Check for updates

AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099268

Critical Role of Groundwater Inflow in Sustaining Lake Water Balance on the Western Tibetan Plateau

Yanbin Lei[1], Kun Yang[2], Walter W. Immerzeel[3], Peiping Song[1], Broxton W. Bird[4], Jiankun He[1], Huabiao Zhao[1,5], and Zhiguo Li[6]

[1]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, [2]Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing, China, [3]Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands, [4]Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI), Indianapolis, IN, USA, [5]Ngari Station for Desert Environment Observation and Research, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, [6]Department of Surveying and Planning, Shangqiu Normal University, Shangqiu, China

Key Points:

- Lake level increased considerably on the western Tibetan Plateau during the ice-covered period, accounting for half of annual lake-level increase
- Lake water surplus during the ice-covered period is mainly attributed to significant groundwater inflow
- The occurrence of groundwater inflow after the 2000s is consistent with the decadal variability of summer precipitation

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Lei,
leiyb@itpcas.ac.cn

Citation:

Lei, Y., Yang, K., Immerzeel, W. W., Song, P., Bird, B. W., He, J., et al. (2022). Critical role of groundwater inflow in sustaining lake water balance on the western Tibetan Plateau. *Geophysical Research Letters*, *49*, e2022GL099268. https://doi.org/10.1029/2022GL099268

Received 21 APR 2022
Accepted 23 SEP 2022

Author Contributions:

Conceptualization: Yanbin Lei, Kun Yang
Formal analysis: Kun Yang, Walter W. Immerzeel, Peiping Song, Broxton W. Bird, Jiankun He, Huabiao Zhao
Investigation: Yanbin Lei, Jiankun He, Huabiao Zhao, Zhiguo Li
Methodology: Yanbin Lei
Visualization: Walter W. Immerzeel, Huabiao Zhao, Zhiguo Li
Writing – original draft: Yanbin Lei
Writing – review & editing: Kun Yang, Walter W. Immerzeel, Peiping Song, Broxton W. Bird

Abstract It is difficult to quantify the amount of groundwater inflow on the Tibetan Plateau (TP), yet it can be critically important for sustaining lake water balance. Here we show that most endorheic lakes on the western TP exhibited considerable water level increase during the ice-covered period, which contrasts with lakes in other regions of the TP. An analysis of lake water balance attributes this water surplus to significant groundwater inflow, which is estimated to be about 59%–66% of total inflow into lakes. The groundwater inflow occurred after the 2000s, which is consistent with the rapid lake expansion and significant increase in precipitation. We suggest that the groundwater inflow is mainly related to large-scale active faults in the limestone bedrock and sufficient meltwater from high elevations. Our results imply that groundwater may be deeply involved in the water cycle and modify the seasonal and inter-annual lake variations on the western TP.

Plain Language Summary Although groundwater inflow can be critically important for maintaining lake water balance, it is difficult to quantify its contribution to endorheic lakes on the Tibetan Plateau (TP). Lake-level changes during the ice-covered period (December to May) can be taken as a good indicator of groundwater inflow into endorheic lakes because there is very limited snowfall, surface runoff, and sublimation. Here we show that most endorheic lakes on the western TP exhibited considerable water level increase during the ice-covered period, which contrasts with lakes in other regions of the TP. An analysis of lake water balance indicates that this water surplus was mainly attributed to significant groundwater inflow. The occurrence of groundwater inflow is consistent with the significant increase in precipitation and rapid lake expansion after the 2000s on the western TP. The formation of groundwater inflow may be mainly associated with the regional geological setting. Large-scale active faults in the limestone bedrock increases lake basin permeability, and together with sufficient meltwater from glaciers and snow in high elevations contribute to groundwater inflow into these lakes. Our results imply that groundwater may be deeply involved in the water cycle and modify the seasonal and inter-annual lake variations on the western TP.

1. Introduction

The Tibetan Plateau (TP) and its surroundings contain the third largest ice storage in the world and maintain the headwaters of several Asia's large rivers, effectively acting as the "Asian Water Tower" (Immerzeel et al., 2010; L. Wang et al., 2021; T. Yao et al., 2022). The TP also boasts the greatest concentration of high-altitude inland lakes in the world, providing essential water resource to the regional environment and ecosystem. Since the late 1990s, most endorheic lakes on the interior TP have expanded significantly in response to a dramatic increase in precipitation as well as cryosphere melt (e.g., Lei et al., 2014; G. Zhang et al., 2017). After a slowdown in the early 2010s, lakes on the TP have resumed their rapid expansion in recent years (Lei et al., 2019; Song, Ye, et al., 2015; Yang et al., 2017; Zhan et al., 2020). On the interior TP, lake water storage increased at a rate of 7.7 × 10^9 m^3/yr between 2003 and 2009, which is generally consistent with the total mass gain derived from GRACE data (Q. Wang et al., 2016; Zhang, Su, et al., 2013; Zhang, Yao, et al., 2013).

Endorheic lake water budget on the TP is usually investigated in terms of the surface water components (i.e., precipitation, surface runoff and evaporation). The contribution of groundwater to lake water budget is seldom

© 2022. American Geophysical Union. All Rights Reserved.

10.1029/2022GL099268

investigated because it is hard to detect and quantify. Groundwater-flow system on the TP can be conceptualized in three regimes: near-surface shallow groundwater above permafrost, deeper groundwater below permafrost and groundwater under low-lying valleys and fault zones (Cheng & Jin, 2013; Ge et al., 2008). Groundwater flow on the TP is usually driven and sustained by the topographic gradient with recharge occurring at high elevations through the infiltration of precipitation and meltwater from snow and ice (Ge et al., 2008; Ma et al., 2021; Y. Yao et al., 2017, 2021). Though limited, studies show that groundwater storage on the TP has increased considerably since the 2000s (Jiao et al., 2015). Groundwater storage on the interior TP, for example, is estimated to have increased at a rate of 5.0×10^9 m^3/yr between 2003 and 2009 (Xiang et al., 2016; G. Zhang et al., 2017), which is comparable to the observed lake volume changes (7.7×10^9 m^3/yr) despite the spatial differences. Using stable isotope tracing, previous studies (Chen & Wang, 2009, 2012) showed that increased groundwater in the Taklamakan Desert and Hexi Corridor northwest China may originate from glacier meltwater from the high mountain areas, suggesting that such processes may play an important role in other regions. These studies indicate that there was an increase in groundwater storage on the TP and we hypothesize groundwater flow is an important contributor to lake-level increase.

Lake ice usually persists for about half a year on the western TP, with complete freeze-up in middle November to early December and complete break-up in middle May to early June (Figures S1 and S2 in Supporting Information S1; Kropacek et al., 2013). Lake-level changes during the ice-covered period can be taken as a good indicator of groundwater inflow into endorheic lakes on the TP because there is very limited snowfall, surface runoff and sublimation during this period. Changes in lake level during the ice-covered period therefore reflect positive or negative groundwater fluxes to endorheic lakes after accounting for the limited contribution from snowfall, surface runoff and sublimation. In this study, we first explore lake-level changes on the western TP during the ice-covered period based on in-situ and satellite observations, then quantify the groundwater inflow into two typical lakes, namely Memar Co and Lumajiangdong Co (Co is lake in Tibetan), and investigate its spatial and temporal characteristics and formation. In addition, we provide evidence of groundwater inflow based on in-situ measurements of springs and geothermal activities.

2. Geological Setting of the Study Area

The Tibetan Plateau, from south to north, includes the Tibetan Himalaya, Lhasa, Qiangtang, and Kunlun–Qaidam blocks, separated by the YarlungZangpo, Bangong–Nujiang and Jinsha sutures, respectively (Ding et al., 2014, 2017; Song, Ding, et al., 2015; Stampfli & Borel, 2002). One striking characteristic in Tibet is the wide distribution of the north-to-northeast-striking trending rifts, which are usually considered to be active until now (Yin & Harrison, 2000). Our study area is located on the western portion of the Qiangtang terrace with the Shiquanhe–Gaize–Amdo thrust to the south and the Altyn Tagh fault to the north (Figure 1a). Several northwest- and northeast-trending active normal faults are distributed in this region (Taylor & Peltzer, 2006; Taylor & Yin, 2009; Taylor et al., 2003). The Xianqie Co fault system, trending northeast-southwest, cuts through Xianqie Co and into Lumajiangdong Co (Taylor et al., 2003). The Bue Co fault originates from Bue Co with a northeast strike, and merges with two northwest striking faults toward Lumajiangdong Co and Memar Co. The bedrock in the study area is mainly composed of Carboniferous and Permian limestones interbedded with sandstones, which favors groundwater storage and transport. Quaternary alluvial sediments are widely distributed as surficial deposit in the valley.

3. Materials and Methods

3.1. Lake Water Level Monitoring

Water levels were monitored at six lakes (i.e., Lumajiangdong Co, Memar Co, Jieze Caka, Longmu Co, Luotuo Lake, and Aksaiqin Lake) using HOBO (U20-001-01) or Solinst (Model 3001-LTC) pressure transducers. More detailed information about these lakes and lake-level monitoring can be found in the Supporting Information S1 (Text S1, S2, and Table S1). Five and three years' lake-level data are available at Lumajiangdong Co (2016~2021) and Memar Co (2017~2019, 2020~2021), respectively. Only one year's data are available at Jieze Caka (2020~2021), Longmu Co and Luotuo Lake (2019~2020).

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

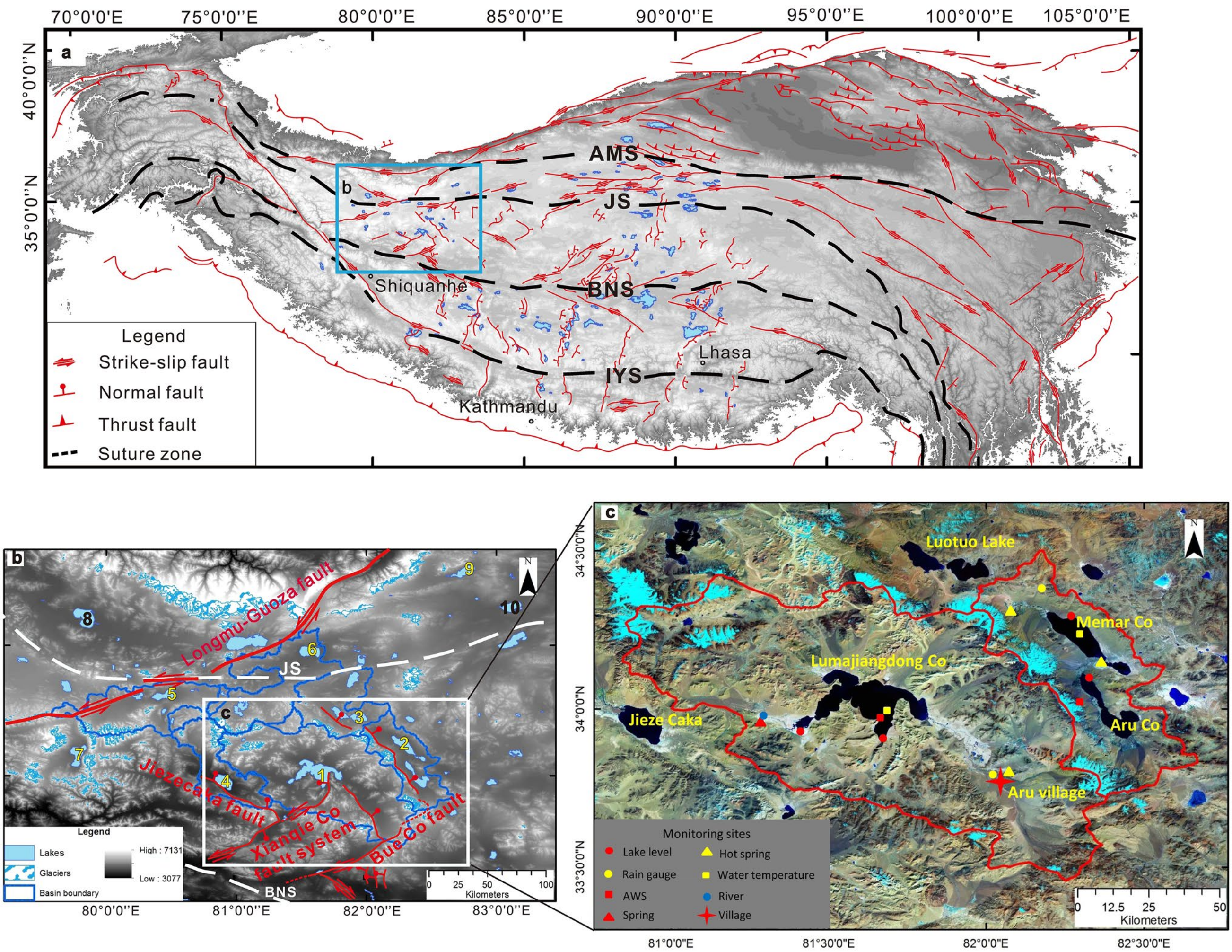

Figure 1. The geological setting of the study area and monitoring sites of lake hydro-meteorology. (a), Geological background of the Tibetan Plateau (TP) (adapted from Taylor et al., 2003) and the location of the study area. IYS, BNS, JS and AMS stand for Indus-Yalu, Bangong-Nujiang, Jinsha and Anyimaqen-Kunlun-Muztagh suture zones, respectively. (b), The distribution of lakes on the western TP and main faults in the study area. Lakes with and without significant groundwater supply are marked with yellow and black numbers, respectively. 1 Lumajiangdong Co, 2 Memar Co, 3 Luotuo Lake, 4 Jieze Caka, 5 Longmu Co, 6 Bamgdog Co, 7 Chem Co, 8 Aksaiqin Lake, 8 North Heishibei Lake, 10 Jianshui Lake. (c) Monitoring sites of lake hydro-meteorology in Lumajiangdong Co and Memar Co basins.

3.2. Hydro-Meteorology Observations

Several automatic weather stations (AWS) were installed in the study area to monitor locale meteorological conditions. An AWS was installed on an island of Lumajiangdong Co in September 2019 (Figure 1c). Precipitation was monitored by RG-3 rain gauge in Aru village. Air temperature, humidity, air pressure, wind speed and wind direction, solar radiation, longwave radiation, and lake surface temperature were acquired from the AWS station. In Memar Co basin, an AWS was installed to the west of Aru Co in October 2016 (Figure 1c). Snowfall and rainfall were monitored by T-200B precipitation gauge at this station.

Both surface runoff and spring discharge were investigated. In Lumajiangdong Co basin, water level of river and springs to the west of the lake was monitored by pressure transducers (HOBO U20-001-01 water-level logger) (Figure 1c). The spring discharge was measured by using a LS1206B propeller-driven current meter (Nanjing Institute of Hydrological Automatization) in October 2020. In Memar Co basin, water level of river and springs is not available because the loggers were lost. Spring discharge to the northwest of Memar Co was measured in October 2020.

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 1
Lake Water Budgets During the Ice-Free and Ice-Covered Periods at Lumajiangdong Co and Memar Co

	Lumajiangdong Co		Memar Co	
Components (mm)	Ice-free period (June–November)	Ice-covered period (December–May)	Ice-free period (June–November	Ice-covered period (December–May)
Lake level changes	137	245	373	357
Precipitation	277	44	212	40
Evaporation/Sublimation	900	173	900	173
Surface runoff	386	0	615	0
Groundwater	374	374	446	490

Note. That the ice-free period is between May 20th and November 20th, and the ice-covered period is between November 20th and May 20th of each year. Groundwater is assumed to be constant throughout a year. Lake water budget at Lumajiangdong Co is the average value during June 2017 ~ May 2021. Lake water budget at Memar Co is the average value during December 2017 ~ May 2019 and December 2020 ~ May 2021. Surface runoff and groundwater inflow are calculated to be equivalent to lake level changes.

3.3. Estimation of Groundwater Discharge

Lake water budget in endorheic basin is mainly related to surface runoff, precipitation, lake evaporation, and groundwater inflow/outflow (Yang et al., 2018). Therefore, groundwater discharge to endorheic lake can be estimated according to lake water budget, which can be written as:

$$G = A_l \times (\Delta L_l + E - P) - R, \tag{1}$$

where G is groundwater discharge, A_l is lake area, ΔL_l is lake-level change, E is lake evaporation or ice sublimation, P is precipitation, and R is surface runoff.

3.4. Estimation of Lake Ice Sublimation and Evaporation

Lake ice sublimation between December and May was estimated through the bulk method (Huang et al., 2016; WMO, 1988), which can be expressed as:

$$E = \rho_a \times C_E \times (q_s - q_a) \times V_a, \tag{2}$$

where E is the rate of lake ice sublimation, ρ_a is the density of air, C_E is the bulk transfer coefficient, $(q_s - q_a)$ is the difference in specific humidity between ice surface and air, V_a is the wind speed and. Meteorological data from the AWS on the island of Lumajiangdong Co, including air temperature, lake surface temperature, humidity, wind speed was used to calculate daily lake ice sublimation. Lake evaporation during the ice-free period is estimated through Bowen ratio method (Text S3 in Supporting Information S1). Snowfall from the T-200B rain gauge to the west of Aru Co was used. Lake water budgets during the ice-covered and ice-free periods were calculated by assuming same lake evaporation and sublimation at both lakes (Table 1).

3.5. Satellite Altimetry Data

ICESat and CryoSat-2 satellite altimetry data were used to detect long-term lake-level changes between 2003 and 2018 (Li et al., 2014; Xue et al., 2018). Lumajiangdong Co and Memar Co were observed by ICESat satellite twice or three times a year between 2003 and 2009 (Phan et al., 2012), and by CryoSat-2 satellite every 2 or 3 months between 2010 and 2018 (Kleinherenbrink et al., 2015). Lake-level variations at Memar Co before 2003 were determined based on the current lake bathymetry and the position of past shorelines (Text S4 in Supporting Information S1, Lei, Yao, Tian, et al., 2021).

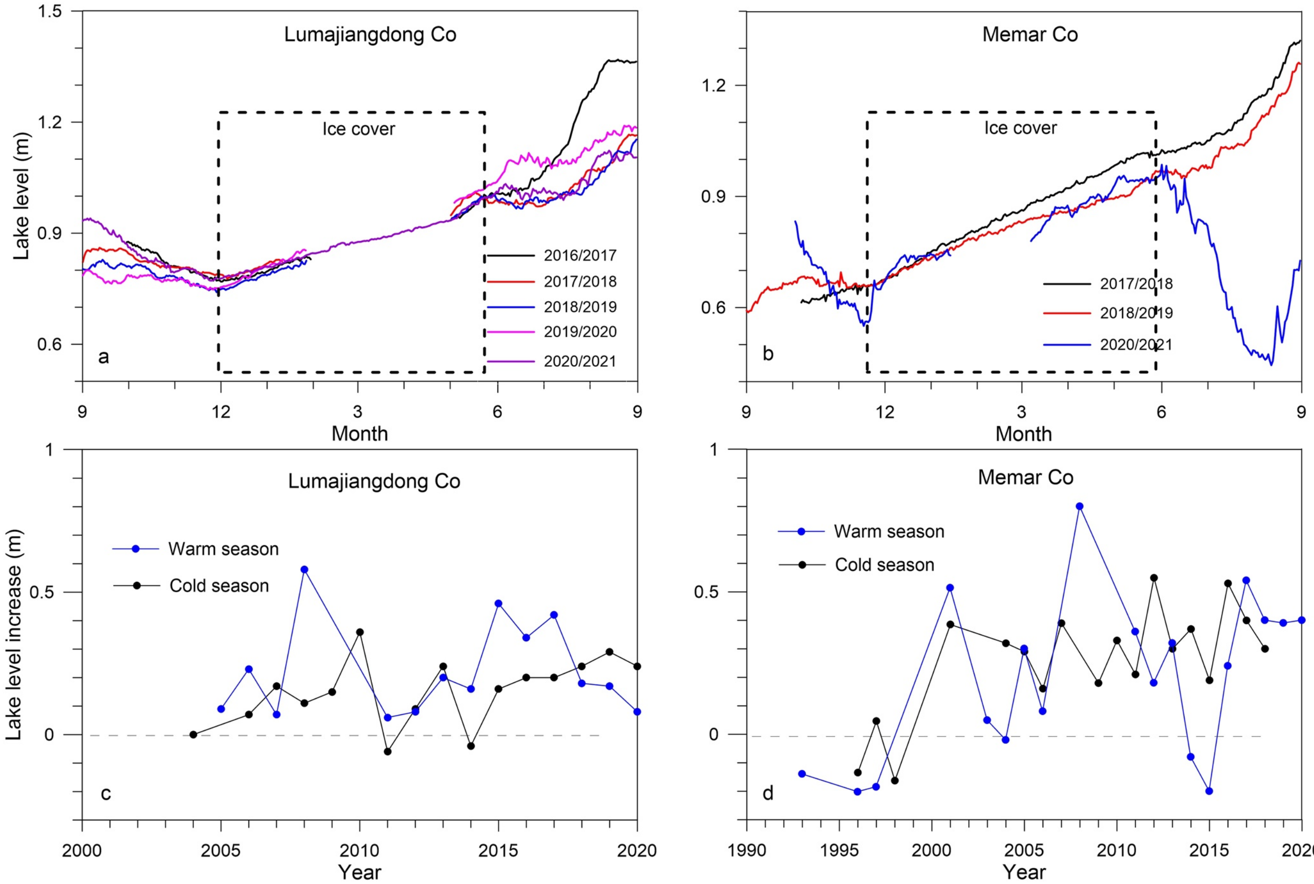

Figure 2. Seasonal and long-term lake level variations for Lumajiangdong Co (a, c) and Memar Co (b, d) on the western Tibetan Plateau. The dashed rectangles (a, b) indicate the ice-covered period. There is no data available when the loggers are frozen. Lake level variations in cold (November to May) and warm seasons (June to October) are derived from ICESat and CryoSat-2 satellite altimetry between 2003 and 2017. Note that lake levels in different years (a, b) were calibrated to the same level to make them easier to compare.

4. Results

4.1. The Distinct Lake-Level Seasonality on the Western TP

The observed lakes exhibited distinct lake-level seasonality (Figure 2). For most lakes on the TP (Figure S3 in Supporting Information S1), water levels were stable or decreased slightly during the ice-covered period, which can be attributed to the lake ice sublimation and negligible inflows. For the observed lakes on the western TP, however, there is considerable lake-level increase during the ice-covered period (December to May). For example, lake levels at Lumajiangdong Co and Memar Co increased by 0.24 m and 0.36 m on average during the ice-covered period, accounting for 64% and 46% of annual lake-level increase, respectively. For the other two observed lakes Longmu Co and Jieze Caka, water levels decreased during the ice-free period, but significantly increased during the ice-covered period (Figure S4 in Supporting Information S1). The turning point from lake-level decrease to increase occurred in late November when the lake surface frozen up, possibly due to higher lake evaporation (output) during the ice-free period compared with the ice-covered period. The positive lake water budget during the ice-covered period cannot be explained by surface inflows because they were very limited during this period. Meanwhile, the nearly linear increase in water level indicates that the water supply to the lakes was stable during the ice-covered period.

Five years of in-situ observations show that lake-level increase during the ice-free period varied considerably from year to year and responded sensitively to summer precipitation, but was much less variable during the ice-covered period. For example, lake level at Lumajiangdong Co increased considerably by 0.35 m in summer 2017 when precipitation was high (Figure S5 in Supporting Information S1). In contrast, the lake level increased

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

by only 0.1 m or even decreased in summer 2020 and 2021 when precipitation was very low. Lake-level increases during the ice-covered period, however, were almost identical during the past 5 years. A similar situation was also observed at Memar Co, namely variable lake-level changes during the ice-free period but stable lake-level increase during the ice-covered period (Figure 2). This suggests that lake-level increase during the ice-covered period is not controlled by seasonal and inter-annual changes in precipitation.

4.2. Estimation of Groundwater Inflow

The lake water balances for Lumajiangdong Co and Memar Co were quantified using in-situ observations of the lake hydro-meteorology. The main surface components of an endorheic lake's water budget during the ice-covered period include snowfall (+), surface runoff (+), groundwater inflow/outflow, and lake ice sublimation (−). The T-200B rain gauge to the west of Aru Co showed that total snowfall had an average value of 44 mm during the ice-covered period (December to May), accounting for 13% of annual precipitation (2016–2019). Lake ice sublimation was estimated to be 29 mm per month based on in-situ observations of meteorological data at Lumajiangdong Co. This rate was slightly lower than that at Beiluhe Lake (47 mm per month, Huang et al., 2016, 2019) and Nam Co (44 mm per month, B. Wang et al., 2020) because of the lower wind speed and air temperature at Lumajiangdong Co. The surface runoff is very limited and negligible during the ice-covered period on the TP (Kan et al., 2018; Y. Yao et al., 2021; Zhang, Su, et al., 2013; Zhang, Yao, et al., 2013), which is also confirmed by field expeditions in late September 2020 (Figure S6 in Supporting Information S1). Therefore, surface runoff was ignored in water balance calculation for the ice-covered period.

Figure 3 shows the main components of lake water budget. Total snowfall accounts for less than 25% of the lake-level increase during the ice-covered period, even without considering snow sublimation, indicating that snowfall cannot account for the significant lake water surplus. Lake ice sublimation, with a total value of ~173 mm between mid-November and late May (Figure 3), would decrease the lake level during the ice-covered period without additional input. Therefore, we conclude that the considerable lake-level increase during the ice-covered period must be attributed to groundwater discharge to the lakes. Based on Equation 1, we estimate that the groundwater discharges over the entire ice-covered period were 374 ± 25 mm and 490 ± 39 mm equivalent to lake-level increase at Lumajiangdong Co and Memar Co, respectively. Assuming that groundwater inflow is stable throughout a year, the annual groundwater inflow would be equal to 13% and 25% of total summer precipitation (June to September). A simple lake water budget analysis for an entire year indicates that groundwater inflow may reach as high as 66% and 59% of total inflow into Lumajiangdong Co and Memar Co (Table 1), which indicates that groundwater inflow plays a critical role in sustaining lake water balance.

4.3. Spatial and Temporal Characteristics of Lake-Level Change on the Western TP

Long-term lake-level changes in cold season at Lumajiangdong Co and Memar Co were investigated by analyzing Cryosat-2 and ICESat satellite altimetry data. Lake-level changes in cold season were defined as the difference between the post-monsoon (November) and pre-monsoon (June) seasons. Figures 2c and 2d show that considerable lake-level increase in cold season occurred almost every year between 2003 and 2018. In contrast, lake levels were stable or decreased slightly in cold seasons in the 1990s (Figure S7 in Supporting Information S1), indicating that the occurrence of significant groundwater inflow mainly occurred since the 2000s. This is consistent with relatively high precipitation, rapid lake expansion on the interior TP (Sun et al., 2020; Brun et al., 2020; Treichler et al., 2019) and increase in terrestrial water storage (Jiao et al., 2015; Xiang et al., 2016; G. Zhang et al., 2017), suggesting that the variability in groundwater inflow into the lakes was primarily driven by decadal changes in precipitation on the western TP.

To validate our finding, lake-level changes in cold season were also investigated for other lake basins on the western TP. Like the four observed lakes, other large lakes, including Luotuo Lake, Bamdog Co, Chem Co and North Heishibei Lake also exhibited considerable water level increase in cold season (Figure S8 in Supporting Information S1). In fact, nearly 80% of the detected lakes on the western TP exhibited considerable lake-level increase in cold season (Figure S8 in Supporting Information S1). This strongly suggests that groundwater supply plays a critical role in lake water balance on the western TP. Notably, lake-level increase in cold season was not apparent at Aksaiqin Lake (Figure S4d in Supporting Information S1). For this lake, there is slight lake-level

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

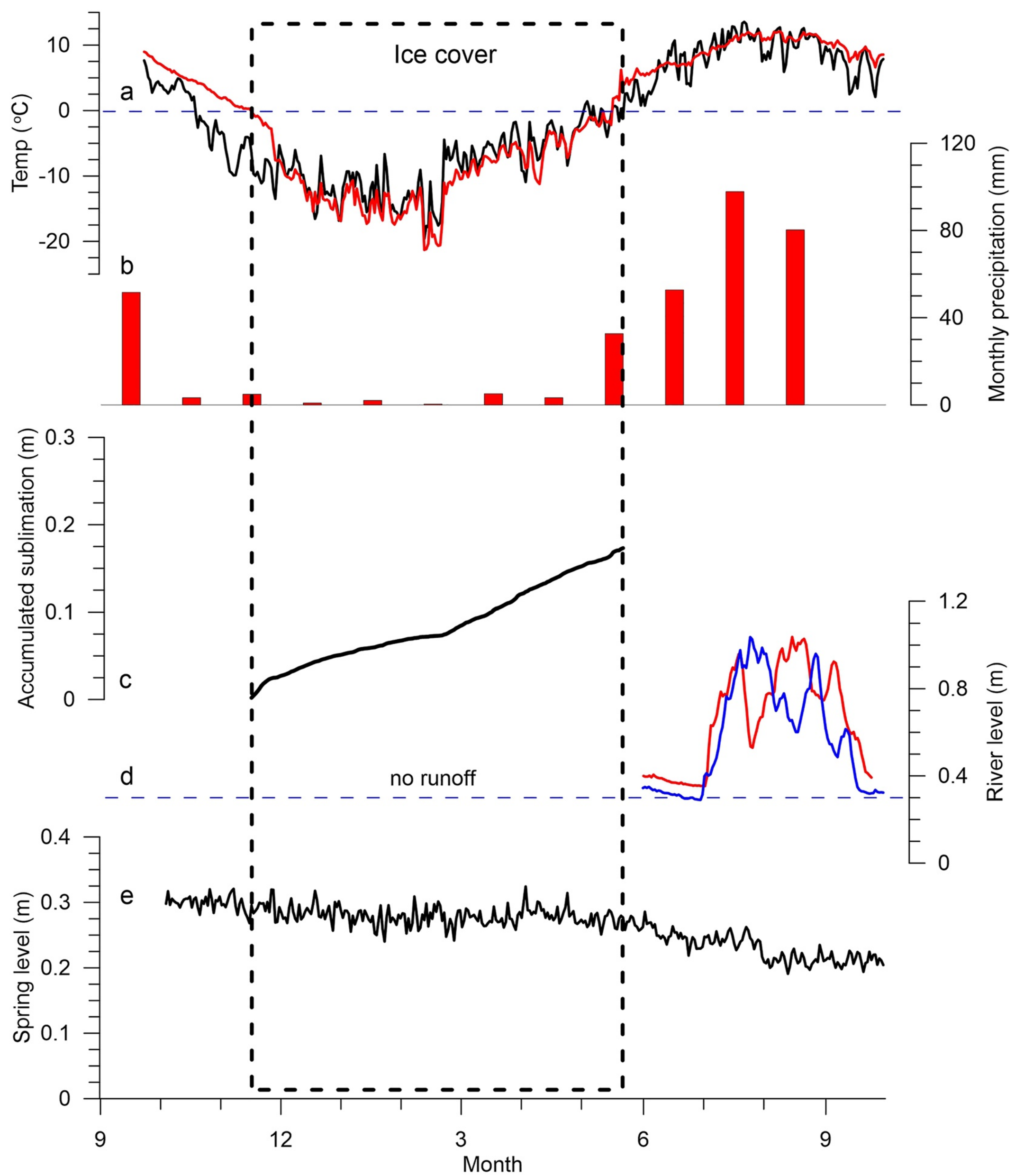

Figure 3. Seasonal variations of the main components of lake water budget at Lumajiangdong Co during the ice-covered period. (a) Lake surface temperature (red) and air temperature (black), (b) Monthly mean precipitation (2016–2020), (c) Accumulated sublimation in the winter season of 2020/2021, (d) Water level of the main river to the west of Lumajiangdong Co in 2019/2020 (red) and 2020/2021 (blue), (e) Water level of the spring discharge to the west of Lumajiangdong Co in 2020/2021.

decrease during the ice-covered period, indicating there is no significant groundwater inflow as other observed lakes on the western TP.

5. Discussion and Conclusions

5.1. The Formation of Groundwater Inflow

Permafrost is widely distributed on the western TP (Zhao & Sheng, 2019). Under the rapid climate warming, the thawing permafrost might open up new conduits and increase groundwater inflow (Zhao et al., 2019), which can potentially contribute to lake-level changes. However, this can not explain the distinct lake-level seasonality on

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

the western TP. For example, lakes on the northern TP do not exhibit considerable lake-level changes during the ice-covered period (Lei et al., 2017), although permafrost is also widely distributed there. Therefore, the significant groundwater inflow on the western TP may not be mainly attributed to thawing permafrost.

Considering the rift system and active tectonic activity, we contend that the significant groundwater inflow on the western TP is mainly related to the geological setting and cryosphere melting. First, the bedrock in the study area is mainly composed of Carboniferous and Permian limestone interbedded with sandstones, which are favorable aquifer lithologies. Second, active normal faults are distributed in each of the lake basins (Figure 1), which can act as favorable conduit and convey groundwater to the downstream lakes (Tan et al., 2014, 2021). In Memar Co basin, an active normal fault with northwest trending is located to the west of Memar Co and stretches northward to Luotuo Lake. An Mw 6.1 earthquake occurred in the northwest of Memar Co basin (epicenter E82.86°, N34.38°) on 5 May 2007, indicating this fault is presently active. In Lumajiangdong Co basin, two active normal faults with northeast and northwest trending are developed and connected with the Xianqie Co and Bue Co fault systems (Taylor & Peltzer, 2006; Taylor & Yin, 2009; Taylor et al., 2003). Third, meltwater from widely distributed glaciers and snow at high elevations may provide a considerable amount of water for groundwater recharge in the summer (Ge et al., 2008). Water from high mountainous regions can percolate vertically and circulate deeply along the active faults (Tan et al., 2014, 2021) and discharge into the downstream lakes.

Springs and geothermal activity may provide further evidence of groundwater inflow. Field observation shows that geothermal activities, including thermal springs, are found to the east of Lumajiangdong Co and west of Memar Co (Figure 1c). This indicates that groundwater is indeed transported via regional active faults and contributes to the lake water budget. Springs to the west of Lumajiangdong Co (81.27°E, 33.99°N) and the northwest of Memar Co (82.07°E, 34.32°N) were investigated and the total water supply was measured to be 0.27 m^3/s and 0.26–0.29 m^3/s, respectively in October 2020 (Figures S9 and S10 in Supporting Information S1). In-situ observation indicates that water supply from the springs was almost constant throughout a year (Figure 3e). In contrast, there was almost no surface runoff in the main river nearby the springs during the field expedition (Figure S6 in Supporting Information S1).

5.2. Implications for the Water Cycle Across the TP

Previous studies on lake water budget on the TP mainly focus on surface water cycle, including precipitation, evaporation, and cryospheric melt etc. The contribution of groundwater to lake water budget has been seldom studied on the TP (Yong et al., 2021; Zhou et al., 2013). Lake-level changes during the ice-covered period can be a good indicator of groundwater supply because other hydrological fluxes, such evaporation and surface runoff, are negligible. Based on comprehensive in-situ observations and water balance calculations, our results indicate that groundwater considerably contributes to the lake-level changes on the western TP. Furthermore, lakes with high groundwater supply are found to be mainly distributed along active faults. Therefore, we hypothesize that lakes with groundwater supply may not only be limited to the western TP, but also in other regions of the TP with suitable geology setting and active fault. For example, considerable lake-level increases in cold season are also observed at Co Nyi (87.30°E, 34.57°N) and Aqikkul Lake (84.41°E, 37.08°N) on the northern TP, in contrast with the slight lake-level increase or even decrease in warm season (Figure S11 in Supporting Information S1). In-situ observations at Amur Co (88.70°E, 33.49°N) near Shuanghu County also indicate that the lake level increased considerably by 0.2~0.3 m during the ice-covered period (Figure S12 in Supporting Information S1).

A previous study reported that there are two types of lake-level seasonality on the TP (Lei et al., 2017). For most lakes of the TP, lake levels are generally stable or decrease slightly during the ice-covered period because lake water input and output are very limited. However, the situation is different on the western TP where lake levels increased dramatically in both the warm and cold seasons. Here we attribute the lake water surplus in the cold season to significant groundwater inflow. Thus, lakes on the TP can be classified as groundwater-fed lakes and surface-water-fed lakes according to the different types of water supply. For surface-water-fed lakes, lake-level changes are mainly affected by monsoon precipitation and lake evaporation. For groundwater-fed lakes, the seasonal lake-level variations are significantly modified by groundwater inflow. For these lakes, surface runoff is considerably limited in summer because part of precipitation and meltwater are used for groundwater recharge. Therefore, for lakes with significant groundwater supply, lake dynamics may be much less sensitive to seasonal and inter-annual climate variability. For this kind of lakes, hydrological models that include a groundwater component are therefore needed to accurately simulate the water balance. As groundwater supply is mainly associated with regional active faults, the groundwater aquifers that feed the lakes may be larger/smaller than the lake surface watershed, therefore our results also imply that tectonic activity may have impact on changes in lake water storage on the TP.

Data Availability Statement

All data about lake-level changes on the western TP are available at National Tibetan Plateau Data center (TPDC) (https://doi.org/10.11888/Terre.tpdc.272314).

Acknowledgments

This research has been supported by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0201), the National Natural Science Foundation of China (41988101, 41971097, 41975125, and 41671072), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA2006020102), and Youth Innovation Promotion Association CAS(2017099). We thank Dr. Shuang Yi and the two anonymous reviewers for their constructive comments that greatly improved this paper. We also thank prof. Fahu Chen, Fengge Su, and Lin Zhao for their discussion on this work. We are grateful to all the members for their help during the fieldwork.

References

Brun, F., Treichler, D., Shean, D., & Immerzeel, W. W. (2020). Limited contribution of glacier mass loss to the recent increase in Tibetan Plateau lake volume. *Frontiers of Earth Science*, *8*, 582060. https://doi.org/10.3389/feart.2020.582060

Chen, J., & Wang, C. (2009). Rising springs along the silk road. *Geology*, *37*(3), 243–246. https://doi.org/10.1130/g25472a.1

Chen, J., & Wang, Q. (2012). A discussion of groundwater recharge source in arid areas of North China. *Water Report*, *28*(3), 5–8.

Cheng, G., & Jin, H. (2013). Permafrost and groundwater on the Qinghai–Tibet Plateau and in northeast China. *Hydrogeology Journal*, *21*(1), 5–23. https://doi.org/10.1007/s10040-012-0927-2

Ding, L., Spicer, R. A., Yang, J., Xu, Q., Cai, F. L., Li, S., et al. (2017). Quantifying the rise of the Himalaya orogen and implications for the South Asian monsoon. *Geology*, *45*(3), 215–222. https://doi.org/10.1130/g38583.1

Ding, L., Xu, Q., Yue, Y., Wang, H., Cai, F., & Li, S. (2014). The Andean-type Gangdese mountains: Paleoelevation record from the Paleocene–Eocene Linzhou basin. *Earth and Planetary Science Letters*, *392*, 250–264. https://doi.org/10.1016/j.epsl.2014.01.045

Ge, S., Wu, Q. B., Lu, N., Jiang, G. L., & Ball, L. (2008). Groundwater in the Tibet Plateau, western China. *Geophysical Research Letters*, *35*(18), L18403. https://doi.org/10.1029/2008gl034809

Huang, W., Cheng, B., Zhang, J., Zhang, Z., Vihma, T., Li, Z., & Niu, F. (2019). Modeling experiments on seasonal lake ice mass and energy balance in the Qinghai-Tibet Plateau: A case study. *Hydrology and Earth System Sciences*, *23*(4), 2173–3186. https://doi.org/10.5194/hess-23-2173-2019

Huang, W., Li, R., Han, H., Niu, F., Wu, Q., & Wang, W. (2016). Ice processes and surface ablation in a shallow thermokarst lake in the central Qinghai-Tibet Plateau. *Annals of Glaciology*, *57*(71), 20–28. https://doi.org/10.3189/2016AoG71A016

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, *328*(5984), 1382–1385. https://doi.org/10.1126/science.1183188

Jiao, J., Zhang, X., Liu, Y., & Kuang, X. (2015). Increased water storage in the Qaidam basin, the north Tibet Plateau from GRACE gravity data. *PLoS One*, *10*(10), e0141442. https://doi.org/10.1371/journal.pone.0141442

Kan, B., Su, F., Xu, B., Xie, Y., Li, J., & Zhang, H. (2018). Generation of high mountain precipitation and temperature data for quantitative assessment of flow regime in the upper Yarkant basin in the Karakoram. *Journal of Geophysical Research: Atmospheres*, *123*(16), 8462–8486. https://doi.org/10.1029/2017jd028055

Kleinherenbrink, M., Lindenbergh, R. C., & Ditmar, P. G. (2015). Monitoring of lake level changes on the Tibetan Plateau and Tian Shan by retracking Cryosat SARIn waveforms. *Journal of Hydrology*, *521*, 119–131. https://doi.org/10.1016/j.jhydrol.2014.11.063

Kropacek, J., Maussion, F., Chen, F., Hoerz, S., & Hochschild, V. (2013). Analysis of ice phenology of lakes on the Tibetan Plateau from MODIS data. *The Cryosphere*, *7*(1), 287–301. https://doi.org/10.5194/tc-7-287-2013

Lei, Y., Yang, K., Wang, B., Sheng, Y., Bird, B. W., Zhang, G., & Tian, L. (2014). Response of inland lake dynamics over the Tibetan Plateau to climate change. *Climate Change*, *125*(2), 281–290. https://doi.org/10.1007/s10584-014-1175-3

Lei, Y., Yao, T., Yang, K., Sheng, Y., Kleinherenbrink, M., Yi, S., et al. (2017). Lake seasonality across the Tibetan Plateau and their varying relationship with regional mass changes and local hydrology. *Geophysical Research Letters*, *44*(2), 892–900. https://doi.org/10.1002/2016GL072062

Lei, Y., Yao, T. D., Tian, L. D., Sheng, Y. W., Lazhu, L. J. J., Zhao, H., et al. (2021). Response of downstream lakes to Aru glacier collapses on the western Tibetan Plateau. *The Cryosphere*, *15*(1), 199–214. https://doi.org/10.5194/tc-15-199-2021

Lei, Y., Zhu, Y., Wang, B., Yao, T., Yang, K., Zhang, X., et al. (2019). Extreme lake level changes on the Tibetan Plateau associated with the 2015/2016 El Niño. *Geophysical Research Letters*, *46*(11), 5889–5898. https://doi.org/10.1029/2019GL081946

Li, Y., Liao, J., Guo, H., Liu, Z., & Shen, G. (2014). Patterns and potential drivers of dramatic changes in Tibetan lakes, 1972–2010. *PLoS One*, *9*(11), e111890. https://doi.org/10.1371/journal.pone.0111890

Ma, R., Sun, Z., Chang, Q., Ge, M., & Pan, Z. (2021). Control of the interactions between stream and groundwater by permafrost and seasonal frost in an alpine catchment, northeastern Tibet Plateau, China. *Journal of Geophysical Research: Atmospheres*, *126*(5), e2020JD033689. https://doi.org/10.1029/2020JD033689

Phan, V., Lindenbergh, R., & Menenti, M. (2012). Seasonal trends in Tibetan lake level changes as observed by ICESat laser altimetry. *ISPRS Journal of Photogrammetry and Remote Sensing*, *1–7*, 237–242. https://doi.org/10.5194/isprsannals-i-7-237-2012

Song, C., Ye, Q., Sheng, Y., & Gong, T. (2015). Combined ICESat and CryoSat-2 altimetry for accessing water level dynamics of Tibetan lakes over 2003-2014. *Water*, *7*(12), 4685–4700. https://doi.org/10.3390/w7094685

Song, P., Ding, L., Li, Z., Lippert, P. C., Yang, T., Zhao, X., et al. (2015). Late Triassic paleolatitude of the Qiangtang block: Implications for the closure of the Paleo-Tethys Ocean. *Earth and Planetary Science Letters*, *424*, 69–83. https://doi.org/10.1016/j.epsl.2015.05.020

Stampfli, G. M., & Borel, G. D. (2002). A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, *196*(1–2), 17–33. https://doi.org/10.1016/s0012-821x(01)00588-x

Sun, J., Yang, K., Guo, W., Wang, Y., He, J., & Lu, H. (2020). Why has the inner Tibetan Plateau become wetter since the mid-1990s? *Journal of Climate*, *33*(19), 8507–8522. https://doi.org/10.1175/jcli-d-19-0471.1

Tan, H., Chen, X., Shi, D., Rao, W., Liu, J., Liu, J., et al. (2021). Base flow in the Yarlungzangbo River, Tibet, maintained by the isotopically depleted precipitation and groundwater discharge. *Science of the Total Environment*, *759*, 143510. https://doi.org/10.1016/j.scitotenv.2020.143510

Tan, H., Zhang, Y., Zhang, W., Kong, N., Zhang, Q., & Huang, J. (2014). Understanding the circulation of geothermal waters in the Tibetan Plateau using oxygen and hydrogen stable isotopes. *Applied Geochemistry*, *51*, 23–32. https://doi.org/10.1016/j.apgeochem.2014.09.006

Taylor, M., & Peltzer, G. (2006). Current slip rates on conjugate strike-slip faults in central Tibet using synthetic aperture radar interferometry. *Journal of Geophysical Research*, *111*(B12), B12402. https://doi.org/10.1029/2005jb004014

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Taylor, M., & Yin, A. (2009). Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism. *Geosphere*, *5*(3), 199–214. https://doi.org/10.1130/ges00217.s1

Taylor, M., Yin, A., Ryerson, F. J., Kapp, P., & Ding, L. (2003). Conjugate strike-slip faulting along the Bangong-Nujiang suture zone accommodates coeval east-west extension and north-south shortening in the interior of the Tibetan Plateau. *Tectonics*, *22*(4), 10449. https://doi.org/10.1029/2002tc001361

Treichler, D., Kääb, A., Salzmann, N., & Xu, C. (2019). High mountain Asia glacier elevation trends 2003–2008, lake volume changes 1990–2015, and their relation to precipitation changes. *The Cryosphere*, *13*(11), 2977–3005. https://doi.org/10.5194/tc-13-2977-2019

Wang, B., Ma, Y., Su, Z., Wang, Y., & Ma, W. (2020). Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau. *Science Advances*, *6*(26), eaay8558. https://doi.org/10.1126/sciadv.aay8558

Wang, L., Yao, T., Chai, C., Cuo, L., Su, F., Zhang, F., et al. (2021). TP-River: Monitoring and quantifying total river runoff from the third pole. *Bulletin America Meteorology Social*, *102*(5), E948–E965. https://doi.org/10.1175/BAMS-D-20-0207.1

Wang, Q., Yi, S., & Sun, W. (2016). The changing pattern of lake and its contribution to increased mass in the Tibetan Plateau derived from GRACE and ICESat data. *Geophysical Journal International*, *207*(1), 528–541. https://doi.org/10.1093/gji/ggw293

World Meteorological Organization (WMO). (1988). *General meteorological standards and recommended practices*. WMO Technical Regulations.

Xiang, L., Wang, H., Steffen, H., Wu, P., Jia, L., Jiang, L., & Shen, Q. (2016). Groundwater storage changes in the Tibetan Plateau and adjacent areas revealed from GRACE satellite gravity data. *Earth and Planetary Science Letters*, *449*, 228–239. https://doi.org/10.1016/j.epsl.2016.06.002

Xue, H., Liao, J., & Zhao, L. (2018). A modified empirical retracker for lake level estimation using Cryosat-2 SARin data. *Water*, *10*(11), 1584–1600. https://doi.org/10.3390/w10111584

Yang, K., Lu, H., Yue, S., Zhang, G., Lei, Y., Zhu, L., & Wang, W. (2018). Quantifying recent precipitation change and predicting lake expansion in the Inner Tibetan Plateau. *Climate Change*, *147*(1–2), 149–163. https://doi.org/10.1007/s10584-017-2127-5

Yang, K., Yao, F., Wang, J., Luo, J., Shen, Z., Wang, C., & Song, C. (2017). Recent dynamics of alpine lakes on the endorheic Changtang Plateau from multi-mission satellite data. *Journal of Hydrology*, *552*, 633–645. https://doi.org/10.1016/j.jhydrol.2017.07.024

Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., et al. (2022). The imbalance of the Asian water tower. *Nature Reviews Earth & Environment*. https://doi.org/10.1038/s43017-022-00299-4

Yao, Y., Zheng, C., Andrews, C., Zheng, Y., Zhang, A., & Liu, J. (2017). What controls the partitioning between baseflow and mountain block recharge in the Qinghai-Tibet Plateau? *Geophysical Research Letters*, *44*(16), 8352–8358. https://doi.org/10.1002/2017GL074344

Yao, Y., Zheng, C., Andrews, C. B., Scanlon, B. R., Kuang, X., Zeng, Z., et al. (2021). Role of groundwater in sustaining northern Himalayan Rivers. *Geophysical Research Letters*, *48*(10), e2020GL092354. https://doi.org/10.1029/2020GL092354

Yin, A., & Harrison, T. M. (2000). Geologic evolution of the Himalayan-Tibetan orogeny. *Annual Review of Earth and Planetary Sciences*, *28*(1), 211–280. https://doi.org/10.1146/annurev.earth.28.1.211

Yong, B., Wang, C., Chen, J. S., Chen, J. Q., Barry, D. A., Wang, T., & Li, L. (2021). Missing water from the Qiangtang basin on the Tibetan Plateau. *Geology*, *49*(7), 867–872. https://doi.org/10.1130/g48561.1

Zhan, P., Song, C., Wang, J., Li, W., Ke, L., Liu, K., & Chen, T. (2020). Recent abnormal hydrologic behavior of Tibetan lakes observed by multi-mission altimeters. *Remote Sensing*, *12*(18), 2986. https://doi.org/10.3390/rs12182986

Zhang, G., Yao, T., Shum, C. K., Yi, S., Yang, K., Xie, H., et al. (2017). Lake volume and groundwater storage variations in Tibetan Plateau's endorheic basin. *Geophysical Research Letters*, *44*(11), 5550–5560. https://doi.org/10.1002/2017gl073773

Zhang, G., Yao, T., Xie, H., Kang, S., & Lei, Y. (2013). Increased mass over the Tibetan Plateau: From lakes or glaciers? *Geophysical Research Letters*, *40*(10), 2125–2130. https://doi.org/10.1002/grl.50462

Zhang, L., Su, F., Yang, D., Hao, Z., & Tong, K. (2013). Discharge regime and simulation for the upstream of major rivers over Tibetan Plateau. *Journal of Geophysical Research*, *118*(15), 8500–8518. https://doi.org/10.1002/jgrd.50665

Zhao, L., Hu, G., Zou, D., Wu, X., Ma, L., Sun, Z., et al. (2019). Permafrost changes and its effects on hydrological processes on Qinghai-Tibet Plateau. *Bulletin of Chinese Academy of Sciences*, *34*, 1233–1246.

Zhao, L., & Sheng, Y. (2019). *Permafrost and environment changes on the Qinghai-Tibetan Plateau*. Science Press.

Zhou, S., Kang, S., Chen, F., & Joswiak, D. R. (2013). Water balance observations reveal significant subsurface water seepage from Lake Nam Co, south-central Tibetan Plateau. *Journal of Hydrology*, *491*, 89–99. https://doi.org/10.1016/j.jhydrol.2013.03.030

References From the Supporting Information

Guo, W., Liu, S., Xu, J., Wu, L., Shangguang, D., Yao, X., et al. (2015). The second Chinese glacier inventory: Data, methods and results. *Journal of Glaciology*, *61*(226), 357–372. https://doi.org/10.3189/2015jog14j209

Kääb, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoin, S., Evans, S. G., et al. (2018). Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nature Geoscience*, *11*(2), 114–120. https://doi.org/10.1038/s41561-017-0039-7

LazhuYang, K., Hou, J., Wang, J., Lei, Y., Zhu, L., Chen, Y., et al. (2021). A new finding on the prevalence of rapid water warming during lake ice melting on the Tibetan Plateau. *Science Bulletin*, *66*(23), 2358–2361. https://doi.org/10.1016/j.scib.2021.07.022

Lei, Y., Yao, T., Yang, K., LazhuMa, Y., & Bird, B. (2021b). Contrasting hydrological and thermal intensities determine seasonal lake-level variations—A case study at Paiku Co on the southern Tibetan Plateau. *Hydrology and Earth System Sciences*, *25*(6), 3163–3177. https://doi.org/10.5194/hess-25-3163-2021

Tian, L., Yao, T., Gao, Y., Thompson, L., Mosley-Thompson, E., Muhammad, S., et al. (2017). Two glaciers collapse in western Tibet. *Journal of Glaciology*, *63*(237), 194–197. https://doi.org/10.1017/jog.2016.122

19448007, 2022, 20, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099268 by Utrecht University Library, Wiley Online Library on [17/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License