Drinking water safety improvement and future challenge of lakes and reservoirs

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Enhancing drinking water safety through improved water quantity and quality management

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Abstract: To meet the Sustainable Development Goal (SDG) target 6.1, China has undertaken significant initiatives to address the uneven distribution of water resources and to enhance water quality. Since 2000, China has invested heavily in water infrastructure of numerous reservoirs, with a total storage capacity increase of 4.704×10^{11} m^3 (increase of 90.8%). These reservoirs have significantly enhanced the available freshwater resources for drinking water. Concurrently, efforts to improve water quality in lakes and reservoirs, facilitated by nationwide water quality monitoring, have been successful. As a result, an increasing number of lakes and reservoirs are designated as centralized drinking water sources (CDWSs) in China. Among the 3,441 CDWSs across all provinces, 40.8% are sourced from lakes and reservoirs, 32.6% from rivers, and 26.6% from groundwater in 2023. Notably, from 2016 to 2023, the percentage of lakes and reservoirs categorized as CDWSs has increased consistently across all 29 provinces, benefitting a growing urban population. This progress has enabled 561.4 million urban residents to access improved drinking water sources in 2022, compared to 303.4 million in 2004. Our findings underscore the pivotal role of water infrastructure construction and water quality improvement jointly promoting lakes and reservoirs as vital drinking water sources. Nevertheless, the nationwide occurrence of algal blooms has surged by 113.7% from the 2000s to the 2010s producing a considerable challenge to drinking water safety. Fortunately, algal blooms have been markedly alleviated during in past four years. However, it is still crucial to acknowledge that lakes and reservoirs face the challenges of harmful algal blooms, and associated toxic microcystin and odor compounds.

Key words: drinking water, lake and reservoir, harmful algal blooms, water quality, water clarity

1. Introduction

Lakes and reservoirs represent fundamental features within the Earth System, acting as important repositories of surface water. Across the globe, natural lakes encompass approximately 4.2×10^6 km^2 of the Earth's surface [1]. In addition, as demands for agricultural irrigation, domestic use, and hydroelectric power generation increase, the area of reservoirs has increased rapidly and is projected to grow by approximately 1–2% annually [1, 2]. While the surface area of lakes and reservoirs remains relatively limited, their significance in promoting the economic and social development of the surrounding regions cannot be overstated [3-6]. Unfortunately, the importance and value of the ecological services that lakes and reservoirs provide have often been underestimated [7]. In reality, lakes and reservoirs fulfil a multitude of ecological functions, including the provision of safe drinking water, regulation and storage of water resources, flood control and drought mitigation, support for national economic development and food security, preservation of biodiversity, utilization of fishery resources, and the promotion of tourism [3-7]. Concurrently, lakes and reservoirs are sensitive to global environmental change and human activities within their basins. Consequently, they serve as invaluable sentinels and regulators of global environmental change and regional climatic variations [2, 8, 9].

Renowned for their pivotal ecological roles, lakes and reservoirs often stand as vital sources of drinking water, as they contain nearly 90% of the world's accessible liquid surface freshwater resources [10]. For example, the Great Lakes collectively serve as the largest and one of the most important providers of freshwater ecosystem services and goods in North America. They play a critical role in providing drinking water to over 24 million people in the United States and Canada [11]. Similarly, Lake Biwa, the largest lake in Japan, supplies drinking water to 14 million people living in its vicinity [12]. Lake Mead, the largest reservoir in the USA, provides drinking water to approximately 40 million people [13]. Dangjiangkou Reservoir and Lake Qiandaohu (also named Xin'anjiang Reservoir) in China provide drinking water for more than 70 million people [14]. However, surface water bodies have experienced a concerning deterioration in terms of water quality in recent years, particularly due to the increased frequency of algal blooms [15-18]. This trend has been primarily attributed to intense human activities and increasing extreme meteorological events, which have led to an increased risk of a potential health impact of drinking water [15, 16, 19-21]. Therefore, the contributions of lakes and reservoirs to drinking water safety are very important and the challenge is very severe but need to be better understood.

China is considered as a severe "water-deficit country" due primarily to emerging water demands, an uneven distribution of water resources and extensive water pollution. Despite being home to 19.0% of the world's population, China possesses only 7.0% of the planet's total freshwater resources [22-24]. To put this into perspective, it is estimated that ~0.257×10^6 km^2 of surface water area supports ~330 million people in the USA [25]. In contrast, ~0.155×10^6 km^2 of surface water area supports over 1.4 billion people in China [22]. Lakes and reservoirs assume a pivotal role as centralized drinking water sources (CDWRs) for urban residents of China. They oftentimes provide a more dependable and stable drinking water supply than rivers and groundwater due to higher standard-reaching rate, fewer water pollution accidents, and lower vulnerability [14]. However, over the past four decades, China's lakes and reservoirs have been subjected to intense human activity and eutrophication, leading to a decline in water quality, ecosystem degradation, and the loss of crucial ecological services. These challenges pose significant threats to water availability, sustainable development, and human well-being. One of the landmark incidents illustrating these challenges was the Wuxi drinking crisis, where the water source from Lake Taihu was contaminated by harmful cyanobacteria blooms. This event resulted in a week-long disruption of the drinking water supply for two million people in Wuxi, Jiangsu Province [17, 26]. Consequently, extensive efforts have been dedicated to the control, restoration, and preservation of aquatic environments and ecosystems. Encouragingly, substantial progresses have been made in safeguarding the aquatic ecological environment and advancing the vision of a more environmentally sustainable China [27-29]. However, a fundamental obstacle in addressing these challenges lies in the limited accessibility, usability, and sharing of water data, including water quantity, quality, and drinking water resources [30]. To fill this gap, we here present a comprehensive mapping, dynamics and quantification of lakes and reservoirs, water quality, and contribution to drinking water safety.

We hypothesise that the construction of water infrastructure, coupled with the concurrent improvement in water quality of lakes and reservoirs, through substantial efforts spanning the past 20 years, will play a pivotal role in driving a significant increase in the utilization of lakes and reservoirs as urban CDWRs [7, 31]. To achieve this objective, this study comprehensively investigates the dynamics and spatial distribution of lakes and reservoirs, shedding light on the ever-changing landscape. Furthermore, we delve into the dynamics and trends shaping the lake environment over the past 20 years, employing a combination of satellite remote sensing inversion and long-term positioning observation. Concurrently, we compile essential baseline information concerning the state of CDWSs in China. Through this comprehensive analysis, we aim to underscore the growing significance and pivotal role of lakes and reservoirs as primary sources of drinking water.

2. Data and methods

2.1 Spatial distribution of lakes and reservoirs

The number, surface area and distribution of lakes and reservoirs ($\geq$1.0 km^2) were extracted from the historical water inundation extent based on Global Surface Water (GSW) and Global Land Analysis and Discovery (GLAD), which were derived from multi-decadal Landsat images, with a supplement from one land cover product based on Sentinel-2 imagery [32-34]. GSW is a remote sensing big data computing platform using Google Earth Engine (GEE). Based on all available Landsat 5, 6, 7, and 8 data acquired from 1984, Pekel et al. [34] used the expert classification system to divide each available pixel into water bodies and non-water bodies and integrated the results into monthly, annual, and decadal timescales. The maximum water boundary, water inundation frequency, water change intensity, water transition, water recurrence, seasonal water, monthly water range, monthly water recurrence, and annual water range were provided. Similarly, GLAD is the global water body map from 1999 to 2019 obtained using GEE based on Landsat 5, 7, and 8 images [33], which employed an independent mapping algorithm and showed superiority in delineating the boundary of small-sized water bodies such as narrow channelled reservoirs. Therefore, we merged the water occurrence layers of the GSW and GLAD datasets to obtain the maximum water area of all lakes and reservoirs with historically inundated area $\geq$ 1 km^2, as the base mask for water quality analyses. The derived water bodies were inspected and edited with rigorous quality-control procedures by referring to the Sentinel-based land cover product and high-resolution Google imagery. The classification of lakes and reservoirs was conducted on the basis of the China Reservoir Dataset [35]. The number, type and storage capacity of reservoirs since 1981 were obtained from the National Bureau of Statistics of China (http://www.stats.gov.cn/english/).

2.2 Secchi disk depth derived from remote sensing

SDD serves as a straightforward yet highly significant metric for assessing the water quality and trophic state of lakes and reservoirs, having been widely used for more than 150 years since 1865. This crucial optical parameter, SDD, can be readily and accurately determined using various satellite imagery sources, encompassing specific sites, regions, or even global water bodies. In this study, we used Landsat data to estimate the long-term dynamics of SDD for China's lakes and reservoirs with a surface area ≥ 1 km^2. Considering the long-term consistent water area of lakes and reservoirs, we used a well-established SDD remote sensing model that has undergone extensive calibration and validation. This model enabled us to estimate SDD for 6,359 lakes and reservoirs from 2000 to 2021 [36], excluding reservoirs constructed after 2000.

2.3 Water quality of lakes and reservoirs

To assess the water quality dynamics of China's lakes and reservoirs, we conducted extensive monthly observations over an extended period. These observations encompassed key parameters such as BOD, TN, NH_4^+-N, and TP in a total of 95 lakes and 261 reservoirs (Fig. S1 online). This comprehensive dataset from 2005 to 2022 was collected by the Chinese National Environmental Monitoring Centre (http://www.cnemc.cn/). The BOD, TN, NH_4^+-N, and TP concentrations were analyzed in the laboratory using the standard water and wastewater monitoring and analysis methods recommended by the Ministry of Environmental Protection of China [37], which did not change over the reported period. The long-term, continuous, and consistent monitoring data within this dataset holds widespread utility in characterizing, analysing, and evaluating the dynamics and long-term trends of the aquatic environment in both lakes and reservoirs [27, 28]. The average values are calculated from all lakes and reservoirs of every province for BOD, TN, NH_4^+-N, and TP.

Furthermore, we augmented our analysis by calculating the occurrence frequency of algal blooms (in %) using Landsat imagery for a total of 1,541 lakes in China from 1980 to 2021 [16]. The dataset of Hou et al., (2022) was divided and updated into four periods: 1980-1990s (1982-1999), 2000s (2000-2009), 2010s (2010-2019), and 2020s (2020-2021) to investigate long-term bloom occurrence changes. To validate our results of bloom occurrence from Landsat imagery, we also used an automated algal bloom detection algorithm for Moderate-Resolution Imaging Spectroradiometer (MODIS) daily images based on a normalized floating algal index (FAI) to estimate bloom occurrence in Lake Taihu and Lake Chaohu from 2003 to 2023 [38].

2.4 Data on centralized drinking water sources

Our data were largely sourced from publicly available bulletins and reports provided by the Chinese government ecological environment departments, ensuring reliability through stringent quality control measures. While it is worth noting that China's water data governance and sharing practices have historically lagged international standards [30], a significant improvement occurred in 2016. This positive change was brought about by the Ministry of Ecology and Environment's release of the "National Centralized Drinking Water Sources Water Quality Monitoring Information Disclosure Plan." Since then, CDWRs data in China has been accessible to the public for most provinces. However, before 2018, only prefecture-level CDWRs data was accessible to the public for most provinces. Subsequently, from 2018 onwards, both prefecture-level and county-level CDWRs data became available to the public for most provinces (Table S1 online). It's important to note that for Xinjiang Autonomous Region and Xizang Autonomous Region, the prefecture-level and county-level CDWRs data is currently not centrally accessible to the public. Instead, this information was gathered from the China National Environmental Monitoring Centre as well as other scattered reports. To facilitate meaningful comparisons between the percentage of CDWRs related to lakes, reservoirs, rivers, and groundwater in 2016 and 2023, we employed the available and comparable prefecture-level or prefecture-level/county-level CDWRs data. For calculating the percentage of CDWRs related to lakes, reservoirs, rivers, and groundwater in 2023 as a proportion of the total CDWRs, we utilized all available prefecture-level and county-level CDWRs data.

Monthly water intake amount data from 2016 to 2023 for the drinking water sources in Zhejiang Province were obtained from the Zhejiang Provincial Department of Ecology and Environment (http://sthjt.zj.gov.cn/col/col1251321/index.html). To quantify the contributions of three types of prefecture-level CDWSs to the drinking water supply in Shanxi Province, monthly water intake data for 2016-2023 were obtained from the Shanxi Provincial Department of Ecological Environment (https://sthjt.shanxi.gov.cn/). To compare the difference of monthly water intake of three types of prefecture-level CDWSs in summer and winter in Heilongjiang Province, monthly water intake data from 2023 to 2024 were obtained from the Heilongjiang Provincial Department of Ecological Environment (https://sthj.hlj.gov.cn/sthj/).

2.5 Other related data

We gathered comprehensive data spanning from 1997 to 2022 on nationwide water supply, encompassing surface water, groundwater, sewage treatment reuse, and rainwater collection. Additionally, we compiled data on water usage, including domestic, industrial, agricultural, and ecological applications. Furthermore, our study incorporated data pertaining to the nationwide water-consuming population and water supply capacity for urban residents. These valuable datasets were sourced from the National Bureau of Statistics (http://www.stats.gov.cn/sj/). The population data was obtained from the website (https://www.hongheiku.com/china/221.html).

2.6 Statistical analyses

All statistical analysis was performed using Statistical Package for the Social Sciences software (SPSS 20, Chicago, IL). A significance level of $p \leq 0.05$ was considered statistically significant in this study. Long-term trends of SDD, BOD, TN, NH_4^+-N, and TP were performed using a linear regression analysis. Additionally, for cases where data did not conform to a normal distribution, we opted for the non-parametric Mann–Whitney (MW) statistic test. This choice is advantageous because it is not sensitive to the distribution type of the sample data. The MW statistic test was utilized to assess the significance of any shifts in mean values within our dataset.

3. Results

3.1 Increasing available freshwater resources by reservoir infrastructure

Until 2020, it is estimated that there were 2,670 natural lakes and 5,156 reservoirs with a surface area ≥ 1 km^2 in China (Fig. 1). The total surface area of lakes and reservoirs are 80,662.4 and 39,697.1 km^2, respectively. For natural lakes, more than 60% are characterised as saline or brackish, rendering them unsuitable for drinking water purposes. These types of lakes are primarily found in the Tibetan Plateau and Nei Mongol-Xinjiang Plateau regions (Fig. 1) [39]. Consequently, given the increasing demand for agricultural irrigation, drinking water supply, and hydroelectric power generation due to population growth, China has embarked on a strategy of constructing new reservoirs and expanding the storage capacity of existing ones. Over the past 40 years, there has been a significant increase in both the number and storage capacity of reservoirs, especially those that are medium-sized or large (storage capacity $\geq 10^7$ m^3), which are capable of meeting drinking water requirements (Table S2 online). Notably, the period from 2011 to 2022 experienced a significant increase ($p \leq 0.001$) in the number and storage capacity of reservoirs, surpassing the rates observed in preceding decades (2001-2011, 1991-2001, 1981-1991). During 2011-2022, the number and storage capacity of large-sized reservoirs increased by 247 and 2,377 × 10^8 m^3, respectively. In contrast, the corresponding numbers for the previous decades were 134 and 1,675 × 10^8 (2001-2011), 66 and 527 × 10^8 (1991-2001), and 39 and 411 × 10^8 (1981-1991), respectively. In total, there has been an increase in storage capacity of 4.704×10^{11} m^3 (90.8% increase) in reservoirs since 2000. Geographically, the distribution of reservoirs aligns closely with population distribution and the associated demand for drinking water (Fig. 1). Predominantly, reservoirs are concentrated in the southeastern region of the Hu Huanyong Line, which is home to more than 94% of the national population.

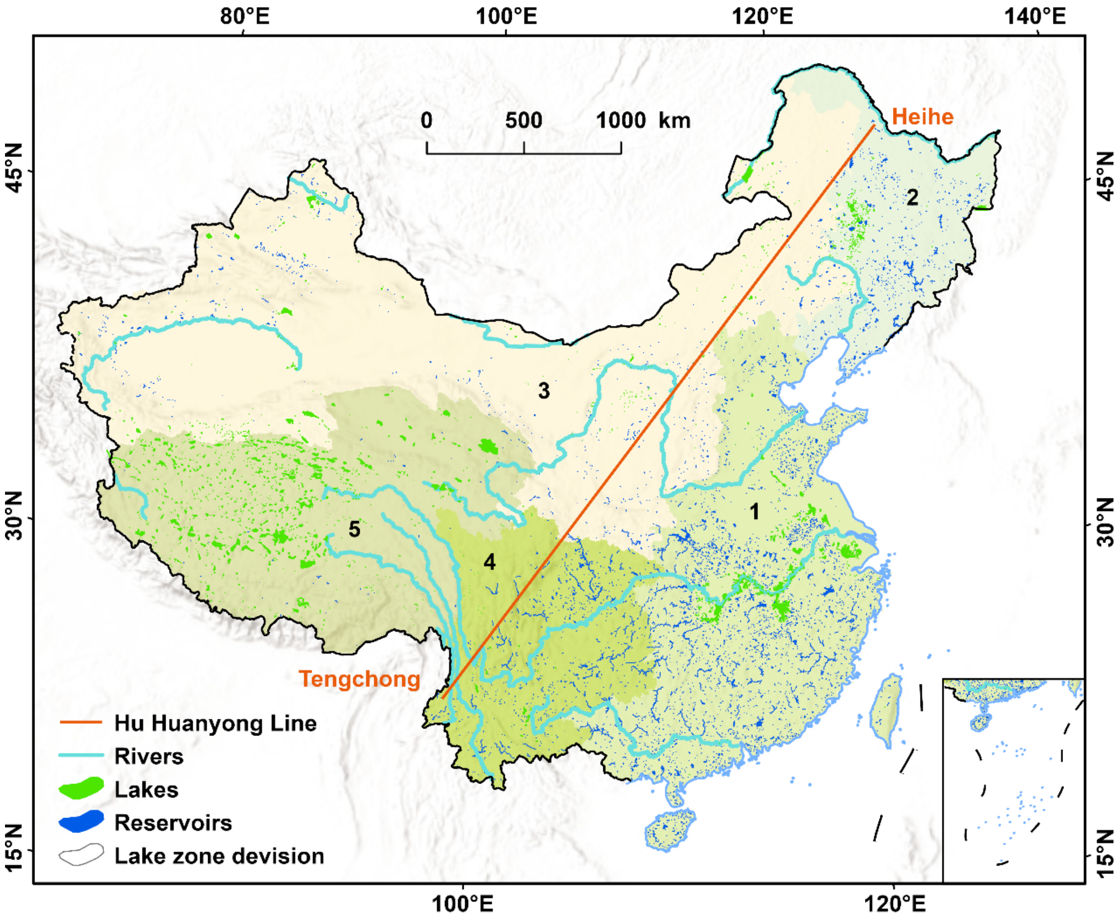

Fig. 1 Spatial distribution of lakes and reservoirs with a surface area of ≥ 1.0 km^2 in China. 1, the Eastern Plain Lake Zone (EPL); 2, the Northeast Plain and Mountain Lake Zone (NPML); 3, the

Nei Mongol-Xinjiang Lake Zone (NMXL); 4, the Yunnan-Guizhou Plateau Lake Zone (YGPL); 5, the Tibetan Plateau Lake Zone (TPL). The Hu Huanyong Line, connecting the city of Heihe (Heilongjiang Province) to Tengchong County (Yunnan Province), is an important divider of population, economic, social, and human activity intensity in China.

3.2 Increase in water clarity in lakes and reservoirs

We compared the spatial distribution and long-term trend of estimated Secchi disk depth (SDD) across the studied lakes and reservoirs between 2000 and 2020 (Fig. 2a, 2b). Our analysis illustrates that 69% of lakes and reservoirs exhibited an increase in SDD, at a rate of 0.49 m/decade. In contrast, 31% of these water bodies experienced a decrease in SDD, with a rate of 0.13 m/decade. Collectively, we calculated a statistically significant increase in mean SDD nationwide, from 0.91±0.66 m to 1.21±0.81 m, corresponding to a 33.0% increase from 2000 to 2020 ($p \le 0.01$). Notably, a total of 3,365 (53%) lakes and reservoirs underwent transitions in their SDD levels between these two years (Fig. 2c). Specifically, 2,596 lakes and reservoirs experienced transitions toward clearer conditions, while 769 lakes and reservoirs shifted toward more turbid conditions. The long-term change rates of SDD across Chinese lakes and reservoirs demonstrated diverse spatially patterns (Fig. 2d). Notably, lakes and reservoirs in the Eastern Plain Lake Zone, the Nei Mongol-Xinjiang Lake Zone, the Yunnan-Guizhou Plateau Lake Zone, the Tibetan Plateau Lake Zone demonstrated an increase in SDD. Conversely, lakes in the Nei Mongol-Xinjiang Lake Zone exhibited a decrease in SDD (Fig. 1, Fig. 2d, Fig. S2 online). Furthermore, an analysis of the long-term mean SDD for Chinese lakes and reservoirs revealed significant improvement in water clarity from 2000 to 2021 (Fig. 2e). A linear fitting model demonstrated a substantial increase of 0.12 m/decade for lakes and 0.11 m/decade for reservoirs over this period (Fig. 2e). Similar trends of SDD, except for the Nei

Mongol-Xinjiang Lake Zone, are found for other four lake zones, indicating a consistent improvement in water quality (Fig. S2 online).

3.3 Improvement of water quality in lakes and reservoirs

Water quality, described here in terms of biochemical oxygen demand (BOD), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP) in lakes and reservoirs throughout continental China changed markedly from 2005 to 2022. We found high spatial heterogeneity in the magnitude of change (in %) in water quality parameters during 2020-2022 compared with that in 2005-2007 for all 31 provinces (Fig. 3, Fig. S1, Fig. S3 online). Notably, we found marked decreases in BOD, TN, NH_4^+-N, and TP concentrations in eastern China, characterised by high population density, in 2020-2022 compared to 2005-2007 (Fig. 3). Conversely, in several western provinces, including Ningxia, Shaanxi, and Guangxi, we found a notable increase in TN during 2020-2022 when compared to 2005-2007 (Fig. 3).

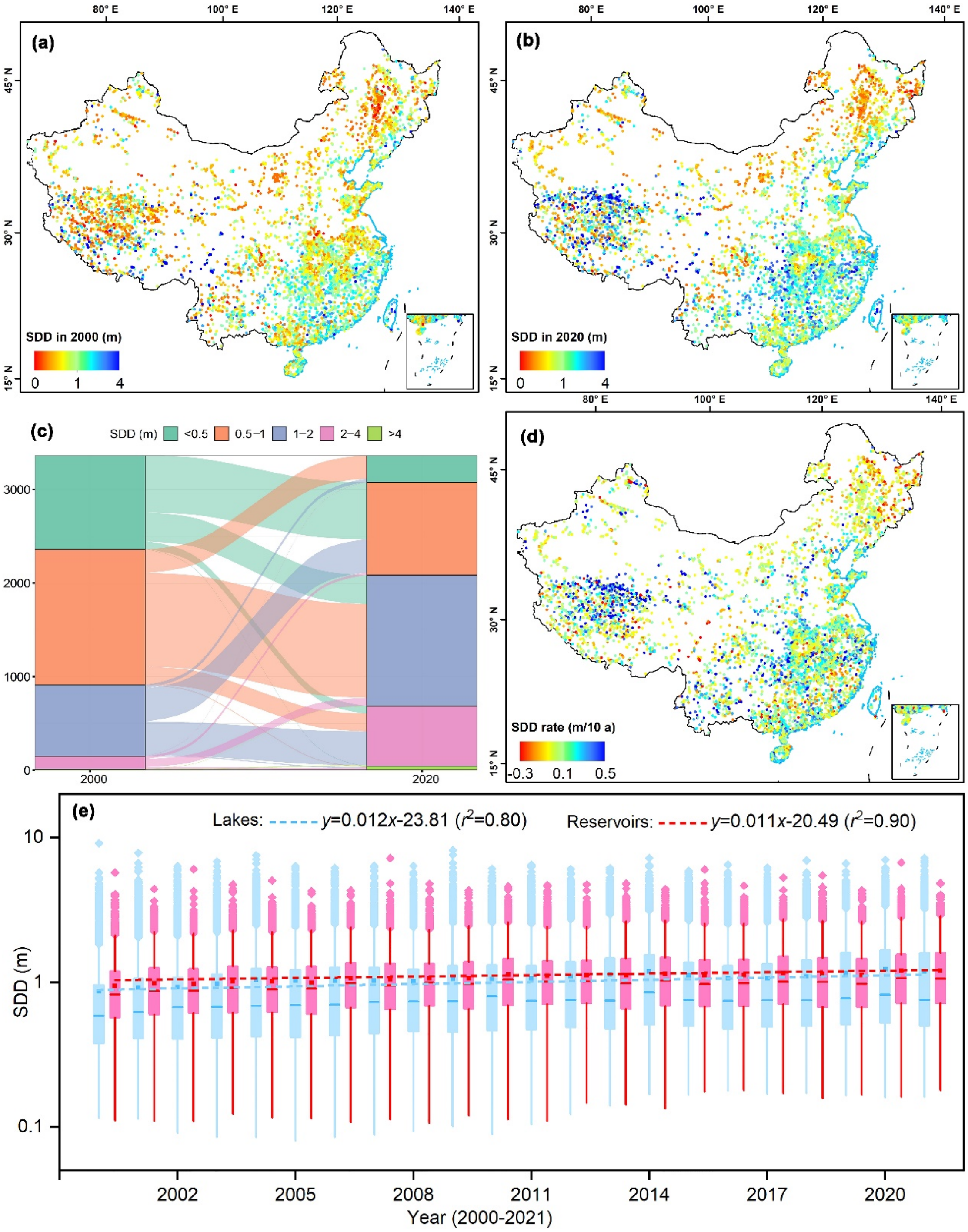

Fig. 2 Comparison of Secchi disk depth (SDD) spatial distribution in 2000 and 2020 (a, b), transitions in SDD levels between 2000 and 2020 (c), spatial distribution of long-term change rates of SDD (d) and long-term trend of SDD (e) from 2000 to 2021.

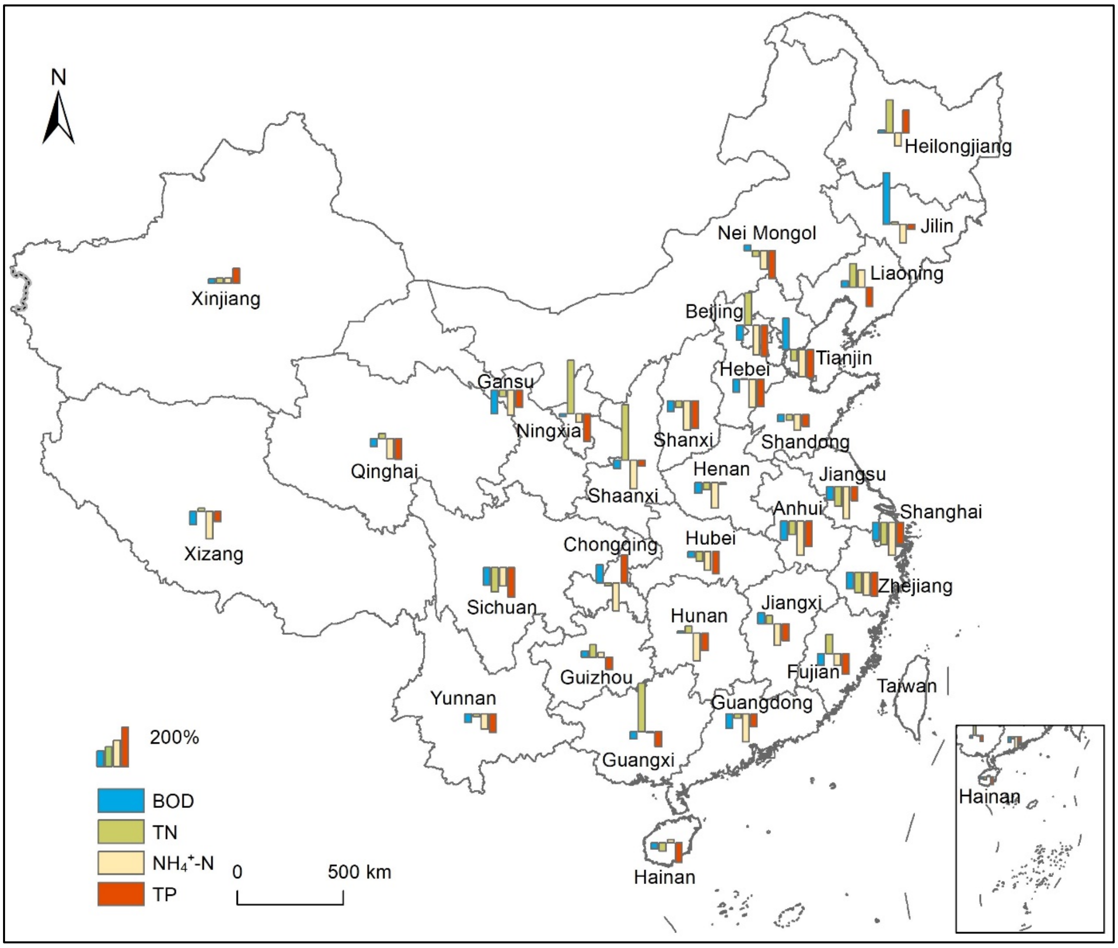

Fig. 3 The percent change of water quality parameters in 31 provinces in 2019-2022 compared to that in 2005-2007 (No data in Taiwan). The bottom color of the figure represents the altitude. BOD: biochemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonia nitrogen, TP: total phosphorus

Overall, we found that BOD, TN, NH_4^+-N, and TP concentrations significantly decreased across Chinese lakes and reservoirs during the same period (Fig. 4). From 2005 to 2022, mean BOD, TN, NH_4^+-N, and TP concentrations demonstrated a significant decline (Fig. 4), which decreased from 2.46 mg/L, 1.72 mg/L, 0.280 mg/L, and 0.072 mg/L during 2005-2007 to 1.77 mg/L, 1.32 mg/L, 0.107 mg/L, and 0.043 mg/L during 2020-2022, with the decrease ratios of 28.3%, 23.5%, 61.8%, and 40.4%, respectively. In addition, our analysis identified a significant decrease in TN and TP in three eutrophic lakes (Lake Taihu, Lake Chaohu, Lake Dianchi) with frequent algal blooms affecting drinking water safety (Fig. S4 online). TN concentration in Lake Taihu, TP concentration in Lake Chaohu and Lake Dianchi have decreased more than 50% from 2005 to 2022 (Fig. S4 online). Collectively, these findings underscore the substantial improvement in water quality across Chinese lakes and reservoirs, signifying significant progress in environmental stewardship and water resource management.

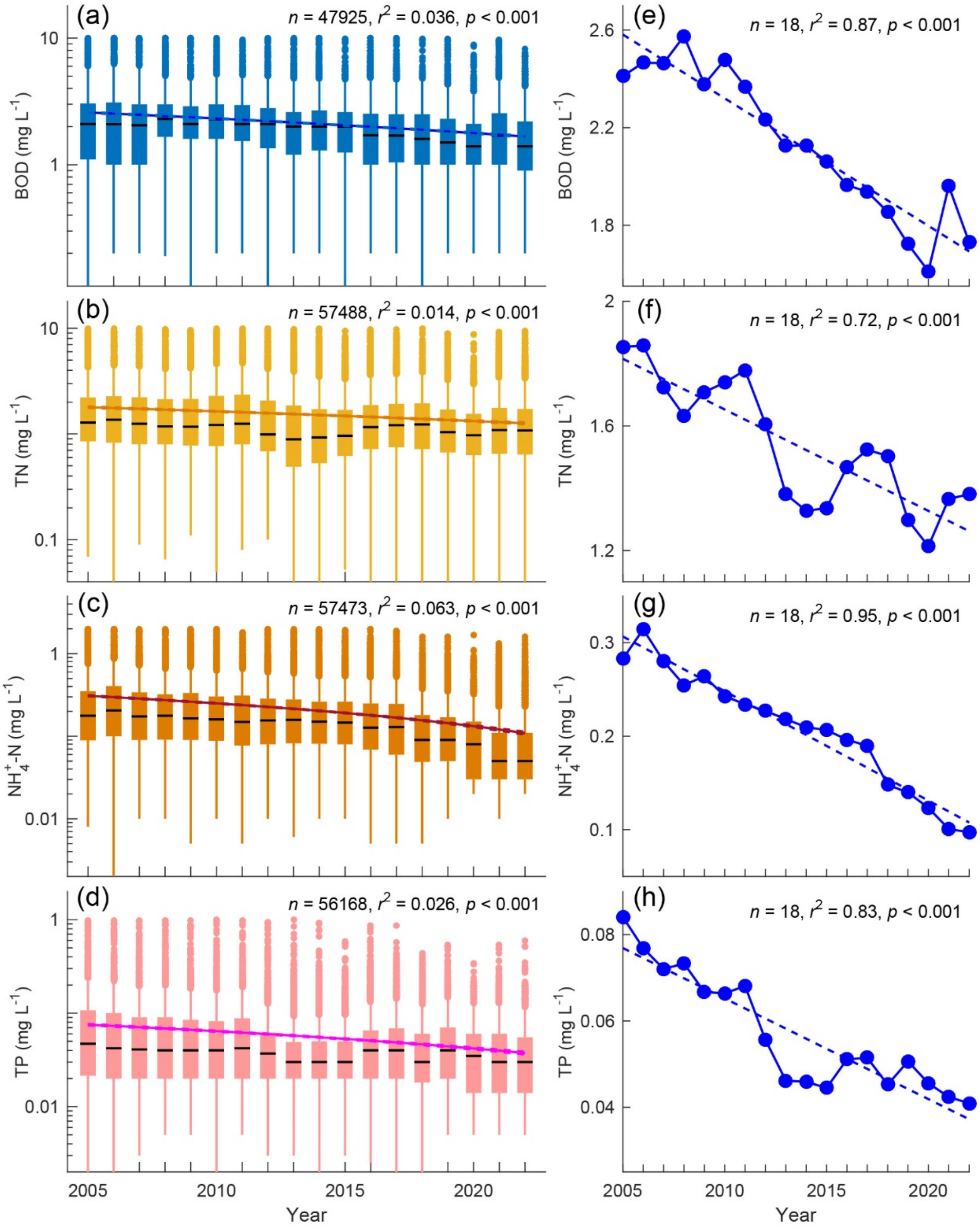

Fig. 4 Long-term variability in water quality for all data (left) and the yearly mean value (right) across continental lakes and reservoirs in China during the past two decades. The black solid line in the middle of each box plot shows the mean value. The solid line throughout each panel shows the linear fitting. BOD: biochemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonia nitrogen, TP: total phosphorus

3.4 Increase of lakes and reservoirs designated as drinking water sources

Among the 3,441 prefecture-level and county-level CDWSs monitored nationwide, 1,404 (40.8%) are lakes and reservoirs, 1,120 (32.6%) are rivers, and the remaining 917 (26.6%) are groundwater sources in 2023 (Table S1 online). Notably, the ratio of lakes and reservoirs may be underestimated, as many prefecture-level and county-level CDWSs do not include the cross-regional and cross-basin water transfer projects from reservoirs in Henan Province and Hebei Province. The total number of CDWSs in our study closely aligns with the numbers reported by the China Ecological Environment Status Bulletin 2022, issued by the Ministry of Ecology and Environment[40], which lists 919 prefecture-level and 2,622 county-level CDWSs monitoring sites. Spatially, the lowest and highest ratios of lakes and reservoirs CDWSs was found in Nei Mongol (11.1%) and Shanghai & Tianjin (100%), respectively. The high ratios of lakes and reservoirs CDWSs were generally observed in the moderately and highly populated southeast regions (Fig. S5 online). More importantly, the ratios of lakes and reservoirs CDWSs to all CDWSs of 29 provinces (excluding Xinjiang Autonomous Region and Xizang Autonomous Region due to no available CDWSs data in 2016) increased markedly in 2023 compared to those in 2016 (Fig. 5). On average, the ratio of lake and reservoir CDWSs to all CDWSs increased from 35.0% (607 *vs* 1734) in 2016 to 42.0% (906 *vs* 2156) in 2023 (Fig. 5, Table S1 online). In contrast, the ratio of groundwater

CDWSs to all CDWSs decreased from 20.5% (356 vs 1734) in 2016 to 18.9% (408 vs 2156) in 2023 (Table S1 online) due to poor groundwater quality, high arsenic geological background and overexploitation. Meanwhile, we compare the ratio of water intake amounts from lake and reservoir CDWSs to all CDWSs for Zhejiang Province with monthly water intake amounts data from 2016 to 2023. The yearly percentage of water intake amounts from lakes and reservoirs CDWSs markedly increased from 59.9% to 71.2% (Table S3 online). All these results underscore the increasing importance of lakes and reservoirs CDWSs in sustaining urban residents drinking water supply.

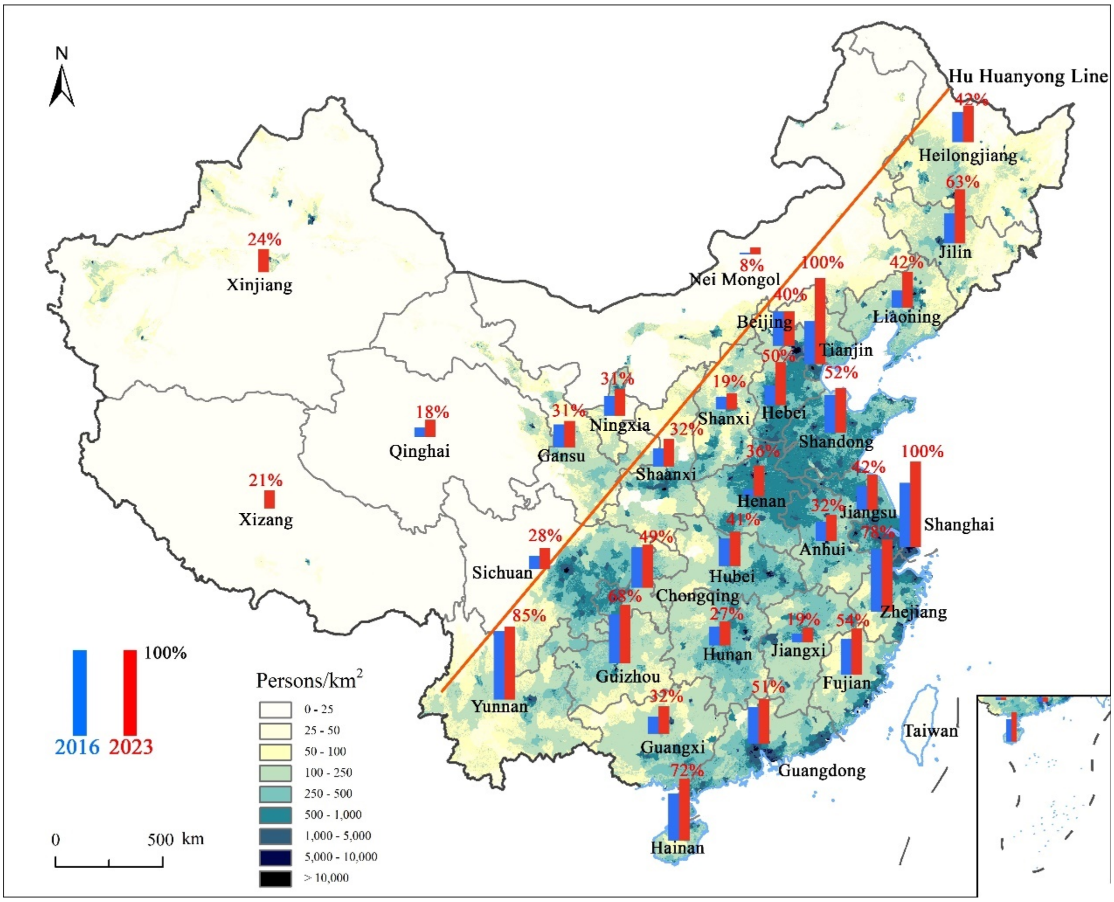

Fig. 5 Increasing ratio of lakes and reservoirs CDWSs accounting for the total CDWSs for every province from 2016 to 2023 (No data in Taiwan)

4. Discussion

4.1 A great challenge for drinking water supply

Ensuring adequate, safe, clean, and affordable drinking water for all is a critical objective within the United Nations' 17 Sustainable Development Goals (SDGs). These SDGs encompass ambitious global targets related to drinking water, sanitation, and hygiene. SDG6.1 especially emphasizes the goal to "achieve universal and equitable access to safe and affordable drinking water for all" by 2030 [41]. Meeting this goal poses a formidable challenge for China, given its immense population of 1.4 billion people coupled with issues related to water scarcity, uneven spatial-temporal distribution of water resources, and extensive water pollution [42]. Notably, the steady increase in population and urbanization over the past few decades has led to a significant increase in domestic water consumption in China (Fig. S6, Fig. S7 online). Domestic water use amount increased by 72.6% and the percentage of domestic water use amount to total water use amount increased by 9.5% to 15.1% from 1997 to 2022 (Fig. S7 online). Historically, decentralized water supply systems, where water was directly sourced from wells, lakes and rivers without proper protection and purification, were common. However, today, CDWSs are the prevailing drinking water supply forms in urban areas worldwide, including China. As a response, China initiated drinking water improvement projects starting in the 1980s. Both central and local governments have made substantial efforts to ensure an adequate water supply and enhanced drinking water quality for urban residents. Widespread adoption of CDWSs in urban areas, along with more standardized supervision and management, has been instrumental in ensuring urban drinking water quality. Moreover, an increasing number of prefecture-level and county-level CDWSs are being protected, and water quality information is regularly made publicly available (Table S1 online). Consequently, by 2022, 561.4 million people in urban areas had access to improved water sources (piped water, public standpipe, protected dug well, and so on). This represents an annual increase of 14.52 million people (Fig. S8 online). As previously reported, China played a pivotal role in achieving the Millennium Development Goals (MDGs) target on safe drinking water [41].

There is still a considerable part of rural areas in China that are either without centralized water source and supply facilities or the centralized water supply is not sufficiently purified. It is estimated that the national rural tap water penetration rate has reached 87% according to the Ministry of Water Resources (http://www.chinanews.com.cn/cj/2022/12-14/9914690.shtml), which means that almost 100 million rural residents still rely on self-supplied drinking water without access to safe and reliable drinking water services, despite substantial progress over several decades. Correspondingly, it is estimated that more than 760 million people relied on self-supply for their drinking water from 26 low- and middle-income countries in South Asia, Southeast Asia and the Pacific [43]. Globally, an estimated 2.1 billion people lack safely managed drinking water, this includes almost the entire population of rural Africa [44]. Even in high-income developed countries, poor drinking water quality and access remain barriers to improved health in many regional and remote communities [45, 46]. All these demonstrate that we have achieved tremendous success but also faced a great challenge for drinking water supply in China. Therefore, the construction of drinking water infrastructures including tap-water pipeline in rural areas and water quality improvement of drinking water source to purge rivers and lakes of industrial and agricultural pollutants are need to resolve the challenges and ensure drinking water safety.

4.2 Increasing importance of lake and reservoir CDWSs

Our findings reveal a growing trend in selecting and safeguarding lakes and reservoirs as the primary sources of drinking water for urban residents over the past decades. In the last 7 years with available CDWSs data, the ratio of lake and reservoir CDWSs to all CDWSs increased 7% (from

35.0% to 42.0%). This shift can be attributed to three main factors: increased water availability, improved water quality, and enhanced water supply reliability.

First, China has witnessed a substantial increase in water resource availability due to the construction of numerous reservoirs or the storage capacity expansion of existing ones, which is contrast to the widespread decline in global lake water storage of 1972 large water bodies [47]. These reservoirs, while originally designed for purposes such as electricity generation and agricultural irrigation, have significantly augmented the overall water resource capacity in the country (Fig. 1, Table S2 online). For example, Lake Qiandaohu (Xin'anjiang Reservoir) was initially designed to generate electricity for Shanghai and act as a contingency measure for Eastern China Power Grid emergencies in 1960s. Today, Lake Qiandaohu supplies annual 9.78×10^8 m^3 drinking water for more than 10 million people of Hangzhou and Jiaxing, Zhejiang Province. Most reservoirs are strategically located in mountainous and hilly areas in the middle and upper reaches of rivers, situated far from urban and industrial areas. These remote locations translate to minimal industrial, agricultural, and domestic pollution, resulting in good water quality. Consequently, these reservoirs can provide a clean and abundant water resource for drinking water as shown by the global increasing dependence of lowland populations on mountain water resources [48]. Meanwhile, many cross-regional and cross-basin water transfer projects and infrastructure construction are increasing the contribution and importance of lake and reservoir CDWSs [14, 49]. For example, the Middle Route Project of the South-to-North Water Diversion (SNWD), which transports water from the Danjiangkou Reservoir to Henan Province and Hebei Province, Tianjin and Beijing municipalities covering 24 cities, 131 counties, and 310 water plants, and benefiting 85 million people. Danjiangkou Reservoir was initially designed for electricity generation and agricultural irrigation, and water level was raised from 157 m to 170 m as water source of the Middle Route Project of SNWD in 2013. In 2022, a total of 92.12 × 10^8 m^3 of water was transported from Danjiangkou Reservoir to meet the demand for safe and clean drinking water with a rapid increase from 2015 (Fig. S9 online). Similarly, there are many other projects such as the East Route Project of SNWD in Jiangsu Province, Lake Qiandao Water Distribution Project in Zhejiang Province, Water Diversion Project from Lake Songhuahu in Jinlin Province etc (Table S4 online). All these water infrastructure constructions significantly increase the available freshwater resource of lakes and reservoirs for drinking water.

Correspondingly, yearly groundwater water supply reached a maximum of 1134×10^8 m^3 in 2012 and gradually decreased to 828×10^8 m^3 in 2022 with a decrease of 27.0% indicating a decreasing contribution (Fig. S7 online). Notably, we further chose the most populous province (Shanxi Province, which is also affected by arsenic-contaminated groundwater) from 6 north provinces with high groundwater CDWS percentages including Nei Mongol, Shanxi, Xizang, Qinghai, Xinjiang, and Ningxia provinces, to quantify the decreasing contribution of groundwater. From 2016 to 2023, the percentages of prefecture-level CDWSs number and annual total water intake amounts of groundwater CDWSs in Shanxi Province decreased markedly. The opposite trend is found for lake and reservoir CDWSs. In addition, a total of 76.2%-81.5% of the groundwater CDWS number corresponded to 58.4%-68.4% of the total water intake amount from groundwater during 2016-2023 (Table S5 online). In contrast, lakes and reservoirs accounted for 14.8%-19.0% of the CDWSs but 27.2%-37.5% of the total water intake amount in Shanxi Province (Table S5 online).

However, it is crucial to acknowledge that there are some negative ecological problems and risks associated with reservoir construction. Dams disrupt the natural flow of materials both upstream and downstream, causing the fragmentation of rivers. This fragmentation substantially hinders the migration of freshwater fishes, leading to the destruction of fish habitats and posing a grave threat to freshwater biodiversity [50, 51]. Simultaneously, reservoirs create an artificial environment that promotes the proliferation of algae, particularly cyanobacteria. The combination of nutrient retention, calm waters, low light attenuation, and a relatively long residence time contributes to an increase of these potentially harmful microorganisms [52, 53]. Therefore, many small-sized reservoirs have been gradually removed to increase river water system connectivity and eliminate negative ecological risks with decreasing small-sized reservoirs since 2018 (4.08% decrease from 2018 to 2022) in China (Table S2 online).

Secondly, water quality indicated by four key parameters (BOD, TN, NH_4^+, and TP) of lakes and reservoirs had been greatly improved over the past 20 years in China (Fig. 3, Fig. 4), which were attributed to the marked decrease of nitrogen and phosphorus consumption of cropland and significant increasing investment in urban environmental infrastructure construction and industrial pollution source control (Fig. S10, Fig. S11 online). Meanwhile, significant increase in water clarity from 2000 to 2021 based on remote sensing estimates suggest water quality improvement of lakes and reservoirs (Fig. 2). However, marked spatial differences were found for different water quality parameters reflecting different human activities and climate change pressures (Fig. 2, Fig. 3). Indeed, water quality of inland waters across China has exhibited marked improvement since 2003, owing to reductions in pollutant discharge [27, 29]. Many water management strategies and specific policies, including the most stringent water resources management system (known as the “Three Redlines”), the water pollution control action plan (known as the “Water Ten Plan”), national standards for surface water quality and sector-specific discharges of point source water pollutants, and large investments in urban environmental infrastructure and industrial wastewater treatment (Fig. S11 online), contributed to water quality improvements in China [28, 29], which will provide the guideline for other countries and regions facing similar challenges. China Ecological Environment Status Bulletin 2022 showed that 87.9% of sampling sites had water quality better than Class III according to the China Surface Water Environmental Quality Standard (GB3838-2002), while only 0.7% of sites had water quality worse than Class V based on a national investigation of 3,641 sampling sites in rivers, lakes, and reservoirs across China [40]. Due to the improvement of water quality in Lake Taihu, a yearly total 12.8×10^8 m^3 of water from the lake was used for the drinking water of Shanghai, the largest city in China, since 2017 with an additional yearly total 12.2×10^8 m^3 of water supplying the surrounding cities of Suzhou, Wuxi, and Huzhou (Fig. S9 online), which benefited more than 15 million people. These findings underscore the ongoing progress in improving water quality in lakes and reservoirs, a trend the we anticipate to continue with the implementation of Beautiful China Initiative, the major strategic idea and task for the sustainable development of China to fulfil the United Nations' SDGs. Specifically, by 2035, there will be a fundamental improvement in the quality of the environment so the goal of building a Beautiful China will be basically attained, which will undoubtedly increase the value of drinking water [7, 31].

Third, lakes and reservoirs can provide more stable water supply than rivers because lakes and reservoirs are less affected by salt intrusion, floods and droughts, as well as complete freeze events. China's coastal areas such as Tianjing, Qingdao, Xiameng, Shanghai, Hangzhou, Shenzhen etc, which are more populated and developed, are more vulnerable to the salt intrusion. Therefore, CDWSs turn to the lakes and reservoirs for freshwater resources supply instead of seagoing rivers. In the natural course of events, droughts or floods typically lead to alterations in catchment runoff, followed by changes in river flow and lake level. Consequently, river-based CDWSs are more vulnerable to the impacts of these extremes, especially considering the escalating frequency and severity of such events associated with climate warming [54]. In contrast, lakes and reservoirs offer the advantage of enabling a seasonal redistribution of water resources. This flexibility allows for the transfer of water from periods of abundance to periods of scarcity, effectively meeting the demand for drinking water during times of shortage [55].

There are many physical, ecological, and environmental issues associated with lakes and reservoir, which comprise them as suitable drinking water sources. We also note that many lakes in north and northwest China are not used for drinking water sources, which is mainly attributed to salinization due to evaporation and long water retention time. In comparison, the freezing level and flowing period in winter in north China only slightly affect the intake amount from lakes and reservoirs CDWSs (Table S6 online) due to incomplete freeze events in lakes and reservoirs. Therefore, groundwater is a good alternative under extreme freezing condition in north China.

4.3 Risk and uncertainty of lake and reservoir CDWSs

At present, harmful algal blooms (HABs) resulting in critical drinking water risk, due to intense human activities and climate warming, is a great challenge for lakes and reservoir CDWSs [15, 16, 20, 21, 56, 57], although water quality has been greatly improved over the past 20 years (Figs. 2-4). Satellite observations of the algal bloom occurrence changes for 1,541 lakes in China during four distinct periods (1980-90s, 2000s, 2010s, and 2020-2021) from 1982 to 2021 revealed that the nationwide mean bloom occurrence showed a lower increase of 40.3% (from 4.84% to 6.79%) from the 1980-90s to 2000s while experienced a significant increase of 113.7% (from 6.79% to 14.51%) from the 2000s to the 2010s (Fig. 6). Pronounced increases in bloom occurrence were detected in lakes across the entire country, with the exception of some lakes in northeastern China during the 2010s. Steady bloom occurrence increases were particularly notable in lakes distributed in eastern, southern, and southwestern regions of China with the extensive distribution of freshwater lake and reservoir CDWSs. Several drinking water sources including Lake Taihu, Jiefangshan Reservoir, Yuqiao Reservoir were ever polluted or closed due to the extensive outbreak of HABs [17, 58].

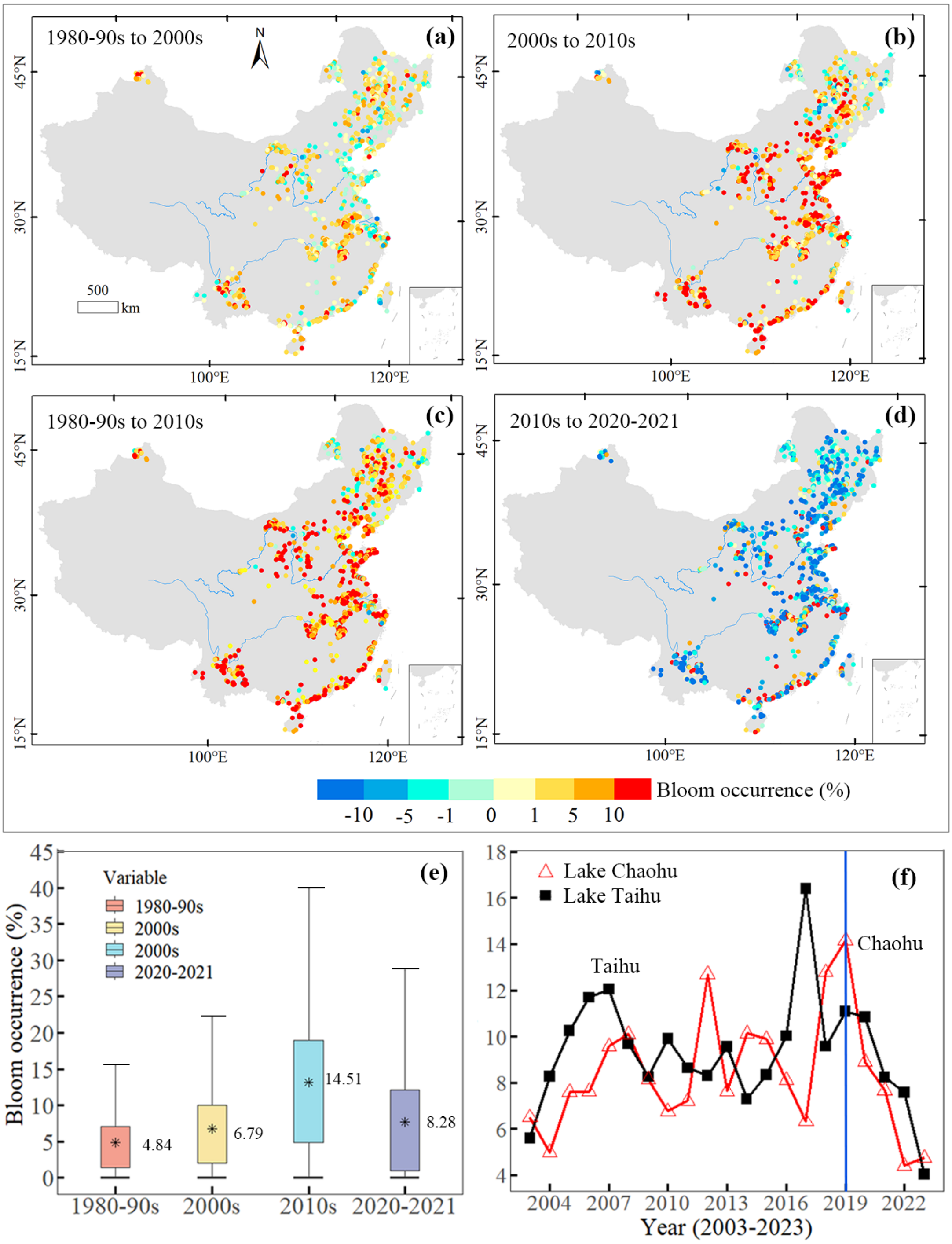

Fig. 6. Decadal changes of lake bloom occurrence in China. a-d, Maps illustrating multidecadal bloom occurrence changes in 1° × 1° grid cells for four periods (a)1980-90s to 2000s; (b) 2000s to 2010s; (c)1980-90s to 2010s; and (d) 2020s to 2020-2021. (e) Box plots of lake bloom occurrence in four periods. The box plots show the distribution (10, 25, 50, 75, and 90%) of lake bloom occurrence. The asterisk and number indicate a mean value of bloom occurrence. (f) Long-term

changes of annual bloom occurrence for Lake Taihu and Lake Chaohu plagued by frequent algal bloom in the past decades.

Compared to the 2010s, bloom occurrence exhibited a marked decrease of 42.9% (from 14.51% to 8.28%) during 2020-2021. We realize that the alleviation of algal bloom lags water quality improvement markedly (Figs. 2-4, Fig. 6). Indeed, the enhancement of water quality parameters such as TN and TP, as well as others, does not necessarily run counter to the occurrence of algal blooms, especially in the context of climate warming. Algal blooms can manifest even in waters characterized by very low concentrations of nitrogen and phosphorus [18, 59]. In summary, there are at least three mechanisms to explain the inconsistent changes between TN, TP improvement and algal bloom appearance.

First, as a typical ecological phenomena and disaster, the outbreak or alleviation of algal blooms often lag significantly behind the deterioration or improvement of water quality due to time-lag effects[60]. Meanwhile, TN and TP have not decreased below the critical thresholds ($TN \leq 0.8$ mg/L, $TP \leq 0.05$ mg/L) to limit phytoplankton growth (Fig. S4) [61]. Therefore, the alleviation of algal bloom by nutrient reduction is slow, resulting in high algal bloom outbreak in China's lakes and reservoirs during the 2010s. Encouragingly, the occurrence of algal blooms has markedly reduced and the negative effects of HABs on drinking water have been alleviated for all lakes especially two typical large eutrophic lakes (Lake Taihu and Lake Chaohu) during 2020-2023 (Fig. 6), which were ever affected by frequent HABs in past decades.

Second, the intensified or amplified HABs risk in lakes and reservoirs are largely attributed to climate warming and increasing climatic and hydrological extreme events (Fig. S12 online) [15, 57, 62, 63]. For example, the extensive or record-breaking HABs were observed in oligotrophic and mesotrophic Lake Qionghai (TN: 0.40 mg/L, TP: 0.021 mg/L in 2019) and Fuchunjiang Reservoir (TN: 1.94 mg/L, TP: 0.063 mg/L in 2021) in 2022 experiencing the unprecedented extreme heatwaves and drought (Fig. S13 online). Similarly, nuisance phytoplankton blooms were found in oligotrophic Lake Qiandaohu by high frequency observation and remote sensing monitoring in summer 2016 suffering from an extreme heatwave [62]. Meanwhile, storm and extreme precipitation played a more important role in HABs formation and expansion by increasing nutrients supply [64, 65]. Severe spring precipitation events in 2011, coupled with long-term increasing trends in agricultural land use and practices, produced a pulse of remarkably high loading of highly bioavailable dissolved reactive phosphorus to the western basin of Lake Erie, which ultimately resulted in a record-breaking HAB with a surface area of more than 5000 km^2 in Lake Erie [15]. Our data showed that lakes and reservoirs are warming in China (Fig. S12 online), which will likely result in the increasing HABs even if nutrient levels remain unchanged.

Third, climate change offsets the alleviation of HABs caused by nutrient reduction. An example analysis in Lake Taihu showed HABs can only be alleviated by about 10% with a 90% probability, but the changes in climatic factors (e.g., declining wind speed, increasing temperature) have offset the alleviation effect of nutrient reduction on cyanobacterial blooms according to the results of Bayesian models [66].

HABs can form surface scums and deplete bottom-water oxygen, which may threaten the safety of drinking water in CDWSs because HABs are toxic and a hazard by releasing microcystin and odor compounds to domestic animals as well as humans [15, 20, 57, 67, 68]. Nuisance and toxic blooms may limit water use and necessitate extensive treatment for water supply systems [57]. For example, a drinking water crisis was caused by heavy cyanobacterial blooms in the western basin of Lake Erie in early August 2014, which disrupted the drinking water supplies of Toledo, Ohio for serval days and directly affected over 400,000 residential customers and hundreds of businesses [18, 69]. Therefore, HABs exerted the increasing microcystins and health risks on lakes and reservoirs CDWSs threatening SDG6.1 [67, 70]. The drinking water crisis caused by HABs may reoccur for lake and reservoir CDWSs in the future warmer and extreme climate. More efforts should be made to alleviate eutrophication and mitigate the impact of climate change on algal blooms to decrease health risk of microcystin and odor compounds and ensure the safety of lake and reservoir CDWSs.

4.4 Implications for drinking water safety

Access to sustainable and safe drinking water supply is essential to human welfare. However, maintaining and safeguarding a good drinking water quality is a global challenge [41, 43, 46], because water scarcity is projected to be more severe. Ongoing groundwater depletion may pose a serious water security risk in intense agricultural regions and cause higher vulnerability under an uncertain climate [49, 71]. At the same time, population, water and land use pressure are expected to increase further leading to considerable challenges to water pollution and environmental sustainability [15, 21]. It will be imperative to also consider the effects and risks of extreme meteorological and hydrological events on lakes and reservoirs especially with a view to global climate changes for facilitating water resources management [15, 56, 72]. Our findings of the growing significance and pivotal role of lakes and reservoirs as primary drinking water sources provide a guide for the government to undertake adaptive management to ensure drinking water safety and achieve SDG6. All of this underscores the special attention and protection to prevent lakes and reservoirs pollution and improve the water quality because lakes and reservoirs are critically important for achieving SDG6 and protecting people's lives and health. Our work also emphasizes the importance of accessibility, usability, and sharing of water data to address SDG6.1 achievement and water scarcity challenges [30].

Acknowledgements

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Author contributions

Y.Z. proposed the main idea, collected the data and wrote the paper. All authors contributed significantly to the analysis and interpretation of the results as well as to the editing of the manuscript.

Conflict of Interest Statement

The authors declare no competing interests.

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Supporting materials

Enhancing drinking water safety through improved water quantity and quality management

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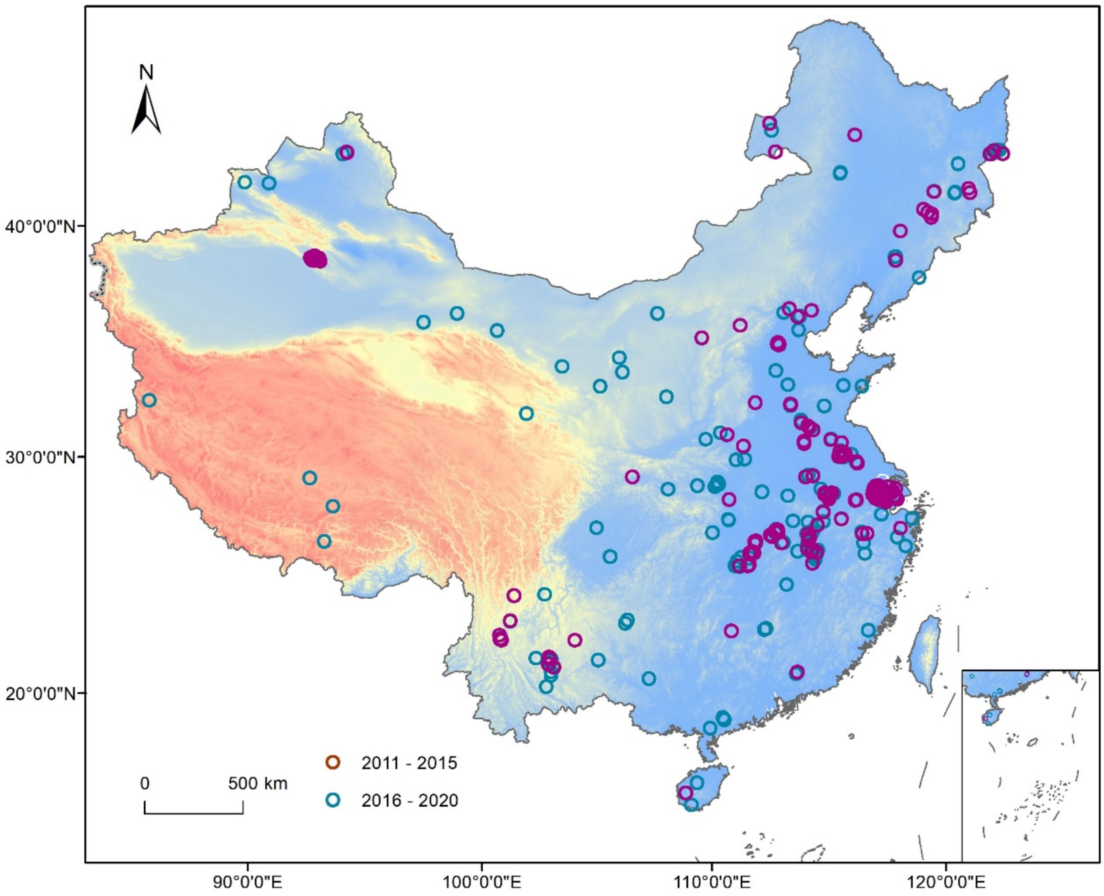


Fig. S1 Spatial distribution of lakes and reservoirs with monthly water quality observations from 2005 to 2022 (No data in Taiwan)

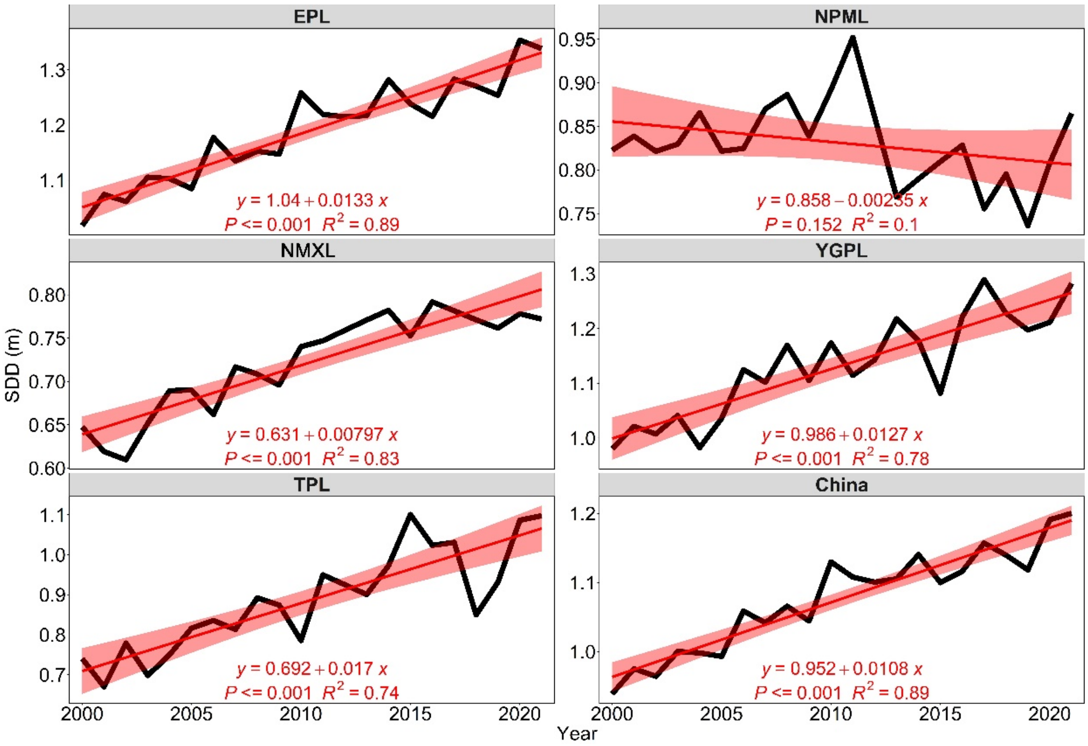


Fig. S2 Long-term trends of SDD for lakes and reservoirs in five different lake zones as indicated in Fig. 1. EPL: the Eastern Plain Lake Zone, NPML: the Northeast Plain and Mountain Lake Zone, NMXL: the Nei Mongol-Xinjiang Lake Zone, YGPL: the Yunnan-Guizhou Plateau Lake Zone, TPL: the Tibetan Plateau Lake Zone

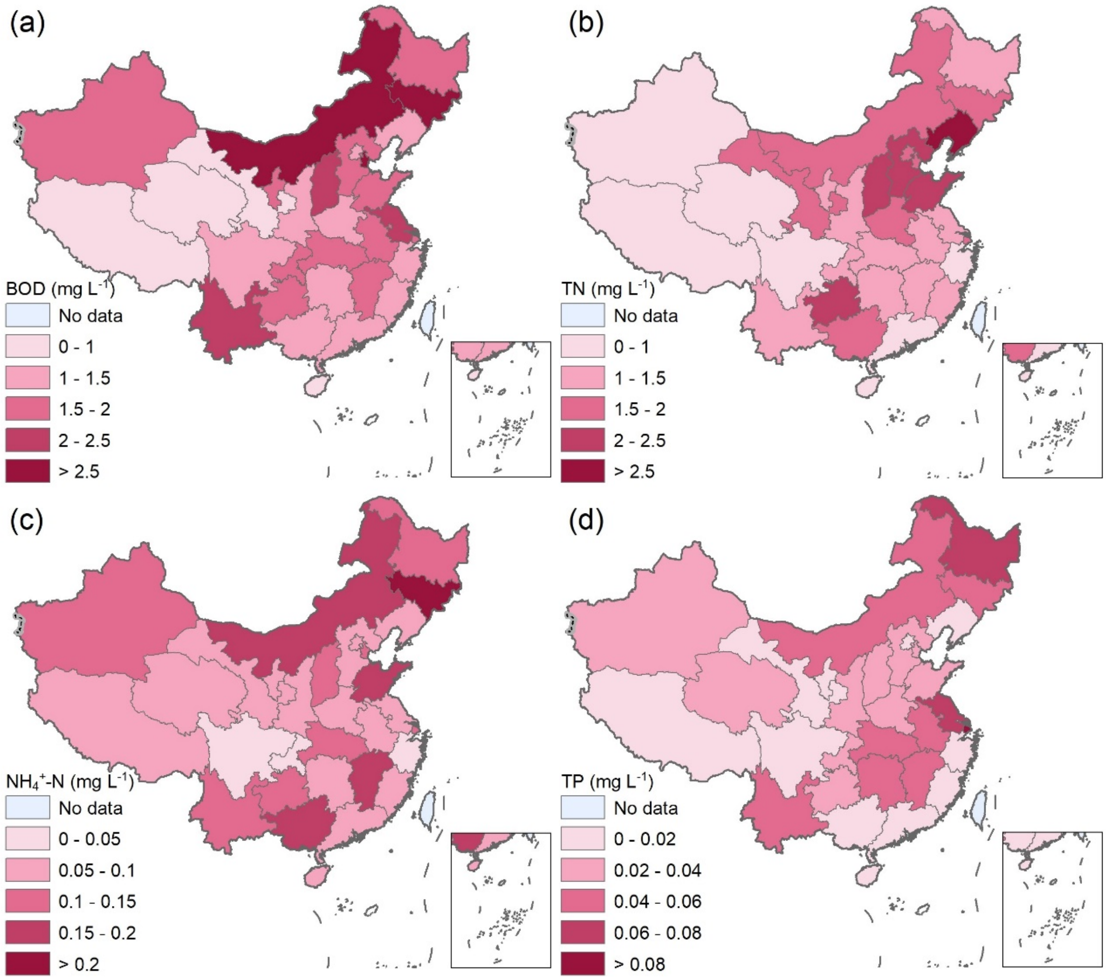


Fig. S3 Spatial distribution of BOD, TN, NH_4^+-N, and TP concentrations averaged 2020-2022 covering 31 provinces including 95 lakes and 261 reservoirs (No data in Taiwan)

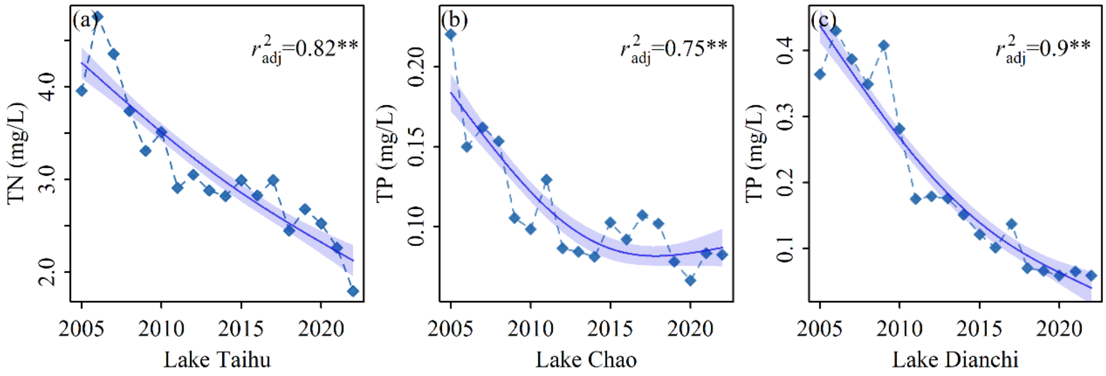


Fig. S4 Long term trend of total nitrogen and total phosphorus of three eutrophic lakes (Lake

Taihu, Lake Chaohu, and Lake Dianchi) from 2005 to 2022

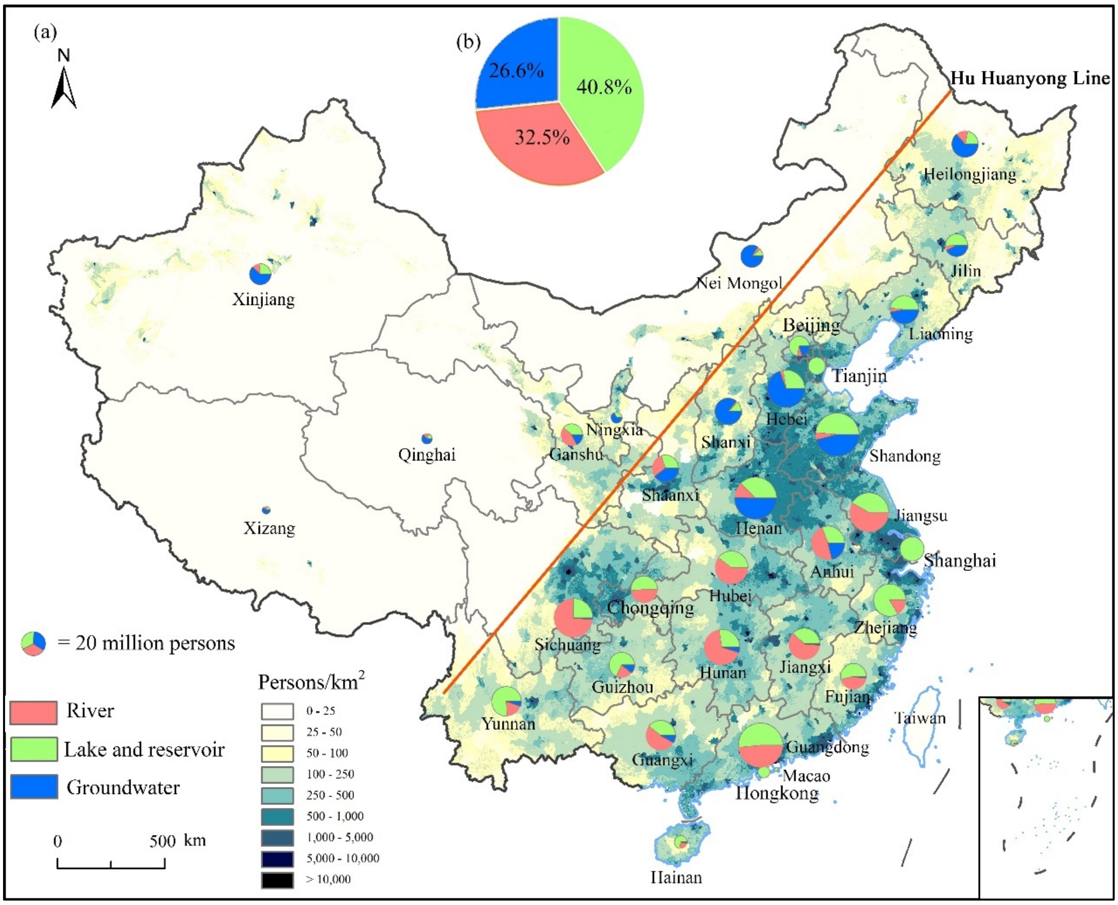


Fig. S5 Spatial distribution and composition of three types of drinking water sources for every province (a) and national average (b) in 2023 (No data in Taiwan)

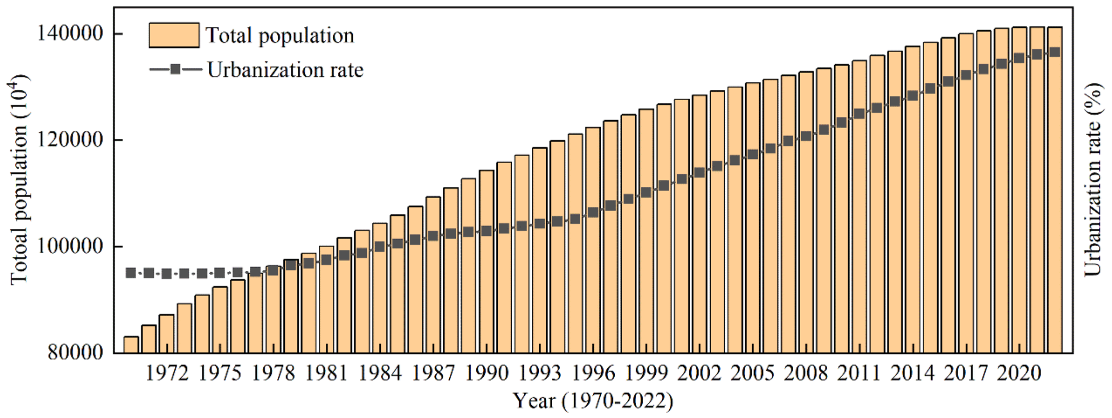


Fig. S6 Increasing total population and urbanization rate in China from 1970 to 2022

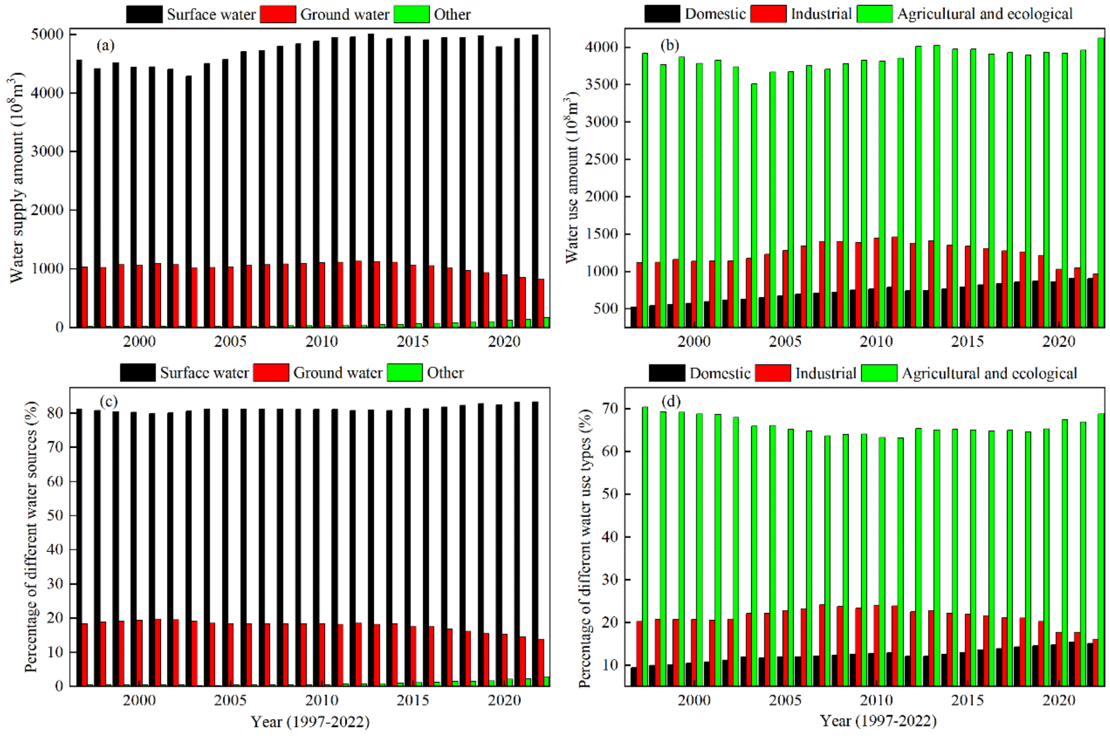


Fig. S7 Yearly water supply and use amount (a, b), the percentage of different sources and different water use types (c, d) from 1997 to 2022 from China water resources bulletin issued by the Ministry of Water Resources

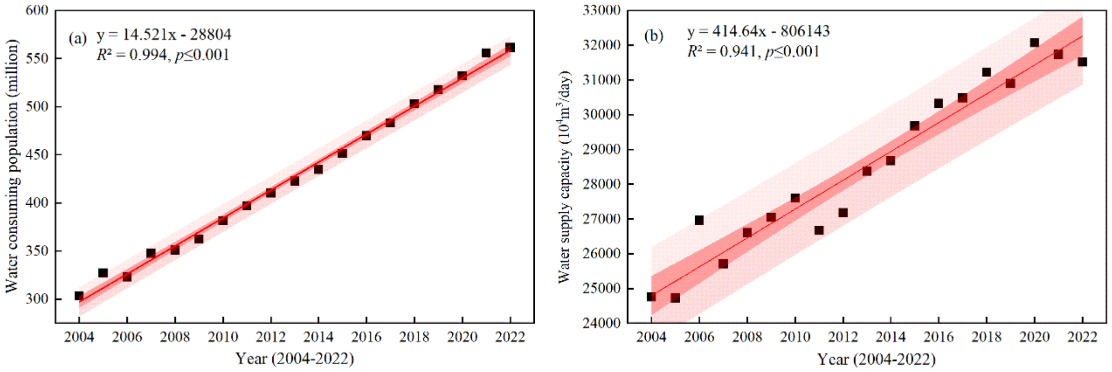


Fig. S8 Increasing water consuming population (a) and water supply capacity (b) for urban residents from 2004 to 2022 in China

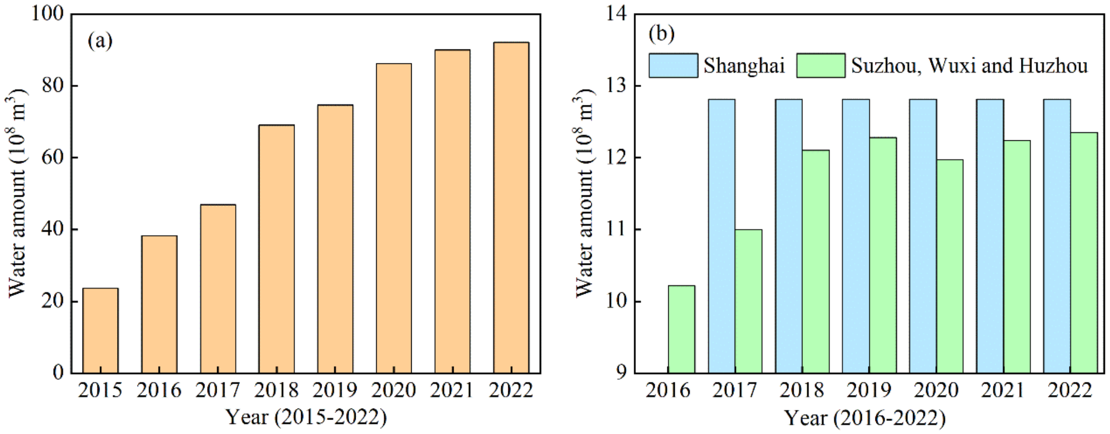


Fig. S9 Increasing water intake amounts from Danjiangkou Reservoir as the water source of the Middle Route Project of the South-to-North Water Diversion (SNWD) (a) and Lake Taihu as the water source of the surrounding Shanghai, Suzhou, Wuxi and Huzhou (b)

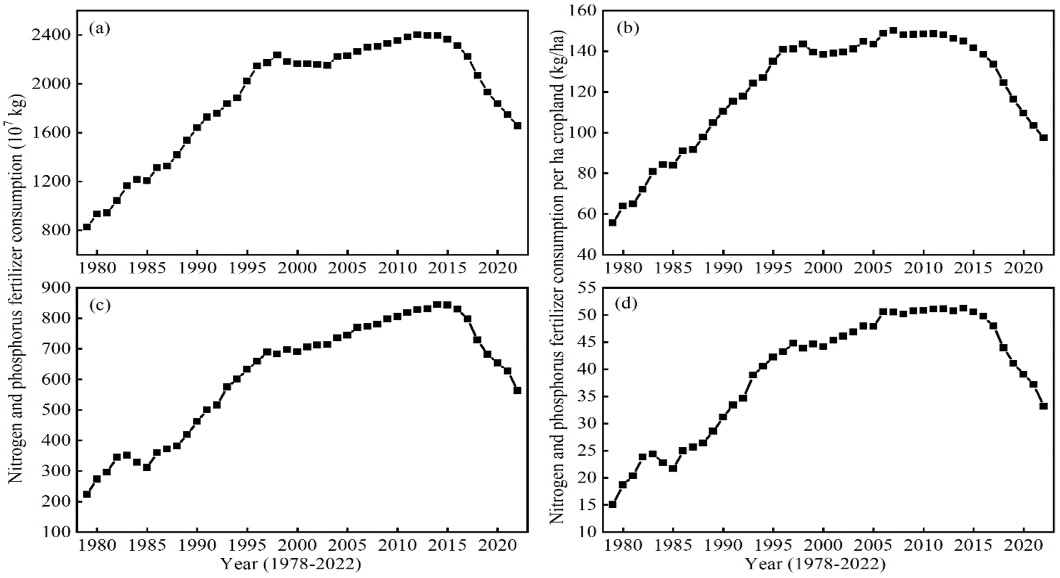


Fig. S10 Long-term changes in national-scale annual nitrogen and phosphorus consumption (a, c) and per hectare of cropland (b, d) in China using data from the National Bureau of Statistics of China (http://www.stats.gov.cn/english/).

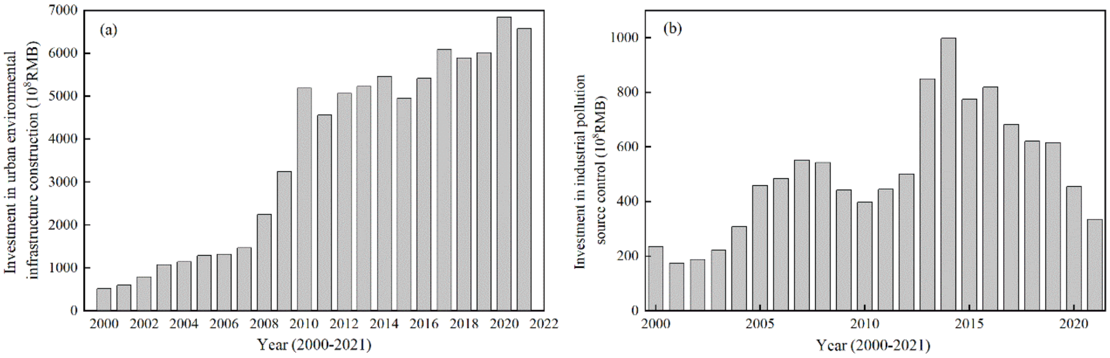


Fig. S11 Increasing investments in urban environment infrastructure construction (a) and industrial pollution source control (b) from 2000 to 2021 in China

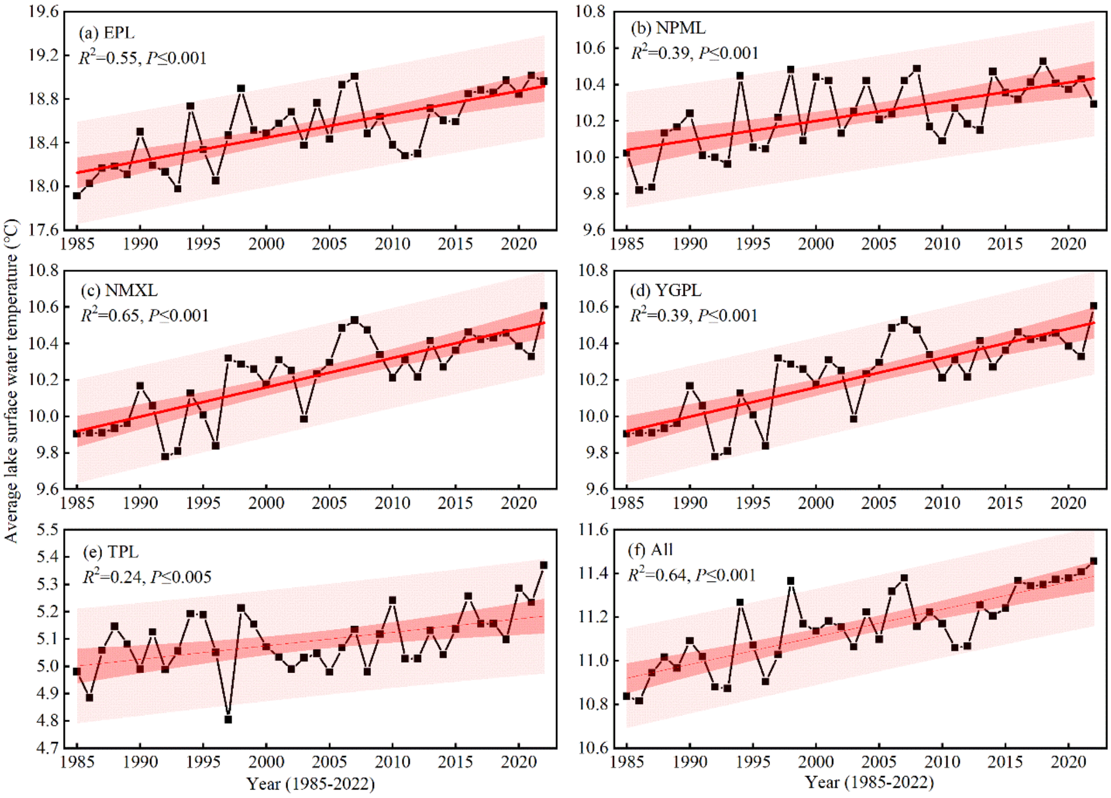
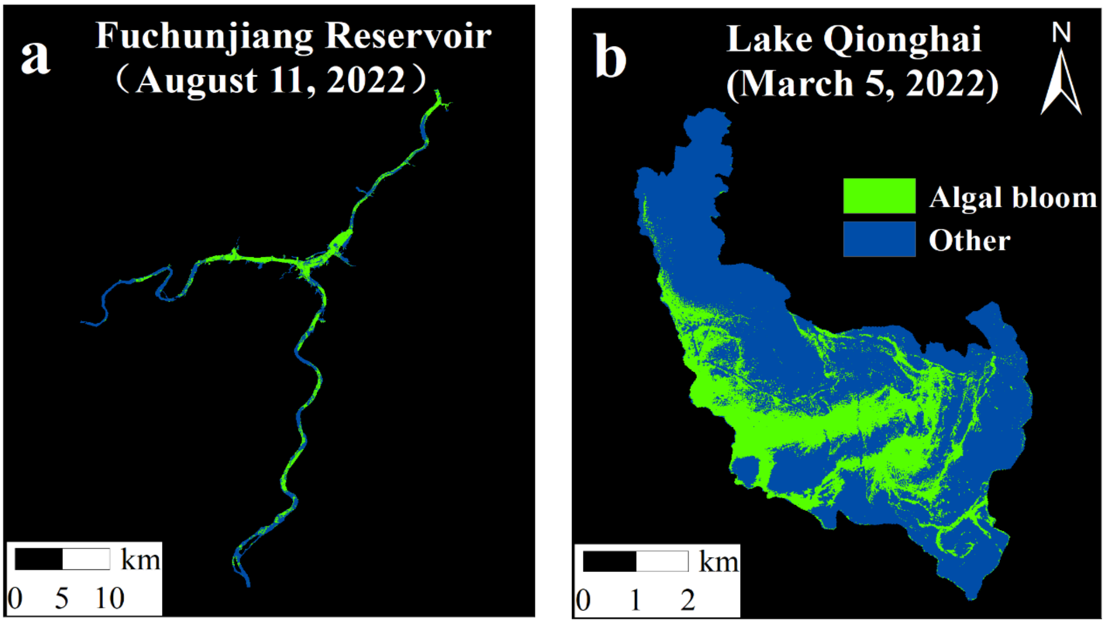


Fig. S12 Long-term trend of average lake surface temperature for lakes and reservoirs of five lake zones and all (n=2260)



Algal Bloom area: 24.13 km^2 (44.6 % of water surface)

Algal Bloom area: 7.99 km^2 (27.30 % of water surface)

Fig. S13 Extensive and record-breaking HABs in oligotrophic and mesotrophic Fuchunjiang Reservoir (a) and Lake Qionghai (a) in the unprecedented 2022 extreme heatwave and drought

Table S1 Detailed information of centralized drinking water sources for every province in 2016 and 2023

Provinces	2016						2023					
	Prefecture-level CDWRs			Prefecture-level and county-level CDWRs			Prefecture-level CDWRs			Prefecture-level and county-level CDWRs		
	Lakes and reservoirs	Rivers	Groundwater	Lakes and reservoirs	Rivers	Groundwater	Lakes and reservoirs	Rivers	Groundwater	Lakes and reservoirs	Rivers	Groundwater
Anhui	5	20	13	26	59	26	9	20	12	38	59	26
Macao	/	/	/	/	/	/	/	/	/	1	0	0
Beijing*	2	0	3	/	/	/	2	0	3	18	2	5
Chongqing	0	12	0	30	34	0	2	11	0	33	31	0
Fujian	/	/	/	50	62	7	/	/	/	58	48	2
Gansu*	9	10	14	/	/	/	10	9	13	36	41	16
Guangdong	29	46	5	68	86	5	41	47	0	86	81	0

Guangxi*	5	14	6	/	/	/	11	21	2	69	92	14
Guizhou	18	4	2	97	49	24	20	4	1	116	37	18
Hainan	/	/	/	16	12	1	/	/	/	23	8	1
Hebei*	9	0	30	/	/	/	20	0	20	30	3	75
Henan*	3	11	24	/	/	/	20	9	27	62	20	83
Helongjiang*	12	5	17	/	/	/	11	6	9	22	15	64
Hubei	9	27	0	40	87	0	12	26	0	59	90	0
Hunan	3	26	0	31	100	9	5	27	0	42	104	7
Jilin*	7	10	3	/	/	/	12	3	4	30	4	25
Jiangsu	4	18	3	31	70	7	25	31	0	49	68	0
Jiangxi*	3	28	0	/	/	/	6	30	0	65	103	2
Liaoning*	11	12	31	/	/	/	16	3	19	41	4	40

Inner Mongolia*	1	7	49	/	/	/	5	5	51	11	5	83
Ningxia	/	/	/	9	29	1	3	8	0	10	0	22
Qinghai	2	1	10	5	12	30	2	0	9	10	8	32
Shangdong*	24	6	25	/	/	/	28	4	22	117	13	111
Shangxi*	4	1	22	/	/	/	8	2	32	21	3	141
Shaanxi*	6	5	17	/	/	/	9	3	16	45	45	59
Shanghai	/	/	/	3	1	0	/	/	/	4	0	0
Sichuan	6	27	5	/	/	/	12	28	3	59	172	3
Tianjin	/	/	/	1	1	0	/	/	/	2	0	0
Tibet	/	/	/	/	/	/	0	5	16	12	9	35
Hong Kong	/	/	/	/	/	/	/	/	/	6	0	0
Xiangjiang	/	/	/	/	/	/	/	/	/	19	8	44

Yunnan*	31	8	0	/	/	/	40	7	0	128	31	9
Zhejiang	/	/	/	67	25	0	/	/	/	82	16	0

Note: * indicates that the prefecture-level CDWRs amount in these provinces is used for the calculation of the ratio of lakes and reservoirs CDWSs to all CDWSs for comparison in 2016 and 2023.

Table S2 Number, type and storage capacity of completed reservoirs from 1981 to 2022 in China

Year	Number	Total storage capacity (10^{8} m^{3})	Large-size reservoir		Medium-size reservoir		Small-sized reservoir	
			Number	Total storage capacity (10^{8} m^{3})	Number	Total storage capacity (10^{8} m^{3})	Number	Total storage capacity (10^{8} m^{3})
1981	86881	4169	328	2989	2333	622	84220	558
1982	86900	4188	331	2994	2353	632	84216	562
1983	86567	4208	335	3007	2367	640	83865	561
1984	84998	4292	338	3068	2387	658	82273	566

1985	83219	4301	340	3076	2401	661	80478	564
1986	82716	4432	350	3199	2115	666	79951	567
1987	82870	4475	353	3233	2428	672	80089	570
1988	82937	4504	355	3252	2462	681	80120	571
1989	82848	4617	358	3357	2480	688	80010	572
1990	83387	4660	366	3397	2499	690	80522	573
1991	83799	4678	367	3400	2524	698	80908	579
1992	84130	4688	369	3407	2538	700	81223	580
1993	84614	4717	374	3425	2562	707	81678	583
1994	84558	4751	381	3456	2572	713	81605	582
1995	84775	4797	387	3493	2593	719	81795	585
1996	84905	4571	394	3260	2618	724	81893	587
1997	84837	4583	397	3267	2634	729	81806	587

1998	84944	4930	403	3595	2653	736	81888	598
1999	85119	4499	400	3164	2681	743	82039	593
2000	83260	5183	420	3843	2704	746	80136	593
2001	83542	5280	433	3927	2736	758	80373	595
2002	83960	5594	445	4230	2781	768	80734	596
2003	84091	5657	453	4279	2827	783	80811	596
2004	84363	5541	460	4147	2869	796	81034	598
2005	84577	5623	470	4197	2934	826	81173	601
2006	85249	5841	482	4379	3000	852	81767	610
2007	85412	6345	493	4836	3110	883	81809	625
2008	86353	6924	529	5386	3181	910	82643	628
2009	87151	7064	544	5506	3259	921	83348	636
2010	87873	7162	552	5594	3269	930	84052	638

2011	88605	7201	567	5602	3346	954	84692	645
2012	97543	8255	683	6493	3758	1064	93102	698
2013	97721	8298	687	6529	3774	1070	93260	700
2014	97735	8394	697	6617	3799	1075	93239	702
2015	97988	8581	707	6812	3844	1068	93437	701
2016	98460	8967	720	7166	3890	1096	93850	705
2017	98795	9035	732	7210	3934	1117	94129	709
2018	98822	8953	736	7117	3954	1126	94132	710
2019	98112	8983	744	7150	3978	1127	93390	706
2020	98566	9306	774	7410	4098	1179	93694	717
2021	97036	9853	805	7944	4147	1197	92057	712
2022	95296	9887	814	7979	4192	1199	90290	709

Note: large-sized reservoir: storage capacity ≥ 1.0 ×10^8; medium-size reservoir: 1.0 ×10^7 ≤ storage capacity < 1.0 ×10^8; small-sized reservoir: 1.0 ×10^5 ≤ storage capacity < 1.0 $\times 10^7$

Table S3 Monthly water intake amounts and percentage of lakes and reservoirs, rivers in Zhejiang Province

Year	Type	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
2016	Rivers	Amount (10^4)	13112	12949	12342	12769	13219	13227	13560	14643	14860	13625	13649	13504	161459
		Ratio (%)	41.4	39.9	40.2	39.9	40.5	40.1	39.9	40.9	39.7	39.3	40.2	39.8	40.1
		Amount (10^4)	18585	19524	18333	19254	19424	19762	20401	21120	22542	21031	20293	20415	240684

	Lakes and reservoir	Ratio (%)	58.6	60.1	59.8	60.1	59.5	59.9	60.1	59.1	60.3	60.7	59.8	60.2	59.9
2017	Rivers	Amount (10^4)	13561	12597	12022	12564	13262	13776	13969	15413	16079	14910	14462	14187	166802
		Ratio (%)	39.2	38.2	38.8	38.8	39.6	40.0	40.1	41.1	40.9	40.0	40.4	39.9	39.8
	Lakes and reservoir	Amount (10^4)	21014	20353	18989	19819	20210	20653	20891	22114	23281	22362	21293	21363	252342
		Ratio (%)	60.8	61.8	61.2	61.2	60.4	60.0	59.9	58.9	59.1	60.0	59.6	60.1	60.2
2018	Rivers	Amount (10^4)	14206	14026	12027	13009	14076	14451	14591	15609	15959	15251	14682	14514	172401
		Ratio (%)	40.9	41.6	39.6	39.0	39.8	40.0	39.8	40.4	39.8	39.4	40.0	40.5	40.1
	Lakes and reservoir	Amount (10^4)	20553	19702	18329	20356	21262	21703	22078	23034	24124	23500	22063	21308	258012
		Ratio (%)	59.1	58.4	60.4	61.0	60.2	60.0	60.2	59.6	60.2	60.6	60.0	59.5	59.9
2019	Rivers	Amount (10^4)	14396	14188	11463	13304	14054	14179	14668	15415	16365	10805	10360	10369	159566
		Ratio (%)	40.3	40.1	38.9	40.6	39.5	40.1	40.0	40.5	39.4	27.3	27.1	27.5	36.6
		Amount (10^4)	21311	21217	18021	19464	21564	21165	21967	22663	25154	28846	27870	27374	276616

	Lakes and reservoir	Ratio (%)	59.7	59.9	61.1	59.4	60.5	59.9	60.0	59.5	60.6	72.7	72.9	72.5	63.4
2022	Rivers	Amount (10^4)	13917	13658	11577	12243	12738	13548	13822	14389	16552	12454	11071	10811	156780
		Ratio (%)	35.2	35.5	34.0	32.0	32.8	35.3	34.5	32.7	33.9	27.6	26.2	27.4	32.2
	Lakes and reservoir	Amount (10^4)	25611	24846	22460	25998	26041	24876	26234	29676	32284	32686	31194	28661	330567
		Ratio (%)	64.8	64.5	66.0	68.0	67.2	64.7	65.5	67.3	66.1	72.4	73.8	72.6	67.8
2023	Rivers	Amount (10^4)	12158	9958	10201	11358	11937	11956	12447	12997	13510	13120	12360	12155	144157
		Ratio (%)	28.3	26.5	27.3	29.2	29.4	29.7	30.3	29.6	29.3	29.1	29.3	30.0	29.0
	Lakes and reservoir	Amount (10^4)	30832	27569	27156	27547	28601	28348	28689	30900	32676	31915	29822	28396	352451
		Ratio (%)	71.7	73.5	72.7	70.8	70.6	70.3	69.7	70.4	70.7	70.9	70.7	70.0	71.0

Table S4 In operation and to be operated important cross-regional water transfer projects from lakes and reservoirs to meet safe and clean drinking water in China

	Water sources	Water diversion	Beneficiary regions	Beneficiary

		amount (10^8 m^3/year)		population (million)
East Route Project of SNWD	Lake Hongzehu, and Lake Luomahu	17	Zaozhuang, Jining, Tai'an, Dezhou, Liaocheng, Jinan, Heze, Laifu, Linyi, Zibo prefecture-level regions in Shandong province, Cangzhou and Hengshui prefecture-level regions in Hebei province, Tianjin municipality	58
Middle Route Project of SNWD	Danjiangkou Reservoir	95	Nanyang, Pingdingshan, Xuchang, Zhengzhou, Jiaozuo, Xinxiang, Hebi, Anyang prefecture-level regions in Henan province, Handan, Xingtai, Shijiazhuang, and Baoding prefecture-level regions in Hebei province, Beijing and Tianjin municipalities	85
Water Diversion Project from Hanjiang River to Weihe River	Huangjinxia Reservoir, Sanhekou Reservoir	15	Xi'an, Xianyang, Baoji, and Weinan prefecture-level regions in Shaanxi province	20
Lake Qiandao Water Distribution Project	Lake Qiandaohu	12.1	Hangzhou and Jiaxing prefecture-level regions in Zhejiang province	10
River Taohe Water	Jiudianxia	5.5	Lanzhou, Dingxi, and Baiyin prefecture-level regions in Gansu province	3

Diversion Project	Reservoir			
Water Diversion Project from Yellow River to Shanxi Province	Wanjiazai Reservoir	12	Taiyuan, Suozhou, Datong prefecture-level regions in Shanxi province	/
Water diversion project from Datong to Huanghe	Shitouxia Reservoir and Heiquan Reservoir	7.5	Xining, Haibei, and Haidong prefecture-level regions in Qinghai province	3
Water diversion project from Lake Songhuahu	Lake Songhuahu	7.3	Changchun, Siping, and Liaoyuan prefecture-level regions in Jilin province	10.6

Table S5 Comparison of the percentages of CDWSs number and annual total water intake amounts of three CDWS types in Shanxi Province during 2016-2023

	Year	2016	2017	2018	2019	2020	2021	2022	2023
CDWSs Number (%)	Groundwater	81.5	81.5	81.5	80.8	80.8	76.2	76.2	76.2
	Lake and Reservoir	14.8	14.8	14.8	15.4	15.4	19.0	19.0	19.0
	River	3.7	3.7	3.7	3.8	3.8	4.8	4.8	4.8
Water intake amounts (10^4 m^3)	Groundwater	29158	30549	32694	33598	33790	34240	34940	34149
	Lake and Reservoir	12729	12903	13682	13337	14557	15665	19299	21914
	River	2233	2525	2160	2160	2160	1980	2344	2387
Water intake amounts (%)	Groundwater	66.1	66.4	67.4	68.4	66.9	66.0	61.7	58.4
	Lake and Reservoir	28.9	28.1	28.2	27.2	28.8	30.2	34.1	37.5
	River	5.1	5.5	4.5	4.4	4.3	3.8	4.1	4.1

Table S6 Comparison of intake amount of 21 prefecture-level CDWSs in Heilongjiang Province in summer (July-August) and winter (November, January, and February) from 2023 to 2024

City	Water source name	Water source type	Monthly intake amount (m^3)				
			Jul.	Aug.	Nov.	Jan.	Feb.
Haerbing	Mopanshan	River	2405.6	2405.6	2328.0	2405.6	2250.4
Qiqihaer	Liuyuan	River	400.0	400.0	400.0	400.0	400.0
Jixi	Tuanshan Reservoir	Reservoir	0	0	0	0	0
	Hada Reservoir	Reservoir	372.0	372.0	360.0	372.0	348.0
Hegang	Wuhao Reservoir	Reservoir	130.0	131.0	113.0	102.0	118.0
	Xilinhe Reservoir	Reservoir	191.0	190.0	171.0	158.0	177.0
Shuangyashan	Hanconggou	Reservoir	120.0	120.0	120.0	120.0	120.0

Daqing	Reservoir						
	Ershuiyuan	Groundwater	65.0	65.0	65.0	65.0	65.0
	Sifangtaikuang	Groundwater	7.0	7.0	7.0	7.0	7.0
	Daqing Reservoir	Reservoir	1080.0	1050.0	1015.0	1010.0	1020.0
	Hongqi Reservoir	Reservoir	450.0	440.0	402.0	395.0	400.0
	Dongcheng Reservoir	Reservoir	520.0	515.0	510.0	510.0	505.0
Yichun	Cuiluanshan	River	90.0	90.0	90.0	90.0	90.0
	Dongsheng	Groundwater	5.0	5.0	5.0	5.0	5.0
Jiamusi	Jiangbei	Groundwater	388.0	388.0	363.0	364.0	342.0
Mudanjiang	Xishuiyuan	River	495.0	545.0	479.0	532.0	528.0
	Tielushuiyuan	River	0	0	0	0	0
Heihe	Xiaojinshan	River	0	71.0	71.0	71.0	71.0
Ruihua	Hulan River	River	136.1	154.1	145.7	0	115.0
	Diyishuiyuan	Groundwater	22.5	21.6	22.1	147.7	107.9
Daxinganling	Jiagedaqi	River	60.0	62.0	56.0	72.0	58.0