Title
Quantifying the major drivers for the expanding lakes in the interior Tibetan Plateau.

Journal
Science bulletin, 67(5)

ISSN
2095-9273

Authors
Zhou, Jing
Wang, Lei
Zhong, Xiaoyang
et al.

Publication Date
2022-03-01

DOI
10.1016/j.scib.2021.11.010

Peer reviewed

Quantifying the major drivers for the expanding lakes in the interior Tibetan Plateau

Article *in* Science Bulletin · November 2021

DOI: 10.1016/j.scib.2021.11.010

Science Bulletin 67 (2022) 474–478

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

Quantifying the major drivers for the expanding lakes in the interior Tibetan Plateau

Jing Zhou [a,*], Lei Wang [a,b,*], Xiaoyang Zhong [a], Tandong Yao [a,b], Jia Qi [a], Yuanwei Wang [a], Yongkang Xue [c]

[a] State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Department of Geography, University of California, Los Angeles, CA 90095-1524, USA

A R T I C L E I N F O

Article history:
Received 1 June 2021
Received in revised form 1 November 2021
Accepted 2 November 2021
Available online 9 November 2021

Lakes are an important component of the terrestrial hydrosphere, and have a strong influence on the regional hydrological cycle [1]. Due to the distinctive geographic location and climatic characteristics of the Tibetan Plateau (TP), the water level, surface area, and water storage of lakes across this region are extremely sensitive to climate change [2–4]. Rapid lake expansion has become one of the most significant environmental changes across the TP [5], motivating the need for continuous monitoring of lake dynamics [4].

Recent advances in measurement technology (e.g., satellite observations) [4,6,7] and the development of a range of superior lake volume estimation methods (e.g., Ref. [8]) have improved our ability to understand spatiotemporal changes of lake dynamics in the TP with increasing accuracy and at a finer resolution. However, the majority of these studies have not assessed the combined effects of meteorology and hydrology at the lake-basin scale. As inland lakes are often considered to be basin-wide integrators of climatic and hydrological conditions [9], investigating hydrological processes in the TP lake basins is critical for understanding the response of lake dynamics to current climate change.

In recent decades, glacial retreat, snowmelt, and frozen soil thawing caused by climate warming have resulted in complex hydrological regimes [10]. The combined contributions of snow cover and glacier meltwater (SGM) to annual streamflow have exceeded 50% in several large river basins of the TP during the last four decades [11]. Current understanding of how the lakes respond to climate change remains limited, since the hydrological processes occurring within the hydrosphere and cryosphere are tightly coupled. Previous studies using multi-source data and quantitative evaluations suggest that precipitation is the primary driver of changing lake dynamics across the TP [12–14]. Enhanced meltwater from snow and glaciers may be insufficient to fully explain the increase of lake volume across the whole TP, but the relative role of meltwater is likely to vary significantly between different lake basins [15]. Since the snowpack plays an important seasonal buffering role in high mountain Asia and the importance of meltwater to water supply in the TP [11], determining the impacts of climate change on the region's cryosphere is also essential to understand changing lake dynamics. However, due to poorly-developed methodologies and a lack of reliable satellite and observational data, quantitative estimates of the contributions from various factors have mainly focused on a small number of typical lakes (e.g., Refs. [13,14]) and are currently missing for the majority of lake basins across the TP.

The interior TP (ITP) contains more than 60% of the total lake water storage across the TP (Text S1.1 online). Owing to its large area and sparse observations, our knowledge of regional hydrology and the resulting lake water balance is very limited. To better understand the underlying drivers of lake dynamics, it is necessary to accurately estimate the closed-basin hydrology and the balance between four hydrological components (lake inflow, precipitation, evaporation and water storage changes). Of these, lake inflow comprises several key components (e.g., rainfall-runoff, SGM), which need to be separated with the aid of a hydrological model. Combining the new generation hydrological models with remote sensing products provides a unique opportunity to test model performance with respect to several hydrological-related properties, such as land surface temperature, snow depth, and lake water storage.

Here, we examine the water budgets of the ten largest endorheic lakes (with areas >500 km^2) in the ITP (Figs. 1a, S1 and S2, and Table S1 online), using long-term (1979–2016) hydrological simulations at the lake basin-scale. We apply a calibrated and verified distributed cryosphere-hydrology model (water and energy budget-based distributed hydrological model, WEB-DHM), coupled

* Corresponding authors.
E-mail addresses: zhoujing@itpcas.ac.cn (J. Zhou), wanglei@itpcas.ac.cn (L. Wang).

https://doi.org/10.1016/j.scib.2021.11.010

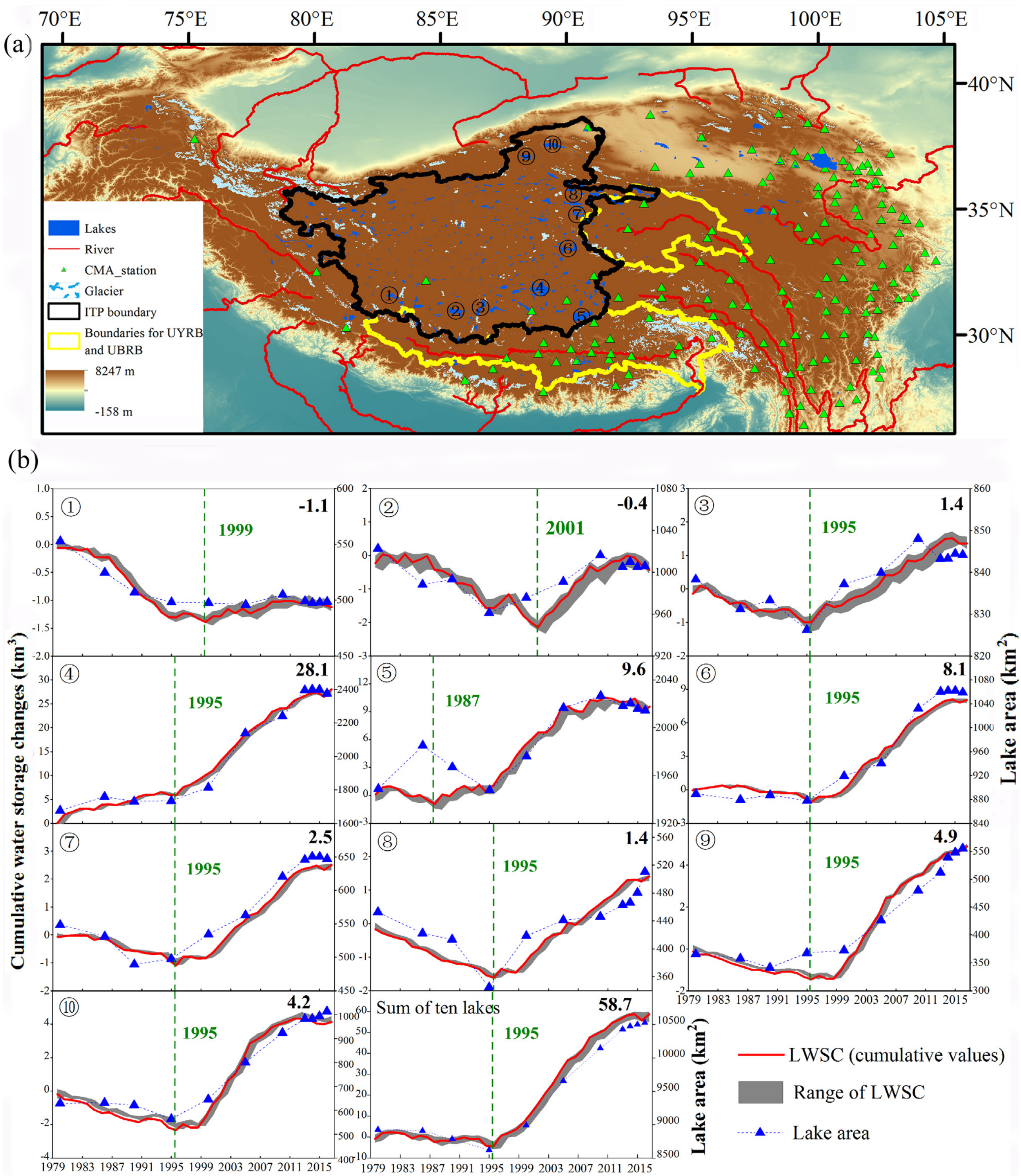


Fig. 1. Locations of the ten studied lakes across the interior Tibetan Plateau, and their simulation-based annual lake water storage change (LWSC) from 1979 to 2016. (a) The distribution of studied lakes in the ITP (individual lake basins can be seen in Fig. S1 online). ① Nganglaring, ② Zharinamco, ③ Tangra Yumco, ④ Seling Co, ⑤ Nam Co, ⑥ MC&DC, ⑦ Ulan Ula Lake, ⑧ Xijir Ulan Lake, ⑨ Aqikekule Lake, ⑩ Ayakeku Lake. MC&DC represents Dorsoidongco and Chibzhang Co, which are now considered to have merged into one lake following expansion. UYRB (upper Yangtze River basin) and UBRB (upper Brahmaputra River basin) are adjacent basins where the WEB-DHM-SF model has been successfully applied. (b) Time series of the simulation-based annual LWSC of the ten lakes. The shaded gray areas represent the range of LWSC estimates (the annual maximum and minimum values). The blue triangles show the changes in the lake area obtained from available datasets (from Ref. [6]) in the corresponding period. The green dashed lines and labelled years indicate the transition years of each lake (except Lake Seling Co). The numbers in the upper right corner are the cumulative LWSC values (km^3) of each lake in 2016. The inset labeled "sum of ten lakes" shows the total LWSC of the ten lakes.

with a three-layer snow module and frozen-ground physics scheme (WEB-DHM-SF) (Text S1.3.1 online). The contributions of various components (i.e., SGM, rainfall-runoff, lake surface precipitation, and lake evaporation (E_w)) to lake water storage change (LWSC) were individually quantified. Our study provides a quantitative assessment of lake volume changes and their driving mechanisms, yielding deeper insights into the role of internal hydrological processes and the changing cryosphere in shaping lake changes.

After model calibration and verification (Text S2, Table S2 and Figs. S3–S11 online), the major hydrological components for both the land-covered and water-covered areas were simulated and calculated, respectively (Text S3 and Figs. S12–S14 online). The LWSC of each lake was then calculated according to the water balance equation (Text S1.3.3 online) and verified with remote-sensing data derived from Ref. [7], demonstrating reliable results (Fig. S11 online). The simulation-based annual LWSCs of the ten lakes (cumulative values from 1979 to 2016) are shown in Fig. 1b. The transition years (turning points) of these LWSC changes were also identified. Transition years are defined as those years when the lakes reached their respective minimum cumulative LWSC during the study period, with the exception of Lake Seling Co (which showed continued growth throughout the study period). The minima of LWSC were followed by significant subsequent expansion. The LWSC of the majority of lakes increased from 1979 to 2016, with turning points mostly occurring in 1995. The exceptions to this trend were the two southern lakes (Nganglaring and Zharinamco), which showed slight declines in LWSC from 1979 to 2016. During the study period, the LWSC of most lakes remained stable or decreased slightly from 1979 to 1995, apart from Lake Nam Co (which decreased until 1987). These trends were followed by a rapid increase in LWSC of the majority of lakes from 1996 to 2010, and some lakes continued to increase until 2013. This period of rapid increase was followed by far slower rates of growth, or slight decreases, in LWSC during 2011–2016, with the exception of Lake Aqikekule that continued to grow rapidly. Changes in LWSC of Nganglaring contrasted with those of other lakes, and showed a decreasing trend from 1979 to 2016, with a total decline of 1.1 km^3 and the most rapid rates of decrease before 1999. The simulation-based LWSC changes found in the present study agree with the trends in datasets reported by Ref. [6] (represented by blue triangles in Fig. 1b), in which the total lake area on the TP decreased between the 1970s and ~1995, and then showed a rapid increase, with the exception of a slight decline in 2015.

The total water volume of the ten lakes increased by 58.70 km^3 from 1979–2016 (Fig. 1b). The largest increase was 28.1 km^3 for Lake Seling Co, followed by 9.6 km^3 for Lake Nam Co. The increased water volume of these two large lakes accounted for 64.2% of the total water volume increase of the ten lakes. Transition years represent a response to variations of major hydrological and meteorological components in their basins, as shown in Figs. S12–S14 and Text S3 (online). Precipitation (over both the land-covered and water-covered areas), rainfall-runoff and SGM in most basins showed increasing trends, especially after transition years (Fig. S12 online); most of these increases were significant (Tables S3 and S4 online). The changes of these components were consistent with the variations of LWSC. Trend change points were further detected by the Mann-Kendall (MK) test (Fig. S15 and Table S5 online), revealing change-points of precipitation and rainfall-runoff for the ten lake basins that were very close to the transition years of LWSC, while the change-points of SGM in most basins were later than the transition years of LWSC (Text S3.3 online). The combined effects of these components led to the transition of LWSC.

SGM accounted for 12.7%–33.6% of the total lake inflow in the ten basins during the study period. SGM increased significantly, especially after its change-points (Tables S3 and S5 online). The percentage of rainfall-runoff in the total lake inflow decreased throughout the study period, even when precipitation increased overall (Fig. S16 and Table S3 online). On the contrary, the intensified cryospheric melting (especially after change points) has gradually increased the percentage contribution of SGM in the total lake inflow for the majority of basins (Fig. S16 and Text S4.1 online). It can be inferred that LWSC was more closely related to precipitation changes, while increasing SGM promoted LWSC variations after transition years.

The contributions of major water balance components to LWSC from 1979 to 2016 were examined using multiple linear regression (Fig. 2). Lake inflow was separated into glacier melt, snowmelt and rainfall-runoff. Resulting differences in the sensitivity analysis (Text S4.2 and Fig. S17 online) were assumed to represent water released from thawing soil. Results showed that the contributions of E_w, snowmelt and glacier melt to LWSC changes ranged from −38.4% to −15.7%, 13.9% to 35.1%, and 5.7% to 18.8%, with the maximum contributions in Zharinamco, and MC&DC, respectively. The sum of SGM contributed 20.5% to 45.4% to LWSC changes in the ten lakes, while thawing soil contributed 2.1% to 6.7%. The contributions of rainfall-runoff were more than 60% in the ten lakes, and the maximum was in Ayakeku Lake (76.4%). Rainfall-runoff contributed relatively little in the three southern lakes (Nganglaring, Zharinamco and Tangra Yumco). Although the individual components made different contributions to LWSC in the different lakes, precipitation (i.e., the sum of rainfall-runoff and lake surface precipitation, including rainfall and snowfall over the lake surface) was the dominant factor, explaining 83.2% to 97% of the LWSC in the ten lakes.

It can be seen from Figs. 1b and 2 that E_w had a relatively large impact on the southern lakes (e.g., Nganglaring, Zharinamco and Tangra Yumco), and SGM had a relatively minor impact on the northern lakes (e.g., Ulan Ula Lake and Ayakeku Lake). The varying contributions of glacier melt may be related to differences in glacial coverage (Table S1 online) and runoff generation between the basins. The LWSC of lakes in the basins with a relatively high glacial coverage (MC&DC) received a larger contribution from glacial melt when compared to the less glaciated basins. The contributions of individual components to LWSC before and after the transition years are shown in Table S6 (online), highlighting that rainfall-runoff played a major role in both periods, while the contributions of SGM increased after transition years in most lakes. Overall, the differences in the contributions to LWSC from different components are caused by several factors, including the topographic and climatic (especially temperature and precipitation) characteristics, glacier distribution, and the geographical location of the basins. The first two of these factors directly affect runoff generation within the basins. Therefore, the contributions of different drivers to lake volume change depend mainly on the climatic and hydrological conditions within the corresponding lake basins.

To improve our understanding of the drivers of TP lake change, the LWSCs of the ten largest endorheic lakes in the ITP were examined using long-term water budget simulations with a verified distributed cryosphere-hydrology model. The majority of LWSCs remained stable or showed slight decreases from 1979 to 1995, then rapidly increased from 1996 to 2010, with turning points at around 1995 (Fig. 1b). LWSCs increased or decreased only slightly from 2011 to 2016. Precipitation contributed 83.2% to 97% of LWSC changes in the ten lakes, while the contributions of E_w and SGM were in the ranges −38.4% to −15.7% and 20.5% to 45.4%, respectively (Fig. 2). Sensitivity analysis showed that soil freeze–thaw processes strongly influence lake volume changes (Fig. S17 online), contributing 2.1% to 6.7% to the LWSC for the ten lakes. However, the scarcity of *in-situ* observations and the limitations of the current model version (Text S4.2 online) necessitate more in-depth studies on soil freeze–thaw contributions in the future. Overall, precipitation was still considered as the dominant factor. However, the contributions of precipitation, E_w (uncertainties of E_w estimations can be seen in Text S5.2 and Figs. S18 and S19 online) and SGM showed regional differences, demonstrating that lake volume changes depend on complex climatic and hydrological conditions

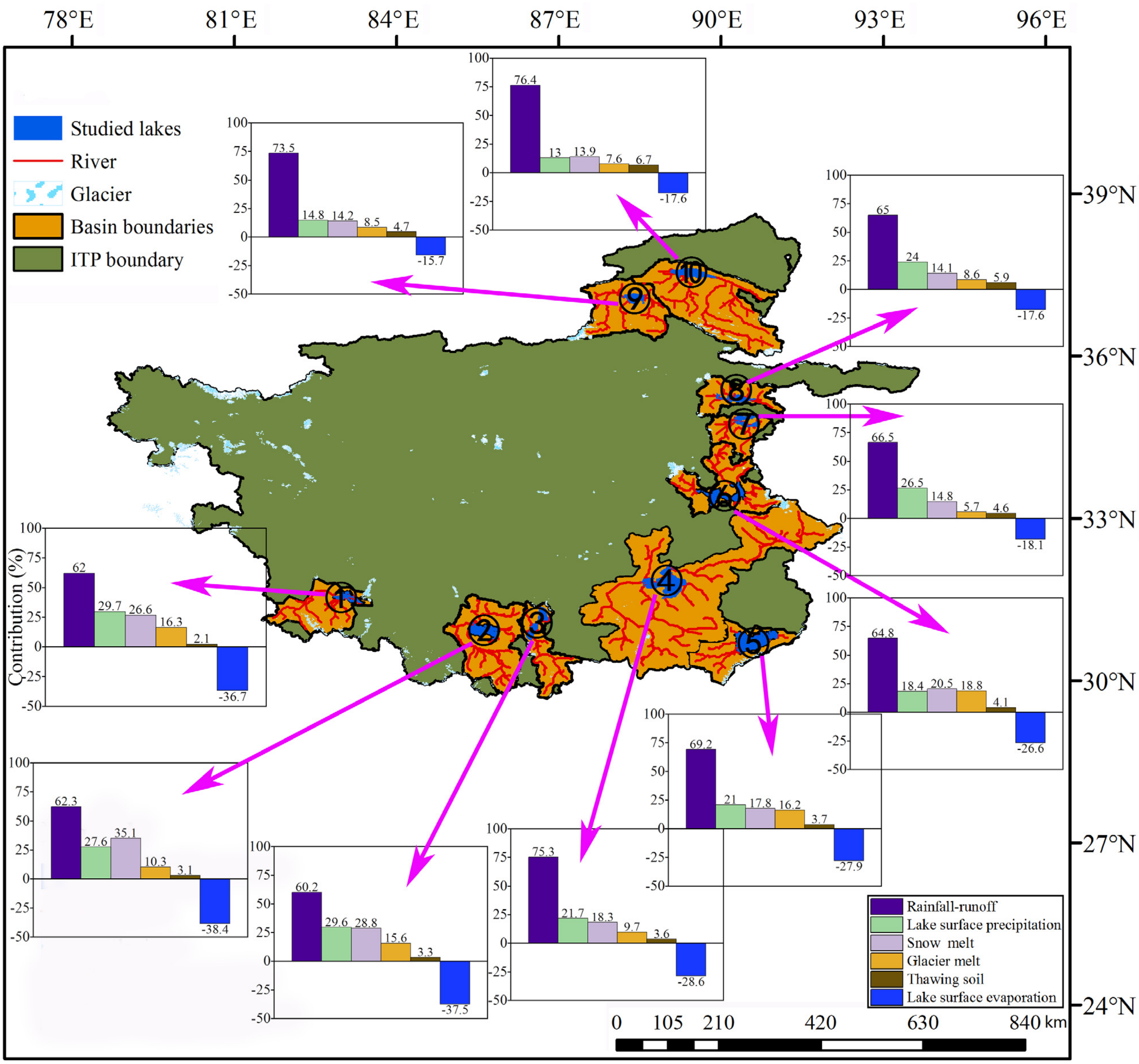


Fig. 2. The contributions of specific components to LWSC of the ten lakes across the interior Tibetan Plateau from 1979 to 2016.

within lake basins. Our numerical simulations enable accurate estimates of basin hydrology and LWSC variations under different climatic and hydrologic conditions, contributing to an improved understanding of the drivers of lake dynamics across the TP.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA19070301), the National Natural Science Foundation of China (41771089 and 41988101), and the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK020604). We thank Prof. Yinsheng Zhang and Dr. Guoshuai Zhang (Institute of Tibetan Plateau Research, Chinese Academy of Sciences), who provided the *in-situ* observed lake inflow data in the Lake Seling Co Basin and Lake Nam Co Basin, respectively.

Author contributions

Jing Zhou and Lei Wang designed the research and text organization. Jing Zhou wrote and revised the manuscript. Jing Zhou and Xiaoyang Zhong performed the research and analyzed data. Tandong Yao and Yongkang Xue provided suggestions. Jia Qi and Yuanwei Wang participated results discussion.

Appendix A. Supplementary materials

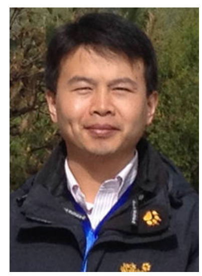
Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.11.010.

References

[1] Yang K, Wu H, Qin J, et al. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. Global Planet Change 2014;112:79–91.

[2] Lei Y, Yang K, Wang B, et al. Response of inland lake dynamics over the Tibetan Plateau to climate change. Clim Change 2014;125:281–90.
[3] Treichler D, Kääb A, Salzmann N, et al. Recent glacier and lake changes in High Mountain Asia and their relation to precipitation changes. Cryosphere 2019;13:2977–3005.
[4] Yao F, Wang J, Yang K, et al. Lake storage variation on the endorheic Tibetan Plateau and its attribution to climate change since the new millennium. Environ Res Lett 2018;13:064011.
[5] Zhu L, Wang J, Ju J, et al. Climatic and lake environmental changes in the Serling Co region of Tibet over a variety of timescales. Sci Bull 2019;64:422–4.
[6] Zhang G, Luo W, Chen W, et al. A robust but variable lake expansion on the Tibetan Plateau. Sci Bull 2019;64:1306–9.
[7] Li X, Long D, Huang Q, et al. High-temporal-resolution water level and storage change data sets for lakes on the Tibetan Plateau during 2000–2017 using multiple altimetric missions and Landsat-derived lake shoreline positions. Earth Syst Sci Data 2019;11:1603–27.
[8] Messager ML, Lehner B, Grill G, et al. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat Commun 2016;7:13603.
[9] Wang J, Song C, Reager JT, et al. Recent global decline in endorheic basin water storages. Nat Geosci 2018;11:926–32.
[10] Yao T, Xue Y, Chen D, et al. Recent Third Pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: multi-disciplinary approach with observation, modeling and analysis. Bull Am Meteorol Soc 2019;100:423–44.
[11] Kraaijenbrink PDA, Stigter EE, Yao T, et al. Climate change decisive for Asia's snow meltwater supply. Nat Clim Chang 2021;11:591–7.
[12] Song C, Huang B, Richards K, et al. Accelerated lake expansion on the Tibetan Plateau in the 2000s: induced by glacial melting or other processes? Water Resour Res 2014;50:3170–86.
[13] Zhou J, Wang L, Zhang Y, et al. Exploring the water storage changes in the largest lake (Selin Co) over the Tibetan Plateau during 2003–2012 from a basin-wide hydrological modeling. Water Resour Res 2015;51:8060–86.
[14] Biskop S, Maussion F, Krause P, et al. Differences in the water-balance components of four lakes in the southern-central Tibetan Plateau. Hydrol Earth Syst Sci 2016;20:209–25.
[15] Qiao B, Zhu L. Difference and cause analysis of water storage changes for glacier-fed and non-glacier-fed lakes on the Tibetan Plateau. Sci Total Environ 2019;693:133399.

Jing Zhou works as an assistant researcher at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. His current research focuses on understanding the cryosphere hydrological processes in the lake basins, in particular lake-basin interaction under climate change over the Tibetan Plateau.



Lei Wang is now a full professor at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (CAS), and the CAS Center for Excellence in Tibetan Plateau Earth Sciences, as well as the University of Chinese Academy of Sciences. His current research is focused on climate change and water cycle (in particular the cryosphere hydrological processes) over the Tibetan Plateau, for an improved predictability of regional water resources and water-related disasters (e.g., floods and droughts).