Widespread declines in water salinity of the endorheic Tibetan Plateau lakes

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Abstract
The Tibetan Plateau (TP) hosts more than one thousand lakes (>1 km²) in its endorheic basins. The changing climate in recent decades has led to significant modifications in the endorheic hydrologic system. Most TP lakes experienced dramatically expanding areas, rising water levels, and increasing storage, which inevitably influenced the lake salinity. This study provides a regional-scale investigation of water salinity changes of the TP lakes (for 83 lakes with two-epoch salinity records, among the approximately 160 lakes >50 km²) by synthesizing multi-source data around the 1970s and 2010s. Our results reveal lake salinity has considerably declined for most expanding lakes across the endorheic basins. The mean salinity of 62 terminal lakes dropped from 92.76 g l⁻¹ to 42.00 g l⁻¹ during the 1970s–2010s, in contrast to the slight variations (3.42 g l⁻¹ to 1.48 g l⁻¹) of the 21 exorheic or upstream lakes. As a result, many hypersaline lakes have become polysaline or oligosaline lakes, such as Cedo Caka, Norma Co, etc. In particular, some large lakes (e.g., Siling Co, ‘Twin Lakes’, and Ayakkum Lake) also experienced significant drops in water salinity, with the exceptional cases for Nam Co and Qinghai Lake probably due to the relatively low ratios of increased water mass to their net storages. The widespread declining water salinities could greatly influence bacterial richness, diversity, and evenness, and affect the aquatic carbon cycle and utilization in the high-altitude endorheic lakes. More attention should be paid on understanding the saline lake ecosystem evolution and the regional carbon cycle in response to changing water salinity of the TP lakes.

1. Introduction
The Tibetan Plateau (TP), the world’s highest plateau, is well known as the ‘Third Pole’ (Yao et al 2012) and ‘Asian Water Tower’ (Immerzeel et al 2010), as more than ten major rivers of Asia originate from its high mountains and influence the water storage and supply for more than one billion people in the downstream areas. In addition to the essential role in the freshwater pool and water cycle, it provides a range of other services, involving maintaining terrestrial species diversity, providing vital ecological resources for human livelihoods, and hosting important cultural and religious heritage. Located in the hinterland of the TP, the endorheic basins are dotted with more than one thousand lakes (>1 km²), which significantly modify the air–land heat and mass fluxes and affect the temperature and precipitation regime on regional scales (Dai et al 2018, Wu et al 2019, Su et al 2020).

During the past several decades, the TP has been experiencing dramatic climate change and was warming faster than low-lying areas owing to the elevation-dependent response (Kang et al 2010, You et al 2020). One notable characteristic lies in the significantly altered hydrologic system, including accelerated glacier mass loss, perturbed snowmelt dynamics, and shifting precipitation and evapotranspiration patterns, further leading to changes in the timing and magnitude of lake water availability (Zhu et al 2010, Yang et al 2011, Ma et al 2016,
Brunet al. 2017, Li and Lin 2017, Ye et al. 2017, Zhang and Ma 2018, Tang et al. 2019). Multi-mission remote sensing observations, including optical imagery, satellite altimetry and gravimetry, and topographic data, have witnessed how these lakes evolve over space and time (Sheng and Yao 2009, Liao et al. 2013, Song et al. 2013, Crétaux et al. 2016, Zhang et al. 2017). The different lines of evidence consistently indicate the expanding inundation area (Lei et al. 2014, Wan et al. 2016, Mao et al. 2018, Mi et al. 2019, Zhang et al. 2019), rising water level (Wang et al. 2013, Song et al. 2014, Jiang et al. 2020, Zhan et al. 2020, Luo et al. 2021), and increasing water mass and storage (Song et al. 2013, Wang et al. 2016, Yang et al. 2017, Zhang et al. 2017, Yao et al. 2018, Qiao et al. 2019, Treichler et al. 2019, Ke et al. 2022) for most Tibetan lakes since the 1990s. To understand the cause of lake water imbalance, many earlier efforts have been paid to clarify the contributions of different driving factors by combining the in situ measurements, satellite data, and hydrological modeling (Lei et al. 2014, Song et al. 2014, Zhou et al. 2015, Li et al. 2017, Zhang et al. 2017, Qiao et al. 2019, Brun et al. 2020).

The lakes on the TP, especially located in the terminal sinks, mostly store saline or salty water with a salinity gradient of 0.1–426.3 g l$^{-1}$ (Zheng 1997, Zheng et al. 2016), due to the progressive desiccation as a closed hydrologic system since the Holocene. Under the wetting and warming climate in recent years, the water chemistry of terminal lakes was inevitably influenced by the changed lake storage through the concentration or dilution of dissolved salts. However, so far, only a few pieces of scattered evidence suggest that the water salinity decreased with lake expansions on the TP (Yan and Zheng 2015, Liu et al. 2021a). The knowledge on how the TP lake salinities vary with water budgets over space and time remains largely unexplored at the plateau scale. This study aims to evaluate the lake salinity variations in response to hydrologic changes on the TP, by comparing the two-epoch lake salinity records, including the historically field-surveyed data from several of China’s key scientific expeditions before the 1980s and the recently sampled water parameters or literature-published records in the 2010s. Elucidation of the change pattern and magnitude of water salinity can provide an important reference for investigating the saline lake ecosystem evolution and potential influences on the regional carbon cycle in a high-altitude environment.

2. Study area

The Tibetan saline lake region lies between 28°N and 39°N in western China, extending from the Karakorum-Himalaya mountains in the west to a line connecting Qinghai Lake in the northeast and Yamzho Yumco in the southeast. It comprises the main body of the eastern salt lake belt of the Northern Hemispheric, also as the world’s highest salt lake region. As shown in figure 1, the annual precipitation across the lake basins ranges from 25 to 800 mm and falls mainly as rain, snow, and hailstorms (Beck et al. 2019). From southeast to northwest, the climate becomes progressively colder and drier, until reaching the Hol Xil where the winter temperatures can drop to $-40$ °C (Liu and Chen 2000, You et al. 2008). Due to the specific environment, including strong evaporation, high insolation, and sparse vegetation, these saline lakes have low concentrations of plankton, organic matter, dissolved oxygen, and suspended materials, but are rich in common saline minerals for industry.
agriculture, and medicine, such as gypsum, mirabilite, and trona. There are also some unique mineral resources such as rubidium, cesium, uranium, and thorium (Zheng 1997, Zheng and Liu 2009).

3. Study data and processing

This study examines the variations of water salinity between two epochs of the circa-1970s and the 2010s in response to the lake water budgets. The data of lake water salinity for the circa-1970s epoch were collected mainly from three literature sources ‘An introduction to saline Lakes on the Qinghai—Tibet plateau’ (Zheng 1997), ‘China Lakes Record’ (Wang et al 1998), and ‘China Salt Lakes Record’ (Zheng et al 2002). Zheng (1997) and Zheng et al (2002) carried out scientific investigations of these salt lakes during the 1960–80 s and collected 550 hydrochemical data from various salt lakes. On that basis, combined with the tectonic characteristics of the plateau, the hydrochemical characteristics of the salt lakes of the region were investigated (Zheng et al 1989, Zheng 1997). Wang et al (1998) document the key parameters and characteristics of all lakes (> 10 km²) in China from the morphologic, hydrological, climatological, and bio-chimerical dimensions and provide the water salinity records of a part of TP lakes surveyed in the period of 1970s–1980s. The lake salinity data for the 2010s epoch were derived from the meta-analyses of lake salinities (field surveys) recorded in published literature and field-sampled water parameter of Total Dissolved Solids (TDS) using the YSI multiparameter probe in summers of the years 2018 and 2019. The details on these literature-derived salinity data can be referenced in Supplementary Text 1. According to the classification standard of lake water salinity suggested by Wang et al (1998) and Zheng et al (2002), we categorized these TP lakes with different water salinities into four classes: freshwater (<1 g l⁻¹), oligosaline (1–35 g l⁻¹), polysaline (35–50 g l⁻¹), and hypersaline (>50 g l⁻¹) lakes.

The lake water storage variations were estimated using satellite stereo and multispectral images (Zhang G et al 2021a). The open-access data set provide the hypsometric curve and time series of water storage variations from 1976 to 2019 for each lake on the TP (https://data.tpdc.ac.cn/en/data/5e537e53-9532-4acd-9b17-65f4f3bb0ef7/). As the historical field-sampled water salinity records are mostly limited to the large and medium-sized lakes, we chose the lakes larger than 50 km² in this study and organized two-epoch (the years of circa-1976 and 2019) data of their water area, level, and storage variation to approximately indicate the lake hydrologic change characteristics on the TP during the 1970s–2010s.

To differentiate the salinity variations for terminal and upstream lakes, which behavior in different patterns of lake water area and storage changes during the past several decades, we further categorized these examined lakes as two types based on their hydrological connectivity. The classifications of different lake types (endorheic group versus exorheic/upstream group) were referenced to the method proposed by Liu et al (2020). In this classification method, the flow direction and hydrological structure features were extracted first for each target lake by the conventional D-8 algorithm; then the elevation profile for each pair of lakes in neighbor drainage watersheds was constructed to identify their potential connection and drain modes; finally the identified upstream and terminal lakes were double-checked by referring to the high-resolution Google Earth imagery and elevation information.

4. Results

4.1. Spatial pattern of water salinity of Asian water tower lakes

According to the remote sensing data set by Zhang et al (2021), the number of lakes larger than 1 km² has increased from ~1,000 in the 1970s to ~1,400 in 2019. In this study, we mainly focus on examining the salinity variations with water storage changes for an approximate number of 160 (in 2019, yet varying with different years) lakes larger than 50 km² on the TP. The salinity of lakes is a compound result of their hydrological characteristics and surrounding environment, which are significantly influenced by climate variability and lake water balances (Mianping et al 2000, Liu et al 2009, Zheng and Liu 2009, Liu et al 2010, Liu et al 2016). Based on the single-parameter classification of lake water salinities as measured in the 1970s, among the totally 117 lakes, there are 19 freshwater lakes (5731.13 km² and 20.5%), 46 oligosaline lakes (15396.84 km² and 54.9%), 10 polysaline lakes (1774.67 km² and 6.3%), and 42 hypersaline lakes (5133.33 km² and 18.3%).

The lakes with different classes of water salinity show contrasting spatial patterns, as shown in figure 2. Overall, freshwater or low-salinity lakes are mostly exorheic (Ngoring and Gyaring Lakes), upstream-type (Puma Yumco, Urru Tso, etc), or a few endorheic lakes (e.g., Nam Co, Yamzho Yumco, etc) that are located in the southern and eastern outflow-inflow transition basins with stronger monsoonical precipitation. For most lakes distributed in the endorheic basins (including the Changtang Plateau and Qaidam Basin), the lake salinities in the southern basins are lower than those in the north, while there is no spatial difference between the western and eastern lakes. The highest salinity can be observed in the lake groups in the Hol Xil and Qaidam Basin in the
north, and most lakes have salinities higher than 50 g l\(^{-1}\), or even exceeding 300 g l\(^{-1}\) for the salt lakes or playas in the Qaidam Basin. As shown in figure 1, the high water salinity could be attributable primarily to their low annual precipitation of 25–75 mm and the high annual aridity (evaporation/precipitation) ranging from 25 to 150 (Zheng and Liu 2009). In comparison, the central and southern Changtang endorheic lake districts, located at an elevation of over 4000 m, are characterized by a mixture of saline, brackish and fresh-water lakes. To differentiate the water salinity by lake type, the endorheic lake group shows much higher median (or mean) salinity values than the exorheic lake group, with a marked contrast of 44.77 g l\(^{-1}\) (102.25 g l\(^{-1}\)) versus 0.76 g l\(^{-1}\) (3.27 g l\(^{-1}\)).

4.2. Lake salinity changes with water storage variations
Many prior studies have reported extensive lake inundation area expansions and rapid water-level rises. The net area of our studied lakes (>50 km\(^2\)) was \(3.22 \times 10^4\) km\(^2\) as measured in the 1970s, which rapidly expanded upon \(3.85 \times 10^4\) km\(^2\), with an increase of 19.6% in the total area during the approximate four decades. In comparison, smaller lakes (~50–100 km\(^2\)) showed obviously higher expansion percentages (54.2% versus 13.0%) than larger lakes (>100 km\(^2\)), while the larger lake group contributed slightly more to the total area increase than the smaller ones (53.9% versus 46.1%). As shown in figure 5, the most rapid lake growths can be observed in the central and northern (around Hol Xil) plateau. By contrast, the lakes located in the periphery exorheic basins or upstream lakes of the terminal sinks kept relatively stable or in slight shrinkage, for example, Yamzho Yumco and Ngoring Lake. The spatial pattern of rates of lake level and storage change is generally consistent with that of area expansions, as shown in figure 1(a). The Siling Co (22.51 Gt) and ‘Twin Lakes’ (Dorsoidong Co/Chibzhang Co, 11.14 Gt) in south of the Tanggula Mountain and the Hoh Xil lake group (~50.00 Gt) located in the northern plateau, have the largest lake water mass gains, which together account for more than half of the regional net storage increase over the past four decades. However, the lakes with the most remarkable level-rising rates behavior in locally inconsistent patterns, which are found in several medium-sized basins (Salt Water Lake: 35.61 m, Yibug Caka: 20.30 m, and Xuejing Lake: 17.83 m) around the western and middle Kunlun Mountains. Another exception is Salt Lake, which had an abnormal rise of 16.27 m in water level due to the substantial upstream water supply from the Zhuonai Lake outburst (Liu et al 2016, Liu et al 2021b). Of the 160 lakes examined, 121 and 39 are endorheic and exorheic lakes, respectively (table S1 (available online at stacks.iop.org/ERC/4/091002/mmedia)). The endorheic lakes, accounting for 79.8% of the total lake area, were attributed to 95.8% of the total water gain.

As most of these saline lakes have been experiencing rapid inundation area expansion and water mass gain during the study period, the dilution effect could largely influence the water salinities. In this study, there are 83 lakes with salinity records in both the 1970s and 2010s. As illustrated in figure 4, the salinity changes between the two epochs were contrasted for the endorheic (62) and exorheic (21) lake groups, respectively. In the exorheic lake group, the water salinities for most lakes were low and only showed slight changes with the median (mean) value from 0.52 g l\(^{-1}\) (3.42 g l\(^{-1}\)) to 0.47 g l\(^{-1}\) (1.48 g l\(^{-1}\)). In contrast, for the 62 terminal lakes, the median

Figure 2. Map of the spatial pattern of lake water salinities on the Tibetan Plateau (measured around the 1970s).
Mean salinity had a substantial reduction from 39.02 g l$^{-1}$ (92.76 g l$^{-1}$) in the 1970s to 15.06 g l$^{-1}$ (42.00 g l$^{-1}$) in recent years.

The dilutional influences are particularly remarkable for the rapidly-developing terminal lakes. It can be revealed clearly in figure 5. For many lakes with obviously rising water levels (e.g., >5 m), their salinities measured in the 2010s were several times lower than those in the 1970s. The most notable decline in water salinity was observed in Salt Lake (see figure 6), which decreased from 221.38 g l$^{-1}$ to 16.10 g l$^{-1}$ during the past four decades. That was because this small and shallow lake experienced more than 16 m level rise and 4.5 times area expansion after the upstream lake outburst in 2011. Its salinity would get much lower as the Chinese government constructed an artificial channel in 2019 and made it become an outflow lake, being linked with the upstream Yangtze (Liu et al. 2021b, Lu et al. 2021). Other lakes that experienced obviously reduced salinity include Norma Co (43.40 g l$^{-1}$ to 4.91 g l$^{-1}$), Cedo Caka (168.39 g l$^{-1}$ to 19.50 g l$^{-1}$), Serbug Co (28.35 g l$^{-1}$ to 4.31 g l$^{-1}$), Dogaicoring Qangco (266.35 g l$^{-1}$ to 42.00 g l$^{-1}$), and Angdar Tso (180.87 g l$^{-1}$ to 32.50 g l$^{-1}$), etc. It
is worth mentioning that most large lakes similarly had considerable drops in water salinity, such as Siling Co (18.86 g l$^{-1}$ to 7.81 g l$^{-1}$), the 'Twin Lakes' (48.19 g l$^{-1}$ to 9.65 g l$^{-1}$), Ayakkum Lake (145.90 g l$^{-1}$ to 49.10 g l$^{-1}$), Zhari Namco (12.39 g l$^{-1}$ to 9.40 g l$^{-1}$), and Tangra Yumco (18.49 g l$^{-1}$ to 7.81 g l$^{-1}$). Nam Co (∼2017 km$^2$ around 2019) and Qinghai Lake (∼4427 km$^2$) stand as exceptional cases, which showed slightly declining salinities from 1.17 g l$^{-1}$ and 13.06 g l$^{-1}$ in the 1970s to 0.91 g l$^{-1}$ and 12.16 g l$^{-1}$ in the 2010s, respectively. That may be because the proportion of increased water mass to their net lake storage is too small to take the strong dilution effect.

In particular, near half of the examined lakes experienced reduced water salinity by more than 50%, and 26 lakes can be divided into different water salinity types due to the salinity changes (freshwater, oligosaline, polysaline, and hypersaline lakes). As shown in figure 6, Yamzho Yumco stands out as an exception, and its water salinity type became from freshwater to brackish water (0.21 g l$^{-1}$ converted to 1.32 g l$^{-1}$) as its water level and storage experienced lasting and rapid decreases over the past two decades. Among the other 25 lakes, 8 and 9 lakes changed from the ‘hypersaline’ type to the ‘oligosaline’ type and ‘polysaline’ type, respectively. Several large hypersaline lakes, such as Dorsoidong Co & Chibuzhang Co near the Geladandong and Purogangri ice caps, Aqqikkol Lake and Jingyu Lake in the central Kunlun Mountains, have become oligosaline lakes. For several medium-sized hypersaline lakes in the central Changtang Plateau (e.g., Norma Co, Cedo Caka, etc), the water salinity measured in recent years (the 2010s) was merely one-tenth of that in 1960/70 s.
5. Discussions

5.1. Environmental impacts of lake water salinity changes

As analyzed above, most endorheic lakes across the high-altitude basins showed widespread declines in water salinity due to the rapid accumulation of water mass in the context of warming and wetting climate. On the one hand, the strong dilution effect could induce adverse influences on mineral resource exploitation, as most of these saline lakes are mostly rich in precious minerals for industry, agriculture, and medicine. Salinity has widely been identified as one of the most important environmental factors influencing bacterioplankton communities in lakes. (Benlloch et al 2002, Wu et al 2006, Casamayor et al 2013). The TP lakes host abundant dissolved organic and inorganic carbon and other nutrition and sustain highly active microbial communities. The substantial declines in water salinity would inevitably alter the habitus environments of the high-altitude lake living beings.

Many prior studies have reported a variety of responses of the bacterial community at the moderate salinity interval, including the reduced diversity (Rodriguez-Valera et al 1985, Benlloch et al 2002, Rodriguez-Valera 2020), no effect (Herlemann et al 2011), or a peak at moderate salinity (Hewson and Fuhrman 2004, Wang et al 2011). The inconsistent influences might be associated with different geolocations and microorganism communities. For instance, the relative abundance of Betaproteobacteria and Gammaproteobacteria were reported to be negatively and positively correlated with water salinity, respectively (Benloch et al 2002, Wu et al 2006). For these plateau lakes, how the bacterial diversity responds to the water salinity gradients was also investigated widely in earlier studies. By scrutinizing the influences of different salinity gradients (ranging from freshwater to hypersaline water) on the lake bacterial community structure and composition, their associations mostly confirm that salinity is one of the dominant environmental factors of microbial community relative richness as well as relative abundance (Wang et al 2011, Liu et al 2013, Liu et al 2018, Ji et al 2019). However, the salinity influences do not behave in a linear process. For example, Wang et al (2011) suggest different evolutionary forces may act on bacterial populations in Tibetan freshwater and hypersaline lakes, thus leading to different diversity patterns and community structures. Ji et al (2019) also emphasized that the influence of salinity on bacterial diversity could be scale-dependent. Hence, whether and to what extent the widespread declining salinity may increase the bacterial richness, diversity and evenness require more large-scale field investigations in longer timescales.

In comparison, the influences of lake salinity changes on the aquatic carbon cycle and utilization could be more straightforward. As the hydrologically terminal lakes receive various materials (nutrients, organic matter, salts) that remain within the basin without exporting downstream, these saline lakes generally have high concentrations of dissolved inorganic and organic carbon and support the high activity of biological communities (Melack 1981, Anderson and Stedmon 2007). The microorganism constitutes an essential productive and extreme ecosystem of the TP lakes. The changing salinity could profoundly impact the bacterial community structure and diversity of microorganisms and further directly and/or indirectly alter the carbon transformation and carbon sink/source budgets in these saline and hypersaline lakes. For example, the

Figure 6. Distribution of totally 26 lakes with water salinity changes between different classes, including five conversion scenarios: one lake in ‘freshwater to oligosaline’, two lakes in ‘oligosaline to freshwater’, six lakes in ‘polysaline to oligosaline’, eight lakes in ‘hypersaline to oligosaline’, and nine lakes in ‘hypersaline to polysaline’ (The definition of salinity classes can be referred in section 2).
Gammaproteobacteria are widely and abundantly distributed in Tibetan lakes and play essential roles in the geochemical cycles of biogenic elements (e.g., C, N, and S) in the saline aquatic ecosystems. The salinity was considered as a critical environmental factor influencing Gammaproteobacterial carbon utilization based on the contrasting experiment across freshwater to hypersaline lakes of the plateau (Liu et al. 2018). Yang et al. (2020) further revealed that the lake salinity influenced the terrestrially derived dissolved organic matter (tDOM) transformation, which is characterized by a more vital ability to utilize tDOM of high for microbial communities from higher salinity lakes than those from lower salinity. Besides the carbon impact through microbial reactions, the salinity affects carbon cycling by influencing sedimentary processes (carbon burial) or atmospheric gaseous exchanges. For example, the 170-yr record of organic matter accumulation in Mono Lake confirmed a positive correlation between accumulation rates and estimated lake salinities (Jellison et al. 1996). Duarte et al. (2008) show that a large fraction of global saline lakes are highly reactive sites for air-water CO2 exchange and tend to be strongly supersaturated with CO2 in respect to the atmosphere. These studies strongly suggested that the considerable salinity changes might significantly affect the regional carbon cycle and carbon budget of inland aquatic ecosystems of lakes on the TP.

5.2. Uncertainties on determining lake water salinity
This study obtained the two-epoch water salinity records of Tibetan lakes from multiple sources. The 1970s-salinity data were excerpted from the two published books (Zheng et al. 1989, Zheng 1997, Wang et al. 1998), which measured lake salinities based on a field survey of water hydro-chemical variables during the 1960s–1980s. The field sampling records in different years of the two-decade time window probably induce some bias for representing the water salinity of one period. By referring to the remote sensing lake area data (Zhang G et al. 2021a), the TP lake areas kept relatively slight fluctuations from the 1960s to 1990, and the decadal areal variations were less than 5% during the period. As the in situ observational data for the TP lakes in that period were completely lacking for cross-evaluation besides the early-stage scientific investigations, we roughly consider these historical records as the initial lake salinity of the circa-1970s. The lake salinities at the 2010s epoch were determined by synthesizing diverse literature sources and the recent field sampling in 2018 and 2019. We excluded the probable ‘noisy’ data based on the following judging rules. Firstly, given that the lake has more than two independent records (≥3) of water salinities and some records have a bias relative to the median value larger than 10%, we kicked out the biases and calculated the average value of the remaining records as the final salinity. Secondly, if there are two independent records and their difference exceeds approximately 10%, we kept the higher priority of our sampled data in 2018/19, followed by the literature record with a detailed description of field sampling and data processing. Thirdly, if there is only one record for some lakes, we left the salinity data depending on whether the changing direction of lake salinities from the 1970s to the 2010s is consistent with that of lake area and storage variations or not. Although we collected the lake salinity data as much as possible and determined the final salinity value with strict quality control, the uncertainties cannot be eliminated entirely due to the different sampling locations and approaches and the inherently seasonal and interannual fluctuations of the lake water salinities.

5.3. Comparison of the TP lake salinity changes with other saline lakes
Lake water salinity is widely deemed as an essential indicator of lake hydrologic conditions and is critical to deciphering terrestrial climatic and environmental changes. In contrast to the widespread declines in water salinity of the high-altitude lakes due to the warming and wetting climate on the Tibetan Plateau, many saline lakes worldwide were shrinking at drastic rates and resulted in remarkable rises in water salinity (Williams 1996, Wurtsbaugh et al. 2017, Wang et al. 2018, Luo et al. 2022). Wurtsbaugh et al. (2017) described the shrinkages of the world’s large saline lakes and revealed considerable increases of lake salinities. The saline lakes in Central Asia stand out as the most conspicuous examples, e.g. Aral Sea, Caspian Sea, and Lake Urmia. The recent desiccation of Lake Urmia in the 2000s increased salinity above 350 g l⁻¹ and severely threatened the living habitats (brine shrimp, flamingos, birds, etc) (Wurtsbaugh et al. 2017, Chaudhari et al. 2018). Aladin et al. (2019) reviewed the substantial changes in hydrological and water salinity conditions (from 10.3‰ in the 1960s to >100‰ in the 2000s) in the Aral Sea since the 1950s, which have immensely affected communities of fish and aquatic invertebrates of the lake. The Great Salt Lake located in the United States was also facing the substantial increase in water salinity above levels tolerated by local species. In the arid and semi-arid regions of China (particularly in Inner Mongolia and Xinjiang), many lakes (e.g., Daibai Lake, Hulun Lake, Bosten Lake, etc) were suffering from the long-term or periodical desiccations and salty water environments in the past several decades, which led to the declining water quality and instable aquatic ecosystem (Rusuli et al. 2015, Wang et al. 2020, Zhang Y et al. 2021b, Jiang et al. 2022). As stated above, these saline lakes are mostly distributed in arid and semi-arid regions with closed surface hydrologic system. The water chemistry of closed lake basins are rather sensitive to the
alterations of hydrological budget, in response to the changing climate and intensified anthropogenic interventions.

6. Concluding remarks

The rapid growth of Tibetan lakes over the last several decades has received many concerns in recent years. The widespread and substantial lake water mass gain was a compounding result driven by increased precipitation, shifting evaporation, and more water supply from glacier melting and permafrost thawing, etc. The gaining water mass would significantly reduce lake salinities and probably cause a series of chain reactions of alpine lake aquatic environment, ecosystem, and mineral resource exploitation.

This study focuses on providing a regional picture of how and to what extent the water salinity responded to the lake hydrologic changes. Our investigation covers 82.50% (94.65%) and 51.88% (80.07%) of the TP lakes exceeding 50 km² in number (area) with water salinity records of one epoch and two contrasting epochs, respectively. The results reveal that most of these expanding lakes had declining water salinities across the endorheic basins. The mean salinity of the 62 terminal lakes examined in this study dropped from 92.76 g l⁻¹ in the 1970s to 42.00 g l⁻¹ in the 2010s, while the 21 exorheic or upstream lakes had relatively slight salinity variations (3.42 g l⁻¹ to 1.48 g l⁻¹). As a result, numerous hypersaline lakes with salinity higher than 50 g l⁻¹ or even >100 g l⁻¹ have become polysaline or oligosaline lakes, such as Cedo Caka, Norma Co, etc. The large lakes (e.g., Siling Co, the ‘Twin Lakes’, and Ayakkum Lake) also experienced significant drops in water salinity, with the exceptional cases for Nam Co and Qinghai Lake probably due to the relatively low ratios of increased water mass to their net storages.

The finding of this study is expected to promote our understanding of the potential evolutions of the high-altitude lake water environment and aquatic ecology caused by the regional hydrological unbalance on the TP. However, the consecutive long-term trajectory of water salinity variations and associated evolution of microbial communities remains largely unrecorded for most of the TP lakes. Given the importance of water resources as Asian water tower to human beings and ecosystems downstream, the establishment of the denser and persistent observational network for monitoring lake hydrological and environmental elements are expected to be launched with the support of the Second Tibetan Plateau Scientific Expedition and Research program and other key scientific research projects of China.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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