Quantitative analysis of water balance and the driving forces for Yan lake expansion from 2015 to 2018 in the Hoh Xil region, Tibetan Plateau

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Abstract: Accelerated expansion of the Yan Lake basin since 2010 has been confirmed by dramatic increases in area determined by remote sensing images and measurements of rapid water level rise (2015–2018). However, the underlying causes of this expansion remain unclear. In this study, lake area, water levels, and volume fluctuations were investigated and the water balance reconstructed. The results showed the Lake Yan area, water level, and volume increased to 59.9 km^2, 7.91 m, and 14.17 Gt, respectively, by 2018, with 60%–70% of the increase during August to October within 1 yr. Over the past 40 yrs, lake area, level, and volume of lake Yan varied in three stages: slight increase (1980s–2011), rapid increase (2011–2013), and steady increase (2014–2018). A Mann-Kendall analysis suggested that precipitation

and air temperature continuously increased at 2.22 mm yr^{-1} and 0.05 ℃ yr^{-1}, respectively. As for the glacier, meltwater was 1.0 ± 0.2 Gt and accounted for a smaller proportion of the lake water supply. The lake water balance identified increased net precipitation as the dominant factor (71%) for the increase in lake water storage, followed by groundwater (16%) and glacial meltwater (15%). These estimates provide the first quantitative evaluation of the water balance components in the Yan Lake basin, which could provide insights into the responses of Tibetan lake dynamics to climate change.

Key words: lake expansion, water balance, Yan Lake basin, Hoh Xil region

1. Introduction

The Tibetan Plateau (TP) is the highest plateau in the world and is also known as the Asian Water Tower (Immerzeel et al., 2010). There are many lakes on the TP, with a total area of 45,000 km^2, accounting for 50% of the total lake area of China (Zhu et al., 2010). Lakes on the TP play an important role in maintaining the water balance of several large Asian river basins and are sensitive indicators of hydrological dynamics associated with climate variability (Song et al., 2014). In the past few decades, the TP has experienced obvious climate change (Yang et al., 2014), such as rising air temperature, changing precipitation, including both direct precipitation and runoff from lake basins, and evapotranspiration (ET) patterns. These changes have caused lakes across the TP to show strong spatiotemporal heterogeneity (Lei et al., 2014). Major lakes in the central TP, such as Nam Co, Selin Co, and most lakes in the Inner TP and Hoh Xil regions, have expanded since the late 1990s (Li et al., 2014;

Yang et al., 2014; Zhang et al., 2017; Yao et al., 2014).

Because many Tibetan lakes are rarely influenced by human activities, their variations are more closely associated with regional climate change, including precipitation, evaporation, and terrestrial ET, as well as glacial melting (Lei et al., 2014; Song et al., 2014). In recent decades, the causes of lake variations in the TP have been widely discussed. Some previous studies have inferred that lake expansion was mainly caused by glacial meltwater supply within the surrounding basins (Huang et al., 2011; Zhu et al., 2010; Yao et al., 2007). However, more recent studies have indicated that precipitation and terrestrial ET are also related to lake variations, in addition to glacier shrinkage (Morrill, 2004; Song et al., 2014; Yang et al., 2014). For example, Lei et al. (2013) found that increased precipitation, runoff, and decreased lake evaporation were the main causes for the growth of six closed lakes on the central TP, accounting for 70% of lake expansion. Song et al. (2014) found that growth of most closed lakes on the TP could be attributed to large water level increases in warm seasons. In addition, the subsurface component of the water cycle has been ignored in nearly all previous water cycle studies of the TP. However, the subsurface component is an important factor in the TP hydrological cycle (Yang et al., 2011; Cheng and Jin, 2013; Ge et al., 2008). To-date, only a few lakes have had their water budgets quantitatively assessed, namely Selin Co, Nam Co, Tangra Yumco, Mapam Yumco, and Paiku Co (Biskop et al., 2015; Li et al., 2017; Tong et al., 2016; Zhou et al., 2015, 2013; Zhu et al., 2010). To what extent glacial melt can influence lake water balance and how to disentangle the contributions of glacier meltwater, permafrost thaw, groundwater, and precipitation to lake water balance are still open questions because of a lack of in situ observations in this high-elevation region and the harsh environment for field investigations.

Yan Lake, with a total area of 2017 km^2 and catchment of 8661 km^2, is located in the Xohi region of the TP, approximately 220 km south of Golmud (Fig. 1); it has no surface outflow. Occupying the north boundary of the basin is the Kunlun Mountain Range, where a large number of glaciers have developed and meltwater rapidly pours into the lake through rivers over a very short distance. Remote sensing studies showed that a burst dike at Lake Zonag in the upper branches of the Lake Yan on 15 September 2011 resulted in three downstream lakes (Kosei, Dinard Noir, and Yan) becoming connected. Since then, the lake area and water level continued to grow rapidly, resulting in a potential threat to the safe operations of major engineering facilities, such as the Qinghai–Tibet Railway (QTR) and Qinghai–Tibet Highway (QTH) (Yao et al., 2018). Qualitative analyses suggested that the warmer and wetter climate in this region was the main reason for lake expansion, followed by glacial melt (Duan, 2013; Zhao et al., 2000). However, quantitative fractions of the lake water balance have not been assessed. The water balance would explain lake expansion, including describing the multiple water sources and their relative contributions to lake growth, which is critical information for decision-making government departments. In this study, we characterized changes in water level, area, and volume over the past 40 yrs based on remote sensing images; then, more importantly, we investigated the factors that have most likely contributed to lake growth through its water balance.

2. Data and Methods

2.1. Lake area, level, and volume

The Landsat satellites are the most popular for lake area mapping because of the long period of data availability, relatively high spatial resolution, and open access (Pekel et al., 2016). In this study, cloud-free or nearly cloud-free Landsat data and Chinese high resolution satellite data were used. The normalized difference water index with an optimal threshold determined from the Otsu method was applied to distinguish water from non-water features. Visual examination and manual editing of lake boundaries were conducted and combined the false color composition (Bands 5, 4, and 3 as red, green, and blue, respectively) of raw Landsat images for each lake. Relative lake area changes were used to estimate their trends. Lake levels were manually monitored once or twice a month by Total Station (South NTS-382R10 with an accuracy of ±2 mm). Finally, we reproduced lake levels during 2015–2018 for lakes with available data. Lake water volume changes were estimated using the following equation:

$$\Delta V = \frac{1}{3} \times (S_1 + \sqrt{S_1 + S_2} + S_2) \times \Delta h \cdots\cdots (1)$$

where ΔV is the change in lake storage, S_1 and S_2 are the lake areas at two stages, and Δh is the change in water level.

2.2. Lake water balance

The change in terrestrial water storage in the study area includes: (1) lake volume changes (ΔV); (2) lake water supply, including direct precipitation over the lake (P), precipitation-induced terrestrial runoff (R), glacial meltwater (G), thawed permafrost water (PM), and groundwater (GW); (3) lake water loss, which was mainly evaporation over the lake surface, as seepage through the lake bed was ignored. The water balance is expressed as:

$$\Delta V = P + R + G + GW - E \cdots\cdots (2)$$

(1) Precipitation-induced terrestrial runoff

If all of the runoff generated by precipitation, except for evaporation, was input into a lake, then R = P − El. For the estimation of the actual evaporation on the land surface (El), the Bagrov method (Terpstra, 2001) was applied. The method uses three parameters: P; potential evaporation, E_0; effectiveness parameter, N, which depends on the land use and soil type. To determine El, we used the following relationship:

$$\frac{dEl}{dP} = 1 - \left[\frac{El}{E_0}\right]^N \cdots\cdots (3)$$

The model uses a numerical solution for Eq. (1) that constitutes a simple relationship between the ratio of precipitation and potential evaporation (P/E_0) and the ratio of actual and potential evaporation (El/E_0):

$$d\left(\frac{El}{E_0}\right) = \left[1 - \left[\frac{El}{E_0}\right]^N\right] \cdot d\left(\frac{P}{E_0}\right) \cdots\cdots (4)$$

(2) Glacial meltwater

Temperature index models have been the most common approach for snow and ice melt modeling because of the wide availability of air temperature data and computational simplicity. Many studies have used a conceptual hydrological model coupled with a degree-day model to analyze the hydrological cycle in different regions/basins across the world (Li et al., 2017; Tong et al., 2016; Huss et al., 2010). In this study, the degree-day factor method was used for the Yan Lake basin to simulate glacier melting in the lake watershed model. Ice or snow melt during a specific period can be estimated:

$$M = \begin{cases} DDF \cdot PDD, PDD > 0 \\ 0, PDD \leq 0 \end{cases} \cdots\cdots (5)$$

where M is the melting of ice or snow for a specific period (mm), DDF is the degree-day factor with subscripts representing snow or ice surface (mm d^{-1} ℃$^{-1}$), and PDD represents the cumulative positive temperature during the same period (℃). The degree-day factors of snow and ice were adopted from Zhang et al. (2006) based on glacier observations in the TP. The ice factors were between 3.6–4.7 mm d^{-1} ℃$^{-1}$ for the Kulun Mountain regions.

3. Results and Discussion

3.1. Lake area, level, and volume changes

The results showed that across the entire Yan Lake basin the annual change in lake area remained almost stable between the 1980s and 2000 (Fig. 2). Figure 2 shows an overall increasing trend in the surface area of Lake Zonag at a rate of 1.20 km^2 yr^{-1} from 2000 to 2011. After the incident on 15 September 2011, the lake area decreased sharply by >115 km^2 and maintained a similar area (155 km^2) after 12 October 2011. This suggests that Lake Zonag lost over 115 km^2 of its functional water storage due to the burst dike and excess water was discharged to the downstream lakes.

Three lakes (Kosei, Dinard Noir, and Yan) located downstream of Lake Zonag were directly impacted by the outburst and resulting flood. The area of Lake Kosei increased rapidly from 286.3 km^2 on 22 August 2011 (before the outburst) to 332.1 km^2 on 19 August 2012 (after the outburst), and then remained stable from 2012 to 2018 (Fig. 2). The area of Lake Yan exhibited a continuously increasing trend from 2000 to 2018 (Fig. 2), with a gradual 1.40 km^2 yr^{-1} increase from 2000 to 2011 before the dike burst event. However, the increase jumped significantly from 2012 to 2013 (41.9 km^2 yr^{-1}), with a steady increase in area of 6.7 km^2 yr^{-1} from 2014 to 2017. Finally, the area increased sharply from 161.4 km^2 to 194.5 km^2 in 2018. This implies that the overflow from Lake Zonag after 15 September 2011 did not directly feed Lake Yan but was stored by Kosei and Dinard Noir lakes. After these two lakes exceeded their storage limits, the water then flowed into Lake Yan.

Although many studies have reported lake area changes in the TP (e.g., Song et al., 2013; Zhang et al., 2017a, 2017b), this study is the first to provide annual observations (monthly data from 2015–2018) of lake area variations. This high temporal information allowed us to examine the evolution of lake stages in greater detail, which, when combined with lake elevation data, provided a time series of lake volume changes.

The volume of Lake Yan increased by 1.81 Gt, 3.15 Gt, and 7.83 Gt in 2016, 2017, and 2018, respectively, and the water level increased by 1.95 m (2016), 1.89 m (2017), and 4.07 m (2018). Lake Yan showed a remarkable water level increase of 7.91 m over 3 years, resulting in a potential threat to the safe operations of major engineering facilities, such as the QTR and the QTH, if the water level increase continued at a similar rate.

The monthly distribution of the lake area, level, and volume was very similar, and expanded mainly from August to October. The accumulative increase in these months represented 60%–70% of the whole year, suggesting that area, level, and volume expansion was mainly focused on these 3 months. In contrast, 80.2% of precipitation was in June to September, suggesting variations in lake area, level, and volume may lag 1 month behind precipitation.

Overall, lake area, level, and volume changes presented four obvious stages: (1) a stable state or slight decrease (1980–2000); (2) slight expansion (2000–2011); (3) sharp expansion (2012–2013); (4) steady expansion (2014–2018). Through the monthly observation data spanning 2015 to 2018, we found that the Lake Yan area, level, and volume increased to 59.9 km^2, 7.91 m, and 14.17 Gt, respectively, in total, with 60%–70% of the increase in August–October. The expansion of the Yan Lake basin was consistent with lakes across the central TP, especially in the Xoh Xil regions, which could be driven by large-scale atmospheric circulation changes in response to atmospheric warming (Zhang et al., 2017a).

3.2. Lake water balance

The water balance was estimated for the Yan Lake basin using P, R, G, GW, and E. The annual volume increase was 3.54 Gt yr^{-1} and grew more rapidly from 2015 to 2018 (Table 1). Some components, such as G and GW, were relatively small in terms of lake balance, in comparison to P and R (Table 1). Furthermore, more precipitation in a region lead to higher contribution to lake water input. In contrast, the interannual variations in glacial meltwater and groundwater were quite small.

From the lake water balance estimate (Table 1), it was apparent that precipitation was the dominant factor (62%–79%, average of 71%) regarding expansion in the Yan Lake basin from 2015 to 2018, followed by groundwater (11%–19%, average of 16%) and glacial meltwater (10%–18%, average of 15%). This result is consistent with Yao et al. (2014) that suggested an increase in precipitation was the dominant factor resulting in the expansion of lakes in the Hoh Xil region. The secondary factor was the increase in meltwater from glaciers and frozen soil due to climate warming. However, this study provides the first quantitative evaluation of water balance components in the Yan Lake basin.

Lake Yan expanded dramatically after 2010, with the greatest rate of change occurring in 2018 (Fig. 3). The total lake area, water level, and storage increased by 33.4 km^2, 4.07 m, and 7.83 Gt, respectively. Figure 5 shows water sources and their contribution based on the water balance analysis. For Lake Yan, the net lake volume increased by 0.89 Gt if it was not connected with three upstream lakes. However, the net lake volume increased 7.83 Gt when the four lakes were all connected. Thus, the massive water flow into Lake Yan from upstream was a key cause for its expansion. Additionally, the net volume increase of Lake Yan was 1.39 Gt in 2015, when the annual precipitation was only 288.8 mm. It was reasonable to predict that the lake would ultimately overflow, resulting in a great threat downstream.

3.3. Variations in meteorological factors

Considering the dominant role of precipitation in expansion of the Yan Lake basin, it is reasonable to analyze the climate trends. In this study, long-term observation data from Wudaoliang and Tuotuohe meteorological stations, the only two around the Yan Lake basin, between 1960 and 2018 were examined, including annual precipitation, air temperature, potential evaporation, and runoff.

Climate trends in the time series were tested by a trend-free pre-whitening procedure based the Mann-Kendall (MK) test (Yue et al., 2002). A positive (negative) value of the MK test statistic Z signifies an increasing (decreasing) trend. Furthermore, an increasing or decreasing slope (change per unit time) was described using Sen's slope (Sen, 1968).

In the annual precipitation time series, a significant increasing trend was observed at the two stations (Table 2). Additionally, a trend analysis suggested that mean annual precipitation at the Wudaoliang station is 299.4 mm with a obviously upward slope of 2.22 mm yr^{-1} during the period 1961–2019. It showed a coincident trend with neighboring Tuotuohe station, which had an upward slope of 1.04 mm yr^{-1}. Figure 6 shows the changes (5-yr moving average) of all precipitation data series. It suggests that basin-wide precipitation demonstrated similar patterns during the whole study period. In general, precipitation remained stable or slowly increased from 1961 to the mid-1990s, and then rapidly increased from the late 1990s to present, especially after 2007.

For the annual air temperature time series, a positive significant trend (99% confidence level) was also detected at Wudaoliang station (Table 2). The slope was 0.05 ℃ yr^{-1}, with a cumulative temperature rise of 1.92 ℃ from the 1980s to 2018. Additionally, the average annual air temperature over the whole basin significantly increased over the period of 1980–2018. The annual runoff at neighboring Tuotuohe station showed a positive significant trend, with a 0.106 Gt increase in water and a slope of potential evaporation close to 0, indicating no obvious trend in evaporation.

As the turning point for precipitation was in the mid-1990s, we examined the relationship between precipitation and runoff to explore the conditions of the underlying surface. Figure 7 shows that the trend of two periods, 1957–1995 and 1996–2018, was almost exactly the same, so that similar precipitation produced almost the same terrestrial runoff from 1957 to 2018. Furthermore, the conditions of the underlying surface of Lake Yan very likely did not change, and terrestrial runoff variations were a result of precipitation changes, as was lake volume. Thus, increased precipitation altered the balance of lake water volume, which was mainly responsible for lake expansion.

3.4. Influence of glacial meltwater and permafrost on lake changes

In addition to precipitation, glacial meltwater and released permafrost water were also the main suppliers of lake water on the TP (Zhao et al., 2006; Li et al., 2011). According to data provided by the Qinghai Province Geographic Situation Monitoring Institute, the glacier area in the Yan Lake basin was 79.2–89.91 km^2 during 2010–2018. It indicated that glaciers were generally stable or slightly retreating over the past 10 yr.

In this study, the glaciers belonged to the Kunlong Mountain regions. The ice DDF factors in this region were between 3.6 to 4.7 mm d^{-1} ℃$^{-1}$. The PDD was 615 d ℃ based on data from the Wudaoliang meteorological station. Considering that the glaciers were all alpine, the PDD was adjusted to 300–400 d ℃ for the calculations of glacial meltwater, which was 1.0±0.2 Gt. In contrast, the total supply to Yan Lake basin was between 8.02 and 14.22 Gt, suggesting the glacial meltwater was not the dominant factor for lake expansion.

From the monitoring results of permafrost at Wudaoliang, the permafrost was thin with a thicker active layer since the 1980s. In addition, the continuous frozen days of the permafrost decreased (Zhao et al., 2000). However, liquid from permafrost accounted for only small proportion of lake water (Yao, 2002). Thus, glacial meltwater and permafrost water might contribute to expansion in Lake Yan, but they were not dominant.

4. Conclusions

The abundant lakes in the TP, the third pole of the Earth, have been regarded as sensitive indicators and sentinels of climate change. The annual lake area, level, and volume in the Yan Lake basin between 2015 and 2018 were examined via available data. The Lake Yan area, level, and volume showed an increase of 59.9 km^2, 7.91 m, and 14.17 Gt, respectively, and 60%–70% of the increase was during August to October. Over the past 40 yrs, lake area, level, and volume of lake Yan varied in three stages: slight increase (1980s–2011), rapid increase (2011–2013), and steady increase (2014–2018).

Air temperature, precipitation, and evaporation had different variation patterns over the past 40 yrs. Both precipitation and air temperature continuously increased (2.22 mm yr^{-1} and 0.05 ℃ yr^{-1}, respectively), but the glacier, with quantitative meltwater of 1.0±0.2 Gt, accounted for a smaller proportion than precipitation in the total lake water supply.

Based upon the present definition and hypotheses of lake water balance, we have calculated variations in lake water quantity during 2015–2018 and analyzed the variations. The results showed that, over 2015–2018, increased net precipitation is the dominant factor (71%) for the increase in lake water storage, followed by groundwater (16%), and glacial meltwater (15%). These estimates provide the first quantitative evaluation of the water balance components in the Yan Lake basin. Finally, significant expansions of Lake Yan have posed a potential threat to the safe operations of major engineering facilities, such as the QTR and QTH. This study provides some scientific information for governments to pay more attention so that possible future devastation could be avoided.

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Data Availability Statement

All data generated or analyzed during this study are included in this article.

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Tables

Table 1. Factors contributing to water balance estimations from 2015 to 2018.

Year	Supplies ($10^8 m^3 a^{-1}$)					Losses ($10^8 m^3 a^{-1}$)	Variation ($10^8 m^3 a^{-1}$)
	P	R	G	GW	Total	E	ΔV
2015	2.02	2.98	1.32	1.71	8.02	6.63	1.39
2016	2.25	3.43	1.28	1.83	8.79	6.98	1.81
2017	2.85	4.07	1.35	1.49	9.77	6.61	3.15
2018	3.56	7.71	1.28	1.69	14.22	6.39	7.83

Table 2. Mann-Kendall test results of annual precipitation, air temperature, potential evaporation, and runoff for the Yan Lake basin.

Station /Altitude	Precipitation (mm)			air temperature (℃)			runoff(Gt)			Evaporation (mm)		
	mean	slope	Z	mean	slope	Z	mean	slope	Z	mean	slope	Z
Wudaoliang /4621	299.4 (n=59)	2.22	4.4	-4.85 (n=39)	0.05	5.4				1272	～0	1.8
Tuotuohe /4533	292.9 (n=61)	1.04	2.1				9.654 (n=62)	0.106	3.4			

confidence levels of 99%.