## Drinking water safety improvement and future challenge of lakes and reservoirs

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1	Enhancing drinking water safety through improved water quantity
2	and quality management
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23	Abstract: To meet the Sustainable Development Goal (SDG) target 6.1, China has undertaken
24	significant initiatives to address the uneven distribution of water resources and to enhance water
25	quality. Since 2000, China has invested heavily in water infrastructure of numerous reservoirs, with
26	a total storage capacity increase of $4.704 \times 10^{11}$ m <sup>3</sup> (increase of 90.8%). These reservoirs have
27	significantly enhanced the available freshwater resources for drinking water. Concurrently, efforts
28	to improve water quality in lakes and reservoirs, facilitated by nationwide water quality monitoring,
29	have been successful. As a result, an increasing number of lakes and reservoirs are designated as
30	centralized drinking water sources (CDWSs) in China. Among the 3,441 CDWSs across all
31	provinces, 40.8% are sourced from lakes and reservoirs, 32.6% from rivers, and 26.6% from
32	groundwater in 2023. Notably, from 2016 to 2023, the percentage of lakes and reservoirs categorized
33	as CDWSs has increased consistently across all 29 provinces, benefitting a growing urban
34	population. This progress has enabled 561.4 million urban residents to access improved drinking
35	water sources in 2022, compared to 303.4 million in 2004. Our findings underscore the pivotal role
36	of water infrastructure construction and water quality improvement jointly promoting lakes and
37	reservoirs as vital drinking water sources. Nevertheless, the nationwide occurrence of algal blooms
38	has surged by 113.7% from the 2000s to the 2010s producing a considerable challenge to drinking
39	water safety. Fortunately, algal blooms have been markedly alleviated during in past four years.
40	However, it is still crucial to acknowledge that lakes and reservoirs face the challenges of harmful
41	algal blooms, and associated toxic microcystin and odor compounds.
42	

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

## 45 **1. Introduction**

Lakes and reservoirs represent fundamental features within the Earth System, acting as 46 47 important repositories of surface water. Across the globe, natural lakes encompass approximately  $4.2 \times 10^6$  km<sup>2</sup> of the Earth's surface [1]. In addition, as demands for agricultural irrigation, domestic 48 49 use, and hydroelectric power generation increase, the area of reservoirs has increased rapidly and is 50 projected to grow by approximately 1–2% annually [1, 2]. While the surface area of lakes and 51 reservoirs remains relatively limited, their significance in promoting the economic and social 52 development of the surrounding regions cannot be overstated [3-6]. Unfortunately, the importance 53 and value of the ecological services that lakes and reservoirs provide have often been 54 underestimated [7]. In reality, lakes and reservoirs fulfil a multitude of ecological functions, 55 including the provision of safe drinking water, regulation and storage of water resources, flood 56 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]. 57 58 Concurrently, lakes and reservoirs are sensitive to global environmental change and human activities 59 within their basins. Consequently, they serve as invaluable sentinels and regulators of global 60 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 67 living in its vicinity [12]. Lake Mead, the largest reservoir in the USA, provides drinking water to 68 approximately 40 million people [13]. Dangjiangkou Reservoir and Lake Qiandaohu (also named 69 Xin'anjiang Reservoir) in China provide drinking water for more than 70 million people [14]. 70 However, surface water bodies have experienced a concerning deterioration in terms of water 71 quality in recent years, particularly due to the increased frequency of algal blooms [15-18]. This 72 trend has been primarily attributed to intense human activities and increasing extreme 73 meteorological events, which have led to an increased risk of a potential health impact of drinking 74 water [15, 16, 19-21]. Therefore, the contributions of lakes and reservoirs to drinking water safety 75 are very important and the challenge is very severe but need to be better understood.

76 China is considered as a severe "water-deficit country" due primarily to emerging water 77 demands, an uneven distribution of water resources and extensive water pollution. Despite being 78 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  $\sim 0.257 \times 10^6$  km<sup>2</sup> of surface water 79 area supports ~330 million people in the USA [25]. In contrast, ~0.155  $\times$  10<sup>6</sup> km<sup>2</sup> of surface water 80 81 area supports over 1.4 billion people in China [22]. Lakes and reservoirs assume a pivotal role as 82 centralized drinking water sources (CDWRs) for urban residents of China. They oftentimes provide 83 a more dependable and stable drinking water supply than rivers and groundwater due to higher 84 standard-reaching rate, fewer water pollution accidents, and lower vulnerability [14]. However, over 85 the past four decades, China's lakes and reservoirs have been subjected to intense human activity 86 and eutrophication, leading to a decline in water quality, ecosystem degradation, and the loss of 87 crucial ecological services. These challenges pose significant threats to water availability, 88 sustainable development, and human well-being. One of the landmark incidents illustrating these

89 challenges was the Wuxi drinking crisis, where the water source from Lake Taihu was contaminated 90 by harmful cyanobacteria blooms. This event resulted in a week-long disruption of the drinking 91 water supply for two million people in Wuxi, Jiangsu Province [17, 26]. Consequently, extensive 92 efforts have been dedicated to the control, restoration, and preservation of aquatic environments and 93 ecosystems. Encouragingly, substantial progresses have been made in safeguarding the aquatic 94 ecological environment and advancing the vision of a more environmentally sustainable China [27-95 29]. However, a fundamental obstacle in addressing these challenges lies in the limited accessibility, 96 usability, and sharing of water data, including water quantity, quality, and drinking water resources 97 [30]. To fill this gap, we here present a comprehensive mapping, dynamics and quantification of 98 lakes and reservoirs, water quality, and contribution to drinking water safety.

99 We hypothesise that the construction of water infrastructure, coupled with the concurrent 100 improvement in water quality of lakes and reservoirs, through substantial efforts spanning the past 101 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 102 103 investigates the dynamics and spatial distribution of lakes and reservoirs, shedding light on the ever-104 changing landscape. Furthermore, we delve into the dynamics and trends shaping the lake 105 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 106 107 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 108 109 drinking water.

## 110 **2. Data and methods**

#### 111 **2.1 Spatial distribution of lakes and reservoirs**

112 The number, surface area and distribution of lakes and reservoirs (≥1.0 km<sup>2</sup>) were extracted from the historical water inundation extent based on Global Surface Water (GSW) and Global Land 113 114 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 115 sensing big data computing platform using Google Earth Engine (GEE). Based on all available 116 Landsat 5, 6, 7, and 8 data acquired from 1984, Pekel et al. [34] used the expert classification system 117 118 to divide each available pixel into water bodies and non-water bodies and integrated the results into 119 monthly, annual, and decadal timescales. The maximum water boundary, water inundation 120 frequency, water change intensity, water transition, water recurrence, seasonal water, monthly water 121 range, monthly water recurrence, and annual water range were provided. Similarly, GLAD is the 122 global water body map from 1999 to 2019 obtained using GEE based on Landsat 5, 7, and 8 images 123 [33], which employed an independent mapping algorithm and showed superiority in delineating the 124 boundary of small-sized water bodies such as narrow channelled reservoirs. Therefore, we merged 125 the water occurrence layers of the GSW and GLAD datasets to obtain the maximum water area of 126 all lakes and reservoirs with historically inundated area  $\geq 1 \text{ km}^2$ , as the base mask for water quality 127 analyses. The derived water bodies were inspected and edited with rigorous quality-control 128 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 129 130 Reservoir Dataset [35]. The number, type and storage capacity of reservoirs since 1981 were 131 obtained from the National Bureau of Statistics of China (http://www.stats.gov.cn/english/).

#### 132 **2.2 Secchi disk depth derived from remote sensing**

133 SDD serves as a straightforward yet highly significant metric for assessing the water quality 134 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 135 136 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 137 reservoirs with a surface area  $\geq 1 \text{ km}^2$ . Considering the long-term consistent water area of lakes and 138 reservoirs, we used a well-established SDD remote sensing model that has undergone extensive 139 140 calibration and validation. This model enabled us to estimate SDD for 6,359 lakes and reservoirs 141 from 2000 to 2021 [36], excluding reservoirs constructed after 2000.

142 **2.3 Water quality of lakes and reservoirs** 

143 To assess the water quality dynamics of China's lakes and reservoirs, we conducted extensive 144 monthly observations over an extended period. These observations encompassed key parameters 145 such as BOD, TN, NH<sub>4</sub><sup>+</sup>-N, and TP in a total of 95 lakes and 261 reservoirs (Fig. S1 online). This 146 comprehensive dataset from 2005 to 2022 was collected by the Chinese National Environmental 147 Monitoring Centre (http://www.cnemc.cn/). The BOD, TN, NH4+-N, and TP concentrations were analyzed in the laboratory using the standard water and wastewater monitoring and analysis methods 148 149 recommended by the Ministry of Environmental Protection of China [37], which did not change 150 over the reported period. The long-term, continuous, and consistent monitoring data within this 151 dataset holds widespread utility in characterizing, analysing, and evaluating the dynamics and long-152 term trends of the aquatic environment in both lakes and reservoirs [27, 28]. The average values are 153 calculated from all lakes and reservoirs of every province for BOD, TN, NH<sub>4</sub><sup>+</sup>-N, and TP.

Furthermore, we augmented our analysis by calculating the occurrence frequency of algal 154 blooms (in %) using Landsat imagery for a total of 1,541 lakes in China from 1980 to 2021 [16]. 155 156 The dataset of Hou et al., (2022) was divided and updated into four periods: 1980-1990s (1982-157 1999), 2000s (2000-2009), 2010s (2010-2019), and 2020s (2020-2021) to investigate long-term 158 bloom occurrence changes. To validate our results of bloom occurrence from Landsat imagery, we 159 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 160 estimate bloom occurrence in Lake Taihu and Lake Chaohu from 2003 to 2023 [38]. 161

162 **2.4 Data on centralized drinking water sources** 

Our data were largely sourced from publicly available bulletins and reports provided by the 163 Chinese government ecological environment departments, ensuring reliability through stringent 164 165 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 166 167 in 2016. This positive change was brought about by the Ministry of Ecology and Environment's 168 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 169 170 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 171 172 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 173 174 and county-level CDWRs data is currently not centrally accessible to the public. Instead, this 175 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 181 Zhejiang Province were obtained from the Zhejiang Provincial Department of Ecology and 182 183 Environment (http://sthjt.zj.gov.cn/col/col1251321/index.html). To quantify the contributions of 184 three types of prefecture-level CDWSs to the drinking water supply in Shanxi Province, monthly 185 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 186 187 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 188 of Ecological Environment (https://sthj.hlj.gov.cn/sthj/). 189

#### 190 **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 (<u>http://www.stats.gov.cn/sj/</u>). The population data was obtained from the website (https://www.hongheiku.com/china/221.html).

#### 198 **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  $p \le 0.05$  was considered statistically significant in this study. Long-term trends of SDD, BOD, TN, NH<sub>4</sub><sup>+</sup>-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.

206 **3. Results** 

#### 207 **3.1 Increasing available freshwater resources by reservoir infrastructure**

208 Until 2020, it is estimated that there were 2,670 natural lakes and 5,156 reservoirs with a 209 surface area  $\geq 1 \text{ km}^2$  in China (Fig. 1). The total surface area of lakes and reservoirs are 80,662.4 and 39,697.1 km<sup>2</sup>, respectively. For natural lakes, more than 60% are characterised as saline or 210 211 brackish, rendering them unsuitable for drinking water purposes. These types of lakes are primarily 212 found in the Tibetan Plateau and Nei Mongol-Xinjiang Plateau regions (Fig. 1) [39]. Consequently, 213 given the increasing demand for agricultural irrigation, drinking water supply, and hydroelectric 214 power generation due to population growth, China has embarked on a strategy of constructing new 215 reservoirs and expanding the storage capacity of existing ones. Over the past 40 years, there has 216 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<sup>3</sup>), which are capable of meeting drinking 217 218 water requirements (Table S2 online). Notably, the period from 2011 to 2022 experienced a significant increase ( $p \le 0.001$ ) in the number and storage capacity of reservoirs, surpassing the rates 219

220 observed in preceding decades (2001-2011, 1991-2001, 1981-1991). During 2011-2022, the number 221 and storage capacity of large-sized reservoirs increased by 247 and  $2,377 \times 10^8 \text{ m}^3$ , respectively. In 222 contrast, the corresponding numbers for the previous decades were 134 and  $1,675 \times 10^8$  (2001-2011), 223 66 and  $527 \times 10^8$  (1991-2001), and 39 and  $411 \times 10^8$  (1981-1991), respectively. In total, there has been an increase in storage capacity of 4.704×10<sup>11</sup> m<sup>3</sup> (90.8% increase) in reservoirs since 2000. 224 225 Geographically, the distribution of reservoirs aligns closely with population distribution and the 226 associated demand for drinking water (Fig. 1). Predominantly, reservoirs are concentrated in the 227 southeastern region of the Hu Huanyong Line, which is home to more than 94% of the national

228 population.

229



Fig. 1 Spatial distribution of lakes and reservoirs with a surface area of  $\geq 1.0$  km<sup>2</sup> in China. 1, the

Eastern Plain Lake Zone (EPL); 2, the Northeast Plain and Mountain Lake Zone (NPML); 3, the

232 Nei Mongol-Xinjiang Lake Zone (NMXL); 4, the Yunnan-Guizhou Plateau Lake Zone (YGPL); 5,

- 233 the Tibetan Plateau Lake Zone (TPL). The Hu Huanyong Line, connecting the city of Heihe
- 234 (Heilongjiang Province) to Tengchong County (Yunnan Province), is an important divider of

population, economic, social, and human activity intensity in China.

235

236 **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) 237 238 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, 239 240 31% of these water bodies experienced a decrease in SDD, with a rate of 0.13 m/decade. Collectively, 241 we calculated a statistically significant increase in mean SDD nationwide, from 0.91±0.66 m to 242  $1.21\pm0.81$  m, corresponding to a 33.0% increase from 2000 to 2020 ( $p \le 0.01$ ). Notably, a total of 243 3,365 (53%) lakes and reservoirs underwent transitions in their SDD levels between these two years 244 (Fig. 2c). Specifically, 2,596 lakes and reservoirs experienced transitions toward clearer conditions, 245 while 769 lakes and reservoirs shifted toward more turbid conditions. The long-term change rates 246 of SDD across Chinese lakes and reservoirs demonstrated diverse spatially patterns (Fig. 2d). 247 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 248 249 in SDD. Conversely, lakes in the Nei Mongol-Xinjiang Lake Zone exhibited a decrease in SDD (Fig. 250 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 251 252 linear fitting model demonstrated a substantial increase of 0.12 m/decade for lakes and 0.11 253 m/decade for reservoirs over this period (Fig. 2e). Similar trends of SDD, except for the Nei

254 Mongol-Xinjiang Lake Zone, are found for other four lake zones, indicating a consistent 255 improvement in water quality (Fig. S2 online).

#### 256 **3.3 Improvement of water quality in lakes and reservoirs**

257 Water quality, described here in terms of biochemical oxygen demand (BOD), total nitrogen 258 (TN), ammonia nitrogen (NH4<sup>+</sup>-N), and total phosphorus (TP) in lakes and reservoirs throughout 259 continental China changed markedly from 2005 to 2022. We found high spatial heterogeneity in the 260 magnitude of change (in %) in water quality parameters during 2020-2022 compared with that in 261 2005-2007 for all 31 provinces (Fig. 3, Fig. S1, Fig. S3 online). Notably, we found marked decreases 262 in BOD, TN, NH4<sup>+</sup>-N, and TP concentrations in eastern China, characterised by high population 263 density, in 2020-2022 compared to 2005-2007 (Fig. 3). Conversely, in several western provinces, 264 including Ningxia, Shaanxi, and Guangxi, we found a notable increase in TN during 2020-2022 265 when compared to 2005-2007 (Fig. 3).





Fig. 2 Comparison of Secchi disk depth (SDD) spatial distribution in 2000 and 2020 (a, b),



269 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, NH4<sup>+</sup>-N: ammonia nitrogen, TP: total
phosphorus
Overall, we found that BOD, TN, NH4<sup>+</sup>-N, and TP concentrations significantly decreased
across Chinese lakes and reservoirs during the same period (Fig. 4). From 2005 to 2022, mean BOD,

277 TN, NH<sub>4</sub><sup>+</sup>-N, and TP concentrations demonstrated a significant decline (Fig. 4), which decreased

- 279 mg/L, 0.107 mg/L, and 0.043 mg/L during 2020-2022, with the decrease ratios of 28.3%, 23.5%,
- 280 61.8%, and 40.4%, respectively. In addition, our analysis identified a significant decrease in TN and
- 281 TP in three eutrophic lakes (Lake Taihu, Lake Chaohu, Lake Dianchi) with frequent algal blooms

<sup>278</sup> 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

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<sub>4</sub><sup>+</sup>-N: ammonia nitrogen, TP: total phosphorus

#### 293 **3.4 Increase of lakes and reservoirs designated as drinking water sources**

294 Among the 3,441 prefecture-level and county-level CDWSs monitored nationwide, 1,404 295 (40.8%) are lakes and reservoirs, 1,120 (32.6%) are rivers, and the remaining 917 (26.6%) are 296 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-297 298 regional and cross-basin water transfer projects from reservoirs in Henan Province and Hebei 299 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 300 301 Environment[40], which lists 919 prefecture-level and 2,622 county-level CDWSs monitoring sites. 302 Spatially, the lowest and highest ratios of lakes and reservoirs CDWSs was found in Nei Mongol 303 (11.1%) and Shanghai & Tianjin (100%), respectively. The high ratios of lakes and reservoirs 304 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 305 306 (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, 307 308 the ratio of lake and reservoir CDWSs to all CDWSs increased from 35.0% (607 vs 1734) in 2016 309 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.





318 Fig. 5 Increasing ratio of lakes and reservoirs CDWSs accounting for the total CDWSs for every

319

province from 2016 to 2023 (No data in Taiwan)

# 320 4. Discussion

## 321 **4.1 A great challenge for drinking water supply**

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

344	people (Fig. S8 online). As previously reported, China played a pivotal role in achieving the
345	Millennium Development Goals (MDGs) target on safe drinking water [41].

346 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 347 that the national rural tap water penetration rate has reached 87% according to the Ministry of Water 348 Resources (http://www.chinanews.com.cn/cj/2022/12-14/9914690.shtml), which means that almost 349 350 100 million rural residents still rely on self-supplied drinking water without access to safe and 351 reliable drinking water services, despite substantial progress over several decades. Correspondingly, 352 it is estimated that more than 760 million people relied on self-supply for their drinking water from 353 26 low- and middle-income countries in South Asia, Southeast Asia and the Pacific [43]. Globally, 354 an estimated 2.1 billion people lack safely managed drinking water, this includes almost the entire 355 population of rural Africa [44]. Even in high-income developed countries, poor drinking water 356 quality and access remain barriers to improved health in many regional and remote communities 357 [45, 46]. All these demonstrate that we have achieved tremendous success but also faced a great 358 challenge for drinking water supply in China. Therefore, the construction of drinking water 359 infrastructures including tap-water pipeline in rural areas and water quality improvement of drinking 360 water source to purge rivers and lakes of industrial and agricultural pollutants are need to resolve 361 the challenges and ensure drinking water safety.

#### 362 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

- 366 35.0% to 42.0%). This shift can be attributed to three main factors: increased water availability,
- 367 improved water quality, and enhanced water supply reliability.

368 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 369 370 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 371 agricultural irrigation, have significantly augmented the overall water resource capacity in the 372 373 country (Fig. 1, Table S2 online). For example, Lake Qiandaohu (Xin'anjiang Reservoir) was 374 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  $9.78 \times 10^8 \text{ m}^3$ 375 376 drinking water for more than 10 million people of Hangzhou and Jiaxing, Zhejiang Province. Most 377 reservoirs are strategically located in mountainous and hilly areas in the middle and upper reaches 378 of rivers, situated far from urban and industrial areas. These remote locations translate to minimal 379 industrial, agricultural, and domestic pollution, resulting in good water quality. Consequently, these 380 reservoirs can provide a clean and abundant water resource for drinking water as shown by the 381 global increasing dependence of lowland populations on mountain water resources [48]. Meanwhile, 382 many cross-regional and cross-basin water transfer projects and infrastructure construction are 383 increasing the contribution and importance of lake and reservoir CDWSs [14, 49]. For example, the 384 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 385 386 municipalities covering 24 cities, 131 counties, and 310 water plants, and benefiting 85 million 387 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 388 Project of SNWD in 2013. In 2022, a total of  $92.12 \times 10^8$  m<sup>3</sup> of water was transported from 389 390 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 391 392 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 393 394 water infrastructure constructions significantly increase the available freshwater resource of lakes 395 and reservoirs for drinking water.

396 Correspondingly, yearly groundwater water supply reached a maximum of 1134×10<sup>8</sup> m<sup>3</sup> in 2012 and gradually decreased to  $828 \times 10^8$  m<sup>3</sup> in 2022 with a decrease of 27.0% indicating a 397 398 decreasing contribution (Fig. S7 online). Notably, we further chose the most populous province 399 (Shanxi Province, which is also affected by arsenic-contaminated groundwater) from 6 north 400 provinces with high groundwater CDWS percentages including Nei Mongol, Shanxi, Xizang, Qinghai, Xinjiang, and Ningxia provinces, to quantify the decreasing contribution of groundwater. 401 402 From 2016 to 2023, the percentages of prefecture-level CDWSs number and annual total water 403 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 404 CDWS number corresponded to 58.4%-68.4% of the total water intake amount from groundwater 405 406 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 407 408 online).

409

However, it is crucial to acknowledge that there are some negative ecological problems and

410 risks associated with reservoir construction. Dams disrupt the natural flow of materials both 411 upstream and downstream, causing the fragmentation of rivers. This fragmentation substantially 412 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 413 414 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 415 416 contributes to an increase of these potentially harmful microorganisms [52, 53]. Therefore, many 417 small-sized reservoirs have been gradually removed to increase river water system connectivity and 418 eliminate negative ecological risks with decreasing small-sized reservoirs since 2018 (4.08% 419 decrease from 2018 to 2022) in China (Table S2 online).

420 Secondly, water quality indicated by four key parameters (BOD, TN, NH<sub>4</sub><sup>+</sup>, and TP) of lakes 421 and reservoirs had been greatly improved over the past 20 years in China (Fig. 3, Fig. 4), which 422 were attributed to the marked decrease of nitrogen and phosphorus consumption of cropland and 423 significant increasing investment in urban environmental infrastructure construction and industrial 424 pollution source control (Fig. S10, Fig. S11 online). Meanwhile, significant increase in water clarity 425 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 426 427 parameters reflecting different human activities and climate change pressures (Fig. 2, Fig. 3). Indeed, 428 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 429 430 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 431

432	standards for surface water quality and sector-specific discharges of point source water pollutants,
433	and large investments in urban environmental infrastructure and industrial wastewater treatment
434	(Fig. S11 online), contributed to water quality improvements in China [28, 29], which will provide
435	the guideline for other countries and regions facing similar challenges. China Ecological
436	Environment Status Bulletin 2022 showed that 87.9% of sampling sites had water quality better
437	than Class III according to the China Surface Water Environmental Quality Standard (GB3838-
438	2002), while only 0.7% of sites had water quality worse than Class V based on a national
439	investigation of 3,641 sampling sites in rivers, lakes, and reservoirs across China [40]. Due to the
440	improvement of water quality in Lake Taihu, a yearly total $12.8 \times 10^8$ m <sup>3</sup> of water from the lake was
441	used for the drinking water of Shanghai, the largest city in China, since 2017 with an additional
442	yearly total $12.2 \times 10^8$ m <sup>3</sup> of water supplying the surrounding cities of Suzhou, Wuxi, and Huzhou
443	(Fig. S9 online), which benefited more than 15 million people. These findings underscore the
444	ongoing progress in improving water quality in lakes and reservoirs, a trend the we anticipate to
445	continue with the implementation of Beautiful China Initiative, the major strategic idea and task for
446	the sustainable development of China to fulfil the United Nations' SDGs. Specifically, by 2035,
447	there will be a fundamental improvement in the quality of the environment so the goal of building
448	a Beautiful China will be basically attained, which will undoubtedly increase the value of drinking
449	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, 454 CDWSs turn to the lakes and reservoirs for freshwater resources supply instead of seagoing rivers. 455 In the natural course of events, droughts or floods typically lead to alterations in catchment runoff, 456 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 457 458 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 459 460 transfer of water from periods of abundance to periods of scarcity, effectively meeting the demand for drinking water during times of shortage [55]. 461

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.

469 **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

476	the 1980-90s to 2000s while experienced a significant increase of 113.7% (from 6.79% to 14.51%)
477	from the 2000s to the 2010s (Fig. 6). Pronounced increases in bloom occurrence were detected in
478	lakes across the entire country, with the exception of some lakes in northeastern China during the
479	2010s. Steady bloom occurrence increases were particularly notable in lakes distributed in eastern,
480	southern, and southwestern regions of China with the extensive distribution of freshwater lake and
481	reservoir CDWSs. Several drinking water sources including Lake Taihu, Jiefangshan Reservoir,
482	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

490

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

491 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 492 493 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 494 blooms, especially in the context of climate warming. Algal blooms can manifest even in waters 495 496 characterized by very low concentrations of nitrogen and phosphorus [18, 59]. In summary, there 497 are at least three mechanisms to explain the inconsistent changes between TN, TP improvement and 498 algal bloom appearance.

499 First, as a typical ecological phenomena and disaster, the outbreak or alleviation of algal 500 blooms often lag significantly behind the deterioration or improvement of water quality due to timelag effects [60]. Meanwhile, TN and TP have not decreased below the critical thresholds (TN  $\leq 0.8$ 501 502 mg/L, TP  $\leq 0.05$  mg/L) to limit phytoplankton growth (Fig. S4) [61]. Therefore, the alleviation of 503 algal bloom by nutrient reduction is slow, resulting in high algal bloom outbreak in China's lakes 504 and reservoirs during the 2010s. Encouragingly, the occurrence of algal blooms has markedly 505 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. 506 507 6), which were ever affected by frequent HABs in past decades.

508 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,
- 510 62, 63]. For example, the extensive or record-breaking HABs were observed in oligotrophic and

511	mesotrophic Lake Qionghai (TN: 0.40 mg/L, TP: 0.021 mg/L in 2019) and Fuchunjiang Reservoir
512	(TN: 1.94 mg/L, TP: 0.063 mg/L in 2021) in 2022 experiencing the unprecedented extreme
513	heatwaves and drought (Fig. S13 online). Similarly, nuisance phytoplankton blooms were found in
514	oligotrophic Lake Qiandaohu by high frequency observation and remote sensing monitoring in
515	summer 2016 suffering from an extreme heatwave [62]. Meanwhile, storm and extreme
516	precipitation played a more important role in HABs formation and expansion by increasing nutrients
517	supply [64, 65]. Severe spring precipitation events in 2011, coupled with long-term increasing trends
518	in agricultural land use and practices, produced a pulse of remarkably high loading of highly
519	bioavailable dissolved reactive phosphorus to the western basin of Lake Erie, which ultimately
520	resulted in a record-breaking HAB with a surface area of more than 5000 km <sup>2</sup> in Lake Erie [15].
521	Our data showed that lakes and reservoirs are warming in China (Fig. S12 online), which will likely
522	result in the increasing HABs even if nutrient levels remain unchanged.
523	Third, climate change offsets the alleviation of HABs caused by nutrient reduction. An example
524	analysis in Lake Taihu showed HABs can only be alleviated by about 10% with a 90% probability,
525	but the changes in climatic factors (e.g., declining wind speed, increasing temperature) have offset

526 the alleviation effect of nutrient reduction on cyanobacterial blooms according to the results of

Bayesian models [66].

527

HABs can form surface scums and deplete bottom-water oxygen, which may threaten the 528 529 safety of drinking water in CDWSs because HABs are toxic and a hazard by releasing microcystin 530 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 531 532 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.

540

#### 4.4 Implications for drinking water safety

541 Access to sustainable and safe drinking water supply is essential to human welfare. However, 542 maintaining and safeguarding a good drinking water quality is a global challenge [41, 43, 46], 543 because water scarcity is projected to be more severe. Ongoing groundwater depletion may pose a 544 serious water security risk in intense agricultural regions and cause higher vulnerability under an 545 uncertain climate [49, 71]. At the same time, population, water and land use pressure are expected 546 to increase further leading to considerable challenges to water pollution and environmental 547 sustainability [15, 21]. It will be imperative to also consider the effects and risks of extreme 548 meteorological and hydrological events on lakes and reservoirs especially with a view to global 549 climate changes for facilitating water resources management [15, 56, 72]. Our findings of the 550 growing significance and pivotal role of lakes and reservoirs as primary drinking water sources 551 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 552 553 lakes and reservoirs pollution and improve the water quality because lakes and reservoirs are 554 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].

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- 567 Author contributions

568 Y.Z. proposed the main idea, collected the data and wrote the paper. All authors contributed 569 significantly to the analysis and interpretation of the results as well as to the editing of the 570 manuscript.

571

## 572 **Conflict of Interest Statement**

573 The authors declare no competing interests.

574

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1	Supporting materials
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3	Enhancing drinking water safety through improved water quantity
4	and quality management
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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



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



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)





58 Fig. S8 Increasing water consuming population (a) and water supply capacity (b) for urban residents

from 2004 to 2022 in China



61 Fig. S9 Increasing water intake amounts from Danjiangkou Reservoir as the water source of the

62 Middle Route Project of the South-to-North Water Diversion (SNWD) (a) and Lake Taihu as the

63

water source of the surrounding Shanghai, Suzhou, Wuxi and Huzhou (b)







66 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/).



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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 73

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zones and all (n=2260)



	2016							2023						
Provinces	Prefec	ture-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 <sup>*</sup>	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 <sup>*</sup>	9	10	14	/	/	/	10	9	13	36	41	16		
Guangdong	29	46	5	68	86	5	41	47	0	86	81	0		

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

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 <sup>*</sup>	9	0	30	/	/	/	20	0	20	30	3	75
Henan <sup>*</sup>	3	11	24	/	/	/	20	9	27	62	20	83
Helongjiang <sup>*</sup>	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 <sup>*</sup>	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 <sup>*</sup>	31	8	0	/	/	/	40	7	0	128	31	9
Zhejiang	/	/	/	67	25	0	/	/	/	82	16	0

81 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

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comparison in 2016 and 2023.

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

		Large-size reservoir Total storage		e-size reservoir	Mediun	n-size reservoir	Small-sized reservoir		
Year	Number	Total storage -		Total storage		Total storage		Total storage	
		capacity (10° m <sup>3</sup> )	Number	capacity (10 <sup>8</sup> m <sup>3</sup> )	Number	capacity $(10^8 \mathrm{m}^3)$	Number	capacity $(10^8 \text{ m}^3)$	
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

85 Note: large-sized reservoir: storage capacity  $\geq 1.0 \times 10^8$ ; medium-size reservoir:  $1.0 \times 10^7 \leq$  storage capacity  $< 1.0 \times 10^8$ ; small-sized reservoir:  $1.0 \times 10^5 \leq$  storage capacity  $< 1.0 \times 10^8$ ; small-sized reservoir:  $1.0 \times 10^5 \leq$  storage capacity  $< 1.0 \times 10^8$ ; small-sized reservoir:  $1.0 \times 10^5 \leq$  storage capacity  $< 1.0 \times 10^8$ ; small-sized reservoir:  $1.0 \times 10^5 \leq$  storage capacity  $< 1.0 \times 10^8$ ; small-sized reservoir:  $1.0 \times 10^8 \leq$  storage capacity  $< 1.0 \times 10^8$ ; small-sized reservoir:  $1.0 \times 10^8 \leq$  storage capacity  $< 1.0 \times 10^8 \leq$  storage capacity <

86	capacity < $1.0 \times 10^7$
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Table S3 Monthly wa	ter intake amounts ar	nd percentage	of lakes a	and reservoirs,	rivers ir	n Zhejiang	Province

Year	Туре	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
2016	Rivers	Amount (10 <sup>4</sup> )	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	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
	reservoir		56.0	00.1	57.0	00.1	57.5	57.7	00.1	57.1	00.5	00.7	57.0	00.2	57.7
2017	Rivers	Amount (10 <sup>4</sup> )	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	Amount (10 <sup>4</sup> )	21014	20353	18989	19819	20210	20653	20891	22114	23281	22362	21293	21363	252342
	reservoir	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 <sup>4</sup> )	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	Amount (10 <sup>4</sup> )	20553	19702	18329	20356	21262	21703	22078	23034	24124	23500	22063	21308	258012
	reservoir	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 <sup>4</sup> )	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 <sup>4</sup> )	21311	21217	18021	19464	21564	21165	21967	22663	25154	28846	27870	27374	276616

	Lakes and	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
	reservoir		57.1	57.7	01.1	57.4	00.5	57.7	00.0	57.5	00.0	12.1	12.9	12.5	05.4
2022	Rivers	Amount (10 <sup>4</sup> )	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	Amount (10 <sup>4</sup> )	25611	24846	22460	25998	26041	24876	26234	29676	32284	32686	31194	28661	330567
	reservoir	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 <sup>4</sup> )	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	Amount (10 <sup>4</sup> )	30832	27569	27156	27547	28601	28348	28689	30900	32676	31915	29822	28396	352451
	reservoir	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

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

Reservoir			
Wanjiazai	12	Taiyuan, Suozhou, Datong prefecture-level regions in Shanxi province	/
Reservoir			
Shitouxia	7.5	Xining, Haibei, and Haidong prefecture-level regions in Qinghai province	3
Reservoir and			
Heiquan			
Reservoir			
Lake	7.3	Changchun, Siping, and Liaoyuan prefecture-level regions in Jilin	10.6
Songhuahu		province	
	Reservoir Wanjiazai Reservoir Shitouxia Reservoir and Heiquan Reservoir Lake Songhuahu	ReservoirWanjiazai12Reservoir12Shitouxia7.5Reservoir and12Heiquan12Reservoir12Lake7.3Songhuahu12	Reservoir       12       Taiyuan, Suozhou, Datong prefecture-level regions in Shanxi province         Reservoir       12       Taiyuan, Suozhou, Datong prefecture-level regions in Shanxi province         Shitouxia       7.5       Xining, Haibei, and Haidong prefecture-level regions in Qinghai province         Reservoir       and         Heiquan       Reservoir         Lake       7.3       Changchun, Siping, and Liaoyuan prefecture-level regions in Jilin         Songhuahu       province

Table S5 Comparison of the percentages of CDWSs number and annual total water intake amounts

	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	Groundwater	29158	30549	32694	33598	33790	34240	34940	34149
amounts (10 <sup>4</sup>	Lake and Reservoir	12729	12903	13682	13337	14557	15665	19299	21914
m <sup>3</sup> )	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

of three CDWS types in Shanxi Province during 2016-2023

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101 Table S6 Comparison of intake amount of 21 prefecture-level CDWSs in Heilongjiang Province in

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summer (July-August) and winter (November, January, and February) from 2023 to 2024

		Water source	Monthly intake amount (m <sup>3</sup> )				
City	Water source name	type	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
	Tuanshan Reservoir	Reservoir	0	0	0	0	0
Jixi	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

	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
Decing	Hongqi Reservoir	Reservoir	450.0	440.0	402.0	395.0	400.0
Daqing	Dongcheng	Deservein	520.0	515.0	510.0	510.0	505.0
	Reservoir	Keservoir					303.0
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
NA 1 "	Xishuiyuan	River	495.0	545.0	479.0	532.0	528.0
windanjiang	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