Hydrological trend of Qinghai Lake over the last 60 years: driven by climate variations or human activities?
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ABSTRACT
Qinghai Lake, as the largest saline inland lake in China, plays an important role in the surrounding semi-arid ecosystem. In recent years, the lake water level has increased rapidly; however, the driving factors causing water body changes are not fully understood. This study aims to investigate the hydrological processes in Qinghai Lake from 1959 to 2016, and to discuss their possible linkages to climatic change and human activity. The results indicate that both the water level and lake area gradually declined to their minima in 2004, before increasing rapidly. Annual evaporation and total runoff vary widely, but have shown an overall shift from decreasing to increasing trends. The annual average temperature has followed an increasing trend, and annual precipitation has increased rapidly since 2004. Hydrological changes (water level and lake) are positively correlated with runoff inflow into the lake and negatively correlated with evaporation from the lake surface. The water body expansion in recent years can be attributed to the decreasing difference between precipitation/river runoff and evaporation. The total water consumption by human activities has had a limited contribution to the water body changes. We conclude that hydrological changes have depended more on climatic variations than on human activities.

Key words | climate variations, human activities, hydrological change, Qinghai Lake

INTRODUCTION
Lakes are essential components of the global hydrosphere and the water cycle, and changes to lake area and water levels, especially in endorheic lakes in arid areas, are very sensitive to climatic change and human activities. Ongoing global warming and climatic change (Hansen et al. 2010) will enhance the global hydrological cycle and affect water availability, which may impact on the management of water resources (Li et al. 2014; Jung et al. 2015). Warming-induced hydrological cycle intensification and its impacts on local and global ecosystems have brought increasing attention to the links between climatic change/variability, hydrological processes and water resources across various temporal and spatial scales during the last few decades (Qin & Huang 1998; Rouhani & Jafarzadeh 2017). Understanding hydrological changes and their potential driving factors can provide insights into lake conservation and management (Li et al. 2014; Rouhani & Jafarzadeh 2017).

Qinghai Lake, as the largest inland lake in China, plays an important role in the semi-arid ecosystem security of the Northeastern Qinghai-Tibet Plateau (Wang et al. 2014). It is not only a natural barrier preventing the spread of desertification from the west to the east, but also has a significant influence on climate in the Yellow River catchment (Che et al. 2009; Chang et al. 2017). However, the ecosystem of the lake is extremely vulnerable, and deteriorating hydrological conditions (e.g. the shrinkage of lake surface area since the 1970s) have triggered a series of serious ecological environment problems (Qin & Huang 1998; Li et al. 2007; Li et al. 2009) such as deteriorating water quality, shore land desertification, grassland...
Lake after 2006 (Cui et al. 2017). Water level and lake area have decreased markedly since the 1900s. The earliest measurement of water level (3,205 m a.s.l.) was taken in 1908 by a Russian explorer (Qin & Huang 1908). The lake area reduced by about 500 km² at a rate of nearly 5 km²/a during the 20th century. Lake level decreased by 3.35, 2.77 and 0.58 m during the periods 1959–2000, 1959–1986 and 1986–2000 respectively (Li et al. 2007). The water area of Qinghai Lake shrank from 4,980 km² in 1908 and 4,568 km² in 1957 to 4,474 km² in 1972 and 4,304 km² in 1986; it then continued to shrink, to 4,094.29 km² in May 2003 (Li et al. 2007; Cui et al. 2017), but since 2005 has expanded due to increased precipitation and snow melt resulting from climate change (Chang et al. 2017; Wang et al. 2018). The lake area reached 4,476 km² in September 2017 (Xinhua 2017). The shape of the lake has varied significantly: several small lakes were isolated from the parent lake (Li et al. 2009), and some were linked with Qinghai Lake after 2006 (Cui et al. 2017). The striking changes have stimulated increased interest in studying the hydrological conditions of the lake. The recent recovery of the water level of Qinghai Lake will undoubtedly benefit the residents and ecosystem. However, the driving factors for water body changes in Qinghai Lake remain poorly understood; therefore, it is imperative to investigate the contributions of climatic changes and anthropogenic activities. In this paper, the authors investigate the history of hydrological and climatic variations and their relationships during the period 1959 to 2016, with the aim of identifying factors causing the increase in lake size in recent years.

MATERIALS AND METHODS

Study area

Qinghai Lake (36°32’ to 37°15’ N, 99°36’ to 100°47’ E) is located in the north-east of the Tibetan Plateau (Figure 1). The lake lies at an altitude of 3,193.8 m above sea level; has a surface water area of 4,476 km² (2017); a length (west to east) of 104 km; a width (north to south) of 62 km; an average water depth of 21 m (maximum depth of 27 m); a water volume of 71.6 × 10⁹ m³; and a drainage area of 29,661 km². The water is brackish to saline (salinity = 15.18 g/l; pH = 9.2) (Lanzhou Institute of Geology & CAS 1979). The lake usually freezes in winter, with the thickest lake ice reaching between 0.6 and 1 m. The Qinghai lake is a national nature reserve and an important water body that influences the ecological integrity of the entire region. The Qinghai Lake basin consists of the lake, alluvial plains, and surrounding mountains. The topography of the Qinghai Lake basin decreases from the north-west to the south-east. The basin is an inter-montane basin surrounded by the Datong Mountains, Rique Mountains, Qinghai Nan Mountains and Qilian Mountains (Figure 1).

Qinghai lake is fed mainly by direct precipitation and runoff from more than 50 intermittent rivers or streams. Only the two largest rivers, the Buha River and the Shaliu River (Figure 1), have longstanding and continuous hydrological records. The longest and greatest river, Buha River, is 286 km long with a 14,337 km² catchment and 46.9% contribution to runoff reaching the lake; the second largest river is Shaliu River with a discharge of 2.46 × 10⁸ m³, contributing 14.5% of the total runoff reaching the lake (Li et al. 2009; Chang et al. 2017). The major water sources of the rivers are precipitation, snow/glacier melt and degradation of permafrost (Cuo et al. 2014; Chang et al. 2017). The basin is dominated by a cold and semi-arid climate influenced by three different monsoon systems: the East Asian monsoon, the Indian monsoon, and westerly jet streams, which make it one of the most sensitive regions to global climate change (Zeng et al. 2014). The temperature, which varies significantly with altitude, declines from south-east to north-west in the basin; the average annual temperature is between −1.1 °C and 4.0 °C, with an extreme maximum temperature ranging from 24.4 °C to 33.7 °C and an extreme minimum temperature of between −26.9 °C and −35.8 °C. The average annual precipitation is between 300 mm and 450 mm, more than 80% of the total precipitation falls during the summer and autumn (from June to September), and precipitation is the main source of rivers, lakes and the groundwater of the Qinghai Lake basin. The average annual evaporation is about 930 mm. The Qinghai Lake basin is windy throughout the year; the dominant wind...
direction is from the south-east in the summer and from the west during the other seasons. The primary soil types include felty, thin dark felty, castanozems, peaty bog, and dark frigid calcic soils. The vegetation in the Qinghai Lake basin is relatively independent and includes coniferous forest, shrub, grassland, and meadow (Shang et al. 2009).

Data source and methods

Meteorological data from 1958 to 2017, including precipitation, temperature and evaporation, were obtained from the National Meteorological Information Centre, China Meteorological Administration. There are only two meteorological stations (Tianjun and Gangcha) in the Qinghai Lake basin (Figure 1). Precipitation and temperature observed at Tianjun meteorological station were consistent with those observed at Gangcha meteorological station (Cui & Li 2016). Gangcha station is approximately 13 km north of the lake and is the nearest meteorological station to the lake (Figure 1). Therefore, the climate-related parameters (precipitation, temperature, evaporation) of Gangcha meteorological station were used to analyze the impact of climate change on lake hydrological processes.

Lake level, water area and runoff data were assimilated from previous reports (Peng et al. 1995; Li et al. 2007; Duo et al. 2009; Li et al. 2009; Luo et al. 2017) based on the hydrological stations (Buha River, Shaliu River, and Xiashi hydrological stations) and satellite remote-sensing data (Zhao et al. 2017; Wang et al. 2018). The combined runoff of Buha River and Shaliu River is chosen to represent the hydrological characteristics of rivers flowing into Qinghai Lake.

Correlation analysis was used to investigate the historic trends of hydrometeorological variables (temperature, precipitation, evaporation, lake water level, water area and annual runoff) and their mutual relationships in Qinghai Lake. Removing the trend from time-series data (detrending) is a useful method to focus analysis on fluctuations in the data.
about the trend. In order to understand the variability of hydrological and climatic changes, we detrended the data by subtracting a linear least-squares regression line, yielding the detrended amplitude of variations of these variables.

**RESULTS**

**Hydrological changes**

Water level and area fluctuations of Qinghai Lake during the period 1959 to 2016 could be divided into two distinct periods (Stages 1 and 2), namely a period of decline (1959–2004) and period of expansion (2004–2017). The variation of annual lake level (Figure 2(a)) indicates a significant stepwise decreasing trend in lake level towards a minimum in 2004, followed by steady expansion. The lake level was at 3,196.55 m in 1959 and gradually fell to 3,192.76 m in 2004, at an average rate of −8.02 cm/a during Stage 1. There were two periods of rapid increase, in 1966–1968 and 1988–1990. The lake level has followed a clear increasing trend since 2004, at an average rate of 15.82 cm/a in Stage 2. Correspondingly, the water area decreased from 4,548.57 km² in 1959 to 4,186.31 km² in 2004 (Figure 2(b)), at an average rate of −7.26 km²/a, and then increased to 4,476 km² in September 2017 (Xinhua 2017) at a growth rate of 19.90 km²/a. Due to lake water level changes, Haiyanwan Lake (≈90 km²) was isolated from Qinghai Lake in 2003 and later rejoined Qinghai Lake in 2006 (Cui et al. 2017). Although total river runoff of Baha River and Shaliu River has fluctuated greatly, from 3.27 to 24.32 × 10⁸ m³/a during the last 60 years, the 5-point running mean reveals a similar trend to those of water level and area, except in the period 1960–1964 (Figure 2(c)). The maximum runoff occurred in 1989. River runoff was relatively high in the 1960s and 2000s and relatively low in the 1970s. A one-year lag of water level and area relative to runoff is observed in these curves, especially in 1967 and 1989. The correlation coefficient (0.9620) showed that lake water area/level and their variations were strongly positively correlated to lake level (Supplementary Information Figure S1, available with the online version of this paper), indicating that water body expansion and retreat are synchronous to the rise or fall of lake level. For example, lake

![Figure 2](https://iwaponline.com/jwcc/article-pdf/10/3/524/598233/jwc0100524.pdf)  
**Figure 2** Hydrological fluctuations of Qinghai Lake from 1959 to 2016. (a) Water level; (b) water area; (c) annual runoff of Bahu and Shaliu Rivers.
water area peaks corresponded to relatively high lake levels in 1967 and 1989 respectively.

**Climatic changes**

Annual average temperatures ranged from −1.5 °C to 1.8 °C and showed an obvious warming trend during the period 1958 to 2016 (Figure 3(a)) at an average rate of 0.32 °C/decade. The warming rate accelerated after the 1990s. The annual precipitation ranged from 260.1 mm to 571.9 mm with an average 388.42 mm, with a fluctuating but generally increasing trend (Figure 3(b)). In general, precipitation increased from 1959 to 1988, and dropped suddenly in 1990, then maintained an increasing trend (Figure 3(b)) with a maximum 571.9 mm in 2014. The annual average precipitation of 375.1 mm during the period 1961–2004 was much lower than that of the period 2005–2016 (435.6 mm). The evaporation is closely related to the temperature, humidity and wind velocity. Annual evaporation varied widely but followed a general stepwise-decreasing trend (Figure 4(c)), in which three stages with boundaries in 1981 and 2004 can be observed. The evaporation was relatively high during the period 1959 to 1981 and relatively low after 2004. There were three low-points in annual evaporation at around 1967, 1988 and 2011, and the maximum evaporation occurred in 1979 (Figure 3(c)). The average annual evaporation during the three stages was 1,483 mm, 1,419 mm and 1,270 mm, respectively. Therefore, temperature and precipitation at Qinghai Lake have increased while evaporation has decreased over the past 60 years.

**Variability of hydrological and climatic changes**

To better understand the variability of hydrological and climatic changes, we subtracted the mean value to detrend all the data (Figures 4 and 5). The results show striking similarity between the variability of water level and area (Figure 4(a) and 4(b)), which can be subdivided into three stages with boundaries in 1979 and 2011. These stages are characterized by decreases in area and level during the period 1979 to 2011, with minima of water level and area...
Figure 4 | Detrended time series of hydrological parameters at Qinghai Lake. (a) Water level; (b) water area; (c) annual runoff of Bahu and Shaliu Rivers.

Figure 5 | Detrended time series of climatic parameters of Qinghai Lake. (a) Annual average temperature; (b) annual precipitation; (c) annual evaporation.
reached in 2004. This was followed by rapid subsequent expansion. Although annual runoff varied widely, there was no obviously decreasing trend. Detrended climatic parameters show much more complicated changes (Figure 5). The temperature variability has increased since 1997, and temperatures have reached higher values than those of the past 60 years (Figure 5(a)). Annual precipitation has also increased (Figure 5(b)), although the variability was higher than the average after 1997. The variability in annual evaporation also increased obviously after 2002 (Figure 5(c)).

DISCUSSION

Relationships between hydrological and climate changes

Ongoing global warming will enhance the global hydrological cycle, which will affect river and lake water availability. The continued warming trend at Qinghai Lake is consistent with that of global temperature during the last 60 years, but the mean rate of warming in the lake basin (0.32 °C/decade) is twice that of the global warming rate (0.15 °C/decade), which means local impacts on the eco-environmental system in this area may have been more severe than those elsewhere under the same global warming background. As the average temperature increases, it is generally expected that the air will become drier and that evaporation from terrestrial water bodies will increase. Paradoxically, observations over the past 60 years in Qinghai Lake area show the reverse (Figures 3 and 5). The contrast between expectation and observation is called the pan evaporation paradox (Roderick & Farquhar 2002; Liu et al. 2004), and has been reported in the adjacent Qilian Mountains (Jia et al. 2009), Northwest China (Liu et al. 2004; Ren & Guo 2006) and elsewhere in the world, e.g. the USA and former Soviet Union (Peterson et al. 1995; Roderick & Farquhar 2002). Previous investigations have indicated that the four main impact factors influencing pan evaporation in Northwest China are daily temperature range, wind speed, relative humidity and air temperature, in contrast to the important factors in other areas in China (Ren & Guo 2006). The decline in daily temperature range and increasing precipitation (Shi et al. 2010) may explain the decreasing evaporation from Qinghai Lake. The decreasing daily temperature range reduces the potential for evaporation, while increased precipitation favors the increased relative humidity of air above the lake water surface. The relative humidity may also be related to the increase in aerosol concentration and cloud coverage caused by air pollution (Liu et al. 2004; Ren & Guo 2006).

As mentioned above, changes in the lake water body can be divided into two periods: a decreasing stage (1961–2004, Stage 1) and increasing stage (2004–2016, Stage 2) (Figure 6). Analysis of the rates of changes clearly shows the increases during Stage 2 as mentioned above, but in contrast these parameters (including water level, evaporation and runoff) display decreasing trends during Stage 1 (Figure 6). Expanding lake area and increasing precipitation are clearly positively correlated to increasing precipitation and decreasing evaporation during Stage 2. This may suggest that the changes to the water body are generally related to the balance of precipitation, evaporation and runoff.

Detailed comparisons between hydrological and climatic parameters (Figure 6) indicate that low evaporation peaks generally correspond to high precipitation and rapidly increasing water level, but also to relatively low temperatures (e.g. 1967, 1983, 1989 and 2011). The evaporation is negatively correlated to precipitation (Supplementary Information Table S1, available with the online version of this paper), which suggests that high evaporation is closely related to a dry climate, and that low evaporation is closely related to a wet climate. The significant drops in river runoff generally correspond to low precipitation and high evaporation (e.g. 1960, 1973, 1995, 2001 and 2008) (Figure 6), which are consistent with the positive relationship with precipitation and negative relationship with evaporation (Table S1). In other words, river runoff has a direct positive effect on the lake level, while evaporation has a significantly negative effect on lake level. However, the correlation coefficient between river runoff and temperature is not statistically significant. These results suggest the river runoff in the Qinghai Lake basin was primarily influenced by the balance of precipitation and evaporation. Three periods of rapid lake growth (1966–1968, 1988–1990 and 2004–2016 as shaded in Figure 6) correspond closely to periods of higher runoff.
and precipitation and lower evaporation. Although the correlation coefficients among these parameters are generally weak, it is clear to see that the lake area or level variations are significantly and negatively correlated with temperature over the complete study period (Table S1); however, this contradicts the result that water body expansion is well correlated with increasing temperature. It is surprising that the correlations between variations in water area or level and precipitation and evaporation are weak and statistically insignificant. These results are clearly contrary to previous reports (Li et al. 2007; Cui & Li 2016) indicating that the variation in lake level was highly positively correlated with surface runoff and precipitation and negatively with evaporation during the period 1959 to 2000.
discrepancy may be attributed to the different study periods, since previous studies have not included the important transition point in 2004. Furthermore, correlations between climatic and hydrological parameters may have changed between different periods. Therefore, we consider that lake water body variability is a complex function of the balance between runoff, precipitation and evaporation, perhaps as well as other factors.

**Possible driving mechanism for hydrological changes**

Considerable research has focused on the influence of climate change on lakes across the Tibetan Plateau. Some of these studies have focused on climatic factors (Qin & Huang 1998; Duo et al. 2009; Cui & Li 2016; Chang et al. 2017), while others were concerned with human activities, or both (Li et al. 2007; Li et al. 2014; Liu et al. 2015; Chang et al. 2017).

Qin & Huang (1998) reported that the water level of Qinghai Lake was sensitive to the climatic changes in both temperature and precipitation, yet our correlation coefficients indicate that there are no significant relationships between lake level and climate (temperature and precipitation) on long timescales. Owing to the closed basin geometry of Qinghai Lake, precipitation and melt water from glacier retreat and permafrost degradation are the main water sources in the basin. Changes in precipitation affect the surface runoff inflow to the lake, whereas changes in temperature affect evaporation through the direct loss of lake water (Li et al. 2007). The warming trend is positively correlated with the lake shrinkage trend during the period from 1959 to 2004, but it is also positively correlated with the expansion of the lake after 2004. This can be interpreted in terms of temperature: as temperature increases, the lake evaporation increases, and effective inflow decreases (Stage 1). The low correlation coefficients between precipitation and lake area indicate that precipitation is not the only factor causing lake shrinkage. Statistics indicate that the most dramatic decline in lake level occurred in the warm and dry years, with only a moderate decline in the cold and dry years, and a slight decline in the warm and wet year (Li et al. 2007). Therefore, the trend towards a warmer and drier climate might be the main reason for the decline in lake level during Stage 1. The recent expansion during Stage 2 may be attributed to abundant precipitation in the surrounding mountains, and increasing runoff because of snow/glacier and permafrost melt due to climate warming in this region (Zhang et al. 2014). Therefore, the lake level trend was directly determined by the balance of precipitation, evaporation and runoff. Water model correlation analysis confirmed that the inflow, evaporation and precipitation in the past year were closely related with the water level of Qinghai Lake.

Generally, more intense human activities will consume much more lake water. This includes direct use by humans and livestock, as well as agricultural irrigation, and industrial water consumption. Based on the lake body and human water consumption data from 1959 to 1987, Peng et al. (1995) suggested that the human domestic use, stock-raising, agricultural and industrial water consumption only contributed about 1–2% of the total consumption in the Qinghai Lake area. Based on a water balance using data from 1959 to 2000, Li et al. (2007) estimated that water consumption by human activities, and by artificial afforestation and grass plantation, accounted for 1.97% and 5.07% of total consumption, and for 1.87% and 5.43% of lake evaporation in the Qinghai Lake basin, respectively (Chang et al. 2017). All these data suggest that the changing lake level depends mainly on climatic factors. Lake level has risen continuously during the last 13 years under a warming trend, despite human economic activity also becoming stronger (Li et al. 2009). Water consumption by human activities was not the primary cause of the water level changes in Qinghai Lake, and instead the increasing lake size suggests that climate change has been a more important factor than human activity. We conclude that increasing precipitation and surface runoff, and decreasing evaporation, had a major contribution to the increase of the water level, which mainly occurred from 2005 to 2016. If the warming trend continues, Qinghai Lake may continue to expand in future decades. Therefore, a better ecological environment and richer biodiversity could be expected in the Qinghai Lake basin, which would be beneficial for local ecological protection and for the prevention of desertification in surrounding areas.
CONCLUSIONS

Both the water level and area of Qinghai Lake gradually declined to their lowest values in 2004. The lake level and area decreased at average rates of ~8.02 cm/a and 7.26 km²/a, respectively, between 1959 and 2004, but since 2005 they have been increasing at average rates of 15.82 cm/a and 19.90 km²/a, respectively. The expansion of the lake is beneficial for the local ecological environment and the prevention of desertification in surrounding areas. The annual evaporation and combined runoff of Buha River and Shaliu River show wide variability but an overall decline to their lowest values in 2004. The lake level and area of Qinghai Lake gradually increased at average rates of 0.32 cm/a and 8.02 cm/a, respectively, between 1959 and 2004, but since 2005 they have been increasing at average rates of 15.82 cm/a and 19.90 km²/a, respectively. The expansion of the lake is beneficial for the local ecological environment and the prevention of desertification in surrounding areas.

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