line is the regression fit between the simulated and observed values, and gray shading is the 0.95 confidence interval of the fitting line.

lake water level were strongly controlled by precipitation, river runoff, and evaporation. However, these variables are also strongly interconnected and interact with each other. River runoff is closely correlated with precipitation (Figure 7A) and lake water level (Figure 7C), resulting in changes in precipitation as the major factor for a rise in lake water level (Figure 7B). The negative correlation between lake water level and evaporation demonstrated that loss of water from the lake surface substantially affected lake water balance (Figure 7D). In addition, changes in air temperature may have a direct influence on evaporation.

4 Discussion

The continued changing trend of Qinghai Lake basin hydrology is consistent with climate change during the last 60 years over the TP (An et al., 2017) and globally (IPCC, 2013; 2021). Ongoing global changes will strengthen the hydrological cycle on the regional scale in

the TP, which will impact river and lake water cycles (Zhang et al., 2020; Chen et al., 2022). The measured results in this study showed distinct increases in air temperature (0.39°C/decade) and precipitation (16.90 mm/decade) from 1961 to 2019 in Qinghai Lake basin. Compare with precipitation, river runoff, temperature has a different perspective on the lake water level because changes in air temperature directly affect lake surface evaporation. As the air temperature increases, it is generally expected that evaporation from lakes will be enhanced. However, evaporation showed a decreasing trend from 1961 to 2019 in Qinghai Lake. The contrast between expectations and observations is known as the pan evaporation paradox (Roderick and Farquhar, 2002), and has been reported in Northwest China (Liu et al., 2004) and in the Qilian Mountains next to Qinghai Lake (Jia et al., 2009). Another study demonstrated that increases in air temperature predominantly occurred during winter months over the TP (An et al., 2017), when the lake surface was covered by lake ice and evaporation was therefore at its minimum level. During the summer months, the air temperature increase was relatively small, and heavier precipitation implied that there were more cloudy days with higher relative humidity, thus less evaporation would occur. This may partially explain why the air temperature increases while evaporation decreases in Qinghai Lake basin. The tendencies in both precipitation and number of days with precipitation increased during 1961–2007 in the TP (Li et al., 2010). Precipitation recorded in the TP exhibited an increasing trend in other studies (Xu et al., 2008; Li et al., 2010; Zhang et al., 2019a), supporting that the predominant factor for the lake fluctuations was precipitation increases; in contrast, the contribution of evaporation to lake water balance was minor (Gao et al., 2015; Ma et al., 2016; Zhang et al., 2019b). Therefore, the main characteristics of climate change in the Qinghai Lake basin are warming and wetting, with decreasing evaporation accompanied by increasing precipitation. Variation in all these climatic factors had direct effects on the rising of the lake water level.

The water level curve for Qinghai Lake from 1961 to 2019 can be split into two phases: an obvious decreasing phase (1961–2004, first phase) and a significant increasing phase (2004–2019, second phase) (Figure 2). The average values of air temperature, precipitation, and river runoff in the first phase were markedly smaller compared with those of the second phase, while there was no significant difference in evaporation between the two phases. Examination of the rates of changes of different variables (including lake water level, air temperature, precipitation, and river runoff) clearly showed increasing trends during the second phase (Table 1), although these parameters displayed decreasing trends during the first phase (Table 1). Rising lake water level and expanding lake surface area were positively correlated to increasing precipitation, increasing river runoff, and decreasing evaporation during the second phase. This may suggest that lake water level dynamics are generally controlled by the balance of precipitation, evaporation, and river runoff.

Lake water level are particularly sensitive to climate changes, primarily driven by changes in precipitation. This study showed that the peaks of lake water level rises corresponded to the highest precipitation in Qinghai Lake, suggesting that the increasing precipitation is closely related to increasing river runoff and lake water level. In general, precipitation can be a direct water source for lakes, but conversely, precipitation on land becomes runoff to rivers,

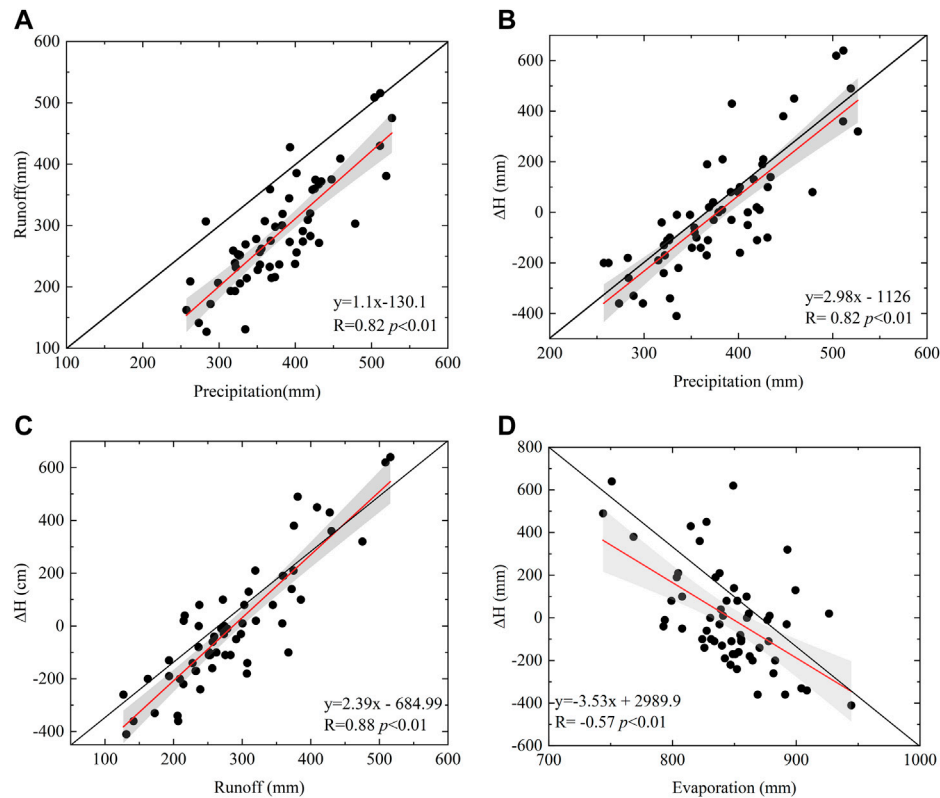


FIGURE 7

Relationship between precipitation and runoff (A), precipitation and ΔH (obtained from Eq. 3) (B), river runoff and ΔH (C), and evaporation and ΔH (D). The black solid line is the 1:1 line, while the red solid line is the regression fit between variables, gray shading is the 0.95 confidence interval of the fitting line.

which flow into the lake as a non-negligible part of its water source. Variations in discharge are strongly related to precipitation changes in cold regions (Krasovskaia, 1995; Yang et al., 2004; DeRy, 2005). Data analyses in this study show that precipitation was more than 450 mm in 1967, 1989, 2005, 2014, 2016, 2017, and 2018, and extremely low (<300 mm) in 1962, 1973, 1978, 1980, 1990, and 2001. Moreover, river runoff was more than 400 mm in 1989, 2005, 2012, 2016, 2017, and 2018. Similar to other studies (Qu, 1994; Qin and Huang, 1998; Li et al., 2007), this study also found that precipitation and river runoff have a significant correlation, with a correlation coefficient of $R = 0.82$ and $p < 0.01$ (Figure 7A). The correlation analyses suggest that the changes in precipitation, especially in the summer, directly impact hydrological processes through river discharge and lake water level in Qinghai Lake, as summer rainfall accounts for a large proportion of annual precipitation in the TP (Wu et al., 2019). Furthermore, summer precipitation has significant impact on lake water level change on different time scales (Duo et al., 2009; Jin et al., 2010; Lee et al., 2011). Recent studies on lake water storage changes (Yao et al., 2018; Treichler et al., 2019) also revealed that a continual increase in precipitation has sustained rising lake water levels, expansion of lake areas, and growth of lake water storage.

The rising lake water level and expanding lake area suggest the presence of an enhanced hydrological cycle in the TP (Zhang et al., 2020). The significant positive correlation between precipitation and lake water level indicated that the increase in precipitation in the Qinghai Lake basin is beneficial to the rise of lake water level. This study clearly reveals the linkage and process between precipitation and

lake water level change, especially the positive feedback on lake water level lift owing to extreme runoff caused by extreme precipitation. However, linkage between climate warming and lake water level is much more complex. In general, temperature increasing will not only intensify water loss (e.g., higher evaporation) but will also increase water gain (e.g., higher permafrost degradation and snow/glacier melting rate). Qinghai Lake has a closed lake basin geometry with no outflow, meaning precipitation and meltwater from snow/glacier melting and permafrost degradation may contribute additional water to the lake. There are large areas of permafrost and seasonally frozen ground, accounting for 83% of the total area of the Qinghai Lake basin (Zou et al., 2017; Cao et al., 2019). The distribution of permafrost has a certain influence on the hydrological process of the basin, and the freezing and thawing processes of the active layer over permafrost and seasonally frozen ground could have an important role in the hydrological cycle in the TP (Zhao et al., 2019; Zhang et al., 2008; Zhang, 2012; Liu et al., 2009; Li et al., 2020; Peng et al., 2020). Therefore, the contributions of precipitation in upstream areas, evaporation, river runoff, permafrost degradation, melt water from glaciers, and human activities needs further research under climate warming in the Qinghai Lake basin.

5 Summary

Changes in water level/area and environmental parameters in the Qinghai Lake basin were investigated using ground-based

measurements and satellite remote sensing data from 1961 through 2019. The results demonstrated that the lake water level changes could be split into two phases: a decreasing phase (1961–2004) and an increasing phase (2004–2019). The lake water level decreased at an average rate of 0.80 m/decade from 1961 to 2004, and then increased persistently and dramatically at an average rate of 1.80 m/decade from 2004 to 2019. The longest period of continuous uplift in the lake water level since 1961 was the 15 years from 2004 to 2019. The lake water area increased between 1990 and 2019, with average rates of 44.70 km²/decade and 47.80 km²/decade for April and September, respectively; however, since 2004, the increases have been more significant, with average rates of 174.50 km²/decade for April and 182.70 km²/decade for September. There was a strong warming tendency and a weak increasing tendency in precipitation and air temperature from 1961 to 2019, but since 2004 annual precipitation has increased rapidly with a trend of 62.40 mm/decade. Annual river runoff tended to decrease from 1961 to 2004 at an average rate of –7.00 mm/decade, and generally exhibited a marked increase during 2004–2019 at average rate of 85 mm/decade. The variation process of evaporation is not a continuous decline, but presents a fluctuating change. The changes in precipitation, river runoff, and evaporation in the lake basin strongly affected the lake water level, and lake water level was significantly positively correlated to precipitation and river runoff and negatively correlated to evaporation.

It is clear that changes in Qinghai Lake hydrology depends mainly on climatic factors, especially precipitation and river runoff. Precipitation, river runoff, and evaporation had direct impacts on the lake, while climatic factors such as air temperature had indirect effects on the lake. Precipitation and river runoff had significantly positive effects on lake water level, while conversely, evaporation negatively impacted lake water level. Variations in precipitation directly impact hydrological processes through river discharge and lake water level in Qinghai Lake. The linkage and process of precipitation change, particularly extreme events, and the impact on river runoff and water level variation was clear. The tendency towards a warmer–drier climate might be the main reason for the observed decrease in lake water level during the first phase. The recent continuous increase in lake water level during the second phase may be attributed to enough precipitation, and abundant runoff from snow/glacier and permafrost melt as a result of climate warming in the Qinghai Lake basin. As a sensitive indicator of regional climate change, the fluctuations of lake water level and lake surface area provide a comprehensive reflection of climate change in the Qinghai Lake basin.

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Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

XL collected data, conducted preliminary studies, and prepared draft manuscript; TZ designed and supervised the research; DY, GW, ZH, and LL participated to conduct field work and collect data. All co-authors participated writing and revising the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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