

20 **Abstract**

21 The Yangtze River Basin (YRB), home to around 400 million people, boasts of
22 abundant water resources and significant spatial heterogeneity. Revealing the driving
23 factors of water storage changes in YRB is essential for effective water resource
24 management and sustainable development. In this study, we assess the drivers of total
25 water storage (TWS) changes derived from the Gravity Recovery and Climate
26 Experiment (GRACE) satellite within YRB from two perspectives: water balance and
27 water storage components, including snow water equivalent (SWE), surface water
28 storage (SWS), soil moisture storage (SMS), and groundwater storage (GWS). We
29 also investigate the influence of reservoirs (e.g., Three Gorges Reservoir (TGR)),
30 lakes (e.g., Dongting, Poyang, and Taihu), and glacier thawing on regional TWS
31 changes. The results reveal an apparent increasing trend in YRB's TWS from 2002 to
32 2022, while trends in precipitation, evapotranspiration, and runoff do not adequately
33 account for this observed trend. In addition, our findings show that the increased TWS
34 primarily occurs during the non-monsoon season, characterized by limited
35 precipitation. The analysis of water components shows that the rise in TWS within
36 YRB is predominantly attributed to GWS accumulation. SWS also contributes to the
37 increasing TWS, primarily driven by the reservoir filling. The filling of TGR explains
38 the observed TWS increase in Hubei province, whereas Lake Poyang accounts for
39 about 30% of the positive TWS trend in Jiangxi province. Our comprehensive
40 analysis systematically unveils the drivers of water storage changes in YRB,
41 providing valuable insights for its sustainable water resource management and
42 utilization.

43 **Keywords:** GRACE; water balance equation; water storage components; groundwater
44 accumulation

45 **1. Introduction**

46 Recognized as one of China's most significant cultural and socioeconomic
47 regions, the Yangtze River Basin (YRB) plays a critical role in national water resource
48 management and ecological conservation (Chao et al., 2023). This region is densely
49 populated and of great importance, with an annual average water resource of about
50 995.5 billion cubic meters, of which over 200 billion cubic meters are allocated for
51 water supply (Wang et al., 2023). Nevertheless, the Yangtze River remains one of the
52 world's top ten rivers in terms of water scarcity (Dai et al., 2008). This is primarily
53 due to the escalating water requirements for agricultural purposes, industrial activities,
54 energy generation, and drinking water within this basin (Yang et al., 2015). Over the
55 past few decades, human activities and climate change have joint forces to
56 significantly alter the hydrological cycle of YRB, resulting in a higher frequency of
57 floods and droughts in this region (Shan et al., 2018; Yang et al., 2021b; Wang and
58 Chen, 2022; Xie et al., 2022). For example, the abnormal heat waves during the
59 summer of 2022 led to long-lasting droughts that severely affected YRB (Lu et al.,
60 2022). Conversely, the summer of 2020 witnessed historic floods in the basin, which
61 had catastrophic socioeconomic consequences (Zhou et al., 2021; Yan et al., 2022). As
62 a result, over the past half-century, more than 50 thousand reservoirs have been built
63 to regulate river flows and secure adequate water supply in YRB. These reservoirs
64 collectively impounded nearly 360 billion cubic meters of water in 2021 (Ministry of
65 Water Resources of the People's Republic of China). In addition, many valuable
66 freshwater resources (e.g., lakes) are readily accessible for human consumption.
67 Therefore, understanding the drivers of water storage changes in YRB can inform
68 sustainable water management practices, help mitigate the impact of water scarcity,
69 and ensure the basin's long-term environmental and economic stability.

70 Since its launch in 2002, the Gravity Recovery and Climate Experiment (GRACE)
71 satellites have provided invaluable observations, i.e., total water storage (TWS), for
72 investigating global or regional water availability and distribution ([Tapley et al., 2019](#);
73 [Gao et al., 2021](#)). Changes in TWS reflect the changes in regional mass redistribution
74 and hydrological cycles from both natural variability and anthropogenic activities
75 (e.g., [Awange et al., 2013](#); [Felfelani et al., 2017](#); [Hosseini-Moghari et al., 2020](#)),
76 which can be used to characterize droughts and floods (see e.g., [Long et al., 2014](#);
77 [Thomas et al., 2014](#); [Tangdamrongsub et al., 2016](#); [Xie et al., 2022](#); [Zheng et al.,](#)
78 [2023](#)), monitor groundwater depletion (e.g., [Agutu et al., 2019](#); [Frappart et al., 2019](#);
79 [Feng et al., 2022](#)), and close the terrestrial water budget ([Chen et al., 2020](#); [Rodell &](#)
80 [Reager, 2023](#)).

81 To date, GRACE-derived TWS observations have been applied to numerous river
82 basins worldwide (e.g., [Awang et al., 2011](#); [Tangdamrongsub et al., 2015](#); [Zhang et al.,](#)
83 [2023](#)), among which YRB was one of the most extensively examined regions
84 regarding spatiotemporal dynamics of TWS (e.g., [Huang et al., 2015](#); [Sun et al., 2018](#);
85 [Wang et al., 2020](#); [Xie et al., 2022](#)). Nevertheless, previous studies predominantly
86 concentrated on delineating and characterizing droughts and floods within this region.
87 Due to the confluence of anthropogenic activities and the impacts of climate change,
88 YRB has experienced a significant upward trend in TWS over recent years ([Chao et](#)
89 [al., 2023](#); [Xu et al., 2023](#)). However, the drivers behind this trend have remained a
90 subject of limited exploration in prior research endeavors. [Huang et al. \(2015\)](#)
91 indicated that the observed trends in TWS over YRB were highly likely due to the
92 anthropogenic interventions in the hydrological cycle rather than natural climate
93 variability. However, their investigation only presented the qualitative results for three
94 specific regions within YRB, leaving systematic and quantitative analysis of the

95 whole basin absent.

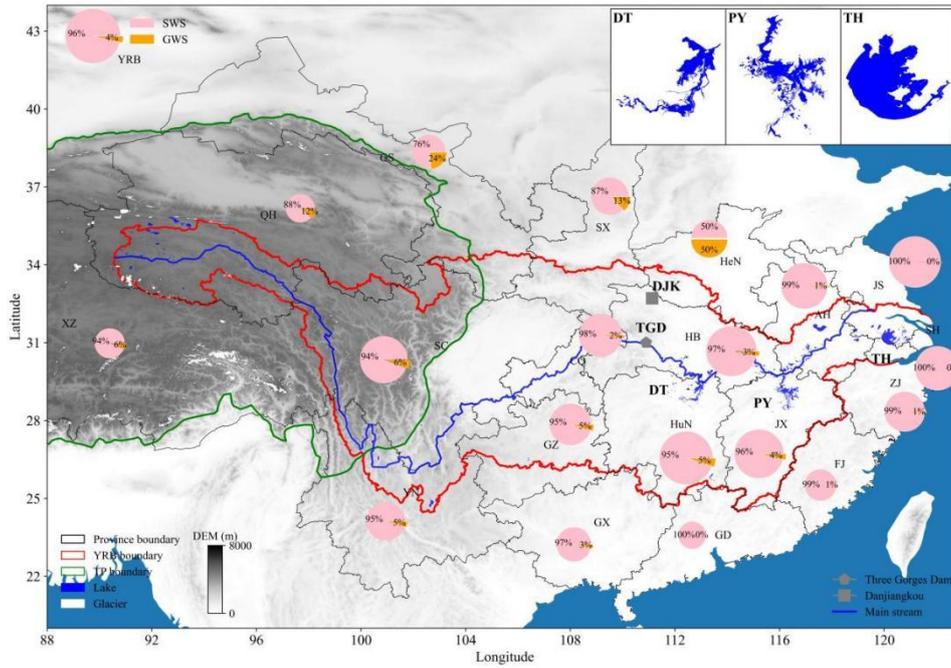
96 GRACE-derived TWS encompasses all terrestrial water components such as
97 snow, ice, surface water (e.g., lakes and reservoirs), soil moisture, and groundwater.
98 Global hydrological or land surface models have been commonly used ([Feng et al.,
99 2022](#); [Schumacher et al., 2018](#)) to discern these distinct water components. The
100 results of [Chao et al. \(2021\)](#) showed that respective contributions of glaciers, surface
101 water, soil moisture, and groundwater to TWS changes over YRB for the period
102 2002-2015 amounted to 15%, 12%, 25%, and 48%, respectively. In their subsequent
103 investigation ([Chao et al., 2023](#)), they further elucidated that precipitation,
104 evapotranspiration, and runoff collectively account for approximately 46%, 27%, and
105 27% of the variations in TWS within YRB, respectively. However, the factors driving
106 the changes in the trend of YRB's TWS and its components were not discussed.
107 Furthermore, TWS over YRB exhibits a heterogeneous spatiotemporal variability
108 owing to its complicated topography and landscapes. The source region of YRB starts
109 from the Tibetan Plateau, where glacier retreat, snowmelt, permafrost degradation,
110 and lake expansion have had a significant impact on TWS due to global warming
111 ([Chao et al., 2020](#); [Deng et al., 2022](#); [Li et al., 2023](#)). In the middle-lower reaches of
112 the basin, numerous lakes and reservoirs, including the three largest freshwater lakes
113 (Poyang, Taihu, and Dongting), Three Gorges Reservoir (TGR), and the Danjiangkou
114 Reservoir (i.e., the origin for the Middle-Line South-to-North Water Diversion
115 Project), are present. Although previous studies have independently reported their
116 contributions to TWS changes within YRB ([Wang et al., 2011](#); [Long et al., 2020](#); [Xu
117 et al., 2020](#); [Chao et al., 2023](#)), a comprehensive, integrated and updated analysis is
118 still lacking.

119 A wealth of multisource data, including satellites, reanalysis data, hydrological

120 models, and in-situ observations, enables a more comprehensive and holistic view of
121 hydrological processes (e.g., [Awang et al., 2014](#); [Awange et al., 2019](#); [Arsenault et al.,](#)
122 [2020](#); [Awange, 2020](#); [Awange, 2021](#); [Chao et al., 2023](#); [Feng et al., 2023](#); [Li et al.,](#)
123 [2023](#)). Meanwhile, integrating these diverse datasets instills robust confidence,
124 providing a solid foundation for facilitating evidence-based decision-making in
125 environmental policies. However, previous studies lacked a mutual verification
126 process with multiple datasets before assessing changes in TWS within YRB.
127 Therefore, the reliability of the research findings needs further validation. In this study,
128 each data employed will undergo a validation procedure to enhance the robustness
129 and reliability of our findings, contributing to the overall credibility of the study.
130 Subsequently, we aim to reveal the drivers of YRB's TWS from two perspectives:
131 water balance and water storage components. This multifaceted approach enables a
132 comprehensive understanding of the intricate processes influencing YRB's TWS,
133 providing valuable insights for future advancements in water resource management.

134 **2. Study area**

135 The Yangtze River, also known as the Changjiang River, is the longest river in
136 China and the third longest in the world. It stretches over 6300 kilometers from its
137 source in the Tibetan Plateau to its mouth at the East China Sea ([Fig. 1](#)). YRB covers
138 an area of approximately 1.8 million square kilometers and 19 provincial
139 administrative regions ([Table 1](#)), accounting for approximately 20% of China's
140 territory. Additionally, YRB contributes about 40% of China's total GDP ([Li et al.,](#)
141 [2021](#)). Due to the influence of the East Asian Summer Monsoon and the South China
142 Sea Summer Monsoon, annual precipitation in YRB is lower in the north than in the
143 south, decreasing from southeast to northwest. In contrast, the annual temperature is
144 higher in the east than in the west, increasing from north to south ([Sun et al., 2018](#)).



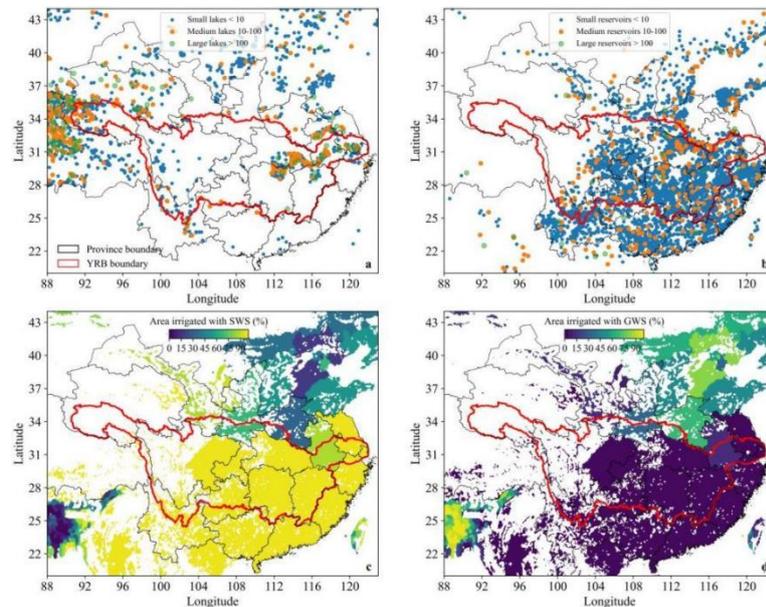
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146 **Fig. 1.** Map of the Yangtze River Basin (YRB) in China, with streams, lakes, the Three Gorges
 147 Dam (TGD), and Danjiangkou (DJK) reservoir. The green line represents the boundary of the
 148 Tibetan Plateau (TP), with glaciers denoted in white. To the upper right of the figure, an enlarged
 149 view is provided of the three largest lakes: Dongting (DT), Poyang (PY), and Taihu (TH). The pie
 150 chart depicts the proportion of surface water and groundwater sources supplied from
 151 provincial-level administrative regions within YRB. The larger size of the chart indicates a greater
 152 volume of total water supply to YRB. These proportions are derived from the data provided by
 153 [Ministry of Water Resources of the People's Republic of China](#) from 2003 to 2021.

154 Surface water bodies, notably lakes and reservoirs, provide valuable water
 155 resources within YRB. In general, most lakes are situated in the regions of Qinghai,
 156 Hunan, Hubei, Jiangxi, and certain coastal cities ([Fig. 2a](#)), whereas reservoirs are
 157 distributed in the middle and lower reaches of YRB ([Fig. 2b](#)). Due to the rapid
 158 expansion of population and economic development, the aggregate water demand (i.e.,
 159 domestic, agricultural, industrial, and environmental water use) in YRB has exhibited
 160 a substantial increase, surging from approximately 170 billion cubic meters in 2003 to
 161 214 billion cubic meters in 2022 ([Ministry of Water Resources of the People's
 162 Republic of China](#)). It is noteworthy that nearly 96% of the region's water supply is
 163 sourced from surface water resources, while groundwater contributes relatively high

164 in the provinces of Gansu, Shanxi, and Henan (Fig. 1). Grain production in YRB
165 accounts for approximately 40% of the total production in China, which commands
166 more than half of the total water consumption within the region (Long et al., 2015).
167 Predominantly, irrigation practices are concentrated in the middle and lower regions
168 of YRB, where a substantial portion of the land is irrigated utilizing surface water
169 sources (Figs. 2c-d).

170 While much research has been conducted on TWS in YRB at various watershed
171 scales, few studies have performed the analysis at the provincial level. Therefore, in
172 this study, we divide YRB into nine sub-regions (Table 1) by merging specific
173 adjacent provinces or autonomous regions while also considering the footprint of
174 GRACE. We have omitted the provinces of Guangdong and Fujian from further
175 analysis due to their relatively minor spatial extent within YRB.



176

177 **Fig. 2.** (a) Distribution of large, medium, and small lakes derived from the China Lake Dataset for
178 the year 2020 (Zhang et al., 2019a), and (b) large, medium, and small reservoirs derived from
179 GeoDAR (Wang et al., 2022). Area irrigated with (c) surface water and (d) groundwater expressed
180 as a percentage of total area equipped for irrigation from WGHM.

181

182 **Table 1.** Information of the 19 provincial administrative regions and specific study regions within
 183 YRB.

Administrative Regions (Abbr.)	Area, 10^4 km^2	Area within YRB, 10^4 km^2	Proportion of YRB, %	Study regions (Abbr.)
Chong Qing (CQ)	8.24	8.24	4.58	Chong Qing (CQ)
Guang Xi (GX)	23.76	0.86	0.48	GX-HuN
Hu Nan (HuN)	21.18	20.68	11.49	(GH)
Gan Su (GS)	42.58	3.63	2.02	GS-HeN-SX
He Nan (HeN)	16.7	2.75	1.53	(GHS)
Shan Xi (SX)	20.56	7.09	3.94	
Gui Zhou (GZ)	17.62	11.57	6.43	Gui Zhou (GZ)
Hu Bei (HB)	18.59	18.44	10.25	Hu Bei (HB)
Jiang Xi (JX)	16.69	16.31	9.06	Jiang Xi (JX)
Jiang Su (JS)	10.72	3.89	2.16	
Zhe Jiang (ZJ)	10.55	1.41	0.78	JS-ZJ-SH-AH
Shang Hai (SH)	0.63	0.63	0.35	(JZHW)
An Hui (AH)	14.01	6.60	3.67	
Qing Hai (QH)	72.23	15.84	8.80	Qing Hai (QH)
Si Chuang (SC)	48.6	46.70	25.94	SC-XJ-YN
Xi Zang (XZ)	122.84	4.30	2.39	(SXY)
Yun Nan (YN)	39.41	10.90	6.06	
Fu Jiang (FJ)	12.4	0.12	0.06	Discarded
Guang Dong (GD)	17.98	0.05	0.03	Discarded

184

185 3. Materials and Method

186 3.1. Data and processing

187 [Table 2](#) summarizes the datasets used in this study and their respective origins,
 188 including GRACE/GRACE-FO data, hydrological data, water storage components,
 189 and other supplementary data. When necessary, the data is resampled to 0.25-degree
 190 grid space to ensure a consistent spatial resolution required for analysis.

191 3.1.1. GRACE and GRACE-FO data

192 GRACE/GRACE-FO was a joint satellite mission between the National
 193 Aeronautics and Space Administration (NASA) and the German Aerospace Centre
 194 (DLR), with the primary objective of monitoring the time variable gravity field. This
 195 field reflects the monthly redistribution of Earth's mass, which is dominated by

196 hydrology (Tapley et al., 2019). GRACE provides gravity data from April 2002 to
197 October 2017 (during its lifetime), while GRACE-FO continues to provide data since
198 May 2018. In this study, mascons data from the Center for Space Research (CSR), Jet
199 Propulsion Laboratory (JPL), and Goddard Space Flight Center (GSFC) are employed.
200 It's worth noting that the gain factors provided with JPL mascons are used to restore
201 much of the lost signal within YRB (Scanlon et al., 2016). The examination in Fig. S1
202 reveals notable correlations and minimal discrepancies among these three products in
203 YRB. As a result, their ensemble is employed for our analysis.

204 3.1.2. Hydrological data

205 In a given river basin, the total water storage changes (TWSC) can be determined
206 by the rate balance between precipitation (P), evapotranspiration (ET), and runoff (R)
207 via the water balance equation as (Chen et al., 2020). We have compared the
208 precipitation series from the Climate Research Unit (CRU) gridded Time-Series
209 datasets (Harris et al., 2020), the NOAH model from the Global Land Data
210 Assimilation System (GLDAS, Beaudoin & Rodell, 2020), and NOAA Climate
211 Prediction Center (CPC, Xie et al., 2007). The results reveal high correlations
212 observed among the three types of precipitation data (Fig. S2), and thus, their
213 ensemble is used in this study. Nevertheless, less agreement was found in
214 evapotranspiration and runoff datasets (Chen et al., 2020; Long et al., 2014). We have
215 compared the evapotranspiration series from NOAH, the European Centre for
216 Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA5, Muñoz-Sabater,
217 2019), and the Global Land Evaporation Amsterdam Model (GLEAM, Martens et al.,
218 2017), as well as the runoff series from NOAH, ERA5, and the Catchment Land
219 Surface Model (CLSM) from GLDAS. While high correlations are observed among
220 these datasets, they show relatively large differences regarding the amplitude (Fig. S3

221 and Fig. S4).

222 To identify the most suitable evapotranspiration and runoff products for use in
223 this study, we conduct a comparative analysis of TWSC derived from GRACE against
224 water balance estimates, which involves systematically testing various combinations
225 of these products. As illustrated in Fig. S5 and Fig. S6, TWSC derived from the water
226 balance equation using the CLSM's runoff data consistently exhibits high consistency
227 with that derived from GRACE, regardless of the specific evapotranspiration products
228 employed. Hence, we employ the runoff data from CLSM and the ensemble
229 evapotranspiration from the three sources in this study.

230 3.1.3. Water storage components

231 As the contribution of the vegetation water storage is negligible over YRB ([Wang
232 et al., 2020](#)), GRACE-derived TWS can be taken to be the summation of snow water
233 equivalent (SWE), surface water storage (SWS), soil moisture storage (SMS), and
234 groundwater storage (GWS) ([Wang et al., 2020](#)) as:

$$235 \quad \text{TWS} = \text{SWE} + \text{SWS} + \text{SMS} + \text{GWS} \quad (1)$$

236 Compared with the dataset of long-term series of snow depth in China, initially
237 developed by [Che et al. \(2015\)](#) using passive microwave remote-sensing data, SWE
238 sourced from NOAH exhibits reliable performance within YRB (Fig. S7). Meanwhile,
239 SMS obtained from NOAH correlates well with that obtained from ERA5 (Fig. S8).
240 Therefore, NOAH-derived SWE and the ensemble SMS derived from NOAH and
241 ERA5 are used for further analysis.

242 Nevertheless, SWS and GWS persist as two of the most underrepresented or
243 unrepresented components in hydrological models ([Beaudoin & Rodell, 2020](#)). The
244 WaterGAP Global Hydrology Model (WGHM), subject to continuous refinement
245 since 1996, has been employed to quantify human use of groundwater and surface

246 water (Müller et al., 2021). The observed agreement between GRACE-derived TWS
247 and WGHM-derived TWS demonstrates the model's efficacy over YRB (Fig. S9). In
248 addition, reservoir water storage derived from WGHM shows a pronounced upward
249 trend, aligning with the notable increase in reservoirs within YRB (Fig. S10b). SWS
250 derived from WGHM shows consistent spatial distribution with the map of lakes and
251 reservoirs (Fig.2 and Figs. S10a-c) and correlates well with the surface water
252 resources data provided by the Ministry of Water Resources of the People's Republic
253 of China (Fig. S11). Therefore, we utilize the SWS data sourced from WGHM, while
254 GWS is determined using equation (5) by deducting other components from TWS.

255 3.1.4. Ancillary data

256 Annual water use data in terms of various water sources (i.e., SWS and GWS)
257 and sectors (agricultural, domestic, industrial, and environmental use) are derived
258 from the Bulletin of Water Resources in the Yangtze River Basin and Southwest
259 Rivers (Ministry of Water Resources of the People's Republic of China). Lakes and
260 reservoirs data are obtained from the China Lake Dataset (Zhang et al., 2019a) and
261 GeoDAR (Wang et al., 2022), respectively. The in-situ daily water level data of the
262 TGR and Danjiangkou Reservoir are sourced from the Hubei Water Resources
263 Commission (<https://slt.hubei.gov.cn/sjfb>). Water level collected at Chenglingji and
264 Hukou stations that are used to calculate the volume anomalies of Lake Dongting and
265 Lake Poyang, respectively, is provided by the Hydrology Bureau of the Changjiang
266 Water Resources Commission, China (<http://www.cjh.com.cn>). Lake Taihu's water
267 level is downloaded from the Taihu Laboratory for Lake Ecosystem Research
268 (<http://thl.cern.ac.cn>). Furthermore, the altimetry satellite-derived water level from the
269 Database for Hydrological Time Series of Inland Waters (DAHITI,
270 <https://dahiti.dgfi.tum.de/en>) and Hydroweb (<https://hydroweb.theia-land.fr/>) are

271 employed for comparison analysis. The glacier runoff data from 2003 to 2015 is
 272 sourced from Wang et al. (2021).

273 **Table 2.** Datasets used in this study

Dataset	Variable	Time span	Resolution, °	Data source	Reference
JPL RL06.1Mv03			0.5	https://podaac.jpl.nasa.gov/dataset/TELLUS_GRAC-GRFO_MASCON_GRID_RL06.1_V3	Wiese et al. (2019)
CSR RL06.2 M	TWS		0.25	https://www2.csr.utexas.edu/grace/RL06_mascons	Save et al. (2016)
GSFC RL06v2.0			0.5	https://earth.gsfc.nasa.gov/geo/data/grace-mascons	Loomis et al. (2019)
CRU V4.07	P, T	2002-2022	0.5	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.07	Harris et al. (2020)
CPC Global Precip	P		0.5	https://www.psl.noaa.gov/data/gridded/data.cpc.globalprecip	Xie et al. (2007)
ERA5-Land	ET, R, SMS		0.1	https://doi.org/10.24381/cds.68d2bb30	Muñoz-Sabater. (2019)
NOAH V2.1	P, ET, R, SWE, SMS		0.25	https://ldas.gsfc.nasa.gov/gldas	Rodell et al. (2004)
CLSM V2.1	R, SWE, SMS		1		
WGHM V2.2d	SWS	2002-2019	0.5	https://doi.pangaea.de/10.1594/PANGAEA.918447	Müller et al., 2021
GLEAM v3.8a	ET	2002-2022	0.25	https://www.gleam.eu/#downloads	Martens et al. (2017)
China snow depth	SD	2002-2021	0.25	https://doi.org/10.11888/Geogra.tpdc.270194	Che et al. (2015)
Glacier runoff dataset	Glacier	2003-2015	-	https://data.tpdac.ac.cn/zh-hans/data/b33dc082-b899-4ee1-8942-d0b5962e4e7f	Wang et al. (2021)
China Lake Dataset	Lake	2020	-	https://data.tpdac.ac.cn/en/data/fa8426c0-d3f0-4615-8e78-0465a0957891/	Zhang et al., 2019a
GeoDAR	Res	-	-	https://zenodo.org/records/6163413	Wang et al. (2022)
TGR, DJK				https://slt.hubei.gov.cn/sjfb	-
CLJ, HK DAHITI	Water level	2003-2021	-	http://www.cjh.com.cn	-
Hydroweb				https://dahiti.dgfi.tum.de/en https://hydroweb.theia-land.fr/	-

274

275 3.2. Method

276 3.2.1. Analyzing trends in hydrological data, TWS and its components

277 The spatiotemporal trends of hydrological data and water storage are detected by
 278 the nonparametric Mann-Kendall test, which does not require distributional
 279 assumptions about the time series and is robust against outliers and missing values
 280 (Panda & Wahr, 2016; Zhu et al., 2021). It has been recommended by the
 281 Intergovernmental Panel on Climate Change (IPCC) to be applied in a series of
 282 environmental, climate, and hydrological data (Meshram et al., 2020). The

283 Mann-Kendall test statistic S is calculated as (Liu et al., 2021):

$$284 \quad S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_i - x_j) \quad (4)$$

285 where x is the examined time series, n is the number of observations, and sgn is the
286 indicator function. For large sample sizes ($n > 10$), the test statistic Z_{MK} is
287 distributed approximately normally:

$$288 \quad Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}}}, & \text{if } S < 0 \end{cases} \quad (5)$$

289 where $\sqrt{\text{Var}}$ is the variance of S . If Z_{MK} is greater than 0, the data shows an
290 increasing trend, while the data shows a decreasing trend if Z_{MK} is less than 0. The
291 significance test is calculated using the Man-Kendall test with p -value < 0.05 ,
292 whereas the magnitude of the trend is estimated using the Theil-Sen's method (Seka et
293 al., 2022). Prior to computing trends, the seasonal cycle is removed following Rodell
294 et al. (2018)'s method.

295 3.2.2. Assessing the role of water components in TWS

296 To quantify the contribution of individual water components to TWS,
297 components contribution ratios (CCR) are used in this study as follows (Wang et al.,
298 2020):

$$299 \quad CCR_s = \frac{MAD_s}{TV} \quad (6)$$

300 where $MAD_s = \frac{1}{N} \sum_t^n |S_t - \bar{S}|$ is the mean absolute deviation (MAD) of a single
301 storage component, while $TV = \sum_s^{storages} MAD_s$ is total variability (TV), which is
302 the summation of MAD of each component. The subscript s denotes individual
303 water components (i.e., SWS, SWE, SMS, and GWS) and N is the number of
304 samples. The higher the CCR, the more significant the component's role in TWS.

305 3.2.3. Estimating volume anomalies in large reservoirs and lakes

306 The volume of the specified reservoirs and lakes is derived using the water
307 level-volume relationship. In particular, the volume V (km^3) of TGR is derived using
308 the in-situ water level H (m) data ($V = 0.2968 \times 1.0284^H$, $R^2 = 0.999$) (Wang et al.,
309 2011). The volume of Lake Dongting and Lake Poyang is estimated using the water
310 level at Chenglingji station (Yang et al., 2021a, $R^2 = 0.82$) and Hukou station (Liu et
311 al., 2013; Liu et al., 2020, $R^2 = 0.86$), respectively. The volume of Taihu Lake is
312 obtained using the water level data, following Zhang et al. (2013) ($R^2 = 0.99$).
313 Volume anomalies are derived by removing the 2004-2009 mean field.

314 4. Results

315 4.1. Trends in TWS and water balance components

316 Figure 3a illustrates a generally coherent increase in TWS within YRB in contrast
317 to apparent negative trends observed over the North China Plain and Eastern Indian
318 Region. These upward trends are particularly pronounced in Sichuan, Chongqing, and
319 Guizhou provinces. The observed positive trends are consistent with increasing
320 precipitation during the study period (Fig. 3b). Nevertheless, it is essential to note that
321 the amplitude of the increasing trends in precipitation is an order of magnitude lesser
322 than that of TWS (note the distinct units of the trend in the color-bar presented in Fig.
323 3). Despite the heightened concentration of precipitation in the southern regions of
324 YRB and coastal provinces, such as Shanghai, Jiangxi, and Hunan, the positive trends
325 in runoff, which generally correspond with the spatial distribution of the precipitation
326 (Fig. 3d), offset the growth of TWS in these areas. In addition, the trends in
327 evapotranspiration are relatively small to be responsible for YRB's TWS changes (Fig.
328 3c).

329 Figure 4 shows the annual changes and trends in TWS, precipitation,

330 evapotranspiration, and runoff for YRB and its nine sub-regions defined in this study.

331 Overall, TWS changes in YRB exhibit a statistically significant increasing trend at a

332 rate of 0.41 cm/yr. In comparison, the magnitude of the precipitation trend (0.09

333 cm/yr) accounts for about 22% of the TWS trend (Table 3). No significant trend

334 observed in the basin-averaged evapotranspiration, whereas runoff reveals a

335 significant positive trend (0.05 cm/yr) during the study period. Specifically, seven of

336 the nine sub-regions demonstrate a significant increase in TWS, with the largest trend

337 of 0.82 cm/yr in CQ and the lowest of 0.2 cm/yr in JZHW. Of the seven regions, only

338 three exhibit significant precipitation trends at rates of 0.05 cm/yr, 0.13 cm/yr, and

339 0.13 cm/yr in SXY, GZ, and GH, respectively. The observed increasing trends of TWS

340 in GHS (0.05 cm/yr) and JX (0.37 cm/yr) are not statistically significant. Although

341 precipitation in JX increased significantly at a rate of 0.16 cm/yr from 2003 to 2022,

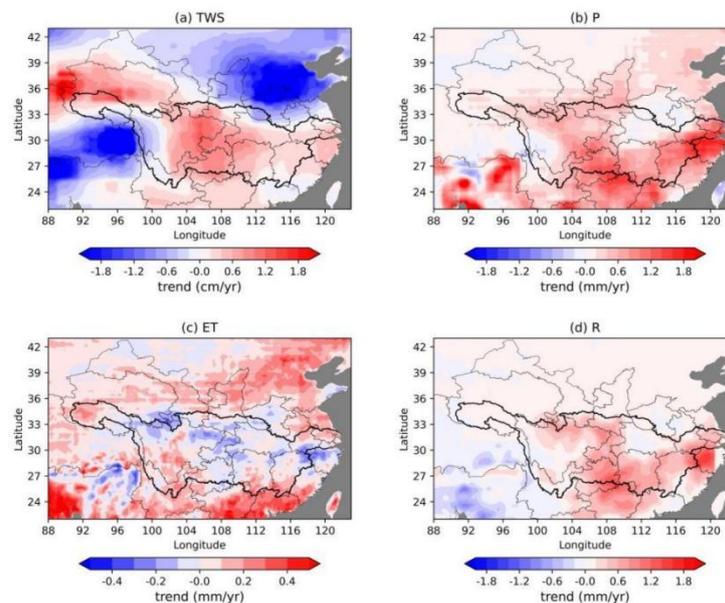
342 the suddenly reduced TWS after 2016, likely caused by the increasing runoff (0.13

343 cm/yr) (Fig. 4), leads to a non-significant trend in TWS over there. In addition, no

344 significant trends in evapotranspiration are observed for these sub-regions. The

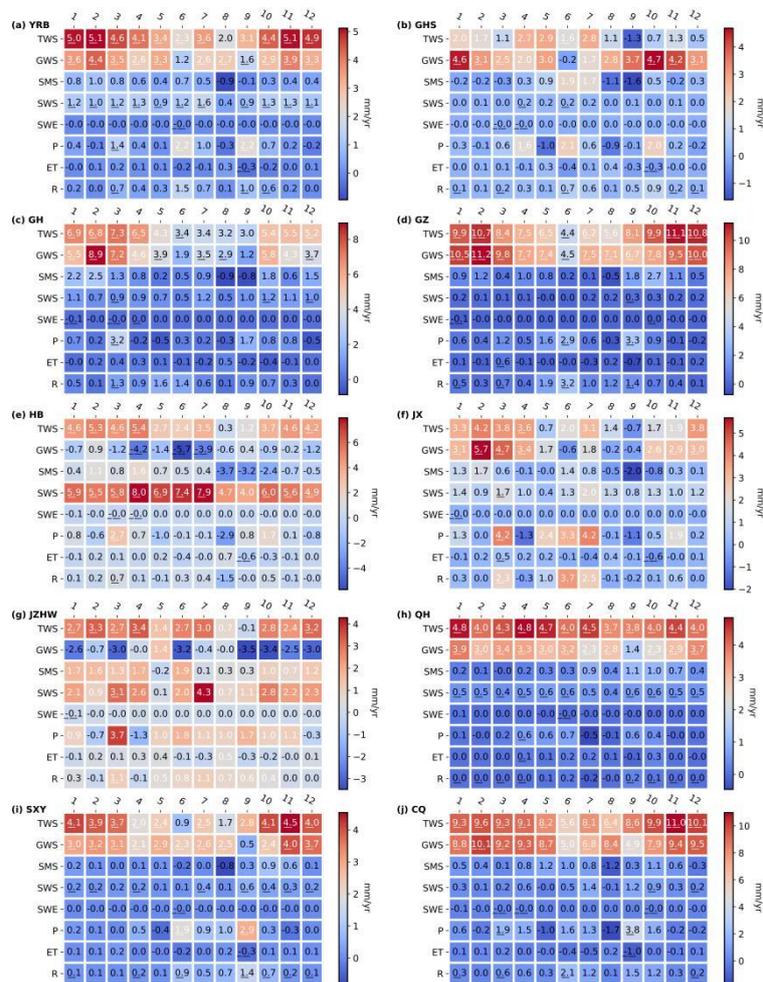
345 increasing trends in runoff over CQ (0.06 cm/yr), GZ (0.11 cm/yr), and GH (0.11

346 cm/yr) primarily result from the increasing precipitation (Fig. 4).



347

368 discernible in all months except August and September. Similar monthly trends in
 369 TWS are observed in GZ, QH, SXY, and CQ (Fig. 5d, h-j). In the GH, HB, and JZWH
 370 regions, noteworthy TWS trends are observed from December to April despite the
 371 absence of discernible increasing trends in precipitation (Fig. 5c, e, and g).
 372 Furthermore, GHS and JX regions generally show no statistically significant positive
 373 trends in TWS and precipitation across all months (Fig. 5b and f)). These findings
 374 indicate the increase in TWS cannot be directly attributed to precipitation.



375

376 **Fig. 5.** Monthly trends in precipitation (P), evapotranspiration (ET), runoff (R), TWS, SWE, SWS,
 377 SMS, and GWS for YRB and its nine sub-regions. The underline signifies significant trends and
 378 correlations at the 95% confidence interval.

379 To further quantify the contributions of precipitation, evapotranspiration, and
 380 runoff to TWS changes, we calculate the trend amplitude ratios by comparing the

381 trends in these variables with respect to TWS. Precipitation predominantly accounts
 382 for the escalating rates observed in GHS and JZWH, contributing approximately 60%
 383 and 65%, respectively. However, in regions such as SXY, CQ, GZ, and GH, where
 384 TWS demonstrates relatively substantial positive trends, precipitation contributes less
 385 than 20% (Table 3). This further suggests that precipitation is not the direct factor
 386 driving the increase in TWS in these areas. Additionally, the trend amplitude ratios of
 387 evapotranspiration to TWS are less than 5%, while runoff contributes prominently in
 388 GHS (60%) and JX (35.14%). Therefore, the observed non-significant increasing
 389 trends in TWS within these specific regions can be partly attributed to the high runoff
 390 ratios, consistent with Figs. 3-4.

391 **Table 3.** Percentage (%) of trends in precipitation (P), evapotranspiration (ET), runoff (R), SWE,
 392 SWS, SMS, and GWS to trends in TWS over YRB and its nine sub-regions.

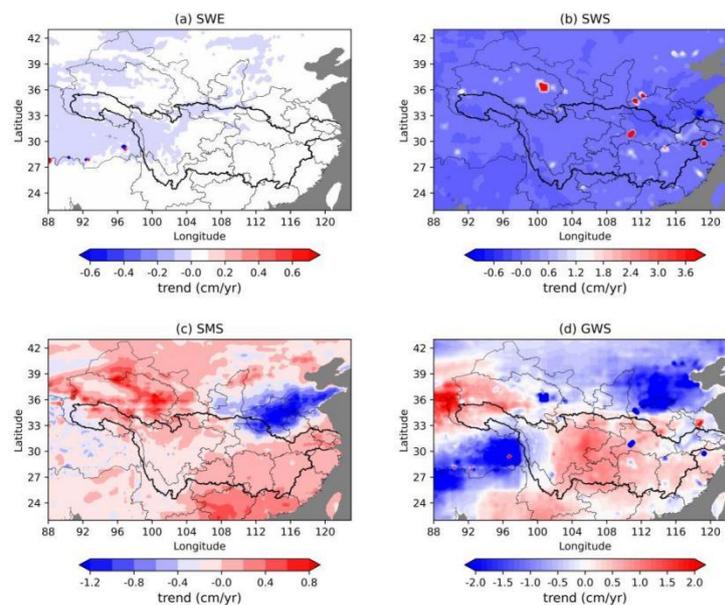
	YRB	QH	SXY	GHS	CQ	GZ	HB	GH	JZHW	JX
P	21.95	5.26	14.29	60.00	10.98	16.05	7.41	20.00	65.00	43.24
ET	0.00	2.63	0.00	0.00	2.44	1.23	3.70	1.54	5.00	0.00
R	12.20	0.00	14.29	60.00	7.32	13.58	0.00	16.92	30.00	35.14
SWE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SWS	29.27	13.16	8.57	20.00	6.10	2.47	218.52	18.46	110.00	40.54
SMS	2.44	13.16	5.71	500.00	2.44	9.88	18.52	27.70	90.00	48.65
GWS	60.98	78.95	80.00	360.00	84.15	98.77	66.67	69.23	170.00	113.51

393

394 4.2. Trends in water storage components

395 In YRB, SWE is predominantly concentrated in the source region, in which
 396 spatially consistent negative trends are observed (Fig. 6a). These trends are attributed
 397 to rising temperatures associated with global warming (Li et al., 2023). The trend map
 398 of SWS generally aligns with the map of lakes and reservoirs within YRB (Fig. 2a-b).
 399 For example, apparent trends in SWS are observed in TGR and the three largest lakes
 400 (Fig. 6b). The observed increasing trends in SWS in YRB are primarily attributable to
 401 the rising number of reservoirs (Rodell et al., 2018). As for SMS, positive trends are
 402 observed in the provinces of GZ, Hunan, Jiangxi, and Yangtze River Delta, whereas
 403 negative trends are concentrated in Sichuan, parts of CQ, parts of Hubei and Anhui

404 provinces (Fig. 6c). These declining trends are highly likely caused by intensive
 405 agricultural activities, given that the agricultural yields of these regions rank among
 406 the top four within YRB (<http://www.stats.gov.cn/sj/nds>). Compared to SWE, SWS,
 407 and SMS, GWS within YRB displays a substantial positive trend in amplitude, except
 408 in instances where significant increasing trends are observed in SWS. This implies
 409 that surface water bodies in YRB are actively intercepting water reserves. Negative
 410 trends are also identified in the western Sichuan province, attributed to reduced
 411 precipitation, as reported by Jing et al. (2020) and Xiong et al. (2022). In addition, the
 412 trend map of GWS closely mirrors the trend map of TWS in Fig. 3a, indicating that
 413 the increased TWS within YRB primarily results from the rise in GWS, which is
 414 consistent with the studies conducted by Chao et al. (2023) and Rodell et al. (2018).

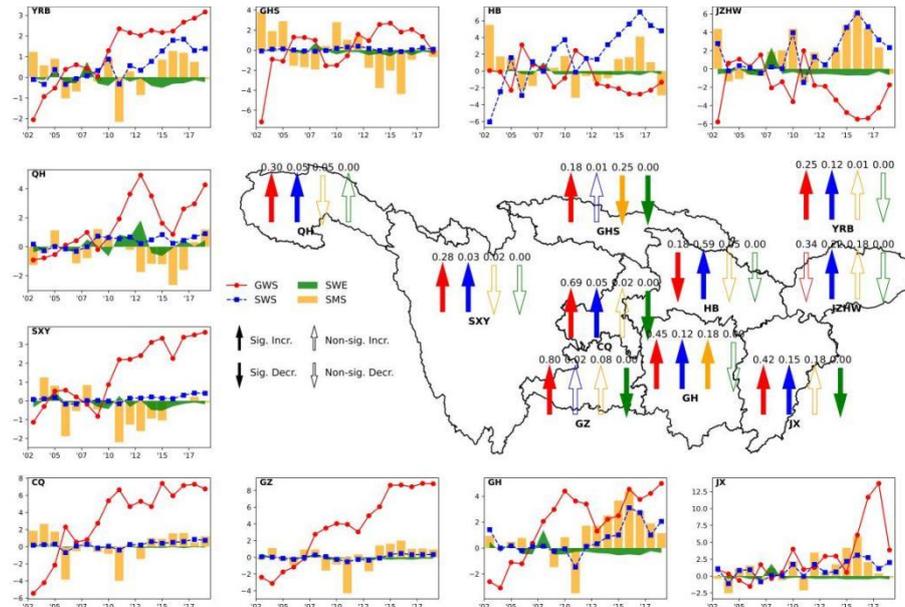


415

416 **Fig. 6.** Spatial trends in (a) SWE, (b) SWS, (c) SMS, and (d) GWS over YRB. The trends in SWS
 417 and GWS are calculated for the period 2002-2019, whereas those in SWE and SMS are calculated
 418 for the period 2002-2022.

419 [Figure 7](#) illustrates the annual changes and trends in SWE, SWS, SMS, and GWS
 420 for YRB and its nine sub-regions. GWS and SWS exhibit statistically significant
 421 increasing trends for the whole basin, with respective rates of 0.25 cm/yr and 0.12

422 cm/yr, while SWE and SMS show minuscule trends. Specifically, SWE within YRB
423 displays negligible trends, even in QH. Statistically significant positive and negative
424 trends in SMS are only discerned in GH and GHS, with rates of 0.18 cm/yr and 0.25
425 cm/yr, respectively. The escalating trend in GHS is ascribed to an augmentation in
426 precipitation at a rate of 0.13 cm/yr, while the decline in SMS over GHS is likely
427 caused by a relatively high consumption of subsurface water (Figs. 1 and 2c-d). SMS
428 in JZHW and JX regions shows increasing trends but falls short of the 5%
429 significance level, while other areas manifest marginal trends. As for SWS, increasing
430 trends are found in QH, SXY, CQ, HB, GH, JZHW, and JX, with rates of 0.05 cm/yr,
431 0.03 cm/yr, 0.05 cm/yr, 0.59 cm/yr, 0.12 cm/yr, 0.22 cm/yr, and 0.15 cm/yr,
432 respectively. These observed trends underscore the spatial distribution of lakes and
433 reservoirs within YRB (Figs. 2a-b). Furthermore, noteworthy positive trends in GWS
434 are discernible in QH, SXY, GHS, CQ, GZ, GH, and JX, with rates of 0.3 cm/yr, 0.28
435 cm/yr, 0.18 cm/yr, 0.69 cm/yr, 0.8 cm/yr, 0.45 cm/yr, and 0.42 cm/yr, respectively.
436 Significant and non-significant declining trends in GWS are observed in HB (0.18
437 cm/yr) and JZHW (0.34 cm/yr), respectively. The negative trend observed in HB is
438 presumed to be a consequence of surface water bodies in the region intercepting
439 precipitation. The increasing trends in TWS with YRB are generally attributed to
440 GWS, followed by SWS, except HB and JZHW. This is evident in Table 3, wherein
441 the ratios between the trends in GWS and TWS generally exceed 60% across YRB.



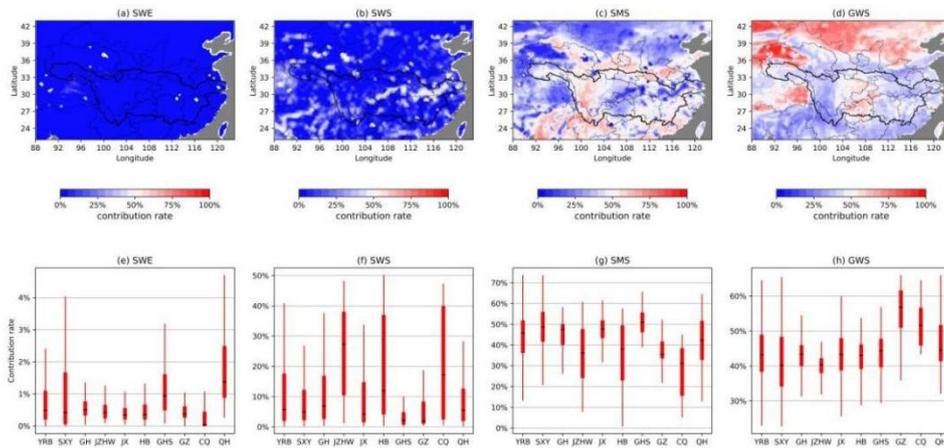
442

443 **Fig. 7.** Annual changes and trends (cm/yr) in SWE, SWS, SMS, and GWS over YRB and its nine
 444 sub-regions for the period 2003-2019. The x-axis represents two-digit years, while the y-axis
 445 indicates annual changes in GWS, SMS, SWS, and SWE in centimeters. The upward and
 446 downward arrows signify increasing (Incr.) and decreasing (Decr) trends, respectively, with
 447 statistically significant (Sig.) trends at the 95% confidence interval filled with distinctive colors.

448 Regarding the monthly trends across the years, GWS in YRB demonstrates
 449 statistically positive trends in all months except June. The rates vary from 1.6 cm/yr in
 450 September to 4.4 cm/yr in February (Fig. 5a). Notably, these trends predominantly
 451 manifest during the non-monsoon season, aligning with the observed trends in TWS.
 452 Similarly, SWS experiences significant increasing trends in all months except August
 453 within YRB. Comparable positive GWS trends are discernible in various regions, with
 454 the exceptions of JZWH and HB, where contrary trends are identified across different
 455 months. Furthermore, noteworthy increasing trends in SWS are identified in HB, SXY,
 456 and QH. SMS does not reveal any statistically significant trends across the entire
 457 basin, whereas the trends in SWE prove to be negligible. These observations
 458 substantiate that the increasing TWS within YRB primarily results from increased
 459 GWS and SWS.

460 We further quantify the contributions of individual components to TWS through

461 the use of CCR. Generally, SWE's contributions are less than 1%, with relatively
 462 higher contributions noted in high-altitude and high-latitude regions, such as QH,
 463 SXY, and GHS (Figs. 8a and e). As for SWS, relatively substantial contributions are
 464 observed in JZHW, HB, and CQ, where a considerable number of lakes and reservoirs
 465 are situated (Figs. 2a-b). Conversely, SWS accounts for less than 20% of TWS in
 466 other regions. The median contributions of SMS and GWS surpass 30% and 40%,
 467 respectively (Figs. 8c-d and g-h). In YRB, SMS and GWS contribute comparably
 468 concerning the amplitude. The most noteworthy and least significant contributions of
 469 SMS are discerned in GHS and CQ, exhibiting median CCR values greater than 50%
 470 and 30%, respectively. The observed CCR values for GWS in YRB, SXY, GH, JZHW,
 471 JX, HB, and GHS demonstrate similar variations, ranging from 40% to 50%. The
 472 highest and lowest contributions are identified in GZ and CQ, displaying median CCR
 473 values exceeding 50%.



474

475 **Fig. 8.** Map of contribution rates of (a) SWE, (b) SWS, (c) SMS, and (d) GWS to TWS over YRB,
 476 with (e-h) box-plots showing the statistical results for YRB and its nine sub-regions.

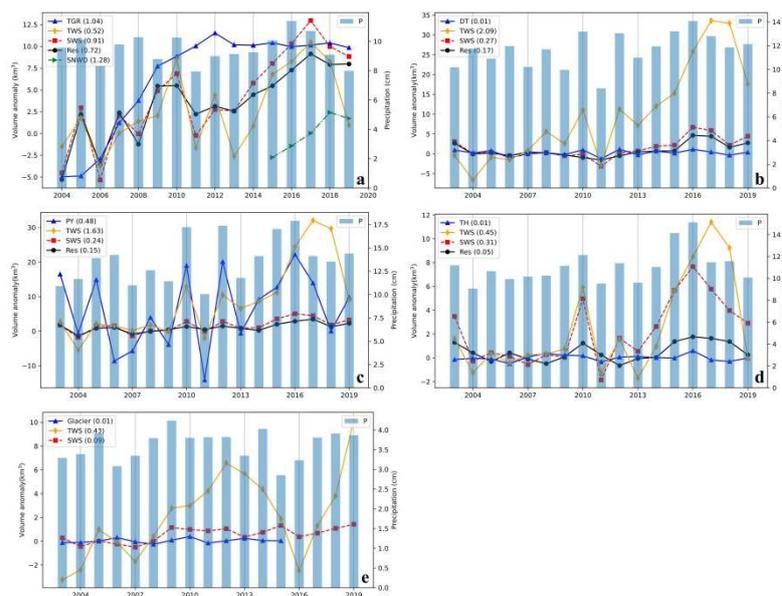
477 4.3. Influence of large lakes and reservoirs on YRB's TWS

478 The changes in TWS within YRB are influenced by several signals, such as those
 479 around the three largest lakes and TGR, as well as the South-to-North Water
 480 Diversion (SNWD) project. To assess their potential influence on the dynamics of

481 TWS in YRB and ensure a fair comparison, we convert TWS, SWS, and reservoir
482 water storage (Res) into volume anomalies by the respective areas of the regions
483 where the water bodies are situated. As the water level of the TGR steadily rose to its
484 target level of approximately 175 meters by the end of the year 2011 and entered into
485 its normal operational phase, the volume anomaly of the TGR showcases a
486 noteworthy positive trend of $1.04 \text{ km}^3/\text{yr}$ from 2004 to 2019 (Fig. 9a). During this
487 period, TWS, SWS, and Res in HB experienced increases at rates of $0.52 \text{ km}^3/\text{yr}$, 0.91
488 km^3/yr , and $0.72 \text{ km}^3/\text{yr}$, respectively. These trends generally display a consistent
489 increasing pattern with that of the TGR. Therefore, the observed rise in TWS in HB is
490 primarily ascribed to the impact of TGR. The lower trend observed in TWS compared
491 to SWS and Res also indicates the interception functions of surface water bodies. This
492 effect contributes to a decrease in GWS at a rate of $0.18 \text{ cm}/\text{yr}$, equivalent to 0.33
493 km^3/yr , as observed in the HB (Fig. 7). Notably, this value is consistent with the
494 observed trend difference between TWS and Res. In addition, the water transferred by
495 the SNWD project registered an increase at a rate of $1.28 \text{ km}^3/\text{yr}$, indicating that the
496 project is poised to substantially influence water storage in HB. However, it is
497 essential to exercise caution in interpreting the impact of SWND, given the relatively
498 short period covered by the analyzed data and the distinct mean field used to compute
499 the volume anomaly (2015-2019) in comparison to TWS, SWS, and Res (2004-2009).

500 Regarding the influence of Lakes Dongting and Taihu, they exhibit limited
501 influence on the increased TWS in GH and JZWH, respectively, reflected in their low
502 increasing rates of both $0.1 \text{ km}^3/\text{yr}$ (Fig. 10b and d). SWS in JZWH show comparable
503 trends with TWS, implying that other surface water bodies together lead to increased
504 TWS. Nevertheless, Lake Poyang exhibits a relatively high influence on JX's TWS.
505 Fig. 10c shows that the volume of Lake Poyang has marked inter-annual variations,

506 correlating well with precipitation. From 2003 to 2019, Lake Poyang revealed an
 507 increasing rate of 0.48 km³/yr, accounting for about 30% of the trend observed in
 508 TWS in JX. Due to the unique geological location of Lake Poyang, it functions as a
 509 massive natural reservoir, playing a crucial role in regulating floods within YRB. JX
 510 can be envisioned as a vast basin tilting towards Lake Poyang, where the five major
 511 water systems within the province converge and discharge into the Yangtze River. In
 512 times of heavy rainfall within JX, the runoff from these five water systems passes
 513 through Lake Poyang before ultimately joining the Yangtze River (Liu et al., 2020; Xu
 514 et al., 2020). Therefore, at an annual scale, Poyang Lake may exert a higher influence
 515 on JX's water storage than SWS and Res (Fig. 10c).



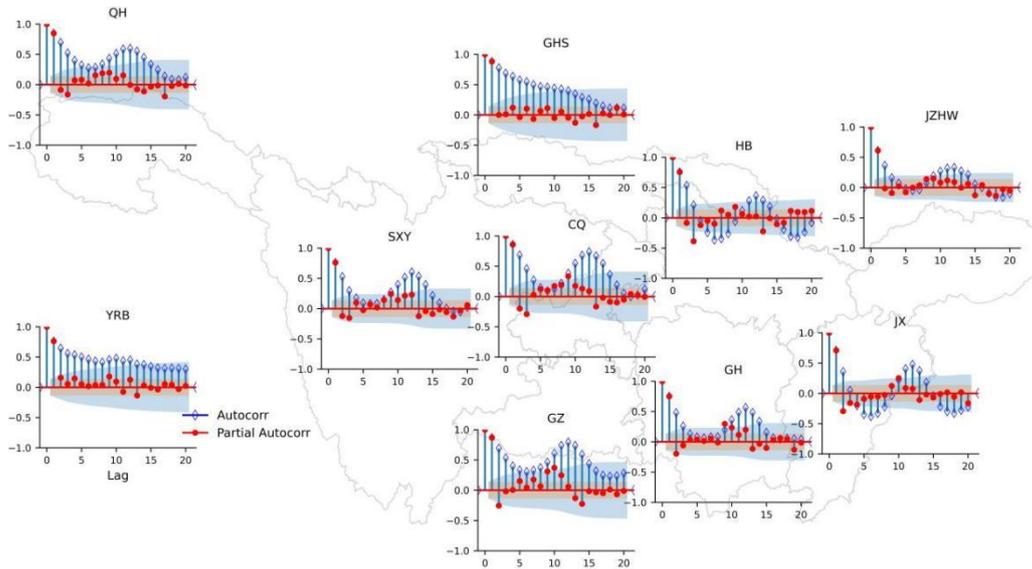
516
 517 **Fig. 9.** Annual volume anomalies of TWS, SWS, reservoir (Res), South-to-North-Water-Diversion
 518 (SWND) project, TGR, Dongting (DT) lake, Poyang (PY) lake, Taihu (TH) lake, and glaciers. The
 519 volume anomaly of TWS, SWS, Res and glacier are computed by multiplying the equivalent water
 520 heights by the area of (a) HB, (b) GH, (c) JX, (d) JZWH, and (e) QH, respectively, with annual
 521 mean precipitation series shown in the right axis. The numbers in the bracket are the trends in
 522 km³/yr.

523 5. Discussion

524 Precipitation, serving as the direct recharge for TWS changes, has been reported

525 in previous studies as the key factor behind the observed increases in TWS in various
526 regions, even in areas where precipitation does not exhibit significant trends (e.g.,
527 [Awang et al., 2014](#); [Rodell et al., 2018](#); [Zhang et al., 2019b](#); [Chao et al., 2023](#)).
528 However, within YRB, we have shown that the observed amplitude of trends in
529 precipitation is notably inferior to that in TWS ([Figs. 3-4](#)), suggesting precipitation is
530 not a direct factor contributing to the augmentation of TWS in YRB. [Figs. 5-8](#)
531 demonstrate that the increased TWS primarily stems from increased GWS. Notably,
532 the GWS for the current month is typically replenished by the precipitation occurring
533 in the same month, primarily through infiltration. Additionally, there is a partial
534 contribution from the residual GWS from the preceding month ([Hipel & McLeod,](#)
535 [1994](#)). This is evident from [Fig. 10](#), which shows a sine exponential decay observed
536 in the autocorrelation plot of each GWS time series within YRB and a significant
537 positive cut-off at lag 1 in the partial autocorrelation plot. This strongly implies that
538 the time series of GWS conforms to a first-order autoregressive model, confirming the
539 contribution of GWS from the previous month to that for the current month. In
540 addition, [Fig. 5](#) reveals that the most significant increase in TWS occurs during a
541 relatively low precipitation period. Therefore, the continuous accumulation of GWS
542 from the preceding month contributes to the observed augmentation in GWS ([Fig. 4](#)).
543 Additionally, the predominant source of water within YRB originates mostly
544 (exceeding 90%) from SWS ([Fig. 1](#)), thereby resulting in minimal depletion of GWS.
545 The cumulative effect of these factors manifests in an increase of GWS and thus TWS
546 in QH, SXY, CQ, GZ, GH, and JX ([Fig. 4](#)). However, the observed significant and
547 non-significant decreasing trends in GWS in HB and JZWH are highly likely
548 attributed to water interception in surface water bodies because SWS in HB and
549 JZWH exhibits significant positive trends at a rate of 0.59 cm/yr and 0.22 cm/yr,

550 respectively (Fig. 7). Furthermore, precipitation does not exhibit decreasing trends
551 (Fig. 4) in these two regions, and the discernible absence of a substantial depletion of
552 GWS, as depicted in Fig. 1.



553

554 **Fig. 10.** The autocorrelation and partial autocorrelation of GWS for YRB and its nine sub-regions,
555 with the light blue and red envelopes denoting the 95% confidence intervals.

556 In addition to GWS, the rising SWS within YRB also plays an important role in
557 the overall increase in TWS. Specifically, in QH, glacier thawing contributes only
558 about 2% to the expanding TWS (Fig. 9e), while lake expansion accounts for a more
559 substantial 21% (Fig. S13). The increasing SWS in SXY and JX result from the
560 increasing water in reservoir and river, whereas significant positive trends in SWS
561 observed in CQ and GH are attributable to the rise in river water storage (Fig. S13).
562 Furthermore, the observed increasing trends in TWS in JZWH are primarily
563 attributable to the wetland and lakes (Fig. S13), whereas TGR contributes to the
564 increasing water storage in HB (Fig. 4). Significant increasing trends in SWS in GZ,
565 GH, and JX are partly explained by the significant increasing trends observed in
566 precipitation (Fig. 4). In addition, Lake Poyang also demonstrates a significant
567 contribution to the increased TWS in JX. The non-significant trend in TWS observed

568 in GHS is balanced by the GWS accumulation (0.18 cm/yr) and SMS depletion (-0.25
569 cm/yr) (Figs. 4 and 7). Overall, the observed increasing trends in TWS within YRB
570 result from GWS accumulation, followed by the increasing SWS (Fig. 4).

571 **6. Conclusion**

572 In this study, we reveal the drivers of TWS changes in YRB using multisource
573 data from 2002 to 2022. The key findings are:

574 1. Most YRB demonstrates notable upward trends in TWS, with the central
575 region exhibiting particularly significant increases. The trends observed in
576 precipitation are an order of magnitude lower than those observed in TWS, suggesting
577 precipitation is not a direct factor contributing to TWS increases.

578 2. The increasing TWS within YRB is attributed to the rising GWS in QH, SXY,
579 CQ, GZ, GH, and JX, along with the increasing SWS in HB and JZHW. The
580 increasing GWS within YRB primarily results from the cumulative increase in GWS
581 combined with minimal depletion of groundwater resources. The increasing SWS in
582 HB results from the TGR filling, whereas the observed increasing trends in SWS in
583 JZWH are ascribed to the lake and wetland expansion. The relatively balanced TWS
584 changes observed in GHS are caused by the GWS accumulation and SMS
585 consumption.

586 3. The increasing precipitation in SXY, GZ, GH, and JX contributes to the
587 increase of TWS, accounting for about 14%, 16%, 20%, and 43%, respectively. Lake
588 Poyang contributes to approximately 30% of the observed trend in TWS in JX, while
589 the influence of Lakes Dongting and Taihu on the respective region's TWS is
590 comparatively limited. In addition, the observed increasing trends in SWS in QH is a
591 consequence of the lake expansion, with limited influence from glacier thawing.

592 **Declaration of Competing Interest**

593 We declare that there are no known competing financial interests or personal
594 relationships that could have appeared to influence the research presented within this
595 manuscript.

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600 **Open Research**

601 The data collected as part of this work are publicly available in Zenodo (Wang,
602 2024). The data were analyzed using Python version 3.8 (Van Rossum & Drake,
603 2009). Figures were made with Matplotlib version 3.5.1 (Hunter, 2007), available
604 under the Matplotlib license at <https://matplotlib.org/>. Maps were created through
605 Cartopy version 0.21.0 (Elson et al., 2021).

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